Toronto and Region Conservation Authority

Carruthers Creek Watershed Plan

Soil Water Assessment Tool (SWAT) Modelling

September 20, 2019

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1 Foreword

The Region of Durham recognizes watershed plans as an effective tool to inform the management of Durham's water resources, natural heritage, and natural hazards, such as flooding. In 2015, the Region retained the Toronto and Region Conservation Authority (TRCA) to update the watershed plan for Carruthers Creek.

This four-year study will build upon the goals, objectives, and management recommendations established in the 2003 *Watershed Plan for Duffins Creek and Carruthers Creek*.

The following report is one of a series of scenario analysis technical reports that follow the watershed characterization studies (completed in 2017). Information contained in these technical reports will examine potential impacts of future growth and land use changes in combination with other influences such as climate change. Additionally, these technical reports provide the knowledge base necessary to develop the plan's management recommendations. Any recommendations contained in the scenario analysis technical reports are consolidated in the Carruthers Creek Watershed Plan's management framework. The Watershed Plan is the final source for goals, objectives, indicators and management recommendations related to Carruthers Creek. Readers are encouraged to refer to the technical reports for more detailed implementation suggestions.

Building upon extensive investments in environmental modelling and decades of research applications by Environment and Climate Change Canada (ECCC) and other researchers in the Great Lakes Basin and across Canada, the Toronto and Region Conservation Authority (TRCA) has adopted the Soil & Water Assessment Tool (SWAT) model as a decision support tool for investigating a range of land use scenarios, observed climate patterns and candidate best management practices (BMPs). Applications of the SWAT model for the Carruthers Creek Watershed Plan is a collaborative effort of Toronto and Region Conservation Authority (TRCA) and Environment and Climate Change Canada (ECCC) scientists who have been working together for a long time, collaboratively investigating water quality linkages between local watersheds and Lake Ontario.

2 Executive Summary

Efforts taken to set up the SWAT model in the Carruthers Creek watershed and to complete its initial calibration are described along with modelling results from continuous simulations of watershed derived flows, nutrient and sediment loads for the climate record of 2005 to 2015 and under five configurations in land use.

Watershed response over time can be evaluated by comparing the five scenarios that depict a range of land use and natural cover configurations, that either currently exist or may occur in the future. Historical conditions, Current conditions, and Scenario 1 (+OP) offer an understanding of how this watershed has responded to previous and currently planned development in the watershed. Scenario 2 (+NHS) proposes the additional benefits of an enhanced Natural Heritage System (NHS). Finally, Scenario 3 (+Potential Urban) evaluates the impacts of potential future development in the watershed based on the assumption that lands not protected by the enhanced NHS proposed in Scenario 2 (+NHS) would at some future point be urbanized. For the purpose of this water quality modelling exercise, these future urban lands were assumed to be high density urban land uses.

Under high precipitation years, there is generally more pronounce increase in the flow, total nitrogen (TN), total phosphorous (TP), and total suspended solids (TSS). This would be expected as higher precipitation volumes would derive increases in nutrients and sediment inputs to the stream. Responses to shifts in land use across the five scenarios are presented but in comparisons to observed shifts in climate are less dramatic.

The SWAT model depicts increases in average flows and total suspended solid loads between 1999 and 2015, and reductions in both TP and (TN) loads for the current land use. These changes are likely reflective of the transformation of agricultural lands into urban land uses during this time period. Simulation of Scenario 2 (+NHS) depict further decline in average stream flows, TSS, TN, and TP loads to the lake. Simulation of Scenario 3 (+Potential Urban) depict an increase in stream flows and TSS and reductions in TN and TP loads in response to conversion of agricultural lands to urban land use and the resulting lower rates of erosion and fertilizer application. Of note is the observation that the enhanced NHS is an effective water quality mitigation tool as flows and total suspended solid loads for Scenario 3 (+Potential Urban) are modelled as being only slighter higher than those reported for Scenario 1 (+OP). Reductions in TP and TN loads are also expected to occur in Scenario 3 (+Potential Urban) compared with Scenario 1 (+OP).

The SWAT model results suggest that additional water quality changes will occur in the future, due to urban growth and the anticipated extremes in climate change making the imperative for better watershed scale management efforts even stronger. Careful considerations are needed to inform future urban growth considerations in the watershed; and to ensure efforts are taken to correct for the SWAT modelled response to the recent build out of the watershed.

The following recommendations are provided as an outcome of the SWAT modelling for the Carruthers Creek watershed. These recommendations address the need for improved local data to set and up and calibrate the model as well as management recommendations going forward.

- That new climate stations be set up in the Carruthers Creek watershed to allow for future calibration and validation of the SWAT or other watershed scale models used in the Carruthers Creek watershed to improve their performance.
- That stream gauge rating curves be updated, and that streamflow monitoring be continued at the four current locations in the watershed.
- The enhanced tributary water quality program for the Carruthers Creek watershed should continue for the foreseeable future, in order to provide accurate monitored loading estimates for the watershed and to allow for future comparisons with water quality model outputs.
- The utility of the SWAT model for water quality flows estimation needs to be considered in a highly urbanized watershed. If there are issues with the threshold for urbanization in SWAT, then a different watershed response model needs to be recommended.
- That the water balance used in SWAT and the streamflow outputs of the SWAT model should be compared with Modflow groundwater estimations and as well the event hydrology model.
- That the rural BMPS modelled in SWAT be considered for roll out in the agricultural areas of the watershed in consultation with the farm community.
- That local information on fertilizer application rates be gathered for rural and urban areas and for the three golf courses and that the fertilizer application rates in the SWAT model be updated using these revised applications rates.
- That an enhanced natural heritage system, which SWAT has been shown to be an effective management tool, be implemented throughout the Carruthers Creek watershed.
- As future climate change scenarios are developed for southern Ontario, they should be applied to model the Carruthers Creek watershed.

3 Introduction

Typically, the initiation of a watershed study includes a program of updating the knowledge base for the watershed through the review of monitoring program data and focused field studies. Through these initial watershed planning efforts, the conditions in the watershed are better understood, albeit for only a specific time period and for the current state of the watershed; in terms of its land use, climate patterns and watershed management efforts. They do not really afford any understanding of past or future conditions in the watershed. Increasingly, environmental models are used in watershed studies to help managers better understand watershed responses to drivers of changes and to help managers with the evaluation of candidate management practices.

Soil & Water Assessment Tool (SWAT) Model

The Soil & Water Assessment Tool (SWAT) model has been widely applied in Great Lakes watersheds for the purposes of simulating stream flow, sediment and nutrient loadings and for the assessment of reduction efforts of BMPs and most recently it has been used with climate change scenarios to project future conditions. Efforts are also underway to enhance this model to Canadian climate conditions (Liu et al., 2016).

SWAT is one of the watershed response tools used in the watershed study to conduct a health assessment that leads to the development of watershed ratings, targets and candidate management actions that will achieve the vision, goals and targets for the watershed. The SWAT model is being used solely as a decision support tool to help TRCA understand the predicted environmental impact and watershed response to various land use, land management practice and climate change scenarios. During the integration phase of this study, TRCA will be comparing the watershed responses predicted by SWAT with the watershed responses from the event-based hydrology model, steady state groundwater water model, and terrestrial and aquatic impact analyses. In addition, the SWAT model provides an estimate of nutrient loads to Lake Ontario, nutrient source areas, and insights into the effectiveness of some potential rural best management practices.

It is important to mention that the SWAT modelling results for Carruthers Creek are not considered to be definitive outcomes with respect to future shifts in stream flow and water quality under these land use and future climate scenarios. TRCA recognizes the full benefits of an expanded natural heritage system (NHS), including enhanced forest and meadow areas. Watershed modelling assumes that the NHS will be fully achieved, over a long-time frame as the meadows, forests, and wetlands become established, and as underlying steady state processes that affect long-term water balance and nutrient levels in the watershed are reached.

4 Methods

The SWAT model was developed by the United States Department of Agriculture (USDA) in the 1990s. SWAT is a widely used decision support tool that can analyze land use, best management practices (BMPs), and estimate nutrient loadings. It is a continuous, semi-distributed, process-based watershed scale model. SWAT is commonly used to predict the impact of land management practices on water flows, sediment, and water quality. A typical set-up for SWAT involves breaking the watershed into hydrologic response units (HRUs). HRUs are lumped areas in the sub-catchments with similar land cover, soils, and topographic features. Model outputs can be watershed, sub-catchments, HRUs and reaches (Figure 1). Basic assumptions for the modelling framework are based upon field observations. SWAT incorporates a curve number method for predicting runoff, which was developed by the USDA Natural Resources Conservation Service, formerly called the Soil Conservation Service or SCS. The SCS number is popularly known as a "SCS runoff curve number" in the literature. The runoff curve number was developed from an empirical analysis of runoff from small catchments and hillslope plots monitored by the USDA. It is widely used and is an efficient method for determining the approximate amount of direct runoff from a rainfall event in a particular area. Soil erosion is modelled using Modified Universal Soil Loss Equation (MUSLE). Additional details on application of the SWAT modelling framework are provided in Junyu (2018), Liu et al. (2016), Yang (2016), and Asadzadeh et al. (2015).

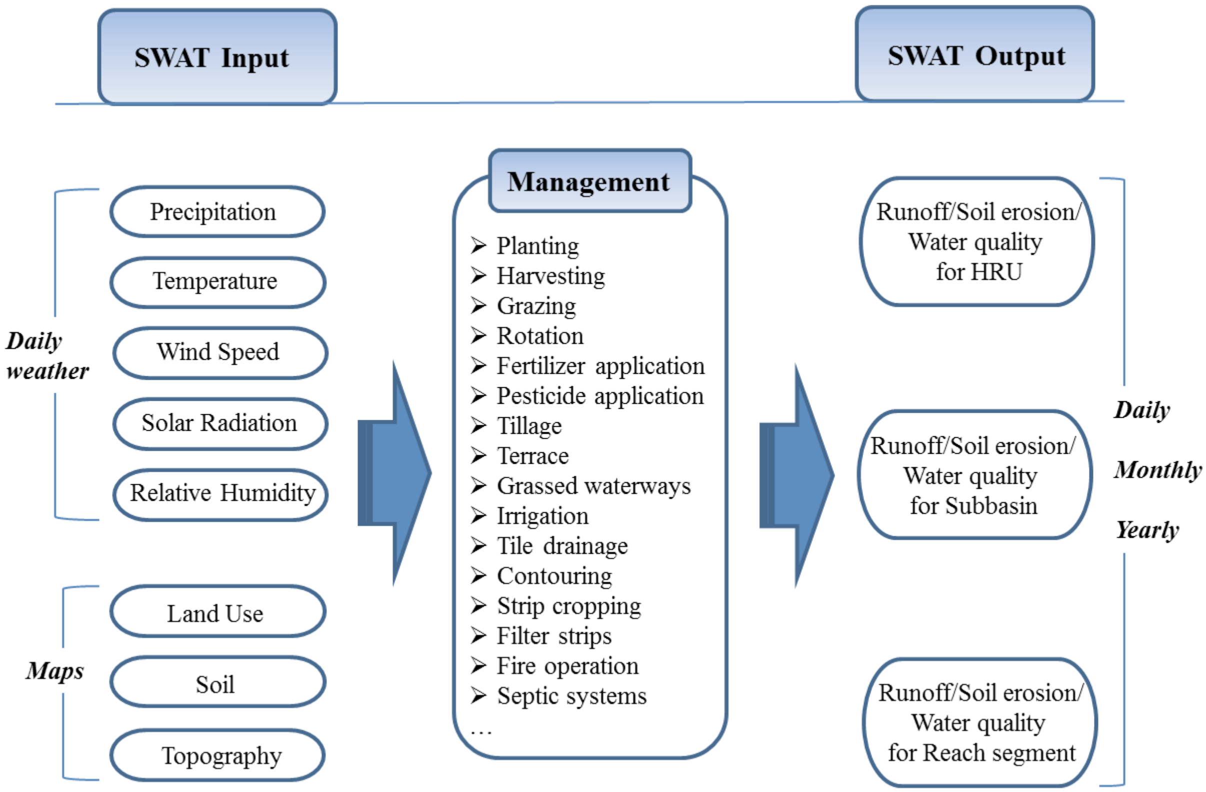


FIGURE 1 MODEL INPUTS, OUTPUTS, AND MANAGEMENT OPTIONS FOR THE SWAT MODEL AS DOCUMENTED BY QI JUNYU, UNIVERSITY OF MARYLAND. USED WITH AUTHOR PERMISSION.

Asadzadeh et al. (2015) set up the SWAT model in the nearby Rouge River and Duffins Creek and reported that the model was capable of accurately simulating the hydrological and water quality processes in these watersheds. Because the land use and soil types in the Carruthers Creek watershed are similar to those in the Rouge River and Duffins Creek, it was assumed that similar modelling practice could be followed for this Carruthers Creek watershed SWAT modelling exercise. Based on the recommendation of ECCC modellers, TRCA approached Dr. Masoud Asadzadeh to oversee the set-up of the SWAT model for TRCA. Once the SWAT set-up was completed ECCC modelers kindly agreed to run the SWAT model for TRCA once we had all the land use scenario mapping for the watershed study completed. Mr. Xu Yang, an undergraduate student at the University of Manitoba, was retained as a Co-op Student by the UOM. Yang (2016) documents the principles he applied in setting up the SWAT model for the Carruthers Creek watershed under the supervision of Dr. Asadzadeh (Appendix A). For the purposes of initially setting up the model, TRCA provided Geographic Information System (GIS) layers, including initial land use classes, soil, slope, and sub classes of agricultural land use and crop rotations. Weather data from ECCC's the nearby Oshawa Water Pollution Control Plant (WPCP) was used (precipitation, maximum and minimum daily temperature, and wind speed) for the period of 2005 to 2015. Gaps in the Oshawa WPCP data were augmented with climate data collected by the Town of Ajax at the nearby Town of Ajax Community Centre. Solar radiation data was compiled from TRCA station HYOO4 located in the Duffins Creek watershed on Bayly Street West, at the Region of Durham Sewage Pumping Station with infilling from NASA predictions for the area. For calibration purposes, TRCA provided measured stream flow data to establish model performance in terms of hydrological processes. Three hydrometric locations were provided by TRCA, HY089, HY090 and HY013 (Figure 2), which has the longest period of record, extending from July 2007 to December 2015. TRCA provided available water quality data for calibration purposes. Yang (2016) presents comparison plots of modelled and observed stream flow in Carruthers Creek for 2007 to 2015. The average simulated stream flow in the Carruthers Creek watershed was 0.34 $m^{3/}$sec., which is 5.6% lower than the measured value of 0.36 m^3/sec. Yang (2016) reports that the annual average components of the water balance are similar to the water balance observed in the modelling for the nearby Rouge River and Duffins Creek watersheds (Asadzadeh et al., 2015). At the time when SWAT was initially set-up for the Carruthers Creek watershed, the availability of water quality data was limited in comparison to the data that was available for the model set up, calibration, and validation for the Duffins Creek and Rouge River watersheds (Asadzadeh et al., 2015). During 2008 and 2009 when a special study was underway for Lake Ontario tributaries, the available water quality data for total phosphorus (TP) and total nitrogen (TN) match very well with model simulations and captures almost all of the low and high values of the TRCA data set.

In the fall of 2018, ECCC reviewed Yang's co-op student's project and made a few adjustments to the model set-up, correcting errors in land use interpretations and initial watershed boundary configurations. These adjustments are documented in Appendix B. Next, the ECCC modellers ran the SWAT simulations required for the Carruthers Creek watershed study as detailed below.

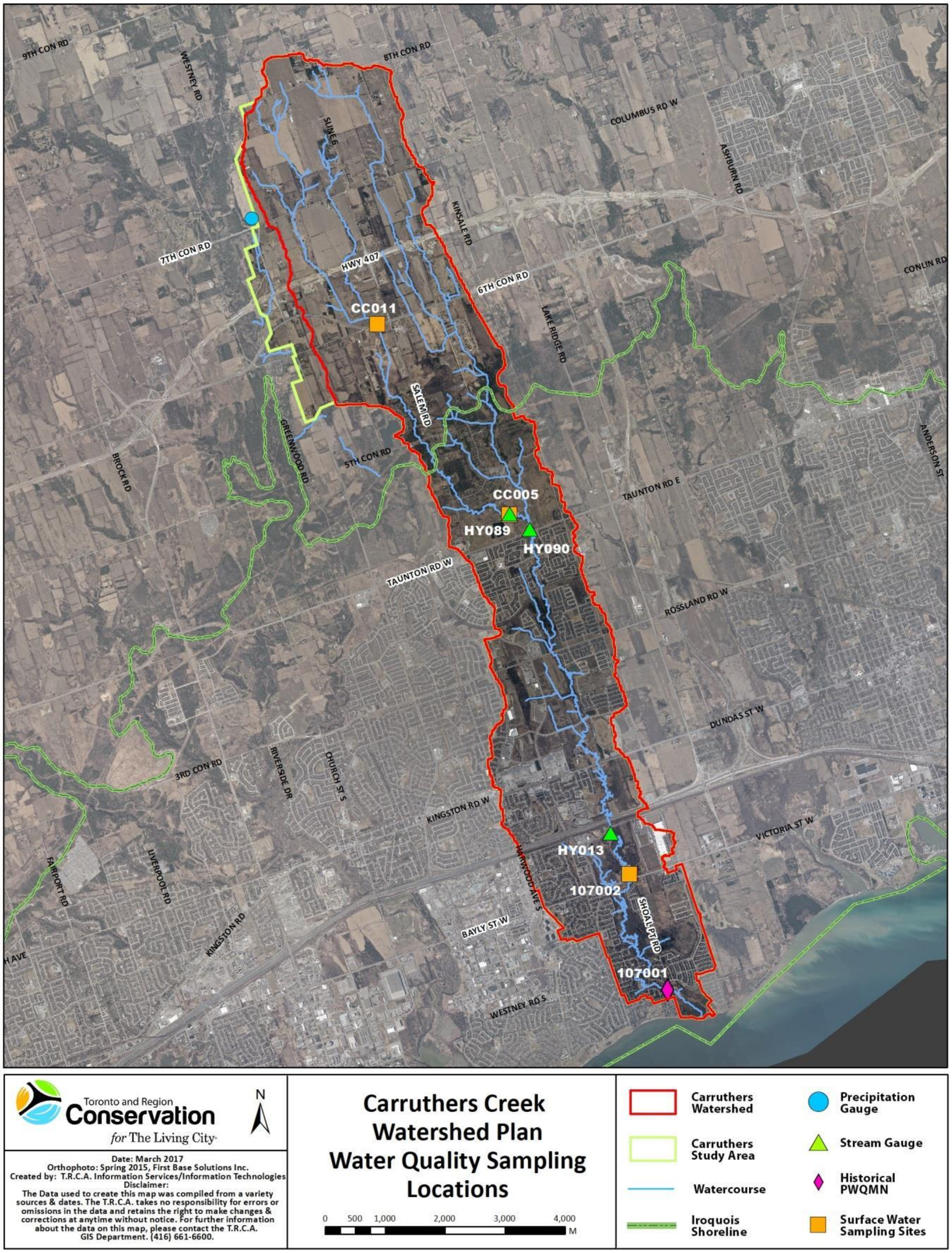


Figure 2 Study area for the Carruthers Creek Watershed Plan with local precipitation (HY015) and stream gauges (HY089, HY090, and HY013), and water quality sampling locations (CC011, CC005, 107002). Oshawa WPCP rain gauge (not pictured) is located approximately 13 kilometers east of the mouth of Carruthers Creek.

Land Use Scenarios

Five land use scenarios (Table 1, Figure 3) have been set-up in the SWAT model to investigate potential impacts to the surface water quality and quantity in the Carruthers Creek watershed.

Watershed response over time can be evaluated by comparing the five scenarios that depict a range of land use and natural cover configurations, that either currently exist or may occur in the future. Historical conditions, Current conditions, and Scenario 1 (+OP) offer an understanding of how this watershed has responded to previous and currently planned development in the watershed. Scenario 2 (+NHS) proposes the additional benefits of an enhanced Natural Heritage System (NHS). Finally, Scenario 3 (+Potential Urban) evaluates the impacts of potential future development in the watershed based on the assumption that lands not protected by the enhanced NHS proposed in Scenario 2 (+NH) would at some future point be urbanized. For the purpose of this modelling exercise, these future urban lands were assumed to be high density urban land uses. Further details on the land use attributes used for the modelling are detailed in the appendixes.

TABLE 1 SUMMARY DESCRIPTIONS OF HISTORICAL AND CURRENT CONDITIONS, AND FUTURE LAND USE SCENARIOS USED FOR FOR THE CARRUTHERS CREEK WATERSHED PLAN AND TECHNICAL STUDIES.

Scenario	Description
Historical	Historical land use conditions from 1999 prior to 2003 CCWP.
Current	Existing land use conditions from 2015 based on aerial photo interpretation.
Scenario 1 (+OP)	Refines current conditions by assuming all lands south of the Greenbelt are now developed as approved up to 2031 in the OPs. Only minor changes from 2015 have resulted as most of the urban area was already developed in 2015.
Scenario 2 (+NHS)	Refines Scenario 1 by adding an enhanced NHS as per the approved OPs and using updated information on terrestrial habitat connectivity, habitat configurations, and climate vulnerabilities.
Scenario 3 (+Potential Urban)	Illustrates prospective development post-2031 in the headwaters area outside of the enhanced NHS identified in Scenario 2. There is no change in the existing urban area south of the Greenbelt.

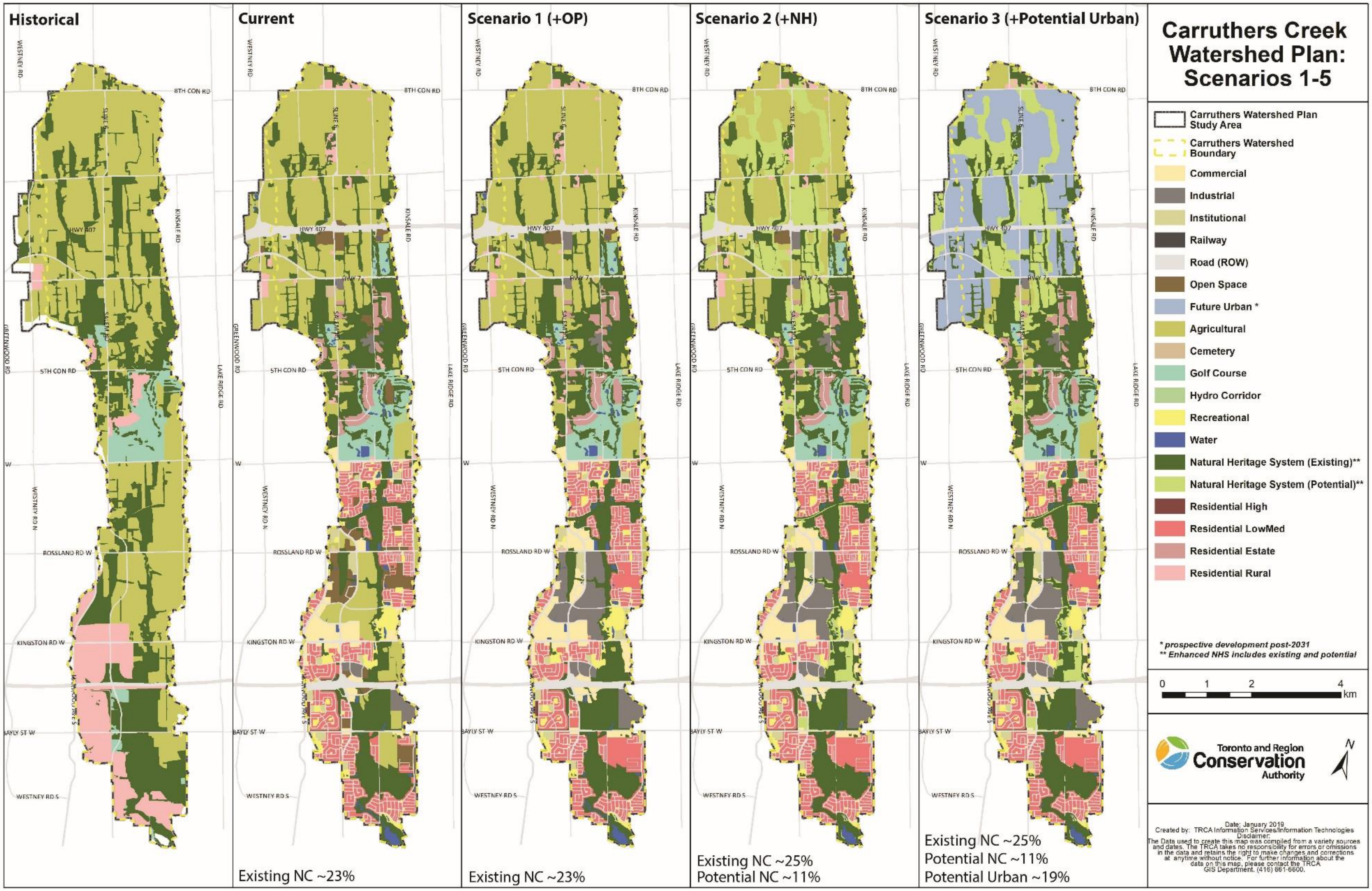


FIGURE 3 THE FIVE LAND USE SCENARIOS DEVELOPED FOR THE CARRUTHERS CREEK WATERSHED PLAN. NC MEANS NATURAL COVER.

Annual and Seasonal Loads of Nutrients and Suspended Solids

The SWAT model's daily output simulations for current land use conditions serves as a reference point for understanding current, past, and future projections for nutrient and Total Suspended Solid (TSS) loads to Lake Ontario. Atmospheric Environment Services (AES) 30-year climate normal, reported on a monthly basis provides insights into comparative drivers of watershed response (land use vs. climate change).

Simulations of Rural Best Management Practices

To understand the effectiveness of candidate rural BMPs, additional SWAT modelling runs using the 2015 land use (Current) as the baseline were undertaken for stream buffers of 15 m, 30 m, and 100 m width along the watercourses. A winter cover crop of clover was also evaluated. Protocols for setting up the BMPs are documented in Appendix B.

5 Results and Discussion

SWAT Model Performance

A critical step in any modelling study is demonstrating the performance of a model through calibration and validation procedures. Our calibration exercise was more of a general check-in; as the model set-up, and by design its performance, was inferred from published results for the Rouge River watershed and Duffins Creek watershed (Asadzadeh et al., 2015).

SWAT modelling results were compared with observed nutrient load estimates for the Carruthers Creek watershed. Table 2 presents a range of annual TP load estimates (in tonnes) based on the results from previous studies completed by ECCC and TRCA for the Credit Valley, Toronto and Region, and Central Lake Ontario (CTC) Source Protection Region and the 2008 Collaborative Science Monitoring Initiative for Lake Ontario (Bowen & Booty, 2011; Makarewicz et al., 2012; Booty et al., 2014). Several different load estimation methodologies were investigated as part of this earlier loading study for the Duffins Creek watershed (Booty et al., 2014). These loading estimation methods were also used to provide a range of TP loads for the Carruthers Creek watershed using the same monitoring data sets.

TABLE 2 COMPARISON OF OBSERVED VS MODELLED ANNUAL TOTAL PHOSPHORUS LOADS (TONNES).

	Observed			Modelled	Difference (model/observed)		
Year	**Low**	**High**	**Average**	**Current Conditions**	**Low**	**High**	**Average**
2007	0.51	2.70	1.59	5.18	10.16	1.92	3.26
2008	1.54	4.90	2.48	14.30	9.29	2.92	5.77
2009	1.72	6.00	3.69	10.10	5.87	1.68	2.74

Average annual TP load estimates for 2007, 2008, and 2009 were compared with the Current conditions land use scenario. Average annual TP loads modelled from the SWAT runs Current conditions were approximately 3 to 6 times higher than the observed loads (Table 2). The modelled loads were 6 to 10 times higher than observed loads on the low end of the spectrum, and 1.7 to 3 times higher on the high end. Uncertainties in the accuracy of the modelled loads exist, due to the relatively short monitoring time span for the water quality data, the reliability of the stream flow records used, and the limitations in observed water chemistry for the Carruthers Creek watershed (Asadzadeh et al. (2015), Appendix A and Appendix B). As a result, it is challenging to ascertain whether the SWAT model is really over-estimating the annual loads. It is probable that existing monitoring data for the Carruthers Creek watershed are not currently adequate for accurate estimation of watershed loads.

Currently, the modelled stream flow response generally aligns with temporal patterns in precipitation, however the modelled stream flow hydrograph does not align with the observed magnitude of flow (Figure 4), as they are substantially higher. Figure 5 and depict the stream response to precipitation at the Oshawa WPCP gauge being offset by one day. A quirk of the SWAT model as discussed by Asadzadeh et al. (2015), is that model response to inputs of daily precipitation has a lag in the timing of flows, with stream responses occurring in the following day. Accordingly, the load estimation from model results are also offset by one day.

Similar data challenges were encountered with the calibration of an event-based hydrology model developed for flood impact scenarios as part of this watershed study. The precision of the current monitored load estimates does not allow for a conclusion to be made at this time on the validity of the SWAT model load estimates. It could be that the actual loads are in fact higher than those currently reported. If this is the case, SWAT is accurately predicting the nutrient and total suspended solid (TSS) loads. While the validity of the estimates of nutrients coming out of the watershed are in question, the overall model performance was deemed adequate to justify SWAT’s use in a decision support role in the study.

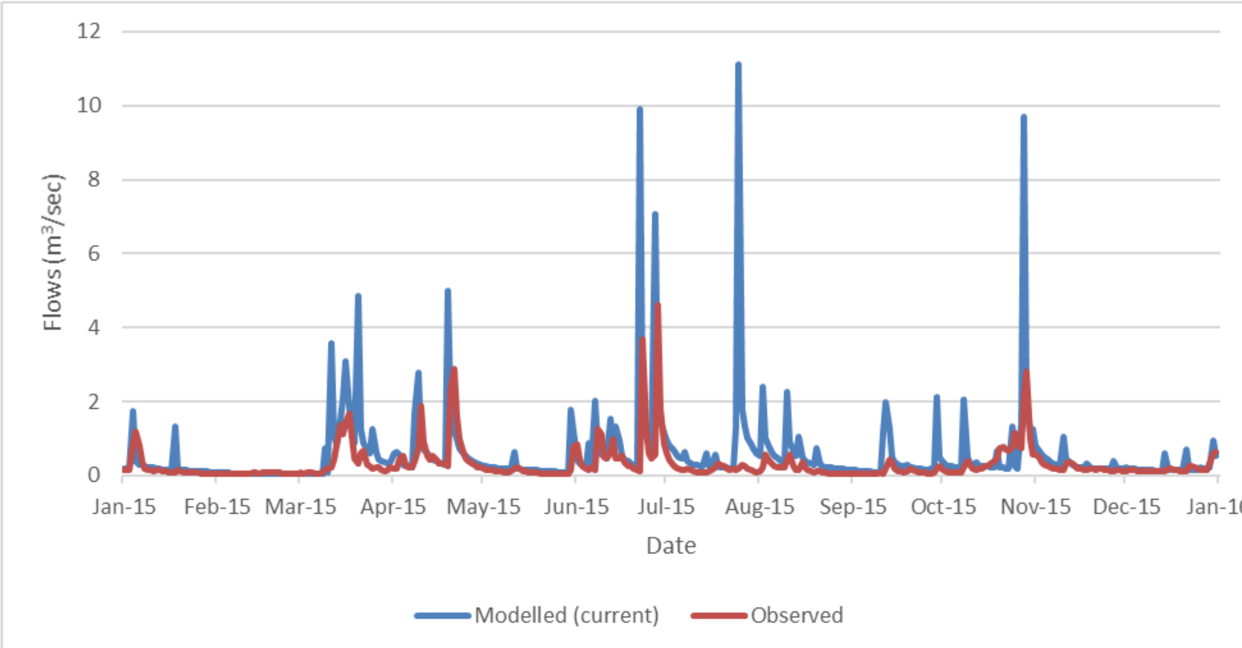


FIGURE 4 OBSERVED FLOWS (RED) COMPARED TO MODELLED FLOWS (BLUE) FOR EXISTING LAND USE (CURRENT CONDITIONS).

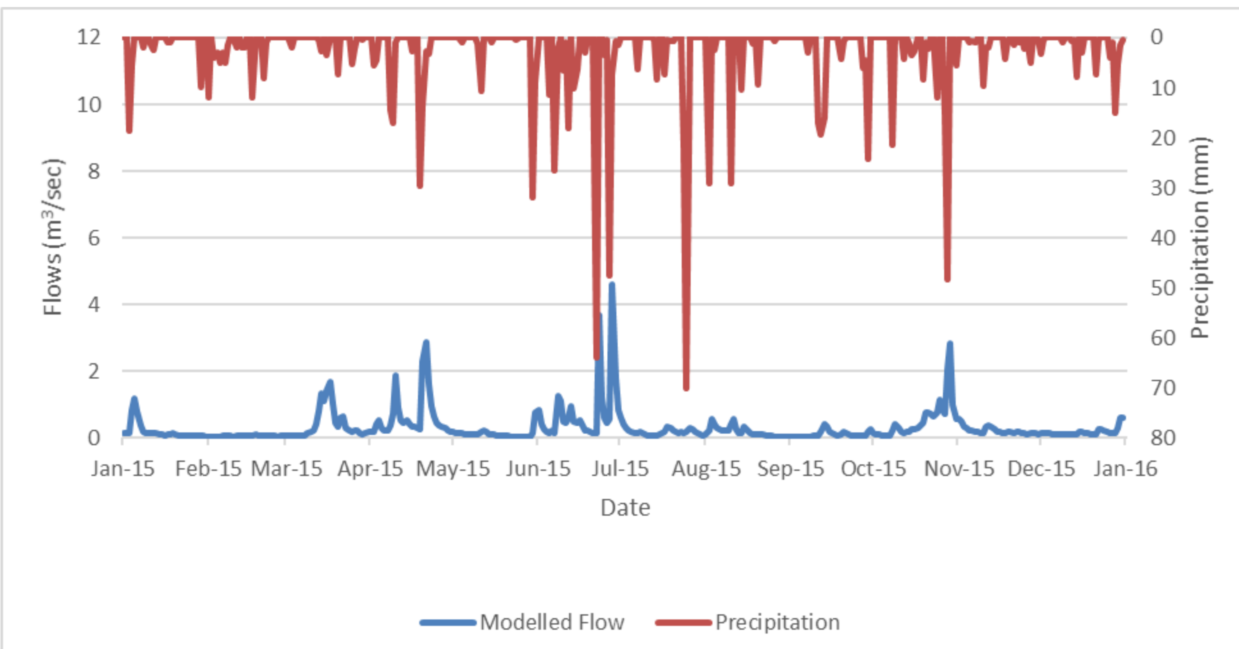


FIGURE 5 MODELLED 2015 STREAM FLOW COMPARED WITH OSHAWA WPCP PRECIPITATION INPUTS.

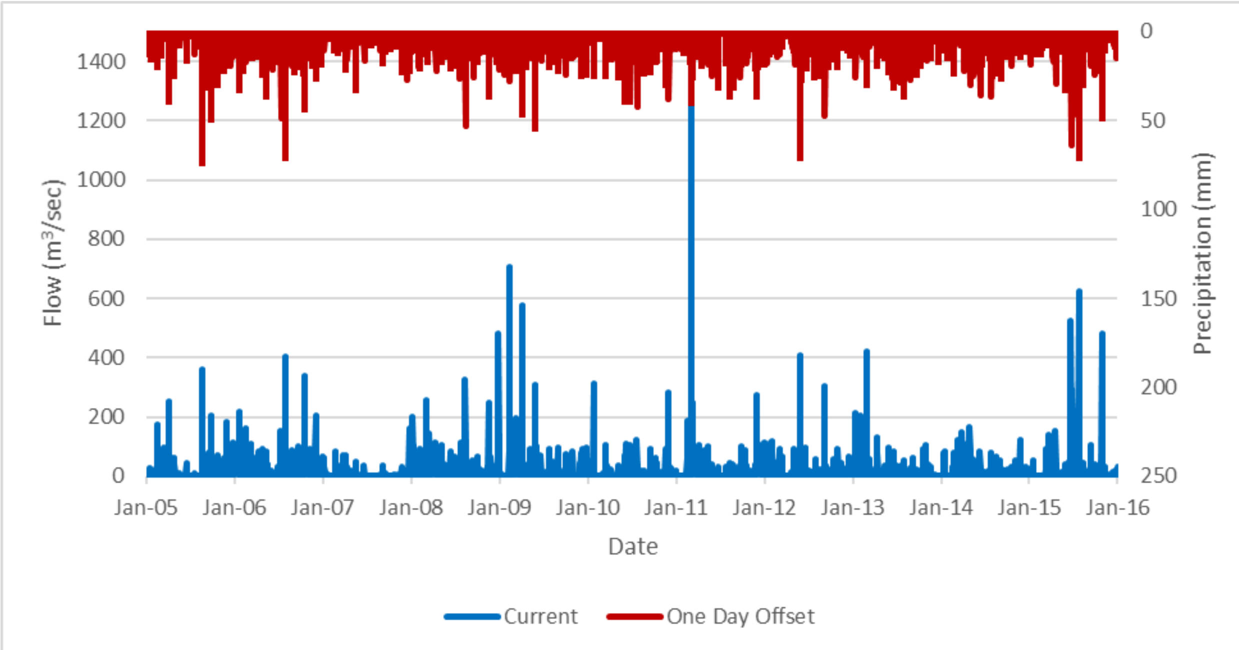


FIGURE 6 MODELLED TOTAL PHOSPHORUS LOADS WITH OSHAWA WPCP PRECIPITATION FOR 2005 TO 2015.

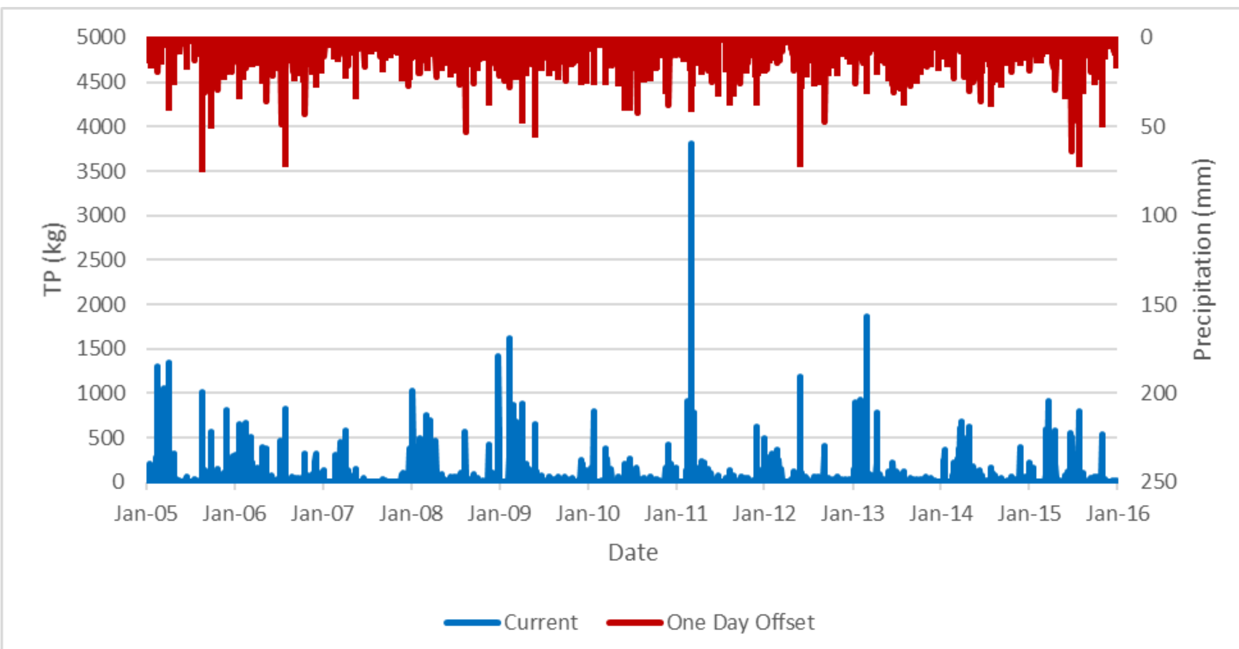


FIGURE 7 TOTAL PHOSPHORUS LOADS IN KG COMPARED WITH PRECIPITATION RECORDS FOR 2005 TO 2015.

Land Use Scenarios

The best way to understand how the Carruthers watershed response to shifts in land use is by modelling response using a long-term record of climate conditions. Plots of average flows (m^3/sec), TSS (tonnes), TP (tonnes), and TN (tonnes) at the outlet of the watershed over the period of 2005 to 2015 are presented in Figure 8. Development in the watershed between 1999 (base conditions for the 2003 watershed plan) and 2015, when this watershed study commenced, occurred primarily within the urban boundary of the Town of Ajax. As appropriate, the Town of Ajax and TRCA incorporated recommendations from the 2003 watershed plan into the planning of these new subdivisions.

The SWAT model depicts increases in average flows and total suspended solid loads over the 16-year time period between 1999 and 2015, and reductions in both TP and TN loads (Figure 8). These changes reflect the transformation of agricultural lands into urban land uses during this time period.

Simulation of Scenario 2 (+NHS) depict further decline in average stream flows, TSS, TN, and TP loads to the lake. Simulation of Scenario 3 (+Potential Urban) depict an increase in flow and TSS and reductions in TN and TP loads in response to conversion of agricultural lands to urban land use and the resulting lower rates of erosion and fertilizer application. Of note is the observation from Figure 8 that the enhanced NHS is an effective water quality mitigation tool as flows and total suspended solid loads for Scenario 3 (+Potential Urban) are modelled as being only slighter higher than those reported for Scenario 1 (+OP). Reductions in TP and TN loads are also expected to occur in Scenario 3 (+Potential Urban) compared with Scenario 1 (+OP).

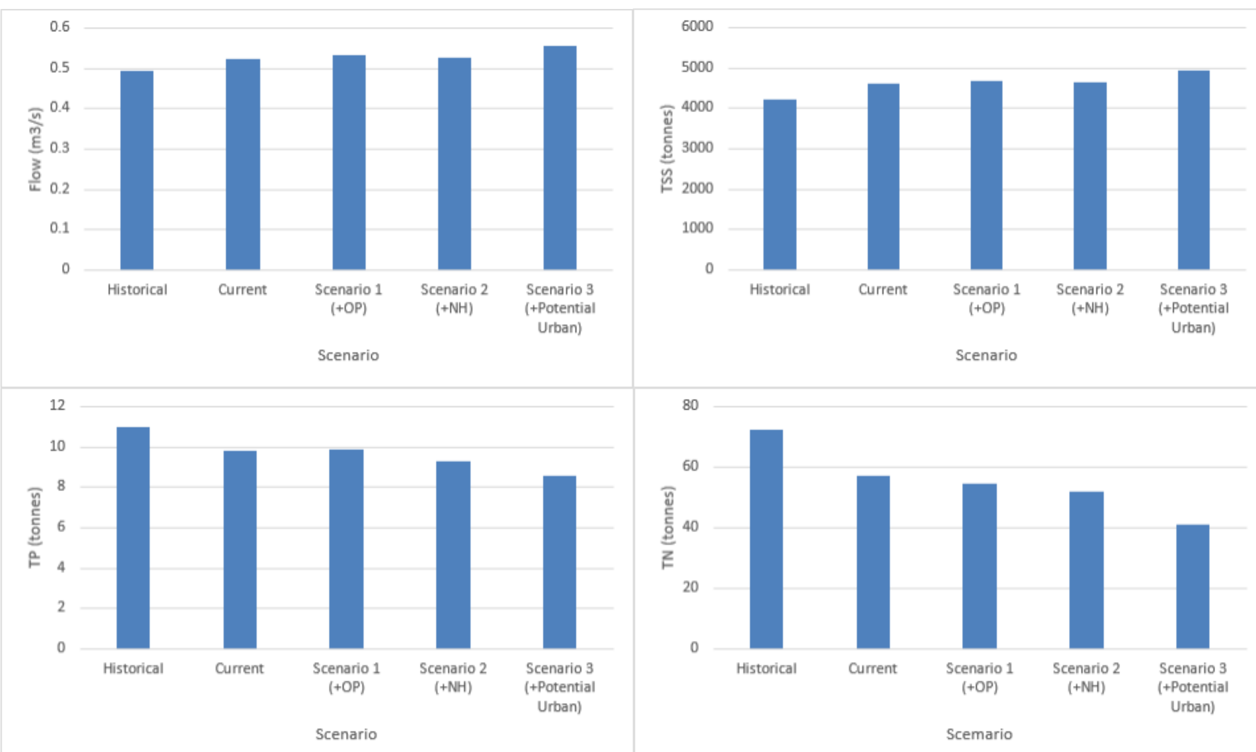


FIGURE 8 AVERAGE STREAM FLOW (TOP LEFT, M3/SEC), TOTAL SUSPENDED SOLIDS (TOP RIGHT, TONNES), TOTAL PHOSPHORUS (BOTTOM LEFT, TONNES) AND TOTAL NITROGEN (BOTTOM RIGHT, TONNES) LOADS FOR THE SIMULATION PERIOD OF 2005 TO 2015.

Land use comparisons as presented in Figure 8, afford a relative comparison of the watershed response to past and future changes in land use. As discussed previously (Section 4.1), the actual magnitude of the flow and loading response are subject to uncertainties, at this time, but the reported directional and comparative shifts in flows and loads are deemed accurate.

Table 3 presents a comparison of the 2005 to 2015 average flows and TSS, TP, and TN loads at the watershed outlet for the five scenarios in tabular form. Comparisons are shown as shifts in flows m3/sec and tonnes or kg across the five scenarios with the reference point being Current conditions when the Carruthers Creek watershed study commenced in 2015 as documented in the phase one baseline studies. Of note, is the similarity in the magnitude of response as reported shifts from Historical to Current and from Scenario 2 (+NHS) to Scenario 3 (+Potential Urban).

TABLE 3 COMPARISON OF 2005 TO 2015 AVERAGE FLOW, TSS, TP, AND TN AT WATERSHED OUTLET FOR BASELINE AND LAND USE SCENARIOS WITH PERCENT CHANGE RELATIVE TO EXISTING 2015 SCENARIO.

	Historical	**Current**	**Scenario 1 (+OP)**	**Scenario 2 (+NH)**	**Scenario 3 (+Potential Urban)**
Flow (m^3/s)	0.493 -5.92%	0.524	0.533 1.72%	0.526 0.38%	0.556 6.11%
TSS (tonnes)	4236 -7.95%	4602	4674 1.56%	4641 0.85%	4939 7.32%
TP (kg)	11000 11.8%	9843	9864 -0.21	9295 -5.57%	8602 -12.6%
TN (kg)	72567 27.2%	57043	54503 -4.45%	51747 -9.28%	41102 -27.9

The 11-year climate record for the Oshawa WPCP climate station provides a comprehensive range of daily, seasonal and annual weather conditions upon which to evaluate shifts in land use. Figures 9 to 11 present annual loads in TP, TN and TSS along with the error bars in the load estimations for each of the five-land use configuration. On annual basis the SWAT models responds to lower pollutant inputs in dry years and higher in wet years; and as well as to pollutant inputs that are attributable solely to configurations in the five land use scenarios. This duality in flows and load response is an important consideration for the development of management recommendations for the watershed.

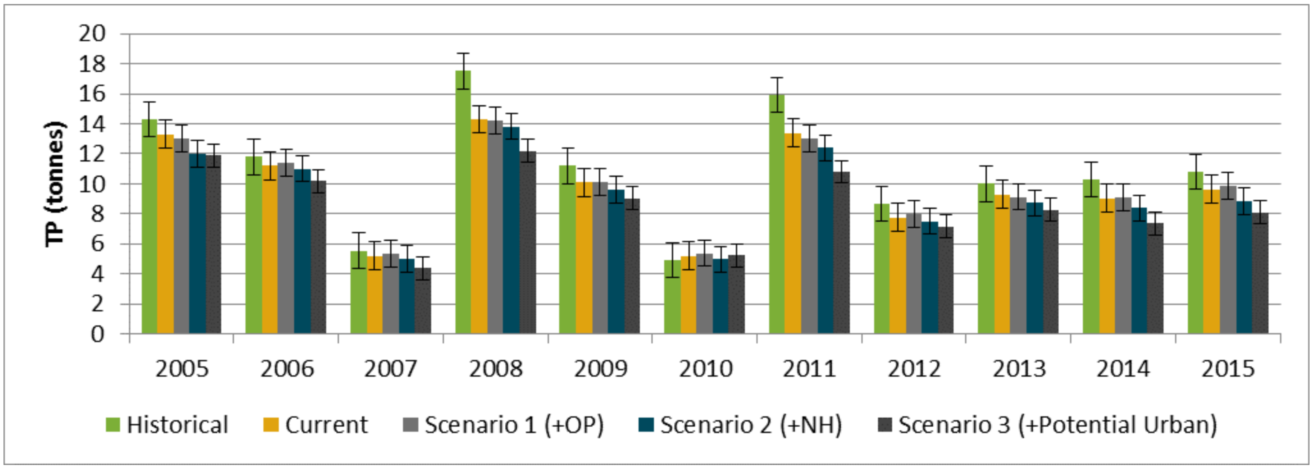


FIGURE 9 SIMULATED ANNUAL TOTAL PHOSPHORUS LOADS BY LAND USE SCENARIO DURING 2005 TO 2015. ERROR BARS REPRESENT ONE STANDARD DEVIATION.

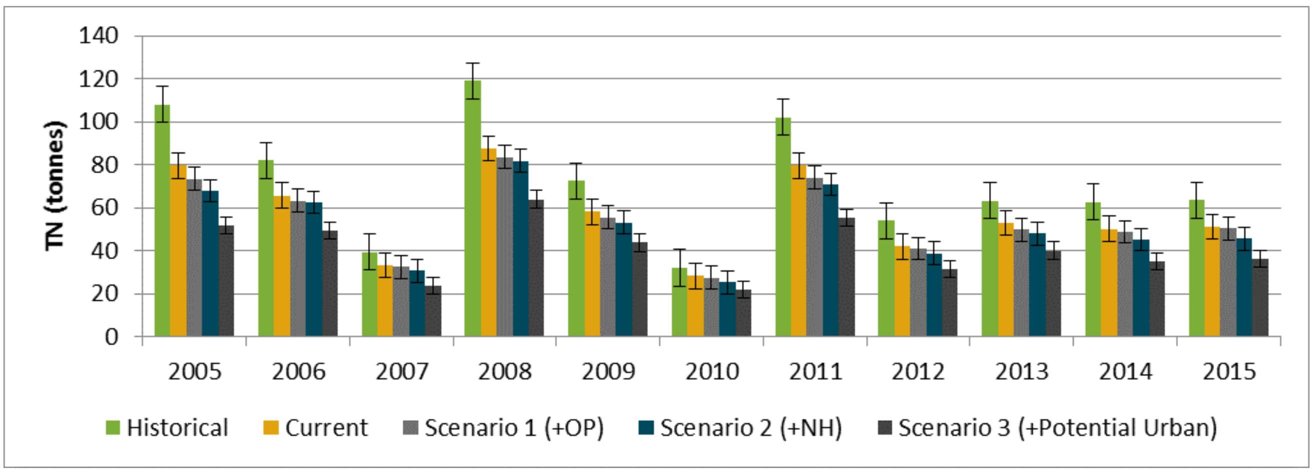


FIGURE 10 SIMULATED ANNUAL TOTAL NITROGEN LOADS BY LAND USE SCENARIO DURING 2005 TO 2015. ERROR BARS REPRESENT ONE STANDARD DEVIATION.

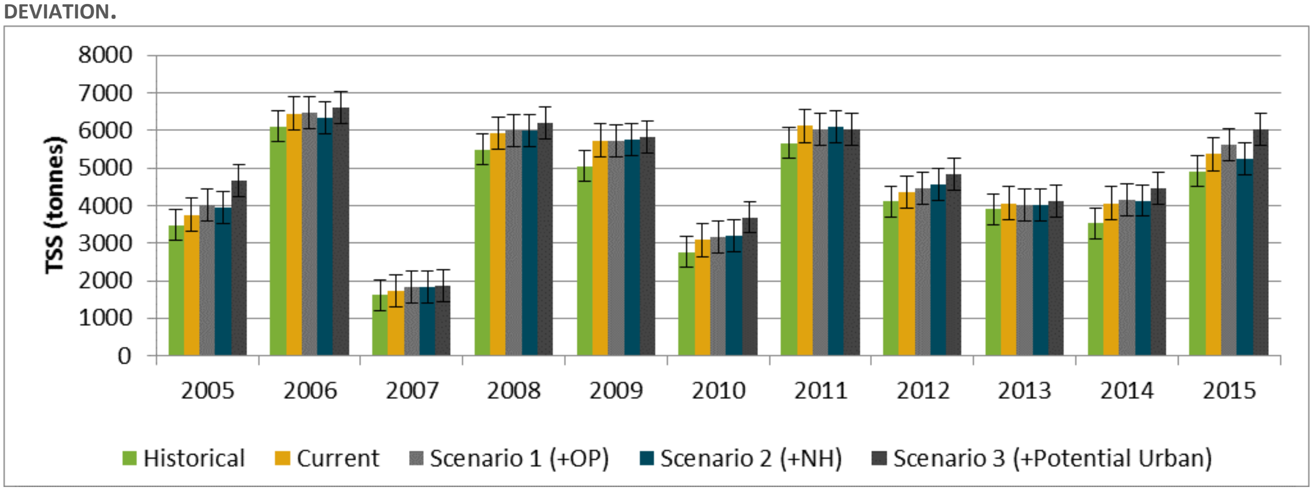
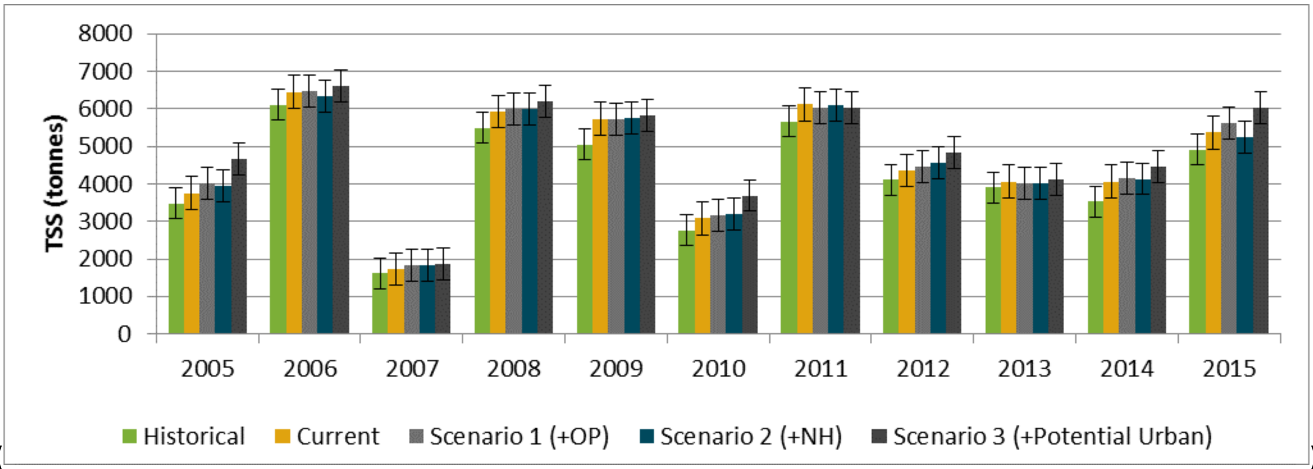


FIGURE 11 SIMULATED ANNUAL TOTAL SUSPENDED SOLID LOADS BY LAND USE SCENARIOS DURING 2005 TO 2015. ERROR BARS REPRESENT ONE STANDARD DEVIATION.

The highest average nutrient loads for TP and TN (Figure 9 andFigure 10, respectively) occurred for Historical conditions, generally followed by reductions in nutrient loads for each of the remaining land use scenarios. The SWAT model appears to respond to reductions in agricultural lands as the watershed becomes more urbanized and water quality improves, attributable to the enhanced NHS. TSS appears to be increasing due to shifts in land use (



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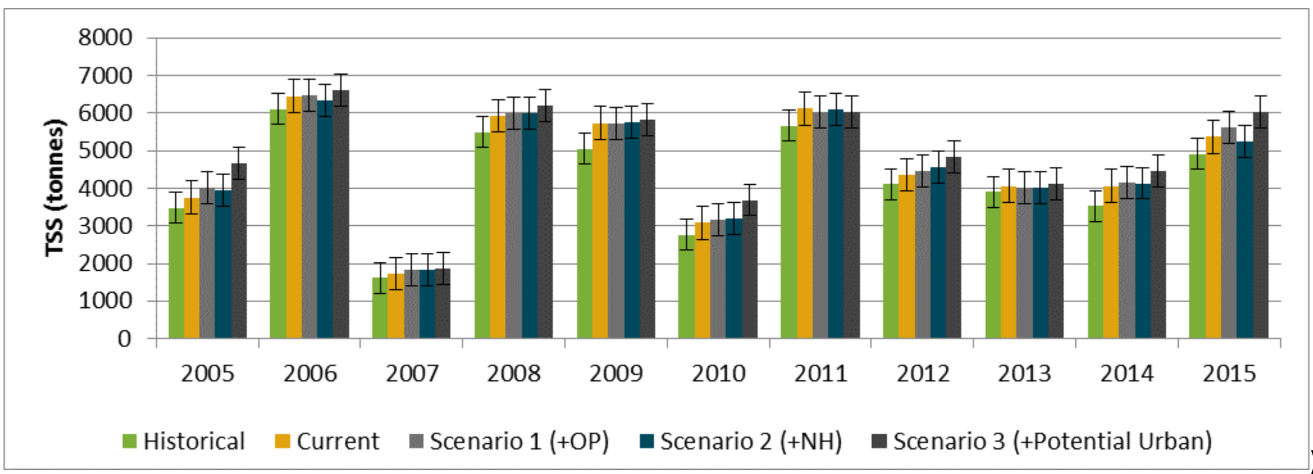
This increase could be related to a change in flows. Urbanization of the southern portion of the watershed that occurred between 1999 (Historical) and 2015 (Current) result in a more noticeable increase in TSS loads to the lake within each of the 11-years modelled. As expected, Current conditions and Scenario 1 (+OP) are very similar in terms of model estimates for TSS loads (Figure
11



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Unanticipated, however, is the observed variable modelled performance of the enhanced NHS in terms of TSS load reductions to the lake. On an annual basis, the TSS loads are similar, with Current conditions, Scenario 1 (+OP), and Scenario 2 (+NHS) with these estimates being higher than TSS loads reported for Historical but lower than for the full build out Scenario 3 (+Potential Urban). With the exception of 2011, the highest TSS loads are reported for Scenario 3 (+Potential Urban).

Sub-Catchment Nutrient and Suspended Solid Loads

A useful feature of the SWAT model is the ability to summarize the modelling outputs on a sub-catchment basis. Figure 12 illustrates the four sub-catchments set-up for the model. Each of these sub-catchments is anchored to a stream flow gauge allowing for the calibration/reporting of results to be undertaken at the sub-catchment scale. Spatial patterns in the TN loads are not presented, as they follow a similar response to TP loads. TP loads for the four sub-catchments are presented by year for simulations of Current conditions (Figure 13). As expected, the annual TP loads increase in response to the relative catchment drainage areas. Further, the TP loads increase in a downstream direction, reflecting the accumulations of upstream contributions. The model accurately depicts known differences in water quality and stream flows observed between the west and east branches of the watershed (TRCA 2017, TRCA 2018). TP loads increase in a downstream direction, reflecting the accumulations of upstream contributions.

The higher total suspended solid loads reported for the upper reaches of the watershed compared with the lower reaches was an unexpected result. It was expected that TSS loads would increase in downstream direction with no losses during transport through the watershed and with additional TSS inputs along the way as observed for nutrients. Northwest (NW, Sub-1) was higher compared with the northeast (NW, Sub-2) sub-catchments, with major deposition for the central (Sub-3) sub-catchment, followed by a slight increase in loads modelled TSS between the central and south (sub-4) sub-catchments (Figure 14). The higher amounts of agricultural lands in the headwaters appear to generate more TSS loads than the urban lands south of Taunton Road. In addition, the mass of TSS reported for the central sub-catchment (3) is reported to be lower than the sum of the west and east sub-catchments (i.e., in the headwater areas), suggesting that some in-stream sediment loss due to depositional process in the channel is occurring. This is a modelling outcome that is consistent with known shifts in stream gradient once Carruthers Creek drops off the former Lake Iroquois shoreline.

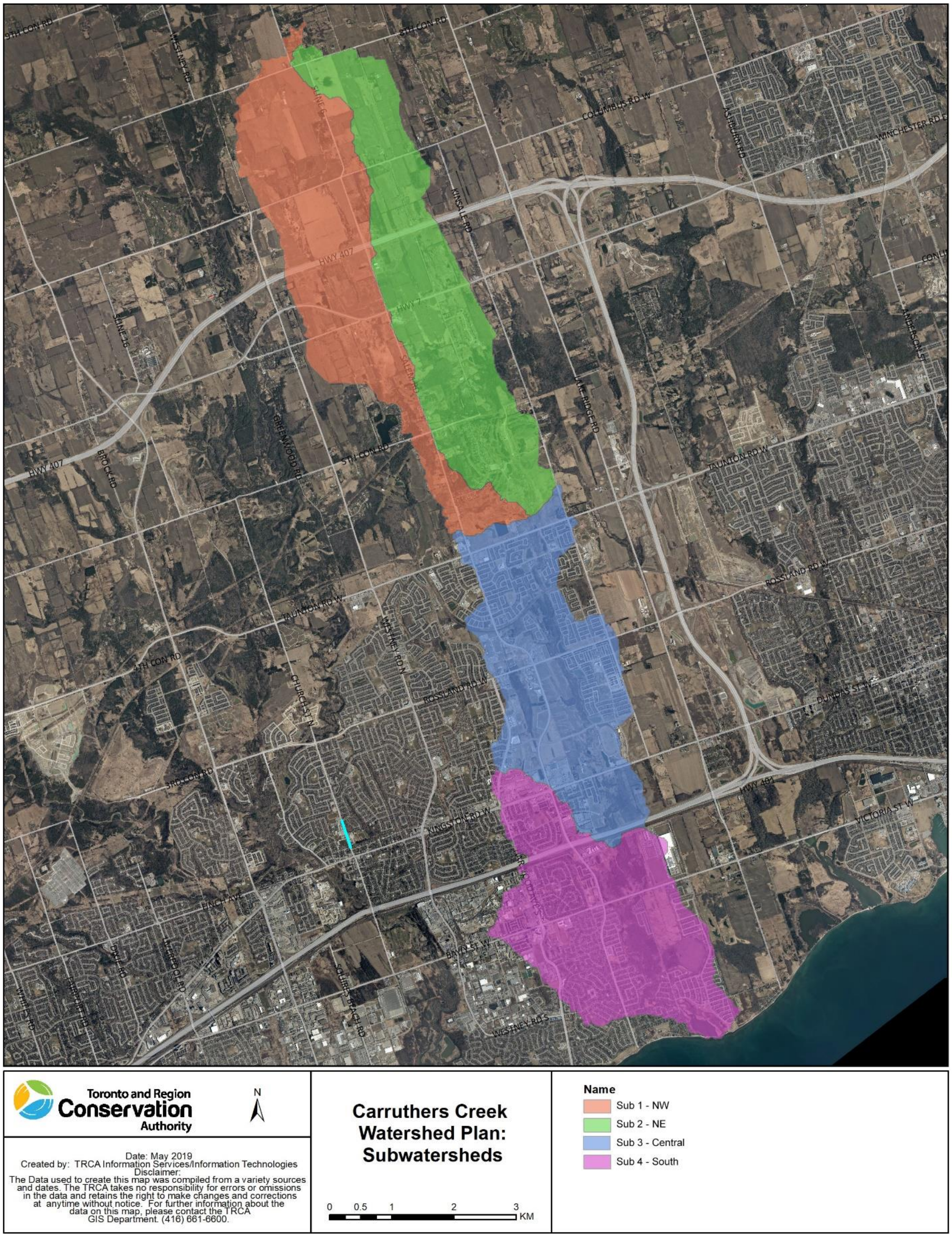


FIGURE 12 THE FOUR SUB-CATCHMENTS (NW, NE, CENTRAL, SOUTH) OF THE CARRUTHERS CREEK WATERSHED USED IN THE SWAT MODEL.

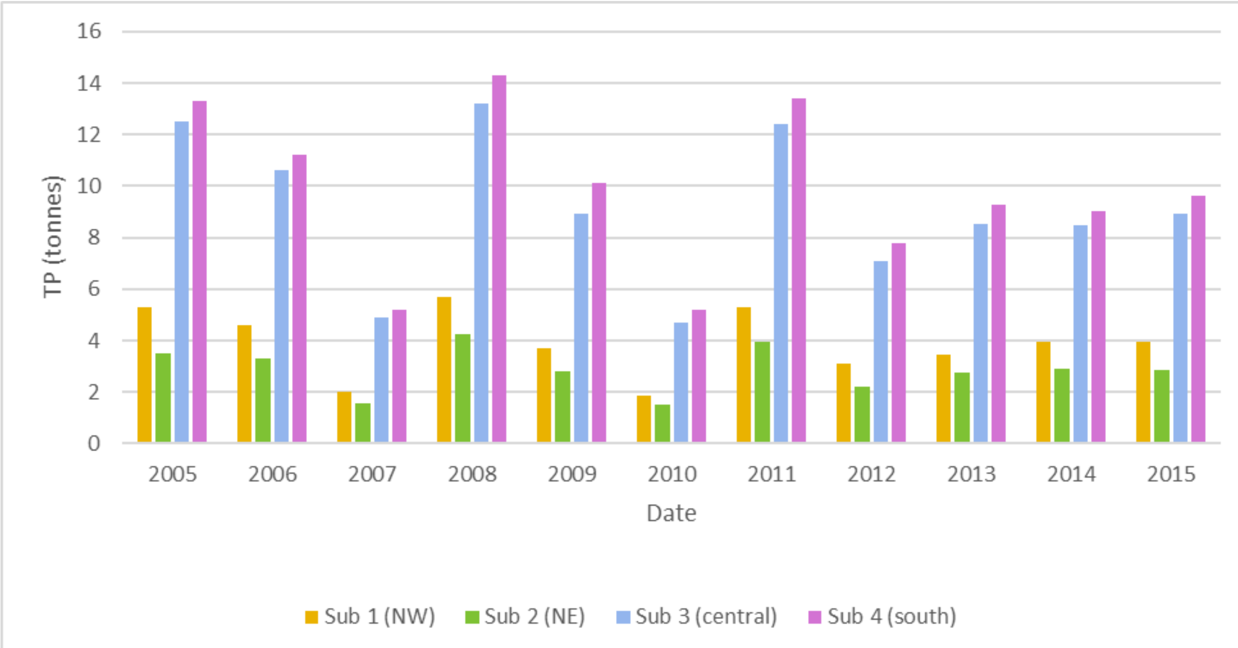


FIGURE 13 ANNUAL TOTAL PHOSPHORUS LOADS BY SUB-CATCHMENT IN THE CARRUTHERS CREEK WATERSHED (2005 TO 2015).

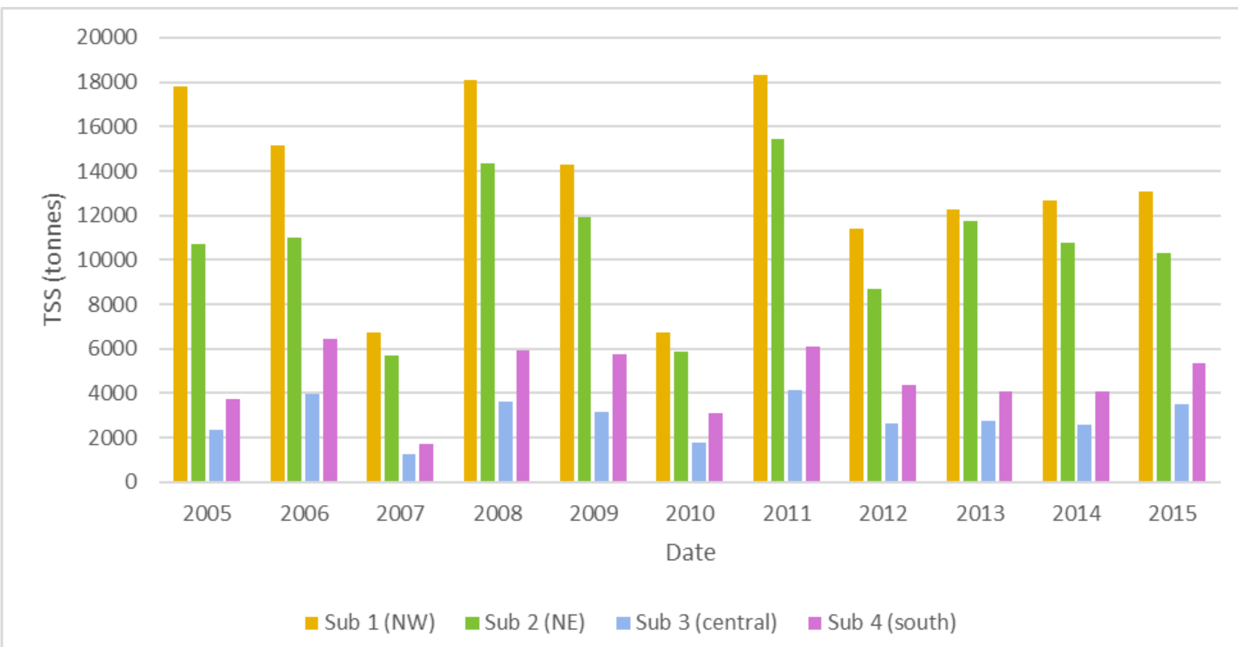
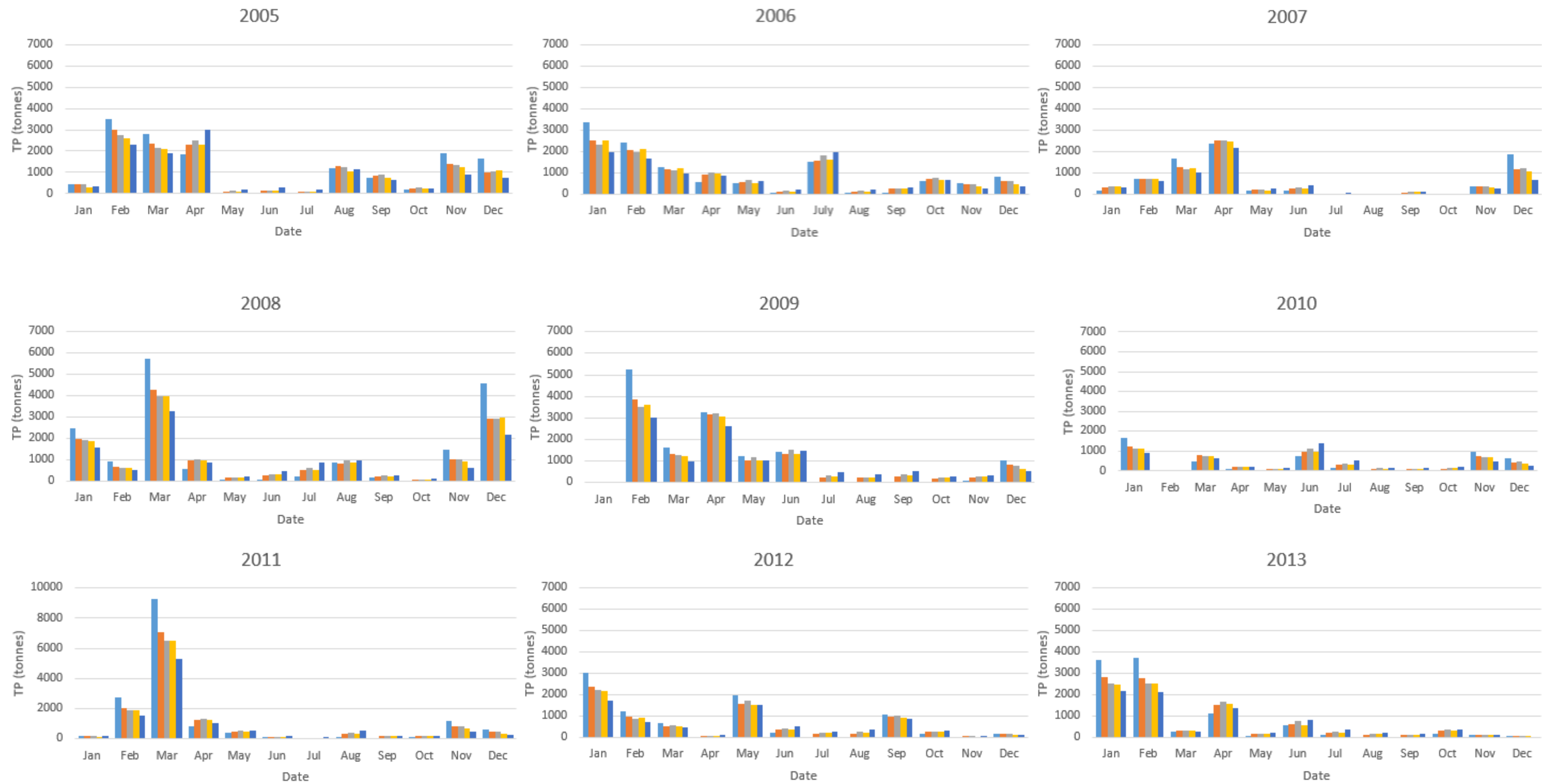


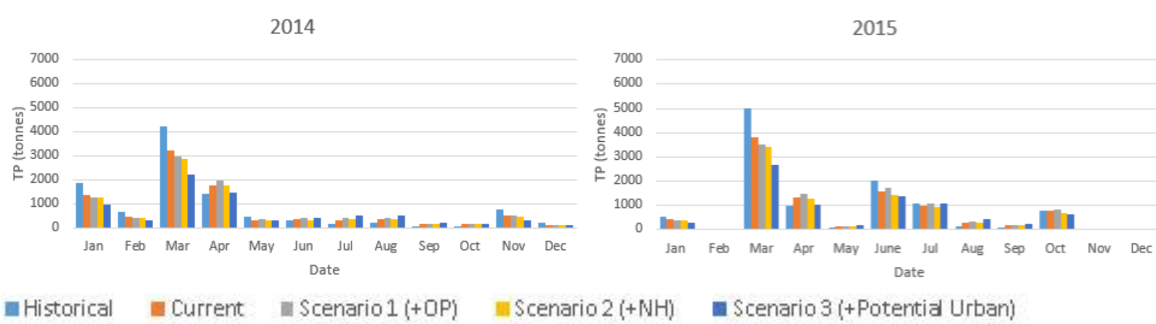
FIGURE 14 TOTAL SUSPENDED SOLID LOADS (TONNES) BY YEAR AND SUB-CATCHMENT IN THE CARRUTHERS CREEK WATERSHED (2005 TO 2015).

Local Climate as a Driver of Nutrient and Total Suspended Solid Loads

Monthly loads of TP and TN for each of the 11 years that the SWAT model was run (2005 to 2015) are presented in Figures 15 and 16. Included in each of these figures are summary tables for years with +/- 30% departure per month from long-term climate normal. The monthly load simulations illustrate that the SWAT model is responsive to climatic shifts in precipitation. These temporal shifts in monthly loads are very important in terms of the timing and magnitude of TSS and nutrient loads delivered to Lake Ontario and as well in terms of identifying periods of better or poor water quality in the watershed itself. For example, in March 2011, the bulk of the annual loads of both TP and TSS occurred in the one month. Traditionally, spring runoff attributable to snowmelt is expected to occur in March to April. However, there are also years when the extremes in total precipitation are distributed over several months during the winter season (as illustrated in the December to January loads for 2006, 2009, 2012, and 2015 in Figure 15). Lower precipitation amounts, and higher evaporation rates resulted in the lowest monthly loads regularly occurring during the summer months—a time when nuisance algae are problematic along the Town of Ajax's waterfront. There are some years during late summer and early fall when much higher TSS loads were delivered to the lake (2005, 2006, and 2008). Of note are the dry years (2007 and 2010), when very low loads of both nutrients and TSS were delivered to the lake from the Carruthers Creek watershed over the entire year (Figure 16).

It is insightful to present nutrient loads on a water year basis (October to October) compared to the calendar year. Sometimes seasonal trends in flows and loads extend over calendar years and are therefore longer duration trends can be masked by annual reporting. For example, extreme winter conditions with heavy snowfall can start in the late fall of one year and extend into the winter of the following year. Or alternatively drought driven low flow streamflow and reduced loads to the lake conditions may persist over a couple of years. Thus, modelling results presented on a water year help watershed manager develop an understanding the timing and duration of periods high and low nutrient and suspended loads is important for aquatic ecology of the Carruthers Creek watershed and as well for patterns in the nearshore water quality and water transparency in Lake Ontario. Figure 17 presents modelled monthly TP loads (tonnes) expressed by water year. In the water years 2006 to 2007 and 2009 to 2010 relatively low amounts of TP were delivered to the lake. The opposite occurs in water years 2005 to 2006 and 2008 to 2009 with the colder winter months (November to March) having higher amounts of nutrients being delivered to Lake Ontario. These temporal differences in in nutrient and TSS are critical for aquatic biota residing in the Carruthers Creek watershed, especially the endangered, visual-feeding insectivore Redside Dace (*Clinostomus elongatus*).





Snowfall Totals (cm)

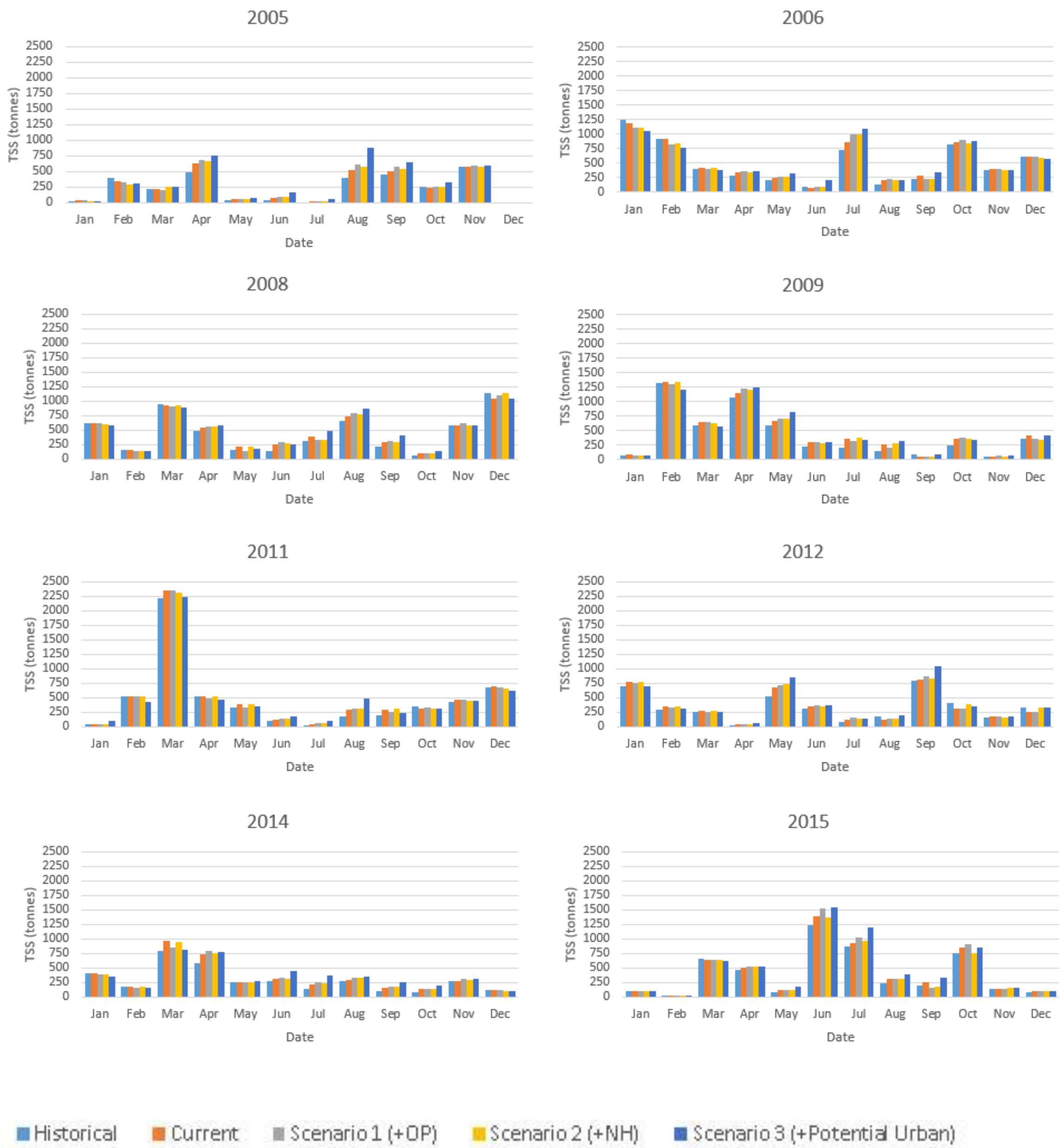
Year	Dec	Jan	Feb	Mar	Total
2006	47	9	37	0	93
2009	26	70	7	0	103
2012	4	26	17	0	47
2015	3	18	61	2	84

>30% below normal
>30% above normal

Rainfall Total

Year	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total	
2006	53	79	81	51	167	52	107	152	537	15%
2009	47	129	125	53	63	83	41	86	494	6%
2012	46	22	115	104	69	81	161	101	552	18%
2015	22	94	55	210	116	82	95	125	652	36%

FIGURE MONTHLY TOTAL PHOSPHORUS LOADS OVER THE 11-YEAR CLIMATE RECORD SIMULATION PERIOD (2005 TO 2015) BY LAND USE SCENARIO.



Snowfall Totals (cm)

Year	Dec	Jan	Feb	Mar	Total
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Rainfall Total

Year	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total	
2006	53	79	81	51	167	52	107	152	537	15%
2009	47	129	125	53	63	83	41	86	494	6%
2012	46	22	115	104	69	81	161	101	552	18%
2015	22	94	55	210	116	82	95	125	652	36%

FIGURE 15 MONTHLY TOTAL SUSPENDED SOLID LOADS OVER THE 11-YEAR CLIMATE RECORD SIMULATION PERIOD (2005 TO 2015) BY LAND USE SCENARIO.

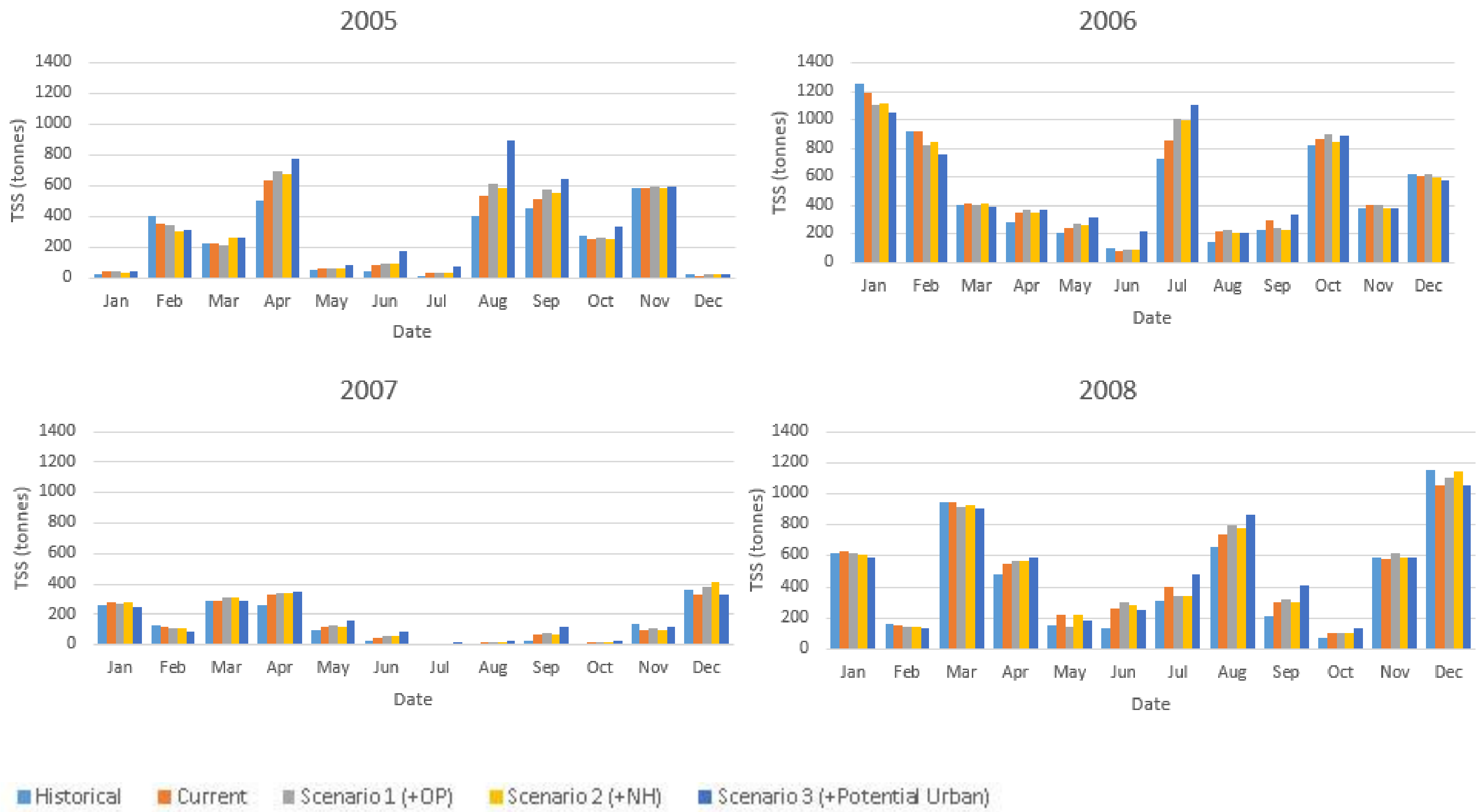

FIGURE 16 MONTHLY TOTAL SUSPENDED SOLID LOADS FOR 2005 TO 2008 SHOWING SEASONAL VARIATIONS.

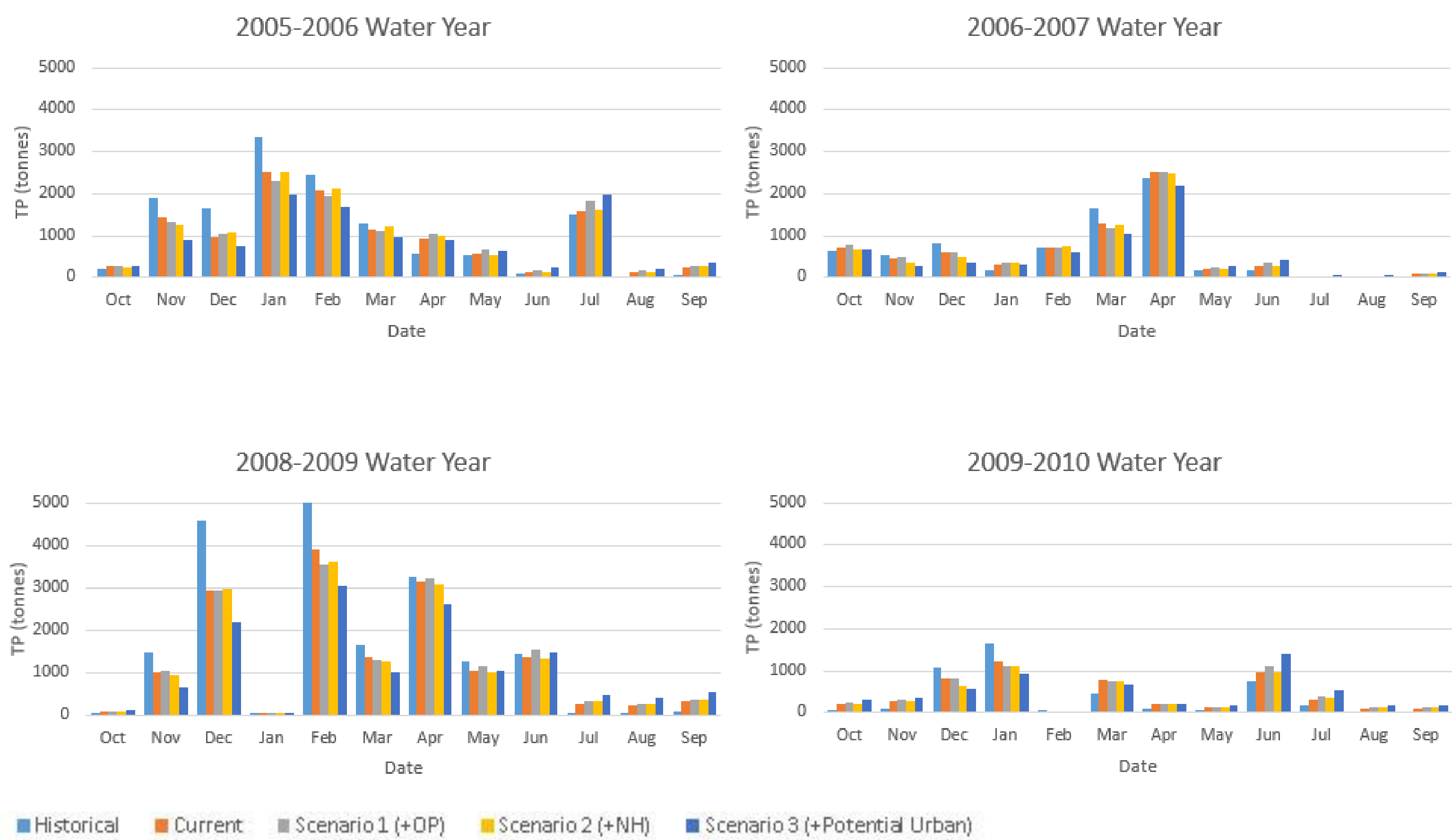

FIGURE 17 TOTAL PHOSPHORUS LOADS FOR SELECTED WATER YEARS.

Rural Best Management Practices

Performance of three widths of vegetated buffer strips (15 m, 30 m, and 100 m) were simulated for stream reaches in the SWAT model for the Current conditions. Procedure for setting up the BMPs are documented in Appendix B. Results of the BMP buffer performance modelled in SWAT are presented in Table 4. HRUs identified in Table 4 are areas of similar land use, soils, land slope and were determined by GIS algorithms in Arc SWAT. Modelling results showed little response to changes in stream flow compared to the various buffer widths, however TSS and nutrients were reduced. Large reductions were observed in both TSS and nutrient loads by sub-catchments, occurring in response to the extent of agricultural lands and to varying buffer widths. For example, a 100 m buffer applied to watercourses in the rural headwaters resulted in a 73%, 60%, and 57% reduction in annual TSS, TP, and TN, respectively, for rural catchments sub-catchments 1 (NW) and 2 (NE). For areas in the sub-catchments that already have extensive natural cover along the streams, the reductions were lower, due to the reduced opportunity for additional nutrient and sediment attenuation. It is recognized that a 100 m buffer would be a lofty management objective. Performance of buffers as modelled by incremental increases in width from 15 m, 30 m, and 100 m result in variable responses to TSS, TP, and TN reductions. Vegetated stream buffers as narrow as 15 m were effective BMPs in the reaches in the headwaters. However, on a watershed scale, the 15 m buffers were not as effective as the 30 m buffers in terms of load reductions at the outlet to Lake Ontario.

The application of a green cover crop of clover in the winter months was modelled as a BMP. All agricultural HRUs were updated with a new management schedule for the 2-year and 4-year crop rotations to include operational considerations for simulating cover crops (plant, kill, crop, tillage). TSS is reduced in the upper reaches of the watershed, and TP and TN are reduced across the entire watershed and at the outlet (Table 5) when cover crops are applied. More than 40% of the upper watershed has agricultural land uses; whereas agricultural lands are only 20% of sub-catchment 3 and less than 4 % in the urban areas in sub-catchment 4.

TABLE 4 COMPARISON OF STREAM BUFFER WIDTHS IN REDUCING AVERAGE ANNUAL LOADS OF TOTAL SUSPENDED SOLIDS, TOTAL PHOSPHORUS, AND TOTAL NITROGEN LOADS.

Reach	Agricultural HRUs			Natural Cover HRUs			Agricultural and Natural Cover HRUs		
	15m	30m	100m	15m	30m	100m	15m	30m	100m
TSS									
1	55.4%	64.3%	73.2%	13.6%	15.2%	16.8%	69.0%	79.5%	90.0%
2	42.4%	46.9%	50.4%	26.1%	30.6%	35.1%	68.5%	77.5%	85.5%
3	0%	0%	0%	0%	0%	0%	0%	0%	0%
4 (outlet)	0%	0%	0%	0%	0%	0%	0%	0%	0%
TP									
1	48.0%	54.0%	59.9%	11.8%	12.9%	13.9%	59.8%	66.9%	73.8%
2	40.4%	43.7%	46.2%	18.5%	21.1%	23.5%	58.9%	64.7%	69.7%
3	28.5%	31.6%	34.4%	9.4%	10.5%	11.5%	37.9%	42.0%	45.9%
4 (outlet)	22.8%	25.3%	27.5%	7.6%	8.4%	9.3%	30.4%	33.7%	36.8%
TN									
1	43.1%	49.6%	57.0%	11.7%	13.2%	14.6%	54.9%	62.8%	71.6%
2	37.8%	42.0%	45.7%	17.4%	20.2%	23.4%	55.2%	62.2%	69.1%
3	27.5%	31.0%	34.9%	9.5%	10.8%	12.3%	37.0%	41.9%	47.2%
4 (outlet)	22.4%	25.3%	28.4%	7.8%	8.8%	10.0%	30.2%	34.1%	38.4%

0 to 10%	10 to 20%	20 to 30%	30 to 50%	50 to 75%	> 75%

TABLE 5 EFFECTIVENESS OF WINTER COVER CROPS IN LOWER NUTRIENT AND TOTAL SUSPENDED SOLID LOADS BY SUB-CATCHMENT.

TSS (tonnes)

Reach	Current	Cover crop	% change
1	146649	94885	-35.30%
2	116480	88249	-24.20%
3	33920	34034	0.34%
4 (outlet)	50623	50648	0.05%

TN (kg)

Reach	Current	Cover crop	% change
1	24305	16285	-33.00%
2	17525	12889	-26.50%
3	53589	40855	-23.80%
4 (outlet)	57043	45423	-20.40%

TP (kg)

Reach	Current	Cover crop	% change
1	3907	2700	-30.90%
2	2876	2193	-23.70%
3	9108	7232	-20.60%
4 (outlet)	9843	8136	-17.30%

Interpretation of watershed modelling results are best undertaken through of combination of comparisons with observations, past modelling efforts and or water quality loading estimations. During the 2003 Duffins Creek and Carruthers Creek watershed study (TRCA 2003, a series of supporting technical studies were undertaken in a manner similar to the technical studies being undertaken for this Carruthers Creek watershed study. These earlier supporting technical studies also examined impact responses in water quality and stream flows due to shifts in land use and climate change. At the time of the first Carruthers Creek watershed study, the continuous watershed response model (e.g. SWAT) was not widely in use. Two different approaches were taken for earlier water quality loading studies for the Carruthers Creek watershed. A simple spreadsheet loading model (Stantec 2003) and a wet weather event-based model, called the Agricultural Non-point Source (AGNPS) water quality model developed by the US Department of Agriculture (TRCA 2003a). The rationale for using the AGNPS model was based on several considerations. The AGNPS model is a robust event model that has been successfully applied in several jurisdictions in the United States, and, to a lesser extent, Canada. Second, the AGNPS model was compatible with the TRCA's GIS layers and Arcview software platform, thereby reducing the amount of time required to enter and modify input data. Finally, the AGNPS modelling work builds upon an extensive field monitoring program and a detailed calibration and sensitivity analysis for the Duffins Creek watershed (Leon et al., 2002), which helps to improve confidence in model results.

Stantec (2003) reported both dry and wet weather event loads for the Carruthers Creek watershed for three land use scenarios. The land use scenarios were: i) Current Land Use (1999), ii) Full build out of the Official Plans (OPs) and iii) Full build out plus an Enhanced Natural Heritage System (ENHS). At the time, the full build out of the watershed was approved to Taunton Road; which was the Town of Ajax's approved urban boundary. The ENHS modelled was the system developed for the 2003 watershed plan and is significantly different than the new NHS developed for this watershed update. It should be noted that when the 2003 watershed plan was developed for the Carruthers Watershed TRCA was not operating the Regional Water Quality Monitoring Network. Consequently, there was no stream flow data for the watershed and the water quality data was dated (1965 to 1993). Stantec 2003 had to prorate flows from the Mitchell Creek subwatershed in the Duffins Creek watershed. The Stantec approach for estimating loads was to simply employ the prorated annual flow estimates with assumed Event Mean Concentrations (EMCs) for TSS, and TP in the Carruthers. Stantec 2003 reported a substantial increase in wet weather TSS loads with the conversion of agriculture to urban land uses. Unlike our current study, they reported an increase in TP loads due to increase in urban land use. They suggest this increase in TP load was accurate, on the basis on known correlations between TSS and TP in many watershed studies.

TRCA 2003a presented results from the AGNPS modelling. In the 2003 AGNPS study, the same three land use scenario used by Stantec 2003 were modelled and reductions in TSS were also reported for these shifts in urban land use in the Carruthers watershed along with additional reductions due to the enhanced natural heritage system. Of note is that for the Miller Creek sub watershed they reported increase in TSS loads (24%) for the OP land use condition vs a 33% reduction for the Carruthers Creek watershed. However, in their study conclusions they state that shifts in sediment loads can be expected to increase in all watersheds, as a result of urban growth. The Enhanced Natural Heritage System (ENS) was shown to compensate for some of the negative impacts of urban growth by at least maintaining existing water quality conditions.

Booty et. al 2005 used the AGNPS model in the adjacent Duffins Creek watershed to investigate water quality shifts due to climate change and as well, in comparison to baseline and future land use conditions, based upon then projected build out of the Duffins Creek watershed. At time of the Booty et. al (2005) study, two internationally recognized climate models were available: the Canadian Centre for Climate Modelling and Analysis (CCCma) CGCM1 And the Hadley Center HadCM2. They concluded for their event modelling of the Duffins Creek watershed that impacts of climate change on stream chemistry can be much more significant than those caused by urbanization of the watershed. Of interest, however, was their observations that at subwatershed scale the response can be significantly different for the same stressor. Worth noting was their finding for the Miller Creek subwatershed was more significantly impacted by land use shifts than by the climate change scenarios. Our approach for examining g local climatic influences was different from the modelling of climate change based upon future predictions of extreme changes in climate. A challenge, for this study and future watershed loading response comparisons will be understanding concurrent shifts in both land use and climate. Careful attention will be needed to understand the respective influences of extremes in climate, shifts in land use and hopefully implementation of an ENHS watershed wide and as well, other appropriate watershed management recommendations.

6 Conclusions and Next Steps

The SWAT model is an informative decision support tool that provides insights into the watershed response to shifts in land use and climate in the Carruthers Creek watershed. Current monitoring data are limited in duration and scope for the Carruthers Creek watershed. As a result, the precision of SWAT estimations of spatial and temporal patterns in flows, TSS, and nutrient levels cannot be fully determined due to short period of field observations (2015 and 2016) and for the existing land use at the time these data were collected. Despite the limited observational data available for the current study, there has been a concerted effort to improve data collection since the original watershed plan was prepared in 2003. While at this time, it cannot be ascertained on a definitive basis what shifts in stream flows, TSS, and nutrient loads will transpire in response to future land use and climate shifts, the SWAT results reported in this study do provide at least some directional shifts in response. Careful consideration of model predictions on when and why flows, nutrient, and TSS loads increase and decrease will be most useful in developing integrated management recommendations that will achieve the stated the vision, goals, objectives, and targets for the Carruthers Creek watershed.

While uncertainties are recognized for the various water quality response assessments undertaken for the Carruthers Creek watershed, the commonality of their directional response lends credence for their use in managing the watershed. Large shifts in stream flow, nutrients and suspended solid loads will occur with future changes in local climate. When the Carruthers Creek watershed experiences more “wetter” or “dryer” weather, it could mean the delivery of higher or lower loads of TSS and nutrients through the system and to the lake. By extension, this could have management implications for both the Carruthers Creek aquatic system and lake management—making the imperative for better watershed-wide management even stronger.

The urban growth that has already occurred in the Carruthers Creek watershed over the past 16 years has resulted in shifts in stream flows, TSS and nutrient loads to Lake Ontario at the mouth of the watershed. The Town of Ajax’s waterfront provides recreational enjoyment for residents and visitors. Nuisance levels of *Cladophora* are routinely reported along the Town of Ajax’s shoreline during the summer months. Bi-national water quality improvement efforts are underway for Lake Ontario, including the monitoring of nutrient loads from Carruthers Creek and neighbouring watersheds as a potential contributor to local nuisance algae. At some point in the future, nutrient loading reduction targets may be established for tributaries to Lake Ontario. If and when this does occur, decision support tools like SWAT will be helpful in evaluating and targeting BMPs. Careful considerations will be needed to inform future urban growth decisions and to advance management efforts that are needed to correct for observed responses in water quality attributable to the recent build out of the watershed and current land use practices in the headwaters.

During watershed characterization, TRCA documented water quality and water quantity conditions in the Carruthers Creek watershed and established a baseline monitoring program. The data collected as part of this program will provide reference points for future reporting of watershed health. New tributary nutrient monitoring programs are now in place for Lake Ontario and include the Carruthers Creek watershed, where a real-time continuous water quality station has been set-up near the creek mouth. This tributary loading study is tracking runoff and water quality in the watershed, on a continuous basis. These additional monitoring data will allow for desired improvements to this initial SWAT set-up and more robust future calibration.

7 Recommendations

The following recommendations are provided as an outcome of the SWAT modelling for the Carruthers Creek watershed. These recommendations address the need for improved local data to set and up and calibrate the model as well as recommendations going forward.

- That new climate stations be set up in the Carruthers Creek watershed to allow for future calibration and validation of the SWAT or other watershed scale models used in the Carruthers Creek watershed to improve their performance.
- That stream gauge rating curves be updated, and that streamflow monitoring be continued at the four current locations in the watershed.
- The enhanced tributary water quality program for the Carruthers Creek watershed should continue for the foreseeable future, in order to provide accurate monitored loading estimates for the watershed and to allow for future comparisons with water quality model outputs.

- The utility of the SWAT model for water quality flows estimation needs to be considered in a highly urbanized watershed. If there are issues with the threshold for urbanization in SWAT, then a different watershed response model needs to be recommended.
- That the water balance used in SWAT and the streamflow outputs of the SWAT model should be compared with Modflow groundwater estimations and as well the event hydrology model.
- That the rural BMPS modelled in SWAT be considered for roll out in the agricultural areas of the watershed in consultation with the farm community.
- That local information on fertilizer application rates be gathered for rural and urban areas and for the three golf courses and that the fertilizer application rates in the SWAT model be updated using these revised applications rates.
- That an enhanced natural heritage system, which SWAT has been shown to be an effective management tool, be implemented throughout the Carruthers Creek watershed.
- As future climate change scenarios are developed for southern Ontario, they should be applied to model the Carruthers Creek watershed.

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Appendices

Appendix A

Watershed Modelling of the Carruthers and Petticoat Creeks with the Focus on Daily Water Quality Estimation

Final Technical Report

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Abstract

The purpose of this project is to build computer daily simulation models of Carruthers Creek and Petticoat Creek watersheds. The models will help to understand the precipitation-runoff relationship and how agronomic activities impact the water quality in terms of total nitrogen, total phosphorus, and total sediment loadings within these watersheds. The developed models can then be utilized to analyze the best management practices in these two watersheds to mitigate these impacts in the future.

In a previous study, Asadzadeh et al. (2015) built the Soil and Water Assessment Tool (SWAT) model of the Rouge River and Duffin's Creek watersheds and showed that SWAT is capable of accurately estimating the hydrological and water quality processes in watersheds under the authority of the Toronto and Region Conservation Authority with significantly large agricultural and natural lands in this region. The land-use classes and soil types in Carruthers Creek and Petticoat Creek are similar to those of the Rouge River and Duffin's Creek watersheds. Therefore, in this project, a similar modeling practice is followed. The 2012 version of SWAT associated with ArcGIS in 10.2 is utilized to build models of the Carruthers Creek and Petticoat Creek watersheds. The models are equipped with forcing data in the period of 2005-2015.

Simulation results show that the model adequately estimates the precipitation-runoff relationship and water quality processes for the Carruthers Creek watershed. The average simulated streamflow is 0.34 cms which is very close to the measured value of 0.36 cms. The time series of simulated and measured daily streamflow shows an acceptable match between the two series. Also, the model adequately estimates the measured water quality data points provided by TRCA.

On the other hand, the SWAT model of the Petticoat Creek watershed perform poorly in comparison with the measured datasets for this watershed. The average simulated streamflow in this watershed is 0.28 cms while the measured value is 0.44. Moreover, time series of simulated versus measured streamflow confirms that the model underestimates the streamflow in this watershed quite consistently. It appears that this watershed receives water from sources outside its boundaries other than precipitation. Potential sources could be significant groundwater contribution to streamflow and/or storm-water diverted to this watershed from nearby watersheds. These results suggest that further studies are required to build a more representative simulation model of the Petticoat Creek watershed.

Table of Contents

1. Introduction

In this project, watershed models of Carruthers Creek and Petticoat Creek are developed in the SWAT 2012 environment associated with ArcGIS 10.2. SWAT is a continuous watershed model that can simulate daily water quality and quantity. Using the spatial digital elevation model maps (DEM), ArcSWAT automatically delineates a watershed and divides it into sub-basins. Inside each sub-basin, SWAT defines non-spatial units called hydrologic response units each of which having a combination of land-use, and soil type classes, land slopes, and land management operations. The land-use and soil type maps for this project ae provided by the Toronto and Region Conservation Authority (TRCA), and DEM maps are inherited from the modeling work by Asadzadeh et al. (2015).

The primary forcing datasets for SWAT are the daily precipitation and daily maximum and minimum air temperature that are obtained from nearby meteorological stations. SWAT can also use the daily average wind speed and relative humidity in the calculation of evapotranspiration. These datasets are also obtained from nearby meteorological stations. Moreover, SWAT can use daily solar radiation data in the calculation of potential evapotranspiration. Since limited solar radiation data points are available at the nearby meteorological stations, the solar radiation data from NASA Prediction of Worldwide Energy Resource (43°50′16.8″N, 79°02′31.9″W) is utilized in this project. The accuracy of this solar radiation dataset is confirmed by comparing it to the dataset used in Asadzadeh et al. (2015).

This report is organized as follows: the study area is introduced in section 2, procedures of structuring the two models are provided in section 3, the model parameters adjustment is explained in section 4, exhibition and analysis of results are discussed in section 5, and concluding memories are provided in section 6.

2. Study Area

2.1 Carruthers Creek watershed

Carruthers Creek is the most eastern watershed under the authority of TRCA located in Southern Ontario. From West to East, it is 3 km wide at its widest point, respectively from 79°04′04″W to 79°00′24″W, spanning the region from Westney Road to Audley Road. From North to South, it is 20 km long, respectively from 43°55′15.3″N to 43°49′38.4″N, spanning the region from part of municipality of Durham to part of Town of Ajax that contribute the highest percentage of urban area in this watershed (Bowen and Booty 2011).

Carruthers Creek drains 38 km^2 of a long narrow watershed and has a less than 50 km of total stream length, which is considered as second smallest watershed under the authority of TRCA (TRCA 2003). The average land slope in this watershed is around 4%.

2.2 Petticoat Creek watershed

The Petticoat Creek watershed is located in Southern Ontario and is surrounded by the Rouge River, Duffins Creek and Frenchman's watershed. It drains an area of 27 Km^2 with a total stream length of 49 km and is considered as the smallest watershed in the TRCA region. As a small watershed, Petticoat Creek responds quickly to precipitation and snow-melt event (TRCA 2012). From North to South, it respectively spans the area between 43°53′30.8″N and 43°47′38.2″N. The headwater of the watershed initially starts from Highway 7 and the York-Durham line. From the most upstream region, the stream flows through a large rural and agricultural preserve land, roads and ditches, forest, meadow, and in the downstream, it flows through mostly urban areas until reaching the Lake Ontario. From West to East, the Petticoat Creek respectively spans the region between 79°10′24.4″W and 79°07′54.7″W, i.e. part of City of Markham, City of Toronto and City of Pickering (TRCA 2012).

The Petticoat Creek watershed is an “urbanizing, warm watershed” (TRCA 2012) with an average slope of 4%. A large part of the watershed is preserved for agriculture and nature protection proposes. So far the environmental condition of this watershed is ranked as “fair” by TRCA since the massive urban development is undergoing within the watershed. The hydrological patterns and some parts of natural systems have also been affected by this urbanization (TRCA 2012).

3. Data Collection and SWAT Model Preparation

In this project, models for both of the Carruthers Creek and Petticoat Creek watersheds are built using ArcSWAT2012. SWAT requires plenty of input data to develop a watershed model. Table 1 summarizes the input file names and the sources for Carruthers Creek and Petticoat Creek watershed models.

Table 1. SWAT input data for Carruthers Creek and Petticoat Creek watersheds

Data Type	**Details**	**Source**
DEM	10m resolution	Scholars GeoPortal
Carruthers Creek network map	Shape file	TRCA
Climate data	Daily or sub-daily data (2005-15)	TRCA & Environment Canada
Land-use data and map	Polygon map file	TRCA
Land management data	Crop rotation and agriculture census	Asadzadeh, (2015)
Soil characteristics data and map	1:50,000 map and data spreadsheets	Detailed Soil Survey
Flow measured data	Daily data sets	TRCA
Water quality measured data	Grab-sample data points	TRCA

3.1 DEM Map and Watershed Delineation

The DEM maps for both of the Carruthers and Petticoat Creek watersheds are clipped from the larger DEM maps obtained from the work by Asadzadeh, et al. (2015). The source of this DEM is the Provincial Tiled Datasets downloaded from Scholars GeoPortal with 10-meter resolution and 3 dimensional and UTM coordinate. A lower resolution DEM was provided by TRCA but was not utilized in this study because of the inability of ArcSWAT to accurately delineate the watersheds at that lower resolution. DEM tile number 92 is used for modeling the Carruthers Creek watershed, and the merged DEM tiles 91; 92 and 93 is used for developing the Petticoat Creek watershed model. To increase the efficiency of ArcGIS in watershed delineation, we have to clip these large DEM files by the region of interest. For Carruthers Creek, the original DEM is clipped by a rectangle with bottom-left corner 43°48′50.8″N, 79°08′06.8″W and the top-right corner 44°01′31.8″N, 78°55′13.6″W. For Petticoat Creek, the original DEM is clipped by a rectangle with bottom-left corner 43°48′01.4″N, 79°12′27.6″W and the top-right corner 43°53′57.8″N, 79°05′48.7″W. Figure 1 and Figure 2 show these clipped DEM maps for the Carruthers Creek and Petticoat Creek watersheds, respectively.

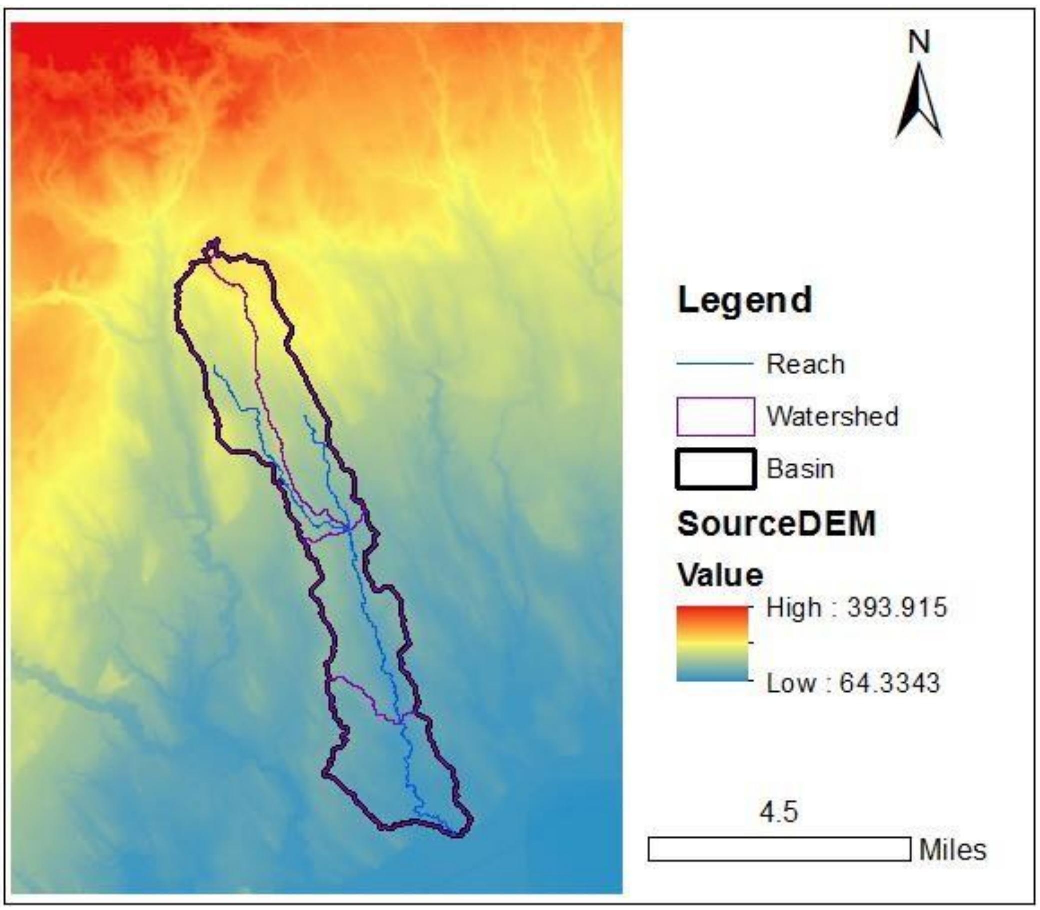

Figure 1. DEM, Carruthers Creek watershed boundary, sub-basins and stream network

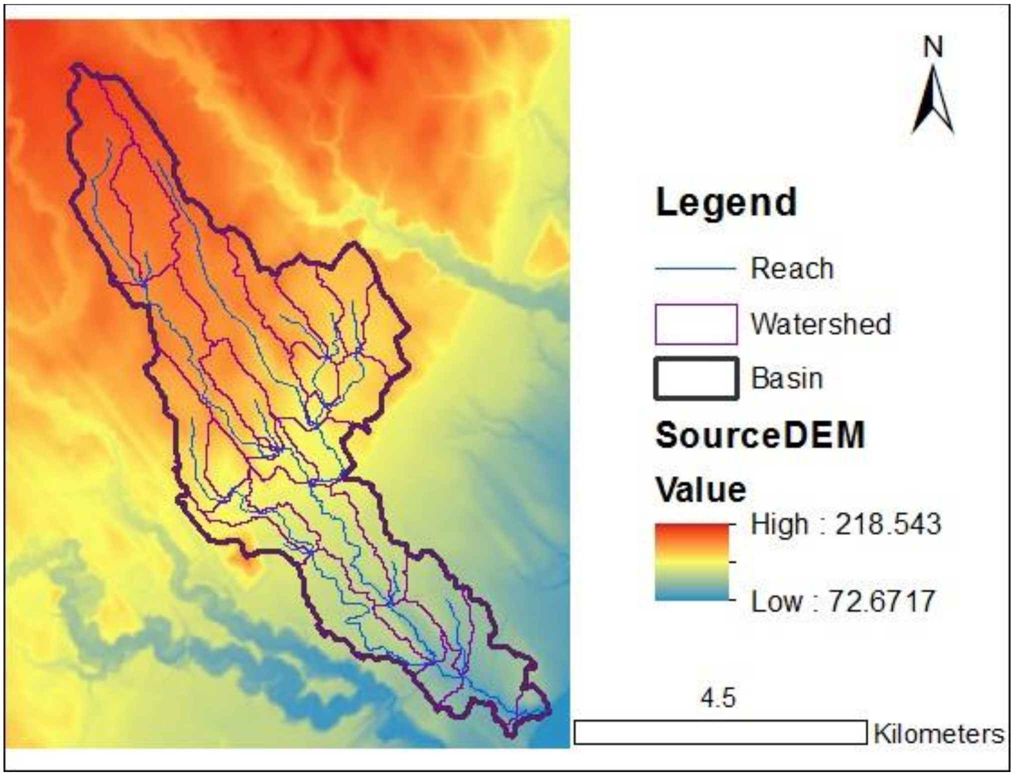

Figure 2. Source DEM, Petticoat Creek watershed boundary, sub-basins and stream network

Based on DEM map, ArcSWAT automatically delineates the whole basin and sub-basins in each watershed and develops the stream networks. For Carruthers Creek, ArcSWAT divides its basin into 4 sub-basins. Similarly, it divides Petticoat Creek's basin into 26 sub-basins. The watershed boundaries, sub-basins and stream networks shown in Figure 1 and 2 indicate that automatic watershed delineation is successfully performed by ArcSWAT.

3.2 HRU Definition

After successfully delineate the watershed delineation, ArcSWAT can analyze the land-use and soil type maps, and land slope information to define HRUs. Moreover, land-use map and soil type map must cover at least 96% of the watershed. The latest land-use and soil type maps are utilized in this project. The land-use classes are described in section 3.2.1, and the soil type classes are introduced in section 3.2.2 for both watersheds. For both watersheds, the land-slope within two watersheds is discussed in section 3.2.3.

3.2.1 Land-Use Classes

The most up-to-date land-use map of the Caruthers Creek watershed provided by TRCA contains 17 different land-use classes listed in column 2 of Table 3. Some of these classes are very similar and therefore are categorized under the same land-use class in SWAT. Cultivated Agriculture and Successional lands are simulated by generic agricultural land. The Estate Residential, Urban Open Space and Cemetery in the TRCA map are simulated by Low Density Residential (URLD) land-use. Golf Course, Natural, and Recreational lands in TRCA maps are simulated under the Tall Fescue (FESC).

Table 2 shows the 12 land-use classes in the SWAT database utilized to simulate all land-use classes present in TRCA maps of the Carruthers Creek watershed. Figure 3 shows the distribution of these land-use classes in this watershed.

Table 2. Land-use (LU) classes in Carruthers Creek watershed in 2016 provided by TRCA

	LU Code	LU Description	Area (%)	SWAT LU	SWAT LU Description
1	AGC	Cultivated Agriculture	43.97	AGRL	Agricultural Land-Generic
2	S	Successional			
3	ESTR	Estate Residential	14.85	URLD	Residential-Low Density
4	UOS	Urban Open Space			
5	CEM	Cemetery			
6	W	Wetland	11.09	WETL	Wetlands-Mixed
7	F	Forest	9.7	FRST	Forest-Mixed
8	GC	Golf Course	6.53	FESC	Tall Fescue
9	B	Natural			
10	REC	Recreational			
11	M	Meadow	4.63	BROM	Meadow Brome grass
12	C	Commercial	4.14	UCOM	Commercial
13	HC	Hydro Corridor	1.62	UTRN	Transportation
14	IND	Industrial	1.43	UIDU	Industrial
15	INS	Institutional	1.36	UINS	Institutional
16	HDR	High Density Residential	0.38	URHD	High Density Residential
17	OW	Open Water	0.30	WATR	Water

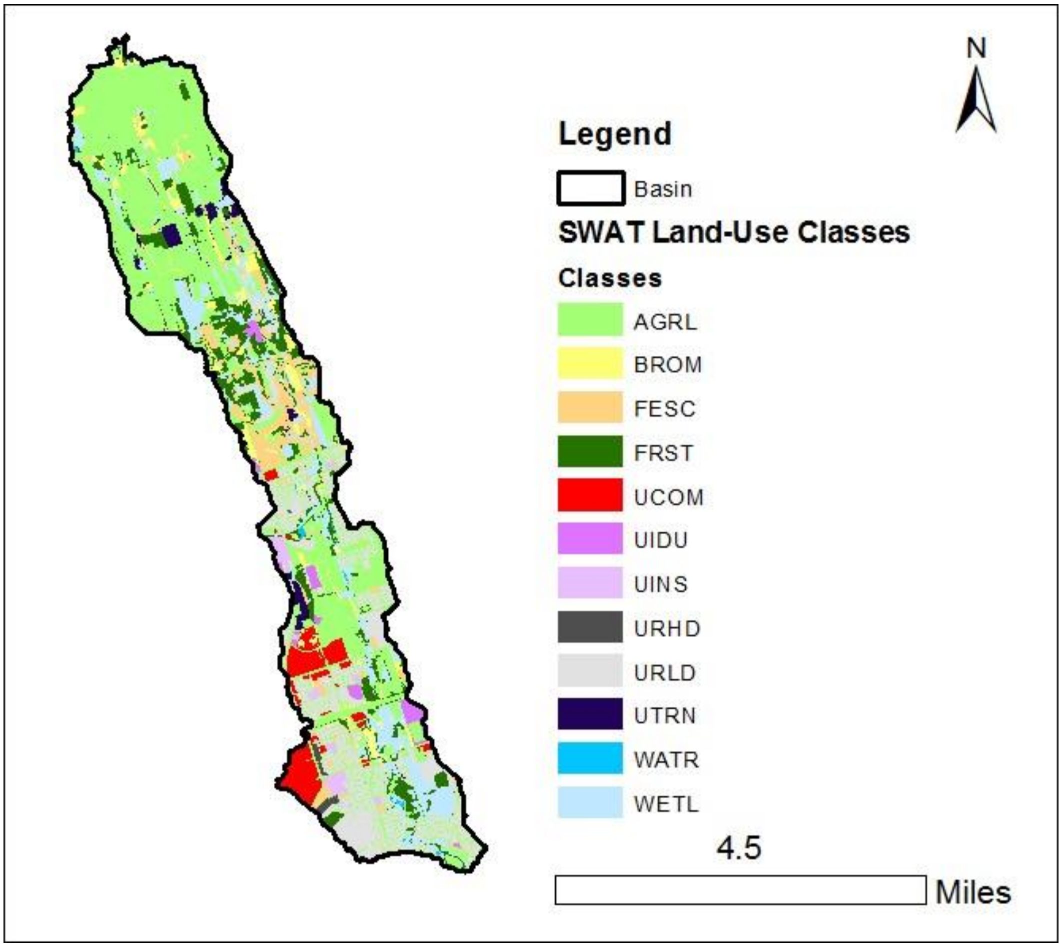

Figure 3. SWAT Land-use classes in Carruthers Creek watershed in 2016

According to Figure 3, the main land-use upstream of the Carruthers Creek watershed is the agricultural (AGRL), in the middle of the watershed, there is a mixture of golf courses (FESC), residential area (URLD), agriculture (AGRL) and forest (FRST), and the downstream of the watershed is mainly covered by commercial (UCOM), residential (URLD) and wetland (WETL) areas.

The land-use map of the Petticoat Creek watershed provided by TRCA has only four land-use classes that are simulated by three different SWAT land-use classes. Table 3 shows these land-use classes with a short descriptions and the portion of this watershed covered by each of them.

Table 3. Land-use (LU) classes in Petticoat Creek watershed provided by TRCA

	LU Code	LU Description	Area (%)	SWAT LU	SWAT LU Description
1	AGC	Cultivated Agriculture	72.34	AGRL	Agricultural Land-Generic
2	GB	Green Belt			
3	ESTR	Estate Residential	22.53	URLD	Residential-Low Density
4	N	Natural	5.13	FESC	Tall Fescue

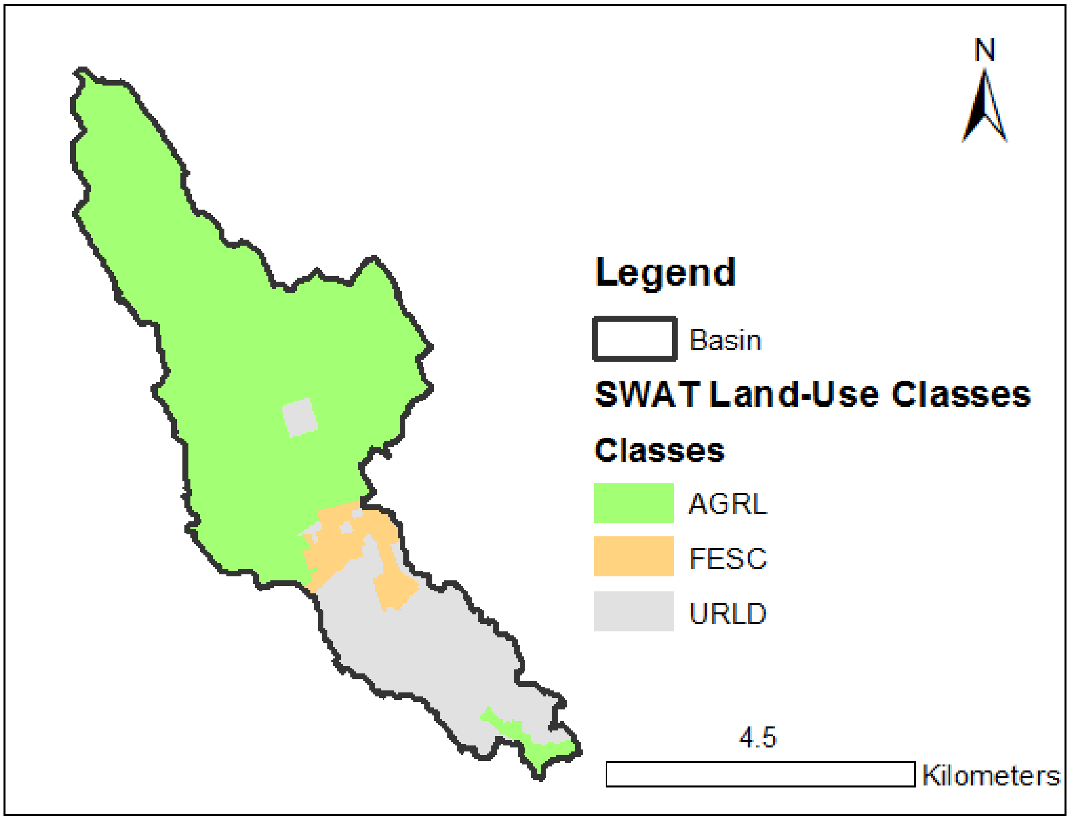

Figure 4. SWAT Land-use classes in Petticoat Creek watershed

The cultivated agriculture and green belt are simulated as generic agricultural land (AGRL) in SWAT model of this watershed. Figure 4 shows the distribution of the three land-use classes in the SWAT model of the Petticoat Creek watershed. The upstream of this watershed is mainly agricultural; there is a relatively small area covered by tall fescue (FESC) in the middle of this watershed; and its downstream is covered by low density residential area (URLD).

Based on the minimal amount of details in the land-use map of this watershed, it appears that this map might not be representative of the current state of the land-use classes in this watershed.

3.2.2 Soil Type Data

In SWAT, soil type data plays a significant role in the precipitation-runoff relationship, because it controls the vertical movement of water through the soil layers. SWAT users can either use default soil data that are archived in SWAT user soil database or add new soil types by defining soil parameters in the SWAT database.

The SWAT model of the Carruthers Creek and Petticoat Creek watersheds are equipped by the soil type maps used in Asadzadeh et al. (2015), the CanSIS maps and dataset that can be downloaded at http://sis.agr.gc.ca/cansis/nsdb/dss/v3/dss_v3_on_20140203.zip. According to Asadzadeh et al. (2015), the soil type maps and data from CanSIS is adequate to model the watersheds in this region. Asadzadeh et al. (2015) calculated all the soil parameters required in the SWAT database for the soil types in these maps. Some of these parameters are not immediately available in a different soil type map and database provided by TRCA. Therefore, that soil map is not used in this project.

Table 4 shows all the 12 soil classes used in the SWAT model of the Carruthers Creek watershed and Figure 5 shows the distribution of the soil hydrologic groups in this watershed.

Table 4. Soil classes in Carruthers Creek watershed

	Soil Classes	Hydrologic Group	Area (%)
1	Unclassified	D	12.38
2	Boundhead	B	17.28
3	Brighton	A	4.68
4	Darlington	B	7.91
5	Guerin	B	2.26
6	Muck	D	2.64
7	Milliken 1	B	0.02
8	Smithfield	C	12.14
9	Schomberg 1	C	1.35
10	Tecumseth 1	B	5.3
11	Whitby Loam	C	32.16
12	Woburn	B	1.91
Total			100

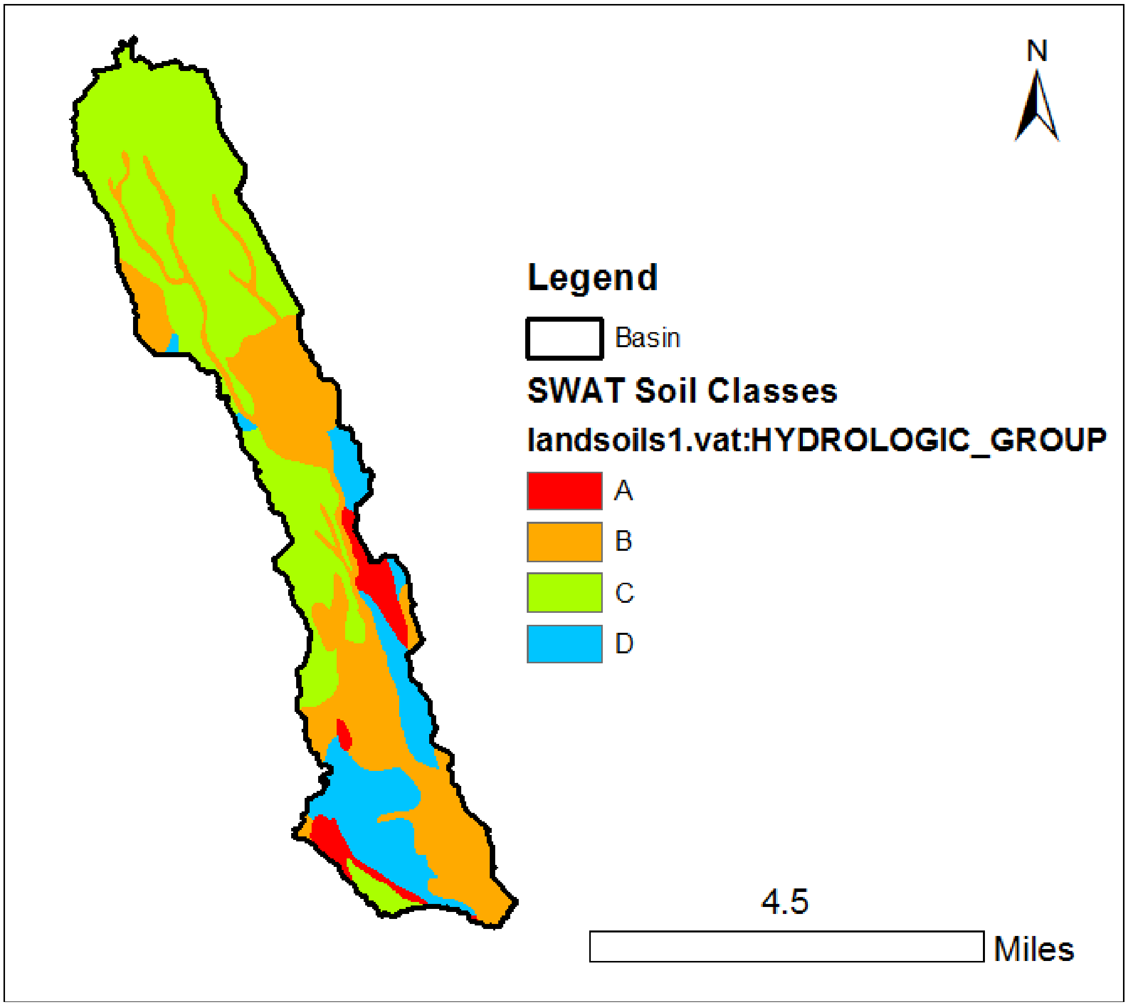

Figure 5. Soil classes distribution in Carruthers Creek watershed

Table 5 shows all the 9 soil classes in the SWAT model of the Petticoat Creek watershed. And Figure 6 shows the distribution of different soil hydrologic groups in the Petticoat Creek watershed.

Table 5. Soil classes in Petticoat Creek watershed

	Soil Classes	Hydrologic Group	Area (%)
1	Unclassified	D	11.6
2	Woburn	B	26.65
3	Brighton	A	8.43
4	Cashel	C	0.76
5	Granby	C	2.72
6	Muck	D	0.48
7	Milliken 1	B	48.4
8	Lyons	C	0.33
9	Peel	C	0.65
	Total		100

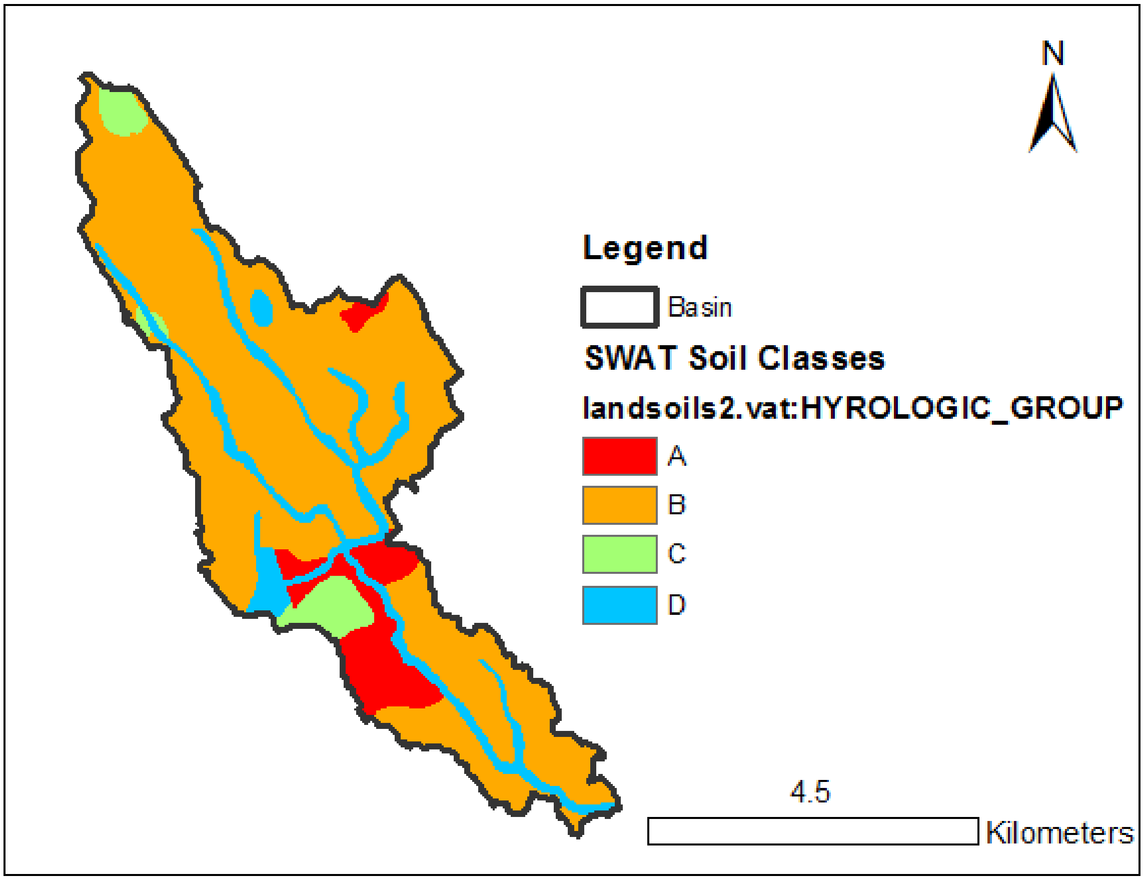

Figure 6. Soil classes distribution in Petticoat Creek watershed

3.2.3 Land Slope

The land slope classification is the last step in land-use/soil/slope HRU definition. SWAT users have the option to define as many land slope classes as they want by defining the threshold between the classes. One of the major impacts of land slope on the precipitation-runoff relationship in SWAT is its impact on the curve number. According to the SWAT user manual (SWAT 2012), SWAT users can adjust the curve number for lands with average slope higher than 5%. A threshold of 4% is used in this project to distinguish between lands with average slope below and above the average in both of the Carruthers Creek and Petticoat Creek watersheds. The following Figures 7 and 8 show the distribution of these two classes of lands in the Carruthers Creek and Petticoat Creek watersheds, respectively.

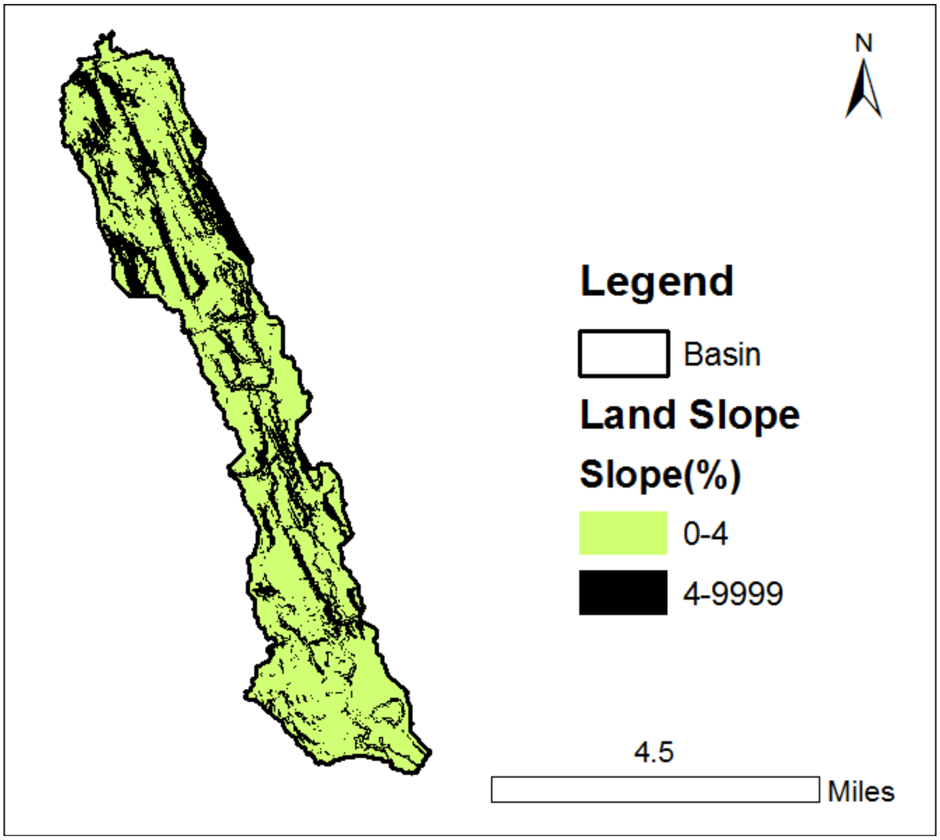

Figure 7. The distribution of land slopes in Carruthers Creek watershed

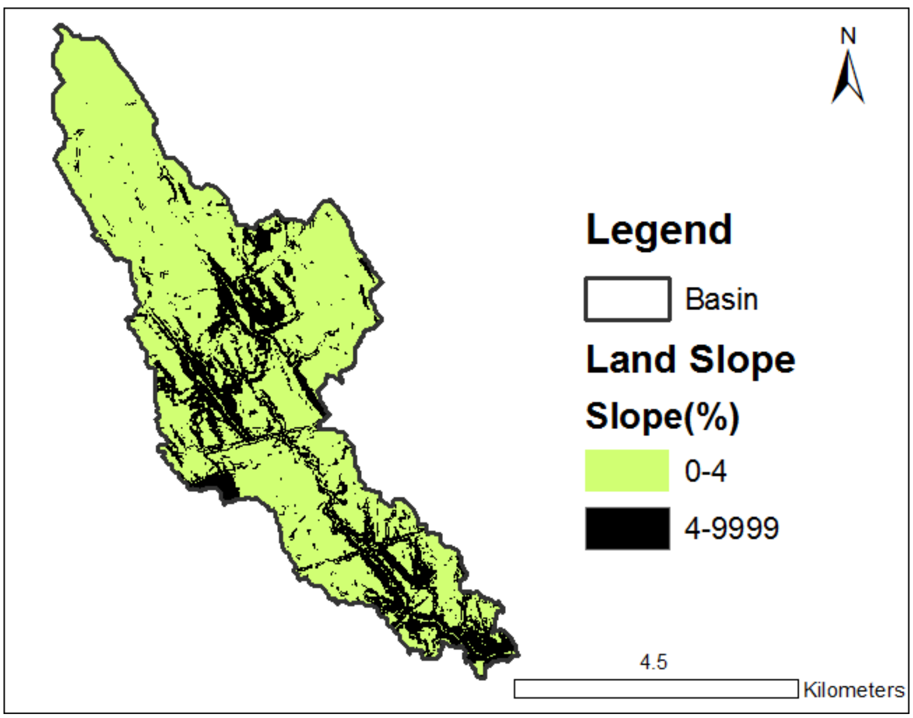

Figure 8. The distribution of land slopes in Petticoat Creek watershed

3.2.4 HRU Definition

After defining the land-use classes, soil types and slope classes for SWAT, HRUs can be defined in the model. Also, HRU definition can be adjusted by refining the land-use based on the management practices in agricultural lands.

Following Asadzadeh et al. (2015), the agricultural land-use is refined based on the management practices in the region. Personal communication with G. Bowen of TRCA reveals that Hay, which was significant in agricultural lands of the Rouge River and Duffins Creek watersheds in Asadzadeh et al. (2015), is not significant in the Carruthers Creek and Petticoat Creek watersheds. Therefore, the agricultural lands in these two watersheds are sub-divided into the following four different 4-year crop rotation practices and two different 2-year crop rotation practices:

- 4-year crop rotation with 4 crops of corn, corn, soybean and then winter wheat (CCBW). There are three other possible classes of this type of crop rotation: corn, soybean, winter wheat and then corn (CBWC); soybean, winter wheat, corn and then corn (BWCC); and winter wheat, corn, corn and then soybean (WCCB).
- 2-year crop rotation with 2 crops of corn and then soybean (CBCB). There is one other possible crop rotation of this type which is soybean and then corn (BCBC).

Each of the 4-year crop rotation types are assigned 20% of the agricultural lands in the SWAT model of the Carruthers Creek and Petticoat Creek watersheds. Each of the 2-year crop rotation types are assigned 10% of the agricultural lands in the SWAT model of these watersheds. This results in 50% of the agricultural lands in these watersheds producing corn, 30% producing soybean and 20% producing winter wheat, in each year. Table 6 shows the agriculture sub-classes of land-use within both watersheds.

Table 6. Sub-classes of agriculture land-use in Carruthers and Petticoat Creek watersheds

		Rotation Year			
LU Sub-Classes	**Area (%)**	**1**	**2**	**3**	**4**
CCBW	20	Corn	Corn	Soybean	Winter Wheat
WCCB	20	Winter Wheat	Corn	Corn	Soybean
BWCC	20	Soybean	Winter Wheat	Corn	Corn
CBWC	20	Corn	Soybean	Winter Wheat	Corn
CBCB	10	Corn	Soybean	Corn	Soybean
BCBC	10	Soybean	Corn	Soybean	Corn

A large number of HRUs in a model can significantly increase the runtime of the model without increasing the model accuracy. Therefore, the number of HRUs has to be controlled. To this end, SWAT lets the users define thresholds for each of the land-use, soil type, and slope classes in the HRU definition process. These thresholds are case-dependent and has to be carefully selected by the user based on the accuracy of the land-use, soil type and land-slope maps and data and with a trial and error. Following Asadzadeh et al. (2015), a 20% threshold for both of the soil-type and land slope classes is used in the HRU definition of the Carruthers Creek watershed.

In the first attempt to define HRUs in the Carruthers Creek watershed, a 0% threshold is used for the land-use to consider all details of the land-use map in defining HRUs. This resulted in 182 HRUs for 4 sub-basins which is significantly and unnecessarily large. Therefore, in the second attempt, a 5% threshold is used for HRUs and this resulted in more than 50% reduction in the number of HRUs (88 HRUs for 4 sub-basins in the Carruthers Creek watershed), which is a more reasonable classification of HRUs.

All major land-use, soil type and land-slope classes appear in the final model; therefore, it is concluded that the 5%, 20%, and 20% thresholds respectively for the land-use, soil type and land slope classes are adequate for the Carruthers Creek watershed. A similar set of thresholds is used in the HRU definition of the Petticoat Creek watershed.

Table 7. Portion of watersheds assigned to land-use, soil hydrologic group and land slope classes

	Carruthers Creek		Petticoat Creek	
	HRU component	**Area (%)**	**HRU component**	**Area (%)**
Land-use	Agriculture	40.07		
	Meadow	3.58	Agriculture	71.00
	Tall Fescue	5.20		
	Forest	12.14	Tall Fescue	5.58
	Wetlands	14.48		
	Urban	19.93	Urban	23.42
	Commercial	4.60		
Soil Hydrologic Group	A	4.08	A	8.21
	B	22.62	B	81.65
	C	57.87	C	2.26
	D	15.43	D	7.88
Land Slope	0%-4%	71.21	0%-4%	81.36
	> 4%	28.79	> 4%	18.64

3.3 Climate Data

Climate data required by ArcSWAT 2012 include: daily total precipitation (mm), maximum and minimum daily air temperature (℃), average daily solar radiation (MJ/m^2), average daily wind speed (m/s) and average daily relative humidity (fraction). The collection of these datasets are described respectively in this section. Since the watersheds of interest in this project are relatively small, one reliable source of climate data should be enough to estimate the distribution of the forcing data in their models. The Toronto Buttonville climate station is the main source of climate data for the Petticoat Creek watershed and the climate stations in Oshawa and Ajax are the main sources of climate data for the Carruthers Creek watershed.

3.3.1 Daily Precipitation (PCP)

Total daily precipitation in millimeters is the main driver of the precipitation-runoff relationship in SWAT. Thus, an accurate daily precipitation dataset from one or more reliable sources is necessary. As shown in Table 8, in the model of Carruthers Creek watershed, the complete dataset of daily precipitation for the simulation period of 2005-2015 is obtained from the Oshawa WPCP climate station. In the model of Petticoat Creek watershed, a complete dataset of daily precipitation is obtained from the Toronto Buttonville climate station.

Table 8. Source of precipitation data in Carruthers Creek and Petticoat Creek watersheds

	PCP	
Date	**Carruthers Creek**	**Petticoat Creek**
2005	Oshawa WPCP	Toronto Buttonville
2006		
2007		
2008		
2009		
2010		
2011		
2012		
2013		
2014		
2015		

3.3.2 Minimum and Maximum Daily Air Temperature (TMP)

The maximum and minimum daily air temperature in degree Celsius is also one of the main drivers of the water balance in SWAT. In the model of the Carruthers Creek watershed, this dataset is obtained mainly from the Oshawa WPCP because the Ajax Community Center climate station which is located inside the watershed has only one and a half years of complete daily air temperature data from 28 August 2014 to 31 December 2015. As it is shown in Table 9, this dataset is used for the SWAT model of the Carruthers Creek watershed, and the remaining missing data points from 1 January 2005 to 27 August 2014 is obtained from Oshawa WPCP.

In the model of Petticoat Creek watershed, a complete dataset of daily air temperature is obtained from the Toronto Buttonville climate station.

Table 9. Source of temperature data in Carruthers Creek and Petticoat Creek watersheds

	TMP	
Date	**Carruthers Creek**	**Petticoat Creek**
2005	Oshawa WPCP	Toronto Buttonville
2006		
2007		
2008		
2009		
2010		
2011		
2012		
2013		
2014.8.27		
2014.8.28	Ajax Community Centre	
2015		

3.3.3 Daily Solar Radiation (SLR)

Daily solar radiation with the unit of MJ/m^2 can be used by SWAT in the calculation of potential evapotranspiration. For both watersheds, very limited measured SLR data points are available at nearby stations. The large number of missing data points can be a source of uncertainty in the model. Therefore, other sources of SLR are explored for this project. The NASA Prediction of Worldwide Energy Resource dataset provides average daily solar radiation data for the region of interest, downloaded at https://power.larc.nasa.gov/cgi-bin/timeseries.cgi for the region of interest. This SLR dataset is compared with the one obtained from HY004 station that is operated by TRCA for the duration of 2010-2012. The visual comparison in Figures 9 and 10 shows an excellent match between these two datasets. Moreover, the mean and standard deviation of these two datasets in Tables 10 confirms that SLR provided by NASA Prediction of Worldwide Energy Resource is reliable to be utilized in this project. Therefore, the missing SLR data points at HY004 are filled in by SLR data obtained from NASA Prediction of Worldwide Energy Resource. Table 11 shows the source of solar radiation data in Carruthers Creek and Petticoat Creek watersheds.

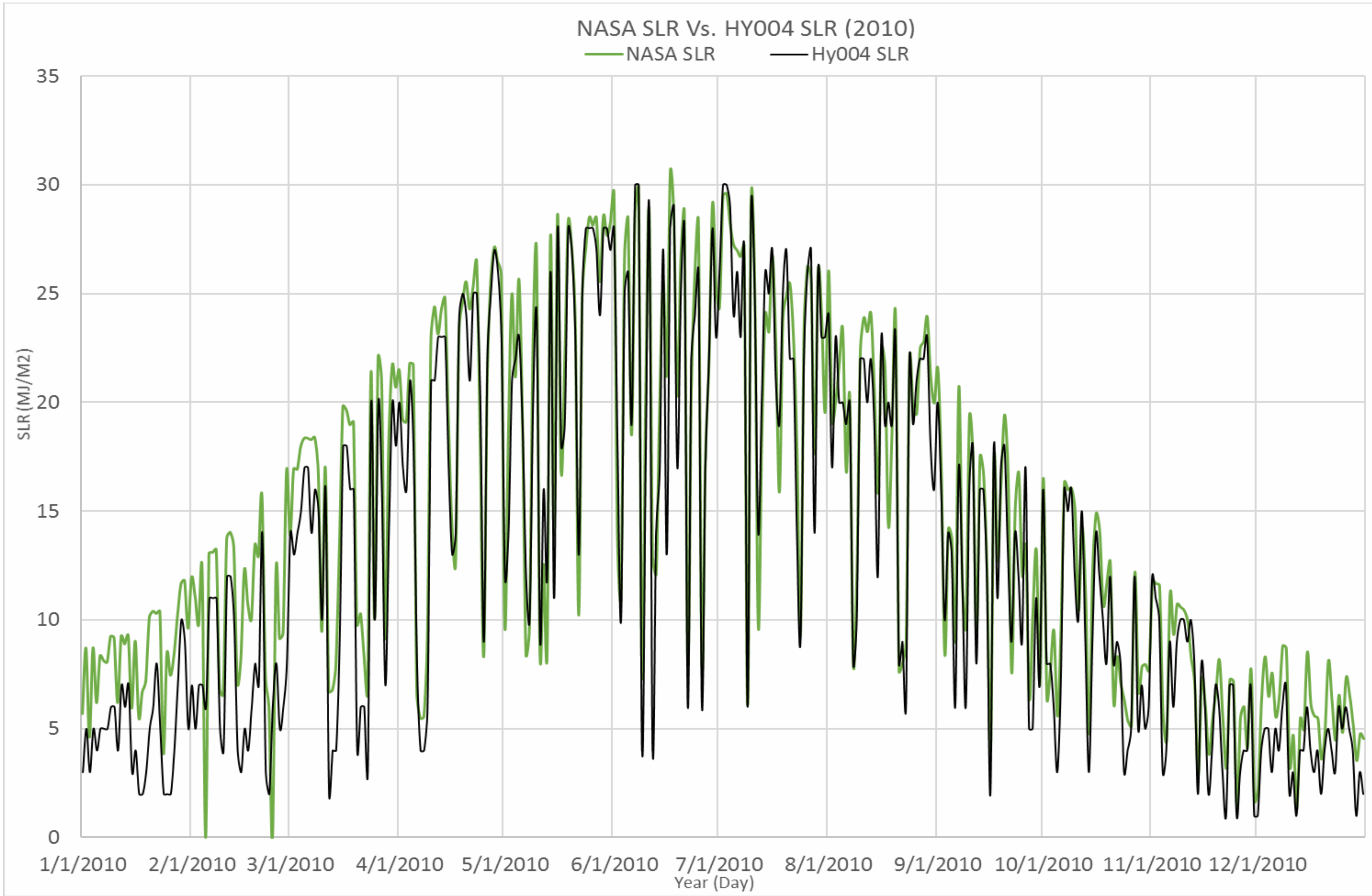

Figure 9. Daily solar radiation data comparison between NASA and HY004 in the year of 2010

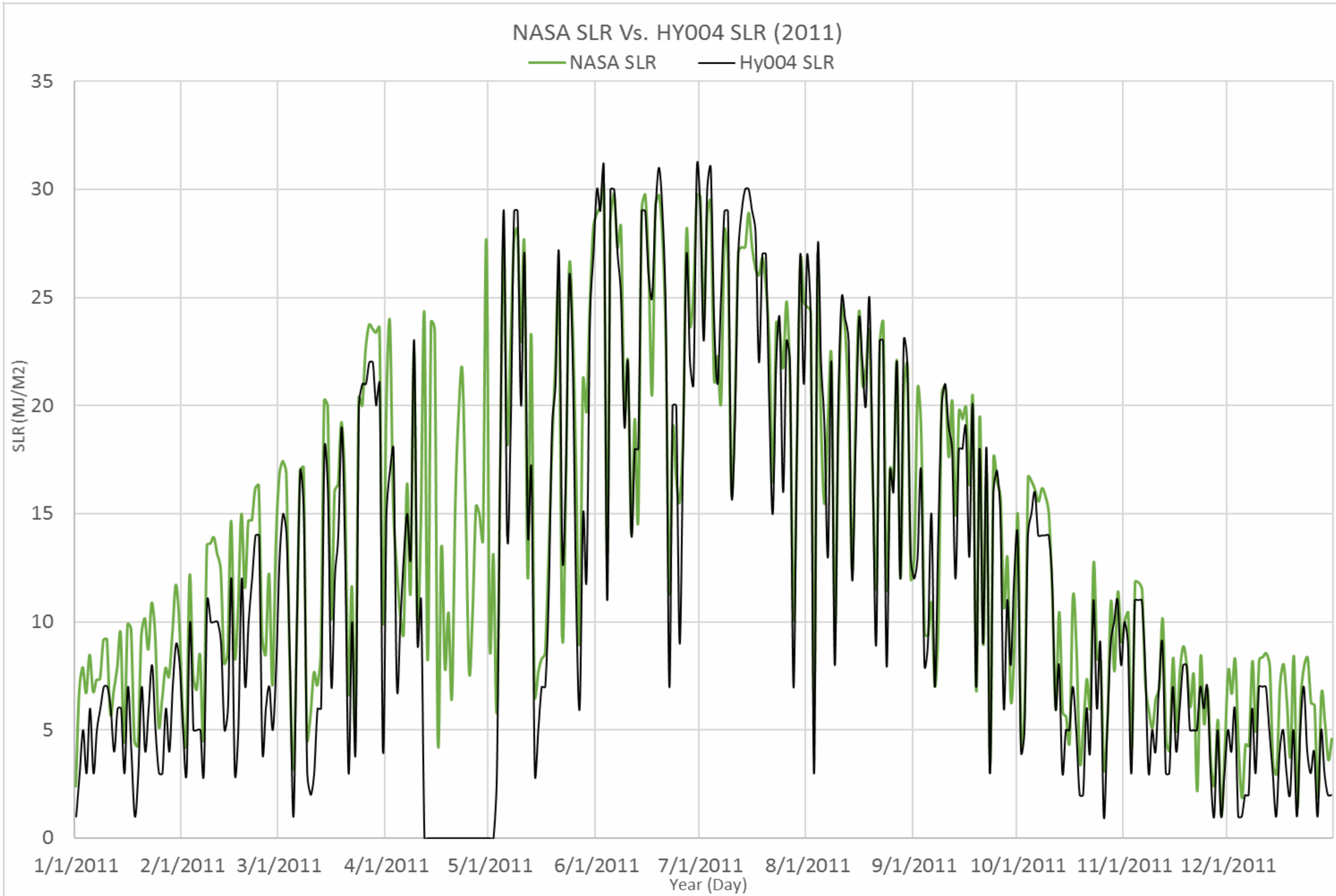

Figure 10. Daily solar radiation data comparison between NASA and HY004 in the year of 2011

Table 10. Mean and standard deviation comparison between HY004 and NASA in 2010-11

Source	Mean		Standard Deviation	
	2010	**2011**	**2010**	**2011**
HY004	13	12	8	9
NASA	15	14	8	8

Table 11. Source of solar radiation data in Carruthers and Petticoat Creek watersheds

Date	SLR
2005	NASA
2006	
2007	
2008	
2009	
2010	HY004
2011	
2012	NASA
2013	
2014	
2015	

3.3.4 Daily Wind Speed (WND SP)

SWAT needs daily average wind speed in meters per second to determine the potential evapotranspiration. In the model of the Carruthers Creek watershed, this data is provided by three stations: HY063, Oshawa and Ajax community center climate station. HY063 is a station monitored by TRCA and used for the Rouge River modeling by Asadzadeh et al. (2015). It is located right in between the Carruthers and Petticoat Creek watersheds, so it provides data for both watersheds. In the model of the Petticoat Creek watershed, wind speed data is provided by HY063 and Toronto Buttonville climate stations. Table 12 indicate the source of the wind speed data in each year for both of the two watersheds.

Table 12. Source of wind speed data in Carruthers Creek and Petticoat Creek watersheds

	WND SP	
Date	**Carruthers Creek**	**Petticoat Creek**
2005	HY063	HY063
2006		
2007		
2008		
2009		
2010		
2011		
2012	Oshawa	Toronto Buttonville
2013		
2014.8.27		
2014.8.28	Ajax Community Centre	
2015		

3.3.5 Daily Relative Humidity (RH)

Same as the daily wind speed data, the average daily relative humidity data in percentage is provided by HY063, Oshawa and Ajax community center climate station for Carruthers Creek watershed and by HY063 and Toronto Buttonville climate stations for the Petticoat Creek watershed. Table 13 indicates the source of the relative humidity in both watersheds in each year.

Table 13. Source of relative humidity data in Carruthers Creek and Petticoat Creek watersheds

	RH	
Date	**Carruthers Creek**	**Petticoat Creek**
2005	HY063	HY063
2006		
2007		
2008		
2009		
2010		
2011		
2012	Oshawa	Toronto Buttonville
2013		
2014.8.27		
2014.8.28	Ajax Community Centre	
2015		

3.4 Land Management Operation Data

The main impact of the land management operations on the precipitation-runoff relationship of SWAT is the dynamically changing SCS curve number (CN) that is a function of the crop type, operation type, soil hydrologic group, and time. Following the footsteps of Asadzadeh et al. (2015), all land management operations are scheduled by date. Also, as noted by Asadzadeh et al. (2015), the CN values are obtained from the recommended values provided by SWAT developers in the SWAT user manual for all four types of soil hydrologic groups.

The land management operations of the Carruthers Creek watershed are applied to the following SWAT land-use classes: agricultural (AGRL), forest (FRST), tall fescue (FESC), meadow (BROM), urban (URLD), industrial (UIDU) and commercial (UCOM) lands. The land-use of the Petticoat Creek watershed does not have any industrial (UIDU) or commercial (UCOM) lands. Other than these two, the same land management operations are applied to the model of the Petticoat Creek watershed. The following Tables 14, 15, 16, 17 and 18 are copied from Asadzadeh et al. (2015) and show the details of the land operation data used in these two watersheds.

Table 14. Management operations for agriculture land with a 2-year crop rotation (Table 16, Asadzadeh 2015)

Year (Crop)	Month	Day	Operation(s)	Hydrologic Soil Group			
				A	B	C	D
1 (Corn)	4	30	Disc Plough GE23ft	76	85	90	93
	5	1	Plant/Grow Corn	67	78	85	89
	5	2	Fertilizer: N 110 kg/ha				
	5	3	Fertilizer: P 22 kg/ha				
	11	1	Harvest and Kill Corn	74	83	88	90
	11	15	Mouldboard Plough (reg 4-6b)	76	85	90	93
2 (Soybean)	5	13	Plant/Grow Soybean	67	78	85	89
	5	14	Fertilizer: P 33 kg/ha				
	10	1	Harvest and Kill Soybean	74	83	88	90

Table 15. Management operations for agriculture lands with a 4-year crop rotation (Table 15, Asadzadeh 2015)

Year (Crop)	Month	Day	Operation(s)	Hydrologic Soil Group			
				A	B	C	D
1 (Corn)	4	30	Disc Plough GE23ft	77	86	91	94
	5	1	Plant/Grow Corn	67	78	85	89
	5	2	Fertilizer: N 110 kg/ha				
	5	3	Fertilizer: P 22 kg/ha				
	11	1	Harvest and Kill Corn	74	83	88	90
	11	15	Mouldboard Plough (reg 4-6b)	76	85	90	93
2 (Corn)	4	30	Disc Plough GE23ft	77	86	91	94
	5	1	Plant/Grow Corn	67	78	85	89
	5	2	Fertilizer: N 110 kg/ha				
	5	3	Fertilizer: P 22 kg/ha				
	11	1	Harvest and Kill Corn	74	83	88	90
	11	15	Mouldboard Plough (reg 4-6b)	76	85	90	93
3 (Soybean and Winter Wheat)	5	13	Plant/Grow Soybean	67	78	85	89
	5	14	Fertilizer: P 33 kg/ha				
	10	1	Harvest and Kill Soybean	74	83	88	90
	10	6	Plant/Grow Winter Wheat	67	78	85	89
	10	7	Fertilizer: N 10 kg/ha				
	10	8	Fertilizer: P 20 kg/ha				
4 (Winter Wheat)	4	10	Fertilizer: N 70 kg/ha				
	7	15	Harvest and Kill Winter Wheat	74	83	88	90
	11	15	Mouldboard Plough (reg 4-6b)	76	85	90	93

Table 16. Management operations for forest land (Table 19, Asadzadeh 2015)

Month	Day	Operations	Hydrologic Soil Group			
			A	B	C	D
5	1	Plant/Beginning of growing season	30	55	70	77
10	10	Kill/End growing season				

Table 17. Management operations for tall fescue and meadow lands (Table 20, Asadzadeh 2015)

Month	Day	Operations		Hydrologic Soil Group			
				A	B	C	D
4	1	Plant/Beginning of growing season	FESC, BROM	30	58	71	78
10	31	Harvest and Kill					

Table 18. Management operations for urban residential, industrial and commercial lands (Table 21, Asadzadeh 2015)

Month	Day	Operation(s)	Hydrologic Soil Group			
			A	B	C	D
4	1	Fertilizer N 12kg/ha				
4	2	Fertilizer P 5kg/ha				
5	1	Plant/Beginning of growing season	30	58	71	78
6	1	Fertilizer N 11kg/ha				
8	15	Fertilizer N 11kg/ha				
9	29	Harvest and Kill	74	83	88	90
9	30	Fertilizer N 11kg/ha				
-	-	Residential	77	85	90	92
-	-	Commercial	81	88	91	93

3.5 Measured Flow Data (cms)

Daily measured streamflow data is necessary to compare the model performance in terms of the hydrologic processes. The most comprehensive evaluation of a hydrologic simulation model can be obtained visually comparing the time series of simulated versus the measured streamflow (ASCE 1993).

TRCA provides the measured streamflow data for both of the Carruthers Creek and Petticoat Creek watersheds. There are three hydrometric locations within Carruthers Creek watershed, which are HY089, HY090, and HY013 highlighted in Figure 11. Moreover, HY013 contains measured streamflow data from 26 July 2007 to 31 December 2015. There is also one hydrometric station within the Petticoat Creek watershed, HY051 highlighted in Figure 12. And HY051 contains complete measured streamflow data for the whole simulation period, 2005- 2015.

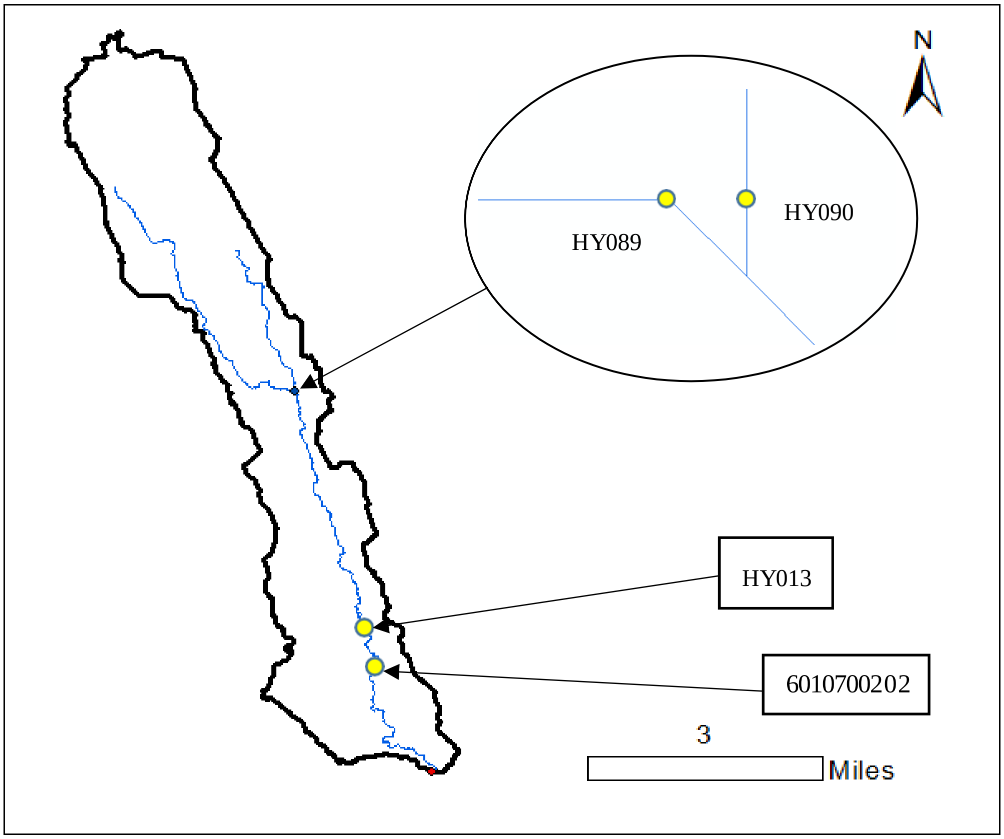

Figure 11. Flow measuring locations in Carruthers Creek watershed

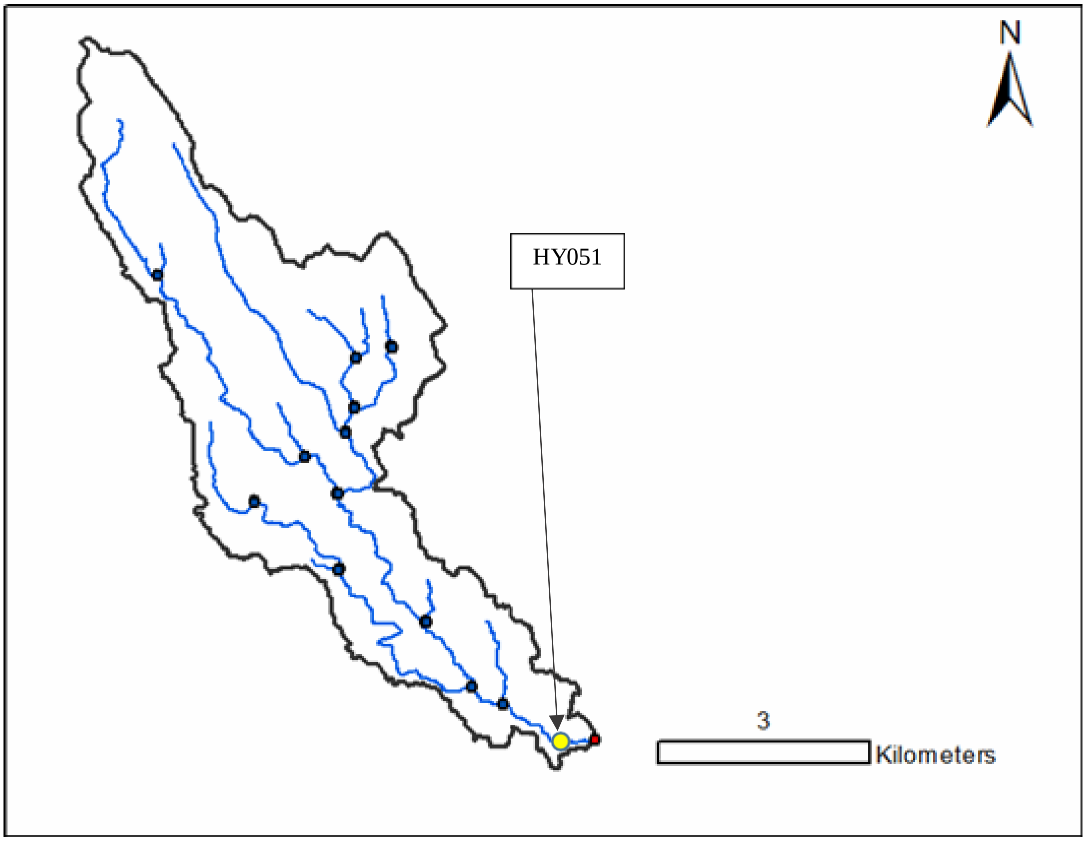

Figure 12. Flow measuring locations in Petticoat Creek watershed

3.6 Water Quality Measured Data

One of the main interests in this watershed modeling project is to adequately estimate daily loading of water quality constituents delivered into the Lake Ontario from these two watersheds. The total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN) are of particular interest in this project. TRCA provides the measured water quality data points for the Carruthers Creek and Petticoat Creek watersheds. The water quality is measured at the hydrometric station with ID 6010700202 in the Carruthers Creek watershed (Figure 11) and at the hydrometric station HY051 in the Petticoat Creek watershed (Figure 12).

4. Model Parameter Adjustment

Just like any other advanced watershed model, SWAT has numerous parameters that can be adjusted to improve its performance in terms of precipitation-runoff relationship and water quality simulation. One of the goals of this project is to keep the SWAT models of the Carruthers Creek and Petticoat Creek watersheds as much as possible similar to the models of the Rouge River and Duffin's Creek watersheds in Asadzadeh et al. (2015). Therefore, the exact same parameter values reported in Asadzadeh et al. (2015) are used in this project. As shown in Table 19, in total, 22 parameters are modified for each watershed model in the bsn, hru, sol, gw, and rte files to replicate the parameter values from Asadzadeh et al. (2015) in the SWAT model of the Carruthers Creek and Petticoat Creek watersheds.

Table 19. Sensitive parameters for calibrating (Table 9, Asadzadeh et al. 2015)

System Behavior	# Par. Number	Name	File Extenison	Method	Default Value	Calibrated Value
Hydrology	1	CN	bsn	Multiply	1	1
	2	SMFMN	bsn	Replace	4.5	1.7
	3	TIMP	bsn	Replace	1	1
	4	ESCO	bsn and hru	Replace	0.95	0.95
	5	EPCO	bsn and hru	Replace	1	0.01
	6	SURLAG	bsn	Replace	4	0.424
	7	SOL_AWC	sol	Multiply	1	1.492
	8	SOL_K	sol	Multiply	1	95.5
	9	GW_DELAY	gw	Replace	31	31
	10	ALPHA_BF	gw	Replace	0.2	0.2
	11	GWQMN	gw	Replace	0	0
	12	CH_N2	rte	Replace	0.014	0.024
	13	CH_K2	rte	Replace	0	21
Water Quality	1	SPCON	bsn	Replace	0.0001	0.0003
	2	SPEXP	bsn	Replace	1	2
	3	NPERCO	bsn	Replace	0.2	1
	4	CDN	bsn	Replace	0	3
	5	SDNCO	bsn	Replace	1.1	0.1
	6	CH_COV1	rte	Replace	0	1
	7	CH_COV2	rte	Replace	0	1
	8	ERORGN	hru	Replace	0	1
	9	ERORGP	hru	Replace	1	0.6

5. Results and Discussion

In this section, the simulated and measured datasets are compared to evaluate the model performance in estimating daily streamflow, total phosphorus, total nitrogen and total suspended solids. In Section 5.1 comparisons are made for the Carruthers Creek watershed, and in Section 5.2 comparisons are made for and Petticoat Creek watershed.

5.1 Carruthers Creek watershed

The average simulated streamflow in the Carruthers Creek watershed is 0.34 cms which is less than 5.6% lower than the measured value, 0.36 cms. This bias is considered reasonably low based on Moriasi et al. (2007). Table 20 summarizes the annual average water balance provided by the SWAT model of the Carruthers Creek watershed. Based on this table, the model estimates that, from 859.1 mm of the annual average precipitation, about 55.2% is lost through the evapotranspiration and about 43.4% is turned into the streamflow and less than 1.6% is the summation of all the other water losses from the system. The surface flow contribution to the streamflow is estimated 50.2%. These annual average components of the water balance are similar to those in the previous work made by Asadzadeh et al. (2015).

Table 20. Annual average hydrologic data and temperature (2005-2015

Average Annual Basin Values					
Precipitation (mm)	**Max. Tmp. (℃)**	**Min. Tmp. (℃)**	**Evapotranspiration (mm)**	**Water Yield (mm)**	**Surface Runoff (mm)**
859.1	12.87	4.22	474.30	372.66	187.18

Figure 13 shows the time series of daily simulated streamflow in comparison with the daily measured streamflow at hydrometric station HY013 in 2014 as a sample of a simulation year from 2005 to 2015. According to this figure, SWAT can adequately simulate the watershed response to some of the major streamflow events in the Carruthers Creek watershed. For example, the model provides a reasonable estimation of the peak flow during the snowmelt period in late February 2014. It is often very difficult for watershed models to accurately simulate the streamflow in spring snowmelt periods. However, Figure 13 shows a reasonable model performance in the snowmelt period of March and April 2014. Some of the measured peak flows in this period are underestimated by the model though. In the period of summer 2014, the model adequately responds to the major precipitation events in comparison with the measure hydrographs. However, the one-day offset issue (1dOI) reported by Asadzadeh et al. (2016) is obvious in many of these major precipitation-runoff events. According to Asadzadeh et al. (2016), 1dOI in small watersheds with sub-daily time of concentration just like the watersheds in this project is mainly due to the late day precipitation events. In reality, the watershed responds to these events on the next day, while the SWAT model responds to the even on the same day because the simulation runs with the daily (not sub-daily) time-steps. The 1dOI is rather the data aggregation issue than a simulation model error (Asadzadeh et al. 2016). In the period of summer 2014, the model accurately estimates some of the extended low-flow periods. But, in the Fall and Winter periods of 2014, the model tends to underestimate the low-flow periods. The time series of simulated versus measured streamflow for the other years in the simulation period (2005-2015) are provided in Figures 21 to 28 in the appendix A. There is no time series of daily streamflow comparison during 2005-2006 in appendix A, because measured streamflow datasets are only available after 2007.

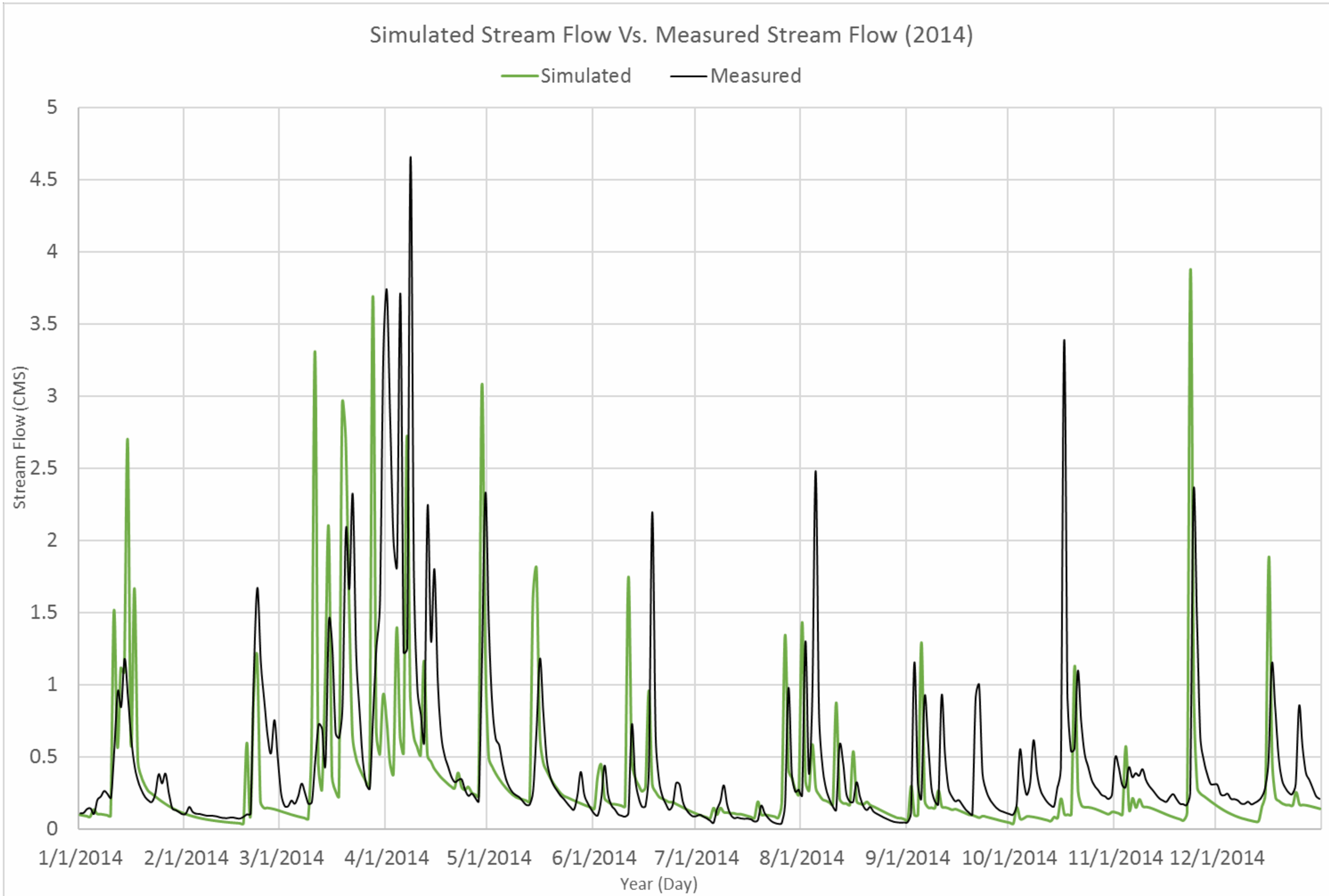

Figure 13. Comparison of streamflow in the year of 2014 in Carruthers Creek watershed

The model performance in estimating the water quality processes in the Carruthers Creek watershed is also analyzed. The following Table 21 show the statistics (average, maximum, and the minimum) of simulated versus measured TP, TN, and TSS in the Carruthers watershed.

Table 21. Summary of average, maximum, and minimum loading of TP, TN and TSS from simulation data, measured data (TRCA) and measured data (Toronto & York-Durham Lab)

Concentration(mg/l) Loading(kg)&(ton)	**TP**			**TN**			**TSS**		
	Average	**Max.**	**Min.**	**Average**	**Max.**	**Min.**	**Average**	**Max.**	**Min.**
Simulated	0.32 mg/l	37.92 mg/l	0 mg/l	2.14 mg/l	253.51 mg/l	0 mg/l	131.14 mg/l	12229.7 mg/l	0 mg/l
	18.10 kg	2136 kg	0 kg	120.31 kg	14280 kg	0 kg	7.39 tons	688.9 tons	0 ton
Measured (TRCA)	0.16 mg/l	1.58 mg/l	0 mg/l	1.39 mg/l	3.74 mg/l	0.8 mg/l	88.75 mg/l	1070 mg/l	5.1 mg/l
	21.37 kg	529.79 kg	0.08 kg	111.22 kg	1254.07 kg	1.18 kg	13.74 tons	358.78 tons	0.01 tons
Measured (Toronto & York-Durham Lab)	0.05 mg/l	0.2 mg/l	0.01 mg/l	1.39 mg/l	3.23 mg/l	0.58 mg/l	18.85 mg/l	140 mg/l	1.4 mg/l
	2.7 kg	36.42 kg	0 kg	0.87 kg	2.01 kg	0 kg	1.15 tons	15.28 tons	0 tons

Comparing with the water quality data from three sources, simulated results of average TP, TN and TSS are more similar to TRCA measurements. Simulated average daily loading of TP, TN and TSS are 18.1 kg, 120.31 kg and 7.39 tons per year, respectively. And the TRCA measured average daily loading of TP, TN and TSS are 21.37 kg, 111.22kg and 13.74 tons. Even though TRCA measurements are limited to the few data points, it can still prove that the simulation is good and has more potential to improve the performance of the model. However, regarding maximum daily loading of TP, TN and TSS, simulated results are way different compared to TRCA measurements.

On the other hand, Toronto and York-Durham Lab measurements are not in the same rage neither with the simulated results nor with TRCA measurements. It may be caused by the inaccuracy of its water quality measurements. Table 22 shows the absolute percentage difference between simulated water quality data and TRCA measured water quality data.

Table 22. Absolute percentage difference between water quality data from simulation and TRCA's measurement

	TP			TN			TSS		
	Average	**Max.**	**Min.**	**Average**	**Max.**	**Min.**	**Average**	**Max.**	**Min.**
Absolute percentage difference (%)	18.07	75.2	100	7.56	91.22	100	85.93	47.92	100

Furthermore, Figure 14, 15, and 16 show the comparison of TP, TN, and TSS in a time series with the simulated data, the measurement done by TRCA, and the measurement done by Toronto and York-Durham Lab respectively.

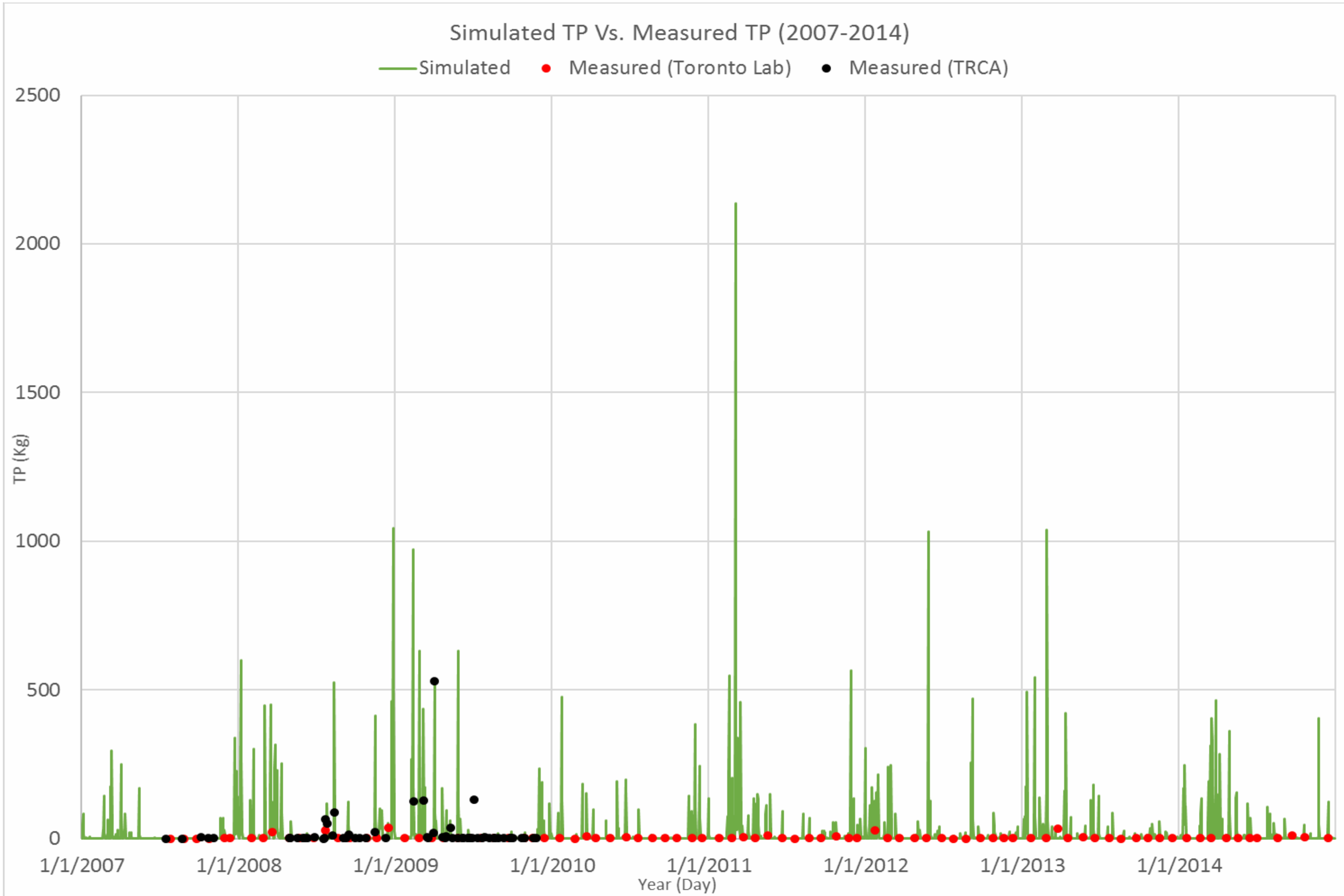

Figure 14. Comparison of TP in the period of 2007-2014

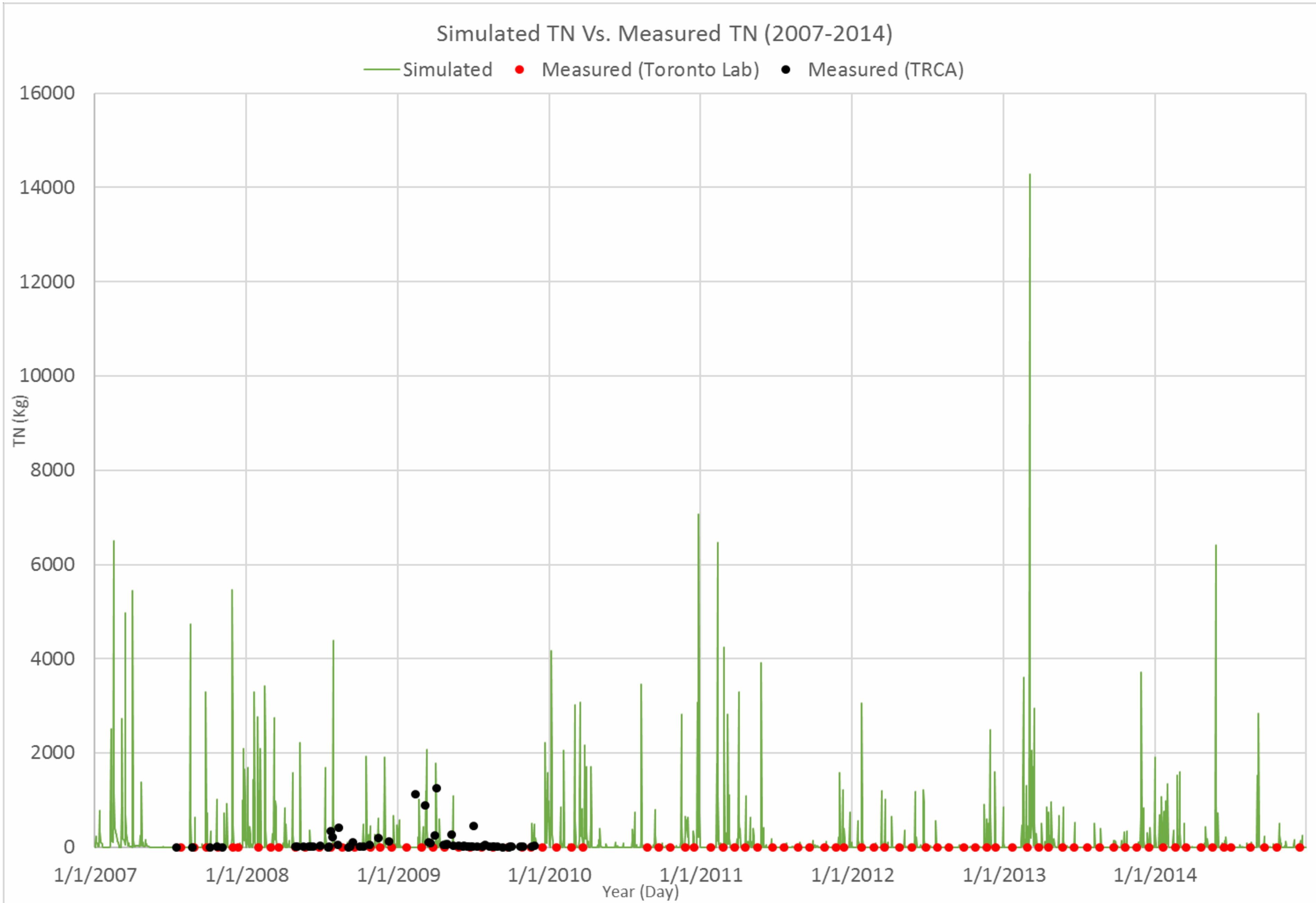

Figure 15. Comparison of TN in the period of 2007-2014

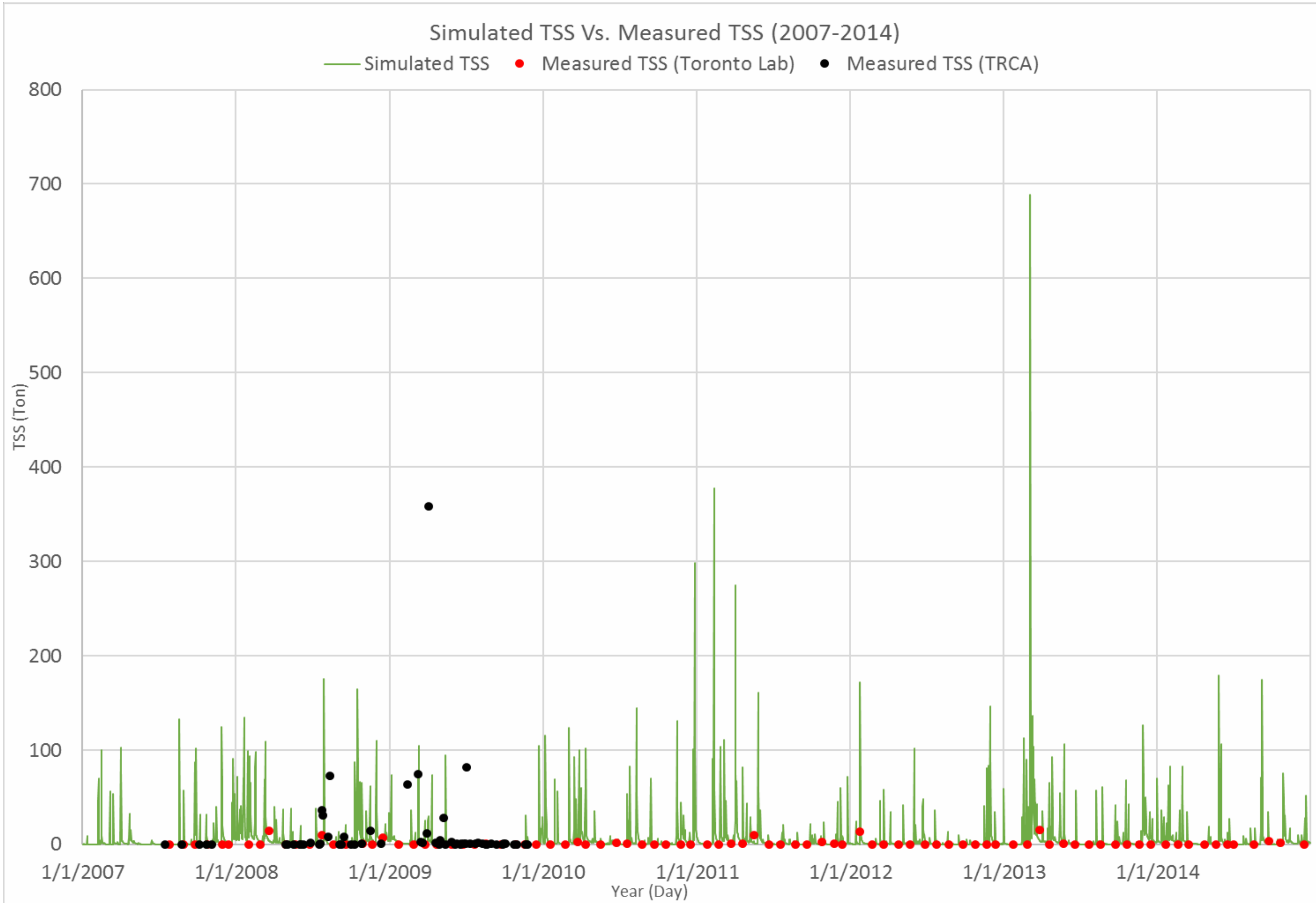

Figure 16. Comparison of TSS in the period of 2007-2014

Figure 14, 15 and 16 clearly show good matches between simulated water quality time and TRCA measured data points. For example, the comparison of TP and TN during 2008-2009 between simulated and TRCA measured water quality data points match very well. The simulation TP and TN during 2008-2009 catches almost all low and high values of the TRCA dataset. The simulated TSS loading also matches some of the measured data points. However,

5.2 Petticoat Creek watershed

Table 23 summarizes the estimated values of the major components of the water balance in the Petticoat Creek watershed. According to the simulation, from 890.1 mm of annual average precipitation in this watershed, 58.8 % is lost through the evapotranspiration, 39.6% turns into the streamflow and less than 1.0% is the summation of all the other losses from the system. Moreover, surface runoff contributes to 57.9% of the streamflow. This relatively high surface flow contribution is expected due to the smaller natural areas in this watershed compared to the Carruthers Creek watershed.

Table 23. Annual average hydrologic data and temperature (2005-2015)

Average Annual Basin Values					
Precipitation (mm)	**Max. Tmp. (℃)**	**Min. Tmp. (℃)**	**Evapotranspiration (mm)**	**Water Yield (mm)**	**Surface Runoff (mm)**
890.1	13.33	3.3	523.1	352.76	204.15

Based on the simulated annual average components of the water balance, the SWAT model of the Petticoat Creek watershed is expected to have a similar performance to the SWAT model of Carruthers Creek watershed. However, when it comes to the model performance in comparison with the measured values, the model shows a poor performance. Based on the measured datasets, the average streamflow in this watershed is 0.44 cms while the model results in 0.28 cms. The Petticoat Creek drains a 30% smaller watershed compared to the Carruthers Creek watershed. Therefore, the model is expected to generate less streamflow in the Petticoat Creek watershed. This discussion leads us to assume that there are some other sources of water input to the Petticoat Creek watershed system that is missed in the model. Possible sources are the significant groundwater contribution and/or the storm-water coming from nearby watersheds such as the Frenchman’s Bay. Therefore, further investigations are required to estimate the major water balance components in this watershed and accordingly adjust the model to be able to improve its performance.

Figure 17 shows the time series of simulated versus measured streamflow at the hydrometric station HY051 in the Petticoat Creek watershed. Although the model adequately responds to the major hydrologic events, it underestimates the streamflow quite consistently. For example, in the period of 1/1/2015-4/10/2015, simulated streamflow reacts with the most hydrologic events but with a lower peak flow than measured peak flow. This issue could also be related to the above discussion about possible sources of water other than precipitation in this watershed. Additionally, the time series of simulated versus measured streamflow for the other years in the simulation period (2005-2015) are provided in Figure 29 to 38 in appendix B.

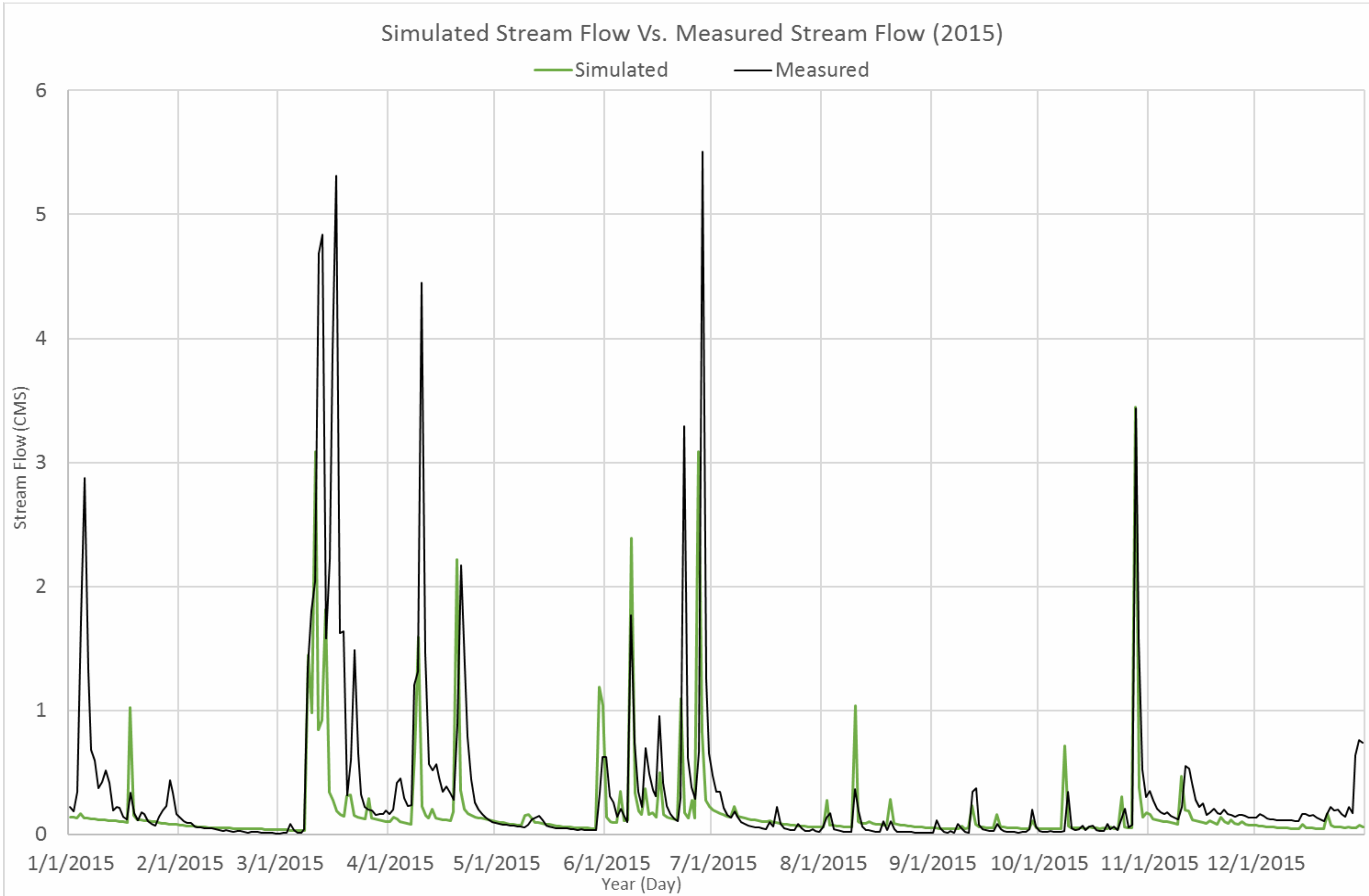

Figure 17. Comparison of streamflow in the year of 2015 in Petticoat Creek watershed

Table 24. Summary of average, maximum, and minimum loading of TP, TN and TSS from simulated data and measured data

Concentration(mg/l) Loading(kg)&(ton)	TP			TN			TSS		
	Average	Max.	Min.	Average	Max.	Min.	Average	Max.	Min.
Simulated	0.45 mg/l	36.93 mg/l	0 mg/l	2.58 mg/l	219.45 mg/l	0 mg/l	357.36 mg/l	35415.75 mg/l	0.8 mg/l
	11.32 kg	923.8 kg	0 kg	64.43 kg	5490 kg	0.01 kg	8.94 tons	886 tons	0.02 ton
Measured (Tronto Lab)	0.03 mg/l	0.13 mg/l	0 mg/l	1.65 mg/l	3.67 mg/l	0.8 mg/l	6.48 mg/l	72.9 mg/l	0.9 mg/l
	2.3 kg	38.11 kg	0 kg	96.87 kg	503.62 kg	0 kg	13.74 tons	19.06 tons	0 tons

Comparing with simulated and measured water quality data in Table 24, it is clear that simulated loading of TP, TN and TSS does not match measured loading. However, the trend of simulated and measured average loading of TP, TN and TSS are similar. For instance, TP from both tables has the lowest loading, which is 11.32 kg and 2.3 kg for simulated and measured result respectively. Then loading of TSS is in between with 8.94 tons and 13.74 tons for simulated and measured result respectively. At last, loading of TN for both of simulated and measured data are the highest, which are 64.43 kg and 96.87 kg. Even though the trend is similar between two sets of data points, the gap between each other is visible. This situation indicates that the simulation is not accuracy and needed more future works on it.

Additionally, the following 18, 19 and 20 will show the comparison of TP, TN, and TSS in a time series with the simulated data and the measurement done by Toronto and York-Durham Lab respectively.

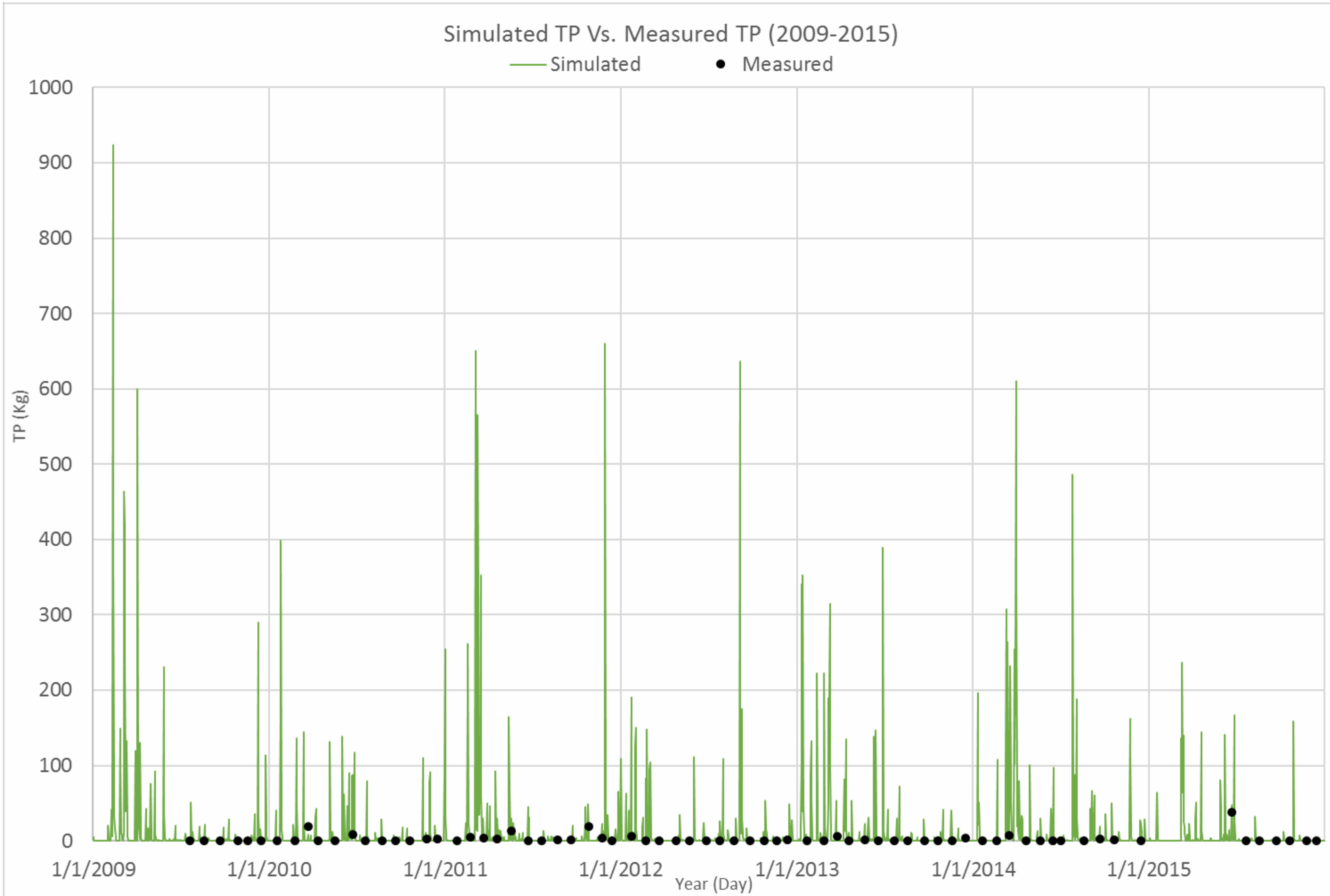

Figure 18. Comparison of TP in the period of 2009-2015

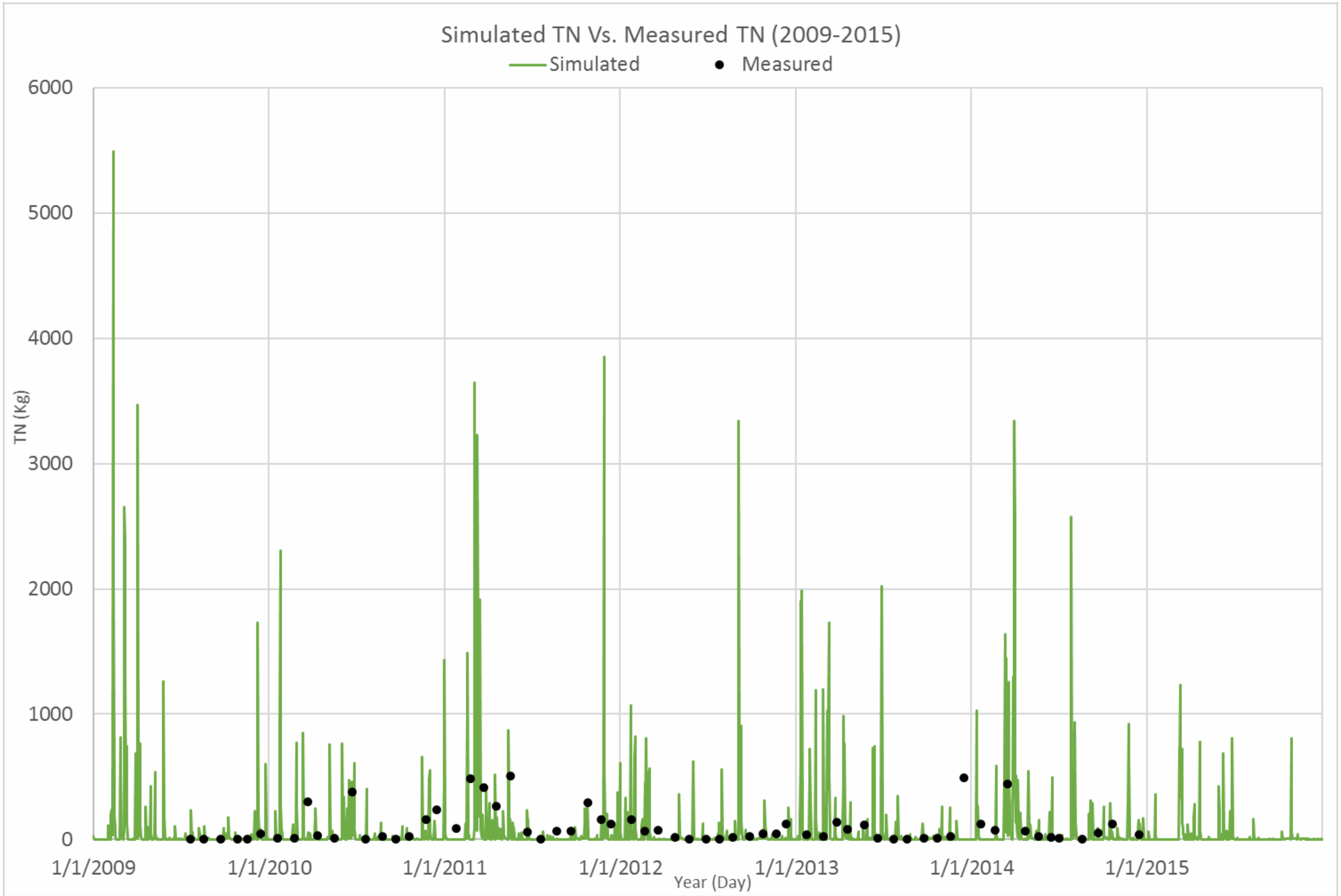

Figure 19. Comparison of TN in the period of 2009-2015

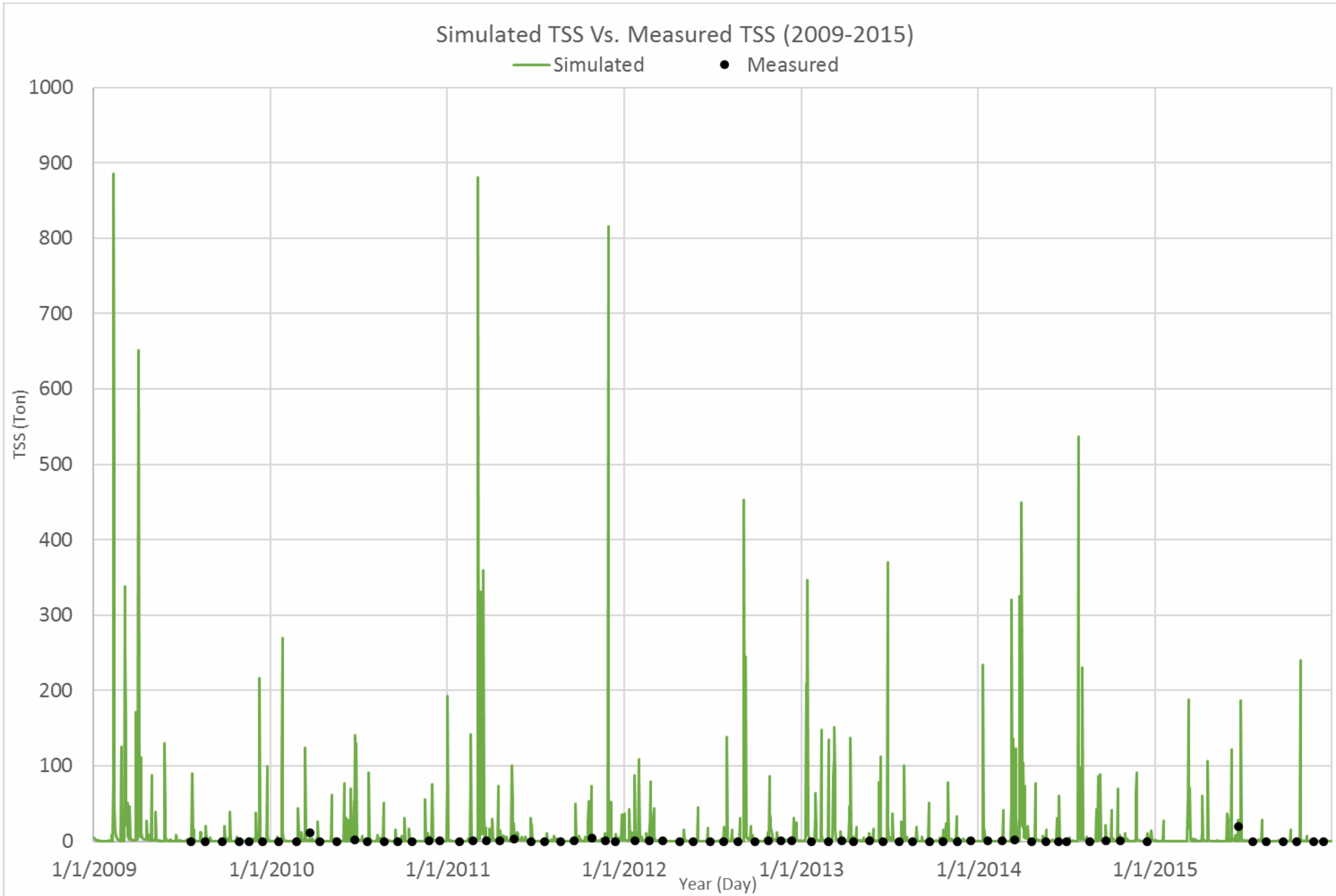

Figure 20. Comparison of TSS in the period of 2009-2015

Unlike for the Carruthers Creek watershed, there is only one set of measured water quality dataset for the Petticoat Creek watershed from Toronto and York-Durham lab. Based on the personal communication with G. Bowen of TRCA, this dataset is not as accurately representative as the TRCA event-based dataset for the actual water quality processes in the watershed. However, Figures 18, 19, and 20 show similar trends in the simulated and measured loadings of TP, TN and TSS. The model has adequately large responds in the events of the significant measured TP, TN and TSS, respectively.

6. Conclusions

In this project, the SWAT watershed modeling tool is successfully set up for the Carruthers Creek and Petticoat Creek watersheds. The models are set up using similar input datasets from the previous SWAT modeling within the region by Asadzadeh et al. (2015). Models in this work also share the exact same parameter values used by Asadzadeh et al. (2015) after calibrating SWAT model for the Rouge River watershed.

The SWAT model of the Carruthers Creek watershed adequately estimates the precipitation-runoff relationship and water quality processes observed in the measured datasets. This conclusion is made after comparing the annual average water balance components, visually comparing the time series of simulated and measured daily streamflow and simulated time series of TP, TN, and TSS compared to the corresponding measured data points.

The SWAT model of the Petticoat Creek watershed does not adequately estimate precipitation-runoff relationship observed in the measured datasets. The model quite consistently underestimates measured daily streamflow. Initial analysis in this study suggests that there might be some sources of input water other than precipitation into the Petticoat Creek watershed that is missing in the model. This conclusion comes from the fact that, the Petticoat Creek watershed drains a significantly smaller area compared to the Carruthers Creek watersheds, while the measured streamflow data suggests that the average streamflow in the Petticoat Creek watershed should be higher. Therefore, it is recommended that future work focuses on identifying other sources of water into this watershed. Potential sources are the groundwater contribution to the streamflow and/or storm-water diverted into the Petticoat Creek from nearby watersheds.

7. Reference

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Appendix A: Comparison of streamflow during 2007-2013 and 2015 in Carruthers Creek watershed

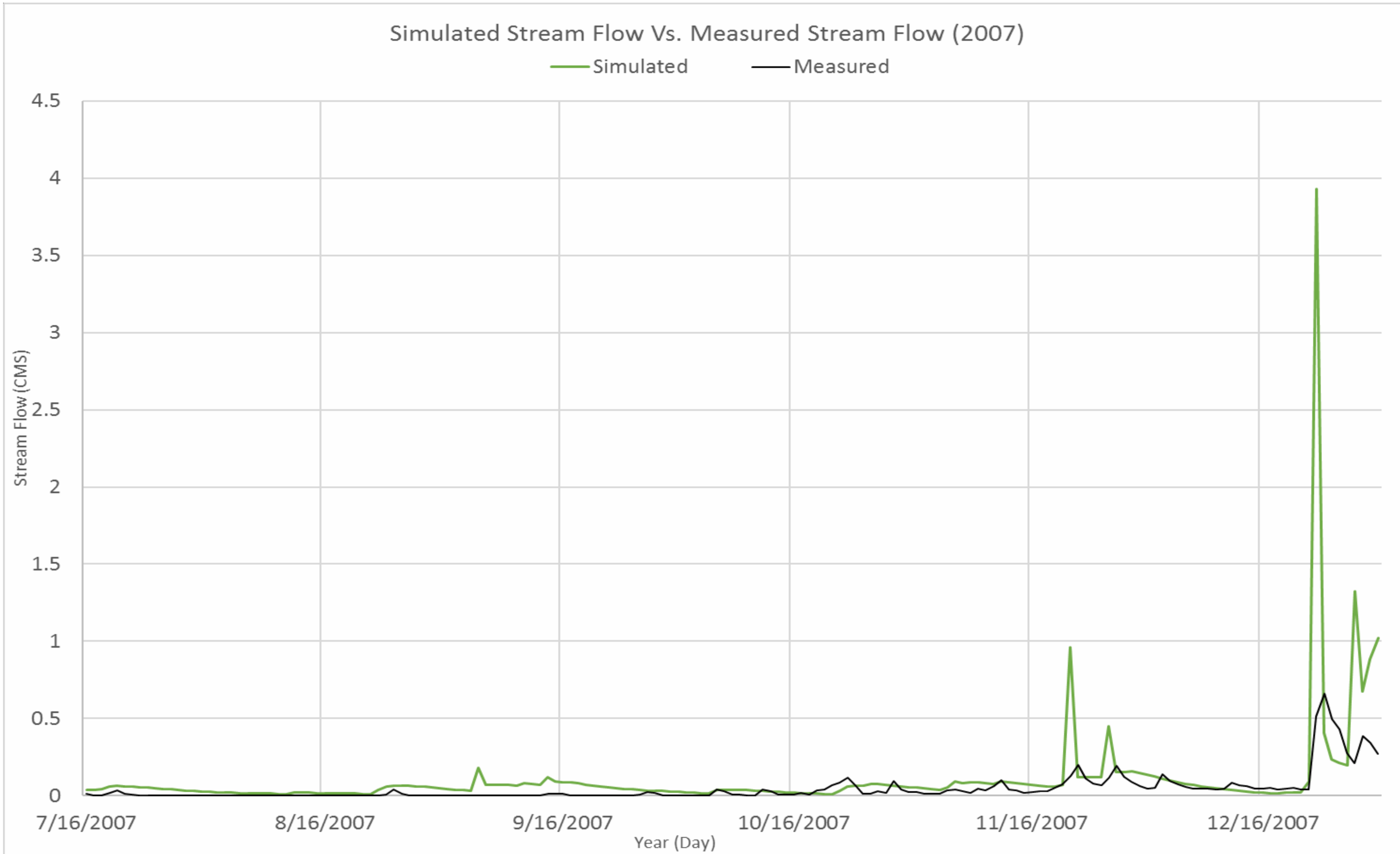

Figure 21. Comparison of streamflow in the year of 2007 in Carruthers Creek watershed

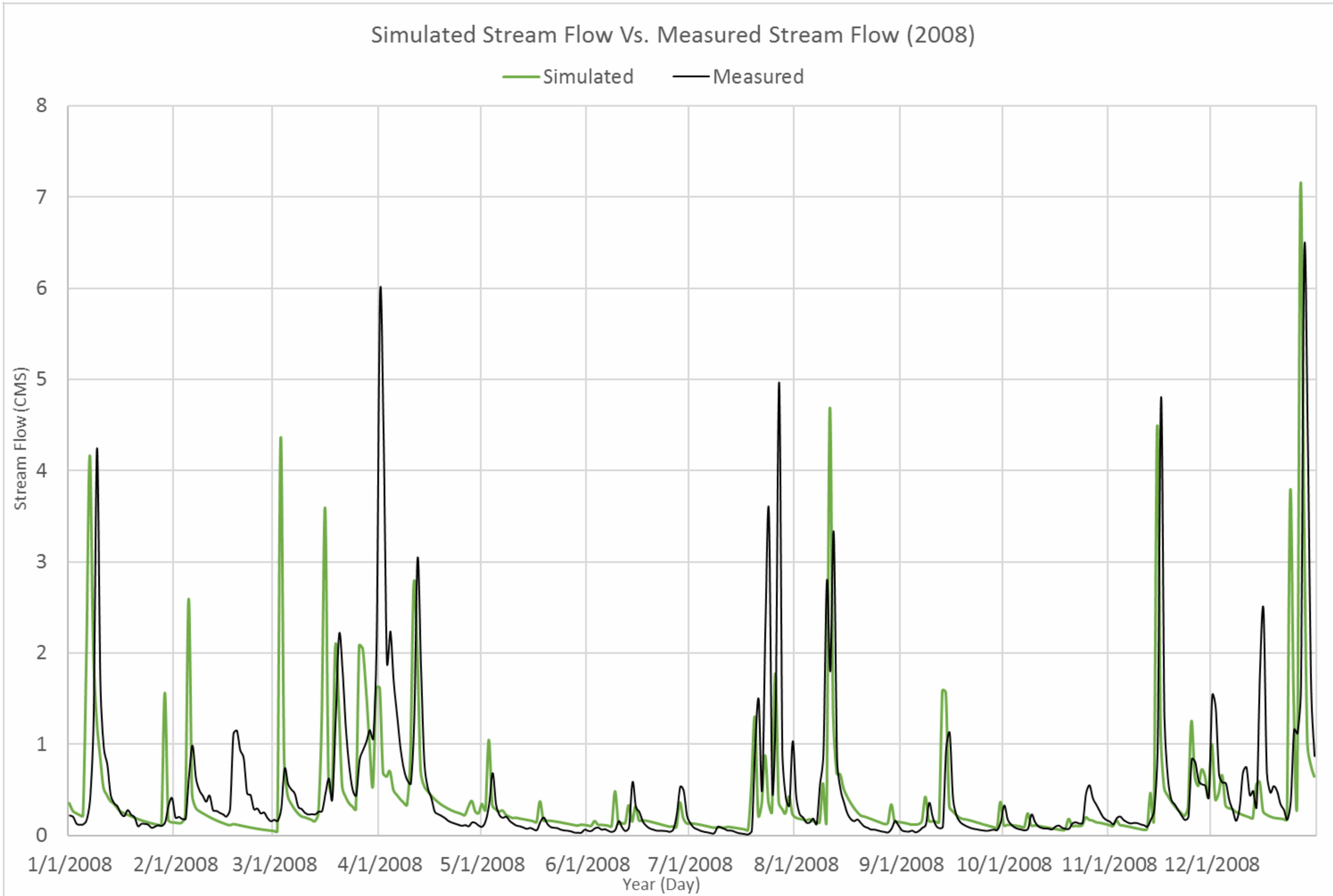

Figure 22. Comparison of streamflow in the year of 2008 in Carruthers Creek watershed

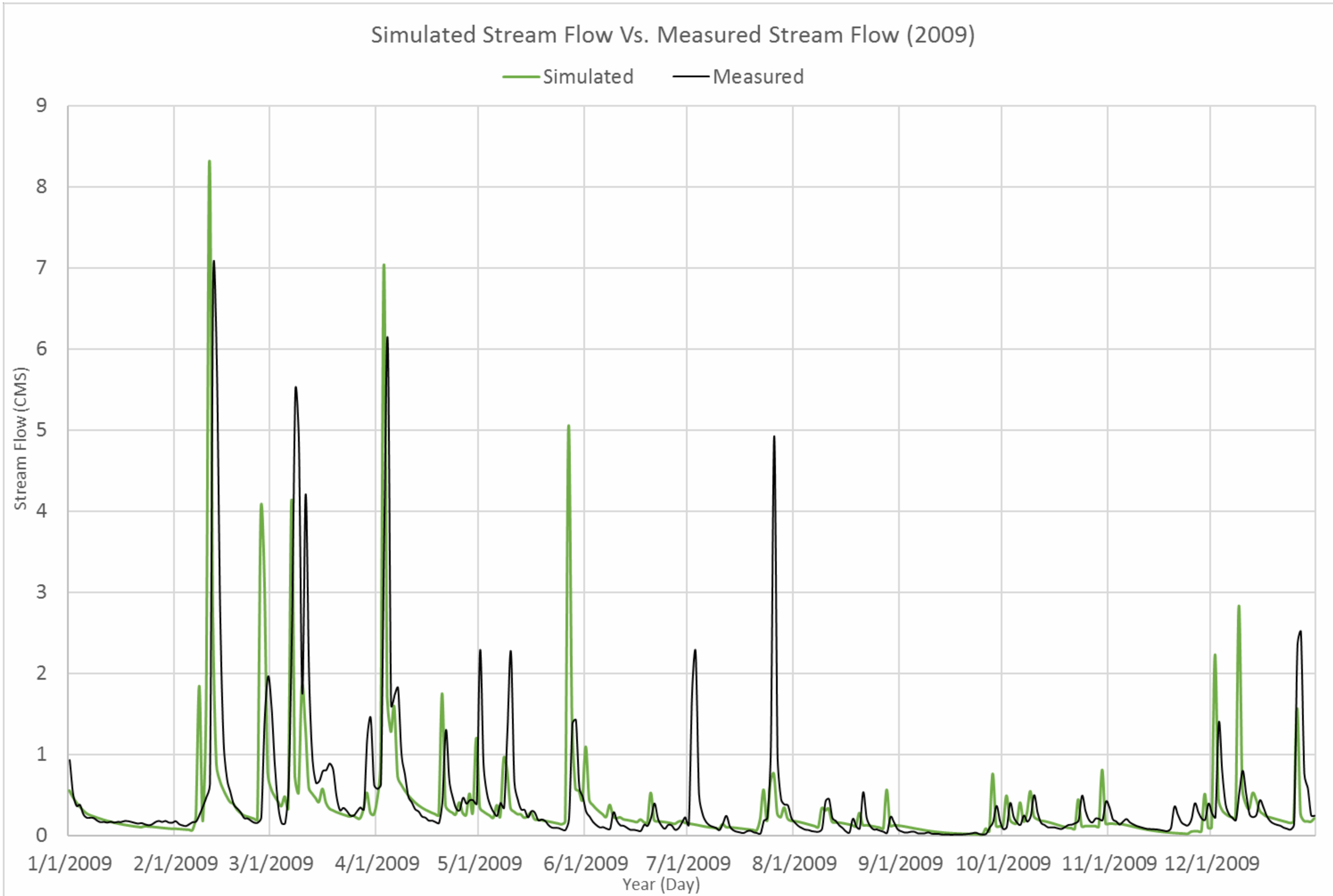

Figure 23. Comparison of streamflow in the year of 2009 in Carruthers Creek watershed

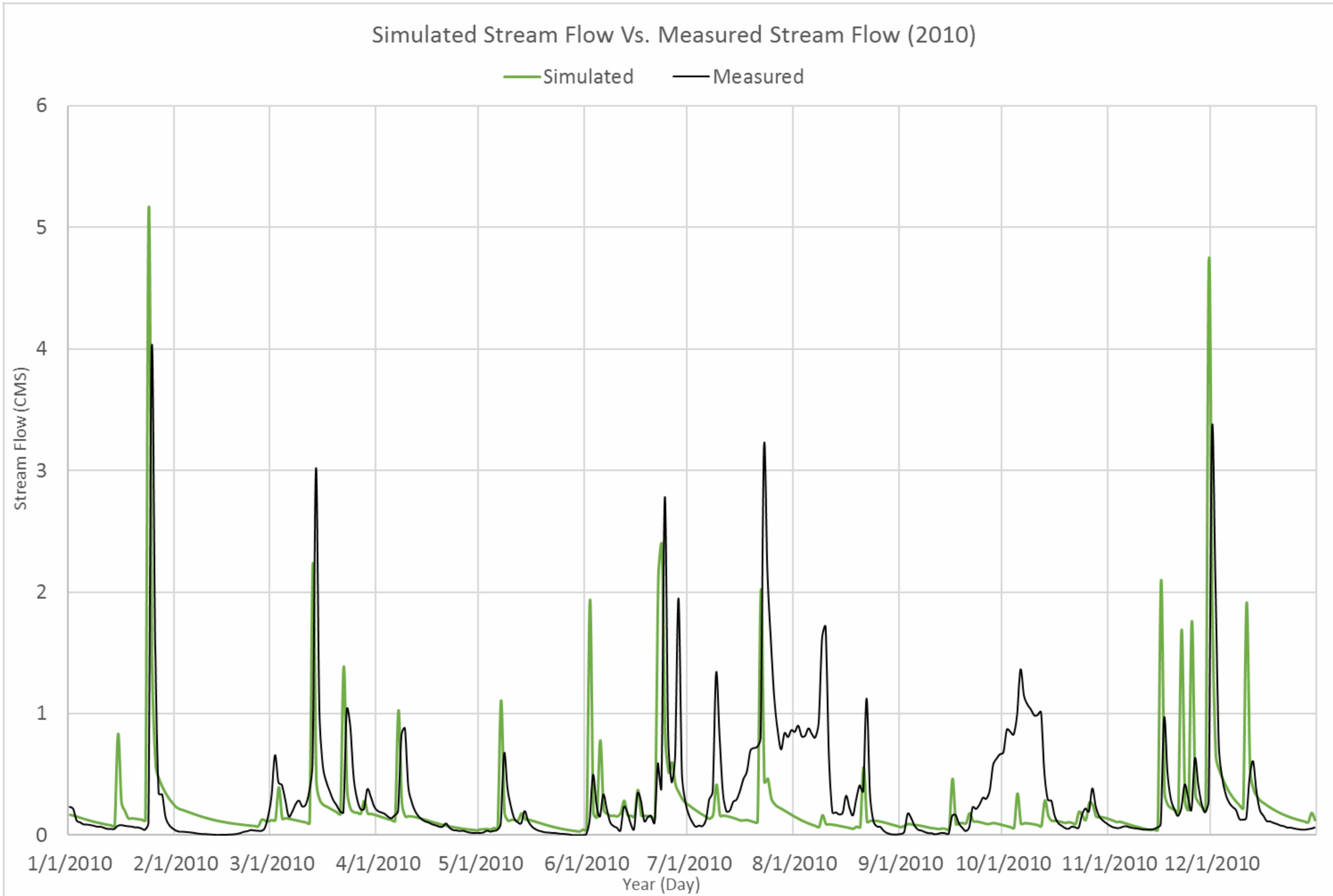

Figure 24. Comparison of streamflow in the year of 2010 in Carruthers Creek watershed

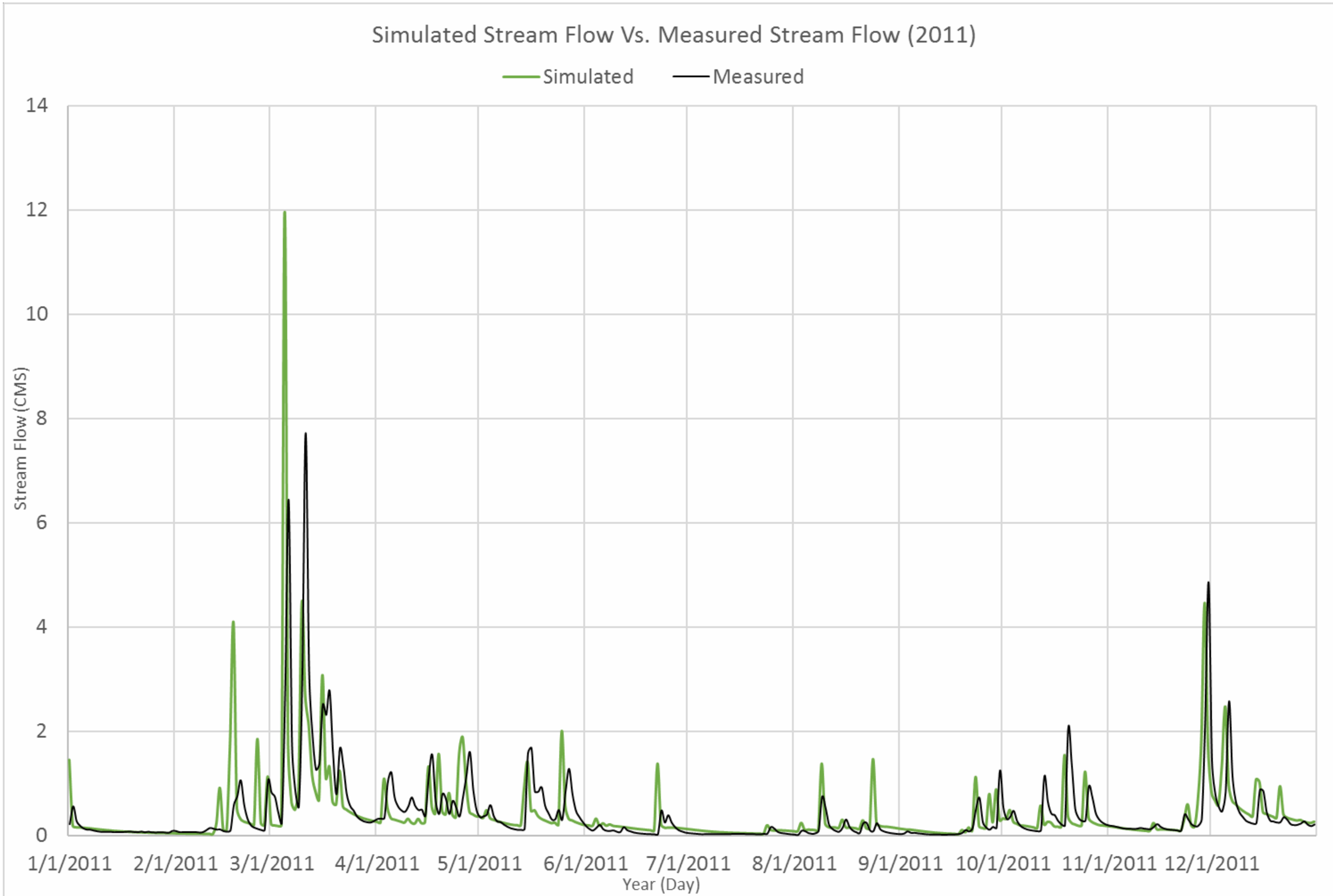

Figure 25. Comparison of streamflow in the year of 2011 in Carruthers Creek watershed

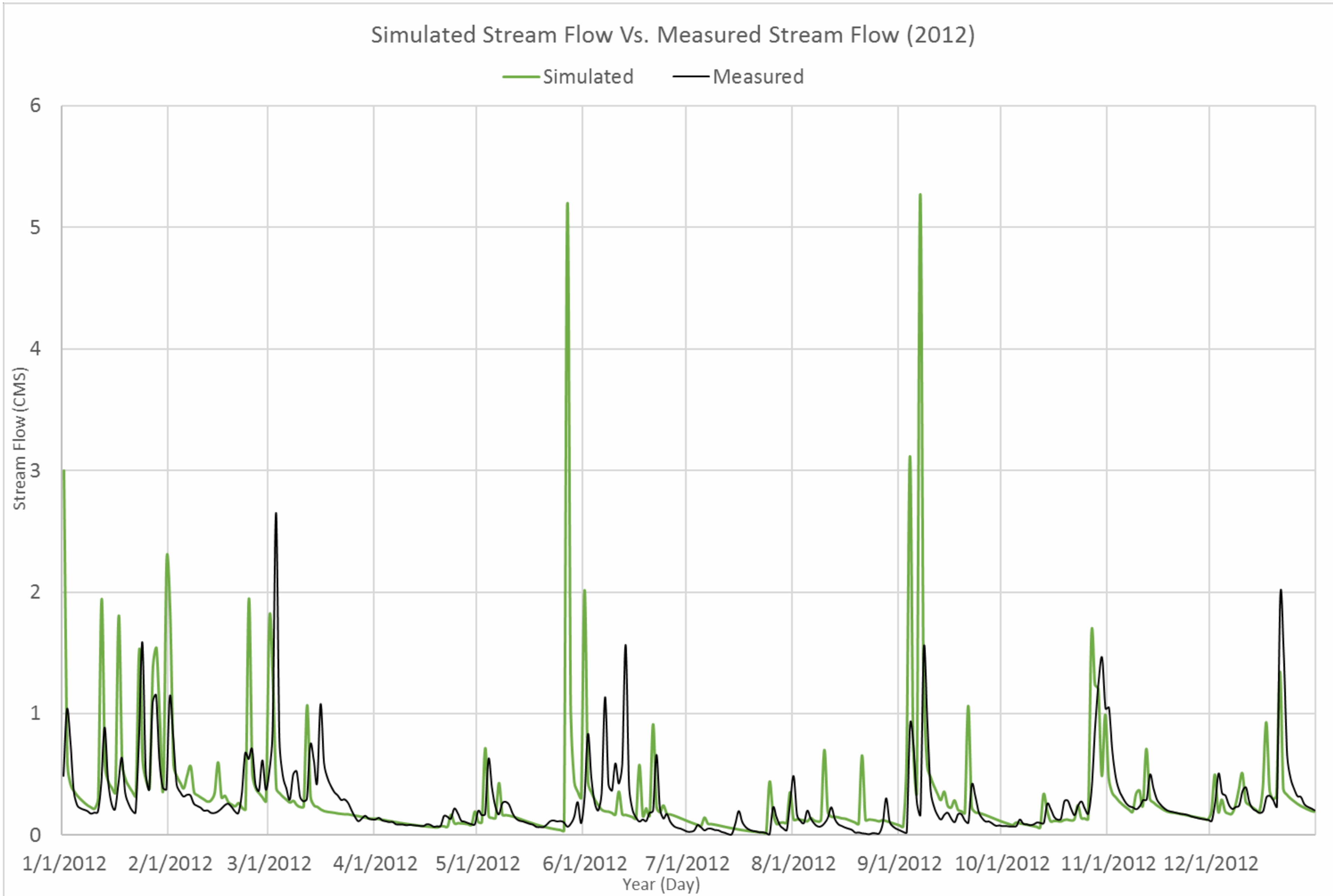

Figure 26. Comparison of streamflow in the year of 2012 in Carruthers Creek watershed

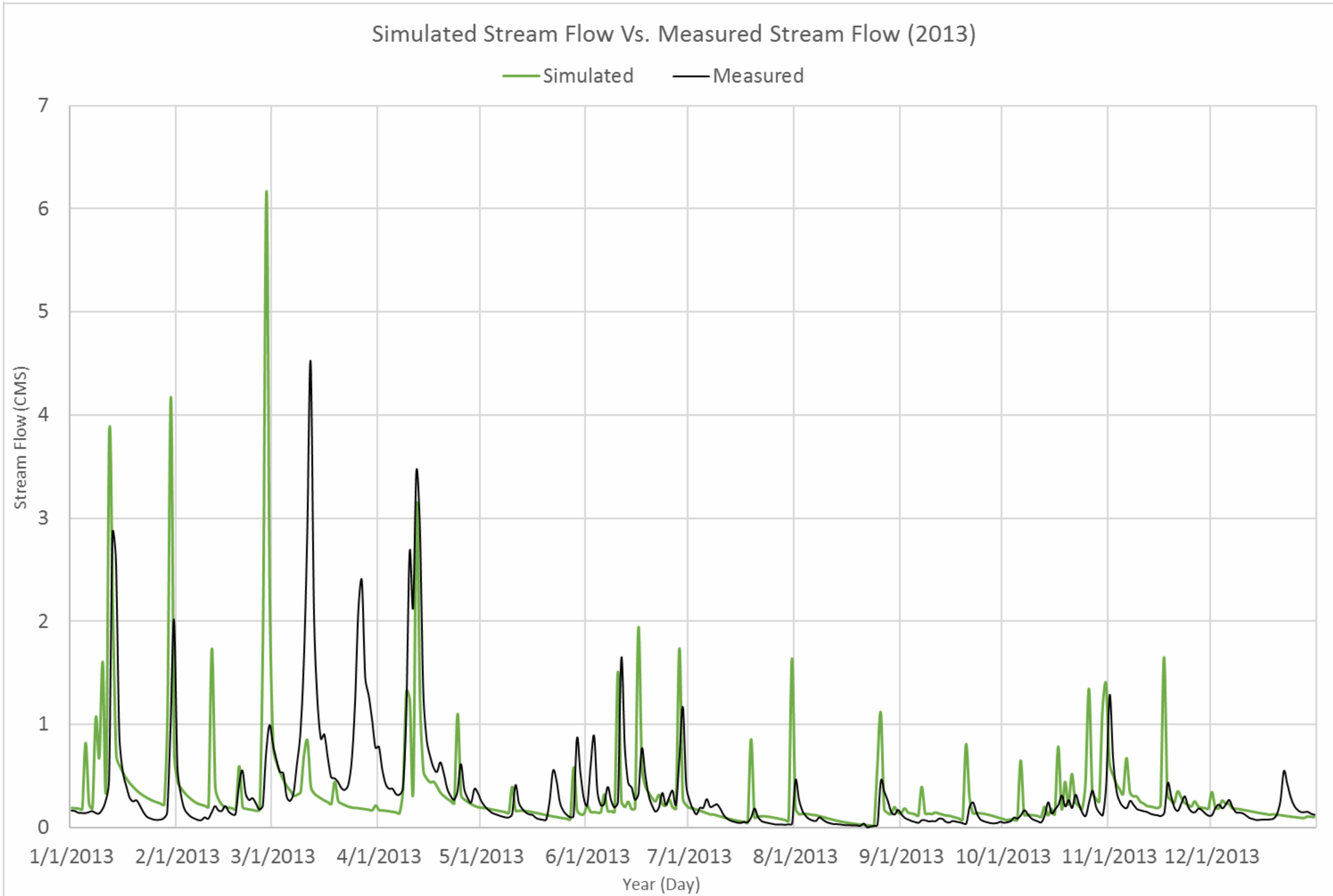

Figure 27. Comparison of streamflow in the year of 2013 in Carruthers Creek watershed

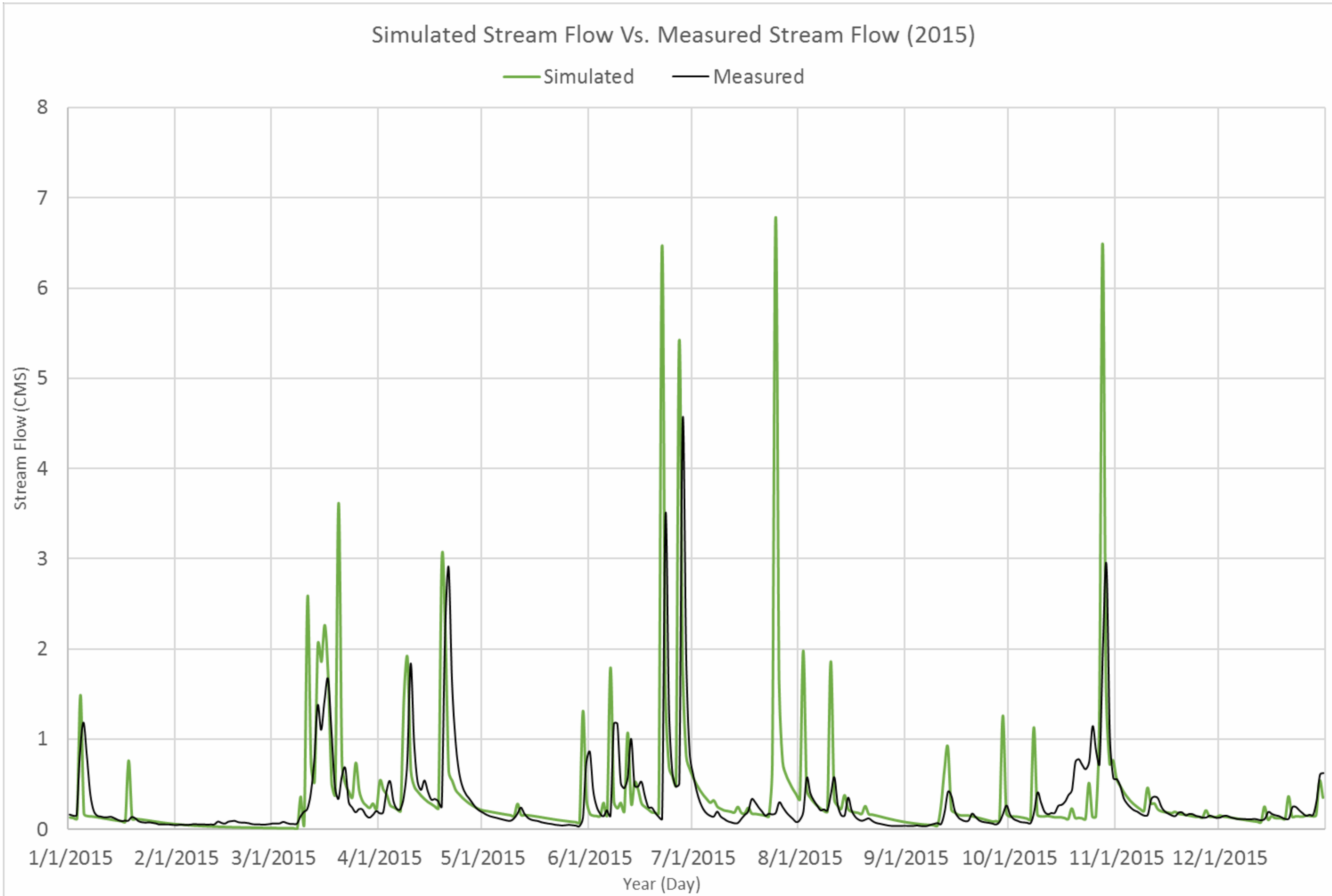

Figure 28. Comparison of streamflow in the year of 2015 in Carruthers Creek watershed

Appendix B: Comparison of streamflow during 2005-2014 in Petticoat Creek watershed

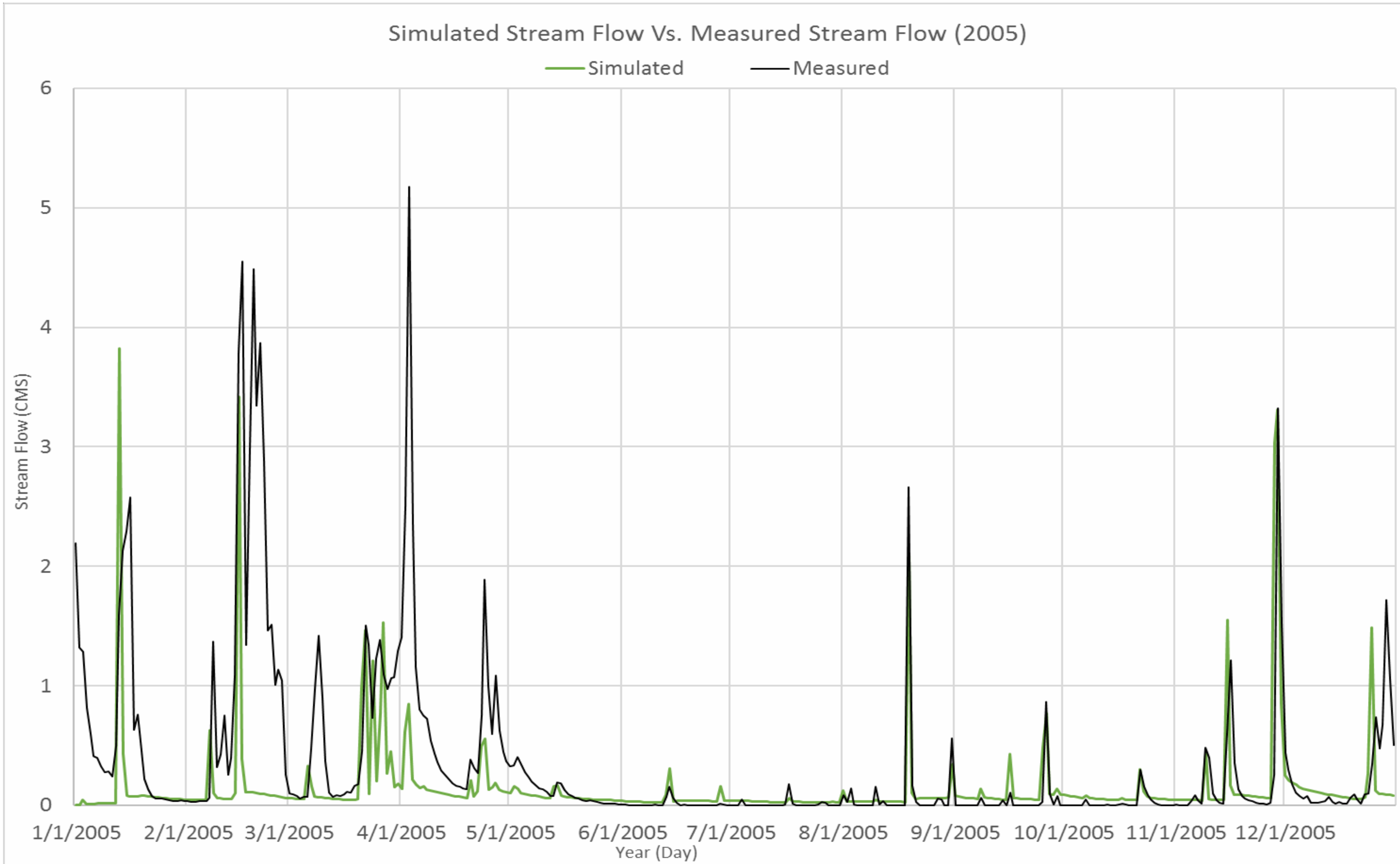

Figure 29. Comparison of streamflow in the year of 2005 in Petticoat Creek watershed

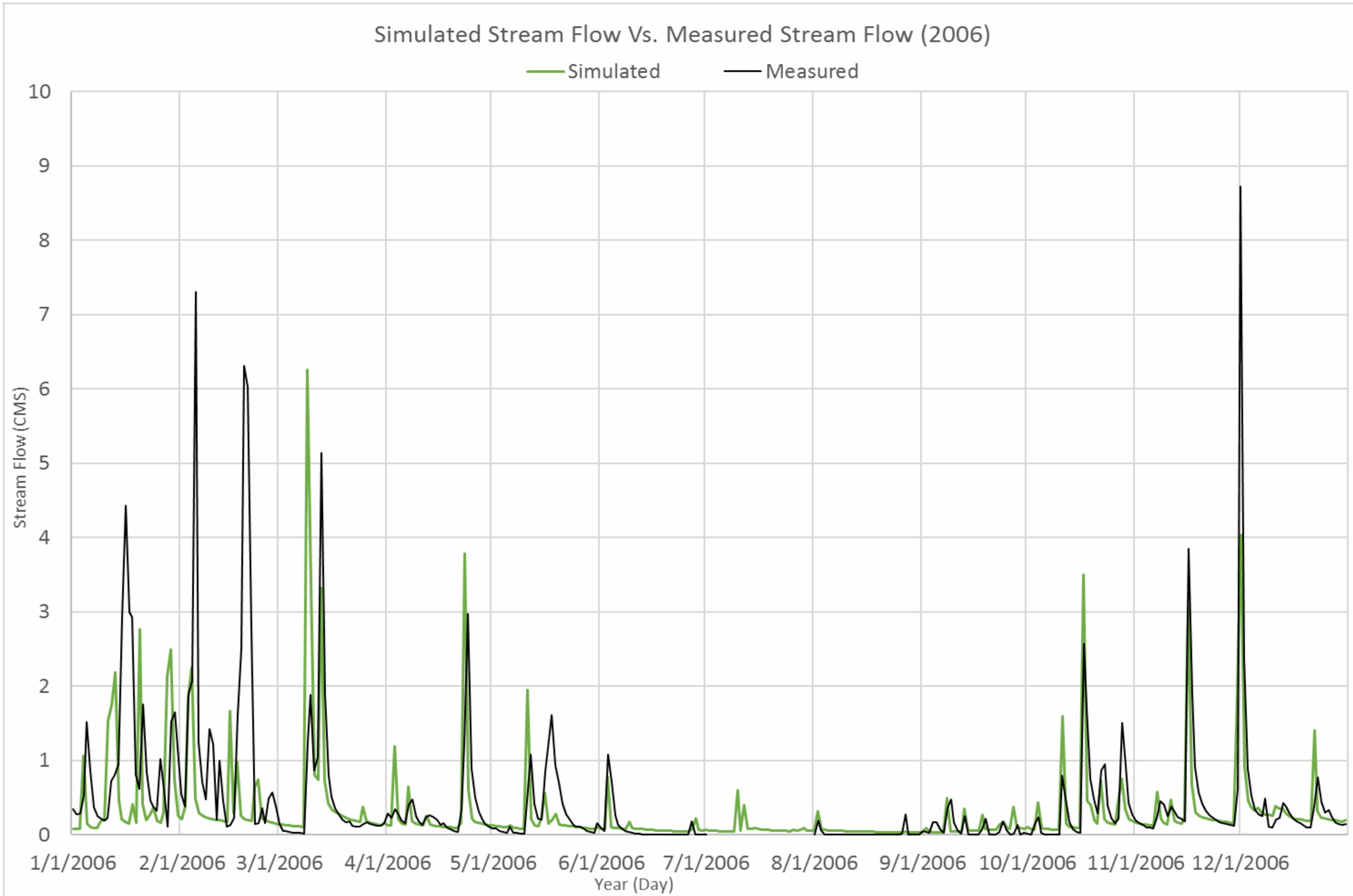

Figure 30. Comparison of streamflow in the year of 2006 in Petticoat Creek watershed

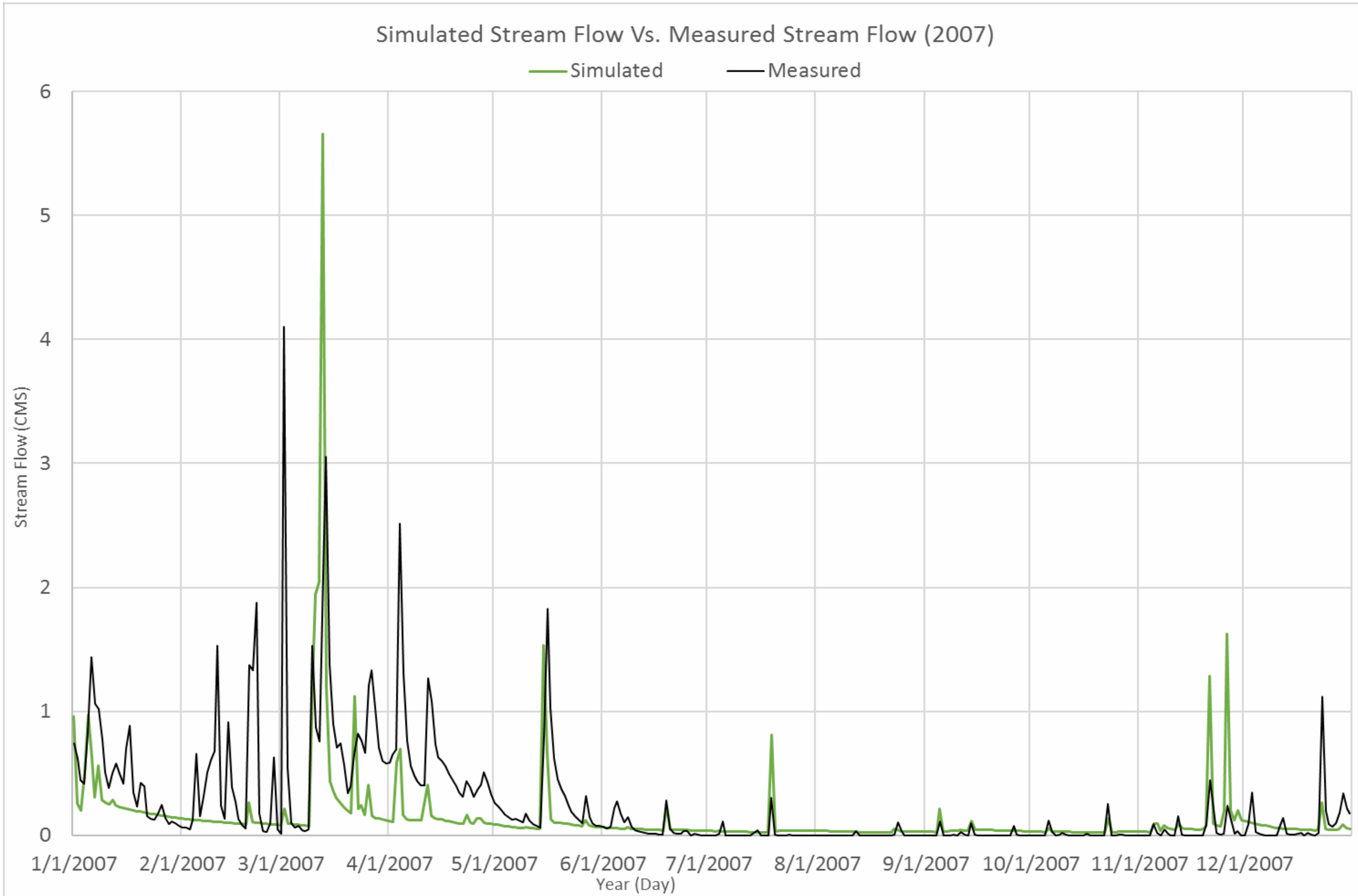

Figure 31. Comparison of streamflow in the year of 2007 in Petticoat Creek watershed

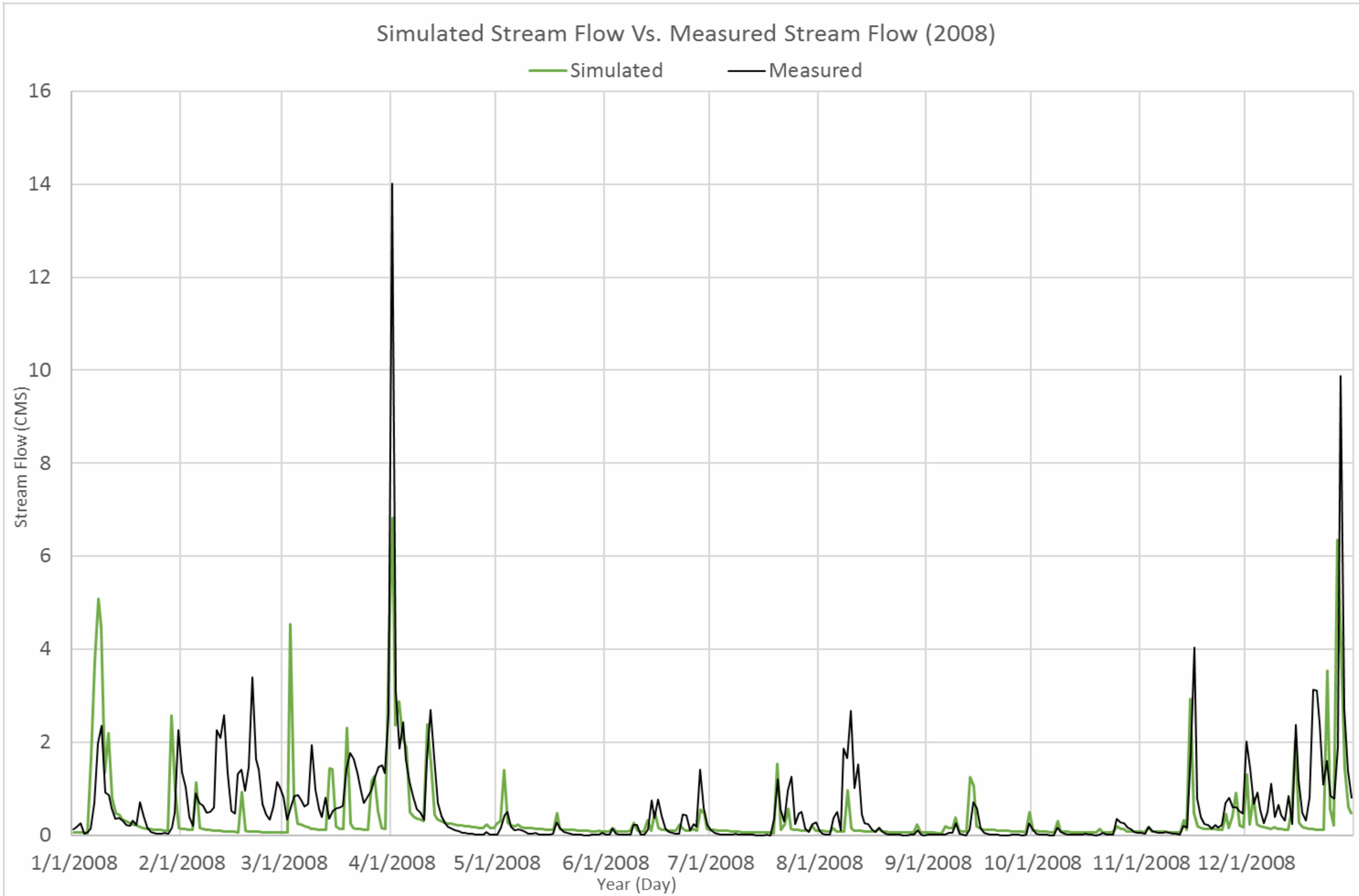

Figure 32. Comparison of streamflow in the year of 2008 in Petticoat Creek watershed

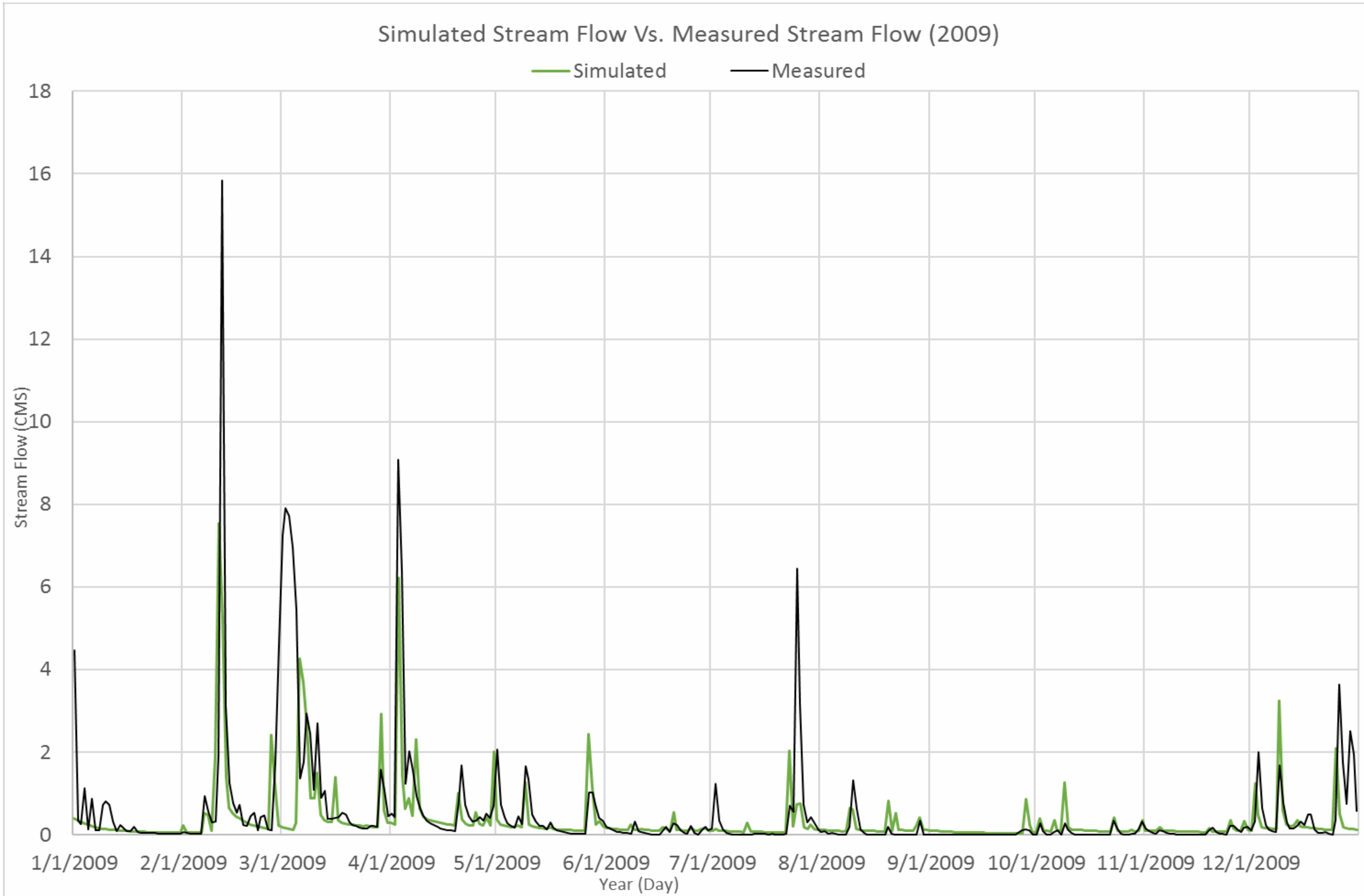

Figure 33. Comparison of streamflow in the year of 2009 in Petticoat Creek watershed

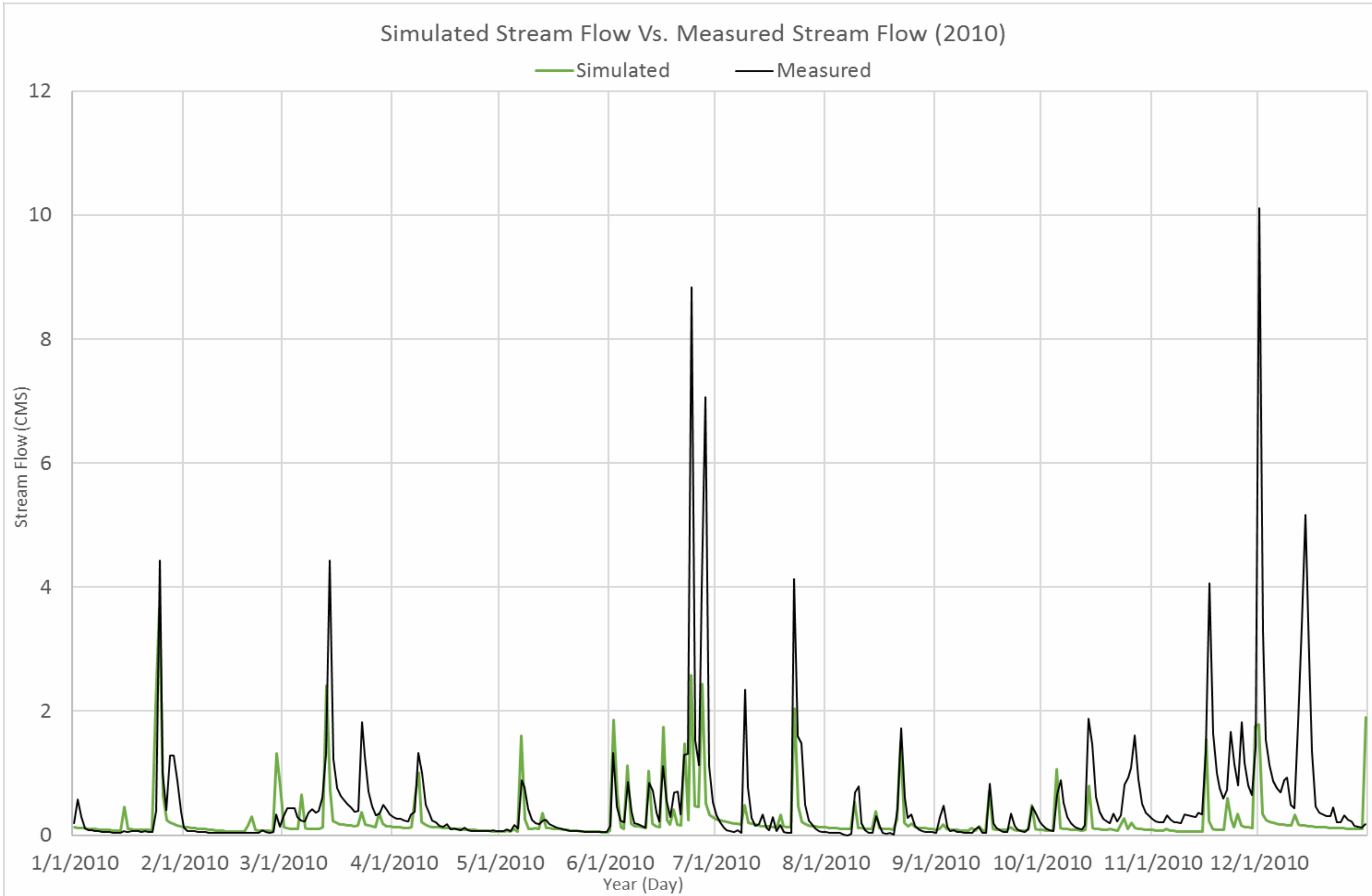

Figure 34. Comparison of streamflow in the year of 2010 in Petticoat Creek watershed

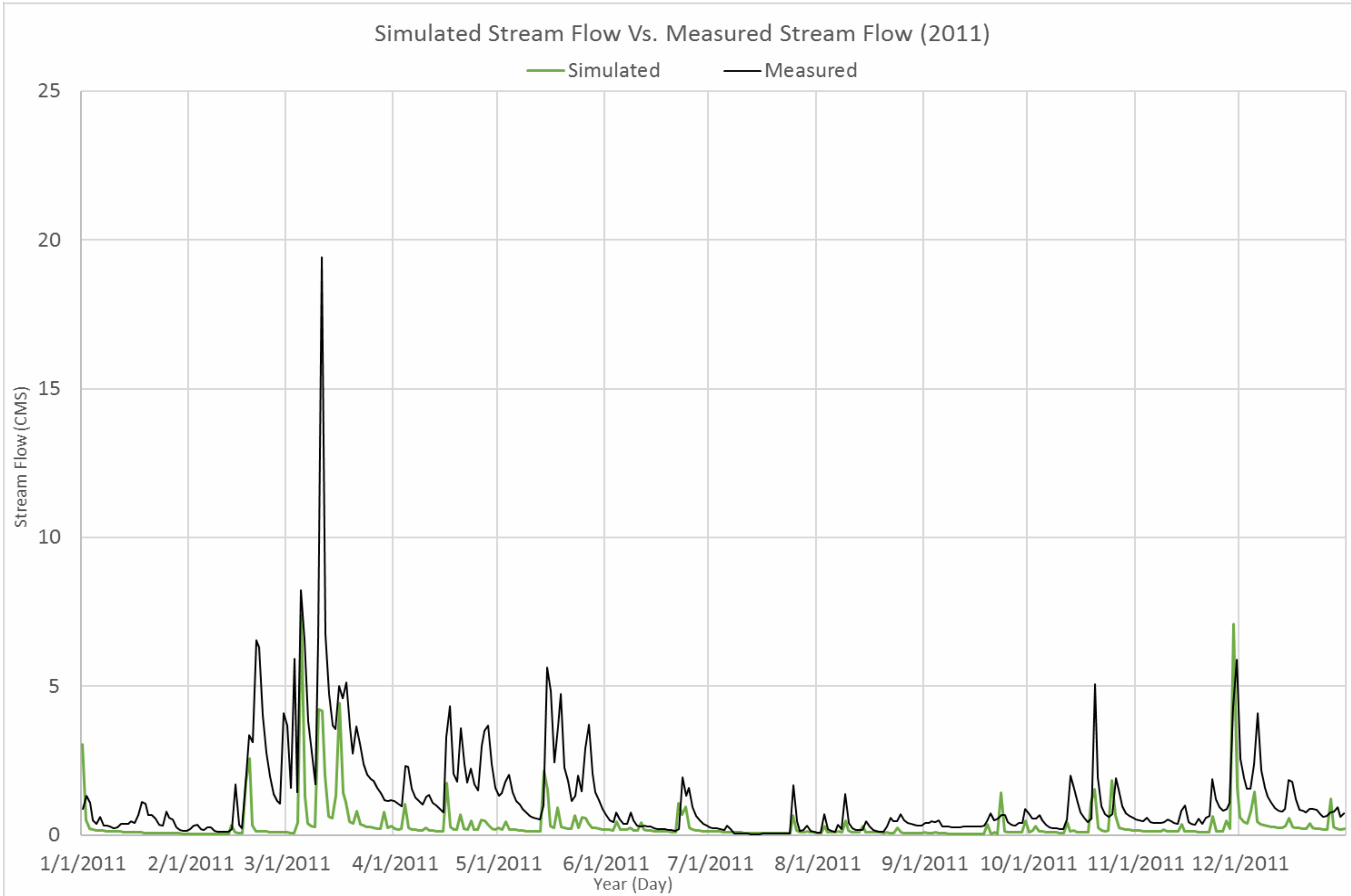

Figure 35. Comparison of streamflow in the year of 2011 in Petticoat Creek watershed

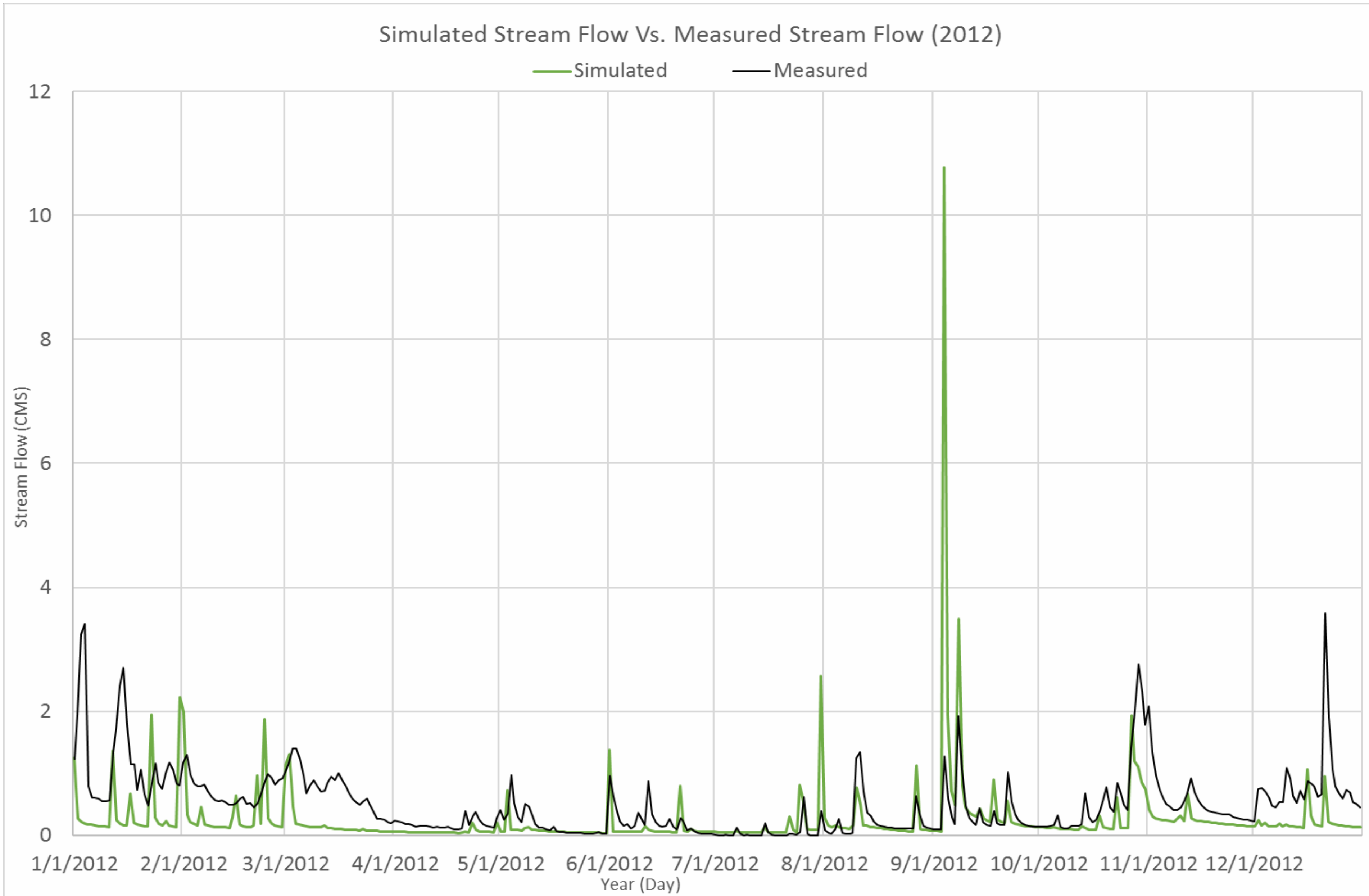

Figure 36. Comparison of streamflow in the year of 2012 in Petticoat Creek watershed

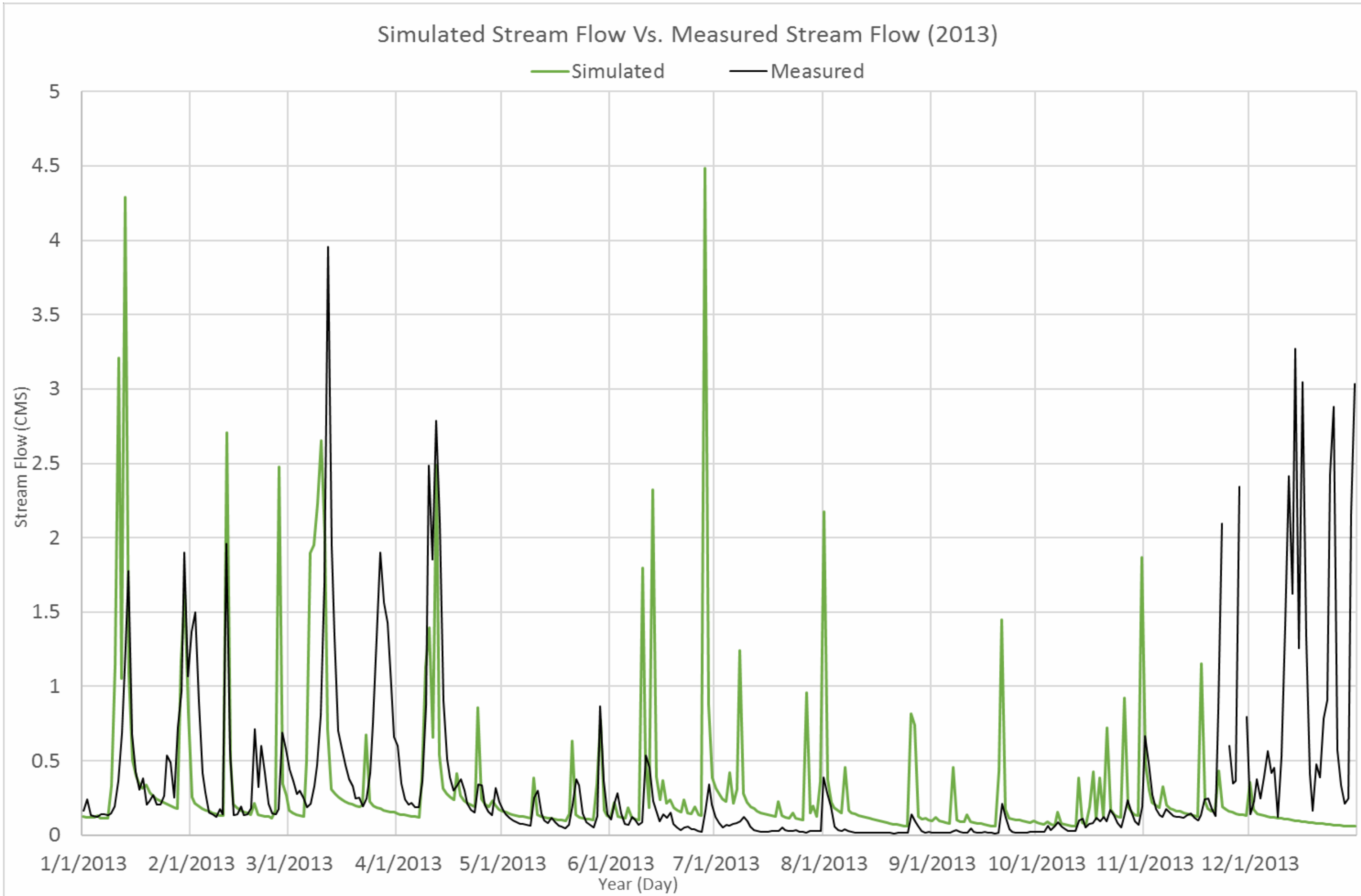

Figure 37. Comparison of streamflow in the year of 2013 in Petticoat Creek watershed

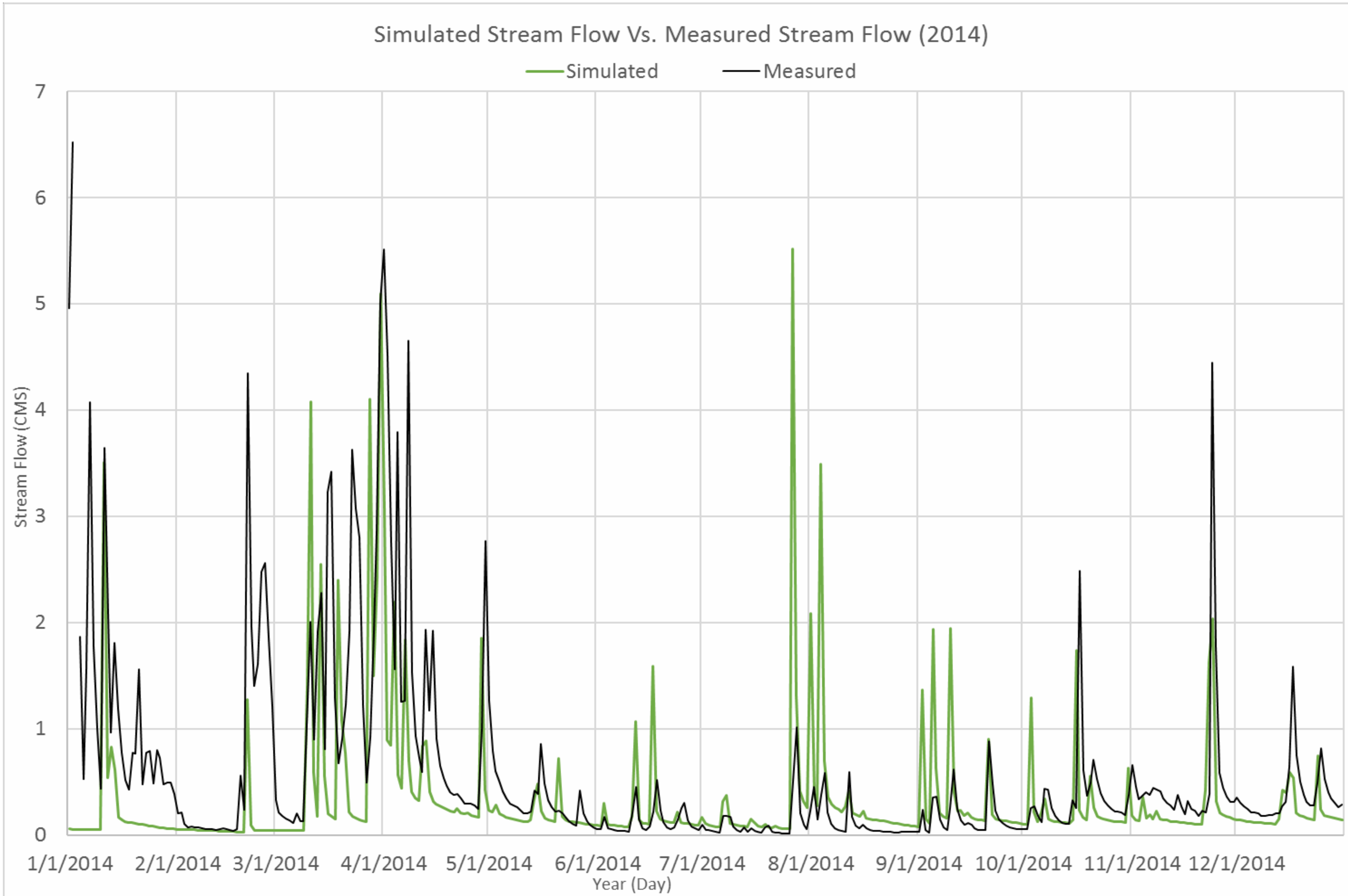

Figure 38. Comparison of streamflow in the year of 2014 in Petticoat Creek watershed

<u>Appendix B</u>

SWAT Modelling of Carruthers Creek Watershed

Land use and Climate Scenarios

Model Set-up Procedures

Sept. 7, 2018
(Revised: March, 2019)

Prepared For

Toronto and Region Conservation Authority

By

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Watershed Hydrology and Ecology Research Division

Environment and Climate Change Canada

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Foreword

This technical memo is an abridged version of the technical memo prepared by Environment and Climate Change Canada (ECCC) for Toronto and Region Conservation Authority (TRCA) that focuses on the steps taken to revise the SWAT model, as set up by the University of Manitoba, to complete the land use scenarios and best management practices (BMPs) runs needed for the Carruthers Creek Watershed Plan. In preparing this appendix, TRCA has simply consolidated the relevant sections of the ECCC technical memo prepared for TRCA.

Introduction

This technical memo details revisions to the University of Manitoba (UOM) SWAT model for the Carruthers Creek watershed prepared for the TRCA and includes necessary revisions for running the following land use scenarios:

- Landuse Existing 2015
- Landuse Existing 2015 Official Plan (OP)
- Landuse Existing 2015 Official Plan – Natural System Heritage (NHS)
- Landuse Existing 2015 Official Plan – Natural System Heritage with Buildout
- Historic 1999

In addition, documentation is provided on the modifications needed to the Carruthers SWAT model to compare Best Management Practices.

The GIS layers for the five land use scenarios were provided by TRCA (link provided by Patricia Moeleirinho, 2018-05-02). It is noted that subsequent to competition of our SWAT modelling some minor adjustments were made to these five scenarios by the TRCA. These adjustments are considered in the overall context of the SWAT model watershed scale responses to be relatively minor and do not affect over all outcomes.

The Carruthers SWAT model was also provided by TRCA.

The Carruthers Creek baseline SWAT model prepared by the UOM was updated in this study because issues were discovered with the original model setup Section 1.

The steps taken to produce the SWAT model runs of the landuse scenarios are described in Section 2

Section 1: UOM SWAT Baseline Model Revision

This narrative describes updates made to the UOM SWAT model of the Carruthers Creek watershed due to issues discovered in the original setup of the baseline. The initial setup is described in the contractor's Carruthers technical report entitled Watershed Modelling of the Carruthers and Petticoat Creeks with the Focus on Daily Water Quality Estimation. Final Technical Report (see Appendix A).

Table 1: Landuse composition of original baseline landuse layer

Agricultural	44.99%
Natural Cover	6.60%
Forest-Mixed	10.38%
Meadow	5.77%
Water	0.25%
Residential Low	14.30%
Wetlands	9.27%
Commercial	3.84%
Industrial	1.57%
Institutional	1.24%
Road (ROW)	1.48%
Residential High	0.32%

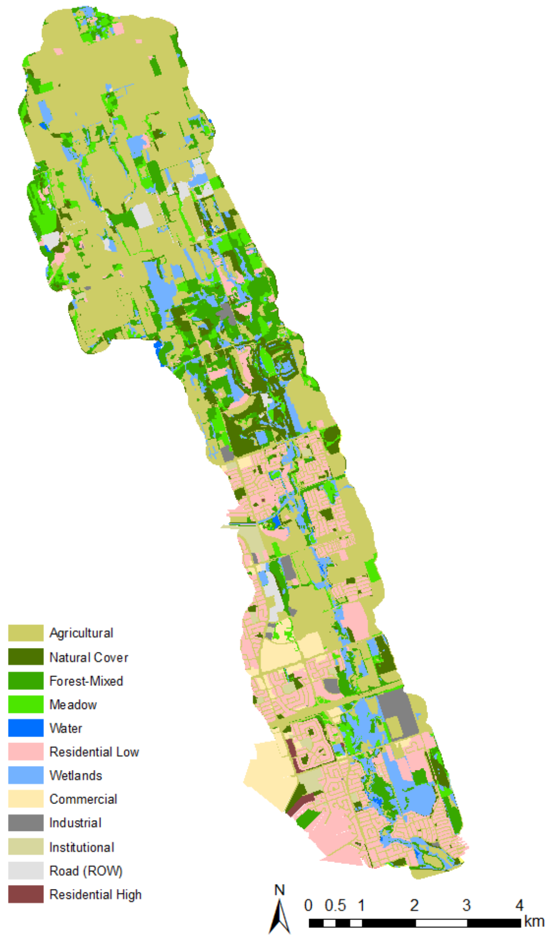

Figure 1: Land use map of baseline land use used to setup SWAT

There was an issue with the original baseline land use layer (carruthers_existing_landuse2015_nov2016_trca_update.shp). The road (transportation) features were assigned as agriculture class as shown in the following map of the downstream end of the watershed.

Figure 2: Baseline Landuse showing mislabeled roads in layers

The road features were then re-assigned to the landuse class UTRN (previously was AGRL). Comparing the landuse composition of the original Carruthers landuse and the updated layer showed that the percent area of AGRL decreased from 44.99% to 34.20% and UTRN increased from 1.48% to 12.27%. Then, ArcSWAT was used to re-import the landuse layer and to update the UOM SWAT model of the Carruthers watershed.

Also, in the original model setup, the .hru input files had the same parameter values (constant) for HRU_FR = 0.04277, SLSUBBSN = 91.46342, HRU_SLP = 0.02429 and OV_N = 0.14 for all HRUs. The HRU_FR values, which are the fractional areas of sub basin contained in HRUs, are not correct since the fractions do not sum to one in each sub basin and HRU areas are all the same size in each sub basin. The other parameters were not calibration parameters and their values are likely incorrect as well. These parameter values have been revised in the updated model when the HRUs were re-created.

Section 2: SWAT Setup of Landuse Scenario

A list of all landuse classes from the 5 TRCA landuse scenarios for Carruthers was created and each class was assigned a SWAT landuse code. It is assumed that Urban is a mix of low and medium residential (URML), and Future Urban is high density residential (URHD). Open space was assigned to range-grasses (RNGE). This was assumed to be similar to vacant lands from the Rouge River SWAT model, which was assigned to range-grasses.

Table 2: Land use classes and SWAT codes

Landuse (TRCA scenarios)	Value1	SWAT LU
Agricultural	1	AGRL
Agricultural/Rural	1	AGRL
Cemetery	10	URLD
Commercial	13	UCOM
Estate Residential	10	URLD
Future Urban	21	URHD
Golf Course	2	FESC
Hydro Corridor	19	UTRN
Industrial	15	UIDU
Institutional	16	UINS
Natural Cover	2	FESC
Natural Cover (Potential)	2	FESC
Open Space	23	RNGE
Open Space (Construction)	10	URLD
Railway	19	UTRN
Recreational	2	FESC
Residential High	21	URHD
Residential LowMed	22	URML
Road (ROW)	19	UTRN
Rural Residential	10	URLD
Urban	22	URML
Water	6	WATR

Section 3: Corrections for different watershed boundary

When the Carruthers SWAT sub basins were overlaid on top of the landuse scenario layers, there were parts of sub basins that were outside of the landuse layer. These areas did not have any landuse from the scenario layer and so the landuse from the baseline model was used.

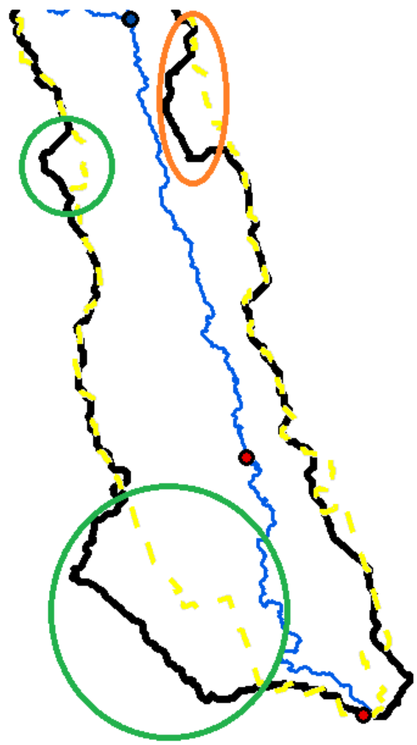

Figure 3: Differences between watershed boundary (yellow dashed) compared to the SWAT boundary (black) (circled). Green circles are where the scenario landuse layers to do not extend to the swat boundary so we would have to use the existing swat landuse

Each of the vector landuse layers (shapefiles) were converted into a raster grid with 10m grid cells. The numbers in the Value1 column were used as the pixel values in the raster.

1. Start ArcGIS.
2. Add the scenario landuse layer (e.g. landuse_existing2015_carruthers_TRCA in the geodatabase CarruthersWP_LandUse_Data.gdb) in ArcGIS.
3. Then, add the landuse table (swat_landuse_mapping.xlsx)

4. Join the data in the landuse table to the attribute table of the landuse layer (join on the landuse names)
5. Save/export the layer into a new layer in the geodatabase: landuse_existing2015_swat
6. Run Polygon to Raster tool (Conversion Tools→To Raster in the ArcToolbox). Select layer "landuse_existing2015_swat" as the input feature. Select "Value1" as the Value field. Select "MAXIMUM AREA" as the Cell Assignment type. Set Cellsize to 10. Set the output raster as LU_existing2015_swat in the geodatabase. Click on Environments, expand Processing Extent and select landuse1 as the Snap Raster and click OK. Click OK.
7. The Landuse raster in step 2 may have some subbasin areas with no land use defined. These areas are filled in with landuse from baseline using Raster Calculator tool (Spatial Analyst Tools→Map Algebra in ArcToolbox). Run this and set the expression to
   Con(IsNull(*scenario_landuse_raster*), *baseline_landuse*, *scenario_landuse_raster*)
   E.g., Con(IsNull(LU_existing2015_swat), landuse1, LU_existing2015_swat)
   This replaces any NoData pixel values in the scenario land use layer with values from the baseline landuse raster (landuse1)
   Set the output raster to LU_existing2015_filled_swat in the geodatabase
8. Use Export Data to Save/export raster created in previous step as an Esri GRID: LUswatex2015
9. Create a copy of the ArcSWAT project folder for the Carruthers baseline model (and give it a name, e.g., CarLUEx2015)
10. Rename the ArcGIS project file Car.mxd and the database Car.mdb in the copied project with name of folder (e.g., CarLUEx2015.mxd, CarLUEx2015.mdb)
11. In Microsoft Access, update the paths and/or filenames in the WorkDir, OutputGDB and SwatGDB fields of the MasterProgress table to those in previous steps.
12. Open this project in ArcSWAT.
13. In ArcSWAT toolbar, select HRU Analysis → Land use/Soils/Slope Definintion

Land Use Data

Land Use Grid: select the landuse raster from disk (e.g., LUswatex2015 from step 8)

Grid field: select VALUE

Lookup Table: select the user table LU_lookup.txt

Value	NAME
1	AGRL
2	FESC
3	FRST
5	BROM
6	WATR
10	URLD
12	WETL
13	UCOM
15	UIDU
16	UINS
19	UTRN
21	URHD
22	URML
23	RNGE

Click Reclassify.

Soil Data

Soil Grid: select the soil raster from disk (e.g., landsoils1 in folder Watershed\Grid of the ArcSWAT project)

Grid Field: select VALUE

Soil Database: select UserSoil option

Lookup Table: select Soil_lookup.txt

VALUE	NAME
1	UNCLASSIFIED
2	BONDHEAD
3	BRIGHTON
4	DARLINGTON
5	GUERIN
6	MUCK
7	MILLIKEN1
8	SMITHFIELD
9	SCHOMBERG1
10	TECUMSETH1
11	WHITBY LOAM
12	WOBURN

Click Reclassify

Slope

Select Multiple Slope option and setup 2 slope classes: 0-4, 4-9999

Click Reclassify

Note: you can turn on Create HRU Feature Class option to create an HRU layer, but this may cause errors.

Click Overlay.

14. In ArcSWAT toolbar, select HRU Analysis → HRU Definitions

HRU Thresholds

HRU Definition: select Multiple HRUs

Threshold option: select percentages 5% land use, 20% soil class, 20% slope class

Land Use Refinement

The following should be defined.

Land Use to split: AGRL

Landuse	Sub-LU	Percent
AGRL	CCBW	20
AGRL	WCCB	20
AGRL	BWCC	20
AGRL	CBWC	20
AGRL	CBCB	10
AGRL	BCBC	10

Land use Threshold Exemptions

Select AGRL from the list and click Add to include agricultural land uses in the HRUs. It appears that the threshold percentages are applied to AGRL after land use refinement. Suppose AGRL has a pre-split percentage of 10%. If there was no land use splitting and threshold was 5%, AGRL would get included. However, if the sub-land use percentages are below 5% after landuse split, they will not be included in the HRUs.

Click Save Edits.

Click Create HRUs

15. In ArcSWAT toolbar, select Write Input Tables → Weather Stations

    For Weather Generator Data, select the "WGEN_US_FirstOrder" table. Select "Simulation"option in all the other climate data.

    Click OK.

16. In ArcSWAT toolbar, select Write Input Tables → Write SWAT Input Tables

    Click Select All and then click Create Tables.

    When prompted for "Use weather database to calculate heat units to maturity (US only)", answer No.

When prompted for “Do you want to re-write the existing …”, answer No to each one.

17. Run the SwatEditor (version 2012.10.0.18) program. Select the databases in the ArcSWAT project for SWAT project geodatabase (e.g. Car.mdb) and SWAT Parameter Geodatabase (e.g., swat2012.mdb). Click Connect to Databases. Select menu Edit SWAT Input → Subbasins Data

    Edit the operations for all land use types in the Mgt input table. Select Management (.Mgt) from the input table list.

    Pick a subbasin number. Pick a landuse that has not been edited. Then pick a soil and slope (does not matter which ones). Click OK. Go to Operations tab. Click on Edit Values. Click Load Schedules. Select the operation schedule for the current selected land use (usually has same name) and click OK. After schedule is loaded, select option “Extend Management Operations” and click on Save Edits. Click OK.

    Then click OK in the Edit Subbasin Inputs dialog to edit the same land use. Go to Operations tab. Click Edit Values. Select the option “Extend Edits to selected HRUS”. Select “All” in Subbasins list. In Land Use list, pick the name being edited. Select “All” in the soils and slope lists. Select option “Extend Management Operations” and click Save Edits. Click OK.
    Repeat the above to edit all the other land use types.

18. In the mgt1 table of database Car.mdb, set NROT = 2 for land uses BCBC and CBCB; set NROT = 4 for land uses BWCC, CBWC, CCBW and WCCB. Microsoft Access can be used to do this.
19. Update the CNOP values in the management operation for planting (MGT_OP 1), tillage (MGT_OP 6) and harvesting (MGT_OP 5) - CNOP values are based on the soil hydrologic group. When the management operations were edited in the previous step, only one set of operations was used in each land use type and did not vary the CNOP values.
    The following information came from the technical report of the Carruthers SWAT model (T:\GS3\GLAPDSS\CarrutherPetticoatSwat\Carruther's Creek model\References\Carruther_Petticoat_Modeling_FinalTechnicalReport_Coop_UM.pdf)

2-year crop rotation (BCBC, CBCB) CNOP values

MGT_OP	A	B	C	D
6	76	85	90	93
1	67	78	85	89
5	74	83	88	90

4-year crop rotation (BWCC, CBWC, CCBW, WCCB) CNOP values

MGT_OP	MONTH	DAY	A	B	C	D
6	4	30	77	86	91	94
1			67	78	85	89
5			74	83	88	90
6	11	15	76	85	90	93

Other land use CNOP values

	MGT_OP	A	B	C	D
FRST	1	30	55	70	77
FESC	1	30	58	71	78
BROM	1	30	58	71	78
URLD, URML, UCOM, UIDU	1	30	58	71	78
URLD, URML, UCOM, UIDU	5	74	83	88	90

Also need to revise CN2 values based on hydrologic soil group

	A	B	C	D
CBCB	76	85	90	93
BCBC, BWCC,	67	78	85	89
CBWC, CCBW,	77	86	91	94
WCCB	74	83	88	90
UCOM, UIDU, UTRN	81	88	91	93
URLD, URML	77	85	90	92
FESC, BROM	30	58	71	78
FRST	30	55	70	77

This can be done using database UPDATE queries (SQL) to update CNOP values in table mgt2 and update CN2 values in table mgt1 of the ArcSWAT project database. The queries are named:

- Q_Update_mgt2_CNOP_BCBC_CBCB
- Q_Update_mgt2_CNOP_BWCC_CBWC_CCBW_WCCB
- Q_Update_mgt2_CNOP_other_landuse
- Q_Update_mgt1_CN2

Import all tables and queries in the database CNOP_and_CN2_queries.mdb into the project database (e.g. CarLUEx2015.mdb). Execute the above queries.

20. Set the swat IGRO parameter to 1 for all hrus. This is the land cover status code and a 1 indicates land cover is growing at the beginning of the simulation. Set the associated PLANT_ID parameter to the land cover identification numbers below. IGRO and PLANT_ID are in the mgt1 table.

Land uses	PLANT_ID
BCBC, BWCC	56
CBCB, CBWC, CCBW	19
WCCB	28
FRST	6
WETL	9
BROM	37
FESC	38
UCOM, UIDU, URLD, URML	39
UTRN	40

SQL queries can be used to updates these parameters.

```
UPDATE mgt1 SET IGRO=1

UPDATE mgt1 SET PLANT_ID = 56 WHERE LANDUSE IN ('BCBC', 'BWCC')

UPDATE mgt1 SET PLANT_ID = 19 WHERE LANDUSE IN ('CBCB', 'CBWC',
'CCBW')

UPDATE mgt1 SET PLANT_ID = 28 WHERE LANDUSE IN ('WCCB')

UPDATE mgt1 SET PLANT_ID = 6 WHERE LANDUSE IN ('FRST')
```

UPDATE mgt1 SET PLANT_ID = 9 WHERE LANDUSE IN ('WETL')

UPDATE mgt1 SET PLANT_ID = 37 WHERE LANDUSE IN ('BROM')

UPDATE mgt1 SET PLANT_ID = 38 WHERE LANDUSE IN ('FESC')

UPDATE mgt1 SET PLANT_ID = 39 WHERE LANDUSE IN ('UCOM', 'UIDU', 'URLD', 'URML')

UPDATE mgt1 SET PLANT_ID = 40 WHERE LANDUSE IN ('UTRN')

21. Update calibration parameter values and other values to match the original Carruthers baseline.
    This can be done using SQL queries (Q_Update_bsn, Q_Update_gw, Q_Update_hru, Q_Update_rte, Q_Update_sol), which were imported in step 21.
    Create a copy of the "sol" table and name it "sol_Original". Execute the above update queries.

.BSN

	default	change to
ANION_EXCL_BSN	0.2	0
BC1_BSN	0.1	10
BC2_BSN	0.1	1.1
BC3_BSN	0.02	0
BC4_BSN	0.35	0.1
CDN	1.4	3
CN_FROZ	0.000862	0
DECR_MIN	0.01	0
EPCO	1	0.01
ESCO	0.95	0.95
FIXCO	0.5	0
HLIFE_NGW_BSN	5	0
IPET	1	2
ISUBWQ	0	1
NFIXMX	20	0
NPERCO	0.2	1
RCN_SUB_BSN	1	0
RES_STLR_CO	0.184	0
RSD_COVCO	0.3	0
SDNCO	1.1	0.1
SMFMN	4.5	1.7
SMXCO	1	0
SPCON	0.0001	0.0003
SPEXP	1	2
SURLAG	4	0.424
TIMP	1	1
VCRIT	5	0

.GW

	default	change to
SHALLST	1000	0.5
DEEPST	2000	1000
ALPHA_BF	0.048	0.2
GWQMN	1000	0
REVAPMN	750	1

HRU

	default	change to
EPCO	1	0.01
ERORGN	0	1
ERORGP	0	0.6
POT_SOLP	0.01	0
POT_K	0.01	0
N_LAG	0.25	0.3

.RTE

	default	change to
CH_N2	0.014	0.024
CH_K2	0	21
CH_COV1	0	1
CH_COV2	0	1

.SOL

	change to
SOL_AWC(1-10)	Multiply by 1.492
SOL_K(1-10)	Multiply by 95.5

22. In the SwatEditor (version 2012.10.0.18), select menu Edit SWAT Input → Rewrite SWAT Input Files
    First, delete files in Scenarios\Default\TxtInOut folder. Click Select All and then Write Files.
    Files are saved to folder TxtInOut.
23. The last step creates the set of swat input files for the landuse scenario. First, make a copy of the SWAT input files folder (TxtInOut) from the original baseline. It can be copied into the Scenarios\Default folder and can be named "TxtInOut updated".
    Then, delete and replace the *.chm, *.gw, *.hru, *.mgt, *.sdr, *.sep and *.sol files in "TxtInOut updated" with those files from the scenario's TxtInOut folder. These files contain updated HRU-level inputs for the landuse scenario.
    In the 4 *.sub files, update the list of files under the "HRU: General" heading with the list from the corresponding *.sub files of the landuse scenario. Update the HRUTOT value in the sub file.

    These steps are repeated for each land use scenario.

Section 4: Forest/Meadow Update in Land Use Scenarios

The UOM SWAT with the natural vegetation land use implemented using tall fescue (code FESC). G. Bowen (TRCA) indicated those areas should be forest and recommended to use 50/50 mix of forest and meadow.

The HRU delineation process in ArcSWAT was performed again using the Landuse Existing 2015 layer with the natural cover assigned to the FRST class.

Table 3: % of subbasin area for FRST and FESC

Subbasin	FRST	FESC
1	24.5%	0%
2	29.91%	10.56%
3	17.41%	8.32%
4	24.84%	0%

The simplest approach of updating the SWAT model files of this scenario to include FRST without having to re-create it entirely was to convert all or some of FESC HRUs into FRST (forest mixed) or BROM (meadow bromegrass) by changing operation schedules (mgt file) and parameters CN2 (mgt file) and HRU_FR (hru file).

The changes were made to reflect the above percentages. The FESC HRUs in subbasins 1 and 4 were all changed into FRST or BROM. In subbasin 2, 0.75 (= 30 / (10 + 30)) of FESC was changed into FRST or BROM and in subbasin 3, 0.68 (= 17 / (17 + 8)) of FESC was changed.

There were multiple FESC HRUs in each subbasin. HRUs with Slope “0-4” were changed to BROM and HRUs with slope “4-9999” were changed to FRST and their HRU fractions (HRU_FR in .hru files) were updated to reflect an equal area of each. For example to calculate new fractions, the HRU_FRs for HRUs 11 and 12 in subbasin 1 were summed and then divided by 2. The operation schedules for FESC in the .mgt files were replaced with the ones for FRST or BROM. Also, the CN2 values in .mgt files were updated using parameter values from TRCA/Civica (T:\GS3\GLAPDSS\CarrutherPetticoatSwat\Carruther's Creek model\References\TRCA Civica HydrologyParameters20181031.pdf)

Table 4: Updated HRU_FR and CN2 parameter values in SWAT after switching to FRST/BROM land use

								Revised		
Subbasin	**HRU**	**Landuse**	**Soil**	**Slope_CD**	**HRU_FR**	**HYDGRP**	**CN2**	**Landuse**	**HRU_FR**	**CN2**
1	11	FESC	BONDHEAD	0-4	0.0422284	B	58	BROM	0.034674996	63
1	12	FESC	BONDHEAD	4-9999	0.0271216	B	58	FRST	0.034674996	63
1	13	FESC	SMITHFIELD	0-4	0.0614272	C	71	BROM	0.040233453	75
1	14	FESC	SMITHFIELD	4-9999	0.0190397	C	71	FRST	0.040233453	75
1	15	FESC	WHITBY LOAM	0-4	0.0763293	C	71	BROM	0.055817594	75
1	16	FESC	WHITBY LOAM	4-9999	0.0353059	C	71	FRST	0.055817594	75
2	11	FESC	DARLINGTON	0-4	0.0824501	B	58	FESC	0.1011883	58
2	12	FESC	DARLINGTON	4-9999	0.0747999	B	58	FRST	0.0758912	63
2	13	FESC	WHITBY LOAM	0-4	0.1131274	C	71	BROM	0.1517824	75
2	14	FESC	WHITBY LOAM	4-9999	0.1343758	C	71	FRST	0.0758912	75
3	21	FESC	BONDHEAD	0-4	0.0699869	B	58	FESC	0.0822364	58
3	22	FESC	BONDHEAD	4-9999	0.0827777	B	58	FRST	0.0436881	63
3	23	FESC	SMITHFIELD	0-4	0.0537245	C	71	BROM	0.0873762	75
3	24	FESC	SMITHFIELD	4-9999	0.0504998	C	71	FRST	0.0436881	75
4	6	FESC	BONDHEAD	0-4	0.0450092	B	58	BROM	0.044939219	63
4	7	FESC	BONDHEAD	4-9999	0.0251043	B	58	FRST	0.067408829	63
4	8	FESC	TECUMSETH1	0-4	0.1047896	B	58	BROM	0.044939219	63
4	9	FESC	UNCLASSIFIED	0-4	0.0722406	D	78	BROM	0.044939219	81
4	10	FESC	UNCLASSIFIED	4-9999	0.0224915	D	78	FRST	0.067408829	81

This procedure was performed on the other landuse scenarios to reclassify natural vegetation areas as forest and meadow.

Table 5: Updated land use composition in SWAT for the land use scenarios after forest/meadow landuse modification. The scenario "Existing 2015 OP NHS buildout" also includes the future urban update described in Appendix D

		Existing 2015	**Existing 2015 OP**	**Existing 2015 OP NHS**	**Existing 2015 OP NHS buildout**	**Historical 1999**
Agricultural LG-BCBC	BCBC	3.22%	2.73%	1.83%	0.33%	5.17%
Agricultural LG-BWCC	BWCC	6.43%	5.46%	3.66%	0.65%	10.34%
Agricultural LG-CBCB	CBCB	3.22%	2.73%	1.83%	0.33%	5.17%
Agricultural LG-CBWC	CBWC	6.43%	5.46%	3.66%	0.65%	10.34%
Agricultural LG-CCBW	CCBW	6.43%	5.46%	3.66%	0.65%	10.34%
Agricultural LG-WCCB	WCCB	6.43%	5.46%	3.66%	0.65%	10.34%
Tall Fescue	FESC	4.49%	4.86%	4.51%	3.94%	3.92%
Forest-Mixed	FRST	12.65%	13.13%	19.72%	18.81%	15.54%
Meadow Bromegrass	BROM	12.65%	13.13%	19.72%	18.81	15.54%
Residential-Low Density	URLD	9.86%	5.81%	4.21%	3.97%	13.30%
Residential-Med/Low Density	URML	11.11%	13.33%	13.12%	13.12%	
Residential-High Density	URHD				19.25%	
Commercial	UCOM	4.90%	6.39%	6.17%	6.17%	
Industrial	UIDU		3.78%	3.63%	3.63%	
Transportation	UTRN	12.15%	12.27%	10.64%	9.04%	

Comparing SWAT outputs between scenarios with tall fescue and the one with forest/meadow mix showed that in general flows were about the same and the latter has smaller sediment and nutrients.

Table 6: Percent relative change in annual average (2005-2015) flow, TSS, TP and TP after switching FESC to a FRST/BROM type in each of the land use scenarios.

Existing 2015 scenario

Reach	Flow	TSS load	TP load	TN load
1	0%	-5.35%	-2.86%	-2.30%
2	-1.63%	-24.30%	-12.50%	-10.70%
3	-1.03%	-1.88%	-8.58%	-7.71%
4 (outlet)	-0.95%	-1.98%	-6.16%	-5.12%

Existing 2015 OP scenario

Reach	Flow	TSS load	TP load	TN load
1	0.00%	-1.84%	-0.33%	0.10%
2	-1.63%	-22.00%	-11.10%	-9.20%
3	-1.01%	-1.30%	-6.54%	-5.87%
4 (outlet)	-0.93%	-1.50%	-4.00%	-2.95%

Existing 2015 OP NHS scenario

Reach	Flow	TSS load	TP load	TN load
1	-0.78%	-12.70%	-5.57%	-4.05%
2	-0.84%	-19.40%	-11.90%	-9.38%
3	-1.28%	-1.33%	-9.32%	-8.43%
4 (outlet)	-0.94%	-1.26%	-6.34%	-5.11%

Existing 2015 OP NHS buildout scenario (includes future urban update)

Reach	Flow	TSS load	TP load	TN load
1	12.50%	-36.50%	-2.33%	-22.80%
2	8.26%	-31.90%	-7.61%	-20.50%
3	5.87%	7.98%	-7.67%	-19.40%
4 (outlet)	4.32%	5.29%	-4.53%	-13.60%

1999 Historic scenario

Reach	Flow	TSS load	TP load	TN load
1	0.00%	-2.78%	-1.17%	-0.73%
2	-1.68%	-11.70%	-5.21%	-3.93%
3	-0.82%	-0.65%	-3.63%	-2.67%
4 (outlet)	-0.20%	0.47%	2.13%	3.66%

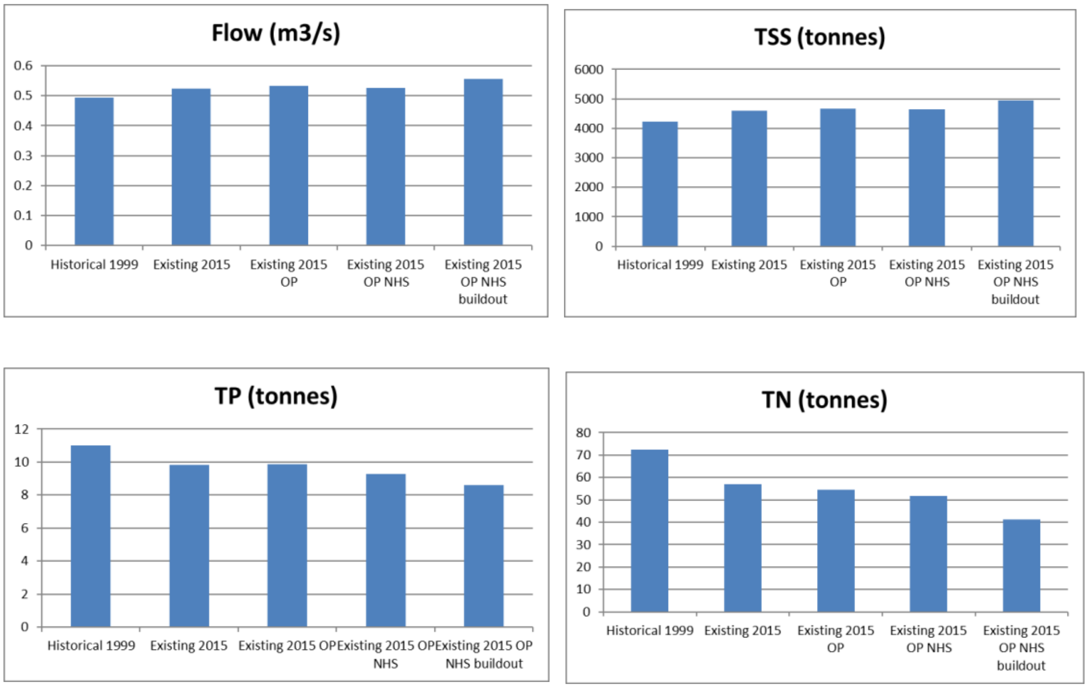

Figure 4: Plots of 2005-2015 average flow, TSS, TP and TN at watershed outlet for the updated landuse scenarios

Section 4: Future Urban areas Update for the Land use Scenarios

The future urban areas in the Landuse Existing 2015 OP NHS buildout scenario were modelled in swat using the Residential –Med/Low Density class (URML). URML is defined with a 20% impervious cover. A. Wallace (TRCA) indicated that Civica is modelling the future urban area in Carruthers with an 85% impervious cover. The swat scenario was updated with a higher impervious cover.

Future urban is present in subbasins 1 and 2. The URML HRUs were changed to a Residential-High Density class URHD, which has an impervious cover of 60%. The URBLU parameter (in .mgt files) was updated from 3 to 1. The urban database (urban.dat) was updated to set URHD's FIMP parameter (fraction total impervious area) to 0.85. Also, FCIMP (fraction directly connected impervious area) was set to 0.80 to be consistent with Civica's parameters (T:\GS3\GLAPDSS\CarrutherPetticoatSwat\Carruther's Creek model\References\TRCA Civica HydrologyParameters20181031.pdf). Civica's values for CN2 were used in the URHD HRUs (and the CNOP values in the operation schedules were set 0.0).

Table 7: Updated URBLU and CN2 parameter values in SWAT

SUBBASIN	HRU	LANDUSE	SOIL	SLOPE_CD	URBLU	CN2	Revised	
							URBLU	CN2
1	13	URML	WHITBY LOAM	0-4	3	90	1	96
1	14	URML	WHITBY LOAM	4-9999	3	90	1	96
2	26	URML	WHITBY LOAM	0-4	3	90	1	96
2	27	URML	WHITBY LOAM	4-9999	3	90	1	96

Table 8: Revised land use composition in SWAT. This also includes the forest/meadow land use update described in Appendix C

		Existing 2015 OP NHS buildout
Agricultural LG-BCBC	BCBC	0.33%
Agricultural LG-BWCC	BWCC	0.65%
Agricultural LG-CBCB	CBCB	0.33%
Agricultural LG-CBWC	CBWC	0.65%
Agricultural LG-CCBW	CCBW	0.65%
Agricultural LG-WCCB	WCCB	0.65%
Tall Fescue	FESC	3.94%
Forest-Mixed	FRST	18.81%
Meadow Bromegrass	BROM	18.81
Residential-Low Density	URLD	3.97%
Residential-Med/Low Density	URML	13.12%
Residential-High Density	URHD	19.25%
Commercial	UCOM	6.17%
Industrial	UIDU	3.63%
Transportation	UTRN	9.04%

Comparing SWAT outputs between scenarios with future urban defined as med/low residential versus high residential showed that flows and TP load increased and TN load reduced in scenario with high residential.

Table 9: Percent relative change in annual average (2005-2015) flow, TSS, TP and TN after implementing future urban areas as high-density residential

Reach	Flow	TSS load	TP load	TN load
1	13.30%	-23.10%	3.81%	-18.10%
2	9.09%	-14.90%	3.00%	-11.50%
3	7.14%	7.89%	2.02%	-10.00%
4 (outlet)	5.25%	6.29%	1.73%	-8.12%

Section 5: Cover Crops

The cover crop BMP scenario explores water quality and erosional benefits of a green cover crop (during the winter months) that are planted in fall and ploughed under in the spring when next year's crops (corn and soybeans) are normally sown. The management schedule of 2-year and 4-year crop rotations in Carruthers were modified to include operations (e.g., plant/kill crop, tillage) for cover crops to implement this BMP in SWAT. Red clover was chosen as the cover crop. It fixes nitrogen for the following crop and thus the N fertilizer application rate of corn was reduced from 110 kg/ha to 60 kg/ha.

Table 10: Revised 2-year crop rotation (updates in red)

	Date	Operation
Corn (year 1)	Apr 25	Kill cover crop
	Apr 30	Disc plough
	May 1	Plant corn
	May 2	N Fertilizer: 60 kg/ha
	May 3	P Fertilizer: 22 kg/ha
	Nov 1	Harvest and kill corn
	Nov 7	Plant cover crop red clover
Soybean (year 2)	May 1	Kill cover crop
	May 2	Mouldboard plough
	May 13	Plant soybean
	May 14	P Fertilizer: 33 kg/ha
	Oct 1	Harvest and kill soybean
	Oct 15	Plant cover crop red clover

Table 11: Revised 4-year crop rotation (updates in red)

Corn (year 1)	Apr 25	Kill cover crop
	Apr 30	Disc plough
	May 1	Plant corn
	May 2	N Fertilizer: 60 kg/ha
	May 3	P Fertilizer: 22 kg/ha
	Nov 1	Harvest and kill corn
	Nov 7	Plant cover crop red clover
Corn (year 2)	Apr 25	Kill cover crop
	Apr 30	Disc plough
	May 1	Plant corn
	May 2	N Fertilizer: 60 kg/ha
	May 3	P Fertilizer: 22 kg/ha
	Nov 1	Harvest and kill corn
	Nov 7	Plant cover crop red clover
Soybean (year 3)	May 1	Kill cover crop
	May 2	Mouldboard plough
	May 13	Plant soybean
	May 14	P Fertilizer: 33 kg/ha
	Oct 1	Harvest and kill soybean
	Oct 6	Plant winter wheat
	Oct 7	N Fertilizer: 10 kg/ha
	Oct 8	P Fertilizer: 20 kg/ha
Winter wheat (year 4)	Apr 10	N Fertilizer: 70 kg/ha
	July 15	Harvest and kill winter wheat
	Oct 15	Plant cover crop red clover

All agricultural HRUs were updated with the above management operations. Model outputs show that water quality is improved with the addition of cover crops. TSS is reduced in the reaches of the upper watershed and TP and TN are reduced across the watershed and at the outlet. More than 40% of area of upper subbasins 1 (61%) and 2 (43%) are agricultural and under 20% in subbasins 3 (19%) and 4 (4%).

Table 12: Percent relative change in annual average (2005-2015) TSS, TP and TN loads when cover crops are included in crop rotation.

TSS (tonnes)

Reach	Existing 2015	Cover crop	% change
1	146649	94885	-35.30%
2	116480	88249	-24.20%
3	33920	34034	0.34%
4 (outlet)	50623	50648	0.05%

TP (kg)

Reach	Existing 2015	Cover crop	% change
1	3907	2700	-30.90%
2	2876	2193	-23.70%
3	9108	7232	-20.60%
4 (outlet)	9843	8136	-17.30%

TN (kg)

Reach	Existing 2015	Cover crop	% change
1	24305	16285	-33.00%
2	17525	12889	-26.50%
3	53589	40855	-23.80%
4 (outlet)	57043	45423	-20.40%

Section 6: Buffer Strips

The buffer strip BMP scenario explores the impact to water quality when buffer strips are applied in rural subbasins (1 and 2) of the Carruthers watershed. Buffer strips are modelled in SWAT using the scheduled management operations file (.ops) to simulate vegetative filter strips in HRUs. From the SWAT Input/Output documentation: *"filter strip is a strip of dense vegetation located to intercept runoff from upslope pollutant sources and filter it. Filter strips remove contaminants by reducing overland flow velocity which results in the deposition of particulates. The filter strip area also acts as an area of increased infiltration, reducing both the runoff volume and non-particulate contaminants. Filter strips reduce sediment, nutrients, bacteria and pesticides, but do not affect surface runoff in SWAT."*

Scenarios were setup using 15m, 30m and 100m buffer strip widths and having buffer strips applied to agricultural HRUs only, natural cover (forest/meadow, fescue) HRUs only and both agricultural and natural cover HRUs in subbasins 1 and 2. Buffer strips were applied to the landuse existing 2015 scenario. Three SWAT parameters were modified:

1. FILTER_RATIO – ratio of field area to filter strip area. Assuming a square-shaped HRU, FILTER_RATIO = $area/(width * \sqrt{area})$ where area is the HRU area (m^2) and width is the buffer width (m)
2. FILTER_CON – fraction of HRU which drains to the most concentrated 10% of filter strips area. Set to 0.50 (default).
3. FILTER_CH – fraction of flow within the most concentration 10% of filter strip which is fully channelized (and is not subject to filtering or infiltration effects). Set to 0.0 (default).

Modelling results showed no (or very little) change in streamflows in the buffer strip scenarios compared to the landuse existing 2015 scenario. However, sediments and nutrients were reduced as shown in Table 13.

Table 13: Percent reduction in annual average (2005-2015) TSS, TN and TP loads for different buffer strip scenarios.

Reach	Agricultural HRUs 15m	Agricultural HRUs 30m	Agricultural HRUs 100m	Natural Cover HRUs 15m	Natural Cover HRUs 30m	Natural Cover HRUs 100m	Agricultural and Natural Cover HRUs 15m	Agricultural and Natural Cover HRUs 30m	Agricultural and Natural Cover HRUs 100m
TSS									
1	55.4%	64.3%	73.2%	13.6%	15.2%	16.8%	69.0%	79.5%	90.0%
2	42.4%	46.9%	50.4%	26.1%	30.6%	35.1%	68.5%	77.5%	85.5%
3	0%	0%	0%	0%	0%	0%	0%	0%	0%
4 (outlet)	0%	0%	0%	0%	0%	0%	0%	0%	0%
TP									
1	48.0%	54.0%	59.9%	11.8%	12.9%	13.9%	59.8%	66.9%	73.8%
2	40.4%	43.7%	46.2%	18.5%	21.1%	23.5%	58.9%	64.7%	69.7%
3	28.5%	31.6%	34.4%	9.4%	10.5%	11.5%	37.9%	42.0%	45.9%
4 (outlet)	22.8%	25.3%	27.5%	7.6%	8.4%	9.3%	30.4%	33.7%	36.8%
TN									
1	43.1%	49.6%	57.0%	11.7%	13.2%	14.6%	54.9%	62.8%	71.6%
2	37.8%	42.0%	45.7%	17.4%	20.2%	23.4%	55.2%	62.2%	69.1%
3	27.5%	31.0%	34.9%	9.5%	10.8%	12.3%	37.0%	41.9%	47.2%
4 (outlet)	22.4%	25.3%	28.4%	7.8%	8.8%	10.0%	30.2%	34.1%	38.4%

0 to 10%	10 to 20%	20 to 30%	30 to 50%	50 to 75%	> 75%

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