Development of a
Rural Stormwater Management Model
to Manage Water Quality in the Lake Huron Watersheds

October, 2014

Healthy Lake Huron
Clean Water, Clean Beaches

Rural Stormwater Management Model Project

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Clean Water, Clean Beaches

Rural Stormwater Management Model Project

AUSABLE BAYFIELD CONSERVATION
CREATING AWARENESS | TAKING ACTION

EOR water ecology community
Emmons & Olivier Resources, Inc.

CHI

MAITLAND VALLEY CONSERVATION AUTHORITY

St. Clair Conservation

SAUGEEN CONSERVATION

This project has received funding support from the Government of Ontario.
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- Final Report, October 2014

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Abbreviations

ABCA	Ausable Bayfield Conservation Authority
BMP	Best management practice
BN	Bayfield North
CHI	Computational Hydraulics International
EOR	Emmons and Olivier Resources, Inc.
GG	Garvey-Glenn
GIS	Geographic Information System
LHSSESC	Lake Huron Southeast Shores Executive Steering Committee
LS	Lambton Shores
MASL	Metres Above Sea Level
MB	Main Bayfield
MNRF	Ministry of Natural Resources and Forestry
MOECC	Ministry of Environment and Climate Change
MUSLE	Modified Universal Soil Loss Equation
MVCA	Maitland Valley Conservation Authority
OMAFRA	Ontario Ministry of Agriculture, Food and Rural Affairs
PR	Pine River
PRWIN	Pine River Watershed Initiative Network
RSWMM	Rural Stormwater Management Model
SCRCA	St. Clair Region Conservation Authority
SPARROW	Spatially Referenced Regression On Watershed Attributes
SRP	Soluble Reactive Phosphorus
SSC	Suspended Sediment Concentration
SVCA	Saugeen Valley Conservation Authority
SWAT	Soil and Water Assessment Tool
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
USGS	United States Geological Survey
WASCOB	Water and Sediment Control Basin

Acknowledgements

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Additional thanks are given to all private landowners for their cooperation and support of this project, especially by allowing property access to gather monitoring data.

1 EXECUTIVE SUMMARY

Land use alterations have caused the loss of historical wetlands and woodlands throughout the watersheds draining to Southeast Lake Huron. Occurrences of nuisance algae and beach closures and postings have become more frequent over the past 20 years. These occurrences are in part caused by excessive nutrients and bacteria in the water draining to Lake Huron from private septic systems, municipal wastewater and runoff, runoff over agricultural lands, among other known and unknown sources, including natural sources. Reducing the amount of nutrients (such as phosphorus and nitrogen) entering Southeast Lake Huron will diminish algae growth, while also potentially decreasing the levels of related pollutants such as E. coli. This could lessen risks to human health by protecting and improving water quality in Lake Huron, which is the source of raw water for drinking water for hundreds of thousands of people and is also used for fishing and recreational activities including swimming and boating.

Government ministries and local public health and conservation agencies are working together to protect property, the vital resource of southeastern Lake Huron, and the overall health of the watersheds draining to the lake. In 2010, the Lake Huron Southeast Shores Executive Steering Committee (LHSSESC), now referred to as Healthy Lake Huron: Clean Water, Clean Beaches, was formed by a partnership of five conservation authorities, three counties, four health units, two federal agencies, and four provincial agencies. Because of the potential significant impact of urban, rural, and agricultural drainage on the health of the lake, Healthy Lake Huron identified the following five priority areas shown in Figure 1 for immediate action in developing and supporting implementation of watershed management plans:

- Pine River
- Garvey-Glenn
- Bayfield North
- Main Bayfield
- Lambton Shores

At the time these priority areas were identified, there was no stormwater management model for rural Ontario that fully met a set of specific criteria that have been identified for the Rural Stormwater Management Model project. Stormwater models are frequently used in urban areas but have limitations in representing the hydrology, hydraulics, and hydrogeology in rural areas. The Rural Stormwater Management Model (RSWMM) has been developed in an effort to begin to address these limitations and maintain the capabilities of modelling urban areas. The RSWMM builds upon PCSWMM, which is a spatial decision support system for US EPA SWMM5, one of the most widely-used models developed and maintained by the United States Environmental Protection Agency (EPA).

The RSWMM project was set out, in part, to *"Develop a physically-based computer model which will help practitioners choose the location for agricultural best management practices (BMPs) or other stewardship projects in a watershed which will have the most water quantity and water quality benefits at the watershed outlet."* Using the five priority areas as sentinel watersheds for model development, five models have been constructed in an upgraded version of PCSWMM that, in addition to the standard storm runoff flow rates and volumes, now includes the ability to simulate:

1. The impacts of a suite of agricultural BMPs on both water quantity and quality
2. Landscape loading of nitrogen, phosphorus, and sediment coming from farm fields
3. Nitrogen and phosphorus depletion along streams and creeks

4. The impact on runoff from the different crop stages throughout the farming season
5. Groundwater hydrology and drain-tile hydraulics

Significant steps have been taken toward the following objectives for the use of the RSWMM model:

a) The ability to identify priority management areas within a watershed;
b) The ability to incorporate both field-scale and treatment BMPs; and
c) The ability to assess the impact of different management alternatives on water quantity and quality at any location within the modeled area.

Several areas for improvement were identified throughout this first phase of the RSWMM project. Firstly, monitoring programs should continue to collect data that can be used to improve the calibrations of the models. Of particular importance is the collection of winter precipitation data, which will aid in the crucial task of accurately calibrating to spring snowmelt runoff events. Secondly, the individual models should be updated to include more detailed hydrologic and hydraulic information, where possible, and to incorporate new BMP developments on the landscape. A detailed summary of recommendations for each model is included in this report. Thirdly, the process of model development should be streamlined through careful coordination among CAs involved prior to future model construction. The improvements summarized in this report will ensure efficient data transfer between the field, the laboratory, and the modelling staff. Finally, further improvements to the PCSWMM software and the RSWMM enhancements should be continually pursued. While great strides have been made toward meeting the project objectives, more robust and efficient methods related to model construction, generating and processing pollutants, and implementing BMPs should all be considered in future phases of the RSWMM project.

Due to the introduction of new capabilities, as well as to the unique and intuitive nature of the PCSWMM software, the RSWMM is a promising, usable tool with broad applicability in rural watersheds. Although a work in progress, the RSWMM will allow watershed managers to better evaluate, prioritize, design and implement soil and water conservation projects to protect Lake Huron.

2 INTRODUCTION

The southeast shore of Lake Huron extends from Sarnia to Tobermory and includes the St. Clair Region, Ausable Bayfield, Maitland Valley, Saugeen Valley, and Grey Sauble conservation authorities' jurisdictions. The area is primarily used for agricultural purposes and has a small base population in the towns along the shoreline. A large tourism industry brings tens of thousands of visitors to the area during the summer.

Land use alterations have caused the loss of historical wetlands and woodlands throughout the watersheds draining to Lake Huron. Occurrences of nuisance algae and beach closures and postings have become more common over past 20 years. These issues are in part caused by excessive nutrients and bacteria in the water draining to Lake Huron from private septic systems, municipal wastewater, agriculture, and natural sources. Reducing the amount of nutrients (such as phosphorus and nitrogen) entering the lake can reduce algae growth while also potentially decreasing the levels of related pollutants such as E. coli. This can reduce risks to human health and result in improved water quality in Lake Huron, which is the source of raw water for drinking water for hundreds of thousands of people in urban and rural areas, and is also a destination for tourism and recreation, including swimming and fishing.

The public and regulatory agencies have worked together to protect property, and uses of the lake (including recreation and drinking water), the tourist industry, and the health of the watersheds. In 2010, the Lake Huron Southeast Shores Executive Steering Committee (LHSSESC), now referred to as Healthy Lake Huron, was formed by a partnership of five conservation authorities, three counties, four health units, two federal agencies, and four provincial agencies. Healthy Lake Huron identified the following five priority areas shown in Figure 1 for immediate action in developing and supporting implementation of watershed management plans:

- Pine River
- Garvey-Glenn
- Bayfield North
- Main Bayfield
- Lambton Shores

The following plans have been published for each priority area:

- Pine River Watershed Integrated Watershed Management Plan, 2012
- Garvey-Glenn Shoreline Watershed Project – Soil and Water Environmental Enhancement Plan (SWEEP), 2012
- Management Plan for the Bayfield North Watersheds, 2010
- Main Bayfield Project Plan, 2013
- Lambton Shores Tributaries Management Plan, 2012

At the time these priority areas were identified, there was no stormwater management model for rural Ontario that fully met a set of specific criteria that have been identified for the Rural Stormwater Management Model project.– discussed in Section 3.1. Stormwater models are frequently used in urban areas but have limitations in representing the hydrology, hydraulics, and hydrogeology in rural areas. The Rural Stormwater Management Model (RSWMM) has been developed to address these limitations and maintain the capabilities of modelling urban areas. The RSWMM builds upon PCSWMM, which is a spatial decision support system for US EPA SWMM5 (James et al. 2010), a software package developed and maintained by the United States

Environmental Protection Agency (EPA). Due to the introduction of these components, as well as to the unique and intuitive nature of the PCSWMM software, the RSWMM is a promising, usable tool with broad applicability in rural watersheds. Although a work in progress, when complete the RSWMM will allow watershed managers to better evaluate, prioritize, design and implement soil and water conservation projects to protect Lake Huron.

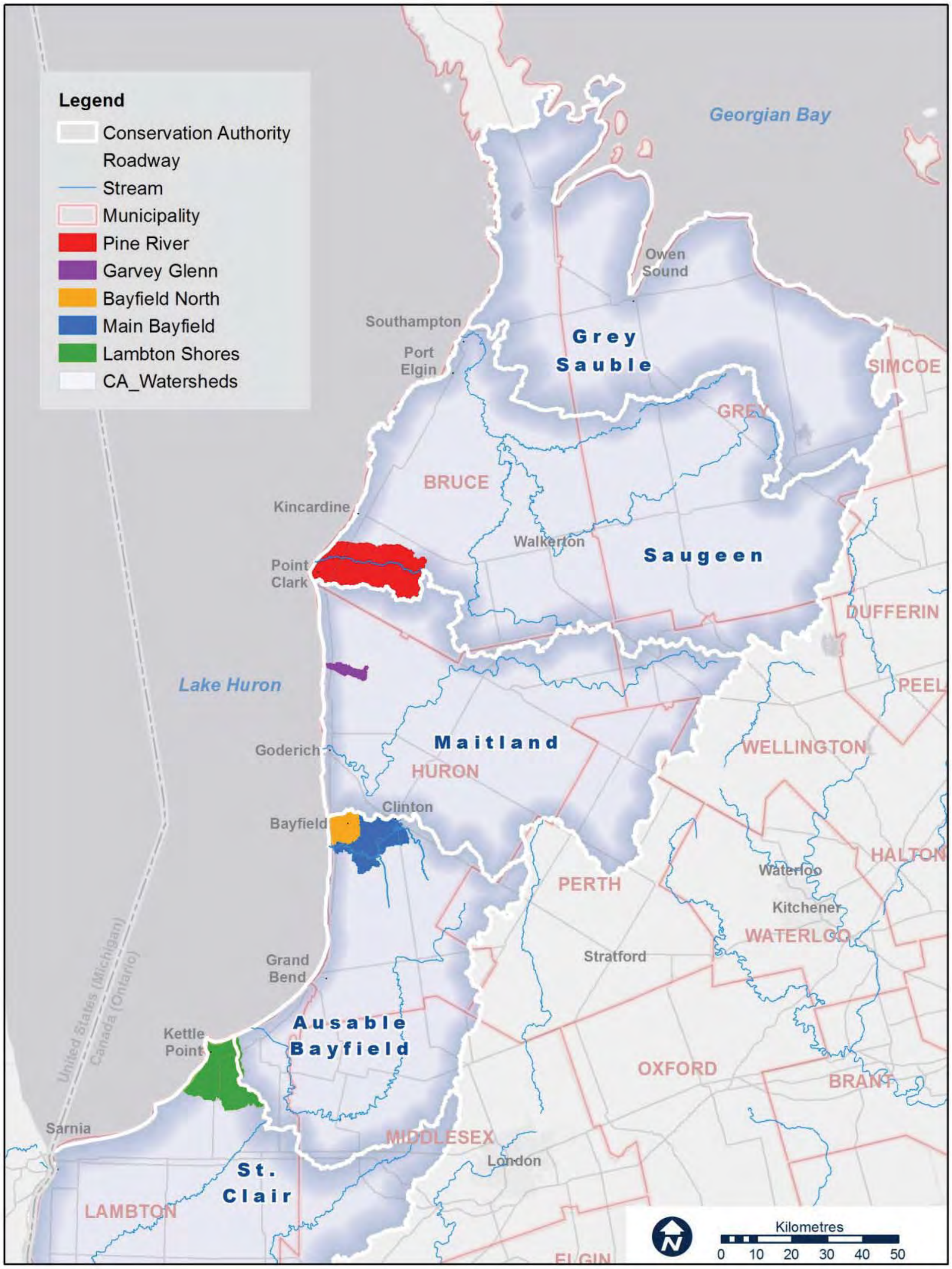

Figure 1: Location Map of the Five Priority Watersheds

3 PROJECT BACKGROUND

3.1 Purpose of Project

The following purpose of this project is defined in the Terms of Reference:

> Develop a physically-based computer model which will help practitioners choose the location for agricultural BMPs or other stewardship projects in a watershed which will have the most water quantity and water quality benefits at the watershed outlet. In addition, the model developed should be able to be used as a tool by municipal drainage engineers when designing new municipal drainage works or making improvements to existing municipal drainage works.

The primary objectives of the project include the following:

1. Ability to model natural, urban, and agricultural landscapes at the field and regional scale with BMPs for sediment, TP, TN, SRP, nitrites, nitrates, and ammonia.
2. Capacity to accurately simulate channels, culverts, bridges and stormwater network hydraulics.
3. Ability to change key input data seasonally to account for diverse crop stages and variability in some hydrologic parameters during the year.
4. Incorporate drain tile hydraulics and groundwater hydrology.
5. Capacity to use MUSLE to model soil erosion from agricultural fields.
6. Account for in-stream processes for P and N depletion.

The secondary objectives for this project include the following:

1. Accurate modelling of snowmelt and spring runoff.
2. Ability to model backwater and reverse flows (dynamic wave equation).
3. Capacity to perform both single event and continuous simulation modelling.
4. Easy to use and upgrade.
5. Moderate training time and full access to technical support.

3.2 Main Technical Contributors

The following individuals have contributed to the development of the Rural SWMM through project management, collection of monitoring data, and construction/calibration of the sentinel models.

Ausable Bayfield Conservation Authority (ABCA)	Alec Scott, Project Manager
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Computational Hydraulics International (CHI)	Rob James, P.Eng. Nandana Perera, Ph.D., P.Eng.

Ministry of Environment and Climate Change (MOECC)	Pradeep Kumar Goel Scott Abernethy
Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA)	Kevin McKague
Saugeen Valley Conservation Authority (SVCA)	Jo-Anne Harbinson
Maitland Valley Conservation Authority (MVCA)	Chris Van Esbroeck Steve Jackson
St. Clair Regional Conservation Authority (SCRCA)	Girish Sankar Steve Clark

3.3 Sentinel Watershed Descriptions

The five watersheds described in Table 1 were selected as priority areas for immediate action by the LHSSESC and are sentinel watersheds for the Rural SWMM. Maps of the watersheds are provided in Appendix A to show the watershed tributaries, monitoring stations, land use, and soil types.

Table 1: Sentinel Watershed Facts

Watershed	Conservation Authority	Watershed Size (km^2)	Number of Outfalls to Lake Huron	Average Catchment Slope (%)*
Bayfield North	ABCA	39	21	5.7
Garvey-Glenn	MVCA	16	2	5.2
Lambton Shores	SCRCA	136	24	5.8
Main Bayfield	ABCA	91	1	9.8
Pine River	SVCA	192	17	2.1

*Slope calculated from elevation grids of varying precision; coarser grids will produce lower slopes

Table 2 shows the land-use distribution in 2013 for each watershed, using the land-use categories developed for the RSWMM project. This information was compiled and re-categorized from a combination of GIS data and windshield surveys provided by CA staff. Here, the predominance of agriculture is illustrated with corn, soybeans, and winter wheat occupying the majority of all five watersheds. More information on the re-categorization of the land-use data can be found in Sections 5.3.1 and 6.2.1, and in the figures located in Appendix A.

Table 2: Land use summary by watershed for the 24 RSWMM land use categories.

Land-use	Bayfield North	Garvey-Glenn	Lambton Shores	Main Bayfield	Pine River
Canola	0.0%	0.0%	0.0%	0.0%	0.6%
Corn	17.1%	26.6%	8.3%	18.6%	23.0%
Edible Beans	0.0%	8.4%	0.0%	1.7%	1.9%
Established Forage	0.9%	1.3%	1.7%	5.6%	7.1%
Fallow	0.0%	0.2%	0.0%	0.0%	0.1%
Fruit	0.3%	0.3%	0.1%	0.0%	0.0%
Idle Grass	2.6%	0.6%	2.7%	3.5%	1.7%
Idle Weeds	2.3%	2.2%	1.7%	2.4%	2.5%
Nursery	0.2%	0.0%	0.0%	0.0%	0.0%
Pasture	1.1%	3.0%	1.1%	1.1%	3.5%
Pastured Woodland	0.0%	0.0%	0.0%	0.0%	0.0%
Quarry	0.1%	0.0%	0.1%	0.8%	0.0%
Soybeans	23.8%	33.6%	50.3%	23.3%	25.6%
Spring Grains	0.2%	1.0%	1.0%	0.4%	4.2%
Tobacco	0.0%	0.0%	0.0%	0.0%	0.0%
Urban	7.5%	2.0%	3.8%	9.3%	5.5%
Vegetables	0.0%	0.0%	0.0%	0.0%	0.0%
Water	3.1%	0.0%	0.1%	1.7%	0.0%
Winter Wheat	13.2%	10.5%	8.1%	9.9%	16.9%
Woodland	27.8%	10.3%	21.0%	21.7%	7.4%

Water quality in all five sentinel watersheds is fairly typical of agricultural watersheds. Observed ranges for nitrate and total phosphorus concentrations at the primary sampling location in each watershed are shown in Table 3. In all watersheds, maximum observed nitrate concentrations exceed the Canadian Water Quality Guideline (CWQG) of 3 mg/L (CCME 2012), and maximum observed total phosphorus concentrations exceed the Provincial Water Quality Objectives (PWQO) of 0.03 mg/L (MOEE 1994).

Table 3: Nitrate-N and Total Phosphorus concentrations in hand (grab) and ISCO samples collected 2011-14.

	Nitrate-N (mg/L)					Total Phosphorus (mg/L)				
	BN	GG	LS	MB	PR	BN	GG	LS	MB	PR
Max	37.8	16.8	17.6	29.9	13.0	5.4	0.8	1.4	3.4	1.1
Min	0.7	0.1	0.0	0.9	0.1	0.0	0.0	0.0	0.0	0.0
Mean*	6.5	5.8	6.5	4.2	4.3	0.4	0.2	0.3	0.1	0.3

*Mean of grab sample concentrations (does not represent a flow-weighted mean)

3.3.1 Pine River

The largest sentinel watershed, Pine River, is located in the southern part of Bruce County in the Municipality of Huron-Kinloss. The watershed covers 192 km^2 and includes the 25 km^2 Clark Creek watershed. The major tributaries to Pine River are Royal Oak Creek and South Pine River, as shown in Figure A.1. The outlet of Pine River to Lake Huron is at Lurgan Beach, while Clark Creek discharges to the lake to the south in Point Clark. The upper reaches of the Pine River watershed (96% of the drainage basin) are primarily used for agricultural purposes with fragmented woodlands along the river valleys and the Village of Ripley located in the centre, as shown in Figure A.2. Residential areas and woodlots are the primary land use along the Lake Huron shoreline in the lower reaches of the watershed (4% of the drainage basin), including Pine River, Point Clark, Lurgan Beach/Blairs Grove, and Bruce Beach. The largest of the few remaining wetlands is the 0.6 km^2 West Kinlough Wetland Complex.

Pine River flows from its headwaters east of Huron-Kinloss Townline Road at a maximum elevation of 305 masl westward at a relatively constant grade of 1.3% to its outlet into Lake Huron at an elevation of 175 masl. The watershed is primarily composed of clay loam with deposits of silt and sand loams to the east and west of Ripley. Sandy soils are predominant along the lakeshore, as shown in Figure A.3.

In 2012, the Pine River Watershed Initiative Network (PRWIN) published an Integrated Watershed Management Plan to identify priority areas for improvement measures over the next five years. To fulfill the recommendation to improve water quality, the PRWIN constructed three Water and Sediment Control Basins (WASCOBs) on the Eadie Farm in 2013.

3.3.2 Garvey-Glenn

The Garvey-Glenn watershed is a small area of 16 km^2 located north of Goderich within the Township of Ashfield-Colborne-Wawanosh and the jurisdiction of the Maitland Valley Conservation Authority (MVCA). Woodlands are located along the lower reach of the watershed and in the headwaters of the southern tributary, as shown in Figure A.4. The majority of the watershed is used for agricultural purposes, as shown in Figure A.5.

The Garvey-Glenn drain flows from its headwaters southeast of Tower Line at a maximum elevation of 266 masl northwestward at a relatively constant grade of 1.7% to its outlet into Lake Huron at an elevation of 177 masl. The watershed has varying soil types with loam and silt loam located in the headwaters while clay and sand loams are found in the middle and lower areas of the watershed, as shown in Figure A.6.

3.3.3 Bayfield North

Twenty small parallel streams drain the 39 km^2 Bayfield North watershed directly to Lake Huron. The watershed is located north of the community of Bayfield and is entirely within the jurisdiction of the Ausable Bayfield Conservation Authority (ABCA). The longest watercourse is Gully Creek. A significant portion of the watershed is forested, especially along the west side of Orchard Line, on the south limits of the watershed, and along Gully Creek, as shown in Figure A.7. Small residential areas are scattered throughout the watershed and the remaining land is used for agricultural purposes, as shown in Figure A.8.

The longest stream, Gully Creek, is 10 km long and flows from its headwaters southeast of Whys Line at a maximum elevation of 280 masl northwestward at a relatively constant grade of 2.8% to its outlet into Lake Huron at an elevation of 176 masl. Clay loam is found in most of the headwater while silt loam is located along the stream corridor, as shown in Figure A.9. The middle of the watershed has the same components as the headwaters and is separated by a distinct north to south deposit of loam soils. The soils in the lower reaches of the watershed are primarily sandy loam and silt loam. There are small areas of clay loam in the lower reaches as well.

3.3.4 Main Bayfield

The Main Bayfield watershed covers 91 km^2 of land from the Lake Huron shore in the community of Bayfield, a village in the Municipality of Bluewater, to the town of Clinton in the Municipality of Central Huron. A significant portion of the watershed is forested along the Bayfield River and its tributaries, especially in the lower reaches of the watershed, as shown in Figure A.10. Several areas of aggregate extraction are located along Trick's Creek, a tributary to Bayfield River, as shown in Figure A.11. Seasonal and permanent residential areas are located in Bayfield, Clinton, and the village of Vanastra in addition to several other small developments in the lower reaches of the watershed. The remaining land is used for agricultural purposes.

The entire length of the Bayfield River is 65 km long; however the Main Bayfield watershed includes only the lower half of the river's entire watershed with 32 km of the Bayfield River. The external watersheds draining into Main Bayfield are the Bayfield Headwaters and Bannockburn. The Bayfield Headwaters watershed includes the Bayfield River and tributaries upstream of the town of Clinton to Dublin in Perth County. The Bannockburn watershed includes the Bannockburn River where it joins the Bayfield River northeast of Varna to the headwaters northwest of the hamlet of Chiselhurst in the Municipality of Huron East.

The Bayfield River extends from the upstream limits of the Main Bayfield watershed in Clinton at a maximum elevation of 313 masl southwest at a relatively constant grade of 0.4% to the outlet into Lake Huron at an elevation of 175 masl. The soils in the town of Clinton are primarily loam and clay loam while the rest of the watershed's headwaters consist of silt loam with small sandy loam deposits, as shown in Figure A.12. The silt loam continues downstream along the river while the watershed soils change to clay loam in the middle to lower watershed with a loam deposit along the areas draining to Tricks Creek. Except for the silt loam found along Bayfield River, the lower watershed soils are primarily loam.

3.3.5 Lambton Shores

The Lambton Shores watershed includes 136 km^2 of land draining to a variety of watercourses and drains that outlet to Lake Huron. The main watercourses include Shashawandah Creek, Duffus Creek, James Creek, and Woods Creek as shown in Figure A.13. The majority of the watershed is located within the Municipality of Lambton Shores and includes small areas within the municipalities of Warwick and Plympton-Wyoming. The upper reaches of the Lambton Shores watershed (80% of the drainage basin) are primarily used for agricultural purposes with scattered woodlands and a portion of the residential community of Forest, Ontario, as shown in Figure A.14. The lower reaches of the watershed along the Lake Huron Shoreline (20% of the drainage basin) consist of forested and residential areas, including the territory of the Chippewas of Kettle & Stony Point First Nation, Cedar Point, Lake Valley Grove, and Ipperwash Beach. The 2013 report card for the watershed (St. Clair Region Conservation Authority 2013) described that the Ontario Ministry of Natural Resources and Forestry (MNRF) identified 141 ha (1% of the watershed) as wetlands. Land use mapping show these wetlands to primarily be located along the shore of Lake Huron.

The watershed is primarily composed of clay loam with deposits of silt and sand loams, as shown in Figure A.15. Silt and clay loams, loams, and clay soils are predominant in the north section of the watershed and along the northeast lakeshore. The longest watercourse in the watershed, the Shashawandah Creek flows from its headwaters northeast of Townsend Line and Northville Road at a maximum elevation of 239 masl to the northwest towards Lake Huron. The creek has a relatively constant grade of 0.5% to its outlet into Lake Huron at an elevation of 175 masl.

4 DESCRIPTION OF MODEL PLATFORM

The first step in the RSWMM project involved the determination of the platform upon which to build the model. A comprehensive review process was undertaken to compare and contrast the existing capabilities of a suite of hydrologic, hydraulic and water quality modelling software, and to attempt to gauge the ease with which modifications and enhancements could be made to the software. This section first provides a brief overview of this review process before defining and clarifying terminology related to the platform that was chosen.

4.1 Model Comparison

The motivation behind the RSWMM project was that, essentially, there was not already a model in existence that satisfied all of the objectives enumerated in Section 3.1. The capabilities of three well-known models (SWMM, HSPF, and SWAT) were compared against these objectives, as summarized in Table 4 – this list is not comprehensive, but review of other model platforms (including agricultural models developed for Ontario) was conducted as part of the project proposal process. While no model satisfied all of the requirements, SWMM was chosen as the best candidate for RSWMM given that its limitations were considered reconcilable (e.g. erosion, seasonal parameters, drain tile flows), and its strengths were related to some of the more complex of the computational requirements (e.g. backwater and reverse flow modelling, hydraulic structures, detailed hydrology/runoff generation). Of particular importance was the fact that SWMM's hydraulic modelling capabilities allow it to be used for both continuous (i.e. multi-month or multi-year) and event-based simulations.

Table 4: Comparison table of selected model platforms.

Objective	Model Platform		
	SWMM	HSPF	SWAT
Urban & ag. BMPs?	No	No	No
Network hydraulics?	Yes	No	No
Seasonality in parameters?	No	Yes	Yes
Drain-tile hydraulics?	No	No	Yes
Erosion from ag. fields?	No	Yes	Yes
In-stream P & N processing?	No	Yes	Yes
Snowmelt & spring runoff?	Yes	Yes	Yes
Backwater & reverse flows?	Yes	No	No
Single event & continuous simulation?	Yes	No*	No**
Easy to use & update?	Yes	No	Yes
Low learning time & technical support?	Yes	No	No

*No support for sub-hourly rainfall distribution or infiltration modelling

**No support for sub-daily rainfall distribution or infiltration modelling

4.2 Description of SWMM

The Storm Water Management Model (SWMM) was developed by the United States Environmental Protection Agency (USEPA) and has undergone significant periodic upgrades since its original release in 1971 – most recently to SWMM5, which was released in 2005. SWMM is a dynamic hydrology-hydraulics-water quality simulation model, which can be used for both single event and long-term (continuous) simulations. A detailed history and description of SWMM5 can be found in James, et al. (2010), available for distribution at no cost online at http://www.chiwater.com/Publications/Books/r242.asp.

The latest version (SWMM 5.1) was released near the completion of the RSWMM project in early 2014, and brought several enhancements to the SWMM5 engine. Notable among these was a separate yet parallel effort to the "Dual-flow Groundwater" functionality that was originally developed as part of the RSWMM project to facilitate the simulation of drain-tile hydraulics. The "Custom Groundwater Equation" of SWMM 5.1 has since been adapted to the RSWMM models and is set up to simulate drain-tile hydraulics. More information about the groundwater routines in RSWMM can be found in Section 5.6.

The USEPA has released SWMM5 with a graphical user interface (GUI) commonly referred to as EPA SWMM, but several third-party GUIs have also been developed to augment SWMM's functionalities in a myriad of ways. The platform chosen for the RSWMM project is PCSWMM, and is described in Section 4.3.

4.3 Description of PCSWMM

First released in 1984, PCSWMM is a spatial decision-support tool for EPA SWMM that was built upon a GIS engine, making it a powerful interface for developing models using GIS-based input data. PCSWMM provides all the hydrologic-hydraulic-water quality computational capabilities of SWMM5 while providing a large number of additional tools for easier model development, parameterization, calibration, results inference and scenario analysis. In addition to supporting the US EPA SWMM5 engine, PCSWMM has developed a new SWMM5 engine with RSWMM modifications (as a result of this project). The new engine supports all the US EPA SWMM computations with additional computer code to allow seasonal variability of some subcatchment hydrological parameters. A detailed history and description of PCSWMM can be found in James, et al. (2010), available for distribution at no cost online at http://www.chiwater.com/Publications/Books/r242.asp.

4.4 Description of RSWMM

The term *RSWMM* refers specifically to the models that have been developed and presented in this report, and to future efforts that may be undertaken to expand the extent of these models within the jurisdictions of the ABCA, MVCA, SCRCA, and SVCA, while *SWMM* and *PCSWMM* refer to the underlying model engine and platform upon which the RSWMMs were developed, respectively.

While the enhancements to PCSWMM that were made during this project will be available to users of the software, the specific parameterization, treatment expressions, groundwater equations, etc. developed for the RSWMMs apply solely to those models developed for the 5 sentinel watersheds.

5 SOFTWARE MODIFICATIONS & ENHANCEMENTS

The following modifications were made to PCSWMM and the SWMM5 engine with RSWMM modifications (engine SWMM5.1.901) to meet all of the project requirements by better representing rural stormwater runoff and the application of various best management practices (BMPs) in an agricultural setting:

- Enhancements to PCSWMM:
    - Improved Restructure Layer Window
    - Improved Replace Tool
    - Addition of an Auto-expressions Editor
- Incorporation of RSWMM capabilities:
    - Ability to model agricultural BMPs
    - Ability to model soil erosion using MUSLE
    - Ability to model in-stream treatment processes
- Modifications to SWMM5:
    - Ability to vary parameters seasonally
    - Ability to model tile drainage (dual groundwater equation)[1]

While some of these modifications (such as the in-stream treatment processes) were applied using capabilities previously available in SWMM5, enhancements to PCSWMM significantly improved the usability and customizability of these capabilities. Other modifications (such as the ability to model agricultural BMPs) would have been essentially impossible without the PCSWMM enhancements and/or SWMM5 modifications. These enhancements – namely the Restructure Layer window, the Replace tool, and the Auto-Expressions Editor – are discussed in detail in Section 5.1.

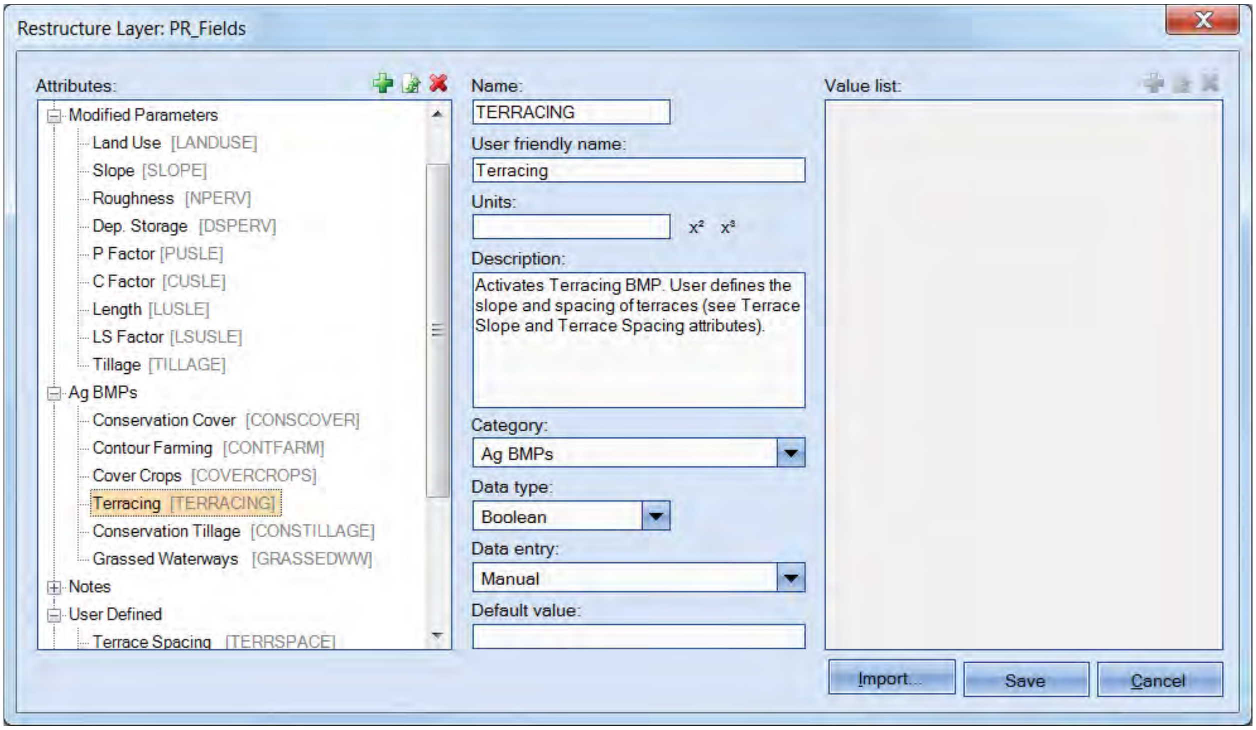
5.1 Enhancements to PCSWMM

5.1.1 Restructure Layer Window

The Restructure Layer Window provides the user with the ability to restructure both SWMM layers (such as the Subcatchments) and other GIS vector layers that are opened in PCSWMM, including adding and removing attributes, defining units and user-friendly names, and assigning auto-expressions (see Section 5.1.3). The conception of this tool enabled the development of the Fields layer, discussed in Section 5.2.1, but can be used for a variety of other purposes. The Restructure Layer window will appear by clicking Alter > Restructure button on the Map toolbar (or right clicking any layer and selecting Restructure), as shown in Figure 2.

---

[1] After the release of the SWMM 5.1 engine in 2014, the tile drainage groundwater equation was able to be incorporated using the newly-added "Custom Groundwater Equation", making the dual groundwater changes to the SWMM 5.0 engine obsolete reticent.


Restructure Layer: PR_Fields

Attributes:

- Modified Parameters
  - Land Use [LANDUSE]
  - Slope [SLOPE]
  - Roughness [NPERV]
  - Dep. Storage [DSPERV]
  - P Factor [PUSLE]
  - C Factor [CUSLE]
  - Length [LUSLE]
  - LS Factor [LSUSLE]
  - Tillage [TILLAGE]
- Ag BMPs
  - Conservation Cover [CONSCOVER]
  - Contour Farming [CONTFARM]
  - Cover Crops [COVERCROPS]
  - Terracing [TERRACING]
  - Conservation Tillage [CONSTILLAGE]
  - Grassed Waterways [GRASSEDWW]
- Notes
- User Defined
  - Terrace Spacing [TERRSPACE]

Name: TERRACING

User friendly name: Terracing

Units:

Description: Activates Terracing BMP. User defines the slope and spacing of terraces (see Terrace Slope and Terrace Spacing attributes).

Category: Ag BMPs

Data type: Boolean

Data entry: Manual

Default value:

Value list:

Figure 2: Restructure Layer Window

The Restructure tool has been expanded to add attributes, assign user friendly names, units etc. Attributes can also be placed under different categories. Categories can be ordered to change how they are shown in the attributes panel. There is an option to create a drop-down list to pre-define what values any attribute can take.

The Fields layer in each RSWMM model includes an Agricultural BMP category including the Avoid and Control BMPs. For these attributes, a drop down list of “yes” and “no” are assigned, “yes” indicating that particular BMP is implemented in the agricultural field selected. The Fields layer can be initialized by selecting all the polygons and assigning “no” to all the BMPs. In addition to the Agricultural BMPs, other attributes can be created under Base Hydrology category and Derived Hydrology category. Candidate attributes for these categories are infiltration parameters, subcatchments slope and roughness and depression storage for pervious areas. Base hydrology attributes can be populated using other background layers such as soils or land cover to represent hydrological conditions available without the BMPs. Base hydrology attributes are optional and they can be used if the derived hydrologic attribute values are computed as a factor of base values.

The expanded Replace tool can be used to compute derived hydrology attributes based on the BMPs implemented in each land parcel. This is done by using mathematical expressions. This allows different hydrological parameters in the model to vary based on the BMPs, so actual physical processes are simulated for implemented BMPs.

5.1.2 Replace Tool

The Replace tool provides the user with the ability to replace attribute values for a SWMM layer or GIS vector layer based on a variety of mathematical and conditional criteria.. Modifications to the tool were prompted in part by the need to provide more flexibility in assigning attribute values based on attributes in other associated layers, primarily for the purposes of implementing in-stream treatment processes (Section 5.4) and agricultural BMPs (Section 5.2). The Replace tool has been improved to undertake many additional mathematical, conditional, and string operations, as listed in Section 5.1.3. The tool is located in the menu bar at the top of the Attributes panel (Figure 3).

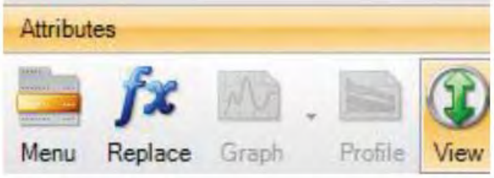
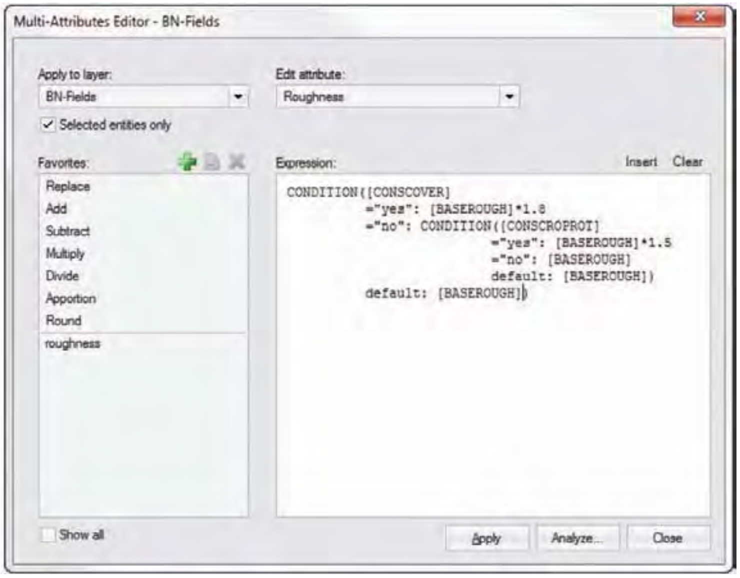


Figure 3: Replace Tool

The Replace tool appearance has been changed as shown in Figure 4 to enter any expression and also allowing users to save commonly used expressions. This tool is similar to the auto-expression editor, but its utility is different in two primary ways:

1. Replace operations are manual, so attributes are not automatically updated
2. The Layer Lookup function (LLOOKUP) can be used only within the Replace tool, as this function is able to reference attributes in layers other than the layer being edited



Apply to layer: BN-Fields

Edit attribute: Roughness

☑ Selected entities only

Expression:

```
CONDITION([CONSCOVER]
          ="yes": [BASEROUGH]*1.8
          ="no": CONDITION([CONSCROPROT]
                          ="yes": [BASEROUGH]*1.5
                          ="no": [BASEROUGH]
                          default: [BASEROUGH])
          default: [BASEROUGH])
```

Figure 4: New Replace Tool Editor

While the Auto-expression editor is useful for expressing dynamic parameters in the model (e.g. attributes that are modified by implementing agricultural BMPs, as discussed in Section 5.2), the Replace tool's utility is primarily for one-time operations such as the adjustment of otherwise static parameters (for example, assigning the average upstream conduit length to a user-defined attribute in the junctions layer).

5.1.3 Auto-Expression Editor

The Auto-expression Editor is another improvement to PCSWMM introduced as a part of the RSWMM project. Its inclusion was prompted primarily by the need to dynamically modify attributes associated with agricultural BMPs. The editor allows mathematical expressions to be entered for SWMM5 parameters that can be based on other SWMM5 parameters or user defined attributes.

Candidate attributes for auto-expression include infiltration parameters, subcatchments slope and roughness, depression storage for pervious areas and MUSLE parameters. Auto-expressions in PCSWMM are flexible to account for any type of mathematical relationship to compute model parameters based on other available attribute values, including any base values. Base hydrology attributes are optional and can be used if the derived hydrologic attribute values are computed as a factor of base values. These base hydrology attributes can be populated using other background layers such as soils or land cover to represent hydrological conditions available without the BMPs. Additionally, auto expressions can be used for other SWMM5 parameters; for example, conduit roughness could be varied based on material and age.

In the Fields layer in the RSWMMs (Section 5.2.1), auto-expressions are used to modify SWMM5 parameters associated with agricultural BMPs. This allows for the varying of different hydrological parameters in the model based on the BMPs, so actual physical processes are simulated for implemented BMPs. Another advantage is that by simply changing the Ag BMPs that are implemented, it is possible to change any affected SWMM5 parameter (both water quantity and quality) automatically. In this way, evaluation of different scenarios is made easier by the auto-expressions.

Since treatment expressions are recognized as strings by the SWMM5 engine, auto-expressions can also be used to generate these expressions using user-defined attributes. This facilitates the implementation of flexible and adaptable treatment expressions that are individualized for junctions, outfalls, and storages – a feature not previously available in SWMM5.

Various functions have been included in the auto-expression editor to make it as flexible as possible. These include the following:

Mathematical operations: +, -, *, /, COS, SIN, TAN, COT, ABS, SIGN, SQRT, LN, EXP, ASIN, ACOS, ATAN, ACOT, SINH, COSH, TANH, COTH, LOG10, ^, ROUND

Conditional expressions:
IF(condition, first expression, second expression)
STEP(x<=0 ? 0 : 1)
CONDITION([Attribute]
    = value1: Expression1
    = value2: Expression2
    ………
    default: value n)

String Operations:
REPLACE(text, old value, new value)
LEFT(text, number of characters)
RIGHT(text, number of characters)
SUBSTRING(text, zero based starting character position, number of characters)

5.2 Agricultural BMPs

Current BMPs commonly used in SWMM5 are urban-centric. Revisions were made to PCSWMM to allow the user to easily apply the following ten Agricultural BMPs for pollutant removal:

- Avoid practices:
    - Conservation cover
    - Contour farming
    - Cover crops
- Control practices:
    - Conservation tillage
    - Grassed waterways
    - Terracing
- Trap practices:
    - Wet and dry ponds
    - Water and sediment control basins (WASCOB)
    - Wetlands
    - Woodchip bioreactors

Among a myriad of other sources, detailed descriptions of each BMP can be found in the Agricultural BMP Handbook for Minnesota (Miller et al. 2012), available for distribution at no cost online at http://www.eorinc.com/documents/AG-BMPHandbookforMN_09_2012.pdf. The handbook is a literature review of empirical research on the effectiveness of 30 conservation practices and so could also be used to expand on the ten practices used in this project. Users can easily change the Avoid and Control BMPs applied on specific farms by using the new Fields layer and editing tools added to PCSWMM. The trap BMPs can be explicitly modeled using storage nodes, control structures, flow dividers, and treatment expression capabilities already available in SWMM5. The following subsections discuss the new Fields layer, BMP mechanisms, BMP pollutant removal efficiencies, and process for adding BMPs.

Other BMPs were also considered for inclusion in the model, and it should be noted that these BMPs merely represent the first iteration of RSWMM. A more detailed discussion of potential future modifications to include additional BMPs can be found in Section 9.2.

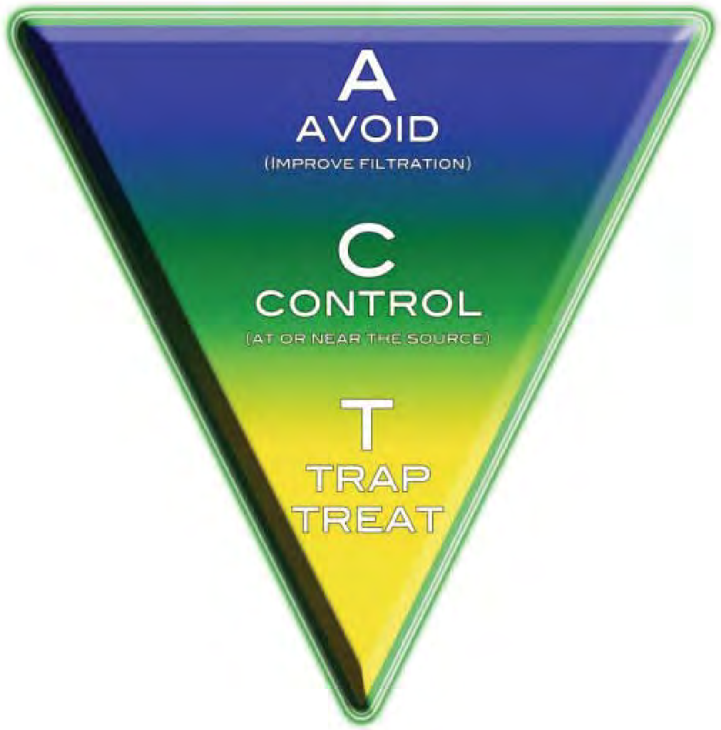


Figure 5: Image adapted from Tomer et al. (2013)

5.2.1 Fields Layer

To facilitate the application of agricultural BMPs on a field scale (as opposed to a subcatchment scale), the land-use shape files for each watershed were used to create a Fields layer. Similar to the other SWMM layers (e.g. the Subcatchments layer), the Fields layer contains a list of attributes that are defined for each field polygon, including attributes used to activate and deactivate agricultural BMPs. The Fields layer is different from the SWMM layers, however, in that it is not used directly by the SWMM5 engine; rather, attributes are passed back and forth between the Fields layer and the Subcatchments layer using area-weighting operations (see Section 6.3). The general process of creating and using a Fields layer involves the following:

1. Create a Fields shape file as a background layer, discretized as required.
2. Restructure the Fields layer to include attributes for Agricultural BMPs, base hydrological parameters, derived hydrological parameters.
3. Each polygon can be assigned one or more Agricultural BMPs.
4. Populate base hydrological attributes in the Fields layer using other background layers (and/or SWMM model).
5. Populate the existing or what-if scenario Agricultural BMPs in the Fields layer.
6. Compute derived hydrological attributes using mathematical expressions (using Replace/Expression tool) based on the Agricultural BMP and base hydrologic parameters. One expression must be developed and saved for each derived hydrological attribute (e.g. 6 expressions for the 6 subcatchment attributes)
7. Finally, the SWMM subcatchment layer's hydrological parameters can be estimated from the Fields layer using PCSWMM's existing area weighting tools.

There are several modifications implemented in PCSWMM to accommodate this process. Restructuring layer attributes were expanded, the Replace tool was revised, and the Auto-expression Editor was added, as discussed in Section 5.1.

5.2.2 Pollutant Reduction Mechanisms

The treatment mechanisms are summarized below and reduction values, based on the state-of-the-science, are shown in Table 5.

For practical purposes within the RSWMMs, BMPs can be divided into two categories: hydrology-based BMPs – which incorporate both Avoid and Control practices and are implemented using the Fields layer – and hydraulic-based BMPs – which incorporate Trap practices and are modeled explicitly. The overall mechanisms vary between the BMP categories as follows:

- *Hydrology-based BMPs modify hydrologic and MUSLE parameters, and land-use*
    - Conservation Cover – Lowers erosion with permanent vegetation and reduces nutrient applications
    - Contour Farming – Lowers erosion by directing flow across the slope
    - Cover Crops – Lower erosion with temporary vegetation and reduces nutrient leaching
    - Conservation Tillage – Lowers erosion by retaining residue/vegetation
    - Terracing – Lowers erosion with reduced slope length
    - Grassed Waterways[2] – Lower soil erosion with permanent vegetated conveyance

- *Hydraulic-based BMPs utilize existing treatment expressions and SWMM elements*
    - Wet and dry ponds – Pollutant removal through settling
    - Water and sediment control basins (WASCOB) - Pollutant removal through settling; reduce peak discharges
    - Wetlands – Pollutant removal through settling and biological uptake
    - Woodchip bioreactors – Denitrification by bacteria

Hydrology-based BMPs

When a BMP is implemented in the Fields layer, the parameters indicated in Table 5 are modified accordingly. Each parameter is treated differently, and so the relative change in a given parameter was determined from a variety of sources. For the MUSLE C- and P-Factors, values were derived explicitly from RUSLE and USLE documentation (Renard et al. 1997; Wall et al. 1997; Stone and Hilborn 2012). While guidance for the modification of some of the hydrologic parameters also came from these sources, the relative change in these parameters was ultimately determined empirically using a field-scale model calibrated to achieve the median pollutant reduction percentage found in the literature (see Table 5). The auto-expression developed for each parameter can be found in Appendix B.2.

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[2] Depending on the scale of grassed conveyances with respect to the agricultural field, these may be explicitly modeled in the conduit layer with increased channel roughness.

Hydraulic-based BMPs

Since SWMM5 already included the ability to apply custom treatment expressions and supports a variety of hydraulic elements, no further modifications were required to facilitate the implementation of hydraulic-based BMPs. Within the RSWMM modifications, three hydraulic BMPs are included with predefined treatment expressions: Sedimentation Ponds, Designed Treatment Wetlands, and Denitrifying Woodchip Bioreactors. These devices all utilize first-order kinetics to provide treatment. When a BMP is chosen, treatment expressions specific to each BMP are auto-expressed and user-defined attributes (including the reaction rate constants) are available for alteration.

Treatment expressions in SWMM can take one of two forms by specifying either the removal rate or the effluent concentration:

$$C_f = C_i * e^{-kt}$$
$$R = 1 - e^{-kt}$$

where C_f is the effluent concentration, C_i is the influent concentration, k is the reaction rate constant, t is time, and R is the fractional removal rate. Functionally, these two forms are equivalent, but it is sometimes convenient to use one form over the other. This is particularly true if the removal rate of one pollutant is dependent upon the concentration of another.

Reaction equations and rate constants used for wetlands are taken from the work of Kadlec and Knight (1995). In these devices it is assumed that both nitrification and denitrification are occurring, and conversion of nitrite to nitrate is assumed to be complete. Treatment expressions for TKN, NO_3, and NO_2, were developed as:

$$C_{TKN_f} = C_{TKN_i} * \alpha * e^{-k_{nitrification} * HRT}$$
$$C_{NO_{3_f}} = (C_{NO_{3_i}} + C_{NO_{2_i}} + C_{TKN_i} * R_{TKN}) * e^{-k_{denitrification} * HRT}$$
$$R_{NO_2} = 1$$

where α is the fraction of TKN assumed to be in the ammonia nitrogen pool, $k_{nitrification}$ and $k_{denitrification}$ are the reaction rates for nitrification and denitrification in a constructed wetland, respectively, and HRT is the hydraulic residence time of the storage node.

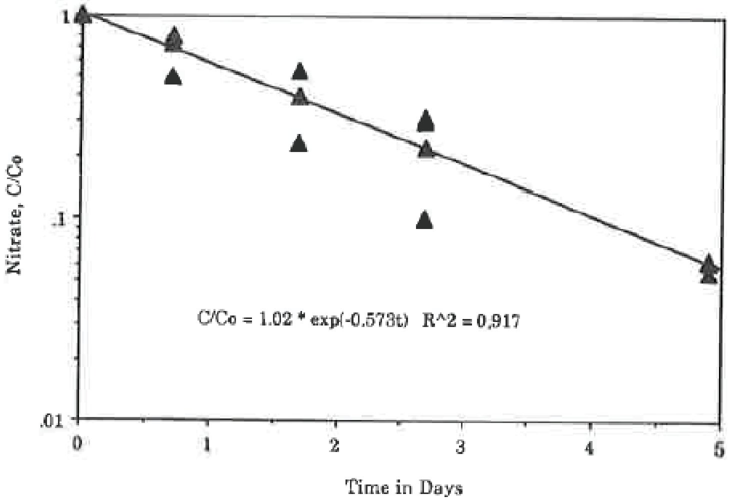

Figure 6: Batch nitrate reduction in cattail mesocosms (from Kadlec and Knight (1995), p. 406).

Reaction equations and rate constants used for woodchip bioreactors are taken from the work of Lucas (2010) and Masi (2011). In contrast to the urban bioreactors modeled by Masi, it is assumed that only denitrification is occurring in these devices since the design of bioreactors used in the agricultural setting is typically not optimized for nitrification. Conversion of nitrite to nitrate is assumed to be complete. Treatment expressions for NO_3 and NO_2 were developed as:

$$C_{NO_{3_f}} = (C_{NO_{3_i}} + C_{NO_{2_i}}) * e^{-k_{denitrification} * HRT}$$
$$R_{NO_2} = 1$$

where $k_{denitrification}$ is the reaction rate for denitrification in a woodchip bioreactor.

Since in-stream processing of certain pollutants is also being simulated at all nodes (including storage nodes) for the upstream conduits, the BMP treatment expressions had to be combined with the in-stream treatment expressions discussed in Section 5.3.2. Effectively, the influent concentrations in the expressions above had to be replaced by the effluent concentration form of the in-stream treatment expressions. The resulting expressions can be found in the Appendix B.2.

Settling of sediment is assumed to occur in both pond and wetland devices. Consistent with the SWMM Applications Manual (Gironás et al. 2009), the first order treatment expressions for sediment are based on settling rate, depth at the node, and model time step. The settling rate for each component of the suspended sediment is based on the median particle size within the range of sand, silt and clay, as described in the Wentworth Scale, and as derived by Stokes' law for frictional force. Treatment expressions for sediment were developed as:

$$C_{p_f} = C_{p_i} * e^{-k_p * DEPTH * DT}$$

where p is the particle component (sand, silt, or clay), DEPTH is the depth of water in the storage node, and DT is the length of the time step. The Auto-expressions used to derive the treatment expressions can be found in Appendix B.2.

Table 5: Reduction of Pollutants by Agricultural BMPs[3].

	Agricultural BMP	Average Annual Reduction (%)			Treatment Mechanisms					
		TSS	TP	TN	C-factor	P-factor	NPERV	DSTOR PERV	SLOPE	LENGTH
AVOID	Conservation Cover	90	75[2]	85[2]	X		X	X		
	Contour Farming	59[8]	30[10]	20[10]		X		X	X	X
	Cover Crops	83[7]	29[2]	52[3]	X					
CONTROL	Conservation Tillage	63[5]	70[3]	62[3]	X		X	X		
	Terracing	75[1]	77[2]	38		X		X	X	
	Grassed Waterways	36[3]	13[6]	6[3]		X	X			
TRAP	Sediment Basin	84[4]	50[4]	30[4]	Explicitly Modeled Dimensions/Outlet(s) Configuration Particle Settling Expressions					
	Water and Sediment Control Basin	20[9]	10[9]	15[9]						
	Wetlands	75[0]	43[3]	68[2]						
	Woodchip Bioreactors	N/A	N/A	43[2]	Storage Device or Node with Treatment Expression					

[0] (Miller et al. 2012)
[1] (Hanway and Laflen 1974)
[2] (*Iowa Nutrient Reduction Strategy* 2013)
[3] (Houston Engineering 2013)
[4] (Minnesota Stormwater Steering Committee 2005)
[5] (*Conservation Tillage Systems and Management* 2000)
[6] (Almendinger 2012)
[7] (Sharpley et al. 1991)
[8] (Van Doren, Stauffer, and Kidder 1951)
[9] (Yang et al. 2013)
[10] (Delvin et al. 2003)

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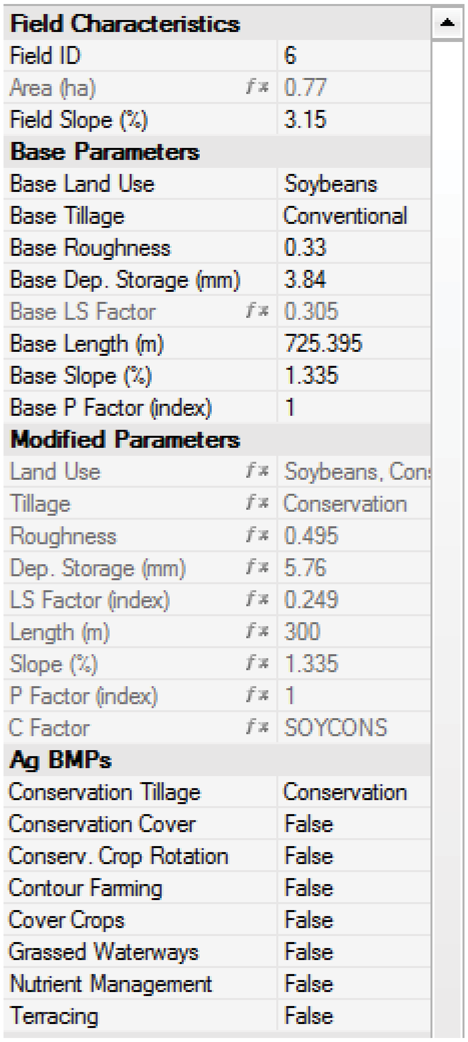
[3] The values in this table represent the median values of the range of reductions reported in the literature. All BMPs are able to be updated to effectively increase or decrease the removal rates.

5.2.3 Adding BMPs to Models

Hydrology-based BMPs

Hydrology-based Agricultural BMPs can be added to the model in the Fields layer attribute editor by selecting the active BMPs in the “Ag BMP” Boolean attribute category. Changing these attributes will activate the auto-expressions that calculate the Modified Parameters within the Fields layer attributes. The revised properties can then be passed to the subcatchment layer using the Area Weighting tool. For example, the impact of Conservation Tillage on parameters such as roughness and depressional storage can be seen by comparing the Base Parameters to the Modified Parameters[4] in Figure 7, which shows a portion of the attributes lists for a particular field. All BMPs can be activated either by using the drop-down menus in the Attributes list (as shown in) or the check-boxes in the Table window (as shown in Figure 8).



Field Characteristics	
Field ID	6
Area (ha)	0.77
Field Slope (%)	3.15
Base Parameters	
Base Land Use	Soybeans
Base Tillage	Conventional
Base Roughness	0.33
Base Dep. Storage (mm)	3.84
Base LS Factor	0.305
Base Length (m)	725.395
Base Slope (%)	1.335
Base P Factor (index)	1
Modified Parameters	
Land Use	Soybeans, Con
Tillage	Conservation
Roughness	0.495
Dep. Storage (mm)	5.76
LS Factor (index)	0.249
Length (m)	300
Slope (%)	1.335
P Factor (index)	1
C Factor	SOYCONS
Ag BMPs	
Conservation Tillage	Conservation
Conservation Cover	False
Conserv. Crop Rotation	False
Contour Farming	False
Cover Crops	False
Grassed Waterways	False
Nutrient Management	False
Terracing	False

Figure 7: Screenshot Illustrating the Implementation of Conservation Tillage on a Soybean Field

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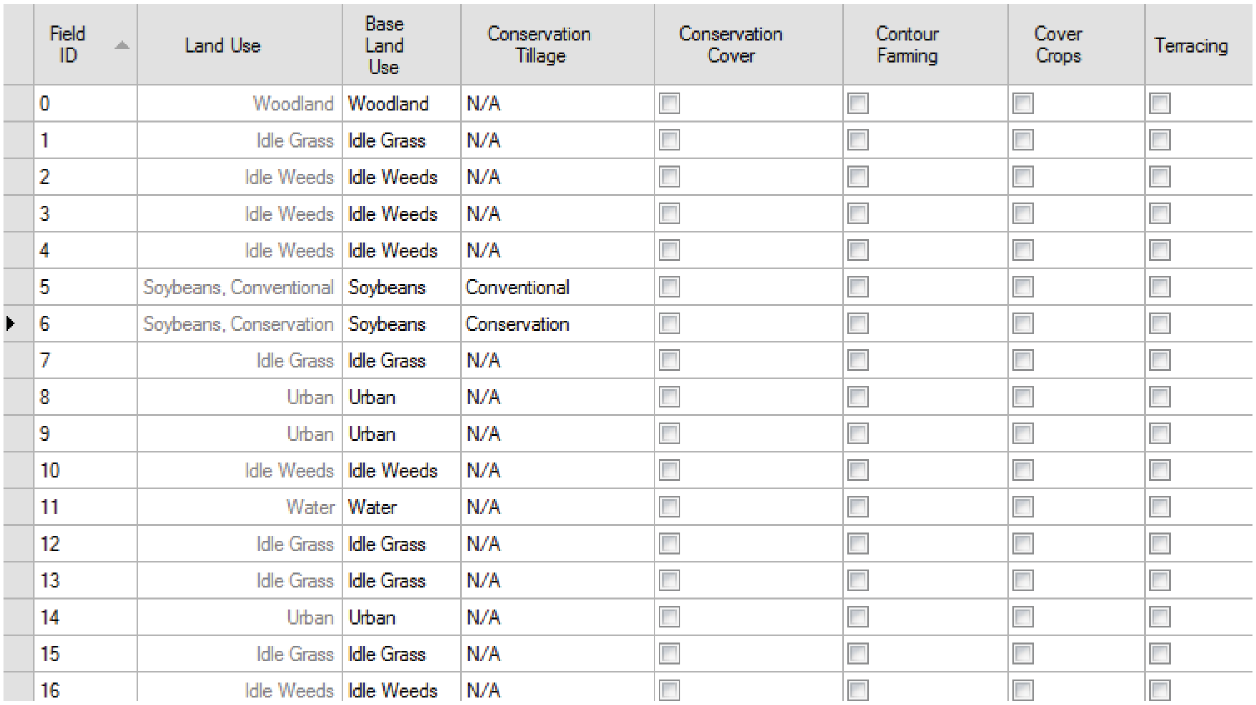
[4] The changes shown for Length and the LS Factor in figure 19 are due not to conservation tillage, but instead to an upper limit for the Length value of 300 m which is used for MUSLE parameterization.



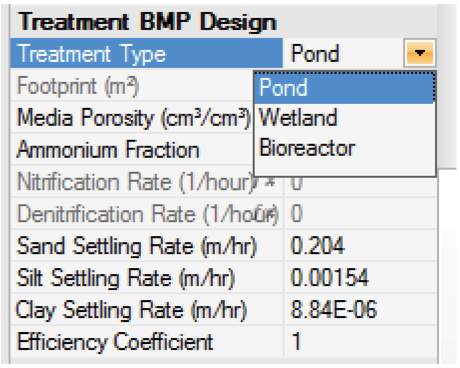
	Field ID	Land Use	Base Land Use	Conservation Tillage	Conservation Cover	Contour Farming	Cover Crops	Terracing
	0	Woodland	Woodland	N/A	☐	☐	☐	☐
	1	Idle Grass	Idle Grass	N/A	☐	☐	☐	☐
	2	Idle Weeds	Idle Weeds	N/A	☐	☐	☐	☐
	3	Idle Weeds	Idle Weeds	N/A	☐	☐	☐	☐
	4	Idle Weeds	Idle Weeds	N/A	☐	☐	☐	☐
	5	Soybeans, Conventional	Soybeans	Conventional	☐	☐	☐	☐
▶	6	Soybeans, Conservation	Soybeans	Conservation	☐	☐	☐	☐
	7	Idle Grass	Idle Grass	N/A	☐	☐	☐	☐
	8	Urban	Urban	N/A	☐	☐	☐	☐
	9	Urban	Urban	N/A	☐	☐	☐	☐
	10	Idle Weeds	Idle Weeds	N/A	☐	☐	☐	☐
	11	Water	Water	N/A	☐	☐	☐	☐
	12	Idle Grass	Idle Grass	N/A	☐	☐	☐	☐
	13	Idle Grass	Idle Grass	N/A	☐	☐	☐	☐
	14	Urban	Urban	N/A	☐	☐	☐	☐
	15	Idle Grass	Idle Grass	N/A	☐	☐	☐	☐
	16	Idle Weeds	Idle Weeds	N/A	☐	☐	☐	☐

Figure 8: Screenshot of a Portion of the Table Window for a Field Layer

Note: Check boxes used to turn a given BMP on or off – with the exception of Conservation Tillage, which is activated via a drop-down menu.

Hydraulic-based BMPs

Hydraulic-based BMPs are implemented by adding a Storage element and choosing between the three options in the Treatment BMP dropdown menu located in the Attribute list for the Storage element, as shown in Figure 9. These BMPs can most easily be applied at the outlet of a subcatchment by using a flow diversion structure to direct a portion of the outflow to the treatment device. In this way, the implementation of hydraulic-based BMPs need not necessitate the modification of the hydrology by re-delineating subcatchments – although this approach can also be taken, and may be required in situations where multiple BMPs are located within the same subcatchment.



Treatment BMP Design

Treatment Type	Pond
Footprint (m²)	
Media Porosity (cm³/cm³)	
Ammonium Fraction	
Nitrification Rate (1/hour)	0
Denitrification Rate (1/hour)	0
Sand Settling Rate (m/hr)	0.204
Silt Settling Rate (m/hr)	0.00154
Clay Settling Rate (m/hr)	8.84E-06
Efficiency Coefficient	1

Figure 9: Screenshot of the Treatment BMP Design Category in the Storage Attribute List

Figure 10 illustrates an example of how three Water and Sediment Control Basins (WASCOB) were modeled in the Bayfield North watershed. These BMPs were set up using a storage node (modeled as a Sedimentation Pond), an orifice connected to a tile network, and an overflow channel. Since these WASCOBs were all located within the same subcatchment, re-delineation of the hydrologic boundaries was required, as can be observed in Figure 10. Re-delineation to the WASCOBs was performed manually in PCSWMM using contour lines generated from the DEM.

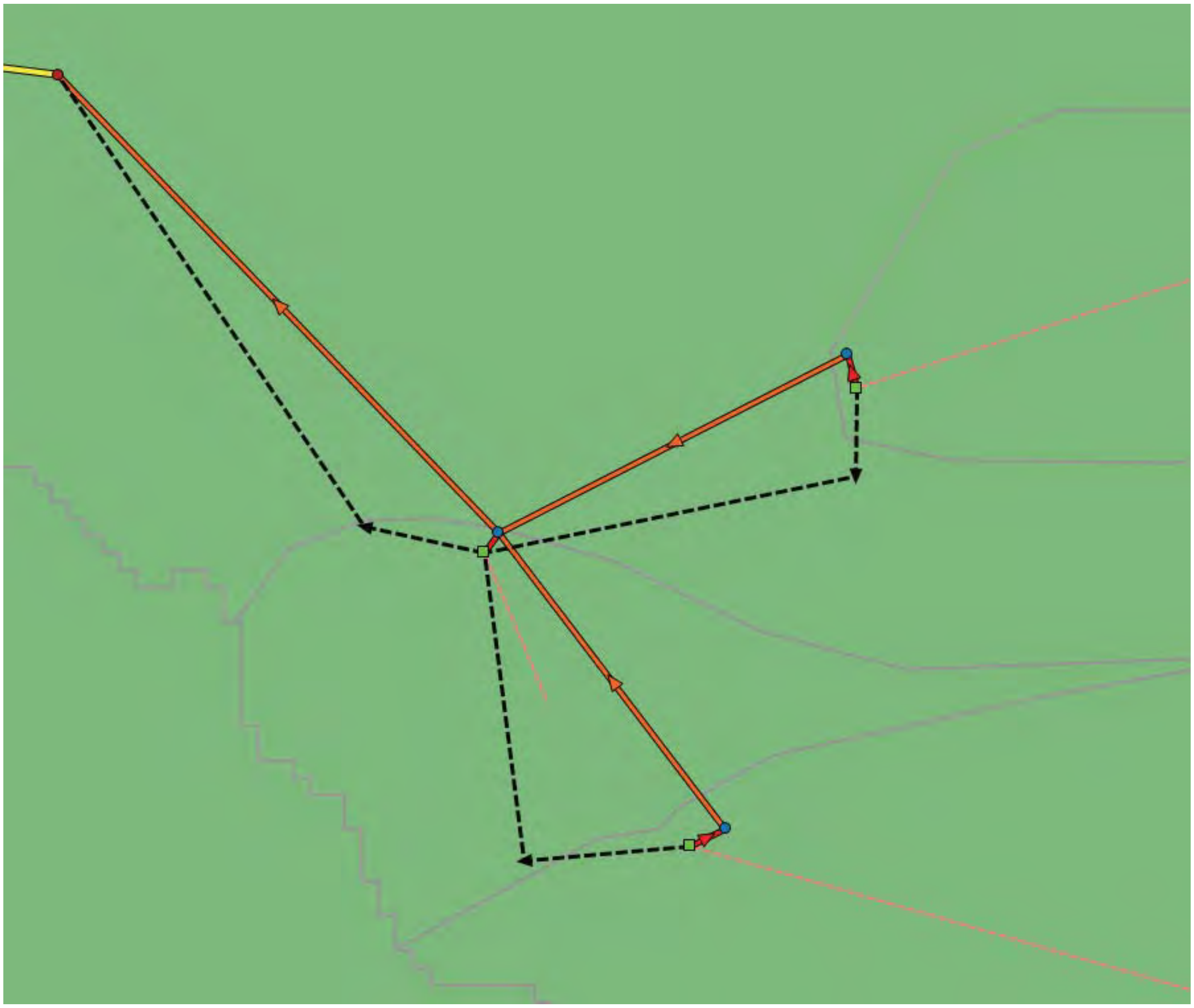


Figure 10: WASCOBs in the Bayfield North watershed.

Note: Shown are the storage nodes (green), junctions (blue), orifices (red), tiles (orange), and overflow channels (dotted black).

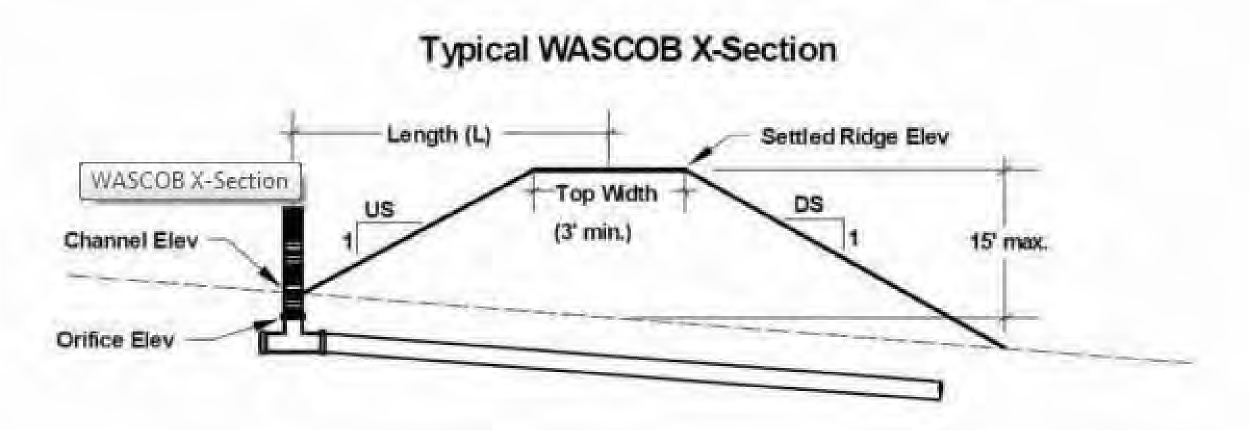


Figure 11: Cross-section of a typical WASCOB design. Source: Younker (2011).

In considering the design of a BMP, it remains necessary for the user to appropriately size the device. While no routines are currently in place for optimization, the RSWMMs developed for the 5 sentinel watersheds are a useful tool in optimizing a design. Building existing devices into the model will require knowledge of the contributing area to each device, as well as an understanding of how SWMM components can be utilized to represent them.

5.3 Soil Erosion using MUSLE

Soil erosion due to overland flow is an important aspect in stormwater/water quality management, especially in agricultural areas. Sediment and sediment-bound pollutants are often associated with soil erosion from agricultural fields, and many agricultural best management practices are aimed at reducing soil erosion.

The US EPA's older SWMM4 software had a soil erosion routine (USLE), however, when the US EPA SWMM5 program was formulated, this routine was omitted. To rectify this limitation, the modified universal soil loss equation (MUSLE) has been incorporated into PCSWMM. The basis for MUSLE is the universal soil loss equation (USLE), an empirically-based model for estimating annual sediment loading based on data collected from standardized field plots (Wischmeier and Smith 1978). Williams (1975) modified USLE by replacing the rainfall-energy factor with a runoff-energy factor, thereby allowing the model to be applied to individual storm events (Jackson, Gebhardt, and Van Haveren 1986).

The following equation is used to estimate the mass of erosion on a daily basis:

$$\boldsymbol{Sediment\,Yield = 11.8 \times \left(Q_{surf} \times q_{peak} \times Area\right)^{0.56} \times K \times C \times P \times LS \times CFRG}$$

where the parameters are defined in Table 6 and Section 5.3.1.

In PCSWMM, MUSLE computes daily soil loss for each subcatchment based on the subcatchment SWMM5 runoff results. Considering SWMM5 runoff calculations are typically performed at a much smaller time step, these daily erosion estimates are then distributed based on runoff flow rates at the discretization of runoff wet time step. The erosion loadings are entered into the model's hydraulics system as sediment inflows at the subcatchment outlet junctions.

Peak runoff is based on a maximum 30-minute averaged SWMM5 runoff estimate. Other models (such as SWAT) use the rational method to estimate this value. Erosion is calculated on a daily basis, based on runoff from the subcatchment pervious area. Erosion simulations are activated by enabling erosion in the Erosion setup dialog box (under File >> Erosion). PCSWMM runs a SWMM5 hydrologic simulation first, only for pervious areas, to estimate runoff values and then post-processes that data on a daily basis to calculate daily erosion estimates using the MUSLE equation.

This simulation and results are saved in a separate sub-folder named projectname_MUSLE. Once the daily erosion values for each subcatchment are calculated, the loading is distributed throughout the day at the runoff wet time step, based on the following relationship from Haan, Barfield, and Hayes (1994):

$$sediment\ loading_t \propto {q_t}^n$$

where t denotes the time step and n is a user-defined exponent. The exponent n provides flexibility to simulate higher sediment concentrations at larger runoff rates. The user can define the exponent to be used to distribute sediment loading.

The sediment loading time series are added to the subcatchment outlet junctions as a pollutant inflow. The user can define the fraction of each component of the MUSLE-generated sediment (sediment can be partitioned into fractions based on particle size distribution, i.e., 0-20 μm, 20-50 μm, 50 -100 μm etc, which will allow for better settling and treatment estimates). Also, users can assign co-pollutants to the sediment (for example, phosphorus can be generated as a fraction of sediment loading, assigned in different concentrations to each sediment component). These fractions are defined in the attributes for each subcatchment, providing the flexibility to adjust particle size distributions based on soils (e.g. using the PCSWMM area weighting tool with a soils layer).

Table 6: MUSLE Parameters

Parameter	PCSWMM Variable	Unit	Description
Sed. Yield		Tonne/day	Daily sediment yield
Q_{surf}		m^3	Daily runoff volume
q_{peak}		m^3/s	30-minute peak runoff rate
Area		ha	Subcatchment Area
K	KUSLE	$\frac{\text{tonne} \cdot \text{hectare} \cdot \text{hour}}{\text{hectare} \cdot \text{megajoule} \cdot \text{millimeter}}$	Soil Erodibility Factor
C	CUSLE	Unitless	Cover and Management Factor
P	PUSLE	Unitless	Support Practice Factor
LS	LSUSLE	Unitless	Topographic Factor
CFRG	CFAG	Unitless	Coarse Fragment Factor

5.3.1 Parameterization of MUSLE in PCSWMM

Sediment Yield, Q_{surf}, and q_{peak} - Variable based on results generated by the PCSWMM program through the SWMM engine calculations using Green-Ampt infiltration methodology and the MUSLE equation.

Subcatchment Area – Entered by the user or automatically calculated based on the GIS spatial layer.

Soil Erodibility Factor K – Calculated by area weighing within each subcatchment based on soil texture lookup table of literature values. In the case of Bayfield North, the K-factors have been assigned based on local knowledge of the organic matter content and work by previously performed by OMAFRA (McPherson 2013).

Cover Factor C – Land use and crop GIS data used to derive the C-factors included both crop in the field “windshield” observations and crop system observations over several years. A total of 92 unique land use combinations are coded in the GIS databases for the 5 sentinel watersheds. These land uses have been grouped into 29 categories (including open water) for assigning daily C-factor time series as displayed in Table 7. Fields that are designated as a system, e.g. GRAIN SYSTEM or CORN SYSTEM, are assigned the same C-factor time series as the individual dominant crop for that system. This assumption yields an area weighted subcatchment time series that will best represent the average year of crop type coverage. Representative cover factors can be either variant, where they increase or decrease throughout the year depending on crop stage or management practices, or invariant, remaining static throughout the year. Variant c-factor values, shown in Figure 12, were generated by using RUSLE2 assuming the London, Ontario area climate and typical dates for various management operations. These include tillage, seeding, and harvest operations as they affect residue and cover levels, for which the reference spreadsheets are packaged with each sentinel watershed model. None of the time series, however, consider the previous crop. The geospatial information for all five sentinel watershed areas includes agricultural production areas with non-specific designations such as “FIELD” or “CONTINUOUS ROW CROP”. These areas were assigned the soybean conventional time series which has a moderately high C-factor. Caution must be taken for catchments that have a relatively large area ratio with non-crop specific information which will result in skewing the overall crop ratio to soybean and thus may over estimate sediment yield from the subcatchment.

Invariant land uses and less frequent crops such as nurseries, pasture, fencerows, and ditches were assigned literature values provided in Revised Universal Soil Loss Equation for Applications in Canada (RUSLEFAC) and from USEPA guidance for TMDL USLE in urban areas (References). These individual land category time series are then area weighted for each subcatchment based on the land category attribute contained in the field polygon layer. Therefore, a unique cover factor time series is generated for each subwatershed in the model.

Using Table 7, updated field crop data can be included in the model by categorizing the new polygon information into one of the 29 categories general categories. Alternatively, a new C-factor time series can be assigned and included in the model by importing daily values.

Table 7: RSWMM Sentinel Watershed Land Use C-Factor Categorization

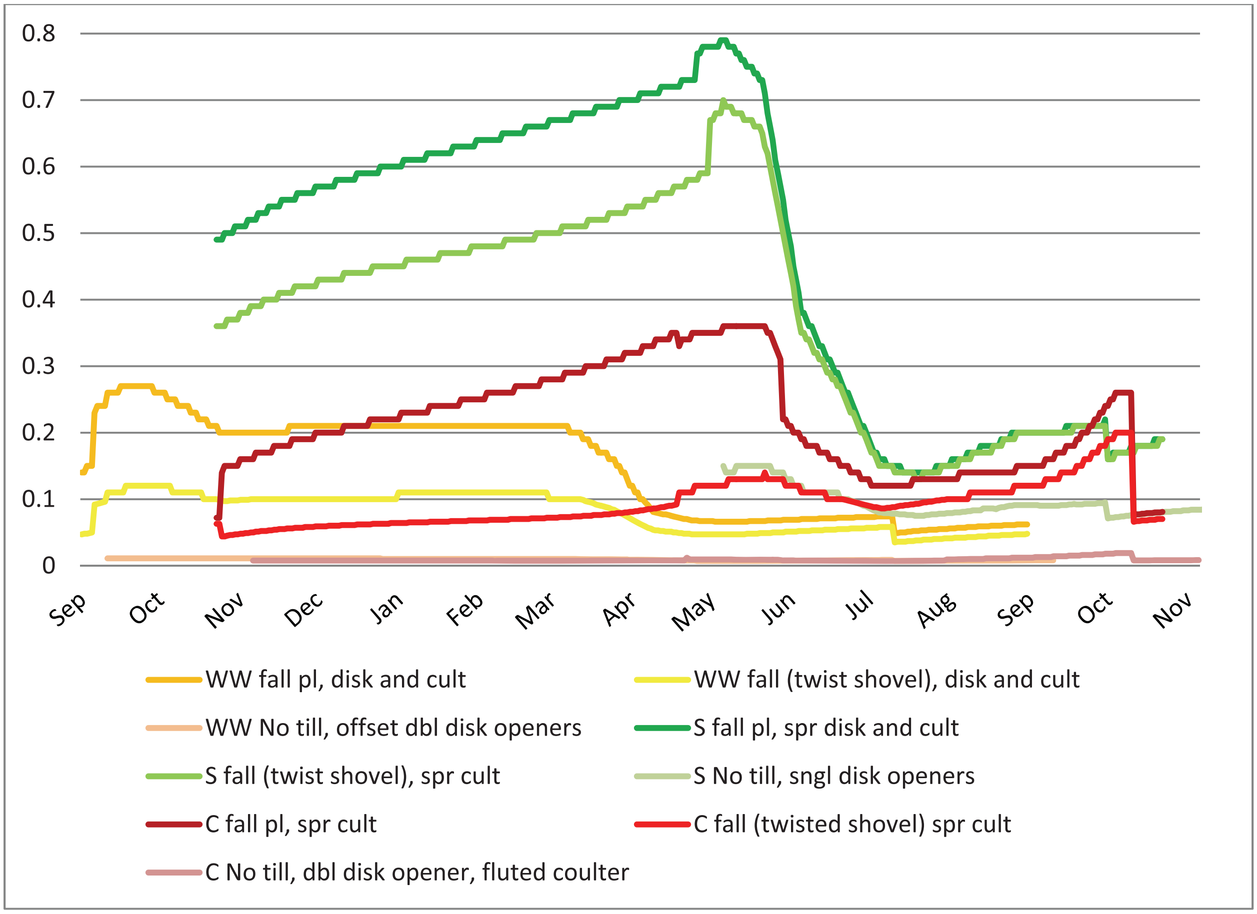
Unique Land Use (ALL watershed areas)	Generalized Category	C-Factor or Variable Time Series (TS)	Source
Corn Conservation	Corn Conservation	Corn Cons. TS	RUSLE2 C-Subfactor Timeseries
Corn	Corn Conventional	Corn Conv. TS	RUSLE2 C-Subfactor Timeseries
Corn Conventional			
CORN SYSTEM			
Corn No Till	Corn No Till	Corn No Till TS	RUSLE2 C-Subfactor Timeseries
Adzuki Beans	Edible Beans	Edible Bean TS	RUSLE2 C-Subfactor Timeseries
Edible Beans			
White Beans			
Alfalfa	Established Forage	0.02	RUSLEFAC Table C-3 established Forage
Alfalfa/Clover			
Alfalfa/Grass or Hay			
Forages			
Hay			
HAY SYSTEM			
Fallow	Fallow	0.5	RUSLEFAC Table C-3a
Apples	Fruit	0.03	RUSLEFAC Table C-3
Fruit			
Orchard			
Plantations - Tree Cult.			
Vineyard/Orchard			
Grass Waterway	Idle Land Grass 80% cover	0.01	RUSLEFAC Table C-5
Grassed Waterway			
Grasses			
Idle Ag. Land > 10 years			
Permanent Cover			
Roughland			
Ditch	Idle Land Weeds 80% cover	0.04	RUSLEFAC Table C-5
Fencerow			
IDLE AGRIC LAND (5-10)			
Idle Agric. Land 5-10 years			
Idle Land			
Not Farmed			
Nursery	Nursery	0.2	RUSLEFAC Table C-3a
Nursery and Landscape			

Unique Land Use (ALL watershed areas)	Generalized Category	C-Factor or Time Series (TS)	Source
Old Pasture	Pasture	0.02	RUSLEFAC Table C-3
Pasture			
PASTURE SYSTEM			
pastured			
Pastured Woodlot	Pastured Woodlot 50% weed	0.14	RUSLEFAC Table C-5
Extraction Pits (Pits/Quarries)	Quarry	0.05	RUSLEFAC Table C-8
Pits and Quarry			
Quarry			
Soybeans Conservation	Soybean Conservation	Soybean Cons. TS	RUSLE2 C-Subfactor Timeseries
CONTINUOUS ROW CROPS	Soybean Conventional	Soybean Conv. TS	RUSLE2 C-Subfactor Timeseries
Field			
Other Crops			
Soybeans			
Soybeans Conventional			
Unknown			
No Till	Soybean No Till	Soybean No Till TS	RUSLE2 C-Subfactor Timeseries
No-Till			
Soybeans No Till			
Canola	Winter Canola	Winter Canola TS	RUSLE2 C-Subfactor Timeseries
Barley	Spring Grains	Spring Grain TS	RUSLE2 C-Subfactor Timeseries
GRAIN SYSTEM			
Mixed Grain			
MIXED SYSTEM			
Spring Cereal			
Spring Grain			
Spring Wheat			
Tobacco System	Tobacco	0.46	RUSLEFAC Table C-3
Built Up/Urban Area	Urban	0.15	Using TMDL USLE to predict sediment loads (USEPA)
Built-Up Area Impervious			
Built-Up Area Pervious			
Farmstead			
RECREATION			
Road			
Transportation			
Urban			
Urban/Industrial/Wooded			

Unique Land Use (ALL watershed areas)	Generalized Category	C-Factor or Time Series (TS)	Source
Extensive Field Vegetables	Vegetable	Soybean Conv. TS	RUSLE2 C-Subfactor Timeseries
Market Garden/Truck Farm			
Vegetable			
Open Water	Water	N/A	
Swamp			
Water			
Wetland			
Winter Wheat Conservation	Winter Wheat Conservation	W Wheat Cons. TS	RUSLE2 C-Subfactor Timeseries
Winter Wheat Conventional	Winter Wheat Conventional	W Wheat Conv. TS	RUSLE2 C-Subfactor Timeseries
Winter Wheat No Till	Winter Wheat No Till	W Wheat NoTill TS	RUSLE2 C-Subfactor Timeseries
Coniferous Forest	Woodland	0.003	RUSLEFAC Table C-6
Deciduous Forest			
Forest			
Hedge Rows			
Mixed Forest			
Reforested Woodlot			
Riparian			
Woodland			
Woodlands			
Woodlot			
WOODLOTS/WOODLANDS			

Table 8: RSWMM C-Factor Categories

Cover Category (v-variant; i-invariant)	RSWMM C-Factor Code (Fields Layer)
CANOLA (v)	CANOLA
CORN CONSERVATION TILLAGE (v)	CORNCONS
CORN CONVENTIONAL TILLAGE (v)	CORNCONV
CORN NO TILL (v)	CORNNOTILL
EDIBLE BEAN (v)	EDIBLEBEAN
ESTABLISHED FORAGE (i)	ESTFORAGE
FALLOW (i)	FALLOW
FRUIT (i)	FRUIT
IDLE GRASS (i)	IDLEGRASS
IDLE WEEDS (i)	IDLEWEEDS
NURSERY (i)	NURSERY
PASTURE (i)	PASTURE
PASTURE WOODLAND (i)	PASTWOOD
QUARRY (i)	QUARRY
SOYBEAN CONSERVATION (v)	SOYCONS
SOYBEAN CONVENTIONAL (v)	SOYCONV
SOYBEAN NO TILL (v)	SOYNOTILL
SPRING GRAIN (v)	SPRGRAIN
TOBACCO (i)	TOBACCO
URBAN (i)	URBAN
VEGETABLE (v)	VEGETABLE
WOODLAND (i)	WOODLAND
WINTER WHEAT CONSERVATION TILLAGE (v)	WWCONS
WINTER WHEAT CONVENTIONAL TILLAGE (v)	WWCONV
WINTER WHEAT NO TILL (v)	WWNOTILL
CORN CONSERVATION COVER CROP (v)	CORNCONSCC
SOYBEAN CONSERVATION COVER CROP (v)	SOYCONSCC
WINTER WHEAT CONSERVATION COVER CROP (v)	WWCONSCC



*Note: "WW" denotes Winter Wheat; "S" denotes Soybeans, and "C" denotes Corn.

Figure 12: Example Daily C-Factors for London Area

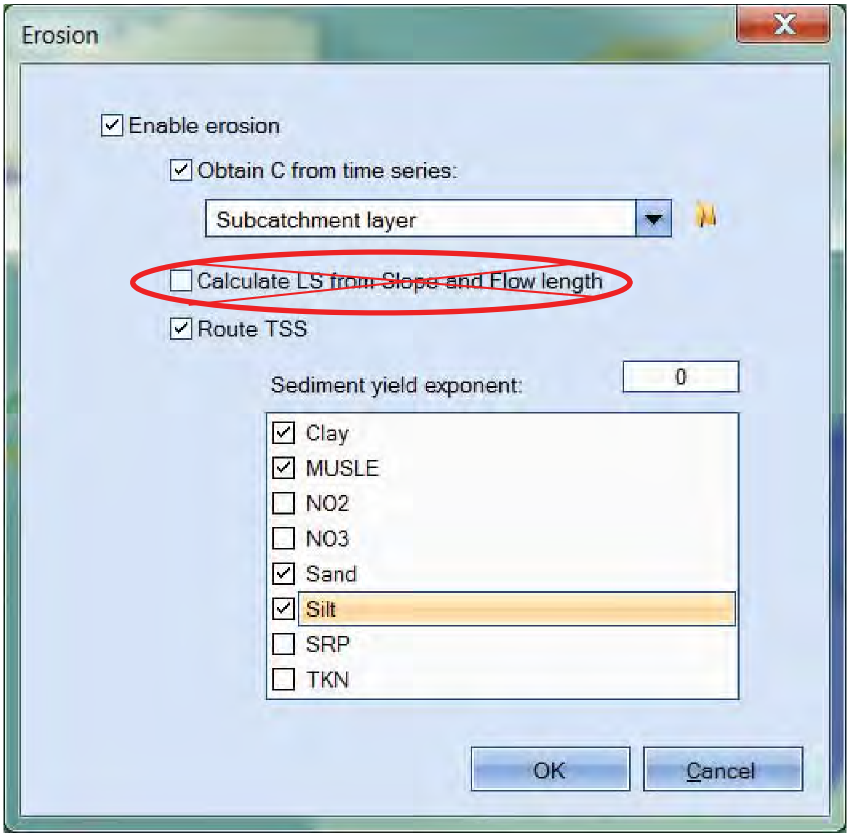
Support Practice Factor P – Intended to account for conservation practices such as terrace, contour and strip cropping tillage and assigned a default value of 1 in the PCSWMM model. The P-factor is adjusted based on land slope, stripcropping width, and terrace spacing (Wischmeier and Smith 1978). These values are automatically calculated in the model via auto-expression in the Fields Layer when agricultural BMP's are assigned.

Topographic Factor LS – Can be assigned to each subcatchment as a user specified value or can be calculated by PCSWMM using subcatchment flow length and slope according to the following equation:

$$LS = \left(\frac{L_{flow}}{22.1}\right)^{m} (65.41\, sin^2\,\theta + 4.56 \sin\theta + 0.065)$$

where:

- L_{flow} is the flow length of subcatchment (metre)
- θ is the angle of subcatchment slope (degree)
- $m = \left(1 - exp(-35.835 \tan\theta)\right)$



☑ Enable erosion

☑ Obtain C from time series:

Subcatchment layer

☐ ~~Calculate LS from Slope and Flow length~~

☑ Route TSS

Sediment yield exponent: 0

☑ Clay
☑ MUSLE
☐ NO2
☐ NO3
☑ Sand
☑ Silt
☐ SRP
☐ TKN

Figure 13: Erosion Dialog Box through File Menu

For the RSWMM, the ”Calculate LS from Slope and Flow length" option is not enabled in the Erosion dialog box, as shown in Figure 13. This is because implementation of BMPs may change either the flow length or slope on the individual fields. An auto-expression is included in the Fields Layer to calculate the individual field LS factors (LSUSLE) which is then area weighted to the Subwatershed Layer via the Layer Area Weighting Tool in PCSWMM.

Coarse Fragment Factor CFRG – Can be area weighted for each subcatchment based on the Stoniness index attribute contained in the soils geospatial information. It is based on the following equation:

$$CFRG = exp(-0.053 \times Rock)$$

where *Rock* is the percent rock in the uppermost soil layer, and *CFRG* can be estimated by the Soils Layer Stoniness Classification shown in Table 9.

Table 9: Soil Stoniness Classification and CFRG

Stoniness Code	Classification	Description	% ROCK FOR CFRG	CFRG
0	Non-stony	No stones or too few are present to interfere with cultivation (<0.01% of surface, stones more than 25 m apart).	0.01	0.999
1	Slightly stony	Some stones are present that hinder cultivation slightly or not at all (0.01-0.1% of surface, stones 8-25 m apart).	0.1	0.995
2	Moderately stony	Enough stones are present to cause some interference with cultivation (0.1-3% of surface, stones 1-8m apart).	2	0.899
3	Very stony	There are sufficient stones to handicap cultivation seriously; some clearing is required (3-15% of surface, stones 0.5-1m apart).	10	0.589
4	Exceedingly stony	The stones prevent cultivation until considerable clearing is done (15-50% of surface, stones 0.1-0.5m apart).	35	0.156
5	Excessively stony	The land surface is too stony to permit cultivation; it is boulder or stone pavement (more than 50% of surface, stones less than 0.1m apart).	60	0.042

5.3.2 Effect of Crop Rotation on Watershed Scale

In order to assess the variability of individual crops in rotation, six years of crop information was provided from a previous Soil and Water Assessment Tool (SWAT) modelling study in the Bayfield North (Gullies) area. As shown in Table 10, the coefficient of variation indicates that the variability of percent area by each crop is small enough that annual averages are a sufficient estimate to model subcatchments that include 3 or more individual fields. Since the ultimate purpose of the model is to be used on event and short duration continuous simulation (2 years or less), this assumption is valid not only at the watershed outfall, but also at the subcatchment scale due to the majority of subcatchments covering an area greater than an individual field or plot. The findings of the variable crop area assessment are extended to all five sentinel watersheds in the study, therefore arriving at a best average catchment sediment yield for any particular year.

It should be noted that, even though the relative proportion of crops in a watershed may be relatively invariant on a yearly basis, the land-use distribution within any one subwatershed will be more variable the closer that it is to field-scale because the crops in individual fields do change from year to year. Thus, in some years sensitive crops like soybeans may be planted in more susceptible locations. Incorporation of a crop rotation model option for multi-year simulations may be in the interest of the RSWMM user community and could be included in a future update of the model as a solution to these issues.

Table 10: Bayfield North Gully Creek Field SWAT Summary

CROP	2008	2009	2010	2011	2012	2013	Mean	StDev	Coef. Var.
Corn	40%	17%	30%	25%	27%	22%	27%	7.8%	0.29
Soybean	27%	48%	33%	33%	33%	41%	36%	7.3%	0.21
W.Wheat	18%	20%	26%	20%	25%	21%	22%	3.1%	0.14
Edible Bean	0.0%	0.0%	0.0%	5%	1%	1%	1%	1.9%	1.75
Forages	1%	2%	5%	3%	2%	2%	3%	1.3%	0.49
Grass	6%	5%	5%	5%	5%	5%	5%	0.3%	0.07
Pasture	8%	8%	1%	7%	7%	7%	6%	2.7%	0.43
Fallow	1%	1%	1%	1%	1%	1%	1%	0.0%	0.00

Note: Percentages shown represent the fraction of the study area under a given cropping practice in each year

5.4 In-Stream Processes

In-stream denitrification processes are well-recognized in the overall fate of nitrogen on a watershed scale. A simplified approach based on state-of-science denitrification relationships was applied to account for in-stream processes for P and N depletion in the model.

The contaminant fraction removed over the length of a reach is estimated as an exponential first-order reaction rate coefficient and the cumulative water time of travel through the reach. Referencing the basic form of the SPARROW model, the fraction of contaminant originating from an upstream node, where pollutant is input into the model, and transported along reach *i* of stream class *c* in discrete intervals of mean stream flow or depth can be expressed as (Schwarz et al. 2006):

$$A = exp\left\{-\sum_{c=1}^{C_s} k_{S_c}\, t_{c\,i}^{S}\right\}$$

where:

$k_{S_c} = Stream\ size\ dependent\ rate\ coefficient$
$t_{c\,i}^{S} = Mean\ water\ time\ of\ travel$

To generally conform to observations that the reaction rate is inversely related to water column nitrate concentration, stream flow rate, and water depth, the following reaction rate constant regression estimate for the *m*th observation is used (Alexander et al. 2009):

$$k_m = b_0 C_m^{b1} H_m^{b2} [sin(2\pi t_m)]^{b3} [cos(2\pi t_m)]^{b4} \varepsilon_m$$

where:

b0 = Model Intercept Coefficient
b1 = Nitrate Concentration Coefficient
b2 = Hydrologic Condition Coefficient
b3 and b4 are Seasonal Coefficients
C = Influent Water Column Concentration
H = Hydrologic Condition (discharge or depth)
t_m = *Decimal Time*
ε_m = *Model Error*

Coefficients b3 and b4 are associated with seasonal variability and are not currently represented in the RSWMM model. Setting these values to zero and one reduces the in-stream reaction rate equation to:

$$k_m = b_0 C_m^{b1} H_m^{b2} \varepsilon_m$$

Thus, the pollutant fraction removed becomes:

$$A = exp\left\{-\sum_{c=1}^{C_s} b_0 {C_m}^{b1} {H_m}^{b2} \varepsilon_m \, t_{c\,i}^{S}\right\}$$

Default coefficients in the RSWMM model follow the Opdyke-David-Royer (ODR) model mean values using depth as the hydrologic condition (Alexander et al. 2009).

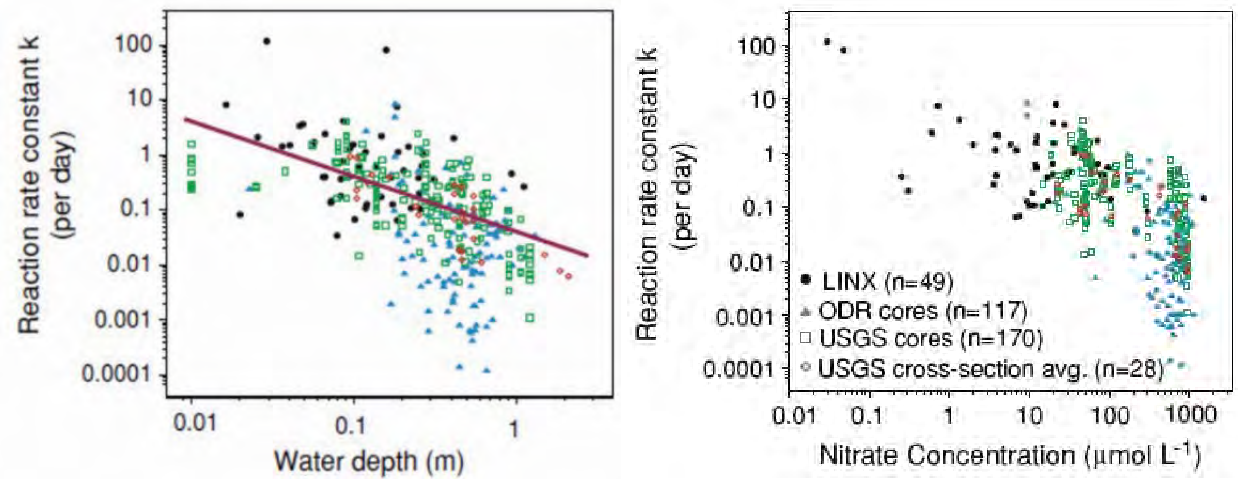


Figure 14: Observed Measures of the Reaction Rate Constant for Separate Field Data Sets (Alexander et al. 2009)

While there is no comparable process to denitrification for phosphorous in a stream system, biochemical exchanges in the sediment and interaction with inorganic sources can still result in situations where dissolved P and coarse particulate P inputs exceed outputs (Meyer and Likens 1979). Stream phosphorus removal rates are less available in the literature than denitrification reaction rates; however, the use of the SPARROW model for pollutant delivery in the Mississippi River Basin suggests in-stream removal rates for total phosphorus at 69% of that for total nitrogen (Alexander et al. 2008).

At present, in-stream sediment sources and sinks are not modelled in the RSWMMs. While there are some capabilities for modelling in-channel erosion processes in PCSWMM, it is difficult to parameterize such routines without information regarding stream bank composition and stability. Furthermore, relatively little was known about the sourcing of the measured sediment component of TSS (e.g. the proportion of sediment that comes from near- and in-stream sources vs. landscape sources). Future projects could consider sediment balance modelling as an improvement to the RSWMM methodology.

The current version of SWMM5 does not allow pollutant removal to occur in the conduit model elements. Therefore, the removal is accounted for at the node, downstream of “Irregular” cross-section conduits representing natural and open channels. This is accounted for by entering Treatment Expressions in the form of the equation above at the nodes for nitrate, nitrite, and dissolved phosphorus. Since the most research has been conducted for nitrate and relatively little literature exists discussing nitrite and phosphorus removal, the current versions of the RSWMMs assume a linear relationship between nitrate removal and nitrate and phosphorus removal. The fractional removal of nitrite is assumed to be equal to the fractional removal of nitrate (i.e. $R_{NO_2} = R_{NO_3}$), while the fractional soluble reactive phosphorus removal is assumed to be 69% of the fractional removal of nitrate (i.e. $R_{SRP} = 0.69 * R_{NO_3}$), as discussed above. It should be noted that, while the results of Alexander et al. are actually for total phosphorus, limitations related to the current representation of particulate phosphorus in the models inhibited its inclusion in the in-stream processing equations at this time.

The mean water time of travel (t) is derived from the average velocity and length for each “Irregular” conduit. This was established by running the period of record (POR) on each of the calibrated sentinel watershed models. These values are included as attributes of the nodes downstream of “Irregular” conduits and updateable via the Replace tool as new monitoring information becomes available. For nodes that have more than one contributing “Irregular” conduit, the stream lengths are summed and the mean conduit velocity is averaged to account for the total travel time in both conduits at the node.

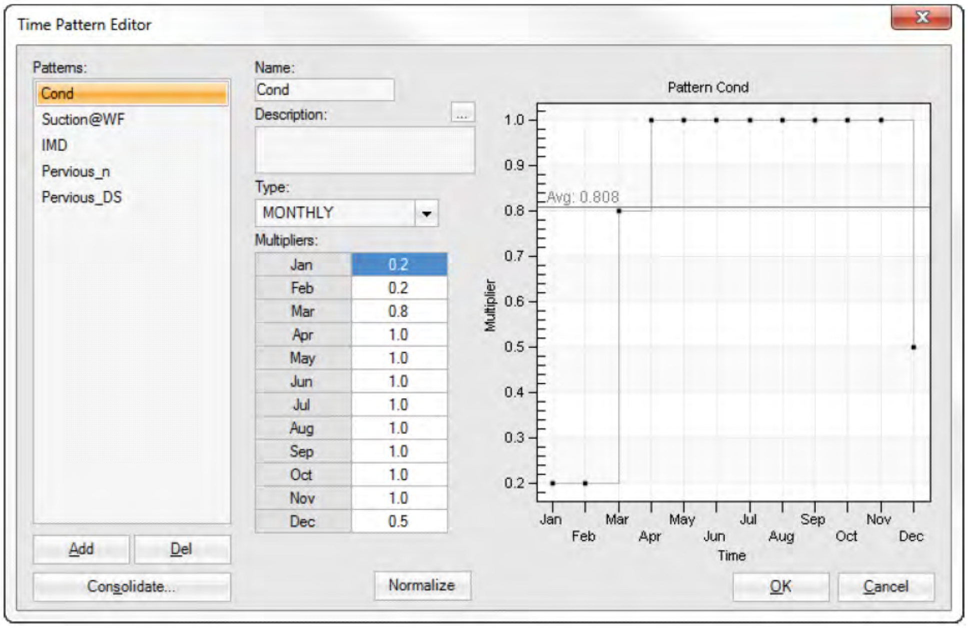
5.5 Parameter Seasonality

Other than evaporation, the US EPA SWMM5 engine currently does not allow seasonal variation in hydrologic parameters. However, many hydrological processes, including infiltration, exhibit seasonal variability. This is especially evident in the agricultural setting where parameters such as surface roughness, depression storage, and infiltration can vary with the stage of vegetation growth. This seasonal variability may have a significant effect on computed model results when conducting a continuous simulation. To overcome this limitation, PCSWMM added seasonal modelling capability with the revised SWMM engine (SWMM5.1.901).

The revised engine allows monthly variation in the following subcatchment hydrologic parameters:

- Pervious area Manning’s n
- Pervious area depression storage
- Green and Ampt infiltration – initial deficit
- Green and Ampt infiltration – hydraulic conductivity
- Green and Ampt infiltration – suction at wetting front

The user can apply monthly variability in these parameters as a time pattern (Figure 15).



Name: Cond

Description:

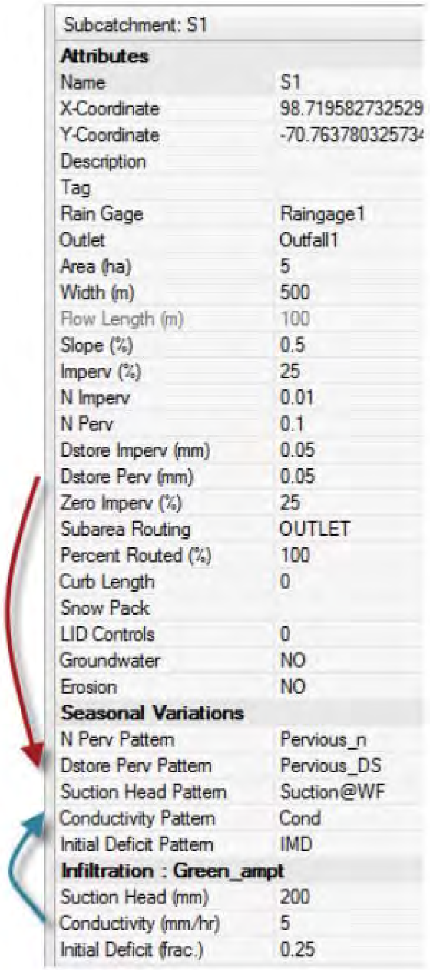
Type: MONTHLY

Multipliers:

Jan	0.2
Feb	0.2
Mar	0.8
Apr	1.0
May	1.0
Jun	1.0
Jul	1.0
Aug	1.0
Sep	1.0
Oct	1.0
Nov	1.0
Dec	0.5

Figure 15: Time Pattern Editor Used to Apply Seasonal Variations in Subcatchment Parameters

In each subcatchment, time patterns should be selected in the “Seasonal Variations” attribute category to represent the seasonal variability in any parameter, as shown in Figure 16. These monthly multiplier values are applied to the appropriate subcatchment parameter values, so the final parameter value = input value x monthly multiplier.



Subcatchment: S1

Attributes	
Name	S1
X-Coordinate	98.719582732529
Y-Coordinate	-70.76378032573
Description	
Tag	
Rain Gage	Raingage1
Outlet	Outfall1
Area (ha)	5
Width (m)	500
Flow Length (m)	100
Slope (%)	0.5
Imperv (%)	25
N Imperv	0.01
N Perv	0.1
Dstore Imperv (mm)	0.05
Dstore Perv (mm)	0.05
Zero Imperv (%)	25
Subarea Routing	OUTLET
Percent Routed (%)	100
Curb Length	0
Snow Pack	
LID Controls	0
Groundwater	NO
Erosion	NO
Seasonal Variations	
N Perv Pattern	Pervious_n
Dstore Perv Pattern	Pervious_DS
Suction Head Pattern	Suction@WF
Conductivity Pattern	Cond
Initial Deficit Pattern	IMD
Infiltration : Green_ampt	
Suction Head (mm)	200
Conductivity (mm/hr)	5
Initial Deficit (frac.)	0.25

Figure 16: Seasonal Variation Time Patterns in Attribute Editor

Currently the multipliers change at the 1st day of the month, without a gradual change or without regard for physical changes which may occur at other times during the month.

As previously discussed in Section 5.3, the MUSLE parameter Cover Factor C was calculated daily by area weighting specific land use in each catchment using seasonal values for each land use. Seasonal variation in evaporation and wind speed were previously available in the climatology editor of PCSWMM.

5.6 Dual Groundwater Equation

As part of this project, CHI has enabled users to model drain tile hydraulics by implementing a dual-flow groundwater equation in the new SWMM5 engine with RSWMM modifications, a feature that had not previously been available in any SWMM platform. This feature enables two groundwater equations to be implemented for each subcatchment; in this case, we are using a form of the Dupuit-Forchheimer equation to simulate lateral groundwater flow to the stream and ditch channels, and the Hooghoudt equation to simulate groundwater discharges resulting from agricultural drain tile systems.

5.6.1 Overview of Groundwater in SWMM

The groundwater equation in SWMM is a generalized equation, shown in the SWMM 5 User Manual (Rossman 2010) as follows with the parameters shown in Figure 17:

$$\boldsymbol{Q_{gw} == A1 * \left(H_{gw} - H^{*}\right)^{B1} - A2 * (H_{sw} - H^{*})^{B2} + A3 * H_{gw} * H_{sw}}$$

where Q_{gw} is the groundwater outflow rate (m³/s), H_{gw}, H_{sw}, and H^* are defined in Figure 17 (m), the units of the groundwater coefficient, *A1,* and the surface water coefficient, *A2,* are dependent upon the magnitude of exponents *B1* and *B2*, and *A3* is the groundwater-surface water interaction coefficient (m³/s/ha).

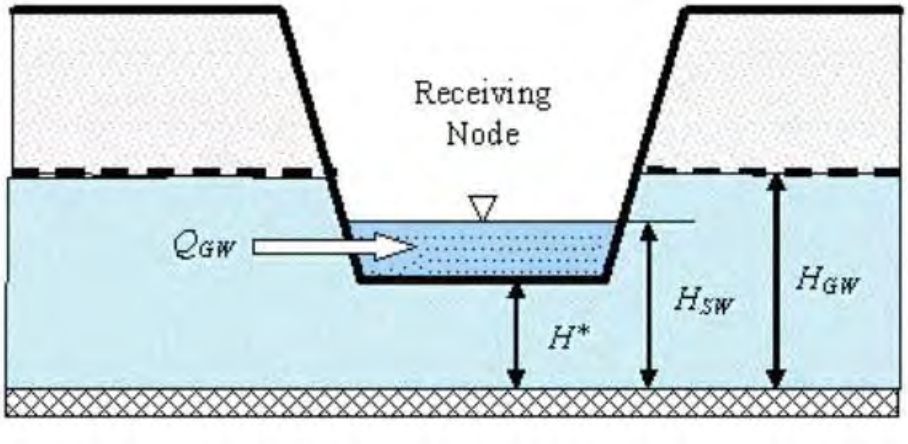


Figure 17: Groundwater Parameters (Rossman 2010)

5.6.2 Application: Dupuit-Forchheimer Equation

As stated in the SWMM User Manual, the Dupuit-Forchheimer approximation for groundwater flow to a ditch can be represented as follows:

$$Q_{gw} = \frac{4k}{L^2}\left[\left(H_{gw} - H^{*}\right)^2 - H_{gw} * H_{sw}\right].$$

In the SWMM groundwater equation, the corresponding parameters are the following:

$A1 = 4k/L^2$
$B1 = 2$
$A2 = 0$
$B2 = 0$
$A3 = -\,4k/L^2$
$FlowElev = H^{*} = 0$
$GWDepth = H_{gw}$ (variable)
$SWDepth = H_{sw}$ (variable)

where:

k = soil lateral saturated hydraulic conductivity
L = ½ ∗ Length.

The calculation of L is approximated as ½ ∗ Length (the subcatchment flow length) since SWMM's groundwater elevation really represents an "average" value, taken as $(H_1 + H_2)/2$ from Figure 18(Huber and Dickinson 1992).

In the RSWMMs, it was decided that the third term in the equation (the surface water-groundwater interaction term) would be excluded due to the undesirable results of groundwater discharge during large storm events (i.e. groundwater discharge decreased during storm events). Thus, in these models A3 was also set to zero.

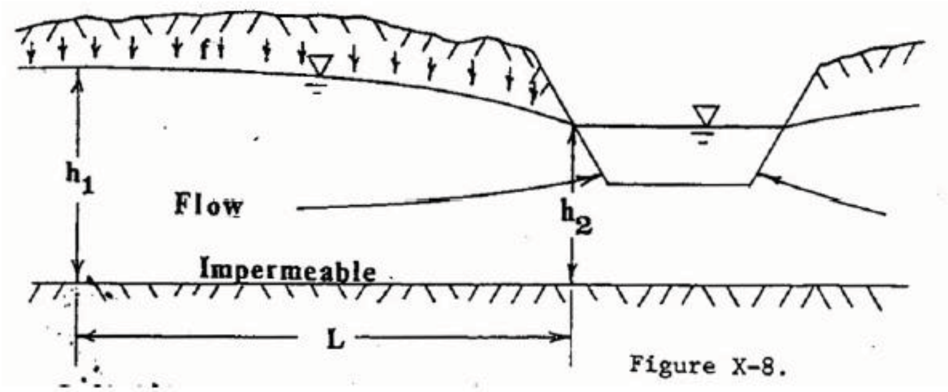


Figure 18: Dupuit-Forchheimer Definitions (Huber and Dickinson 1992)

5.6.3 Application: Hooghoudt Equation

As stated in the SWMM User Manual, the Hooghoudt equation for steady-state groundwater flow to a system of drain tiles can be represented as follows:

$$Q_{gw} = \frac{16k}{L^2}\left[\left(H_{gw} - H^*\right)^2 - D_e * b_0 + D_e * H_{gw}\right].$$

In the SWMM groundwater equation, the corresponding parameters are the following as illustrated in Figure 19:

$A1 = 16k/L^2$
$B1 = 2$
$A2 = 16kD_e b_0/L^2$
$B2 = 0$
$A3 = 16kD_e/H_{sw}L^2$
$FlowElev = H^* = SurfaceElev - D_d$
$GWDepth = H_{gw}$ (Variable)
$SWDepth = H_{sw} = b_0$

where:

k = soil lateral saturated hydraulic conductivity
L = drain spacing
D_d = drain depth
D_e = equivalent depth to impermeable layer
b_0 = impermeable layer (= aquifer bottom) depth below drain.

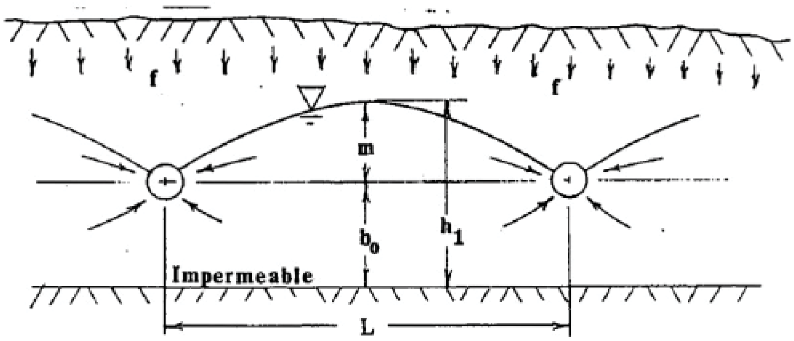


Figure 19: Hooghoudt Definitions (Huber & Dickinson, 1992, p. 488)

5.6.4 Groundwater-Related Parameters

There are several other parameters that must be estimated, descriptions of which can be found in the User's Guide to SWMM5 (James et al. 2010). These include the following:

- Subcatchment
  - Surface elevation (SurfaceElev) – estimated as (outlet invert elevation) + (flow length)*(slope)/2
- Aquifer
  - Porosity – area weighted using soil texture (Rawls, Brakensiek, and Saxtonn 1982)
  - Wilting point – area weighted using soil texture
  - Field capacity – area weighted using soil texture
  - Conductivity – area weighted using soil texture
  - Conductivity slope – calibration parameter (initialized as default)
  - Tension slope – calibration parameter (initialized as default)
  - Upper evapotranspiration fraction – calibration parameter (initialized as default)
  - Lower evapotranspiration depth – 3 m (pending sensitivity analysis)
  - Lower groundwater loss rate – calibration parameter (initialized as default)
  - Bottom elevation – estimated as (outlet invert elevation) – (depth to impermeable layer)
  - Initial water table elevation – calibration parameter (based on initial conditions)
  - Unsaturated zone moisture – calibration parameter (initialized as default)
- Independent variables
  - Depth to impermeable layer – set at 10 m (pending sensitivity analysis)
  - Tile drain depth – set at 1 m (per ABCA recommendation)
  - Tile drain spacing – set at 20 m (per ABCA recommendation)

5.6.5 Discussion

Both groundwater equations require an input of the *lateral* saturated hydraulic conductivity. For this project, we are estimating *vertical* saturated conductivity (and all other soil water properties) using an empirical relationship with soil texture. Literature suggests that small-scale lateral saturated conductivity is generally between 1 and 4 times that of vertical (Salazar, Wesström, and Joel 2008; Halford 1997), but the effective lateral conductivity has been found to be as much as 100 times that of vertical on a large scale (Brooks, Boll, and McDaniel 2004). In light of consultation with a professor and expert in tile drainage at the University of Minnesota (Sands 2014) we have chosen to initialize the lateral values as 1.5 times vertical and to use this scaling factor as a calibration parameter.

While testing the accuracy of this approach to modelling tile drainage compared to other more robust drainage models is beyond the scope of this project, it is worth mentioning that because SWMM represents the water table as one-dimensional, the second groundwater equation will only become active when the water table reaches the specified drainage depth below the mean surface elevation. This implies that as the subcatchments are delineated closer to field scale, the method becomes more representative of reality. Thus, for this version of RSWMM the performance of the tile drainage equation and the sensitivity of the parameters – such as the drain spacing and depth – remain relatively unknown.

6 WATERSHED MODEL CONSTRUCTION

Models of the five sentinel watersheds were developed and calibrated in PCSWMM using the new features and several external parameterization methods. The calibration used observed water quantity and quality data collected throughout the watersheds from 2012 to 2014 by the CAs. The model development included the following tasks discussed further in this section:

1. Collection of existing Geographic Information System (GIS), hydraulic structure data, and design drawings of municipal drains.
2. Delineation of preliminary subcatchments using ArcSWAT.
3. Importation of existing GIS into PCSWMM.
4. Revision of subcatchment delineation in PCSWMM.
5. Parameterization of data inputs required for the models.
6. Calibration of the models using observed water quantity and quality data

6.1 Data Collection

Monitoring data was collected at the locations listed in Table 11 and shown in Figures A.1, A.4, A.7, and A.13. Input data for model construction can be summarized in three categories: 1) GIS and survey data, 2) water quantity and meteorological data, and 3) water quality data. This section discusses the types of data collected and the method of collection; a detailed discussion of how the data was processed for inclusion in the models follows in Section 6.2.

Table 11: Climate, Water Level, and Water Quality Monitoring Stations

Watershed	Name	Number	ID in Model	Drainage Area (km^2)	Data Collected
Pine River	Lurgan	WSC 02FD001	Conduit 1	154	Met/QL/QN
	Ripley	SPR11	Conduit 58	28	Met/QL/QN
	Temporary Level Logger	SPR13	Conduit 76	8	QL/QN
Garvey-Glenn	Kerry's Line	-	Conduit CB-20	13	Met/QL/QN
	Division Line North	-	Conduit CB-40	6	QL/QN
	Division Line South	-	Conduit CB-50	3	QL/QN
Bayfield North	Porters Hill Line	GULGUL5	Conduit CH-G189	11	Met/QL/QN
	Tower Line Road	GULGUL7	Conduit CH-G188	2	QL/QN
	-	NGmetVB	-	12	Met
Main Bayfield	Trick's Creek	B8-1	CH-B74	20	Met/QL/QN
	Varna	-	BW-B80	51	Met/QL/QN
	-	W233-1	-	-	Met
	Mill Road	HBJOHN	BW-B82	4	Met/QL
	-	MBmetAB	U57-09	0.2	Met
Lambton Shores	Shashawandah	SHASH20	Conduits C12 and C13	25	Met/QL/QN
	Duffas	DUFF02	Conduit A5	6	QL/QN

Notes:
Met – Meteorological Monitoring Station
QL – Water Quality Monitoring Station
QN – Water Quantity Monitoring Station

6.1.1 Survey and GIS Data

GIS and survey data was provided in a variety of formats, including shapefiles, raster datasets, and spreadsheets. The following GIS data was provided and is shown in the watershed maps provided in Appendix A:

- Hydrography: watersheds, watercourses, municipal drains, bridges, culverts, and berms/BMPs
- Soils
- Land use
- Roads
- Digital Elevation Model (DEM)
- Air photos

The resolution of the DEM varied by watershed:

- 1m grid for Bayfield North, Main Bayfield, and Lambton Shores
- 2m grid for Garvey-Glenn
- 10m grid for Pine River

The CAs also provided structure survey information for the bridges and culverts at varying levels of detail for each sentinel watershed, as well as photographs of the surveyed structures. Design drawings for the municipal drains were also provided for most watersheds. Reduced-size versions of these files (photos, PDFs, etc.) are attached to each model in the Documentation window. Original files can be obtained from the CAs.

Some additional metadata was provided in the land-use and soils shape files, including information on additional (i.e. secondary) tillage operations, residue cover, and livestock. However, no information regarding such things as fertilizer application, soil phosphorus tests, or other agronomic practices were reported. The lack of such information for some of the watersheds – as well as the inherent difficulty of incorporating it into the existing SWMM framework – informed the relatively simple, empirical method by which pollutants were defined in the RSWMMs. A more detailed discussion of the potential future improvements to the water quality modelling methodology can be found in Section 9.2.

6.1.2 Water Quantity and Meteorological Data Collection

Water quantity data was provided in HEC-DSS databases and included flow, stage, and rating curves measured at various intervals. Meteorological data was also provided in HEC-DSS databases and included precipitation, temperature, wind speed, and reference evapotranspiration measured at various intervals.

Within each of the five sentinel watersheds, two locations were monitored to provide information on surface water quantity, beginning in August 2012 and ending in April 2014 (Table 11; Figure A.1; Figure A.4; Figure A.7; Figure A.10; Figure A.13). It should be noted that at the time of this report, the data collection programs are continuing.

For permanent locations, water level data were collected using a data logger (Sutron 8210 or FTS Axiom H2) connected to either a float recorder or bubbler pressure transducer technology.

At temporary locations, water level data were collected using pressure transducer loggers (Schlumberger Mini-Divers or Solinst Level Loggers).

The majority of water level datasets were collected at 5-minute intervals, although for two stations that already existed, the time interval varied from 15 to 60 minutes.

Flow datasets for the hydrometric stations were created by converting water level datasets with the use of a rating table. The rating table was compiled with low flows measured manually (area-velocity method) and higher flows that were obtained theoretically through the use of Manning's equation when it was not practical or safe to enter the watercourse to obtain manual measurements.

Meteorological data were collected at one location within each of the priority watersheds with DAVIS Vantage Pro2 weather stations. These stations consisted of an integrated suite of meteorological sensors logging data at pre-programmed intervals. The stations included a tipping bucket rain gauge (non-heated), anemometer, and UV, relative humidity, and temperature sensors. They generated the following datasets at 10-minute intervals:

- Precipitation
- Temperature
- Wind speed
- Reference Evapotranspiration (calculated)

Additional non-heated tipping bucket rain gauges logged by Sutron 8210 or FTS Axiom H2 data loggers also recorded precipitation at 5-, 15-, or 60-minute intervals, where available.

To supplement the precipitation data in winter months, snowpack depth and water equivalent were recorded at one location in each watershed at the first and fifteenth of each of the winter months.

6.1.3 Water Quality Sample Collection

Water quality data was collected by ISCO samplers at permanent stations and grab samples at temporary monitoring locations. Within each of the five sentinel watersheds, two locations were monitored to provide information on surface water quality, beginning in August 2012 and ending in April 2014 (Table 11; Figure A.1; Figure A.4; Figure A.7; Figure A.10; Figure A.13). A total of 928 samples were collected up to the end of April 2014 at the permanent and temporary sites. It should be noted that at the time of this report, the data collection programs are continuing.

Once per month, water samples were collected by grab sampling from all of the sites. These grab samples were mostly representative of baseflow conditions. The permanent monitoring station in each watershed was outfitted with a Teledyne Isco 6712 automatic sampler, which enabled the collection of water samples throughout the duration of storm hydrographs. Samples collected by the ISCO samplers were taken at regular intervals (generally 1 or 2 hours) and a subset of these samples was selected for analysis. In general, the samples submitted for analysis were based on being representative of the rising and falling limbs as well as the peak of the hydrograph for the event. Additional grab samples were collected during storm events from the temporary monitoring stations, and sometimes also from the permanent stations to supplement the automatic samples.

Water quality samples were shipped to either the Ministry of the Environment and Climate Change (MOECC) laboratory in Etobicoke, Ontario, or to a private laboratory (usually ALS in Waterloo, Ontario). The samples were analyzed for a suite of water quality indicators:

- Nitrate-N and Nitrite-N
- Total Ammonia-N
- Total Kjeldahl Nitrogen
- Dissolved Ortho-phosphorus
- Total Phosphorus
- Total Dissolved Solids
- Total Suspended Solids
- Total Solids
- Dissolved Oxygen
- Water Temperature

Additional water quality data have been collected from the five sentinel watersheds over longer time periods under other monitoring programs. These data could be used in the future to further refine the modelling.

6.2 Data Processing

6.2.1 GIS Data

A portion of the GIS data provided required some processing before it could be used in model construction. Firstly, for some watersheds general land-use shape files and the shape files generated from the windshield surveys of agriculture had to be combined into a single file. Since the polygons in these two layers did not align, artifacts ("sliver polygons") had to be cleaned up using both automated and manual methods. The generation of these combined land-use/agriculture layers was also necessary for the development of the Fields layers, discussed in Section 5.2.1. After the land-use files were consolidated, a re-categorization of land-use categories had to be performed in order to be left with a manageable number of land-uses for inclusion in the model. Further discussion related to this issue can be found in Sections 0 and 9.3.

Additionally, while the aerial photos provided were all in usable formats (in that PCSWMM can use virtually any format available), some of the file formats did not perform as well as others during model construction (i.e. they had long reload times during panning and zooming, possibly due to the type and degree of image compression), and had to be converted to other formats. It was determined that the TIFF format was most efficient, and is also convenient in that it is widely supported and open-source. Conversely, considerable difficulty was encountered when attempting to use and convert files from the MrSID format, for example, because of its proprietary nature and high level of compression.

Once converted to TIFF format, multiple resampled files of various resolutions were generated for both the aerial photos and digital elevation models in order to make model construction more efficient by facilitating faster render times while panning and zooming.

6.2.2 Precipitation Data

The highest frequency of measurement provided for the precipitation datasets was five minutes and the lowest least frequency was one hour. Because continuous simulation requires constant interval precipitation data, these data were aggregated on an hourly basis for all time periods. Precipitation data was processed by first exporting data from HEC-DSS as a text file and importing into PCSWMM. While HEC-DSS itself includes tools for data processing and aggregation, inconsistencies in the outputs obtained using these tools prompted the use of similar functionalities within the PCSWMM interface instead.

QA/QC performed on the data revealed issues within the various datasets, including missing intervals and shifted data. The missing data intervals were found particularly in the high-frequency (5-minute) data and were reportedly due to data-loggers running out of memory. In addition, the Pine River watershed precipitation data recorded at the Ripley gauge was shifted two days later than the precipitation recorded at the Lurgan gauge during the summer and fall of 2013. The Ripley precipitation data recorded after April 20th was shifted two days earlier for the present analysis, however additional investigation is recommended to determine the reason for the shift and if it was shifted back to the correct date later in the monitoring period.

6.2.3 Climate Data

The SWMM5 engine uses a daily climate file to accumulate, melt, and distribute snow cover, and to estimate evapotranspiration from subcatchments and evaporation from surface water features. The file consists of eight columns where each row contains the station name, year, month, day, maximum temperature, minimum temperature, daily evaporation depth, and average hourly wind speed.

The temperature, evaporation, wind speed, and snowmelt data was imported into the climatology editor in PCSWMM by use of an externally-referenced, tab-delimited climate file[5]. The precipitation data was collected using non-heated rain gauges and was imported into PCSWMM after adjusting Snow Catch Factor based on limited snow water content information provided by the CAs. Heated rain gauges or bias-corrected radar precipitation estimates would be required in the future to collect appropriate precipitation data for calibration during the winter months. At this time, the models could not be calibrated during the winter and the snow pack surveys also completed by the CAs could not be compared to the snow accumulation in the models. More discussion on this issue is located in Sections 6.5 and 9.3.

Additional review and improvements may be required to the precipitation and flow data at the Ripley gauge in Pine River. A two-day delay throughout the summer of 2013 was observed at Ripley in comparison to the Lurgan gauge. It was assumed that the data had somehow been shifted but additional investigation is required to confirm.

6.2.4 Flow Data

A minimum of two gauges were installed or already present in each sentinel watershed to collect water quantity data. Rating curves were provided by the CA's to calculate flow based on water level measurements. A rating curve was not provided, however, for the water levels recorded at the Duffas gauge in the Lambton Shores watershed and this station was not used in the model calibration.

Flow data was provided in HEC-DSS format and exported to text files, which were then used to import the data into PCSWMM time series file format (.TSF). The name of the location for each gauge was changed to correspond to the appropriate model element; for example, in the Bayfield North watershed the gauge called "GULGUL5" was changed to "CH-G189(obs)". The "(obs)" is used

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[5] Information on climate file format can be found in the SWMM 5 User Manual

to inform PCSWMM that this is observed data, and the program is able to automatically compare these data with the simulated data. This same renaming scheme was also applied to the water quality data, discussed in the next section.

In one case, flow rates had to be converted from litres per second to m^3 per second, but otherwise relatively little processing of the flow data was required. There were several anomalies discovered in the datasets – more discussion on these can be found in Sections 6.4 & 9.3.1.

6.2.5 Water Quality Data

A set of water quality data was provided by each CA, as discussed in Section 6.1.3. The first step in processing these data was determining which water quality indicators were both applicable to the project and feasible to model. Observed indicators were partitioned into three pools for calibration: sediment, phosphorus and nitrogen – a more detailed discussion of which can be found in Section 6.3.2.

A total of 24 different water quality indicators were reported, though not all were reported by each CA. Of these, four pollutants were chosen to be directly simulated, and an additional three pollutants were derived[6]. More information on pollutant setup can be found in Section 6.3.2.

Several issues were addressed during data processing. Firstly, numerous nitrite monitoring results were equal to 0.1 mg/L and included the remark "actual result less than reported value". These values were excluded from the data set used for calibration of the models. Additionally, it was discovered that suspended sediment concentrations (SSC) were reported for three of the five watersheds (Bayfield North, Main Bayfield, and Garvey-Glenn), while the datasets for the remaining two watersheds (Lambton Shores and Pine River) contained values for total suspended solids (TSS). It was eventually learned that the laboratory procedures used in all cases were for TSS and that the inconsistency was merely in reporting, but not until after the parameterization methodology (discussed in Section 6.3.2) was developed referring to sediment in terms of SSC. Throughout the remainder of the report, the observed values for sediment will be referred to as TSS, while the simulated values will be referred to as SSC. More discussion on this topic can be found in Section 9.3.2.

6.3 Parameterization Methodology

A combination of established and new methodologies was used to determine the appropriate parameters for the watershed models. New categories and attributes were added to various layers by right clicking the layer and selecting "Restructure". In addition, Auto-Expressions were used to automatically calculate various parameters within PCSWMM. A set of lookup tables was created to quickly parameterize the model using the area weighting tool and is included for reference in Appendix B.1.

A full list of the parameters used in the models is provided in Appendix C. The parameters in the Subcatchments layer are outlined in Table 46. The attributes of the watercourses and drains were developed based on topography, site visit information, and municipal drain design drawings. The parameterization methods are outlined in Table 47 through Table 52.

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[6] This excludes the simulation of the MUSLE-simulated components, namely Sand, Silt, and Clay.

6.3.1 Lookup Tables

Several lookup tables were developed to area- weight parameters in the models, including the following tables provided in Appendix B.1:

- Table 38: Subcatchment Infiltration Parameterization by Soil Type
- Table 39: Subcatchment Erosion Parameterization By Soil Type
- Table 40: Subcatchment Parameterization By Land Use
- Table 41: Subcatchment Land Use Percentage
- Table 42: Transect Manning's n (not used with area weighting tool)

Infiltration parameters are defined in Table 38 based on Soil Type similar to the default lookup table provided with PCSWMM. These values are derived from the work of Rawls et al. (1982) .

Erosion parameters were defined for each soil type in Table 38. The fraction of clay, silt, and sand within each soil texture class are derived from the median value of the range of each particle size within a given texture class, as defined by USDA soil texture classification. The K-factor for MUSLE was derived from The Revised Universal Soil Loss Equation for Application in Canada (RUSLEFAC) published by Agriculture and Agri-Food Canada in 2002.

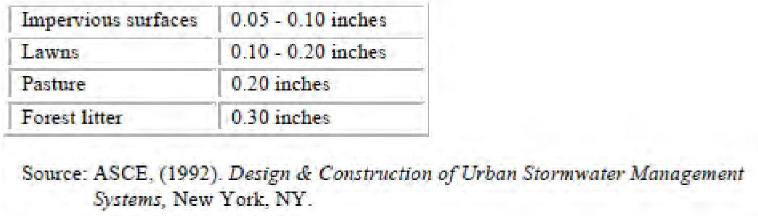
Three subcatchment parameters were determined using the Land Use layer and Table 40. Percent impervious was determined using typical impervious percentages in each land use. Manning's roughness of pervious surfaces was defined for each land use using values from reports by the U.S. Army Corps of Engineers (USACE 1998) and the Soil Conservation Service (Soil Conservation Service 1986). These values were then used for initialization of hydrologic parameters, and were modified in the calibration process.

Very little literature exists regarding the determination of depressional storage values for subcatchments in SWMM. Initially, an approach utilizing a topographical depression analysis (with LiDAR) was considered. This approach might be appropriate for a watershed-scale model, and while the RSWMMs will be essentially watershed-scale to begin with, the ability to increase the resolution of these watersheds to nearer the field scale in the future suggests that a land-use-based approximation of depressional storage might be more appropriate. Thus, due to the inherent time commitment in performing and troubleshooting such a method, as well as the independence from land-use that the results would have, a different approach was chosen.

Depressional storage has a clear correlation with surface roughness (Onstad 1984) so it was decided to use Manning's Roughness for overland flow as a surrogate, assuming a linear relationship between the two. Boundary values were chosen as the lowest and highest values cited in the SWMM 5 User Manual (see Table 12) and were used in conjunction with corresponding land uses in the table of Manning's Roughness values provided (see Table 13). If a range of values was provided instead of a single value for Manning's Roughness, the median value of that range was used.

Table 14 shows the depressional storage values resulting from this interpolation method. This method has the benefits of being based on land-use (which can change significantly in an agricultural setting at near-field-scale resolution), and that it can be adjusted easily through modification of the lookup table if desired.

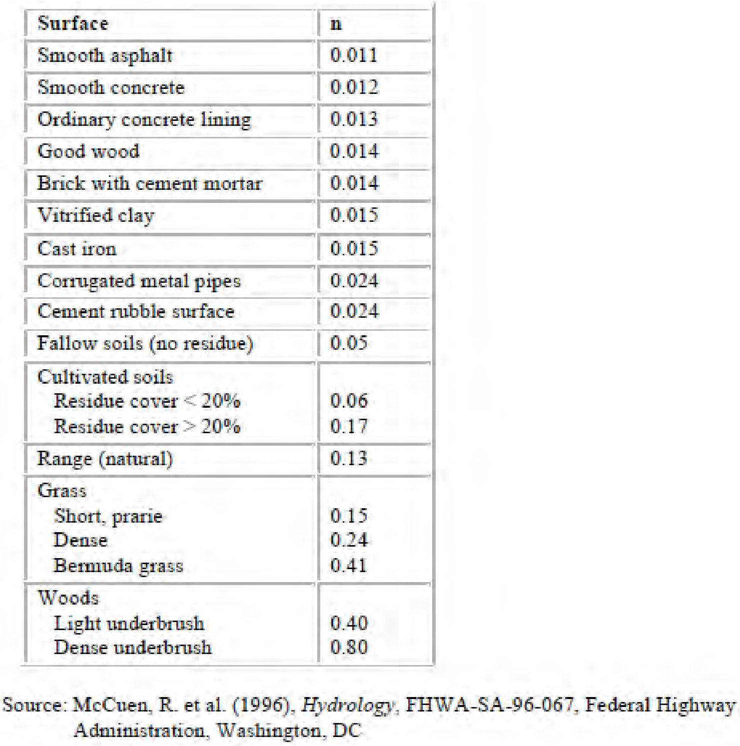
Table 12: Depressional Storage Values (Rossman 2010)



Impervious surfaces	0.05 - 0.10 inches
Lawns	0.10 - 0.20 inches
Pasture	0.20 inches
Forest litter	0.30 inches

Source: ASCE, (1992). *Design & Construction of Urban Stormwater Management Systems*, New York, NY.

Table 13: Manning's Roughness (n) for Overland Flow (Rossman 2010)



Surface	n
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipes	0.024
Cement rubble surface	0.024
Fallow soils (no residue)	0.05
Cultivated soils Residue cover < 20% Residue cover > 20%	 0.06 0.17
Range (natural)	0.13
Grass Short, prarie Dense Bermuda grass	 0.15 0.24 0.41
Woods Light underbrush Dense underbrush	 0.40 0.80

Source: McCuen, R. et al. (1996), *Hydrology*, FHWA-SA-96-067, Federal Highway Administration, Washington, DC

Table 14: Manning's N and Depressional Storage Relationship

Example land use categories	Manning's roughness		Depressional storage
	Range	Median	(mm)
Avg Grass Cover	0.4	0.4	4.40
Chisel plow	0.06 - 0.16	0.11	2.07
Commercial/Industrial	0.11	0.11	2.07
Conventional	0.16 - 0.22	0.19	2.71
Dense Cover of…	0.8	0.8	7.62
Dense Grass	0.17 - 0.30	0.235	3.07
Dense shrubbery…	0.4	0.4	4.40
Fallow	0.05	0.05	1.58
Impervious	0.011	0.011	1.27
Light Underbrush	0.4	0.4	4.40
No-Till	0.04 -0.1	0.07	1.74
Rangeland: Typical	0.13	0.13	2.23
Road	0.015	0.015	1.30
Rural Residential	0.4	0.4	4.40
*Blue value is the upper boundary, red value is the lower boundary			

The percentage of each land use in a subcatchment was calculated using the Fields layer & Table 41. The roughness of transects was set using Table 42 based on conduit material using values obtained from Chow (2009) and the American Society of Civil Engineers (Bizier 2007).

6.3.2 Pollutant Setup

Sediment, phosphorus, and nitrogen were the pools of interest for the RSWMM project. Seven pollutants were added to be modelled empirically using the Pollutant Editor: Sand, Silt, Clay, Nitrite (NO2), Nitrate (NO3), Total Kjeldahl Nitrogen (TKN), and Soluble Reactive Phosphorus (SRP). Of these, Sand, Silt, and Clay were selected in the Erosion window to be generated by MUSLE; the others were generated using washoff equations, the values for which are specified in the Land-Use Editor. Four additional pollutants were setup using the Derive time series editor: Total Nitrogen (TN), Suspended Sediment Concentration (SSC), Particulate Phosphorus (PP), and Total Phosphorus (TP). Table 15 summarizes each observed water quality component and its status in the models.

Table 15: Summary of observed water quality data.

Observed Water Quality Component	Model status	Pollutant Pool	Pollutant Name
Alkalinity	Not included	-	-
Ammonia-N	Not included	-	-
Ammonium-N	Not included	-	-
Chloride	Not included	-	-
Conductivity	Not included	-	-
Dissolved Oxygen	Not included	-	-
E. Coli	Not included	-	-
Nitrate-N	Simulated	Nitrogen	NO3
Nitrite-N	Simulated	Nitrogen	NO2
Nitrogen, Total	Derived	Nitrogen	TN
Nitrogen, Total Kjeldahl	Simulated	Nitrogen	TKN
pH	Not included	-	-
Phosphate-P	Simulated	Phosphorus	SRP
Phosphorus, Total	Derived	Phosphorus	TP
Phosphorus, Total Dissolved	Not included	Phosphorus	-
Residue, Filtered	Not included	-	-
Residue, Total	Not included	-	-
Solids, Total	Not included	-	-
Solids, Total Dissolved	Not included	-	-
Solids, Total Suspended	Simulated	Sediment	SSC
Stream Condition	Not included	-	-
Sulfate	Not included	-	-
Water Temperature	Not included	-	-

Sediment

Sediment was divided into Sand, Silt, and Clay components to facilitate a more accurate representation of sediment and phosphorus removal via settling than would be dictated by using a single "Sediment" pollutant. In fact, it is possible to divide the sediment loading into many more categories, but these three components were chosen based on the availability of literature values for phosphorus content (this issue is discussed further below). Suspended Sediment Concentration was derived as:

$$SSC = Sand + Silt + Clay.$$

Phosphorus

Phosphorus was considered to be present in two pools: particulate and dissolved (Wetzel 2001). Particulate phosphorus (PP) was derived as:

$$PP = Sand * P_{sand} + Silt * P_{silt} + Clay * P_{clay}.$$

where P_{sand}, P_{silt}, and P_{clay} represent the phosphorus content of each particle size, derived from the work of Dong et al. (1983). The dissolved phosphorus pool was assumed to consist of soluble reactive phosphorus (SRP) – often referred to as orthophosphate or dissolved inorganic phosphorus (Wetzel 2001) – and soluble unreactive phosphorus (SUP). While SUP may constitute a non-negligible fraction of total phosphorus (Jarvie, Withers, and Neal 1999; Wetzel 2001), the observed water quality data was only reported for SRP and TP and as such it was not possible to determine the relative magnitude of SUP, since both SUP and PP are unknown quantities in the following equation:

$$TP = PP + SRP + SUP.$$

Thus, the dissolved component of phosphorus was assumed to be represented solely by SRP, and the simplified representation of total phosphorus (TP) was derived as:

$$TP = PP + SRP.$$

Due to observed correlation between SRP and flow rate at selected sampling locations (see Figure 20), SRP was parameterized using the Rating Curve form of the washoff equation as suggested by James et al. (2010).

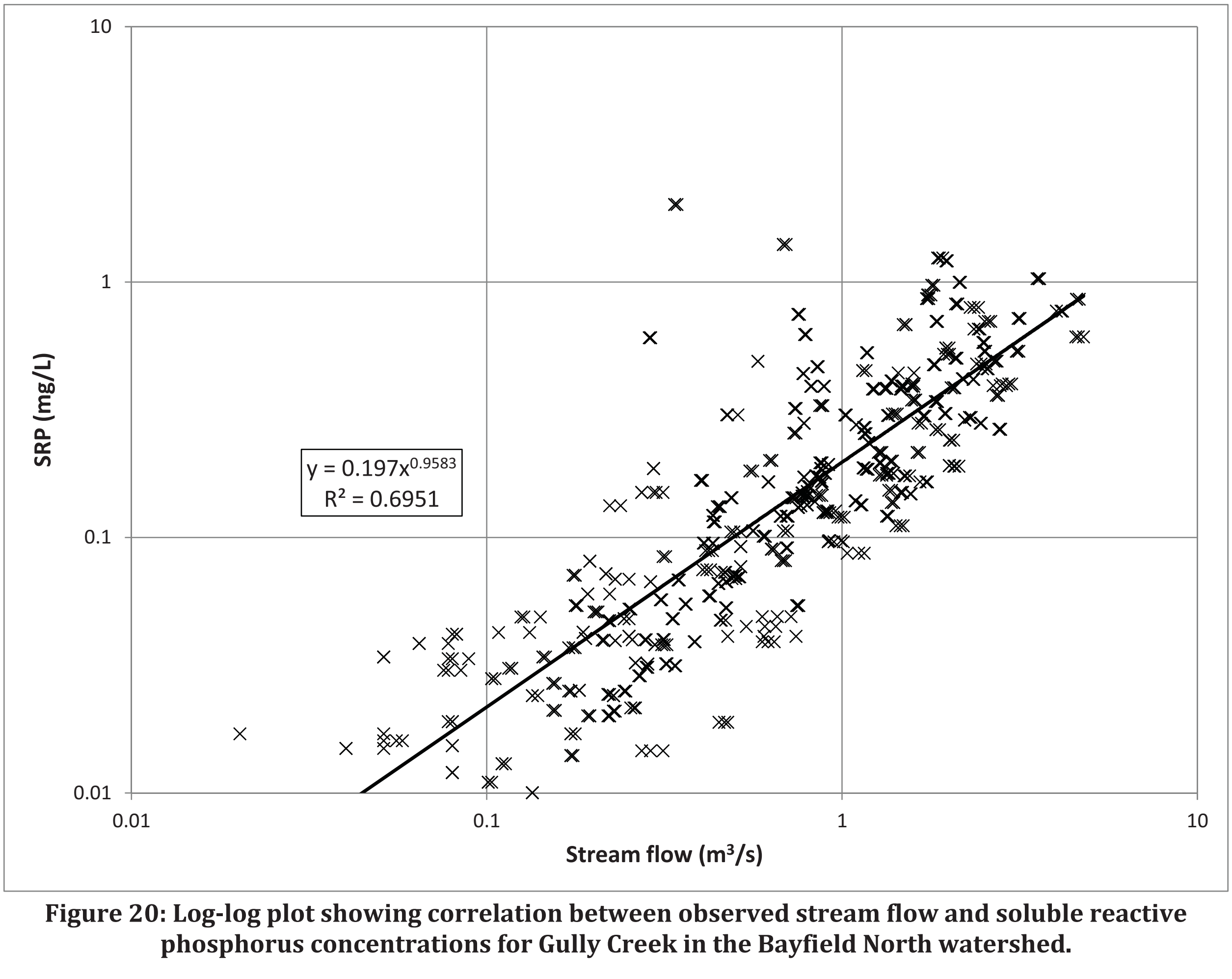


Figure 20: Log-log plot showing correlation between observed stream flow and soluble reactive phosphorus concentrations for Gully Creek in the Bayfield North watershed.

Nitrogen

Nitrogen was assumed to be completely accounted for by Nitrite, Nitrate, and TKN, which were all observed, water quality components. Due to the observed absence of correlation between any of the nitrogen components and flow rate at selected sampling locations, these pollutants were parameterized using Event Mean Concentrations form of the washoff equation within the Land-Use Editor. Since all three were reported as mg/L of nitrogen, Total Nitrogen was derived as:

$$TN = NO3 + NO2 + TKN$$

as supported by Kadlec and Knight (1995) and Wetzel (2001).

The groundwater concentration of each pollutant was set using the average baseflow concentration. These values are set in the Pollutant Attributes menu, which also facilitates the parameterization of other concentrations and process-related attributes as shown in Table 16.

Table 16: Pollutant Attributes

Attribute/Category	Value/Description
Units	mg/l
Rain Concentration	0
GW Concentration	Varies based on calibration of each pollutant
I&I, DWF, Init., and Decay Concentration	0
Snow Only	No
Co-Pollutant	n/a
Co-Fraction	0

6.4 Model Calibration

All five sentinel watershed models were calibrated for the period of May 1st to September 30th, 2013 using the observed water quantity and quality data collected at numerous monitoring stations by the CAs. The quantity calibration was limited to the spring through fall period due to the difficulty encountered in simulating timing and volume of precipitation to that captured in unheated, un-wind-shielded rain gauges. As a result, the model could not accurately simulate snowpack accumulation and snow melt. The month of April was run for use as a model warmup period but is not reported due to the persistence of snow into April 2013. Information regarding snow water content collected for use in this project can and should still be used in a future update of the model. More discussion on recommendations for future modelling improvements can be found in Section 9.3.

Similarly, validation was not performed for the spring 2014 period due to the lack of accurate precipitation data. Precipitation data accurately reflecting snowfall timing and volume (such as heated, shielded rain gauge data or radar rainfall data) would provide sufficient information to model the snowmelt in the spring.

The same period was used for both quantity and quality calibration due to the dependency of pollutant concentrations on runoff peak flows and volumes. As such, the water quality monitoring performed in 2014 may be used in future model calibration or validation.

The models were calibrated to individual rainfall events that occurred during the 2013 period. The multiple events included within the continuous simulation of the summer 2013 period reflect the model's ability to represent watershed response to storms of varying intensities and duration.

Specific synthetic storms can be run and the resulting synthetic hydrographs will be fairly well calibrated for the range of storm intensities using the continuous calibration. For similar accuracy in running higher intensity storms, future calibration to periods including such storms will be necessary.

Flow data was collected at one to three gauges in each watershed and one primary gauge was selected as the focus for quantity calibration efforts, as summarized in Table 17. Where possible, the primary gauge was located at the gauge farthest downstream to calibrate the largest area possible by general parameter adjustment. Secondary calibration locations were typically located upstream with a smaller contributing drainage area. Calibration to the secondary locations was challenging due to limited input information and the lack of attenuation that a large contributing areas and stream network tended to provide (as found at the primary gauge). Additional, watershed specific discussion of the calibration locations is provided later in this section.

Table 17: Flow Calibration Locations

Watershed	**Flow Calibration Locations**	
	Primary	**Secondary**
Pine River	Lurgan	Ripley and Temporary Level Logger
Garvey-Glenn	Kerry's Line	Division Line North and South
Bayfield North	Porters Hill Line	Tower Line Road
Main Bayfield	Trick's Creek	Varna
Lambton Shores	Shashawandah	none

Quantity calibration was performed using the Sensitivity-based Radio Tuning Calibration (SRTC) tool[7] in PCSWMM to improve the goodness of fit between the computed and observed hydrographs. First, uncertainties were set for the following parameters using the Uncertainty Estimator shown activated in Figure 21 and Figure 22:

- Subcatchment width
- Subcatchment slope
- Transect Manning's n
- Storage node constant
- Aquifer conductivity
- Monthly time patterns for:
    - Evaporation
    - Manning's n of pervious surfaces
    - Depression storage of pervious surfaces
    - Green-Ampt Parameters (conductivity, suction head, and initial deficit)

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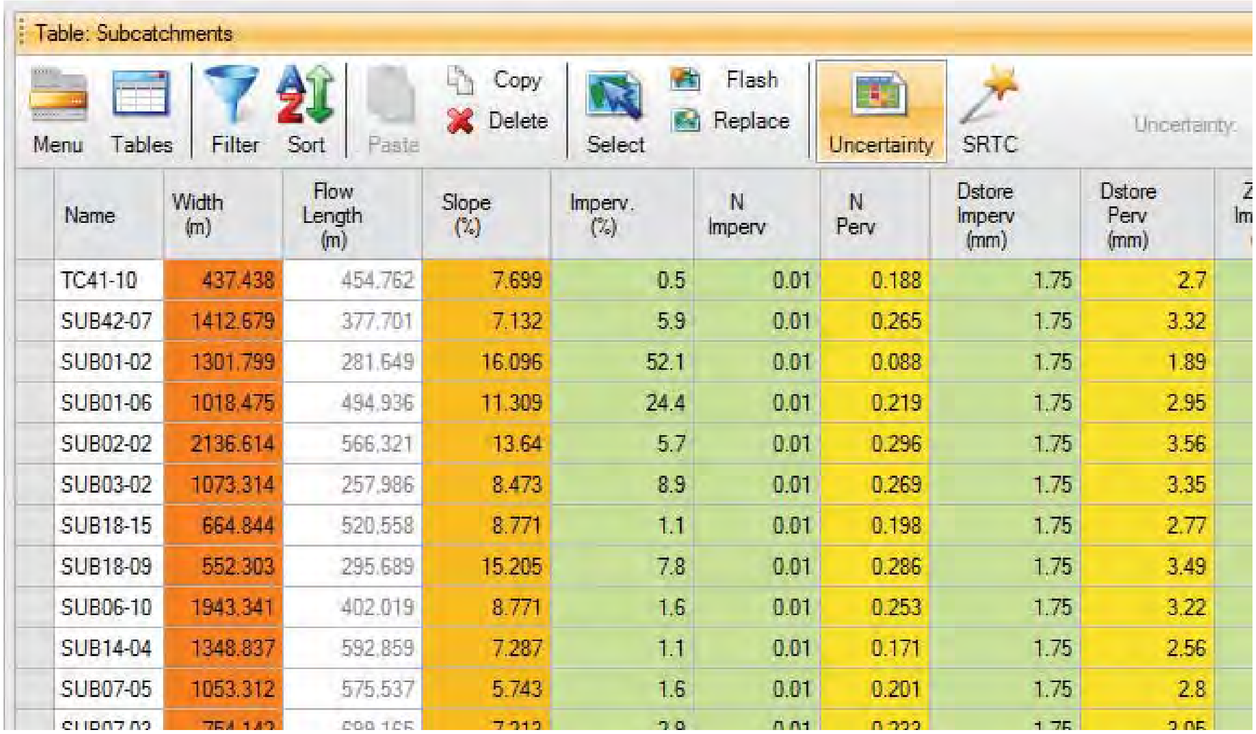
[7] More information on the SRTC tool can be found on CHI's support website: support.chiwater.com.



Name	Width (m)	Flow Length (m)	Slope (%)	Imperv. (%)	N Imperv	N Perv	Dstore Imperv (mm)	Dstore Perv (mm)
TC41-10	437.438	454.762	7.699	0.5	0.01	0.188	1.75	2.7
SUB42-07	1412.679	377.701	7.132	5.9	0.01	0.265	1.75	3.32
SUB01-02	1301.799	281.649	16.096	52.1	0.01	0.088	1.75	1.89
SUB01-06	1018.475	494.936	11.309	24.4	0.01	0.219	1.75	2.95
SUB02-02	2136.614	566.321	13.64	5.7	0.01	0.296	1.75	3.56
SUB03-02	1073.314	257.986	8.473	8.9	0.01	0.269	1.75	3.35
SUB18-15	664.844	520.558	8.771	1.1	0.01	0.198	1.75	2.77
SUB18-09	552.303	295.689	15.205	7.8	0.01	0.286	1.75	3.49
SUB06-10	1943.341	402.019	8.771	1.6	0.01	0.253	1.75	3.22
SUB14-04	1348.837	592.859	7.287	1.1	0.01	0.171	1.75	2.56
SUB07-05	1053.312	575.537	5.743	1.6	0.01	0.201	1.75	2.8

Figure 21: Uncertainty of some subcatchment parameters

Custom: 23 %

Figure 22: Example of the Uncertainty Assignment window

The SRTC tool was then used to iteratively adjust the parameters with uncertainties. A computational grid was used to run SRTC tool scenarios in parallel and reduce the overall time required for calibration. When calibrating the time patterns, the SRTC adjusts all factors of the same month with uncertainties simultaneously. As such, each time pattern was given an uncertainty one at a time. The initial groundwater table elevation calculated outside of PCSWMM was also used as a calibration parameter but could not be revised through the SRTC tool. A summary of the error between the final computed and observed hydrographs for the summer of 2013 (May 1st to September 30th, 2013) is provided in Table 18. Main Bayfield and Bayfield North have the best fit calibration of all five models. The largest watershed with the lowest detail in input data, Pine River, has the poorest fit calibration.

Table 18: Summary of Quantity Calibration Results

Watershed	Monitoring Location Name	NSE	R^2
Pine River	Lurgan (1)	-0.153	0.379
Garvey-Glenn	Kerry's Line (CB-20)	0.301	0.403
Bayfield North	Porters Hill Line (CH-G189)	0.428	0.673
Main Bayfield	Trick's Creek (CH-B74)	0.651	0.672
Lambton Shores	Shashawandah (C12)	0.387	0.498

Notes:
NSE – Nash-Sutcliffe efficiency (NSE)
R^2 – Coefficient of Determination

Quality calibration was performed for dissolved (NO_2, NO_3, SRP, and TKN) pollutants by adjusting the concentration in groundwater to improve the fit with observed low concentrations and by adjusting the washoff coefficients and exponent to match the magnitude of high concentrations. In light of the absence of knowledge regarding the proportions of TP made up by PP and SUP, as well as the absence of simulation for in-stream phosphorus dynamics, reasonable simulated total phosphorus targets for calibration could be assumed to be well below observed values.

Suspended sediment concentration (SSC) was calibrated using the soil erodibility factor, *K*, primarily because it is the easiest of the MUSLE factors to vary when considering the method of derivation in the model[8]. The intention was to adjust *K* by the same factor in all five models, however the goodness of fit of the calibration could not be evaluated based on the sparse observed data in Pine River, Lambton Shores, and Garvey-Glenn. Sediment was only calibrated, therefore, for Main Bayfield and Bayfield North by increasing *K* by a factor of six in both models. The modelled concentration was calibrated to be lower than observed SSC levels because in-stream erosion is not modelled.

The difference in modelled SSC compared to the observed TSS in Pine River and Lambton Shores is also partially due to how the loadings were monitored and how they were calculated in the model. The observed data for suspended solids was measured as TSS, whereas the model generates sediment loading from fields alone (i.e. in-stream and near-stream sediment sources are not considered at this time). Furthermore, the low SSC calculations result in underestimating total phosphorus because a significant portion of total phosphorus is attached to sediment. More discussion on the differences between TSS and SSC can be found in Section 9.3.2.

A summary of the error between the final computed pollutographs compared to the observed data for the summer of 2013 (May 1st to September 30th, 2013) is provided in Table 19 for each calibrated pollutant. The NSE calculation in PCSWMM is suitable for use with a sparsely populated grab sample data set. NSE is calculated by interpolating between computed results to the time steps of observed data values and then uses these two data sets (interpolated computed results and observed data) to calculate error functions.

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[8] The other MUSLE factors are either calculated by SWMM or through auto-expressions or are not appropriate for calibration.

Table 19: Summary of Quality Calibration Results NSE

Watershed	Monitoring Location Name	NO_2	NO_3	SRP	TKN	SSC
Pine River*	Ripley (58)	-1.62	-1.52	0.123	-4.01	-0.439
Garvey-Glenn	Kerry's Line (CB-20)	-0.603	-0.101	0.168	-0.781	-6.73*
Bayfield North	Porters Hill Line (CH-G189)	0.331	0.0452	-0.173	-2.63	-0.025
Main Bayfield	Trick's Creek (CH-B74)	-0.168	-0.736	-0.149	-0.764	0.185
Lambton Shores	Shashawandah (C13)	-0.576	-0.639	0.602	-0.59	0.28*

* Not calibrated due to limited monitoring data.

Not all of the statistical measures of model fit were within acceptable ranges, especially for those watersheds with limited observed water quality data during the simulation period. Often, the timing of spikes in certain water quality indicators (such as increased nitrates in late spring) corresponded with typical agronomic practices (e.g. spring fertilizer application), but at this point time-variable washoff parameters are not available in SWMM. Improvements to the hydraulics of the models, expansion of the observed datasets, and improving the methodology of pollutant washoff should all be considered necessary steps toward a future calibration effort. More discussion on recommendations for future improvements to the models can be found in Section 9.3. The following subsections discuss the calibration results of each sentinel model.

6.4.1 Pine River

The primary calibration point in the Pine River watershed model was the Lurgan gauge, which was one of three flow monitoring locations. The final calibration of the Pine River watershed model is shown in Figure 23 comparing the computed and observed hydrographs. The calibration has an an NSE of -0.153 and an R^2 error of 0.379. Calibration was limited by the relatively dry summer of 2013 providing few events for calibration. The calibration shows two events in late May corresponding with the timing of observed peak flows. However, the calibration does not show the event in late June. This may be due to a localized storm not captured by the rain gauges in the Pine River watershed. The calibration also shows several events that were not observed in late August and September. This may be due to rainfall that occurred locally at the meteorological monitoring stations but was applied across the watershed in the model. There also may be attenuation or infiltration not accounted for throughout the watershed. As the largest of the five sentinel watersheds, representing localized rainfall events is a substantial challenge. An additional challenge was the absence of baseflow (low flows) recorded at the Lurgan gauge.

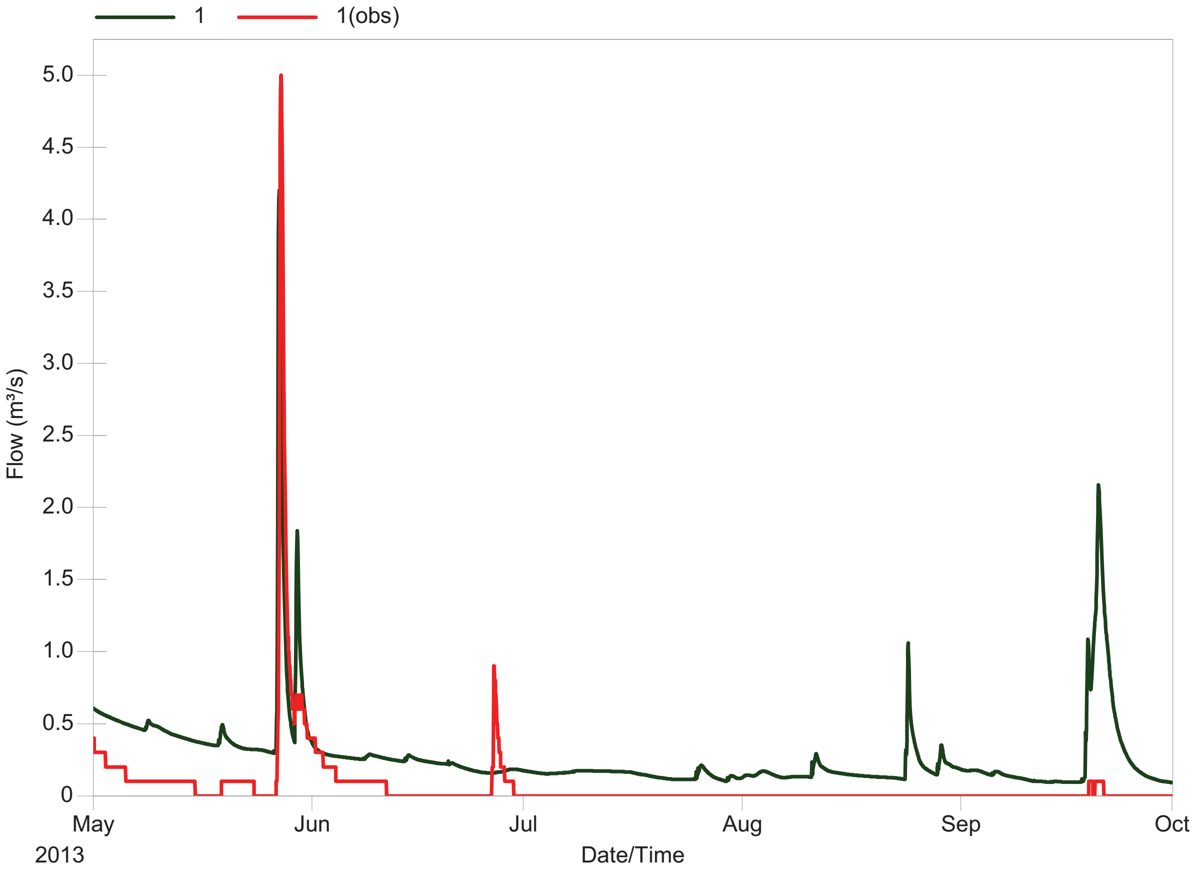
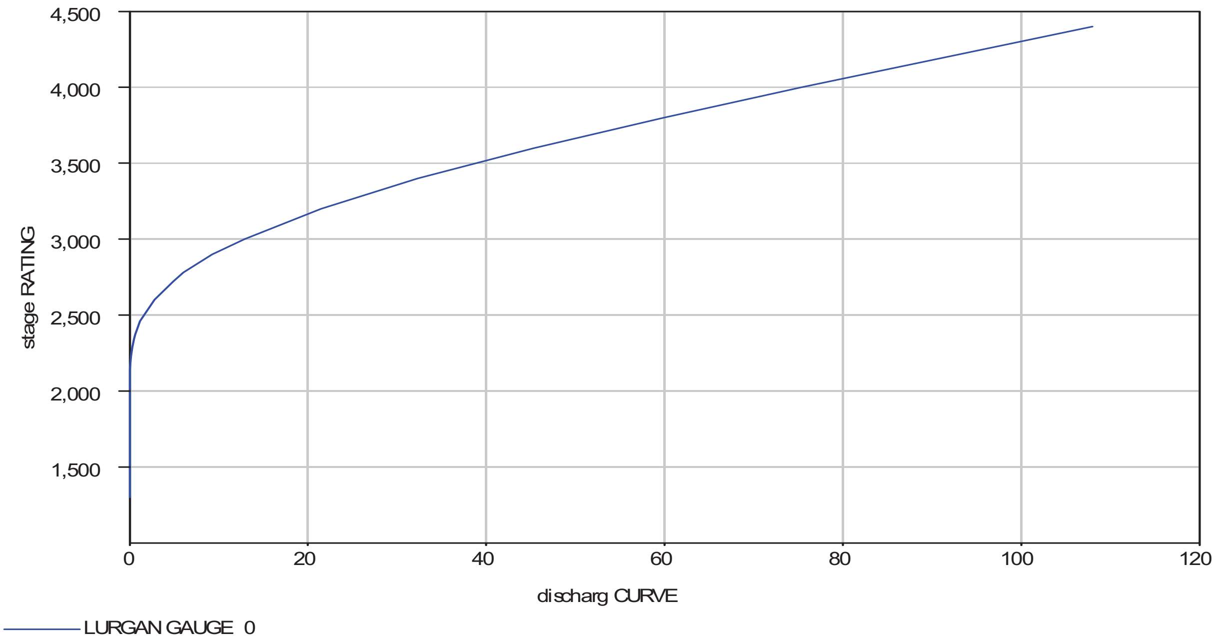


Figure 23: Pine River Calibration - Flow at Lurgan (Bridge 1)

The Lurgan gauge is Water Survey of Canada station 02FD001 and is owned by Environment Canada. The monitoring data published online by Environment Canada notes that flow data is not available after August 25, 2011 due to dredging activity. However, the absent baseflow in 2013 is consistent with historical data also showing low to no baseflow during the summer months. The gauge is located at the last major road crossing upstream of Lake Huron and has an upstream drainage area greater than 15,000 ha. The absence of baseflow in the observed data shown in

Figure 23 may be associated with minor inaccuracies in rating curve calculations at low water levels. The rating curve in Figure 24 shows the flow associated with water levels less than 2.2 metres to be zero. The raw stage and discharge data are provided in Figure 25 and Figure 26, respectively.



Note: Discharge in m^3/s and stage in mm

Figure 24: Stage Discharge Curve for Lurgan Gauge (Bridge 1)

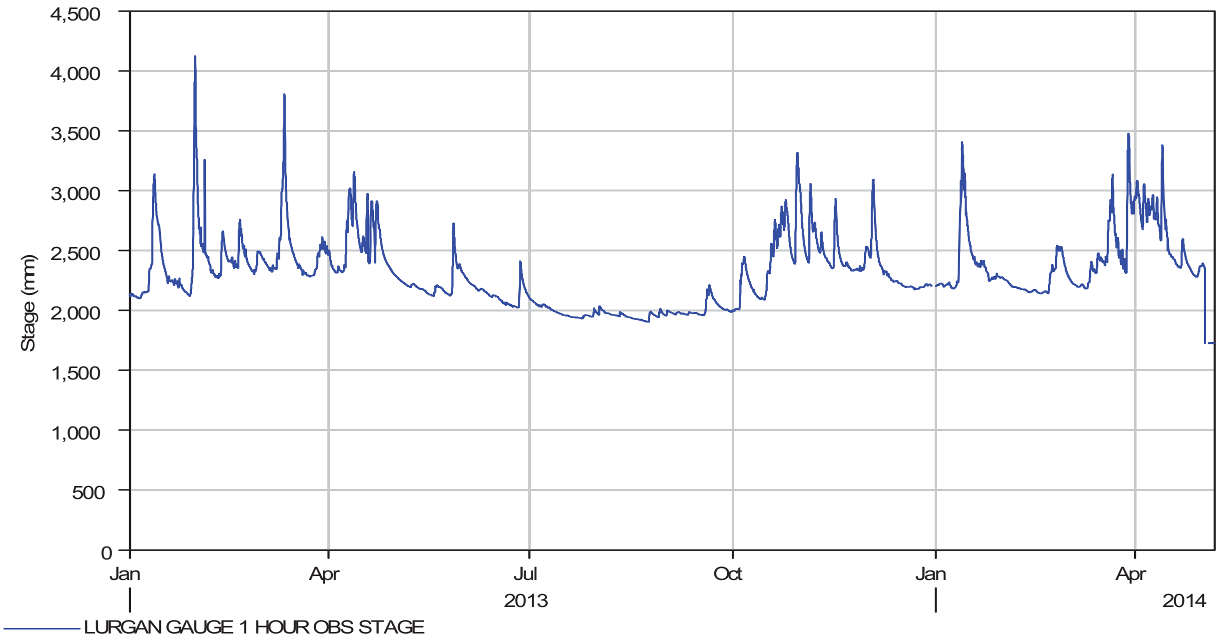


Figure 25: Water Level at Lurgan Gauge (Bridge 1)

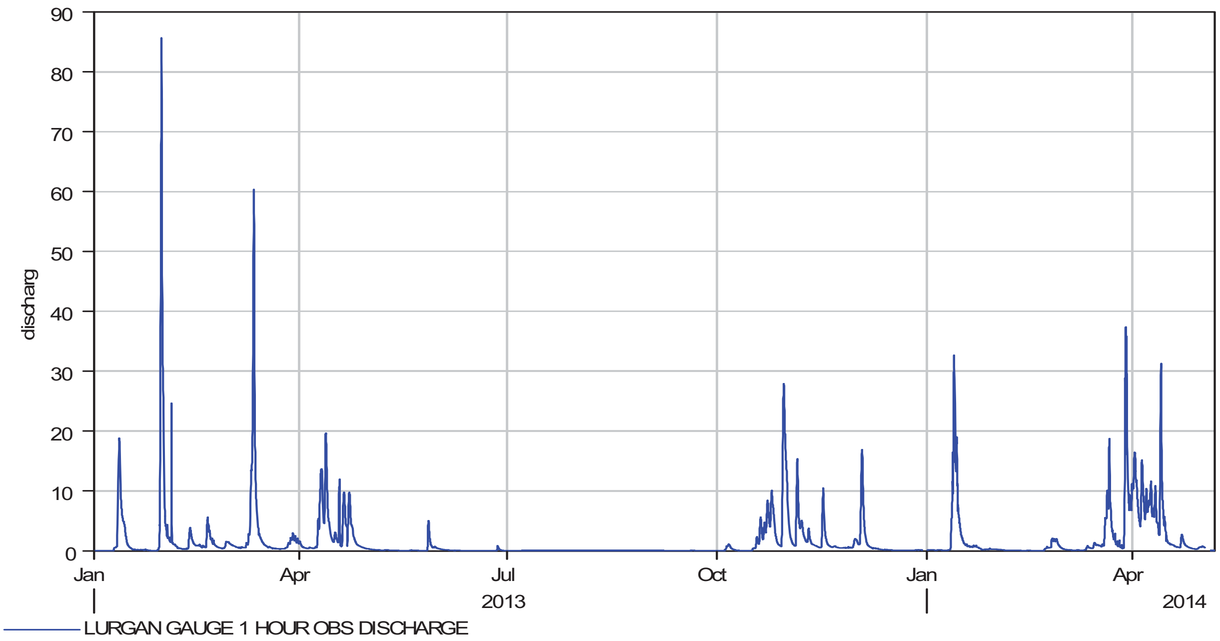


Figure 26: Discharge at Lurgan Gauge (Bridge 1)

In contrast, baseflow was observed at the Ripley gauge located upstream of Lurgan in the South Pine River tributary at Bridge 58. As such, the calibration of baseflow at the Lurgan gauge was limited by maintaining appropriate baseflow at the upstream Ripley gauge.

However, Ripley could not be used as the primary calibration point due to concerns with the recorded precipitation and flow data. In addition to these concerns, a test scenario focussing on calibrating to the Ripley gauge resulted in downstream peak flows at Lurgan being greatly overestimated. An error in the flow monitoring data at the Ripley gauge was also noted at the end of April, where the observed peak had a vertical recession curve that did not look realistic. An additional issue with shifted precipitation data was also noted, as previously discussed in Section 6.2.

The third flow monitoring station, the Temporary Level Logger, was located upstream of the Ripley gauge in the South Pine River tributary at Culvert 76, as shown in Figure A.1. Although the gauge captured response to two events at the end of May, the low attenuated peak flows throughout the rest of the summer of 2013 appeared to be caused by storage or structures not accounted for in the model inputs. It was also noted that a fence was installed at the upstream end of Culvert 76 and could have had an impact on the gauge's data. The model results were not calibrated to this location.

Quality calibration was not completed for the Pine River model because only three grab samples were taken during the summer of 2013 and were insufficient to calibrate pollutant concentrations calculated in the model. Other periods where more water quality data was collected, such as spring 2014, could not be used because pollutant concentrations are dependent on the runoff and quantity calibration that was not be performed due to inaccuracies in snow data. An ISCO sampler was used in 2013 before and after the summer calibration period. The observed water quality samples are compared to the un-calibrated pollutographs for NO_2, NO_3, SRP, TKN, and SSC in Figure 27 to Figure 31.

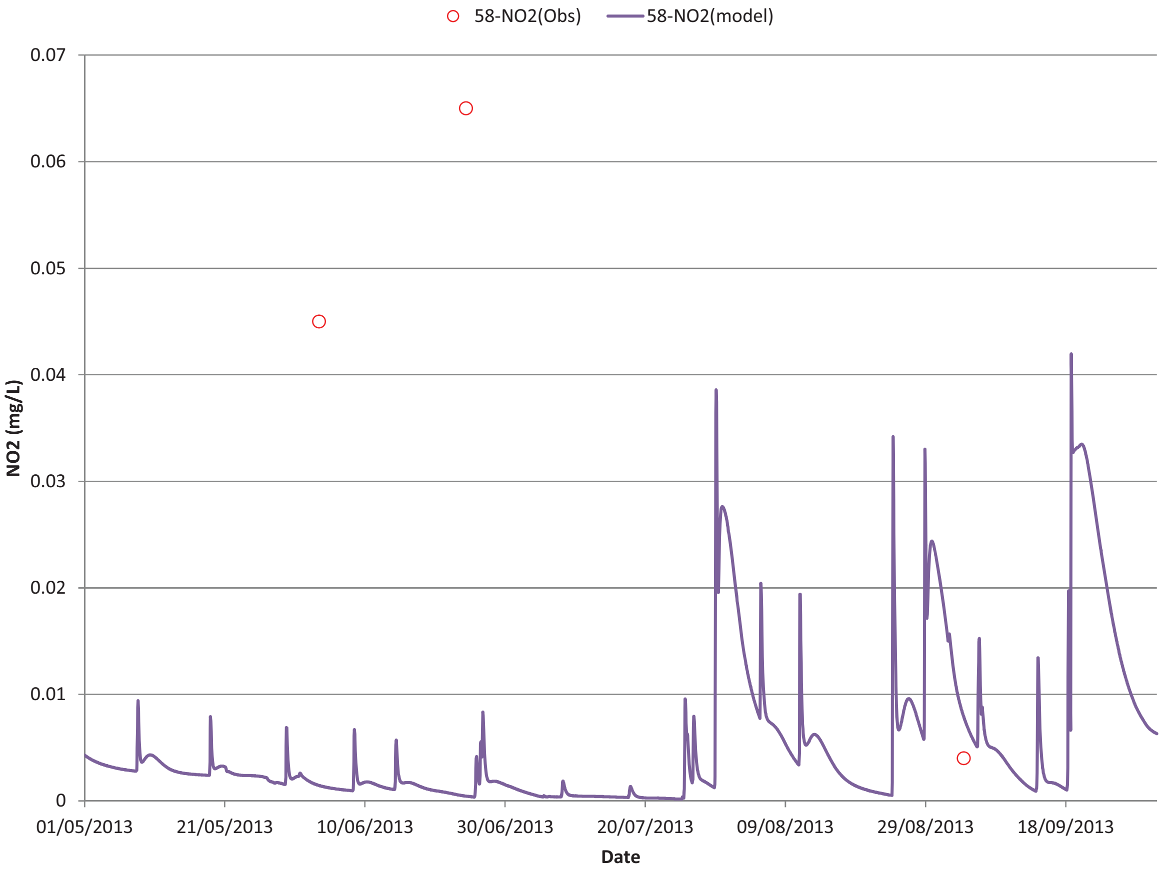


Figure 27: Pine River – Uncalibrated NO_2 Pollutograph at Ripley (Bridge 58)

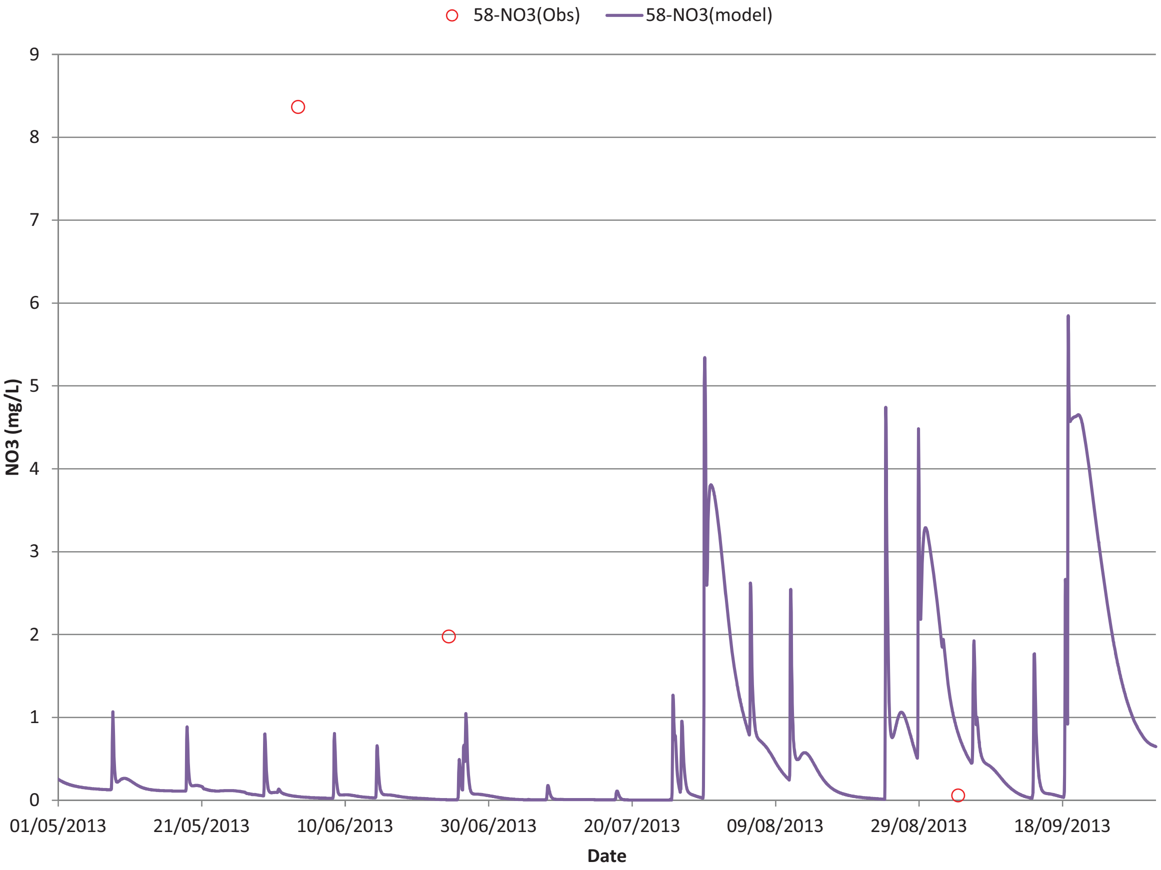


Figure 28: Pine River – Uncalibrated NO_3 Pollutograph at Ripley (Bridge 58)

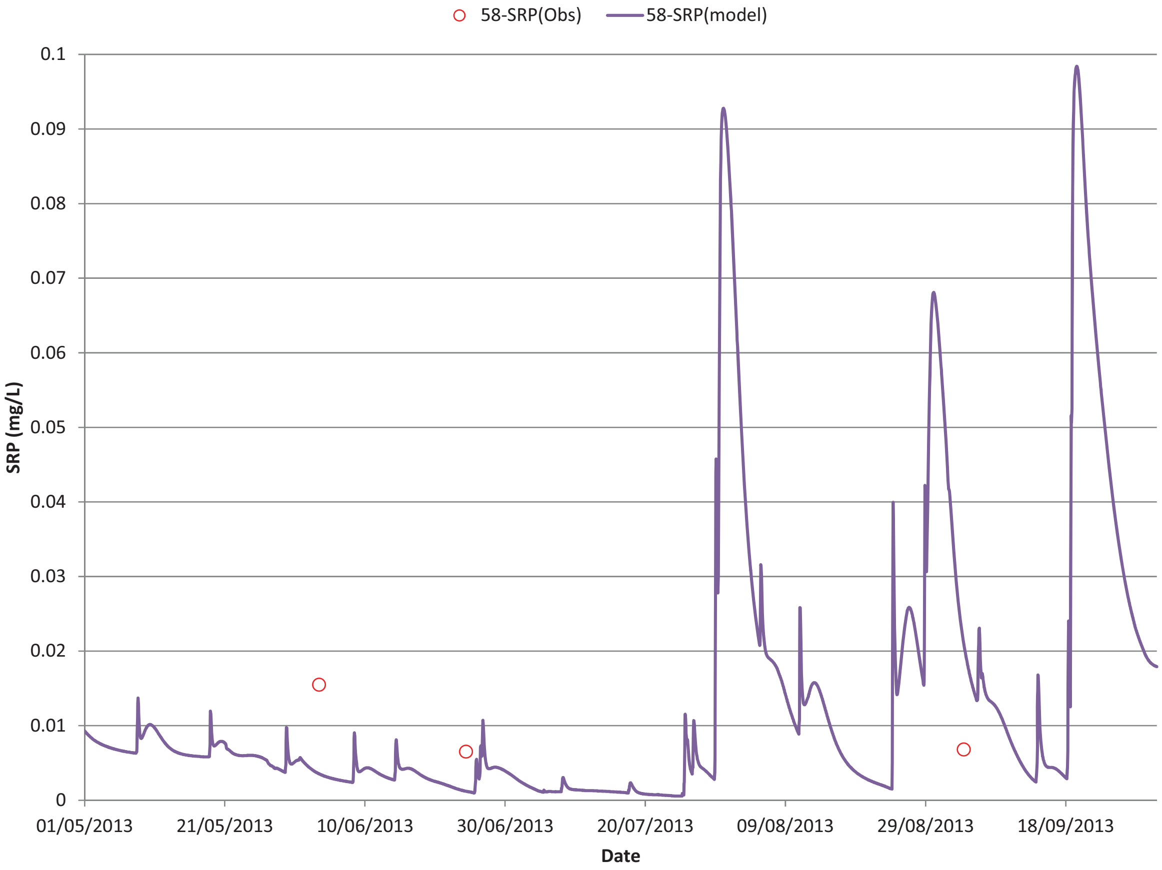


Figure 29: Pine River - Uncalibrated SRP Pollutograph at Ripley (Bridge 58)

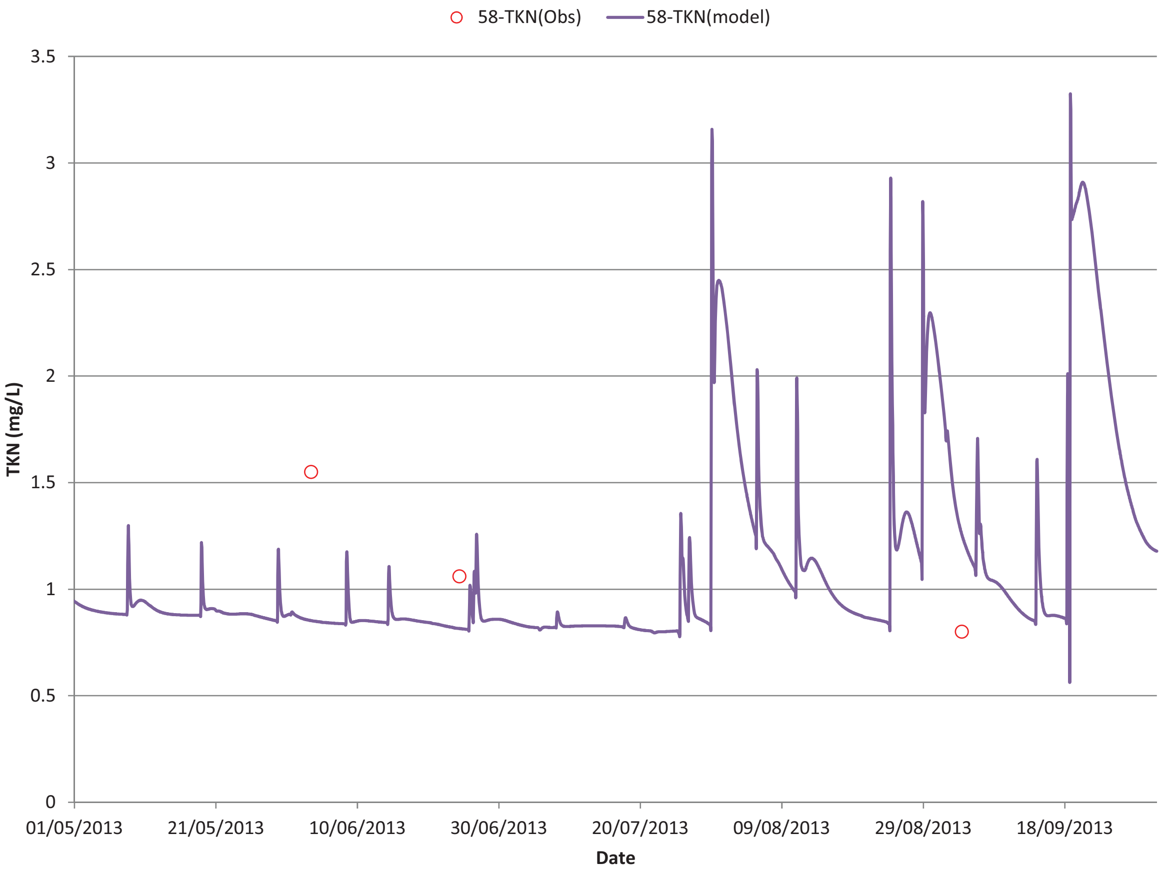


Figure 30: Pine River - Uncalibrated TKN Pollutograph at Ripley (Bridge 58)

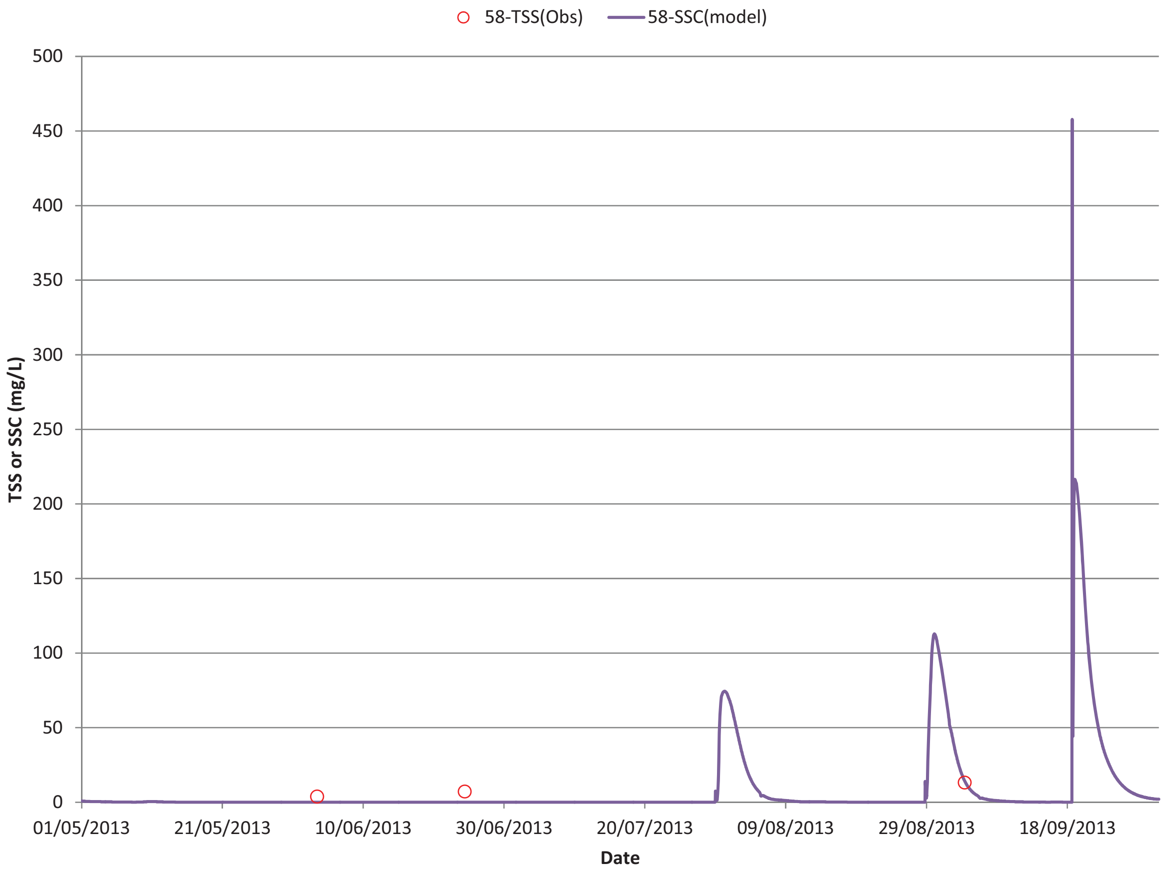


Figure 31: Pine River - Uncalibrated SSC Pollutograph at Ripley (Bridge 58)

6.4.2 Garvey-Glenn

The Garvey-Glenn watershed model was calibrated to the observed quantity and quality at the concrete box culvert crossing Kerry's Line (CB-20). The observed and computed hydrographs are compared in Figure 32 showing a good fit with an NSE of 0.301 and an R^2 error of 0.403. The calibration underestimates extended peak flows in May, which may cause the overestimated peak flows in early June and overestimated receding limb at the end of June. Only two storms were recorded in May 2013 and the calibration from May to June was limited by aquifer conductivity. The calibration has a good fit with baseflow for the remainder of the simulation and the event in early August. The calibration shows a peak flow event at beginning of September that is not observed. This may be due to a localized storm captured by the precipitation gauge that did not cover the area upstream of CB-20. The calibration shows no watershed response to the observed event later in September. The calibration underestimates the final event at the end of September.

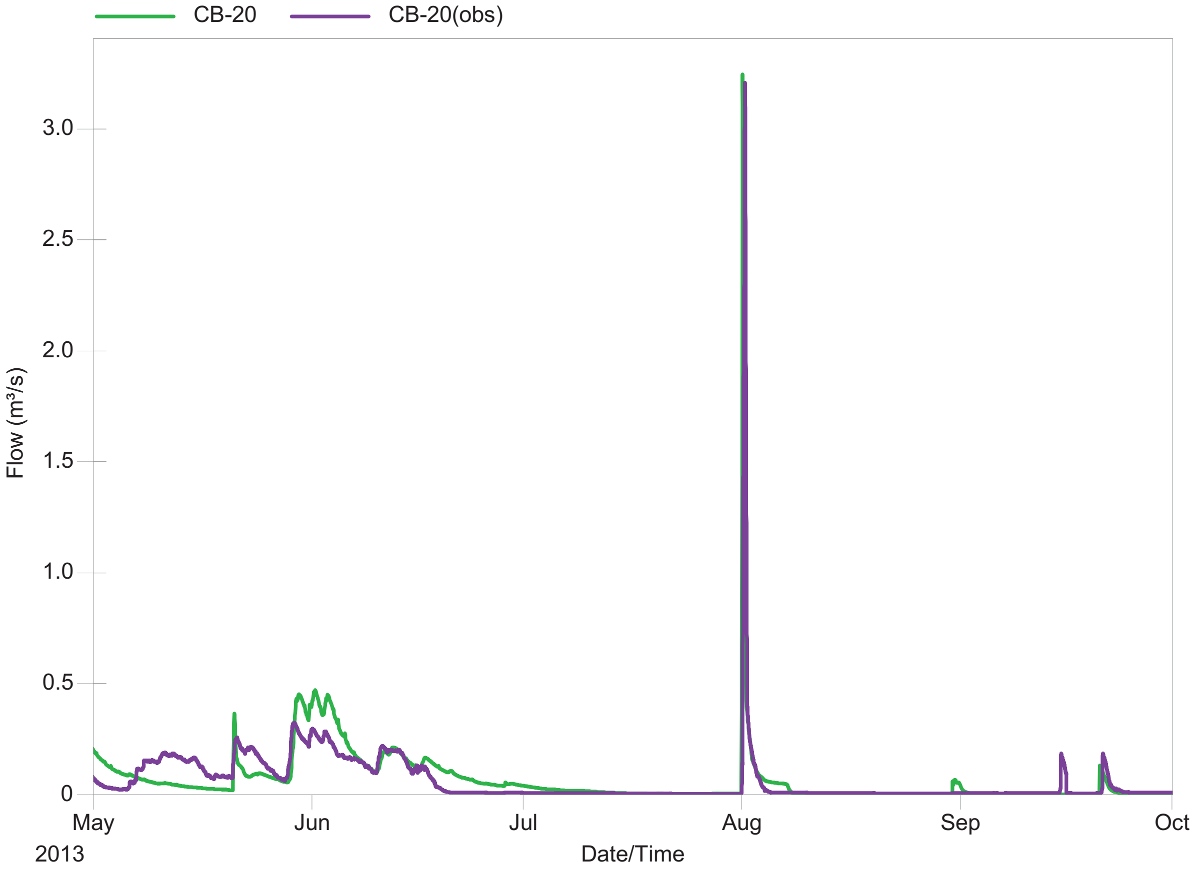


Figure 32: Garvey-Glenn Calibration – Flow at Kerry's Line (Culvert CB-20)

Flow was also monitored upstream of Kerry's Line at two crossings of Division Line. Minor parameter adjustments were made specific to these locations to improve the calibration, however peak flows were overestimated at the upstream gauges to prevent underestimating the May and June events at the Kerry's Line gauge. Suggested improvements to the model are discussed in Section 9.3.

The final quality calibrations of the Garvey-Glenn watershed model at Kerry's Line (CB-20) are shown in Figure 33 to Figure 37 comparing the computed pollutographs for NO_2, NO_3, SRP, TKN, and SSC to the observed data. The NSE of each calibration is summarized in Table 20.

Table 20: Summary of Garvey-Glenn Quality Calibration Results NSE at Kerry's Line (CB-20)

	NO_2	NO_3	SRP	TKN	SSC*
NSE:	-0.603	-0.101	0.168	-0.781	-6.73

* Not calibrated due to limited monitoring data.

The observed peak in nitrite concentration in June shown in Figure 33 was assumed to be caused by application of fertilizer, the washout of residual soil nitrogen, or some other source. These time-variant sources are not considered in the models at this time, so the calibration was focused on matching the peaks in concentration later in the summer.

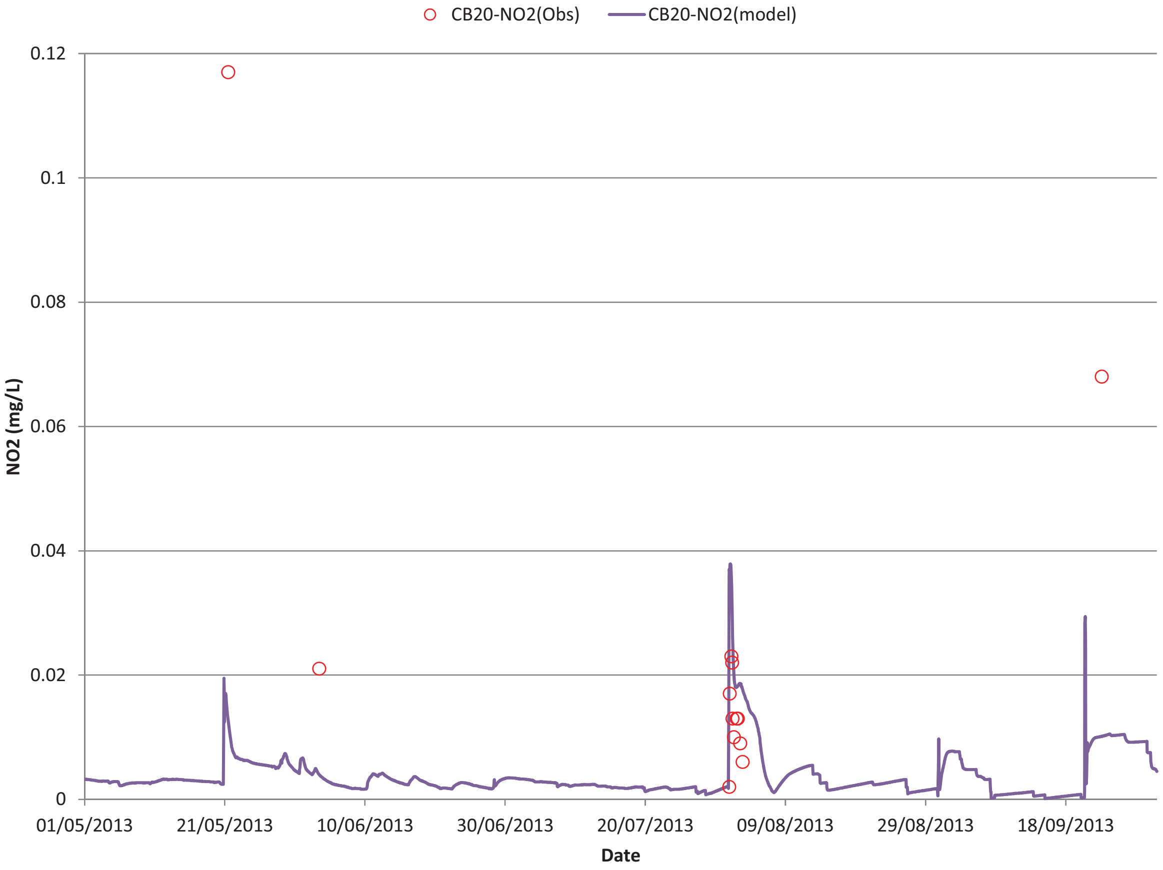


Figure 33: Garvey-Glenn Calibration – NO_2 Pollutograph at Kerry's Line (Culvert CB-20)

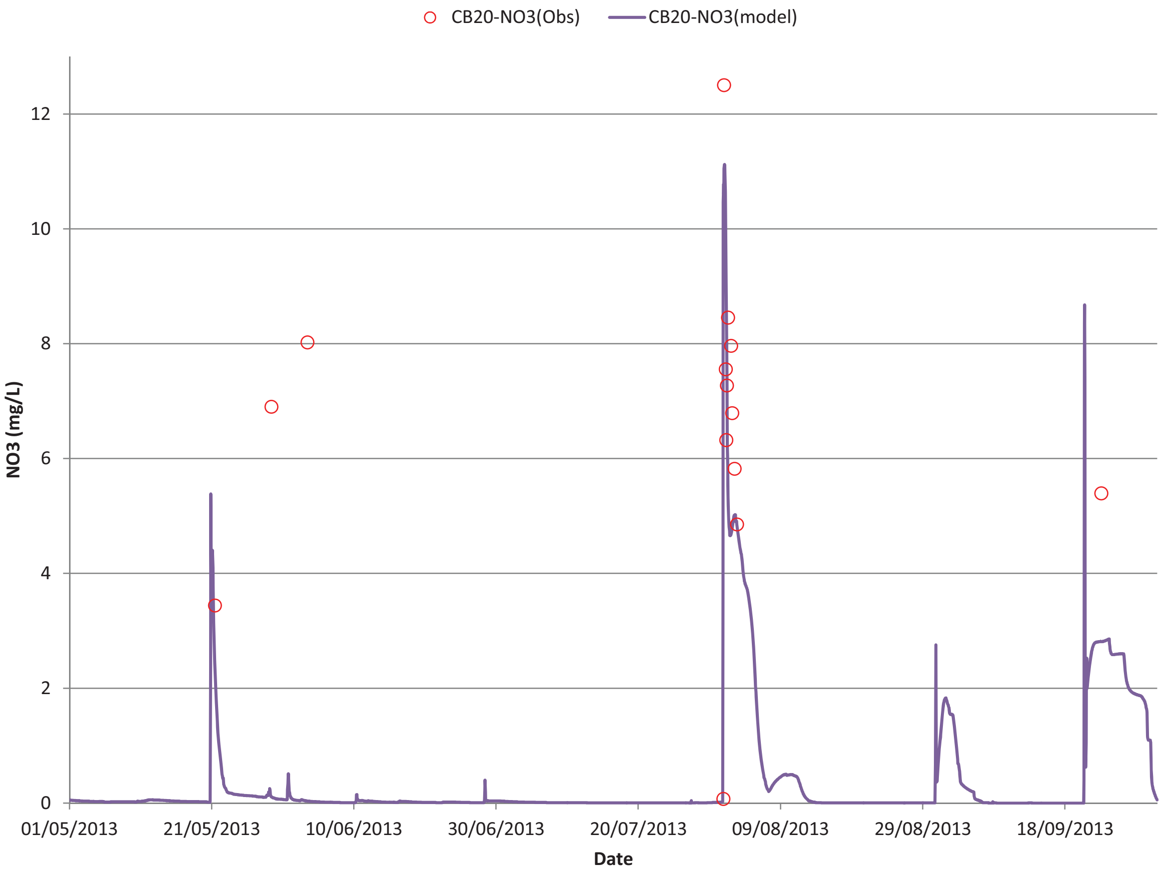


Figure 34: Garvey-Glenn Calibration – NO_3 Pollutograph at Kerry's Line (Culvert CB-20)

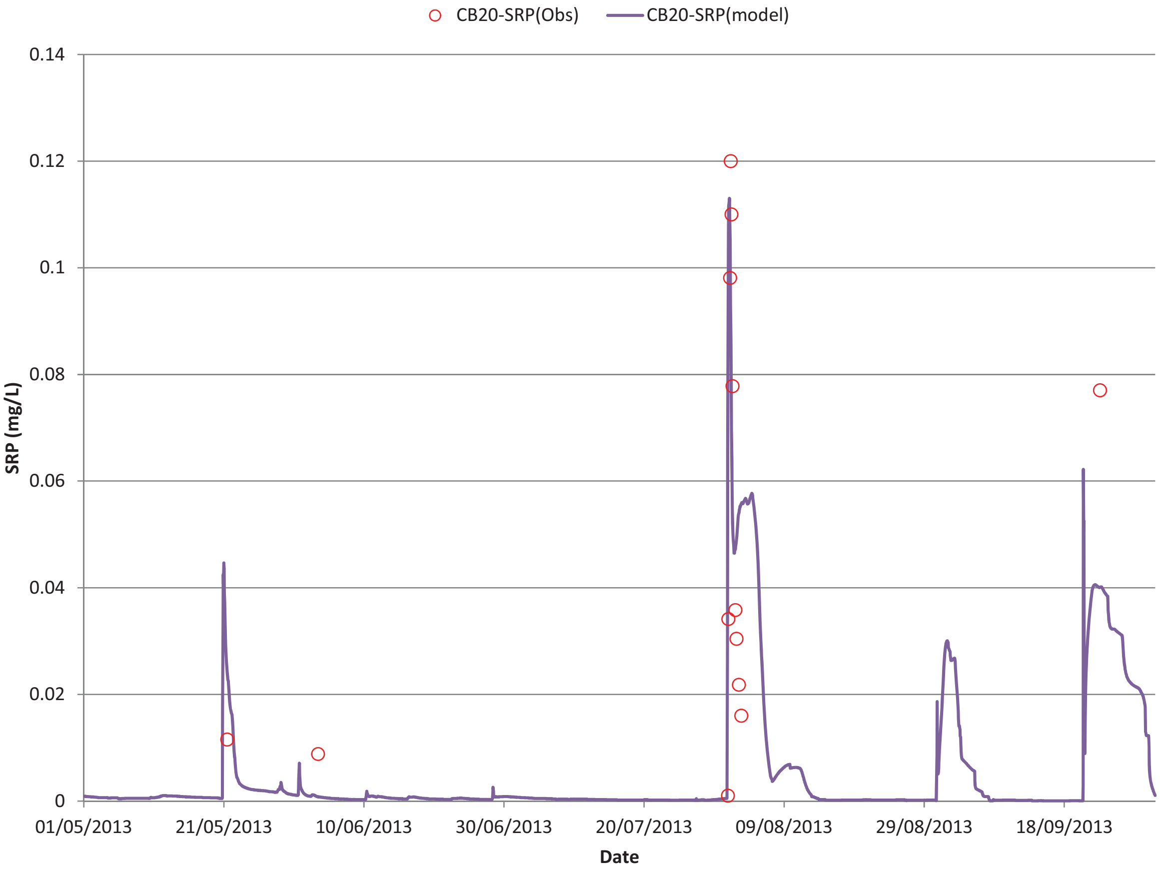


Figure 35: Garvey-Glenn Calibration – SRP Pollutograph at Kerry's Line (Culvert CB-20)

The simulated TKN pollutograph in Figure 36 shows sustained elevated concentrations in August and September. This anomaly is also found in the Bayfield North model and needs to be investigated further in future model improvements. At this point, no logical explanation can be provided for this behaviour, but it is possible that the issue stems from either a numerical error in the SWMM code or an unknown issue with the method of treatment expression setup.

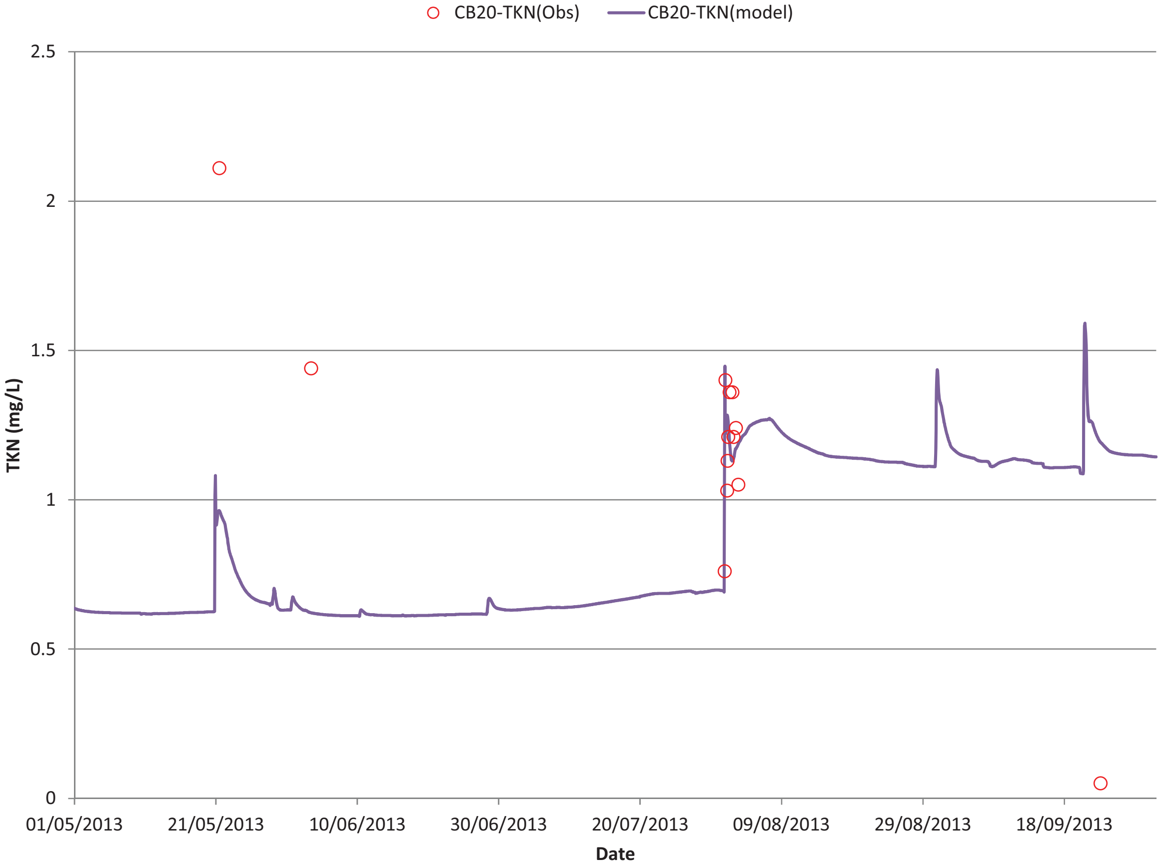


Figure 36: Garvey-Glenn Calibration – TKN Pollutograph at Kerry's Line (Culvert CB-20)

The calibration for SSC shown in Figure 37 has a very low NSE because the calculated SSC is much greater than the observed data. SSC was not calibrated in the Garvey-Glenn model because the sparse data was insufficient to evaluate the goodness of fit.

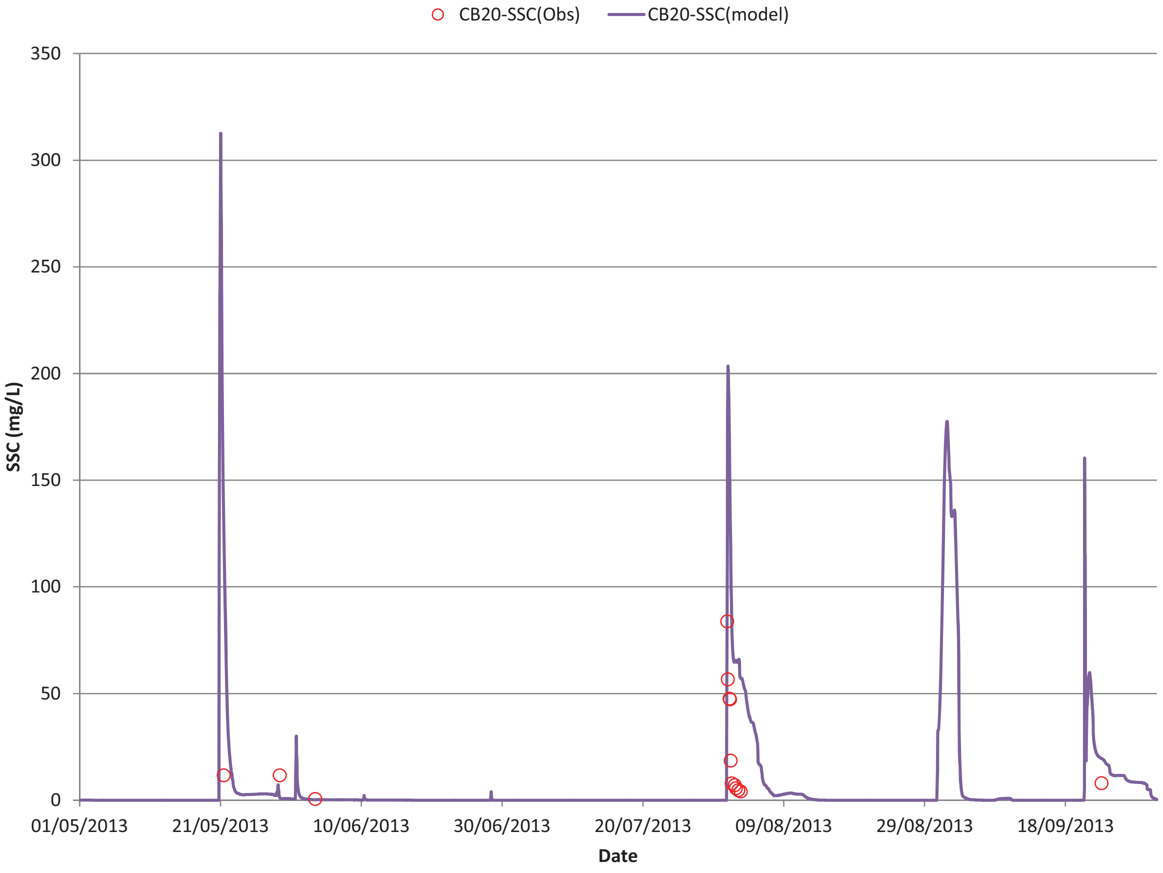


Figure 37: Garvey-Glenn – Uncalibrated SSC Pollutograph at Kerry's Line (Culvert CB-20)

6.4.3 Bayfield North

Quantity calibration of the Bayfield North model was limited to two flow monitoring stations on Gully Creek, although there are many separate tributaries draining to Lake Huron in this watershed. The parameter adjustments made based on the Gully Creek calibration points were applied across the watershed. The final calibration of the Bayfield North watershed model at Porters Hill Line (Culvert CH-G189) is shown in Figure 38 comparing the computed and observed hydrographs. The calibration has a very good fit with an NSE of 0.428 and an R^2 error of 0.673. The peaks in early June and August are slightly overestimated in the calibration and multiple peaks are delayed compared to the timing of observed flow.

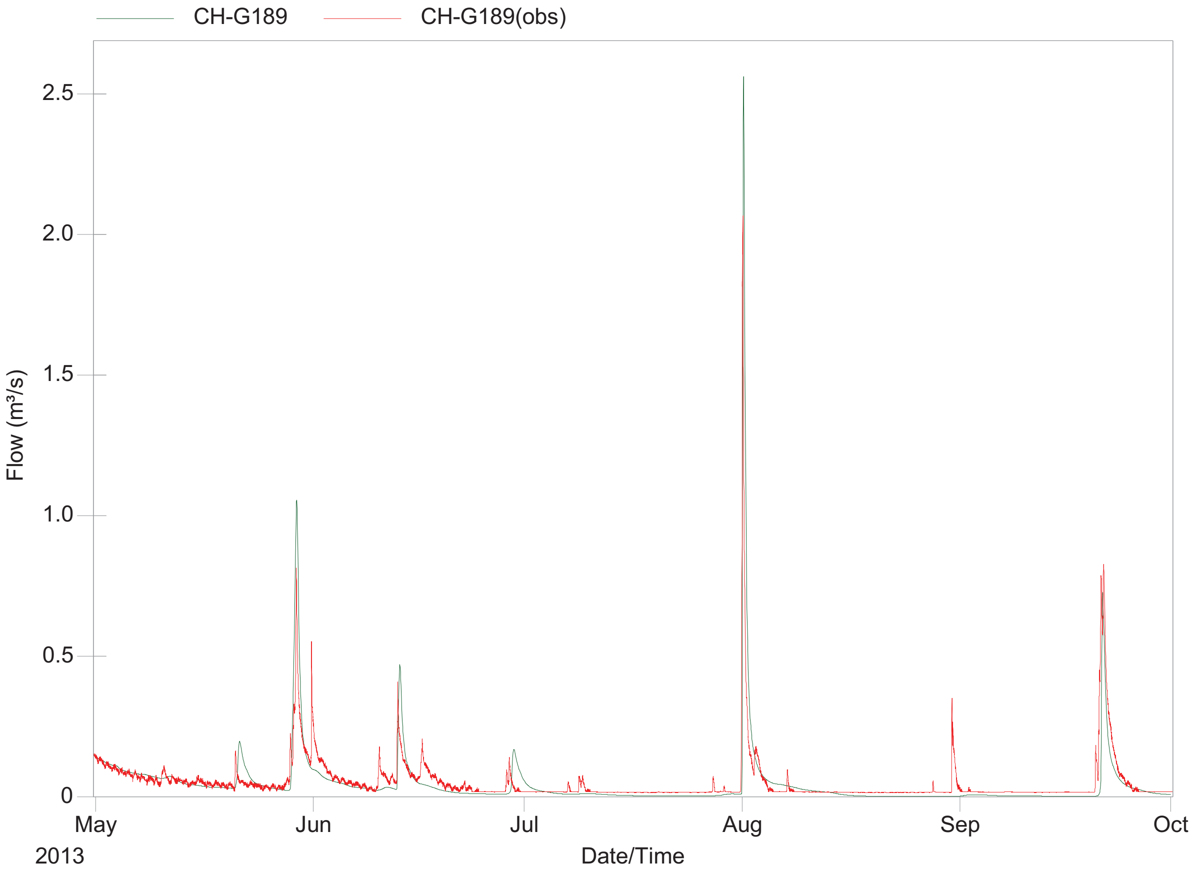


Figure 38: Bayfield North Calibration – Flow at Porters Hill Line (Culvert CH-G189)

The secondary calibration point is located upstream of the primary calibration point on Gully Creek at Tower Line Road (CH-G188). The calibrated model generally overestimates peak flows at the secondary location. Suggested improvements to the model are discussed in Section 9.3.

The final quality calibrations of the Bayfield North watershed model at the Porters Hill Line (CH-B74) are shown in Figure 39 to Figure 43 comparing the computed pollutographs for NO_2, NO_3, SRP, TKN, and SSC to the observed data. The NSE of each calibration is summarized in Table 21.

Table 21: Summary of Bayfield North Quality Calibration Results NSE at Porters Hill Line (CH-G189)

	NO_2	NO_3	SRP	TKN	SSC
NSE:	0.331	0.0452	-0.173	-2.63	-0.025

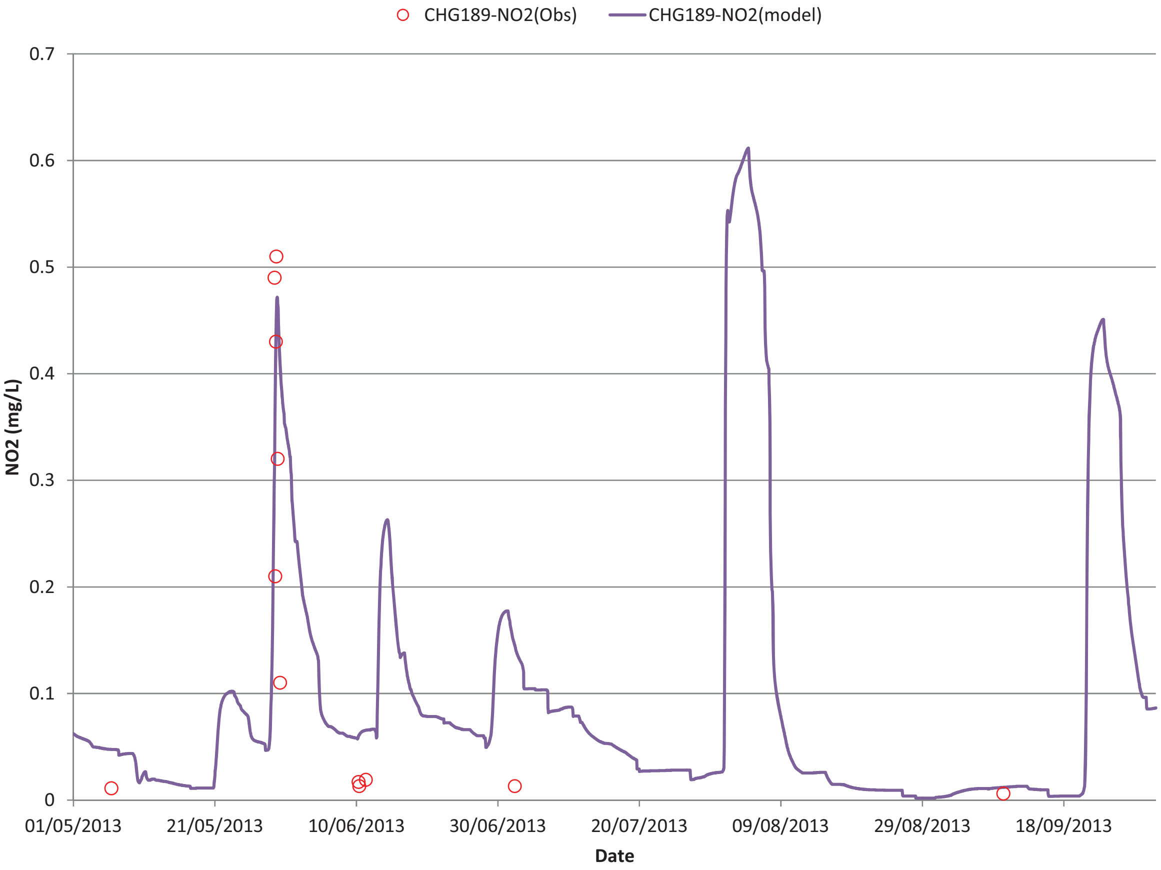


Figure 39: Bayfield North Calibration – NO_2 Pollutograph at Porters Hill Line (Culvert CH-G189)

The nitrate calibration shown in Figure 40 assumed that the large peak in concentration in June was due to fertilizer application, the washout of residual soil nitrogen, or some combination of these and other time-variant processes not accounted for in the models at this time.

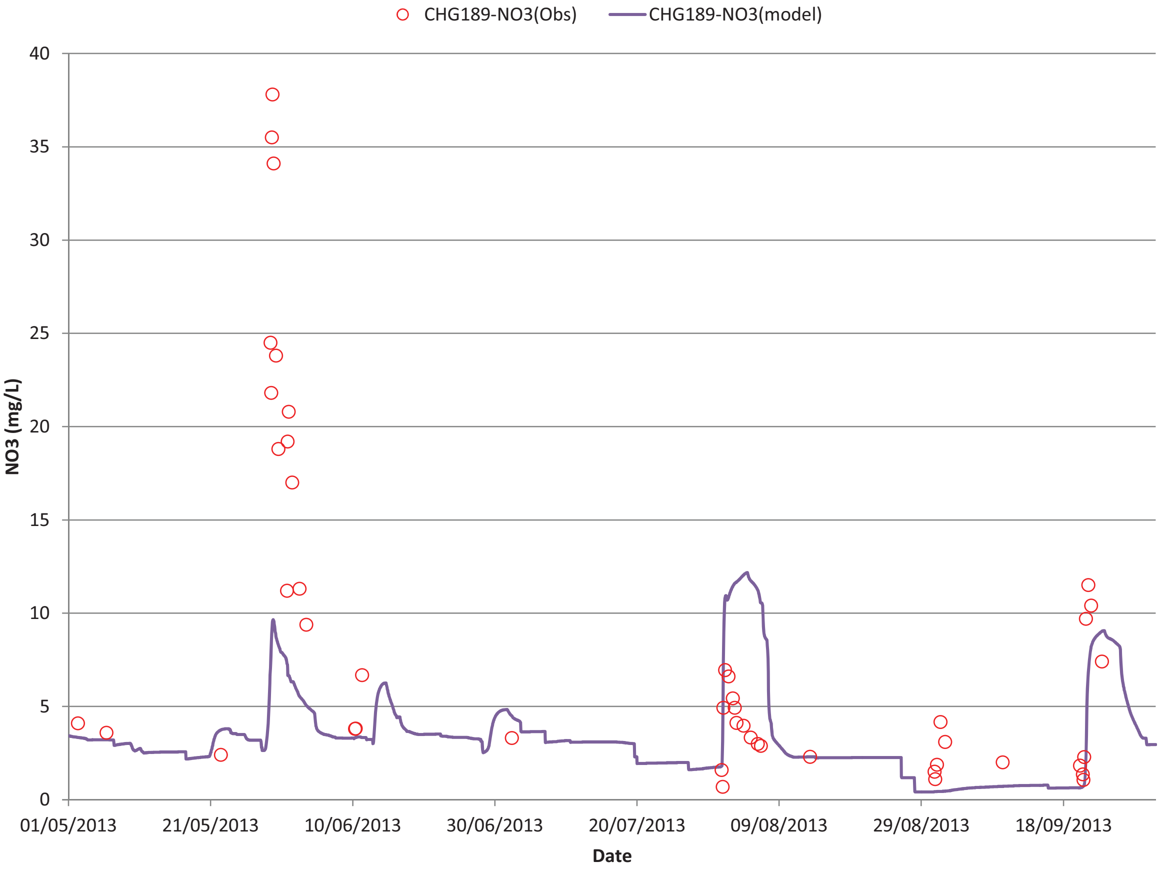


Figure 40: Bayfield North Calibration – NO_3 Pollutograph at Porters Hill Line (Culvert CH-G189)

The elevated observed SRP concentrations in late September shown in Figure 41 may be due to agronomic practices not currently included in the models (e.g. harvest, fall tillage).

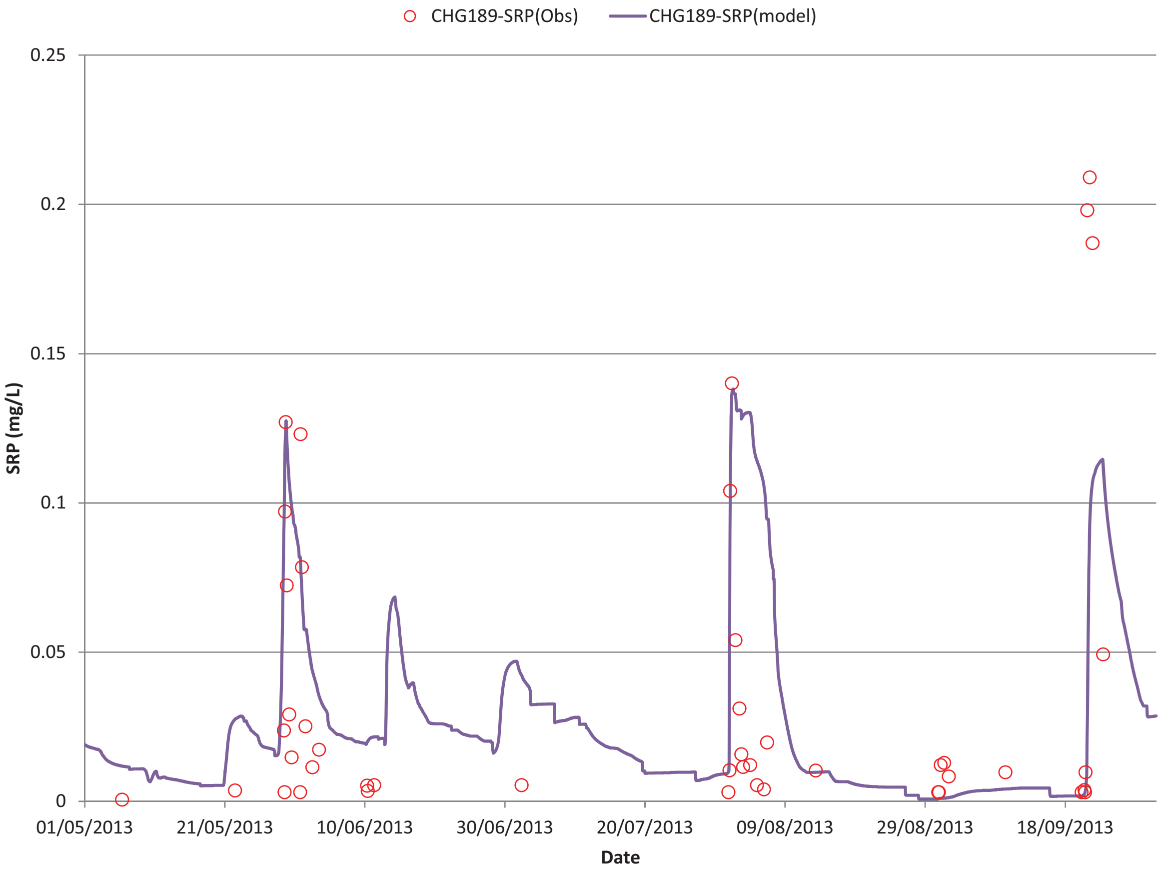


Figure 41: Bayfield North Calibration – SRP Pollutograph at Porters Hill Line (Culvert CH-G189)

The simulated TKN pollutograph in Figure 42 shows sustained elevated concentrations in August and September. This anomaly is also found in the Garvey Glenn model and needs to be investigated further in future model improvements. At this point, no logical explanation can be provided for this behaviour, but it is possible that the issue stems from either a numerical error in the SWMM code or an unknown issue with the method of treatment expression setup.

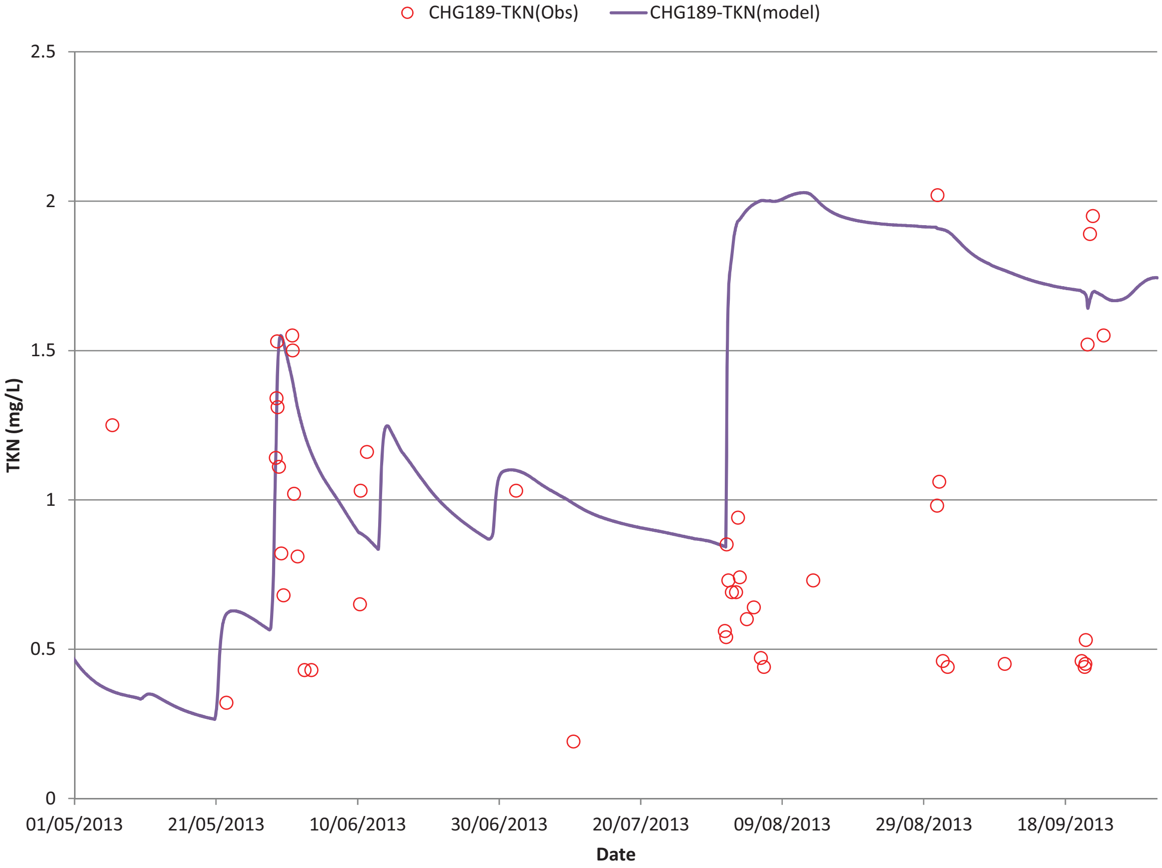


Figure 42: Bayfield North Calibration – TKN Pollutograph at Porters Hill Line (Culvert CH-G189)

Figure 43 shows the modelled SSC is consistently less than the observed TSS. As previously discussed, this is because in-stream erosion is not modelled in PCSWMM. The difference between calibrated and observed SSC may be greater in June compared to other peak concentrations because additional erosion occurred during the June event when soils were saturated following the snowmelt and spring rainfall events. The difference is lower in late August and September because established crops and vegetation provide erosion protection.

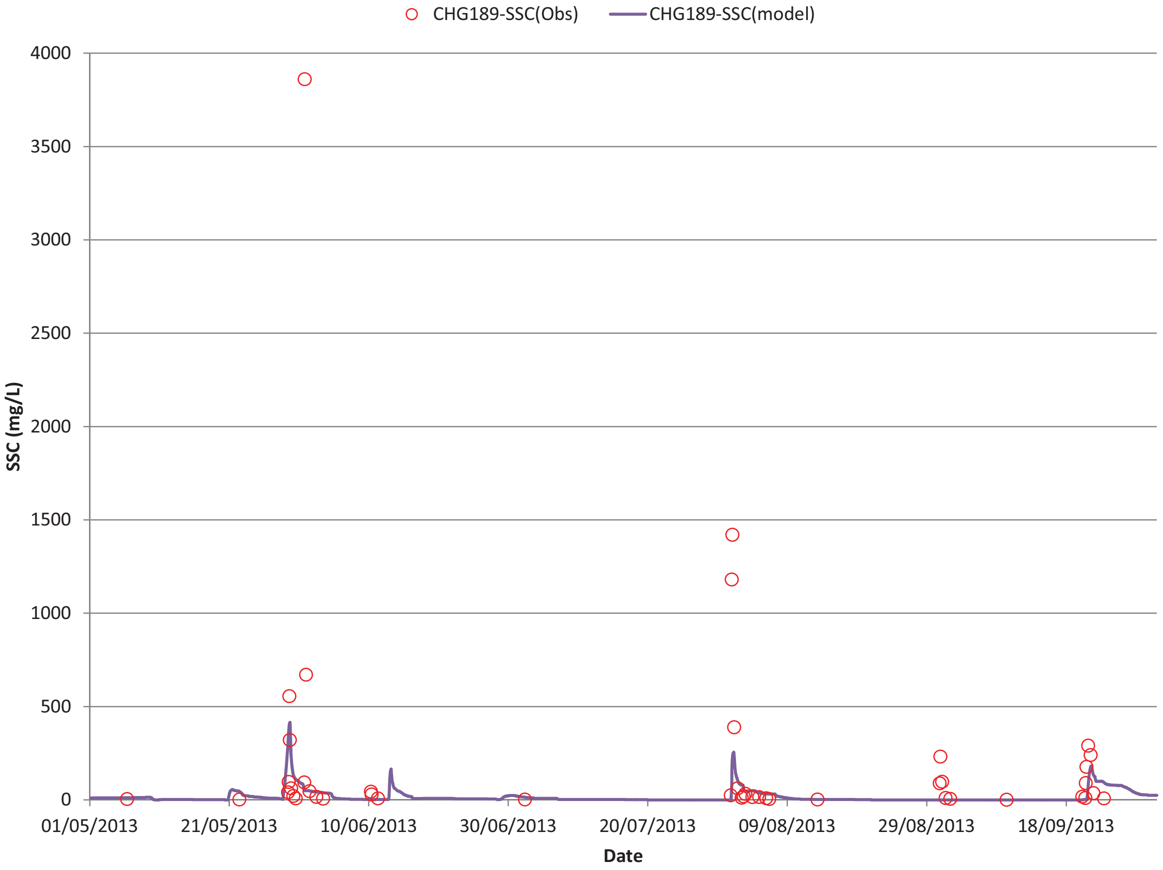


Figure 43: Bayfield North Calibration – SSC Pollutograph at Porters Hill Line (Culvert CH-G189)

6.4.4 Main Bayfield

The final calibration of the Main Bayfield watershed model at Trick's Creek (Culvert CH-B74) is shown in Figure 44 comparing the computed and observed hydrographs. The calibration has a very good fit with an NSE of 0.651 and an R^2 error of 0.672. There is a sensor malfunction in the observed data in mid-July 2013.

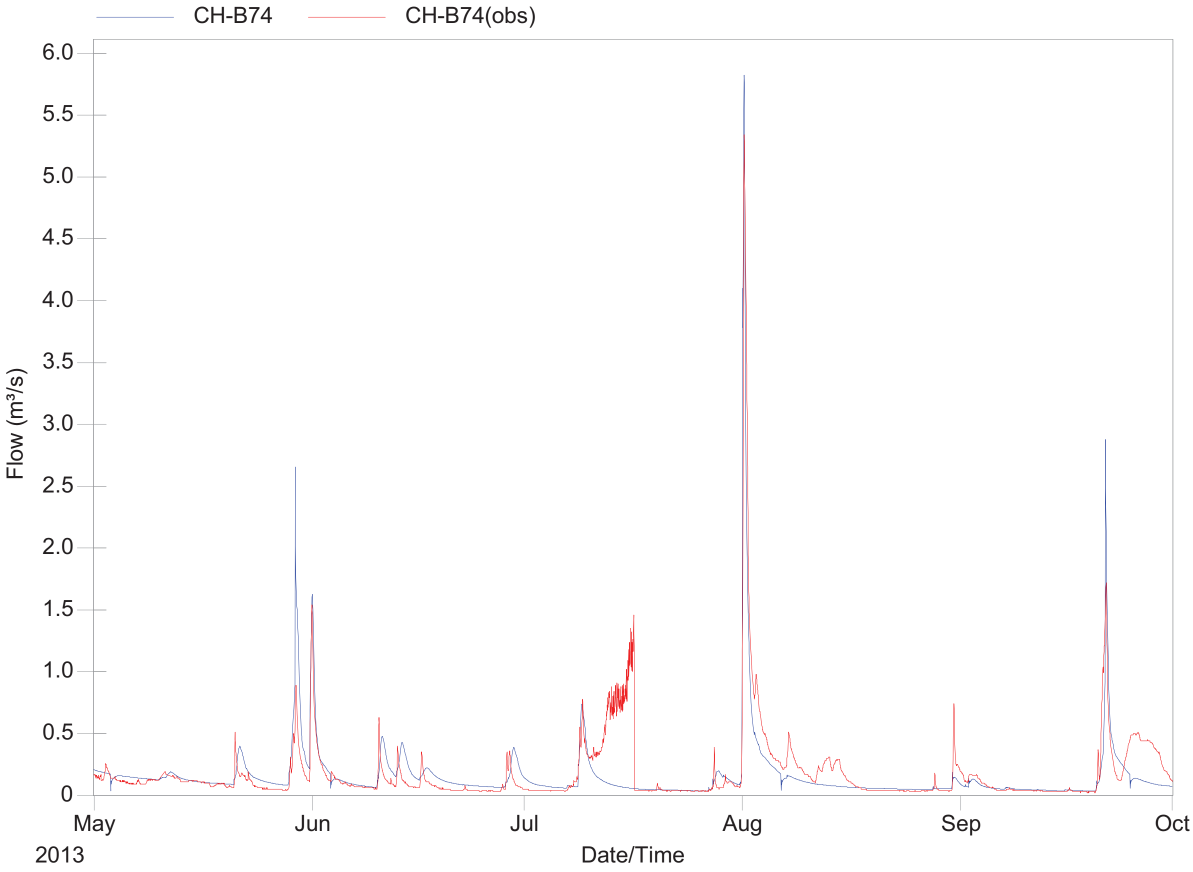


Figure 44: Main Bayfield Calibration – Flow at Trick's Creek (Culvert CH-B74)

The second flow monitoring location in the Main Bayfield watershed was the Varna gauge. During construction of the Main Bayfield model, it was noted that external areas were draining into the Main Bayfield watershed that had not been included in the scope of this project. These were significant watersheds encompassing the headwaters of the Bayfield River, referred to as Bannockburn and Bayfield Headwaters, as shown in Figure 45. The Varna gauge was located downstream of both external watersheds and so flow could not be calibrated at this gauge. The Trick's Creek location was used as the primary calibration location instead because the full upstream drainage area was included in the model. Suggested improvements to the model, in addition to adding the headwater watersheds, are discussed in Section 9.3.

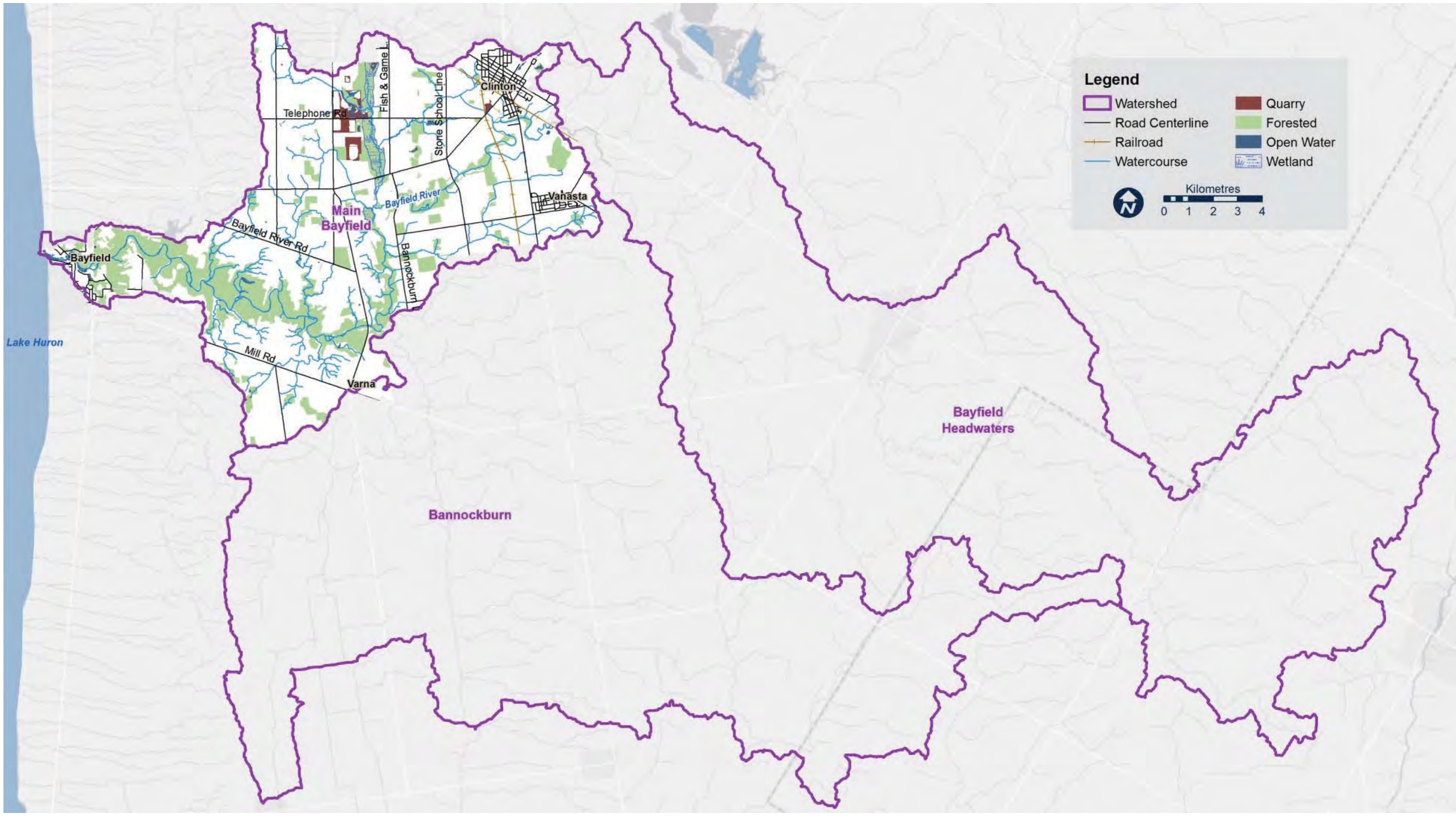


Figure 45: Bayfield River Watersheds

The final quality calibrations of the Main Bayfield watershed model at the Trick's Creek gauge (CH-B74) are shown in Figure 46 to Figure 50 comparing the computed pollutographs for NO_2, NO_3, SRP, TKN, and SSC to the observed data. The NSE of each calibration is summarized in Table 22.

Table 22: Summary of Main Bayfield Quality Calibration Results NSE at Trick's Creek (CH-B74)

	NO_2	NO_3	SRP	TKN	SSC
NSE:	-0.168	-0.736	-0.149	-0.764	0.185

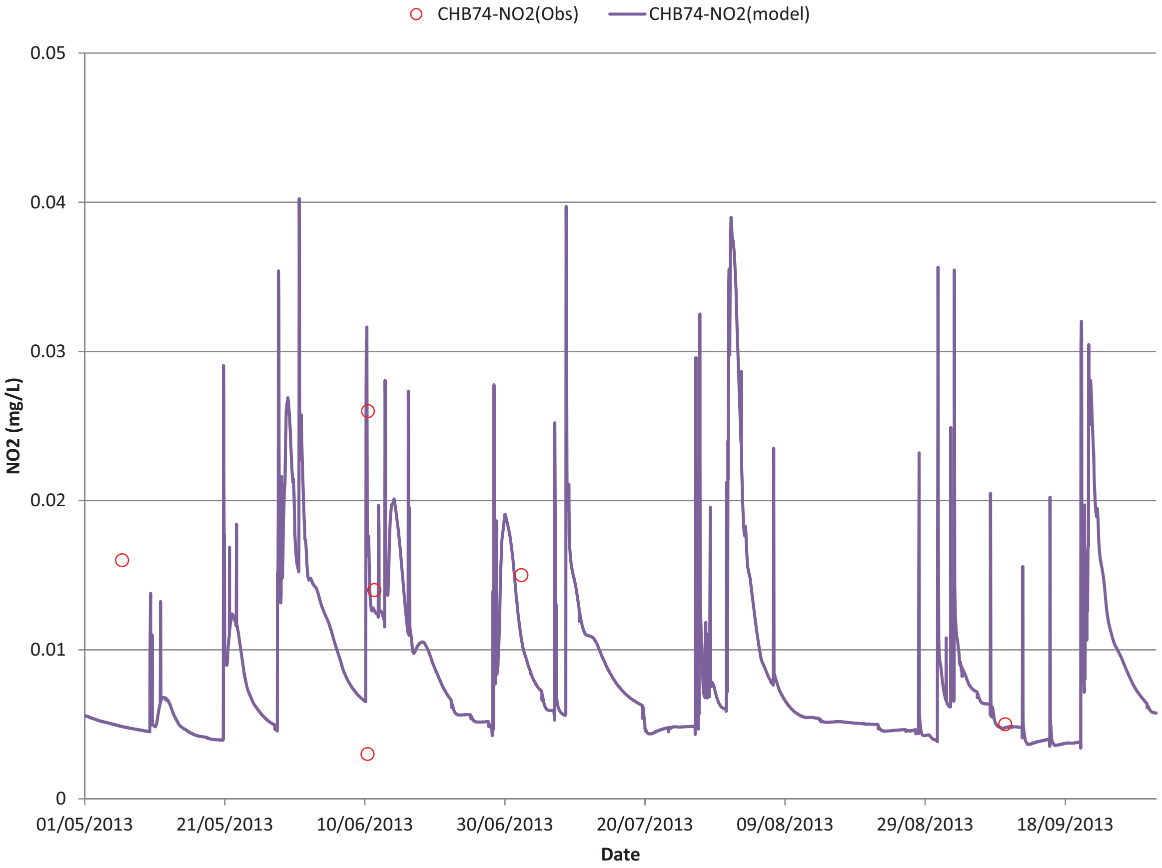


Figure 46: Main Bayfield Calibration - NO_2 Pollutograph at Trick's Creek (Culvert CH-B74)

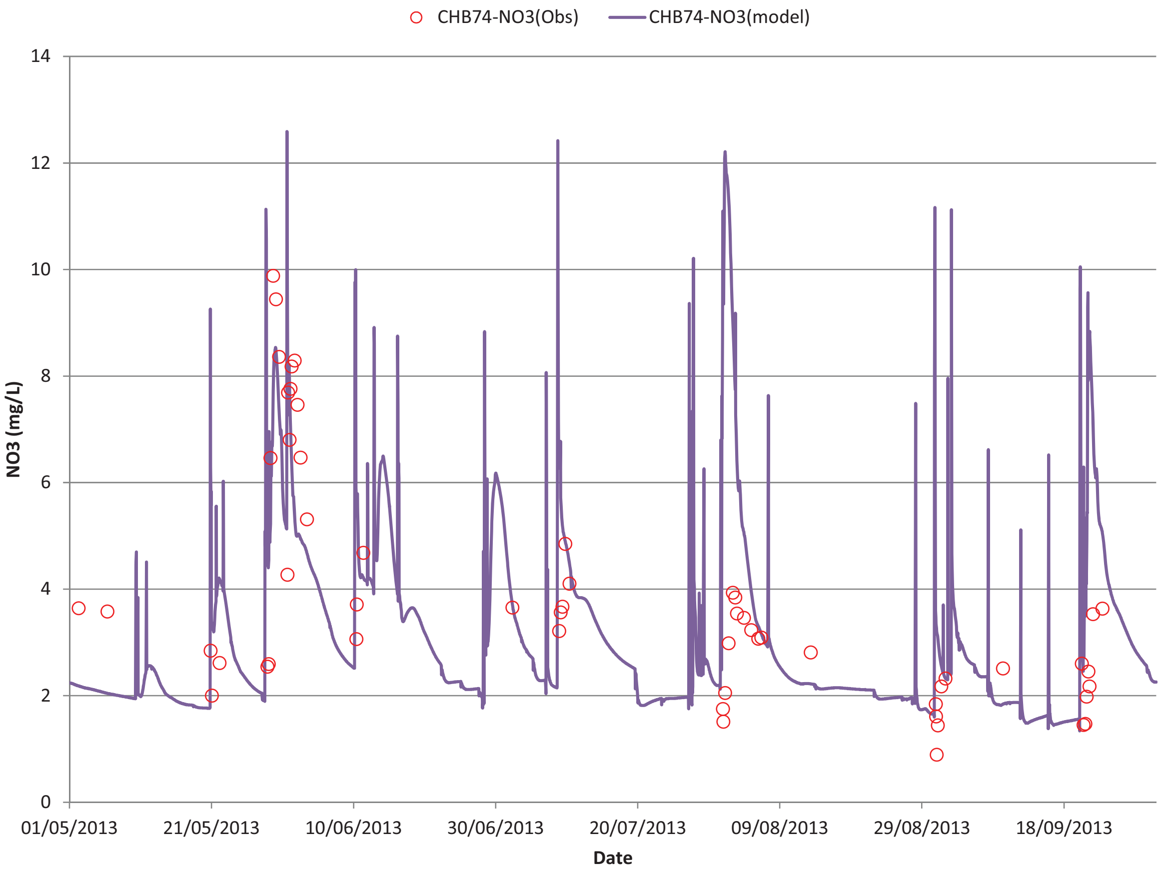


Figure 47: Main Bayfield Calibration – NO_3 Pollutograph at Trick's Creek (Culvert CH-B74)

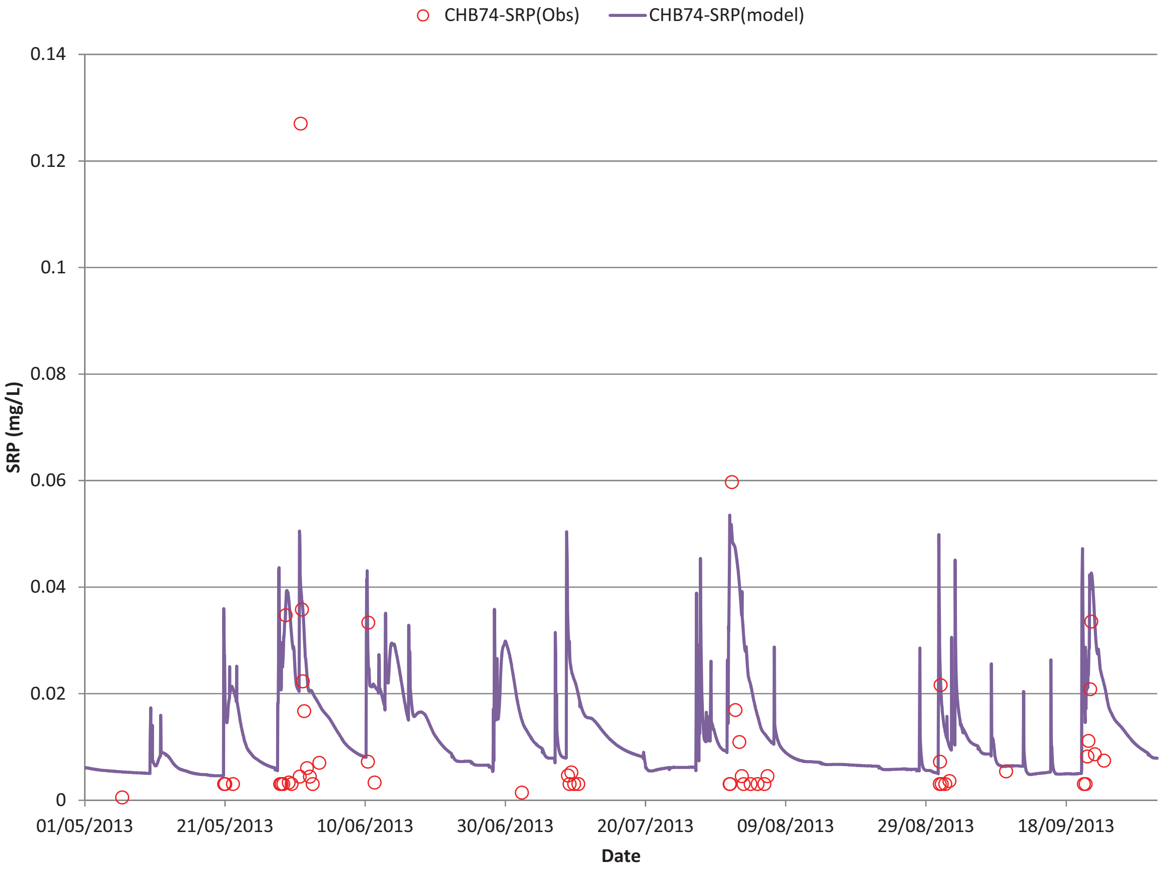


Figure 48: Main Bayfield Calibration - SRP Pollutograph at Trick's Creek (Culvert CH-B74)

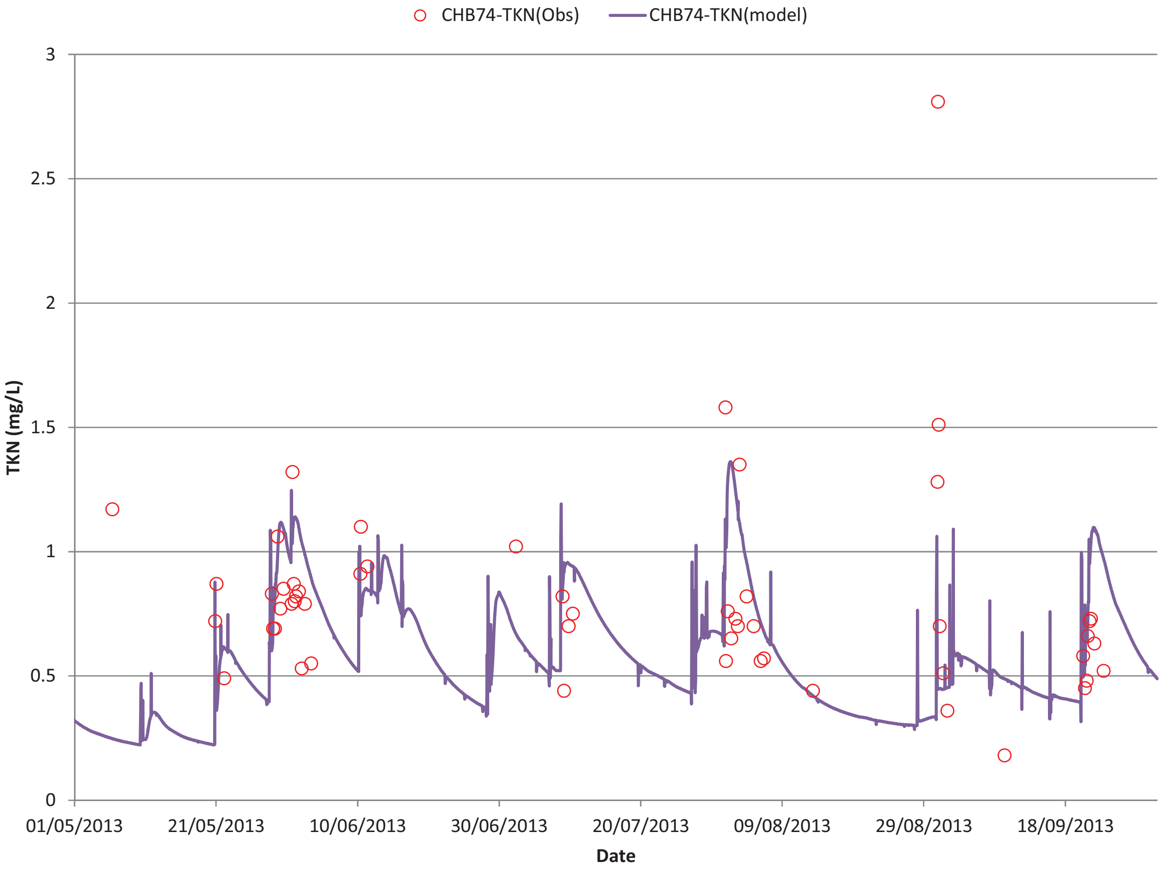


Figure 49: Main Bayfield Calibration - TKN Pollutograph at Trick's Creek (Culvert CH-B74)

SSC was calibrated by increasing the soil erodibility factor, *K*, by a factor of six. This resulted in the peak concentrations calculated in July and August to be greater than the observed SSC, as shown in Figure 50. It appears that the observed values were sampled on the receding limb of the peak in the pollutograph, making the difference acceptable. The difference between calibrated and observed SSC may be greater in June compared later in the simulation because additional erosion occurred during the June event when soils were saturated following the snowmelt and spring rainfall events. The difference is lower in late August and September because established crops and vegetation provide erosion protection.

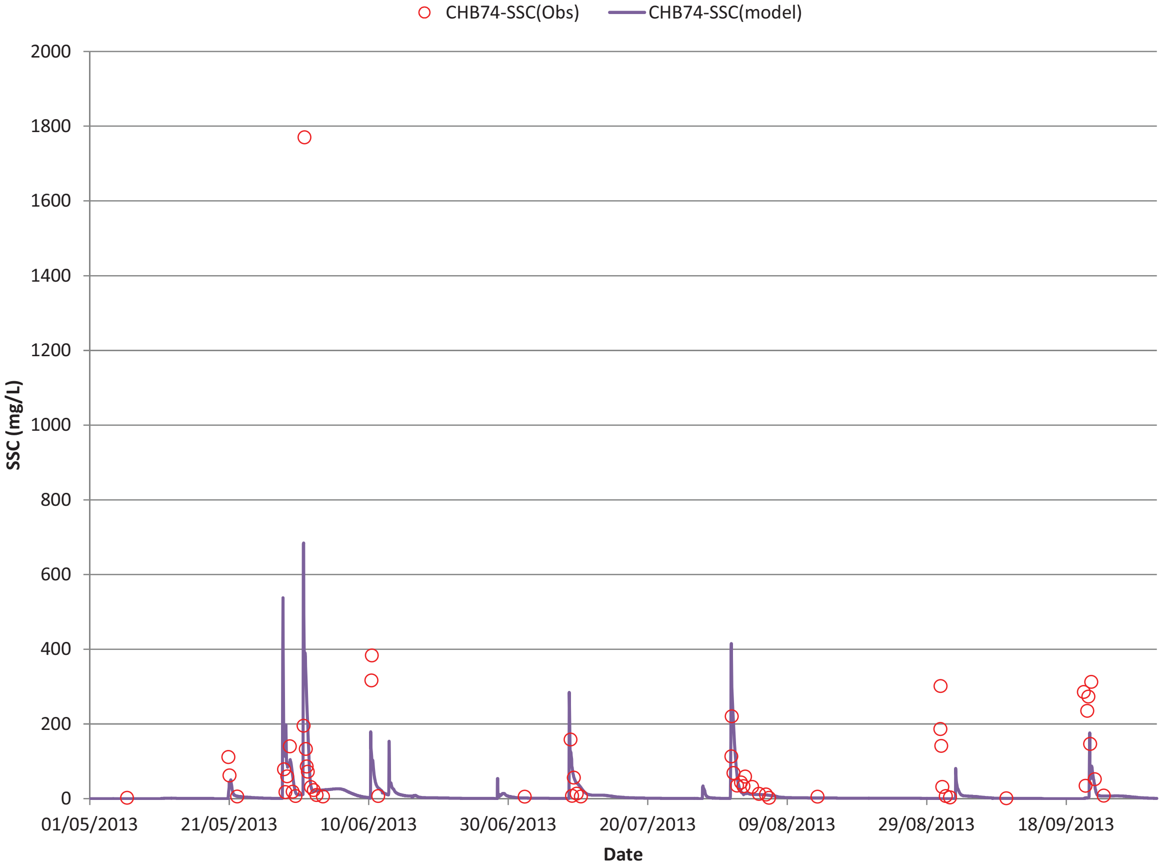


Figure 50: Main Bayfield Calibration - SSC Pollutograph at Trick's Creek (Culvert CH-B74)

6.4.5 Lambton Shores

Quantity calibration of the Lambton Shores model was limited to one flow monitoring station on Shashawandah Creek, although there are many separate tributaries draining to Lake Huron in this watershed. The same parameter adjustments made based on the Shashawandah calibration point were applied across the watershed. The final calibration of the model at Shashawandah (Bridge C12) is shown in Figure 51 comparing the computed and observed hydrographs. The calibration has a good fit with an NSE of 0.387 and an R^2 error of 0.498. The calibration could be improved by collecting flow data along the separate watercourses in the watershed and by collecting more detailed physical information about the watershed, as discussed in further detail in Section 9.3.

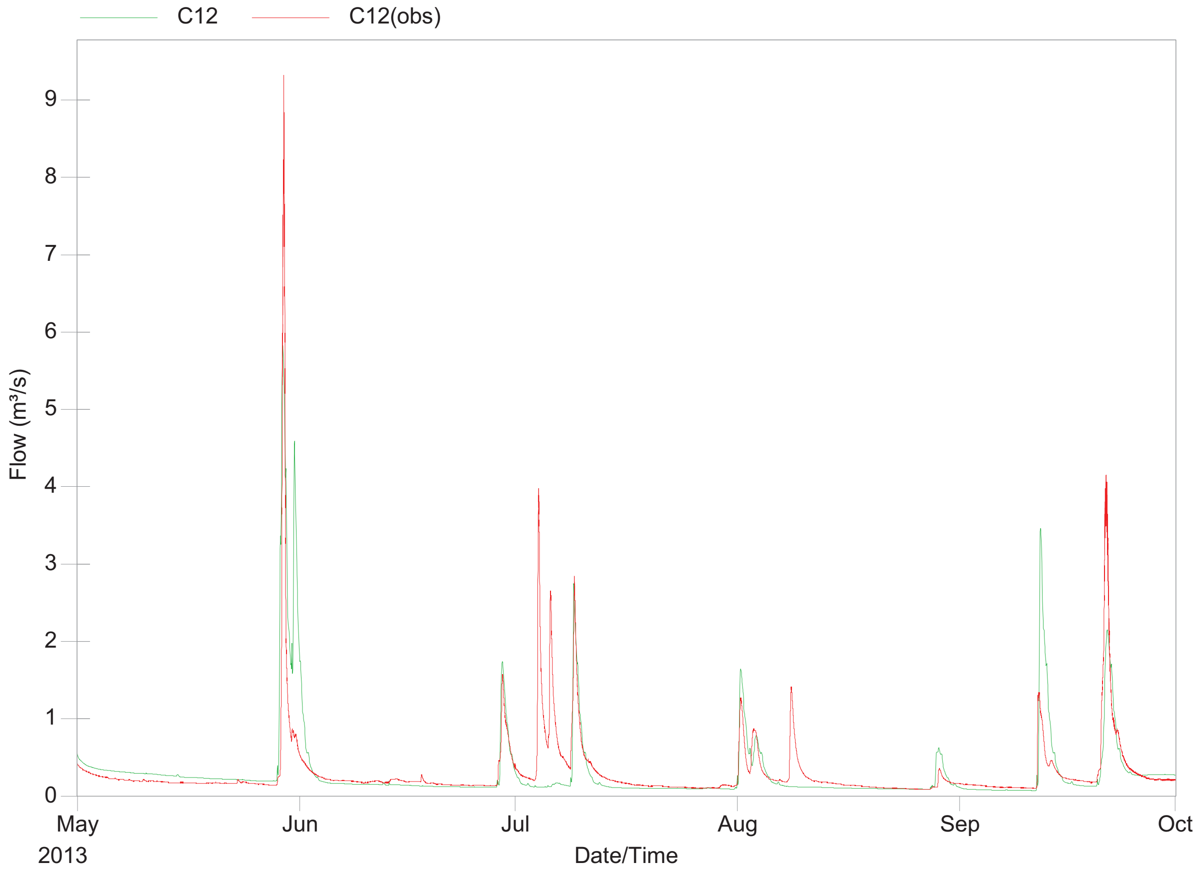


Figure 51: Lambton Shores Calibration – Flow at Shashawandah (Bridge C12)

The final quality calibrations of the Lambton Shores watershed model at the Shashawandah gauge (Bridge C13) are shown in Figure 52 to Figure 56 comparing the computed pollutographs for NO_2, NO_3, SRP, TKN, and SSC to the observed data. The NSE of each calibration is summarized in Table 23.

Table 23: Summary of Lambton Shores Quality Calibration Results NSE at Shashawandah (C13)

	NO_2	NO_3	SRP	TKN	SSC*
NSE:	-0.576	-0.639	0.602	-0.59	0.28

* Not calibrated due to limited monitoring data.

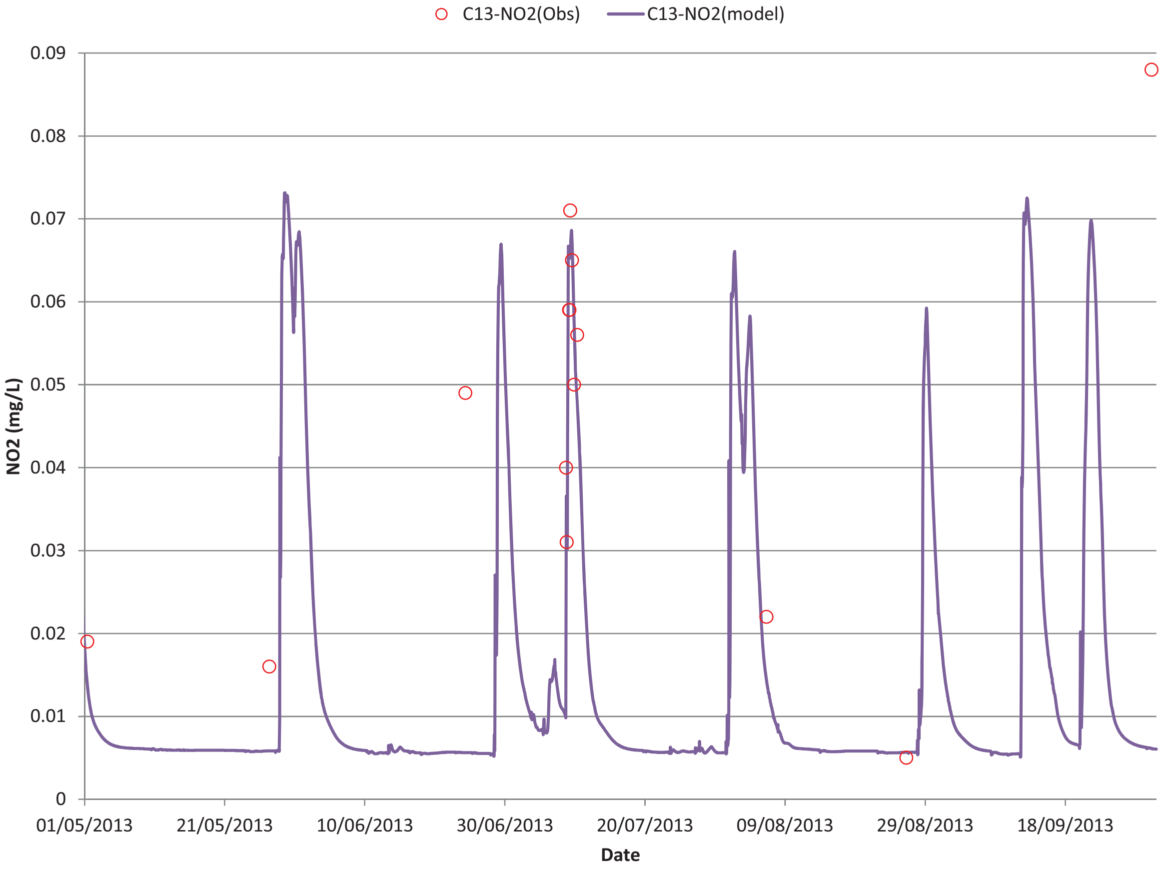


Figure 52: Lambton Shores Calibration – NO_2 Pollutograph at Shashawandah (Bridge C13)

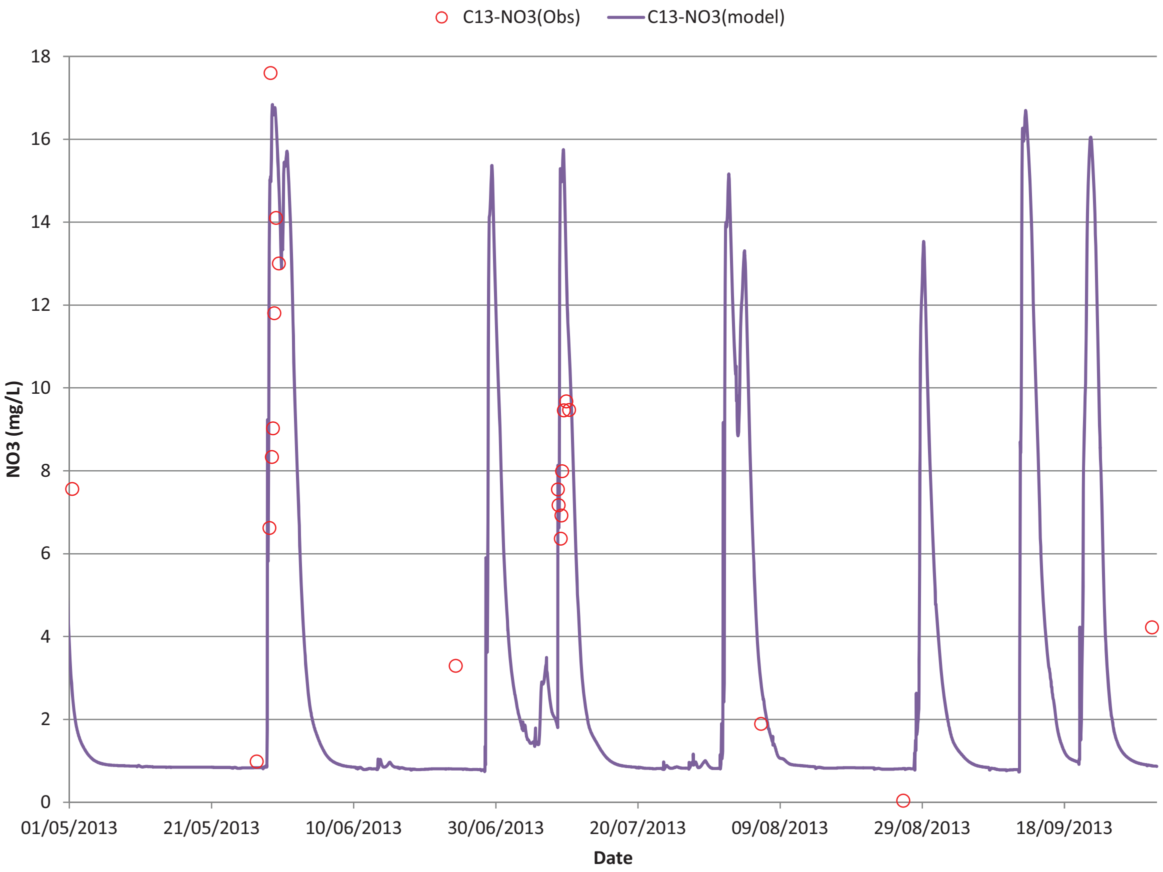


Figure 53: Lambton Shores Calibration – NO_3 Pollutograph at Shashawandah (Bridge C13)

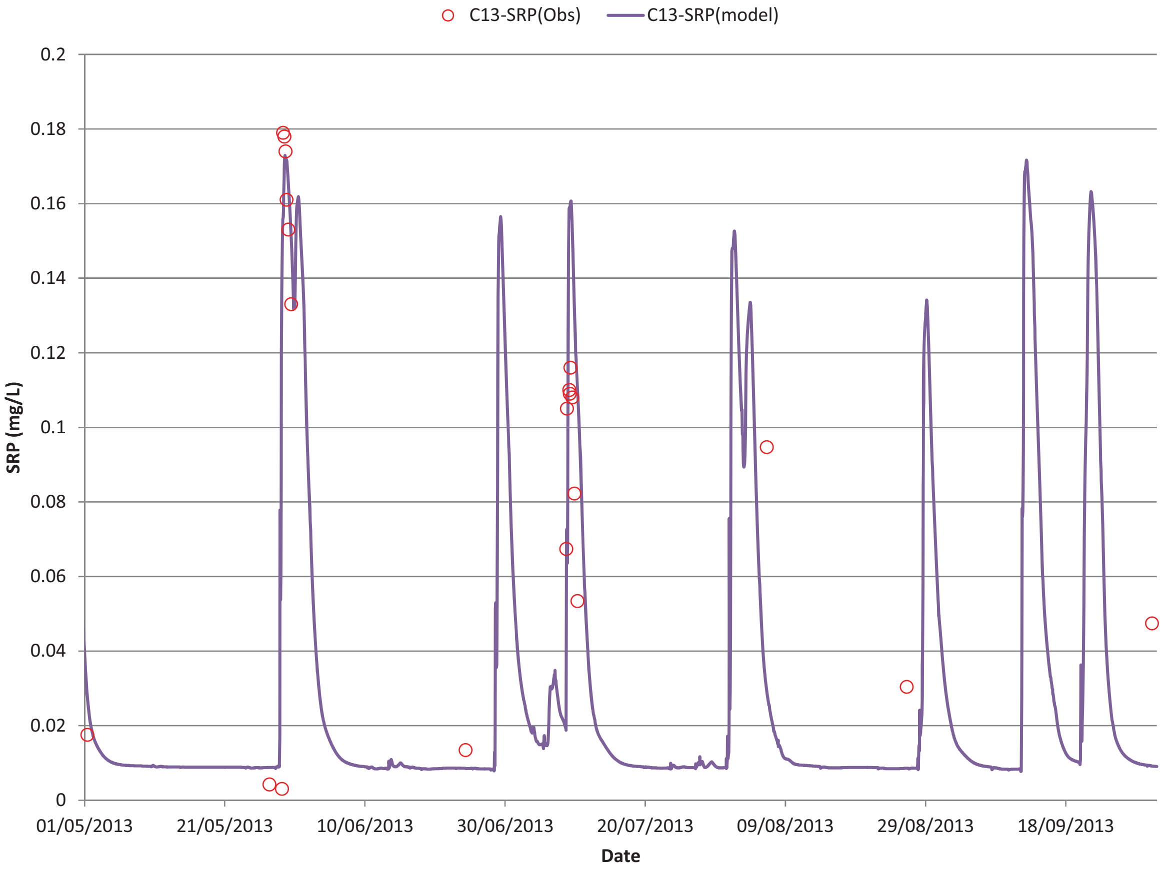


Figure 54: Lambton Shores Calibration - SRP Pollutograph at Shashawandah (Bridge C13)

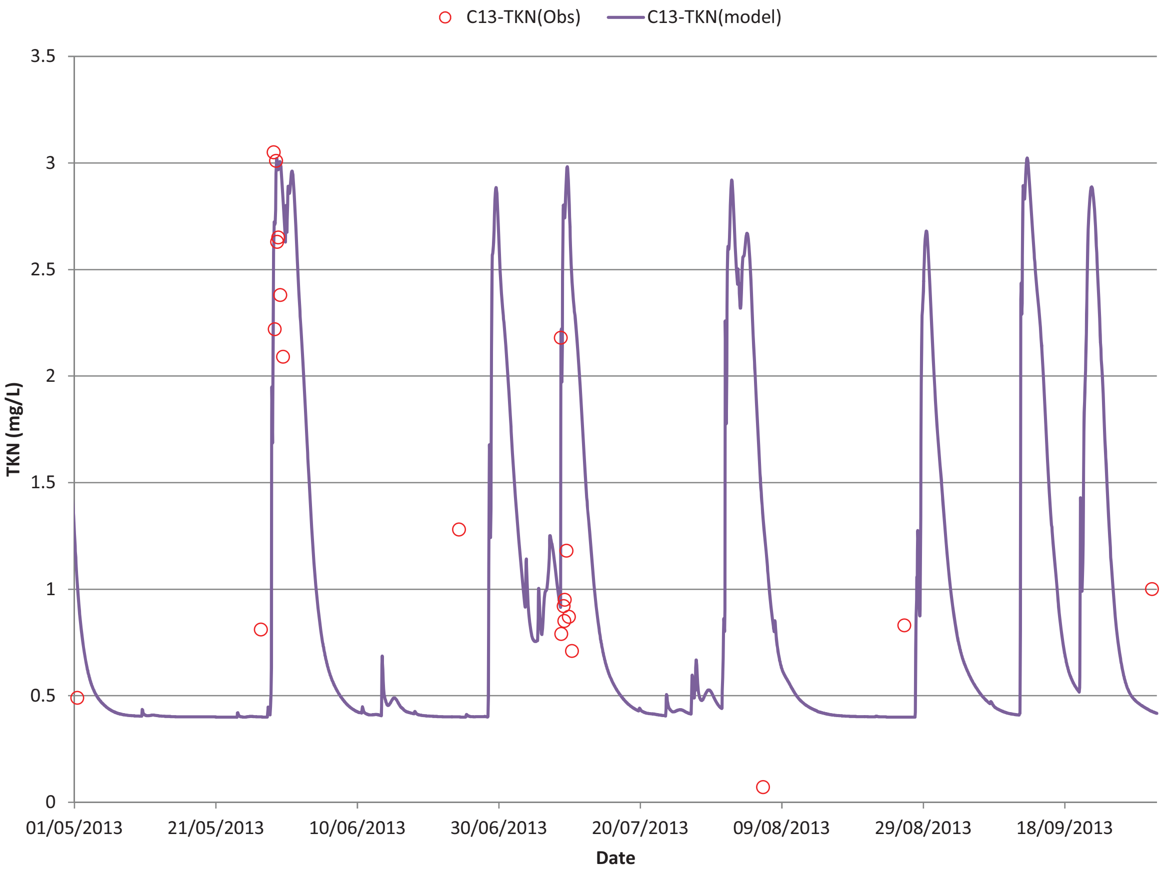


Figure 55: Lambton Shores Calibration - TKN Pollutograph at Shashawandah (Bridge C13)

Figure 56 shows the modelled SSC is consistently less than the observed TSS. As previously discussed, this is due primarily to other sediment source processes that are not currently modelled in PCSWMM.

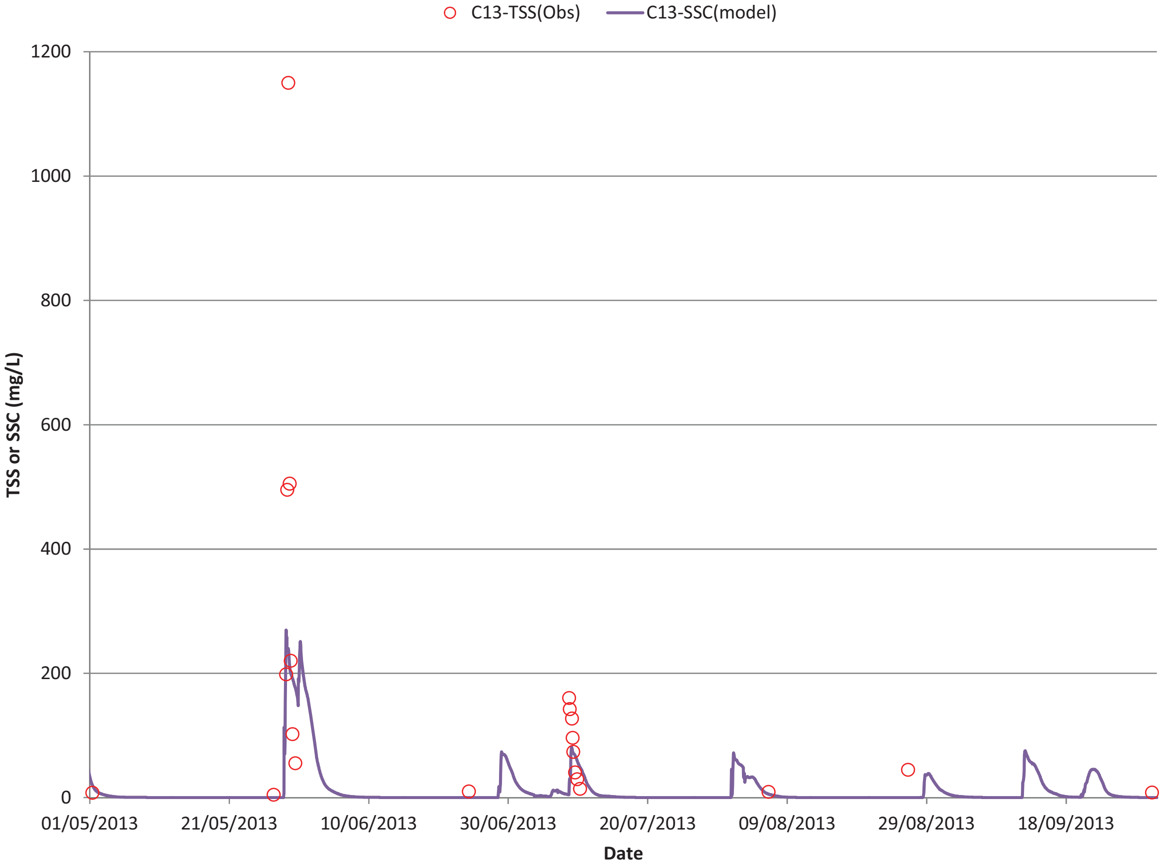


Figure 56: Lambton Shores – Uncalibrated SSC Pollutograph at Shashawandah (Bridge C13)

6.5 Winter Calibration

6.5.1 Measuring Snowfall

The collection of winter precipitation data is a difficult and time consuming endeavor due to its dynamic nature and inherent spatial variability, and the automated measurement of snowfall remains both challenging and costly (Doesken and Judson 1997; Savina et al. 2012). While tipping bucket rain gauges are relatively cheap to install and maintain in at least some density on the landscape, the acquisition and installation of gauges specifically designed to accurately capture snowfall requires more funds, more planning, and greater attention to detail.

There are many methods of making snowfall measurements, as discussed in detail by Doesken and Judson (1997), among other sources, but automated collection is most typically accomplished with tipping bucket or weighing gauges – both of which must have heated components to prevent clogging during snowfall events. Generally, heated weighing gauges are the most accurate, but are more costly than heated tipping-bucket gauges. There are many issues associated with collecting snowfall in gauges, mainly related to clogging, wind, precipitation timing, and volume loss to vapor during the melting process (Doesken and Judson 1997; Savina et al. 2012). To deal with clogging, gauges should not be equipped with permanent funnels, and the size of the opening should be considered (Doesken and Judson 1997). Shielding is often used to decrease the impact of wind on the capture efficiency of gauges (Anderson 1973; Doesken and Judson 1997), as illustrated in Figure 57. This figure also depicts the importance of the snow gauge catch deficiency correction factor (or snow catch factor, SCF) – one of the input parameters for winter precipitation data in SWMM. Even using heated tipping-bucket gauges, the timing of recorded precipitation data can be delayed by 30 minutes or more (Savina et al. 2012), and since the melting of any captured snow in an unheated gauge is controlled by ambient conditions alone, the delay in the recording of precipitation could be much longer. Accounting for long time delays in the data requires a great degree of post-processing, sometimes with manual correction, in order to be utilized without significant caveats.

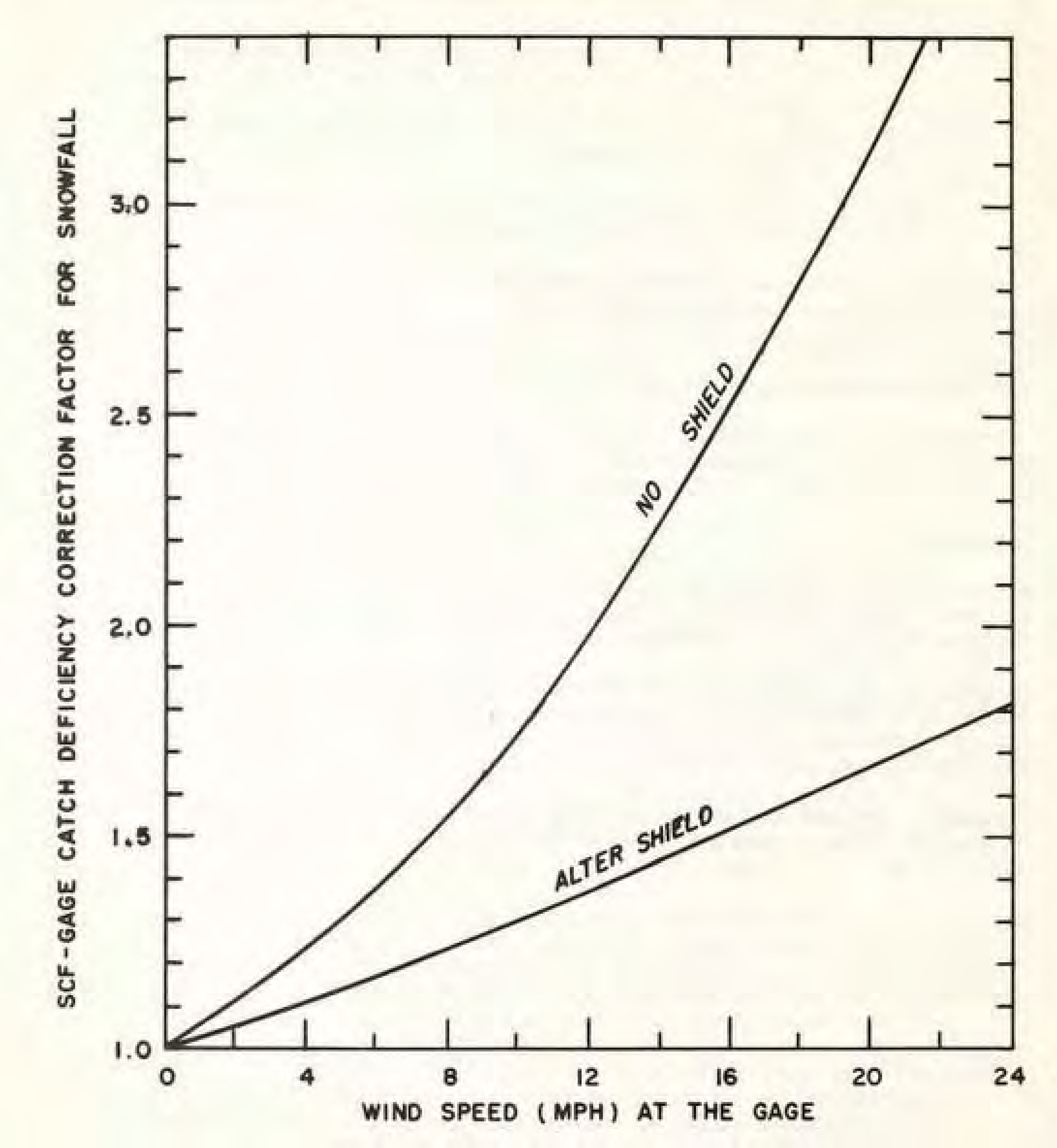


Figure 57: Snow gauge catch correction factors from Anderson (1973)

6.5.2 Winter Precipitation Data – Expected Issues

The winter precipitation data collected for this project used unshielded, unheated tipping bucket gauges. Due to these facts, the data can be presumed to have four primary issues:

1. Underestimation of precipitation volume due to clogging of the funnels (caused by the lack of heating elements), especially during large, wet snowfall events. The accuracy of the recorded precipitation will also decrease as a storm event progresses, since once the gauge is clogged and filled, additional snow cannot be collected.
2. Underestimation of precipitation volume due to sublimation of snow that has been collected in the funnel, but has not yet been melted and accounted for by the tipping bucket.
3. Underestimation of precipitation volume due to low snow capture efficiency (caused by the lack of shielding), especially during snowfall combined with high winds.
4. Delay in timing of precipitation due to the freezing and melting cycles that are not controlled in unheated gauges following snow capture.

Thus, when using the provided precipitation data to parameterize models in SWMM, it can be expected that volume will be significantly underestimated, the degree of underestimation will be variable both inter- and intra-storm, and that timing will be significantly delayed.

6.5.3 Winter Calibration Parameters

Initialization of the snow melt routine involves setting region specific parameters such as elevation, latitude, longitude correction, as well as the dividing temperature between when simulated precipitation is rain or snow. The dividing temperature can vary due to geographical and meteorological conditions such as lake-effect and air temperature differential between the ground and atmosphere. A normal temperature range for model dividing temperature is between -1° and 3° Celsius (Tarboton and Luce 1997). A dividing temperature value of 2.5° C was arrived at through review of air temperature during times of precipitation with no apparent stream response and calibration of simulated snow pack depth and duration. An areal depletion curve, to account for the variation in actual snow covered area that occurs following a snowfall, was assigned based on SWMM 4 documentation for simulation of drifting and the delayed melting effect that deeper snow packs can have on heat transfer (Huber et al. 1988). As previously mentioned, a Snow Catch Factor must be assigned for each rain gauge in the watershed and was used as a primary calibration parameter to match overall winter discharge volumes and snow accumulation.

In addition to regional and climatic-specific settings, several parameters are assigned for defining snowmelt and snow packs in SWMM. These parameters are individually entered for the pervious, impervious and plowable impervious areas within the catchment. While populating the impervious area snow pack parameters is required, winter calibration for RSWMM focused on the pervious area parameters as this represents the predominant coverage in each watershed. A single snow pack is defined for the watershed and referenced in all subwatersheds. Minimum and maximum melt coefficients, base temperature, and free water capacity were initialized with values suggested for rural areas in the User's Guide to SWMM5 (James, Rossman, and James 2010). The depth of snow at 100 percent coverage was initialized based on the snow survey information submitted. Snow pack parameters were then calibrated utilizing the SRTC Tool within PCSWMM as had been completed for water quantity and quality. The objective of winter calibration was to mimic seasonal total discharge volume and trends while approximating snow melt runoff leading into spring. Therefore, calibration to flow hydrographs was given more focus than snow pack depth.

Apart from the SCF, calibrated parameters remain more or less within acceptable ranges. The snowpack free water holding capacity calibrated on the higher end, similar to what would be expected in a shallow spring pack or with a slush layer (Anderson 1973; U.S. Army Corps of Engineers 1956). This is substantiated by the relatively high water equivalent ratios in the measured data of 15 to 50 percent occurring throughout the monitored season. While the calibrated melt coefficients remain within reference range, constraining the maximum and minimum to a very narrow margin was found necessary in order to approach measured peak flow values and to retain the snow pack into the spring without melting at too rapid of a rate.

6.5.4 Winter Calibration Attempt – Garvey-Glenn

The first model for which an attempt at winter calibration was made was the Garvey-Glenn watershed. Snow depth information was measured at a location in the upper watershed in a field off of Tower Line Road at approximately two week intervals between December and April (Figure 58). Initial efforts to calibrate snow depth (via snow water equivalence or SWE) forced the SCF to approximately 9 – far outside the range of values used by other modellers (e.g. Singh et al. 2005 used a range of 1.2-1.5 in HSPF and SWAT) and beyond the scale of Figure 57 (showing a maximum SCF of approximately 3.5). Figure 59 displays a -2.7 percent discrepancy between calculated and observed flow that occurred between October 1, 2013 and May 1, 2014 using SCF equal to 9. Delayed events and flow peaks are also observed in this calibration attempt, likely due to the capture of snow during an event, but the recording of precipitation when the captured snow eventually melted and passed through the gauge. As displayed in Figure 60, extending the SCF to a value of 9 also resulted in increasing the simulated snow depth beyond what was measured at the Tower Line site.

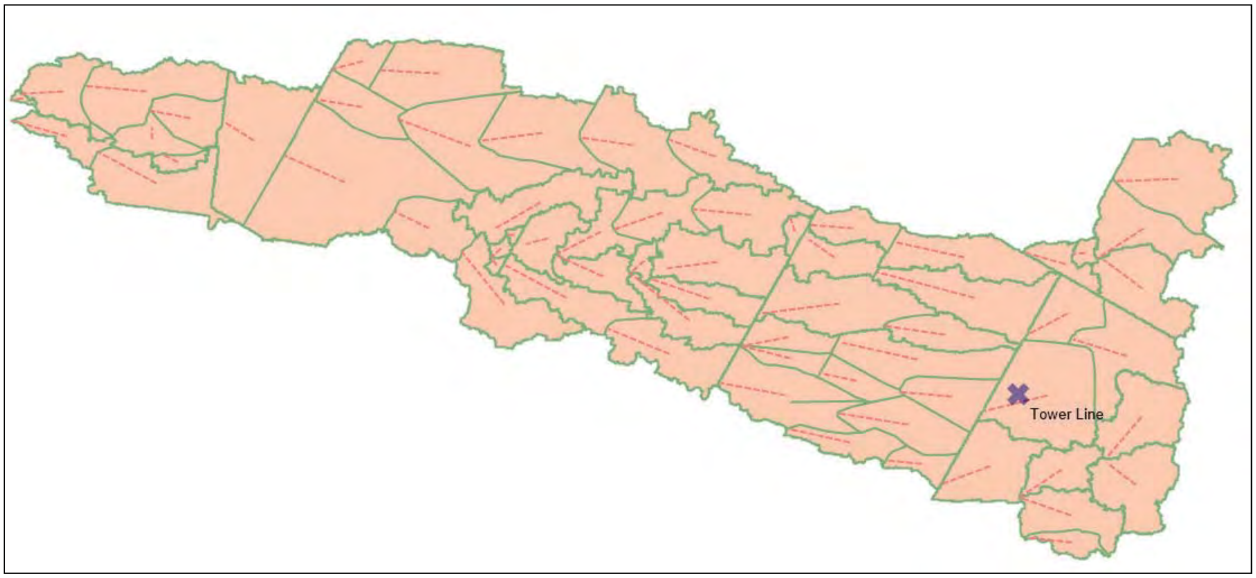


Figure 58: Garvey Glenn – Snow Depth Measurement Location (DLN20-08)

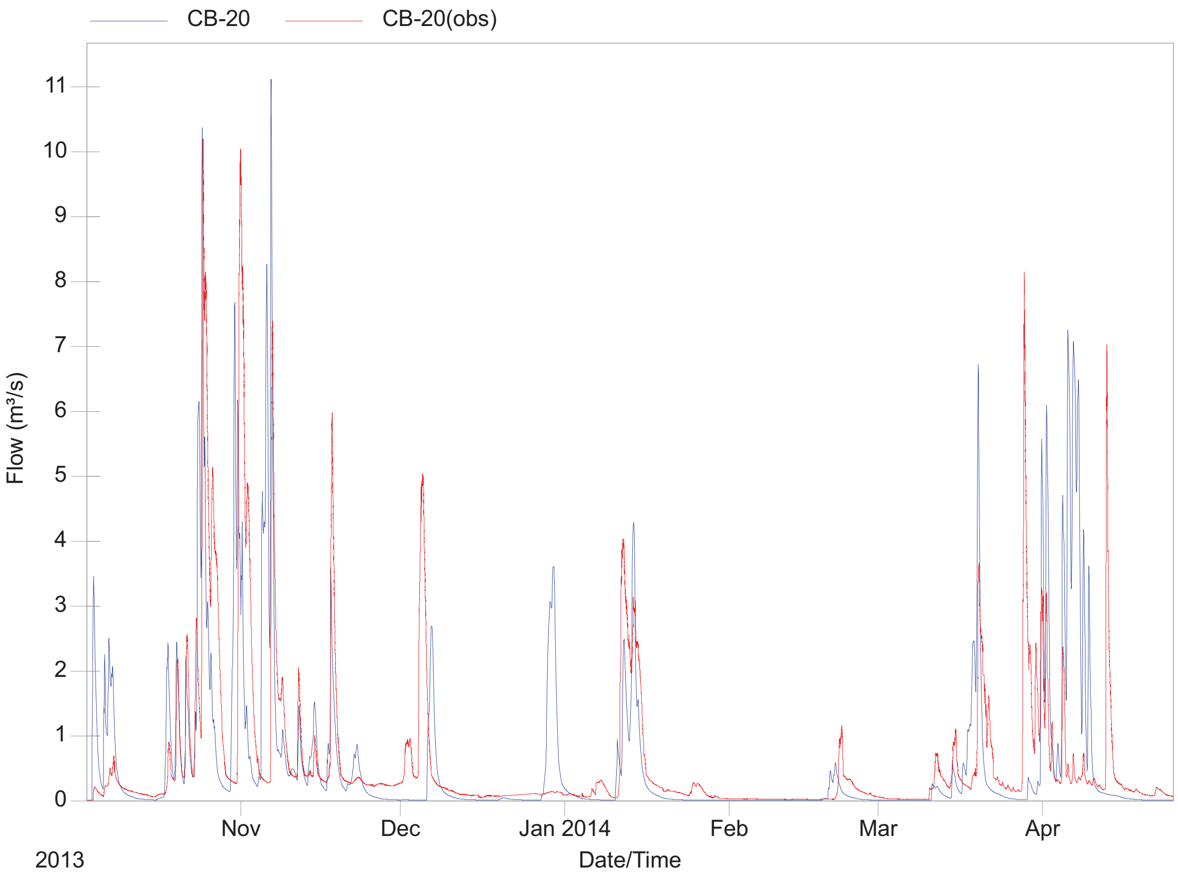


Figure 59: Garvey Glenn – Winter Flow Calibration at Kerry's Line (CB-20)

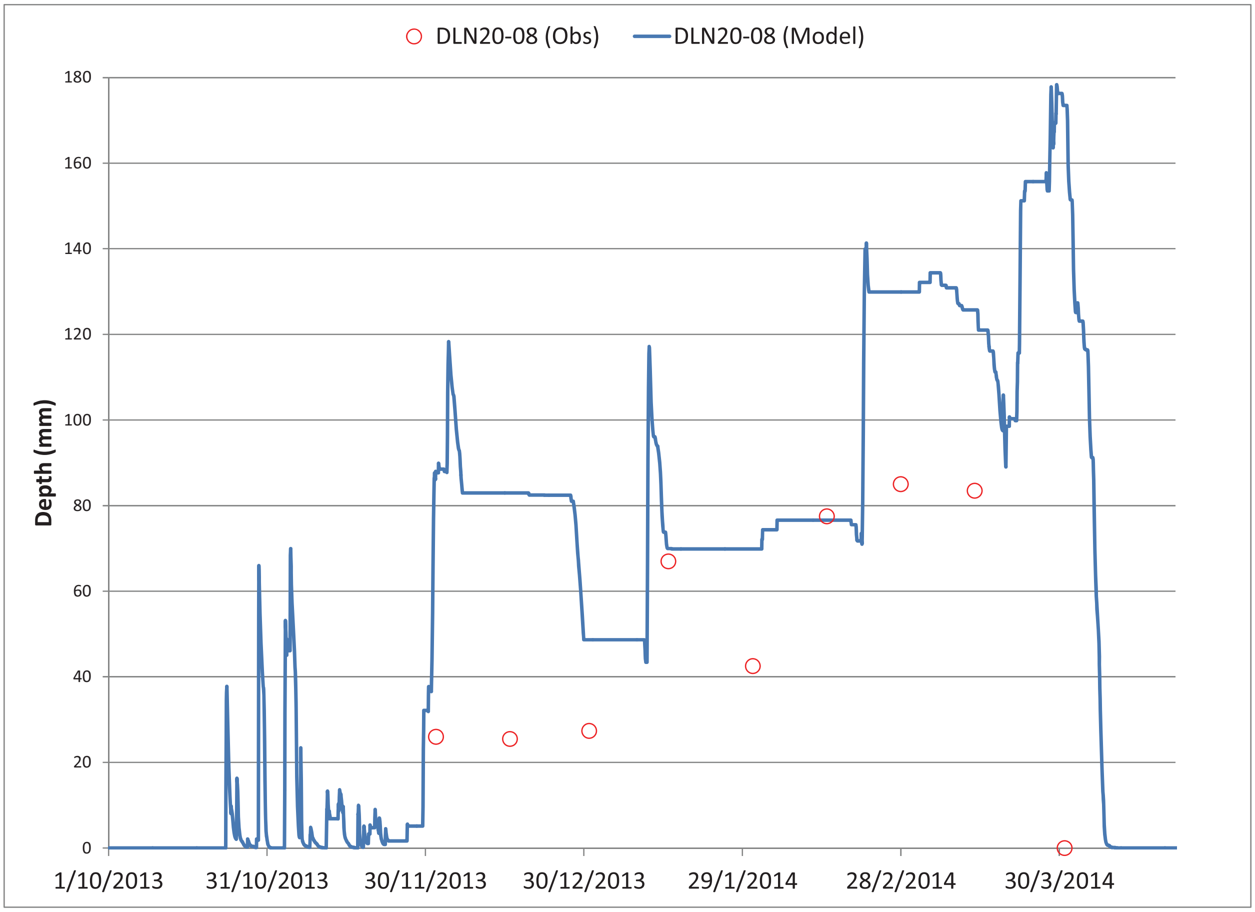


Figure 60: Garvey-Glenn – Winter Snow Depth Calibration at Tower Line Road (DLN20-08)

6.5.5 Winter Calibration Attempt – Bayfield North

The Bayfield North model contains some of the most reliable monitoring, hydrologic and hydraulic information. It contains two snow measurement locations in the upper watershed as shown in Figure 61. The snow depth SWE varied considerably across the watershed as shown in Figure 62 and Figure 63. While two separate snow packs could have been parameterized to calibrate to each snow depth measurement site, flow data is only associated with the watershed containing the Bettles site. Since the emphasis of the snowmelt calibration was more heavily weighed on discharge volume than snow pack depth, the Bettles snow accumulation trend was the focus of this calibration. A SCF of 4.4 was used to approximate discharge volume at the Porter's Hill Line site (CH-G189), resulting in a 9.9% volumetric discrepancy from what was monitored between October 1, 2013 and May 1, 2014. Some of the same symptoms of delayed melt and missed snow catch are reflected in the calibrated results seen in the Porter's Hill Line hydrograph shown in Figure 64.

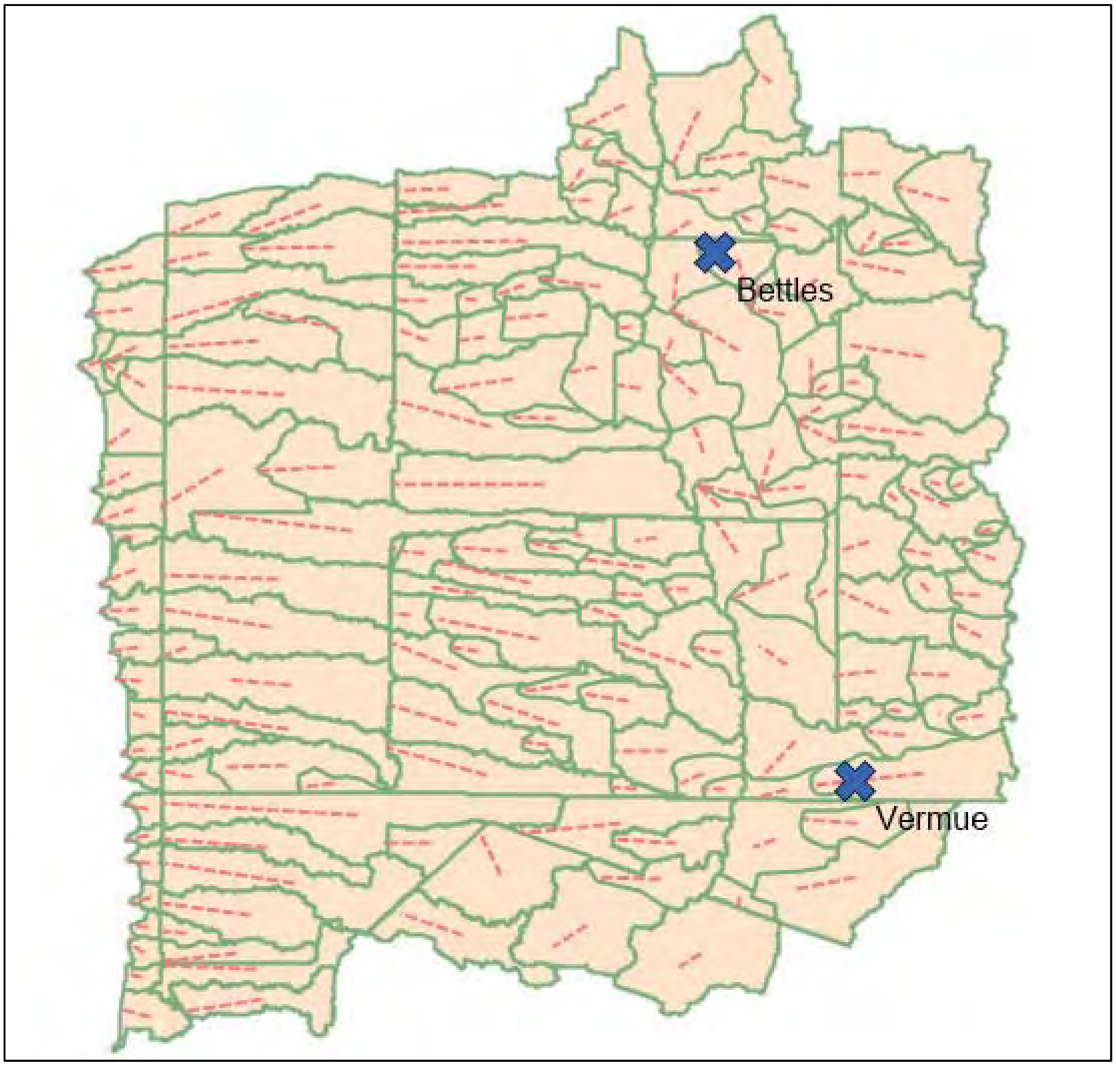


Figure 61: Bayfield North – Snow Depth Measurement Locations (SGulyC59 & SStorGODM37)

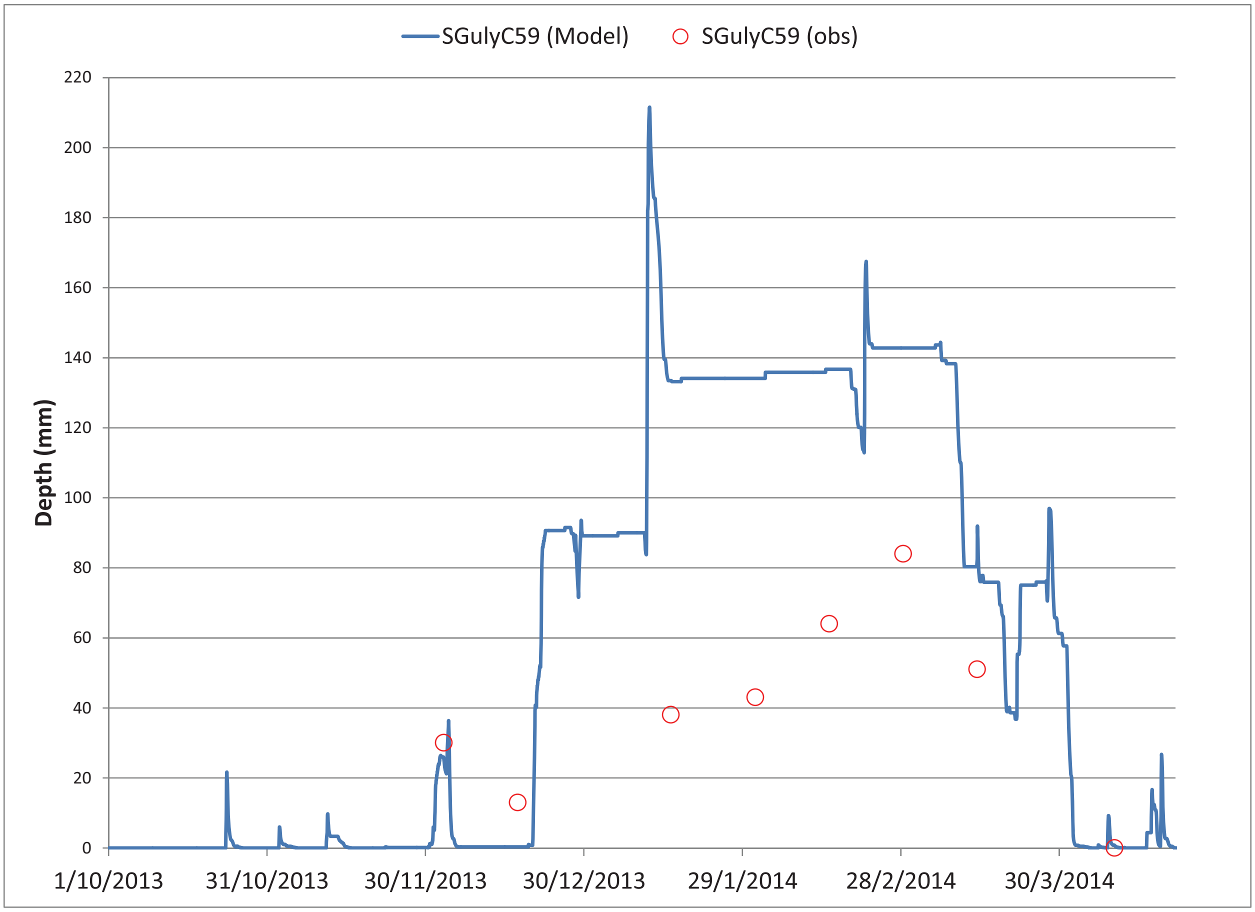


Figure 62: Bayfield North – Winter Snow Depth Calibration at Bettles (SGulyC59)

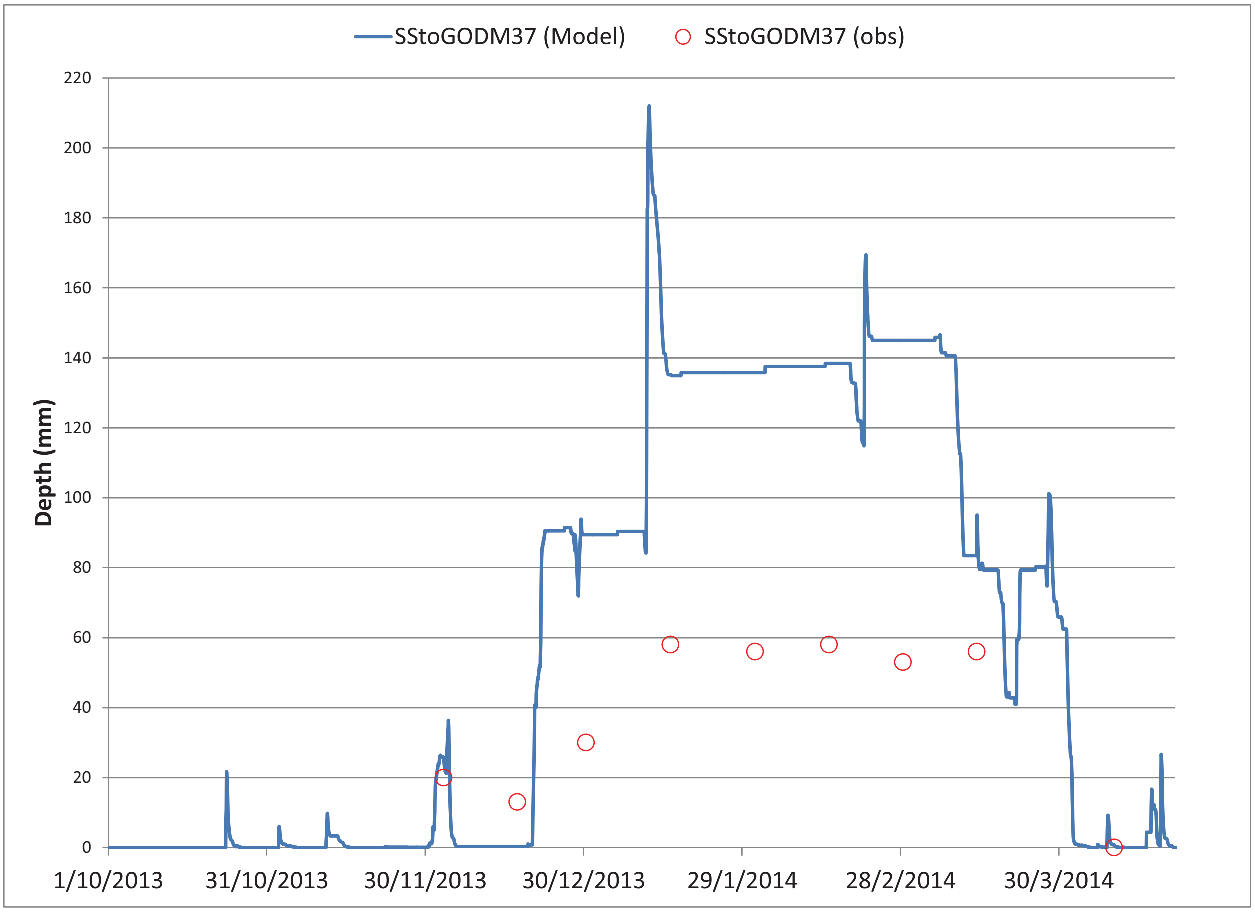


Figure 63: Bayfield North – Winter Snow Depth Calibration at Vermue (SStoGODM37)

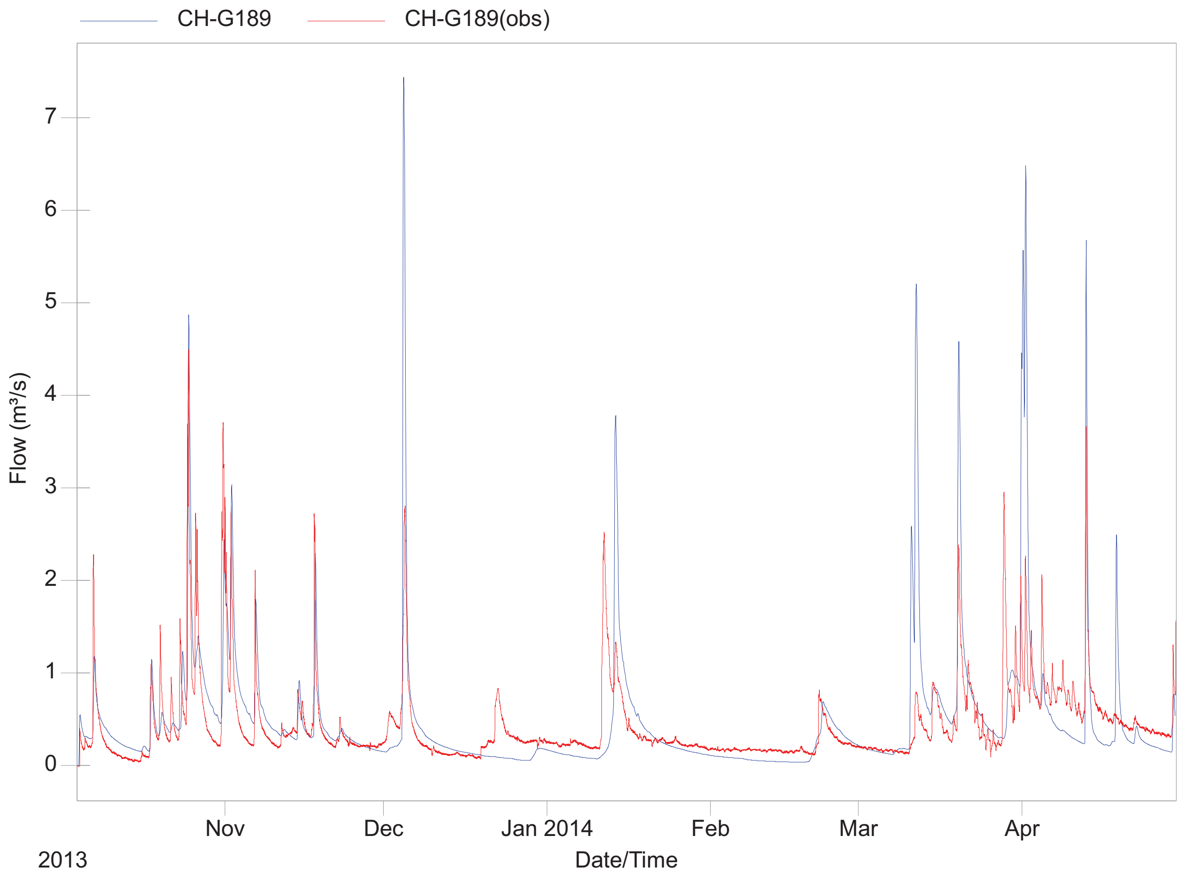


Figure 64: Bayfield North – Winter Flow Calibration at Porters Hill Line (CH-G189)

6.5.6 Winter Calibration Summary

In general, and as displayed in the winter calibration figures, adjustment of the SCF functions to provide the additional volume to balance with measured flows and maintain snow depth throughout the season, but results in over-estimating the snow pack depth. Winter calibration models also exhibited a higher runoff continuity error than the growing season models, yielding higher precipitation volume than what is accounted for in losses through infiltration, evaporation, surface runoff and surface storage. More accurate precipitation volume and timing, combined with several monitoring locations throughout the watershed can assist in defining multiple snow packs within the watershed. The importance of a reasonable density in snow depth and precipitation measurements is amplified in lake-effect areas where near-shore conditions can vary considerably from at the top of a watershed. A summary of the error between the final computed and observed hydrographs for the winter calibration period is provided in Table 24. It is anticipated that translating the snowpack parameters to watersheds with a lower level of input detail will trend similarly or poorer calibration goodness of fit.

Table 24: Summary of Winter Calibration Results

Watershed	Monitoring Location Name	NSE	R^2
Garvey-Glenn	Kerry's Line (CB-20 Flow)	-0.185	0.190
Garvey-Glenn	Tower Line Road (DLN20-08 Snow Depth)	-2.830	0.014
Bayfield North	Porters Hill Line (CH-G189 Flow)	-0.556	0.418
Bayfield North	Bettles (SGulyC59 Snow Depth)	-4.43	0.607
Bayfield North	Vermue (SStoGODM37 Snow Depth)	-7.050	0.794

7 MODELLING RESULTS

7.1 Scenarios Modeled

Each watershed model was run for the summer of 2013, from May 1st until September 30th (only until September 1st shown in calibration graphics above) with a warmup period in April. This scenario provided the best observed data for calibration. Calibration during the winter was not possible due to the methods used to collect precipitation data, as previously discussed.

Additional scenarios were run to model the application of BMPs in the Bayfield North watershed. In one watershed, several hydrology-based BMPs were applied to a selection of fields and their results impacts were assessed.

7.2 Peak Flows and Volumes

The peak flow and total runoff volume over the duration of the model scenario (May 1st to September 30th, 2013) are summarized for each watershed in Table 25 to Table 29. The points of interest are located at monitoring locations, main outfalls to Lake Huron, and confluences of major tributaries, as shown on the watershed maps provided in Appendix A. The name of the junction, outfall, and conduit (object) at which each point of interest is located is provided in Appendix D. The hydrograph for each point of interest, except for the calibration locations previously discussed, are also provided in Appendix D.

Table 25: Pine River Model Results – Peak Flow and Runoff Volume

Point of Interest	Area (ha)	Peak Flow (m^3/s)	Total Runoff (m^3)	Figure
1	15,495	4.16	3,800,000	Figure 69
2	15,382	4.20	3,661,000	Figure 23
3	15,342	4.18	3,644,000	Figure 70
4	13,794	2.63	3,283,000	Figure 71
5	5,573	2.10	1,457,000	Figure 72
6	2,757	2.81	539,900	Figure 73
7	756	1.95	132,200	Figure 74
8	7,629	2.10	1,652,000	Figure 75
9	2,463	2.09	783,900	Figure 76

Table 26: Garvey-Glenn Model Results – Peak Flow and Runoff Volume

Point of Interest	Area (ha)	Peak Flow (m^3/s)	Total Runoff (m^3)	Figure
1	48	1.41	51,310	Figure 77
2	1,579	3.46	1,105,000	Figure 78
3	1,578	3.46	1,105,000	Figure 79
4	1,291	3.25	868,900	Figure 32
5	210	0.64	156,200	Figure 80
6	276	1.40	182,600	Figure 81
7	641	1.48	406,900	Figure 82
8	102	0.35	64,670	Figure 83
9	223	0.92	113,800	Figure 84
10	114	0.54	81,330	Figure 85
11	54	0.09	34,340	Figure 86
12	139	0.18	20,130	Figure 87

Table 27: Bayfield North Model Results – Peak Flow and Runoff Volume

Point of Interest	Area (ha)	Peak Flow (m^3/s)	Total Runoff (m^3)	Figure
1	511	0.31	348,300	Figure 88
2	218	0.26	208,300	Figure 89
3	90	0.13	48,970	Figure 90
4	120	0.06	79,740	Figure 91
5	213	0.12	101,900	Figure 92
6	212	0.33	131,100	Figure 93
7	424	0.87	283,400	Figure 94
8	1,421	2.57	823,400	Figure 95
9	133	0.31	71,370	Figure 96
10	287	0.63	197,500	Figure 97
11	256	0.88	147,400	Figure 98
12	1,057	2.56	633,000	Figure 38

Table 28: Main Bayfield Model Results – Peak Flow and Runoff Volume

Point of Interest	Area (ha)	Peak Flow (m^3/s)	Total Runoff (m^3)	Figure
1	8,951	31.44	11,180,000	Figure 99
2	434	9.75	759,500	Figure 100
3	5,111	28.23	5,934,000	Figure 101
4	294	3.87	377,100	Figure 102
5	1,992	5.83	2,167,000	Figure 44

Table 29: Lambton Shores Model Results – Peak Flow and Runoff Volume

Point of Interest	Area (ha)	Peak Flow (m^3/s)	Total Runoff (m^3)	Figure
1	2,471	5.42	4,144,000	Figure 103
2	3,707	6.67	6,350,000	Figure 104
3	3,141	6.52	5,236,000	Figure 105
4	2,514	5.85	4,195,000	Figure 106
5	2,488	5.83	4,152,000	Figure 51
6	851	0.97	1,587,000	Figure 107
7	2,636	4.27	4,831,000	Figure 108
8	2,534	4.25	4,626,000	Figure 109
9	358	0.60	631,700	Figure 110
10	596	1.61	1,055,000	Figure 111

7.3 Dissolved and Attached Pollutant Loadings

The total loadings of TN, TP, SRP, and SS over the duration of the model scenario (May 1st to September 30th, 2013) are summarized for each watershed in Table 30 to Table 34.

Table 30: Pine River Model Results – Pollutant Loadings

Point of Interest	Area (ha)	TN (kg/ha)	TP (kg/ha)	SRP (kg/ha)	SS (kg/ha)	Figure
1	15,495	0.62	0.05	0.005	10.5	Figure 112
2	15,382	0.60	0.05	0.005	10.7	Figure 113
3	15,342	0.60	0.05	0.005	10.6	Figure 114
4	13,794	0.55	0.05	0.004	10.0	Figure 115
5	5,573	0.57	0.04	0.005	8.2	Figure 116
6	2,757	0.67	0.07	0.008	12.6	Figure 117
7	756	0.95	0.08	0.014	14.3	Figure 118
8	7,629	0.51	0.04	0.004	8.8	Figure 119
9	2,463	1.25	0.07	0.013	12.2	Figure 120

Table 31: Garvey-Glenn Model Results – Pollutant Loadings

Point of Interest	Area (ha)	TN (kg/ha)	TP (kg/ha)	SRP (kg/ha)	SS (kg/ha)	Figure
1	48	7.47	0.419	0.086	68.3	Figure 121
2	1,579	1.58	0.084	0.012	18.5	Figure 122
3	1,578	1.59	0.087	0.012	19.1	Figure 123
4	1,291	1.44	0.078	0.010	17.6	Figure 124
5	210	2.11	0.103	0.014	18.6	Figure 125
6	276	2.04	0.114	0.013	26.8	Figure 126
7	641	0.98	0.043	0.006	10.8	Figure 127
8	102	1.37	0.053	0.010	14.6	Figure 128
9	223	0.98	0.050	0.007	13.4	Figure 129
10	114	1.34	0.067	0.007	20.9	Figure 130
11	54	0.98	0.010	0.006	1.3	Figure 131
12	139	0.12	0.004	0.001	1.0	Figure 132

Table 32: Bayfield North Model Results – Pollutant Loadings

Point of Interest	Area (ha)	TN (kg/ha)	TP (kg/ha)	SRP (kg/ha)	SS (kg/ha)	Figure
1	511	1.7	0.04	0.013	6.19	Figure 133
2	218	3.4	0.15	0.028	26.58	Figure 134
3	90	2.4	0.10	0.017	20.64	Figure 135
4	120	1.6	0.01	0.004	1.14	Figure 136
5	213	2.3	0.09	0.015	16.95	Figure 137
6	212	2.5	0.13	0.012	24.16	Figure 138
7	424	4.6	0.07	0.031	9.84	Figure 139
8	1,421	3.9	0.26	0.032	48.05	Figure 140
9	133	2.5	0.11	0.021	18.64	Figure 141
10	287	5.4	0.41	0.054	73.49	Figure 142
11	256	4.2	0.40	0.040	75.38	Figure 143
12	1,057	4.5	0.31	0.039	57.92	Figure 144

Table 33: Main Bayfield Model Results – Pollutant Loadings

Point of Interest	Area (ha)	TN (kg/ha)	TP (kg/ha)	SRP (kg/ha)	SS (kg/ha)	Figure
1	8,951	11	1.2	0.06	277	Figure 145
2	434	27	3.9	0.12	768	Figure 146
3	5,111	9	0.7	0.04	178	Figure 147
4	294	20	2.2	0.11	432	Figure 148
5	1,992	7	0.2	0.02	58	Figure 149

Table 34: Lambton Shores Model Results – Pollutant Loadings

Point of Interest	Area (ha)	TN (kg/ha)	TP (kg/ha)	SRP (kg/ha)	SS (kg/ha)	Figure
1	2,471	16	0.54	0.12	65	Figure 150
2	3,707	15	0.72	0.12	96	Figure 151
3	3,141	16	0.77	0.13	102	Figure 152
4	2,514	17	0.80	0.14	104	Figure 153
5	2,488	17	0.81	0.14	105	Figure 154
6	851	4	0.09	0.03	13	Figure 155
7	2,636	11	0.49	0.09	64	Figure 156
8	2,534	12	0.51	0.09	67	Figure 157
9	358	5	0.15	0.05	17	Figure 158
10	596	16	0.74	0.13	96	Figure 159

8 MODEL APPLICATION

As part of the 2014 RSWMM technical workshop, two examples of BMP implementation and impact analysis were developed and showcased. These examples were analyzed using the model that was constructed for the Bayfield North watershed within the ABCA. This section discusses some of the methods available for the identification of priority areas with a watershed, as well as some of the results of the example BMP scenarios. It should be noted that there are many methods by which these analyses can be performed, and it is beyond the scope of this section – and moreover, this report – to provide a comprehensive tutorial on water quality modelling.

8.1 Identifying Priority Areas

The first step in modelling agricultural BMPs is to first determine where the priority areas are located in a watershed – essentially targeting subwatersheds where BMPs are most needed. One convenient tool included with PCSWMM is the ability to render features based on their attributes, including both inputs and outputs. Figure 65 and Figure 66 below show examples of RSWMM layers rendered to highlight potential priority areas. Figure 65 is an example of using outputs – in this case nitrate concentration in the runoff from the Subcatchments layer – and Figure 66 is an example of using inputs – in this case the average slope of the polygons in the Fields layer. It was in using renderings like these that the locations for the BMP scenarios in the next section were chosen.

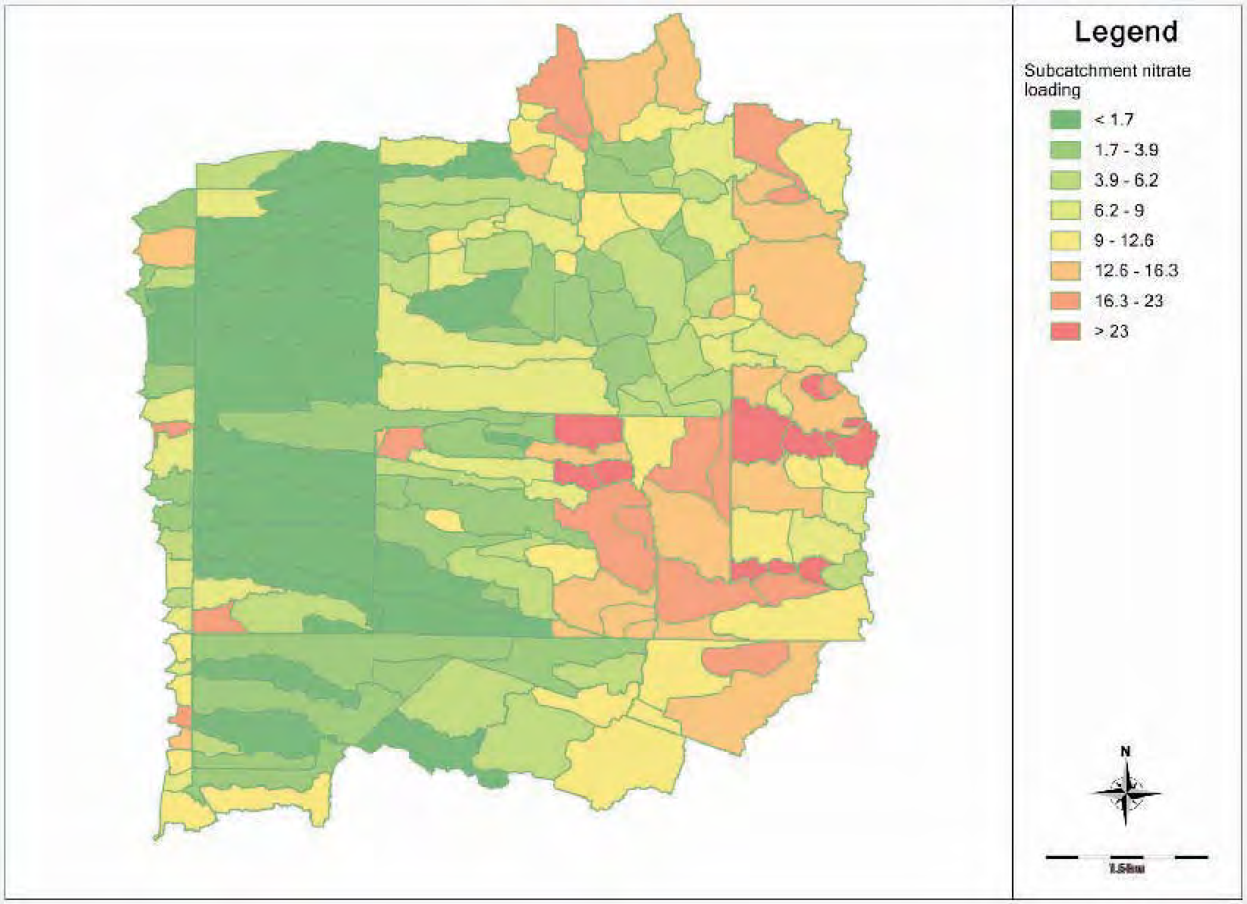


Figure 65: Subcatchments in the Bayfield North watershed rendered to display nitrate (NO_3^-) loading in kg/ha for a simulation period from May to September, 2013.

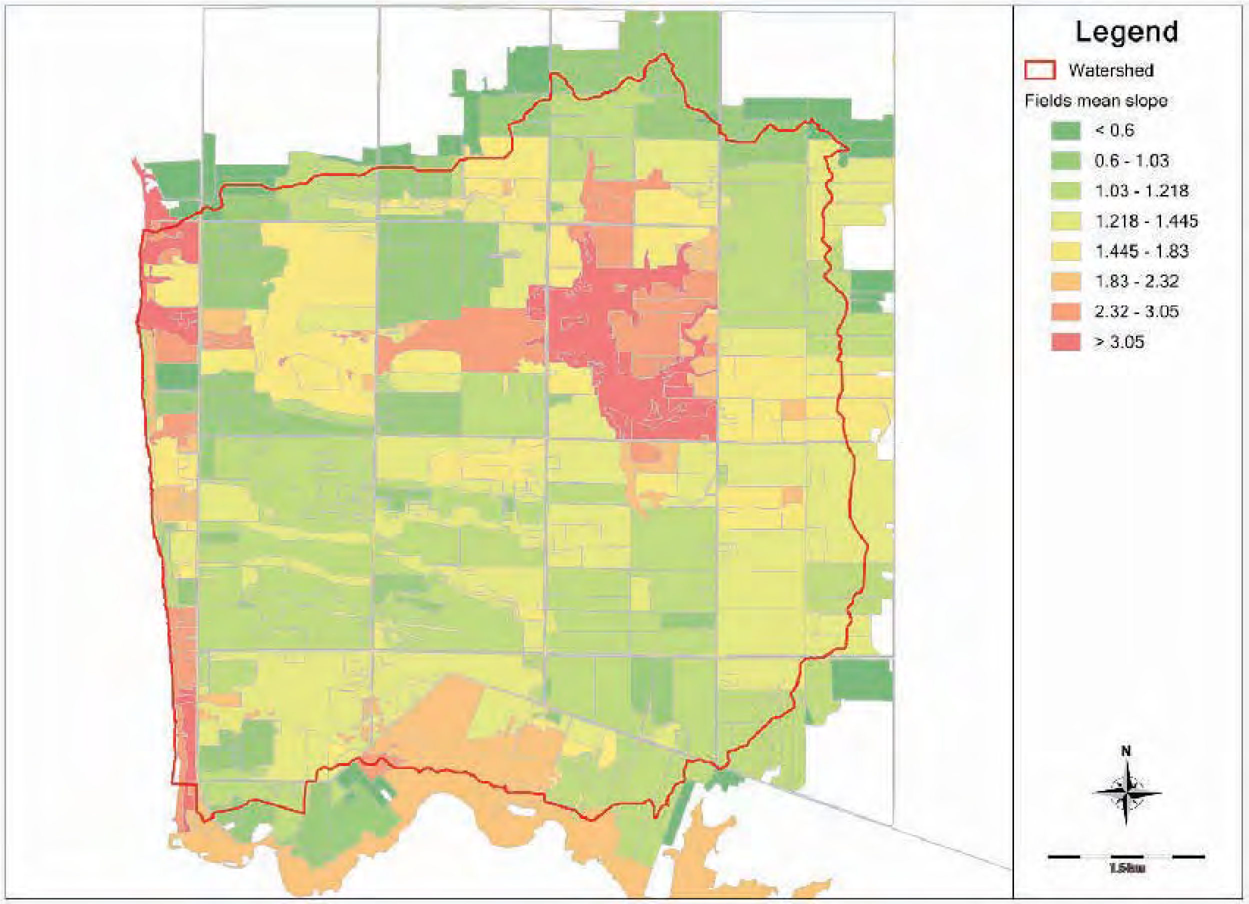


Figure 66: Fields in the Bayfield North watershed rendered to display mean slope in %.

8.2 Using Scenarios to Assess BMPs

The first example involved an area of the model in which seven WASCOBs were present, constructed prior to the 2013 calibration period. Scenarios with and without the WASCOBs were modeled and the results are discussed in Section 8.2.1.

The second example included 3 separate scenarios that involved a single watershed in which several soybean fields (accounting for nearly 50% of the subwatershed area) were chosen to host several agricultural BMPs. This example is discussed in Section 8.2.2.

8.2.1 Example: WASCOBs

The configuration of the WASCOBs as they were modelled is shown in Figure 67. These features were originally located in a single subwatershed but re-delineation was performed in order to model each WASCOB explicitly and, in doing so, more closely represent reality. Since the calibration accounted for the presence of the WASCOBs, assessing their impact on flow and water quality merely required removing them from the model, and the simplest way to do this was to set their storage volume equal to zero. In this way, two scenarios were created and compared to perform an impact assessment at a point immediately downstream. The impact on flow and water quality observed at the first culvert downstream (named CH-G182 in the model) can be seen in Table 35.

More information on WASCOBs and other hydraulic-based BMPs can be found in Section 5.2.

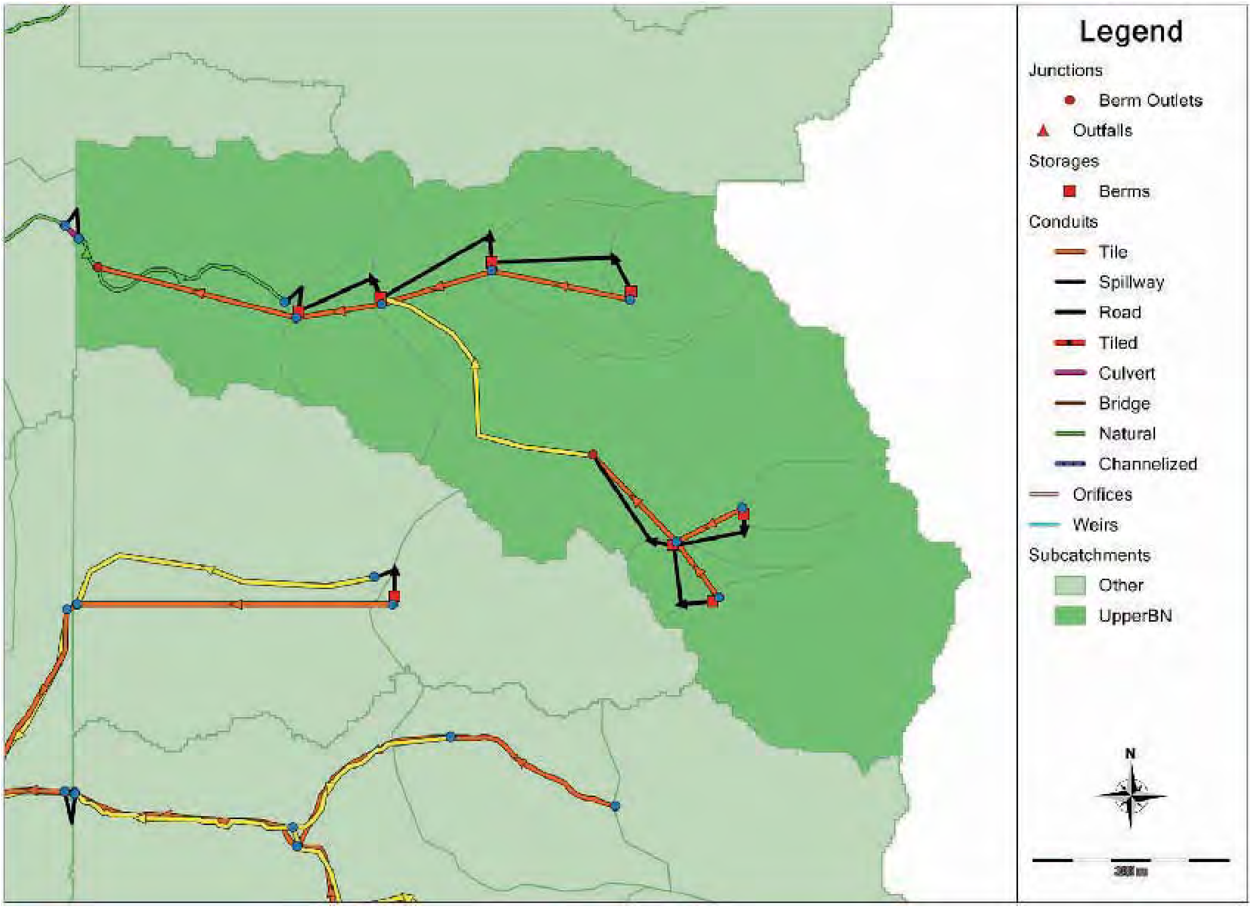


Figure 67: Subwatersheds (shown in dark green) and seven WASCOBs located upstream of culvert CH-G182 in the upper Bayfield North watershed.

Table 35: Impact of WASCOBs on water quantity and quality at culvert CH-G182 for a simulation period from May to September, 2013.[9]

Model scenarios:	**Runoff Volume (m^3)**	**SS (kg)**	**TP (kg)**	**TN (kg)**
No WASCOB	51,660	31.4	0.160	1.36
WASCOB	46,450	24.8	0.128	1.38
Reduction Percentage	*10%*	*21%*	*20%*	*-2%*

As seen in Table 35, there is a volume reduction associated with the modelling of the WASCOBs in this scenario. These results – including the pollutant reductions – are dependent upon estimates of infiltration and evaporation rates of water during retention in the devices, and so care should be taken to keep these values within reasonable limits to avoid over- or under-estimating their efficacy.

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[9] Note: the reported values were generated using a partially-calibrated model, and should be considered for illustrative purposes only.

8.2.2 Example: Selected Hydrology-based BMPs

Four scenarios were compared for a subwatershed (named SGulyC53 in the model) in the upper portion of the Bayfield North watershed shown in Figure 68. A base scenario (2013 conditions) was compared with three scenarios in which three agricultural BMPs – namely Conservation Cover, Conservation Tillage, and Contour Farming – were applied to three fields under soybean cultivation in 2013 and comprising roughly 48% of the subwatershed area. The impact on flow and water quality as observed at the first culvert downstream (named CH-G185 in the model) can be seen in Table 36.

More information on agricultural BMPs can be found in Section 5.2.

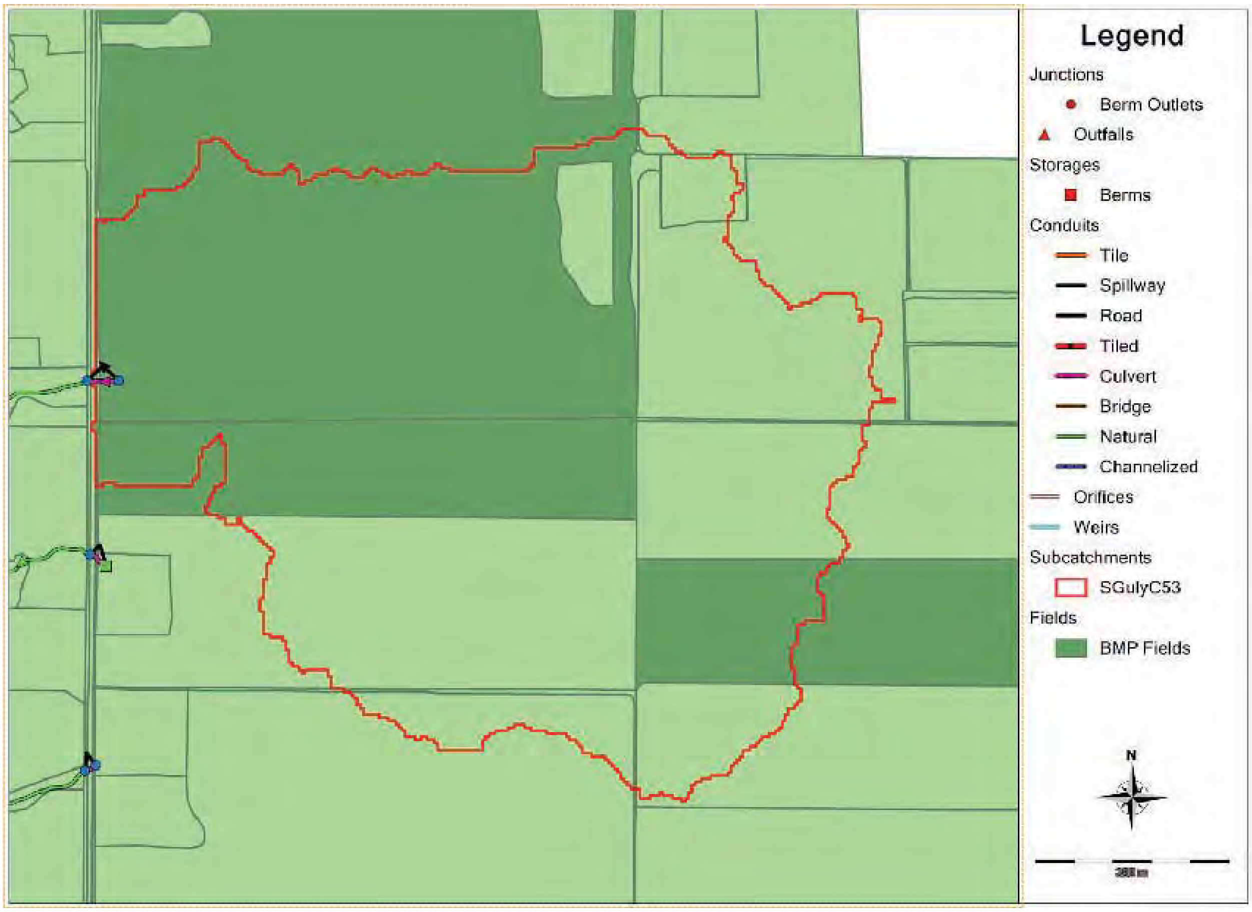

Figure 68: Soybean fields chosen for BMP implementation (shown in dark green) intersecting subwatershed SGulyC53 in the upper Bayfield North watershed. Drainage from this subwatershed is directed to culvert CH-G185.

Table 36: Example of the impact of various BMPs on water quantity and quality at culvert CH-G185 for a simulation period from May to October, 2013.[10]

Model Scenarios:	Runoff Volume (m^3)	SS (kg)	TP (kg)	SRP (kg)	TN (kg)
Current Conditions	22,470	1,195	6.4	0.62	252
Conservation Tillage	18,020	807	4.3	0.41	182
Conservation Cover	20,470	416	2.5	0.52	198
Contour Farming	21,210	620	3.6	0.49	234
Conservation Tillage Reduction %	*20%*	*33%*	*32%*	*34%*	*28%*
Conservation Cover Reduction %	*9%*	*65%*	*61%*	*17%*	*22%*
Contour Farming Reduction %	*5%*	*48%*	*44%*	*20%*	*7%*

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[10] Note: the reported values were generated using a partially-calibrated model, and should be considered for illustrative purposes only.

9 DISCUSSION & RECOMMENDATIONS

9.1 Required Level of Detail

The building of hydrologic, hydraulic, and water quality models always requires detailed and accurate information to correctly represent reality. However, the application intent often dictates the level of detail required for a particular effort. The application of a particular model varies widely, and so the input requirements vary in kind. Fortunately, SWMM5 is a platform that was developed for a wide variety of applications and is very adaptable to investigating water quantity and quality concerns at both large and small scales. This same flexibility, however, contributes to the difficulty in determining the level of detail required for building a model in SWMM5 since there is virtually no limit to how coarsely- or finely-detailed a model can be.

In this project, five watersheds were modeled with varying levels of detail as determined by the data collected and provided by each CA. Although difficult to quantify precisely due to the wide range of input types used to build them, the models can be approximately ranked by level of detail, from most to least[11]:

1. Bayfield North
2. Main Bayfield
3. Garvey - Glenn
4. Lambton Shores
5. Pine River

In fact, the level of detail in the inputs can, in part, be inferred from the model outputs, as shown by the calibration results in Section 6.4. While it is true that model calibration can always be refined – often seemingly to no end – greater attention to detail in data collection and model setup can both reduce the time required to calibrate and increase the quality of the calibration. The conclusion that seems to be implied by the results of this project is that more detail is indeed better, but in the end, the resources available for data collection and model construction will usually be the deciding factor in how detailed a model becomes.

9.2 Model Limitations

Several limitations involving the US EPA SWMM5 engine and the structure of SWMM in general prevented the inclusion of a number of desirable upgrades in RSWMM. These include:

- Crop rotation BMP
- Nutrient management BMP
- Modelling of nitrogen fixation by legumes
- Nutrient cycling processes, including nitrogen and phosphorus dynamics
- In- and near-stream erosion processes (e.g. bank and gully erosion)
- Modification of treatment processes in response to changes in water temperature or dissolved oxygen availability
- Real-time tracking of sediment depth in retention facilities
- Calibrations are currently valid only for the growing season

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[11] A majority of the disparity in detail stems from the varying resolution of the digital elevation models (DEM) provided for each watershed, outlined in Section 5.1, and the size of the watershed.

Further enhancements to PCSWMM could potentially be performed to address any or all of these limitations. It is recommended that discussion be initiated to determine which limitations are most important to address.

Water Quality Modelling Approach

The empirical approach to parameterizing and modelling water quality indicators used in RSWMM was beneficial for its simplicity and adaptability, as well as its relative ease of incorporation into the existing SWMM5 framework. However, simplicity does not come without limitations. The program still lacks the ability to easily incorporate a variety of time-dependent processes that are prominent in agricultural watersheds, particularly such activities as fertilizer application and tillage operations. Then again, one development of this project was the ability to vary input parameters with time, and this should be considered a significant step toward facilitating time-variance in other areas of the model as well.

Because the observed datasets for SRP, NO3, NO2, and TKN were used in parameterization, calibration merely amounts to a fine-tuning of the coefficients and exponents in the washoff equations. The convenience of this approach is that the calibration can be easily updated for additional or more robust observed water quality datasets. However, there are several drawbacks to this approach. The first is that – much like the representation of hydrology in SWMM – the representation of the water quality indicators is essentially a lumped-parameter approach. Concentrations in simulated runoff vary by land-use proportional to values found in available literature, but it is difficult or impossible to partition observed water quality data and determine the relative proportions of the pollutants contributed by land-uses in the real world.

The use of MUSLE in modelling sediment loading has many benefits, including its long history and acceptance of application in other hydrologic models (or perhaps more accurately, the application of USLE and USLE-based routines), its simplicity, and the relative ease of incorporation into PCSWMM. Since MUSLE is empirically-based it suffers from similar limitations to those mentioned above. It should also be noted that MUSLE does not have sufficient detail to account for variation in detachment and transport of different particle sizes in response to rainfall or runoff intensity. The distribution of particle sizes in runoff for a subcatchment is setup to be calibrated and refined in response to any detailed information gathered in the future, but the current sediment model would need to be altered to include an empirically- or physically-based routine for detachment and transport dynamics in runoff.

The calibration of sediment loading also suffers from the current lack of any stream bank erosion, in-stream sediment dynamics (e.g. settling, re-suspension, scour), or gully erosion modelling. Additionally, literature suggests that the relative proportion of the total sediment loading in a stream contributed by these processes varies greatly by watershed (Schottler, Engstrom, and Blumentritt 2009; Schilling et al. 2011; Koiter et al. 2012; Voli et al. 2013). More research is required to determine the feasibility of incorporating such processes into PCSWMM, as well as to determine the most cost-effective method of sourcing sediment within RSWMM watersheds.

In addition to the portion of total phosphorus (TP) loads that are unaccounted for due to the lack of any sediment load predictions aside from MUSLE, the soluble unreactive phosphorus (SUP) is also not being directly accounted for. This is not an oversight, but rather a limitation resulting from the observed water quality data set, which (as discussed in more detail in the Section 6.2.5) only included TP and SRP. Since TP is really made up of three pools (PP, SRP, and SUP), one equation with two unknowns prevented the simulation of SUP. It should be noted that although PP loading was technically simulated, it could not be independently calibrated for this same reason.

Two important water quality components – namely water temperature and dissolved oxygen – were excluded as the result of difficulty in modelling them empirically. Water temperature was not considered because SWMM5 currently does not support thermal modelling, which is quite complex and requires process-based modelling techniques. Dissolved oxygen was not considered because its relationship to biological and chemical components in natural waters is also quite complex and, like temperature, requires process-based modelling. This is important to note because the rates of many chemical transformation processes are temperature dependent, and the rates of all redox reactions (e.g. nitrification and denitrification) are entirely dependent upon dissolved oxygen availability (Brezonik and Arnold 2011). While the inclusion of these modelling capabilities would constitute a tremendous improvement to SWMM, their incorporation would not be without significant effort.

BMP Modelling Approach

In general, the method by which the hydrology-based BMPs (see Section 5.2) have been implemented is quite unique in that the removal mechanisms are both physically based (as they modify hydrologic attributes) and empirical (as the degree to which these attributes are modified was calibrated to literature values for removal). This enables the BMPs to be widely applicable and easily updated as more research becomes available, or updated for project-specific research or research performed locally.

Feedback from the technical advisory committee and others has suggested that crop rotation and nutrient management are perceived as perhaps the most important additions to RSWMM that should be made in the future. Implementation of crop rotation will likely require a modification to the SWMM engine, and it may be necessary to reassess the current approach to land-use assignment. Implementation of nutrient management will need to go hand-in-hand with improvements in the way that pollutants are generated (discussed in the previous section) – which currently does not involve using build-up equations.

Another improvement that could be made involves increasing the level of detail used in the modification of MUSLE parameters resulting from the implementation of agricultural BMPs. Publications on RUSLE (Renard et al. 1997; Wall et al. 1997) contain more complex relationships for some of the USLE parameters than those presently used, which require the definition of additional attributes and more detailed user input regarding specific agricultural BMPs. While some of these relationships were too complicated to include in RSWMM at this time, more research could be conducted to determine how they might be incorporated into the existing framework of auto-expressions with the addition of more user-defined BMP attributes. Recent improvements to the auto-expressions editor should also greatly simplify future efforts.

The modelling approach to hydraulic-based BMPs is based on generally accepted methodology, including first-order kinetics for pollutant removal. The strength of SWMM5 in hydraulic modelling lends itself well to the modelling of these devices. However, knowledge of hydraulic modelling, of the chemical and physical processes in these devices, and of SWMM5 in particular is required in order to properly and accurately incorporate these devices.

Currently, the RSWMMs provide an interpretable set of outputs that can assist in siting BMPs on the landscape, but there is no automated process to assess the feasibility or efficacy of constructing a BMP in any particular location. In this regard, of particular interest is the work by Tomer et al.

(2013), who developed a framework for computer code that can predict optimal BMP locations using terrain analysis techniques. Incorporating this work was far too complex to consider as part of this iteration of RSWMM, but a beta version of the follow-up work to the 2013 paper – which uses ArcGIS software to implement the framework – is currently under development and should be available to the public within approximately one year. Integrating this ground-breaking work into the RSWMM interface (or simply, via ArcGIS, into the modelling workflow) would be a powerful and entirely novel approach to siting BMPs on the landscape in a hydraulic and hydrologic model.

9.3 Recommendations for Future Work

Based on the calibration results for the five sentinel watersheds, EOR has several recommendations for future work on these models. These include improvements to the existing models as well as recommendations for data collection as part of the expansion of the project to additional areas.

9.3.1 Improvements to the existing models

The influence of detailed inputs can be seen in the quality of the calibrations. As such, one of the main recommendations is to improve the detail of the models that did not calibrate as well. This section includes some general recommendations, followed by recommendations for the individual models.

Updated calibrations

In general, model calibrations should be updated when additional monitoring data become available. Recent weather patterns indicate that the growing season of 2014 may prove to yield a better set of observed water quantity data than did 2013, so efforts should be made to ensure proper collection and QA/QC of these data sets. Moreover, any addition of or modification to a significant hydraulic feature should be documented for eventual inclusion in the model. For instance, it is currently known that there was at least one ongoing project during 2013 to construct several WASCOBs within one subwatershed in the upper Bayfield North watershed. It should be noted that once hydrologic and/or hydraulic features are updated in a model, previous calibrations – while still valid – should be expected to display decreased model fit, since observed data are obviously not impacted by features that did not exist on the landscape when they were collected. Recalibration remains a better option than maintaining multiple past and present versions of a model.

Winter calibration

As discussed in Section 6.5, efforts were made to perform winter calibration with the existing winter precipitation data. However, issues with precipitation timing and water balance continuity (i.e. snow pack depth and flow volumes) led to the decision to concentrate most of our efforts on the 2013 growing season in this iteration of the models.

Full winter calibration was, nevertheless, performed for the Bayfield North model since it had one of the most reliable monitoring, hydrologic and hydraulic information. Some of the key winter calibration input parameters had to be brought significantly outside the recommended ranges to obtain a satisfactory calibration. These Bayfield North calibrated winter parameters were incorporated in the other 4 models for now. Future models' improvements should incorporate data from heated, wind-protected rain gauges or radar-derived rainfall into the calibration. This will significantly increase the winter and spring runoff reliability of the models.

Priority cross-section surveys

One issue in all five models is that transects generated using the DEM do not provide the cross section of rivers and creeks below the water level. Cross sections including the channel bottom could be surveyed at key locations in all watersheds, particularly for larger stream and river channels.

Bayfield North

Bayfield North had the most detailed and comprehensive information regarding hydraulic structures, particularly regarding crossings and WASCOBs. However, more information could be included regarding storage features such as ponds, lakes, and reservoirs. The relative lack of municipal drain information provided compared with that for Main Bayfield, its neighboring watershed, suggests that there may be more drains present in the watershed than are currently modeled. Additional investigation is needed during future model improvements to address the elevated TKN concentrations in August and September.

Main Bayfield

The Main Bayfield watershed is bisected by the Bayfield River, which drains two larger watershed areas to the east and southeast. The incorporation of these areas into the Main Bayfield model would facilitate calibration at the largest of the gauging stations within the watershed – referred to as the Varna gauge. This watershed had the most detailed information on municipal drains, but there are a few major drains that had insufficient information to build them into the model. It is recommended that the Brand Drain in particular be included, as its potential contributing drainage area is approximately 180 hectares. In addition to this drain, there were a few key areas upstream of the Trick's Creek gauging station where data was insufficient to properly model the complexity of the terrain, including the cross-section of Trick's Creek itself (due to poor DEM quality, likely the result of dense coniferous tree canopy in this area) and the aggregate extraction area to the west of the creek. It is recommended that investigation be performed in this part of the watershed and model detail updated to improve the calibration at this monitoring location.

Garvey-Glenn

A good level of detail was provided for the Garvey-Glenn model, although additional berms and culverts not included in the model were identified using aerial imagery. More detailed inventory of these structures could improve the calibration. Additional investigation is needed during future model improvements to address the elevated TKN concentrations in August and September.

Lambton Shores

All models will benefit from the incorporation of additional information regarding municipal drains, but Lambton Shores in particular has many closed drains that are known to exist yet are not currently modeled. The municipal drains identified in the latest GIS data are currently modeled and can be updated when more details are available. The Brand and Anderson municipal drains direct runoff from approximately 300 ha to the southernmost outfall to Lake Huron within the watershed. Additional municipal drain information could also improve the delineation of drainage divides in the flat areas commonly found throughout the watershed. More detailed topography from on-site surveys is recommended in heavily forested areas, such as the northwest corner of the watershed along the Ipperwash Drain. In addition, the calibration of the Lambton Shores watershed could be improved by generating a rating curve for the Duffas gauge.

Pine River

Many design drawings were provided for the municipal drains in the Pine River watershed, however the model was limited by a DEM with only 10 m resolution. No municipal drain information was provided for the separate watercourse, Clark Creek, on the south side of the watershed. Model results in Ripley and along the Lakeshore could be improved with more detailed information on storm sewers and ditches. It is recommended that any ponds, wetlands, or improvement projects such as WASCOBs are also added to better represent surface storage in the model.

9.3.2 Data collection for future models

In order to achieve an accurate understanding of the nutrient loading from any watershed there needs to be year-round monitoring of both water quantity and water quality. Of course, this is no simple task, but there is no substitute for high quality observed data for use in model refinement and for gaining insight into the prioritization of BMPs based on the distribution, timing, and intensity of nutrient loadings.

There are several areas that can be focused on to improve the efficiency of data collection and model building during future expansion of the RSWMM project area. Some of these involve improving the consistency of data collected by the CAs and their delivery to the consultant or modelling team, while others are merely recommendations regarding the best type of data to collect.

Develop categorization schema

Coordination among the CAs to develop a consistent, well-defined and manageable number of values for variables like land-use, soil texture, and water quality indicators is of the utmost importance prior to any future model development efforts, as their development would significantly streamline the model development process.

For example, when EOR modellers attempted to define a discrete set of land-use categories for inclusion in the models they encountered over 90 unique land-use classifications within the five sentinel watersheds, leading to a time-consuming re-categorization process. As another example, SVCA and SCRCA reported total suspended solids (TSS) for the sediment component of water quality, while ABCA and MVCA reported suspended sediment concentration (SSC); these two terms have distinct laboratory procedures and are generally considered not to be equivalent (Gray et al. 2000). While this issue was eventually traced back to mere mislabelling (all reported values were for TSS), it was not before the models were setup referring to sediment in terms of SSC. The naming conventions of some of the other water quality components were also reported inconsistently or without sufficient description (e.g. it was unclear whether nitrate was being reported as mg/L of nitrate or mg/L of nitrogen). All samples taken for this project were already sent to the same laboratory for analysis, but these inconsistencies could be rectified by developing or following a set of water quality data reporting guidelines. Table 37 demonstrates this need by summarizing the water quality data as it was reported for each watershed.

Table 37: Reported water quality values by watershed.

	Watershed				
Observed Water Quality Component	**BN**	**MB**	**GG**	**LS**	**PR**
Alkalinity					X
Ammonia-N				X	X
Ammonium-N	X	X	X		
Chloride		X		X	X
Conductivity	X	X			X
Dissolved Oxygen	X	X			
E. Coli	X	X	X	X	X
Nitrate-N	X	X	X	X	X
Nitrite-N	X	X	X	X	X
Nitrogen, Total			X	X	X
Nitrogen, Total Kjeldahl	X	X	X	X	X
pH	X	X			X
Phosphate-P	X	X	X	X	X
Phosphorus, Total	X	X	X	X	X
Phosphorus, Total Dissolved				X	
Residue, Filtered	X	X			
Residue, Total	X	X			
Solids, Total			X	X	X
Solids, Total Dissolved	X	X	X	X	X
Solids, Total Suspended				X	X
Stream Condition	X	X			
Sulfate					
Suspended Sediment	X	X	X		
Water Temperature	X	X			

Use updated and appropriate laboratory techniques

Analytical laboratories are more often processing wastewater samples than natural water samples, and some of the standard methods that are used are, in fact, not suitable for the analysis of natural waters. Below are two noteworthy examples, but it would be prudent to further discuss this issue with an expert in the field of environmental water chemistry prior to future RSWMM monitoring work.

While the decision to simulate *suspended sediment concentration* (SSC) rather than *total suspended solids* (TSS) was partially influenced by the false assumptions made regarding the analysis of the observed data, it was ultimately based on recommendations from Gray et al. (2000), who claimed that the methodology for measuring TSS is "fundamentally unreliable for the analysis of natural-water samples" due to bias that increases with the amount of sand-size material in the samples. The authors suggest that the use of SSC for the reporting of suspended solid-phase concentrations, rather than TSS, would increase the accuracy and comparability of these measurements. Methodologies for converting between the two metrics have been developed (Ellison, Savage, and Johnson 2014), so it is also possible that TSS data collected in the past could be rectified to be more comparable with future SSC data.

Also noteworthy is the assertion by Brezonik and Arnold (2011) that the Kjeldahl method – which has long been used to measure ammonium and other organic forms of nitrogen (reported as *Total Kjeldahl Nitrogen,* TKN*)* – is no longer considered particularly well-suited as a laboratory analysis technique for natural waters. The authors recommend it be replaced with a technique for total nitrogen determination involving oxidation by alkaline persulfate, which takes less time, is more environmentally-friendly, and has the added benefit that the same sample can be used for the analysis of both TN and TP. Many labs already use this updated technique but still report results as TKN, so it is important to verify which method was used.

Perform in-house QA/QC

Several of the issues that were encountered during the course of the project might have been prevented by having in-house QA/QC of the observed water quality and flow data. It is difficult for an end-user to determine if anomalies or inconsistencies in the data were introduced by equipment, during data download or transfer, during laboratory analysis, or during reporting. On the other hand, someone who is intimately familiar with the watershed and the data collection procedures may be able to immediately identify the sources of error and either correct them or inform modellers of their existence. Their expert knowledge of the local conditions is also likely to enable them to catch errors that might remain unseen to outsiders.

Perform pre-processing of data

In this context, pre-processing of monitoring data simply amounts to using the most efficient method of data transfer. The current effort involved a combination of HEC-DSS databases (for water quantity and climate data) and Excel spreadsheets (for water quality data). While HEC-DSS provides a convenient database management tool with very small file sizes (due to its binary format), PCSWMM also supports the creation of small time series formats, and the pre-processing of data directly into one of these file types would significantly streamline their incorporation into the models. Water quality data of irregular time intervals (e.g., grab samples) are also be supported by the SWMM time series formats. These time series files can also be managed in PCSWMM using a Time Series Project file, within which data could likely be imported directly to these formats following collection.

Compile metadata in GIS files

Because RSWMM has a strong GIS component, the most efficient form of spatial data is that which is provided in a GIS format. Much of the data provided for this project was of this nature; however, some data (such as the municipal drain information) was extracted by EOR modellers from construction documents and spreadsheets. It is recommended that any information to be included in future model development be compiled as metadata in GIS shapefiles by local staff before being delivered to the model developers. Formatting of the metadata – for example, column headings – can be informed by observing the names of corresponding SWMM attributes within the RSWMM environment, and by observing how specific features were incorporated in to the five sentinel watersheds. Additional information such as notes and stationing can also be included via the creation of user-defined attributes.

Determine priority datasets

Resource limitations commonly prevent all input data from being collected in high resolution for all projects, so one important consideration involves the type and resolution of data to be collected for future modelling efforts. As suggested by the calibration of the models for the five sentinel watersheds, RSWMM is affected most significantly by three input datasets: the DEM; the hydraulic features in the watershed; and the temporal and spatial resolution of rainfall data. Once obtained, a high resolution DEM can provide a great level of detail regarding certain aspects of both hydrology and hydraulics with very little effort by using standard terrain analysis techniques within PCSWMM and other commonly-used GIS software. Data on hydraulic features, on the other hand, require a significant effort to collect, and so careful planning should be undertaken to hierarchically identify structures of interest prior to the start of any modelling effort. Rainfall data should be as heterogeneous as possible (i.e. as many rain gauges in as many places as possible), and heated rain and wind-shielded gauges should be used to fully account for the water content in snowfall and to increase gauge capture efficiency. An emerging alternative to this necessity is the possibility of incorporating radar-derived rainfall directly into the model, providing greater spatial and temporal resolution than is possible with any number of rain gauges. This option is newly supported for Canadian radar in PCSWMM and is recommended for incorporation into both existing and future models.

While the DEM, hydraulics, and precipitation data may be the most crucial to ensure high resolution, among the other SWMM parameters there are still minimum data requirements. The hydrologic input parameters (e.g., depressional storage, Manning's roughness, and soil hydraulic properties) are also important in SWMM, but their uncertainty is such that they are better suited for calibration than other input data. Still, some information on the spatial variability of these components is required to develop a model. For agricultural watersheds – as will likely be the focus of any RSWMM-related projects – the development of a field layer for the investigation of BMP impacts does necessitate relatively high-resolution land-use data, and so digitization of field polygons for any area in which BMPs will be modeled is required to properly use the model. Climate data need only be incorporated on a daily time step, and include daily maximum and minimum temperature, average hourly wind speed, and daily evapotranspiration depth. Evaporation depth can be derived either using a pan (pan evaporation coefficients are available in SWMM for correction) or from other sources such as a weather station that calculates reference evapotranspiration, as was used for this project.

10 FINAL NOTES

No modelling effort can – or should even strive to – supplant the need for expertise, so the development, maintenance, use, and interpretation of these models will require extensive knowledge of agricultural practices, BMP design, as well as hydrologic, hydraulic, and water quality modelling. Without proper consideration for things such as model limitations and uncertainty, a novice modeller is easily capable of drawing invalid conclusions from model results.

The capabilities added to PCSWMM as part of the RSWMM project have resulted in a dramatic increase in usability for modelling stormwater in rural landscapes. The agricultural BMP tools built into the models can be used to make decisions regarding the type, location, and extent of BMPs required to achieve water quantity and quality goals in a watershed. While default parameters are provided for many of the BMPs included, care should be taken to verify the applicability of such parameters, and as new research is conducted and new literature is published, the improved knowledge base upon which RSWMM has been built should be incorporated to improve model reliability.

The goal of the RSWMM project was to develop a better tool for rural stormwater management, yet the RSWMMs and the enhancements to PCSWMM do not represent a final solution. Rather, a great many steps have been made toward a better model that can be expanded and improved upon to further that goal and to improve water quality not only in Ontario, but around the world.

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APPENDIX A WATERSHED MAPS

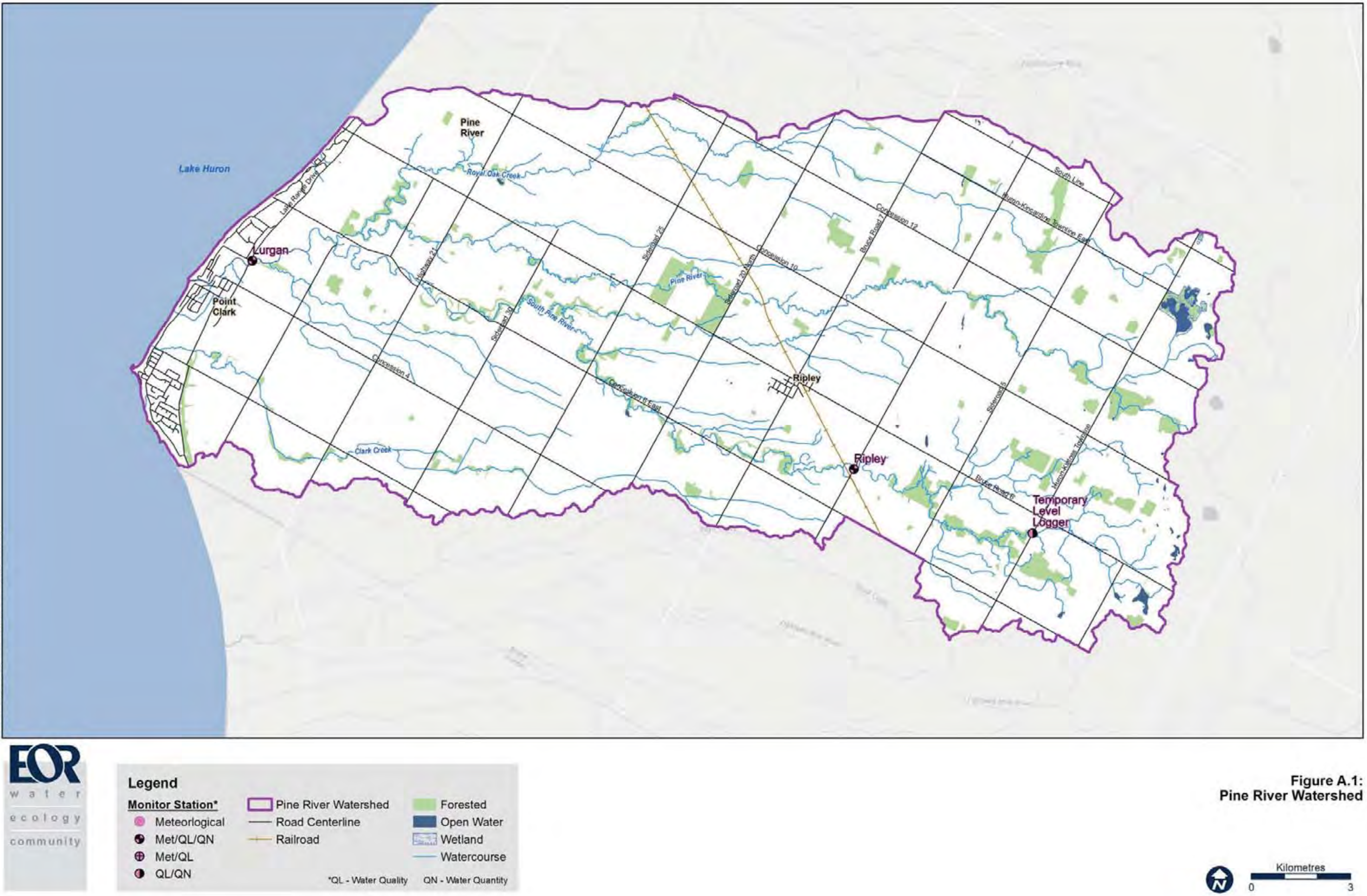

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Figure A.1:
Pine River Watershed

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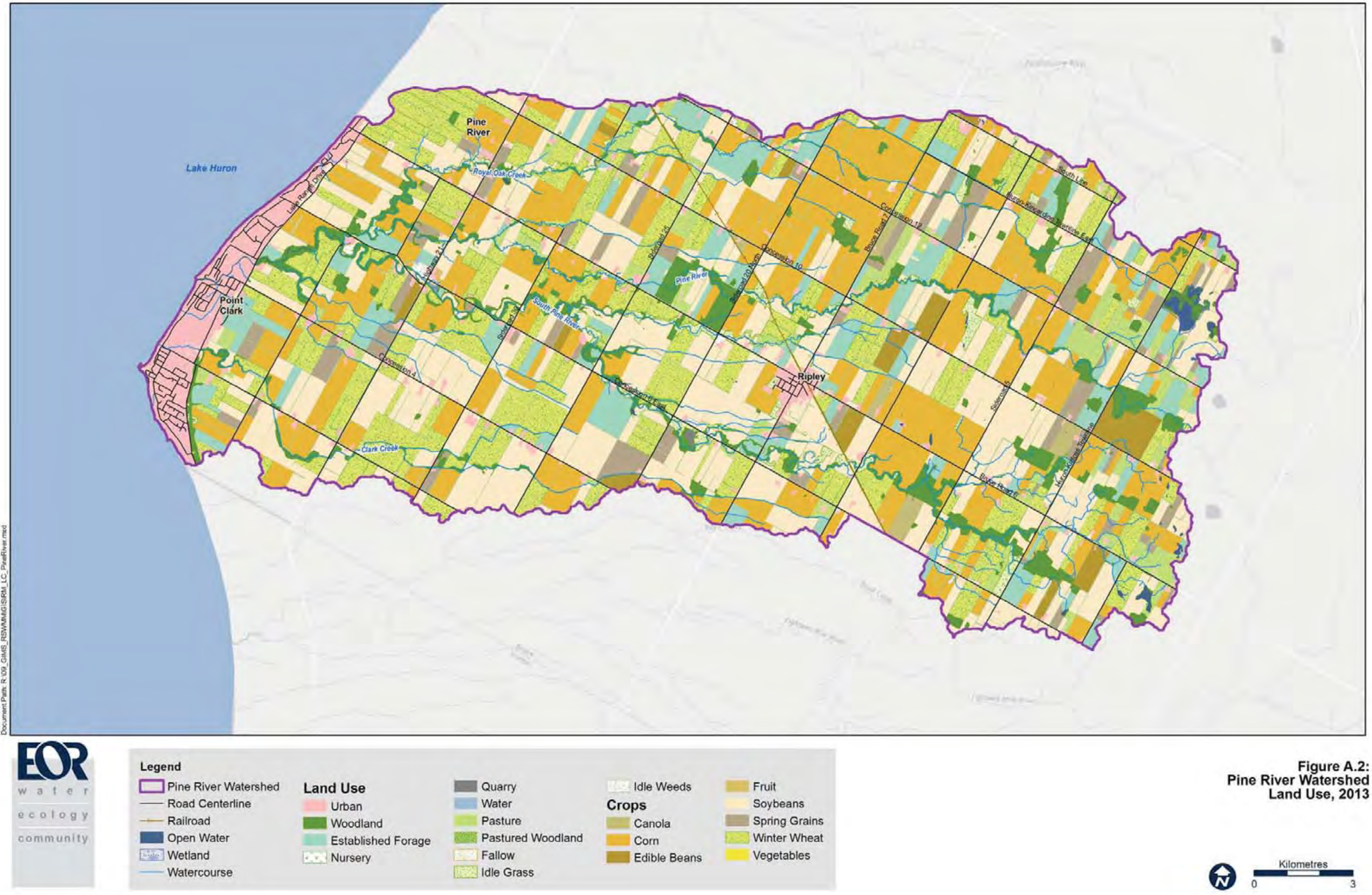

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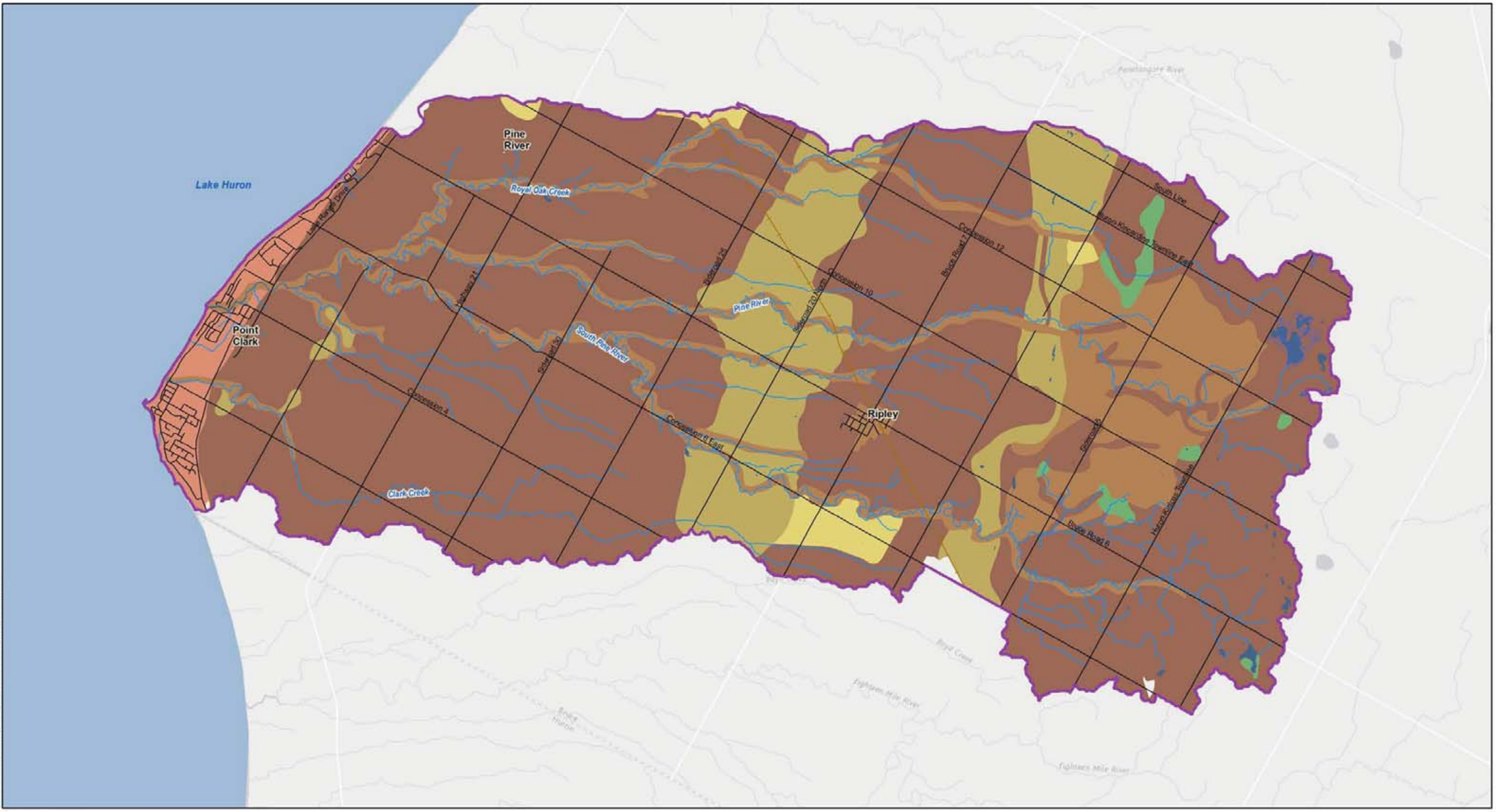
Figure A.2:
Pine River Watershed
Land Use, 2013



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Legend

- ▭ Pine River Watershed
- — Road Centerline
- ┼ Railroad
- ■ Open Water
- ▨ Wetland
- — Watercourse

Soil Type

- ■ Clay
- ■ Clay Loam
- ■ Loam
- ■ Organic
- ■ Sand
- ■ Silty Clay Loam
- ■ Silt Loam
- ■ Sandy Loam

Figure A.3: Pine River Watershed Soils

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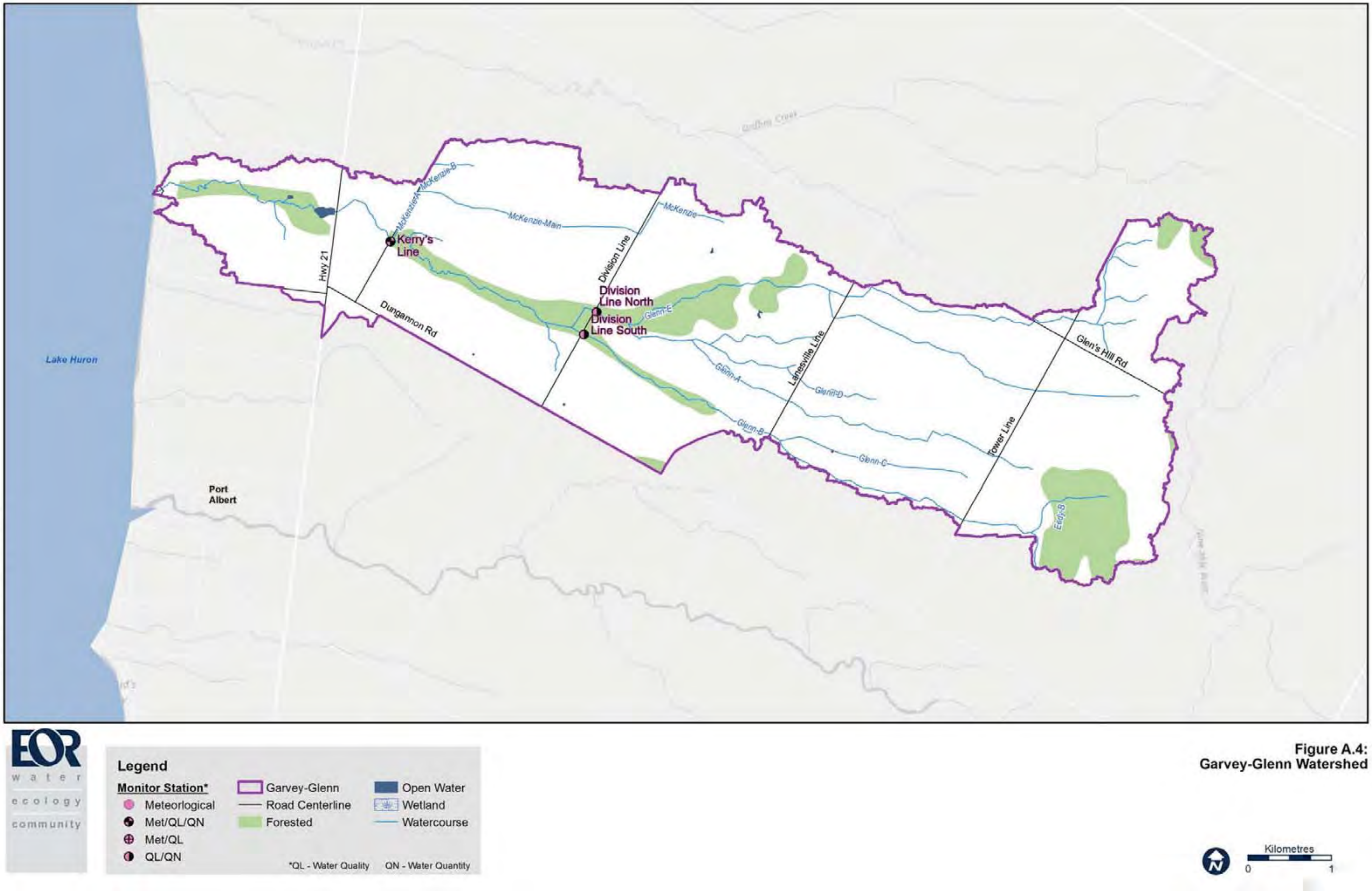

Figure A.4:
Garvey-Glenn Watershed

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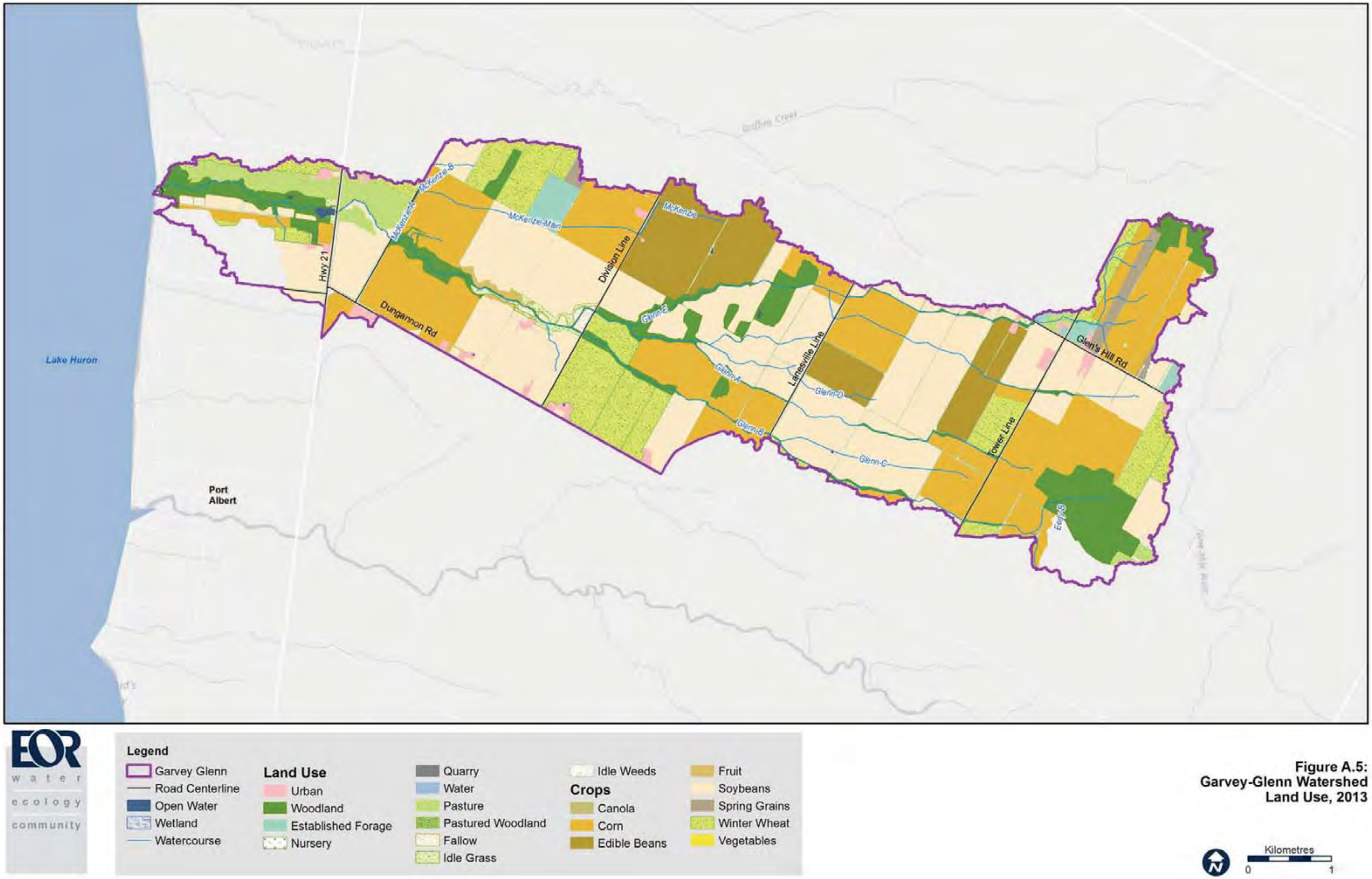

Figure A.5:
Garvey-Glenn Watershed
Land Use, 2013

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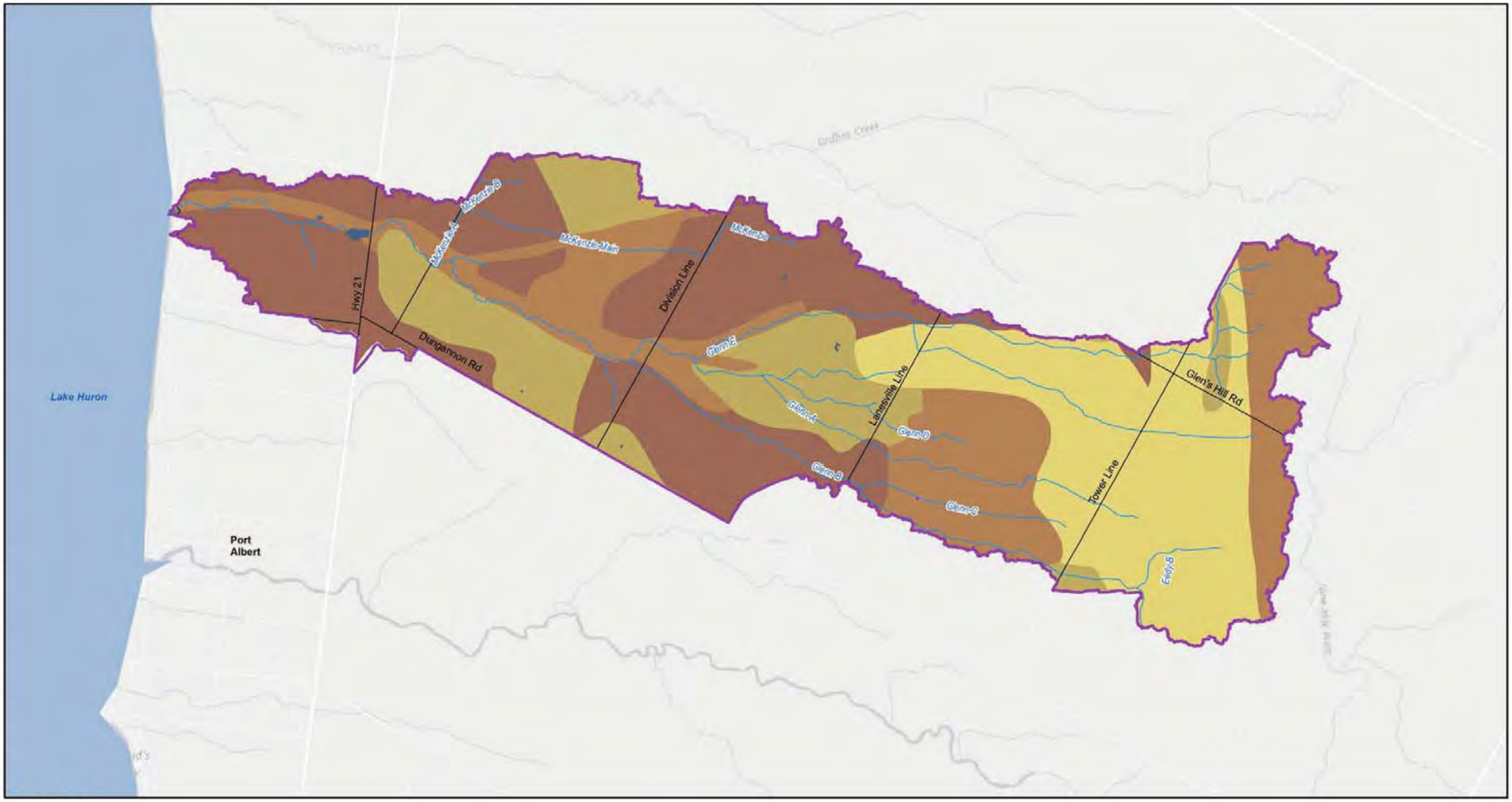

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Figure A.6:
Garvey-Glenn Watershed
Soils

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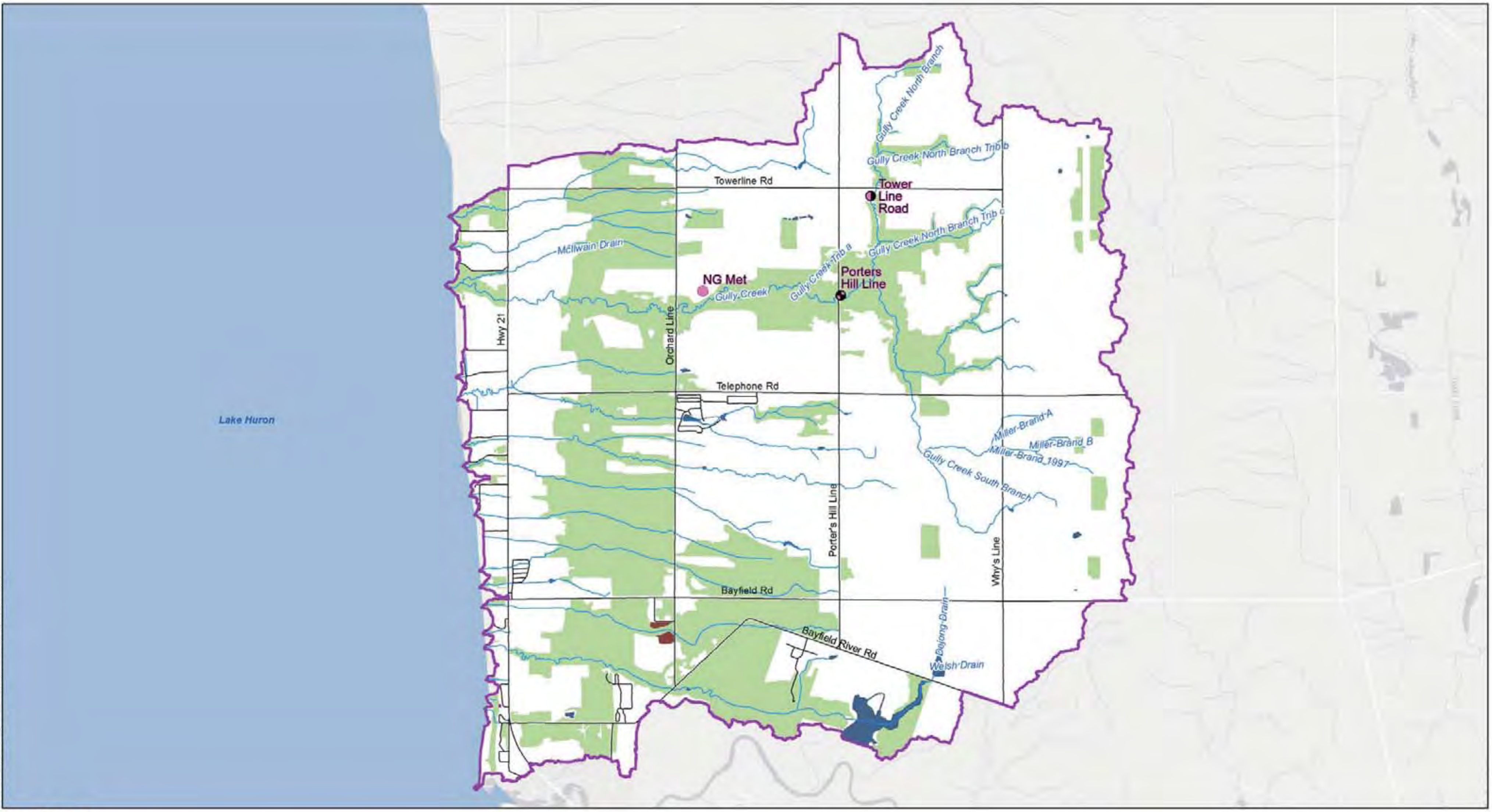

Figure A.7:
Bayfield North Watershed

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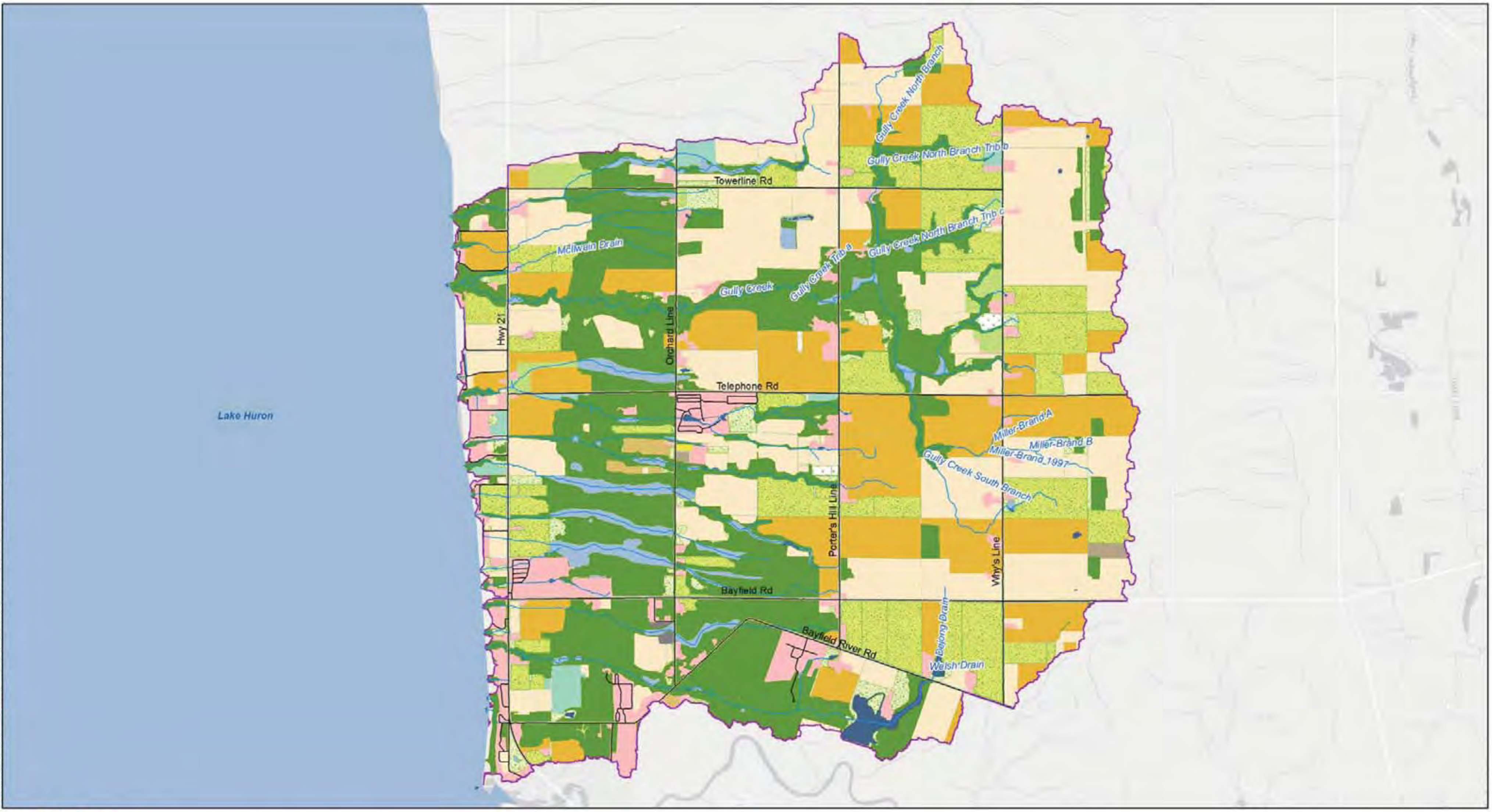

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Legend

- ▭ Bayfield North
- — Road Centerline
- ┼ Railroad
- ■ Open Water
- — Watercourse

Land Use

- ■ Urban
- ■ Woodland
- ■ Established Forage
- ▨ Nursery
- ■ Quarry
- ■ Water
- ■ Pasture
- ▨ Pastured Woodland
- ▨ Fallow
- ▨ Idle Grass
- ▨ Idle Weeds

Crops

- ■ Canola
- ■ Corn
- ■ Edible Beans
- ■ Fruit
- ■ Soybeans
- ■ Spring Grains
- ▨ Winter Wheat
- ■ Vegetables

Figure A.8:
Bayfield North Watershed
Land Use, 2013

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Kilometres
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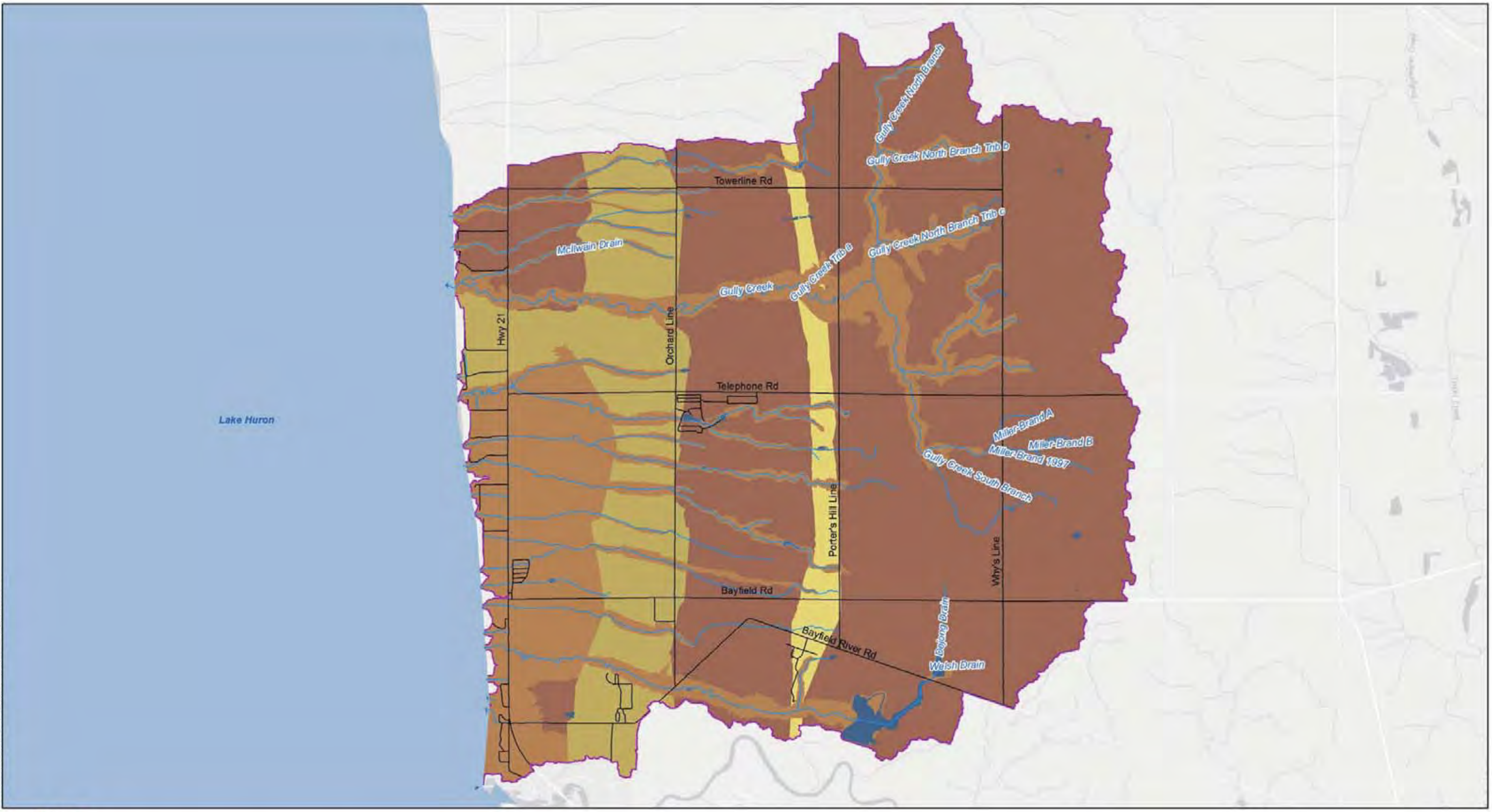

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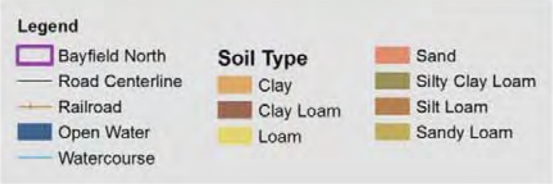

Figure A.9: Bayfield North Watershed Soils

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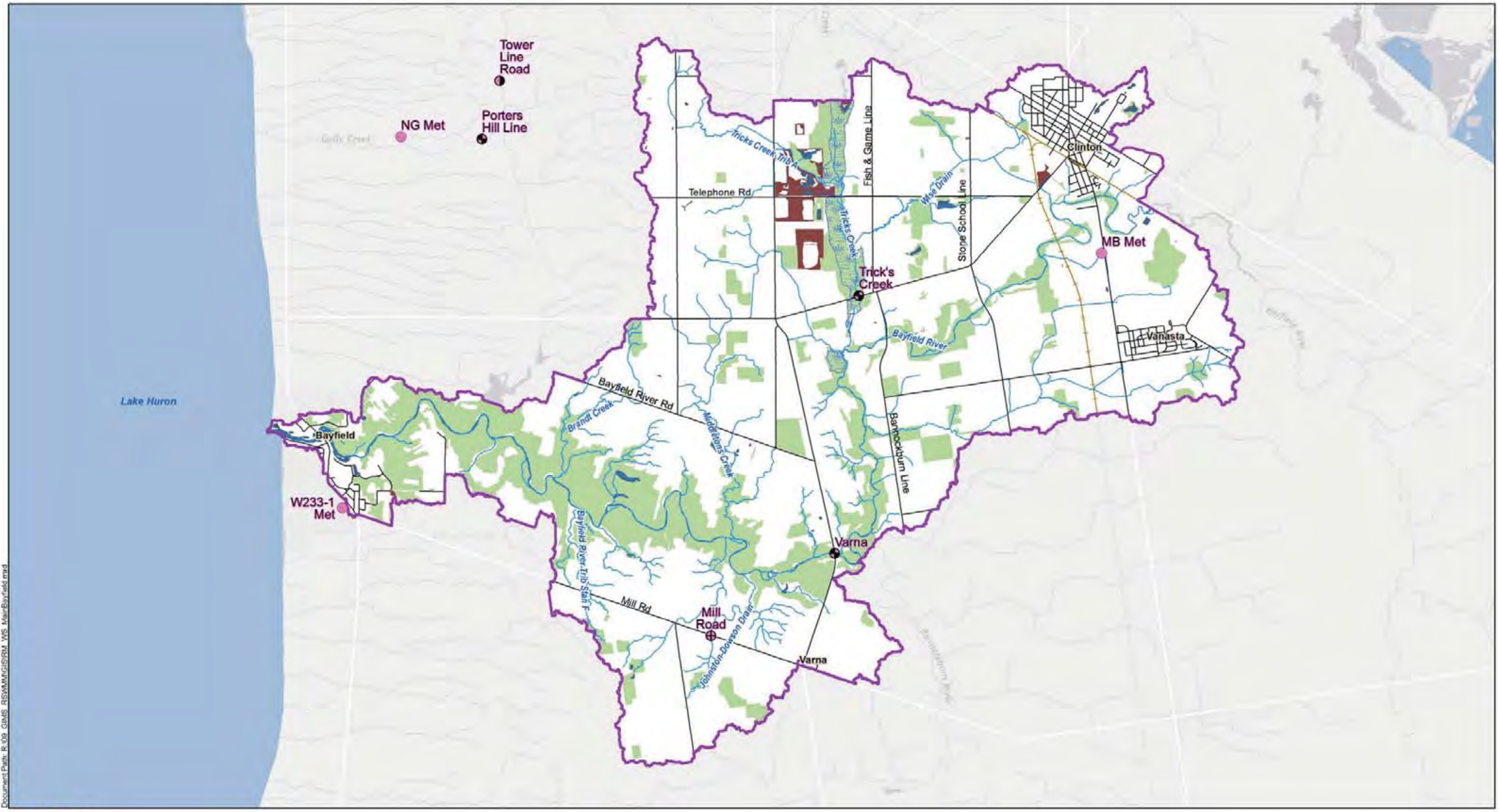

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Legend

Monitor Station*
- ● Meteorlogical
- ● Met/QL/QN
- ⊕ Met/QL
- ◐ QL/QN

*QL - Water Quality QN - Water Quantity

- ☐ Main Bayfield
- — Road Centerline
- —+— Railroad
- ■ Quarry
- 🟩 Forested
- ■ Open Water
- ▨ Wetland
- — Watercourse

Figure A.10:
Main Bayfield Watershed

Kilometres
0 1 2

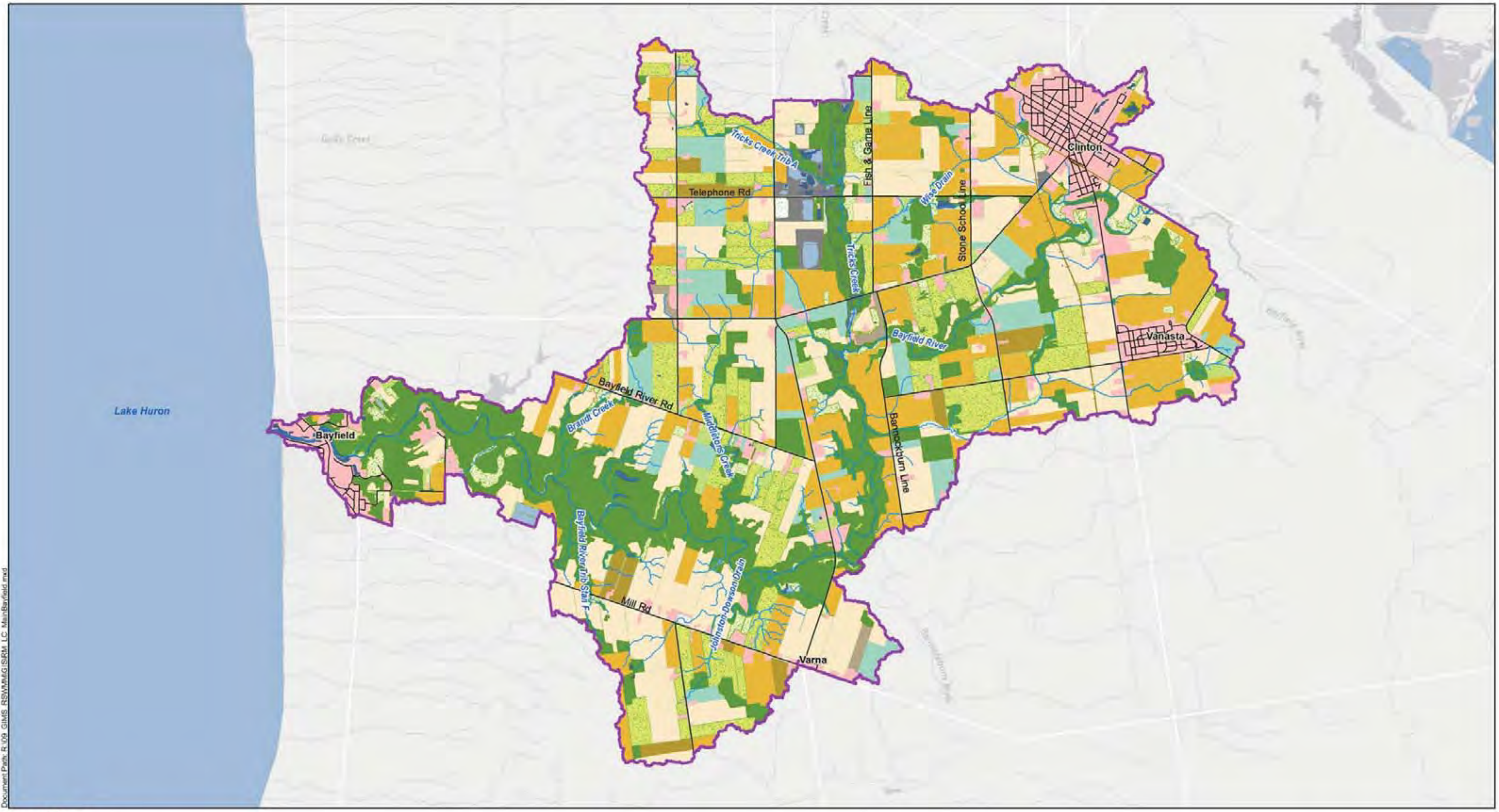

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Figure A.11:
Main Bayfield Watershed
Land Use, 2013

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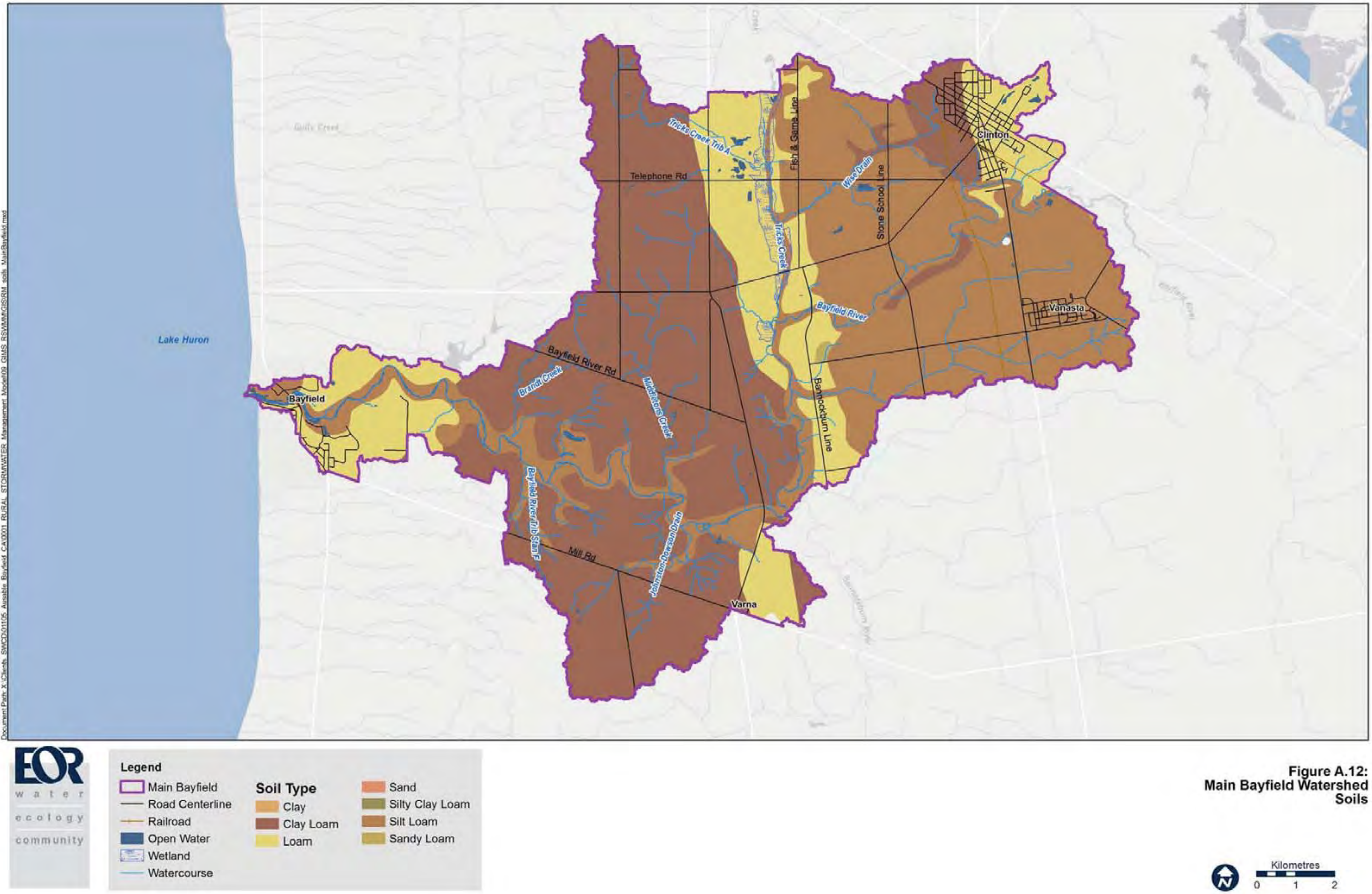

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**Figure A.12:
Main Bayfield Watershed
Soils**

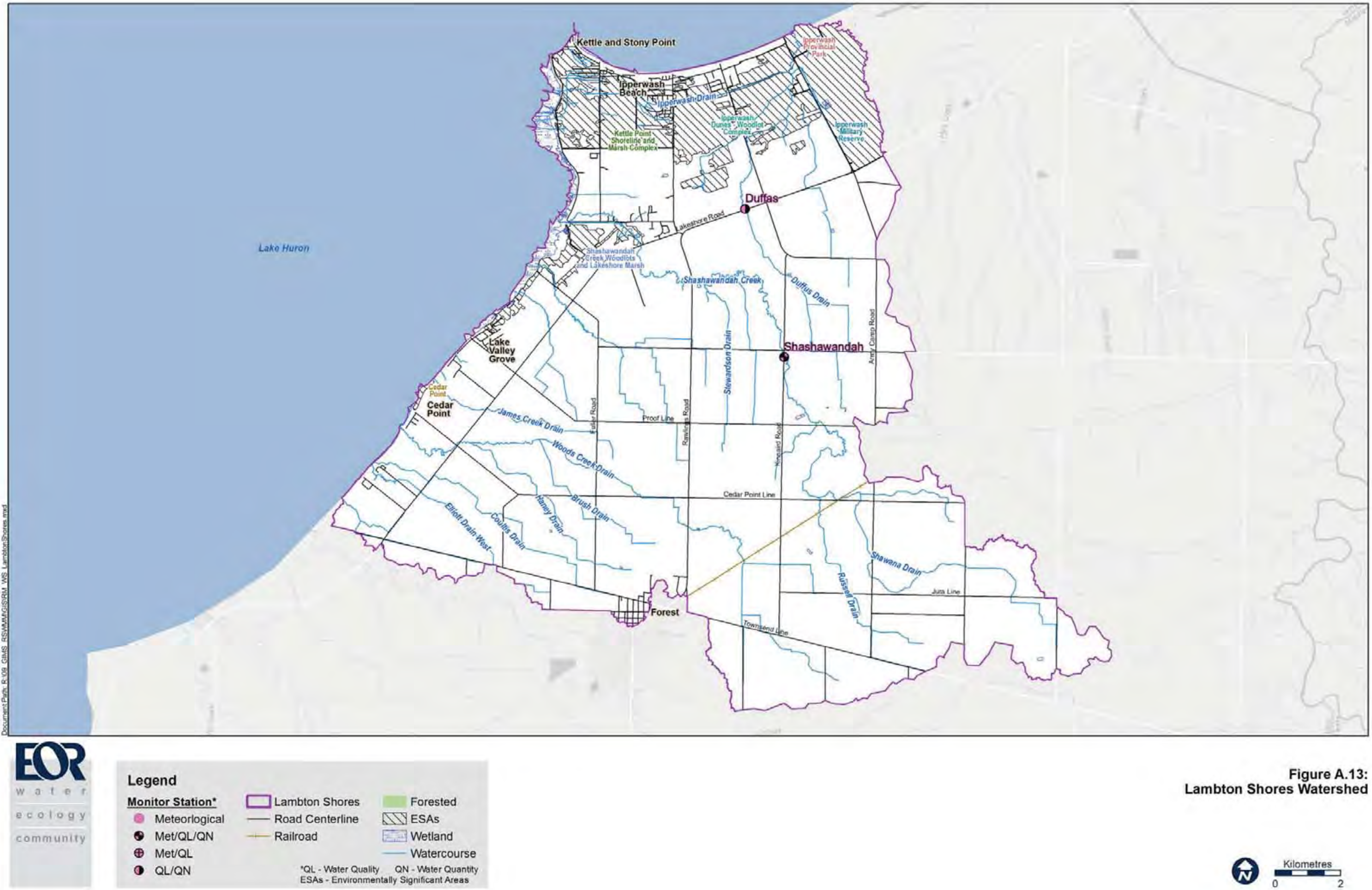

Figure A.13:
Lambton Shores Watershed

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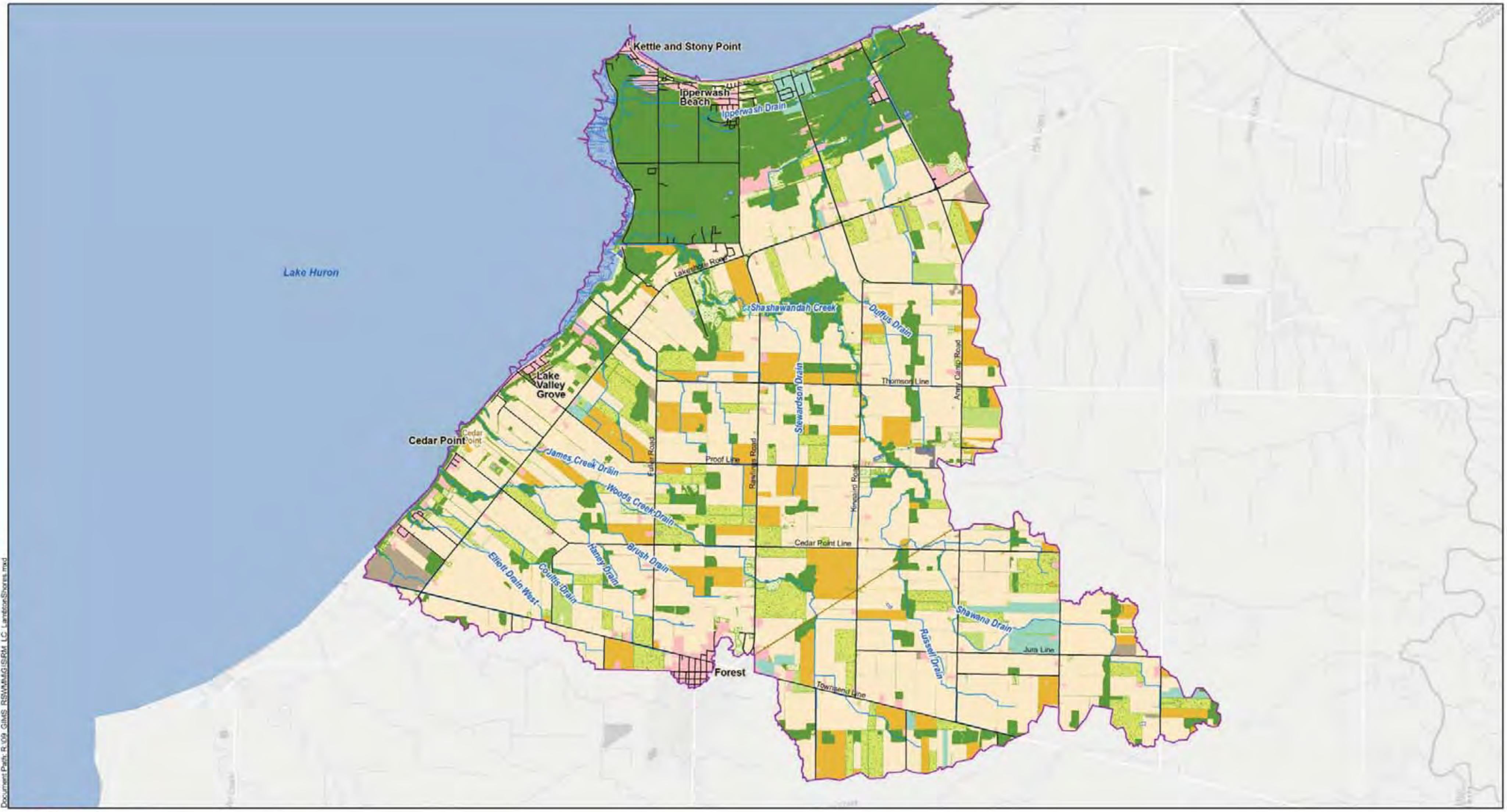

Legend

- ▭ Lambton Shores
- — Road Centerline
- ┼ Railroad
- ▨ Wetland
- — Watercourse

Land Use

- 🟥 Urban
- 🟩 Woodland
- 🟦 Established Forage
- ▨ Nursery
- ■ Quarry
- 🟦 Water
- 🟩 Pasture
- ▨ Pastured Woodland
- ▨ Fallow
- ▨ Idle Grass
- ▨ Idle Weeds

Crops

- ■ Canola
- 🟧 Corn
- ■ Edible Beans
- 🟨 Fruit
- ■ Soybeans
- 🟫 Spring Grains
- ▨ Winter Wheat
- 🟨 Vegetables

Figure A.14: Lambton Shores Watershed Land Use, 2013

Kilometres
0 2

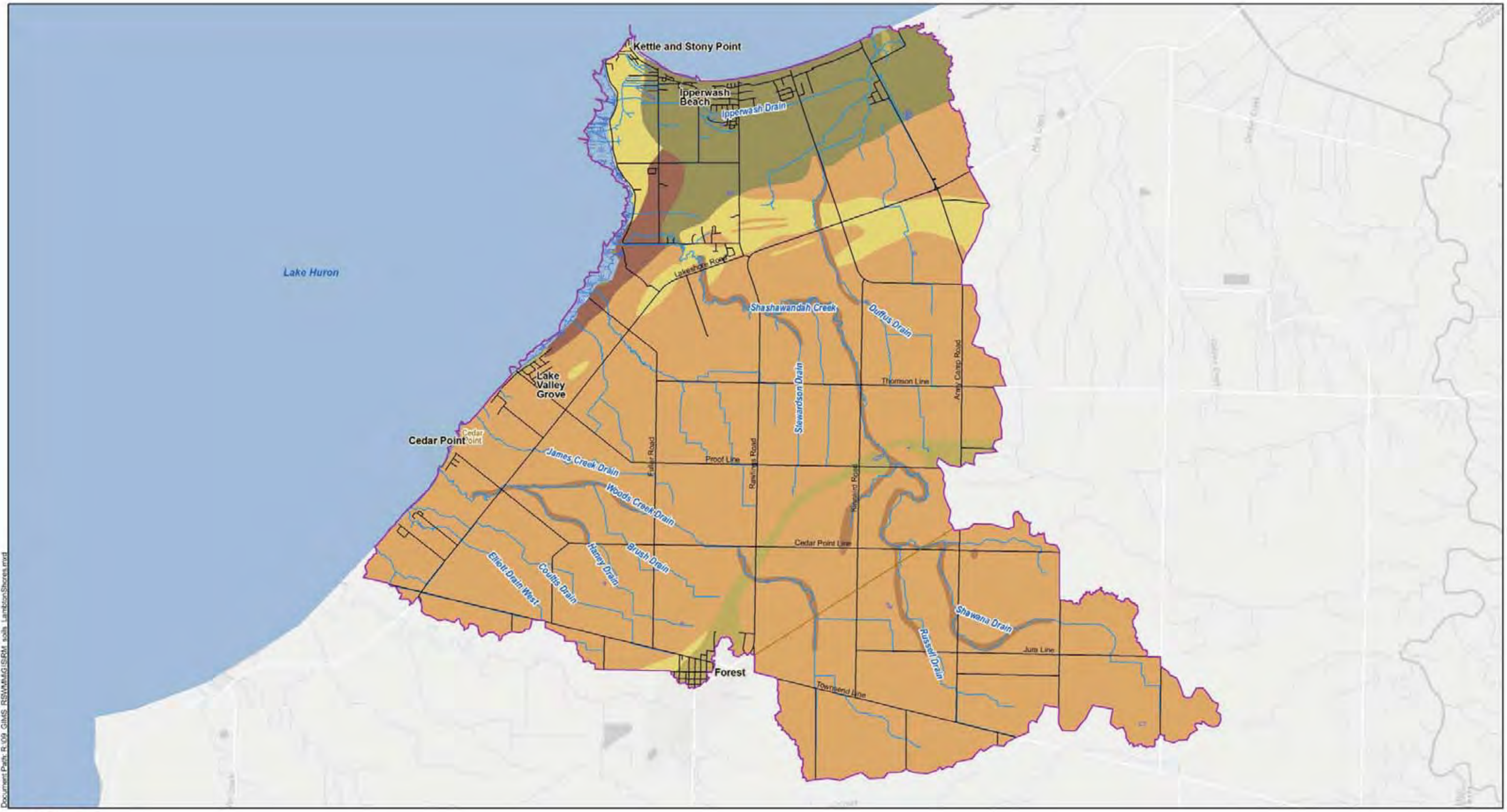

Figure A.15:
Lambton Shores Watershed
Soils

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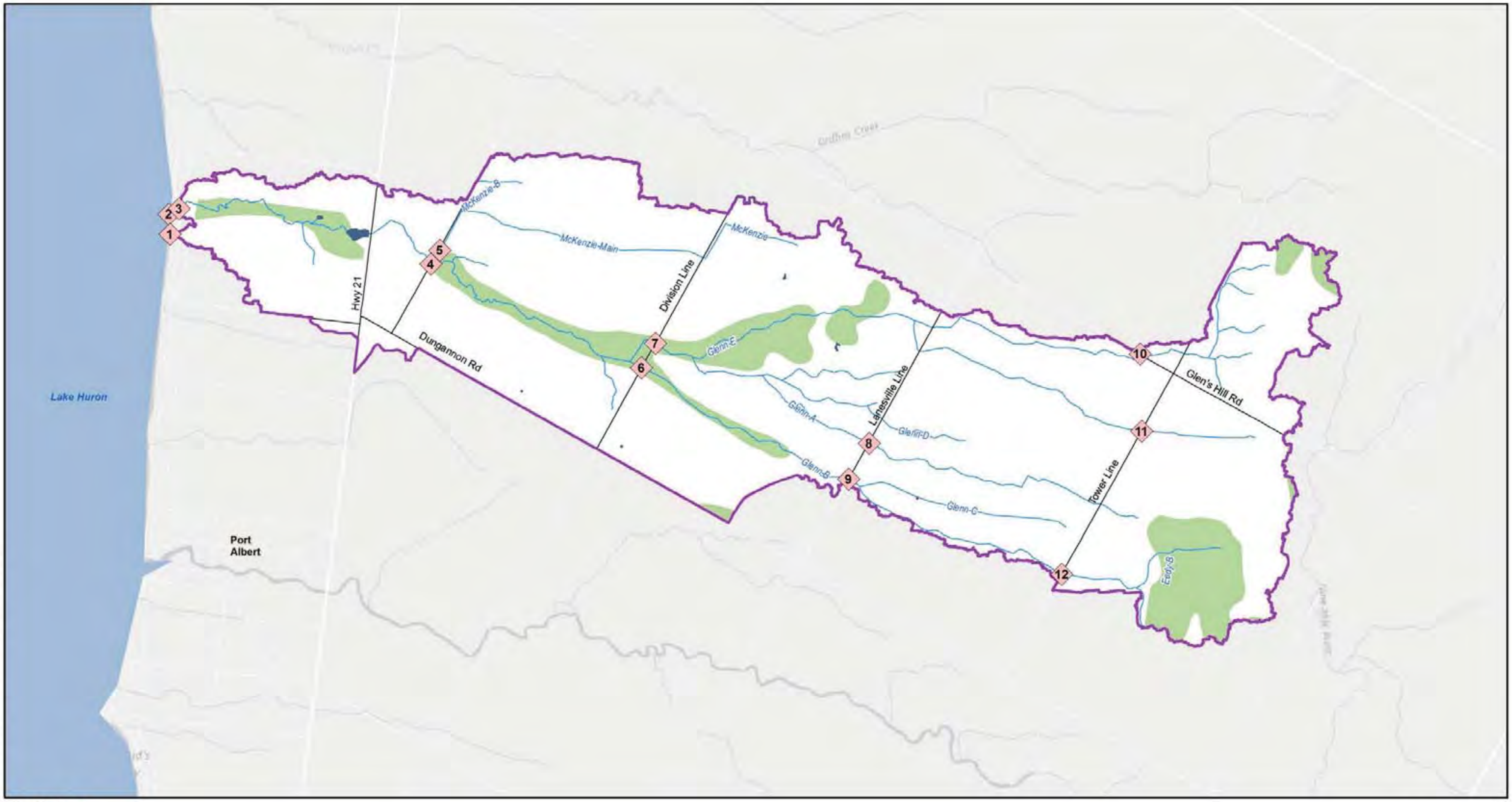
Legend

- ◆ Point of Interest
- ▭ Pine River Watershed
- — Road Centerline
- —+— Railroad
- 🟩 Forested
- ■ Open Water
- ▨ Wetland
- — Watercourse

Figure A.16: Pine River Watershed Points of Interest

Kilometres
0 3



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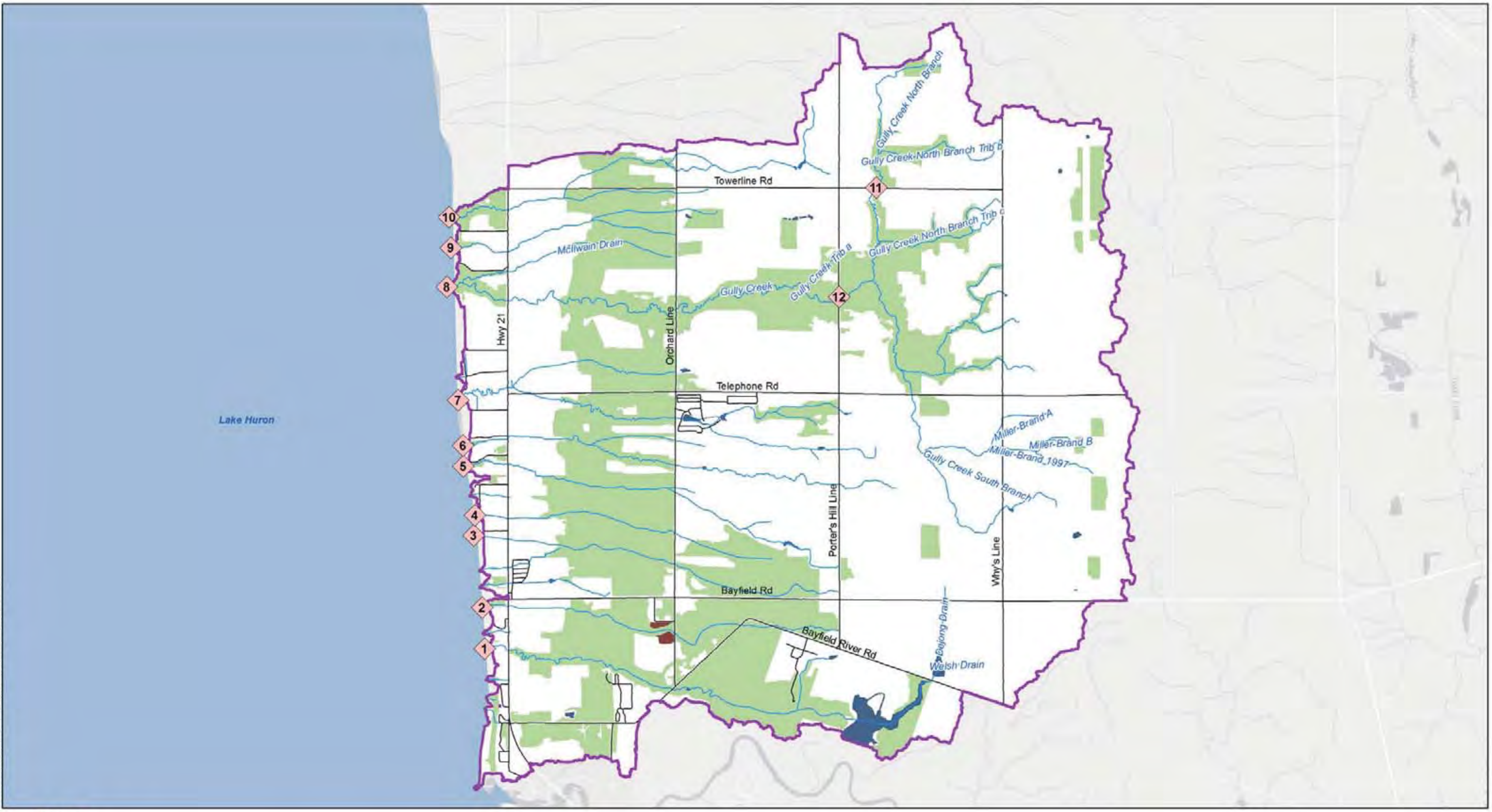
Legend

- ◆ Point of Interest
- ▭ Garvey Glenn
- — Road Centerline
- 🟩 Forested
- ■ Open Water
- ▨ Wetland
- — Watercourse

Kilometres
0 1

Figure A.17:
Garvey-Glenn Watershed
Points of Interest

Date: 8/25/2014 Time: 3:53:31 PM Author: ejensen
Document Path: R:\09_GIMS_RSWMMGIS\RM_PoI_NBayfield.mxd



Legend

◇ Point of Interest

▭ Bayfield North

— Road Centerline

— Railroad

■ Quarry

🟩 Forested

■ Open Water

▨ Wetland

— Watercourse

Kilometres
0 1 2

Figure A.18:
Bayfield North Watershed
Points of Interest

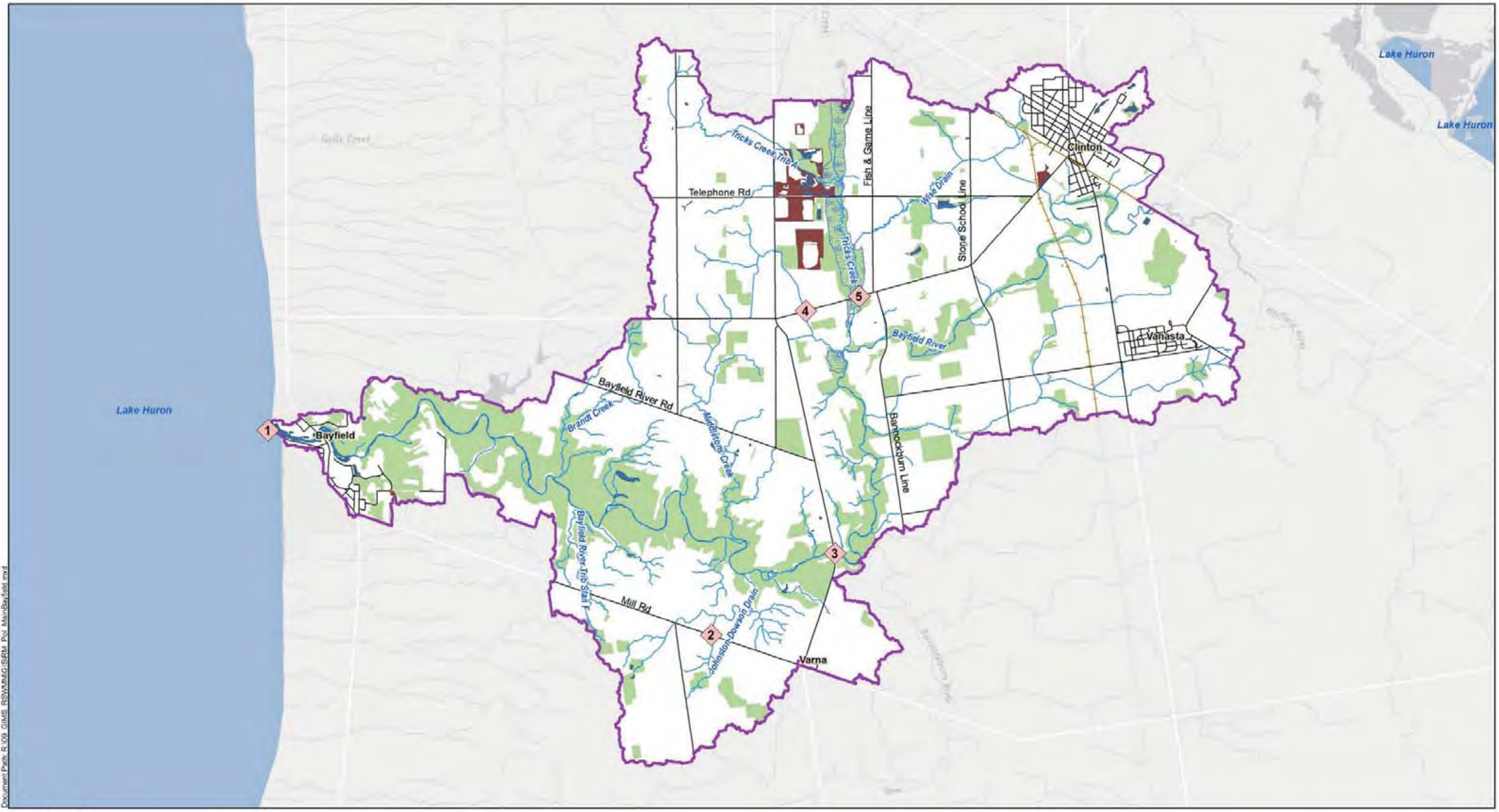
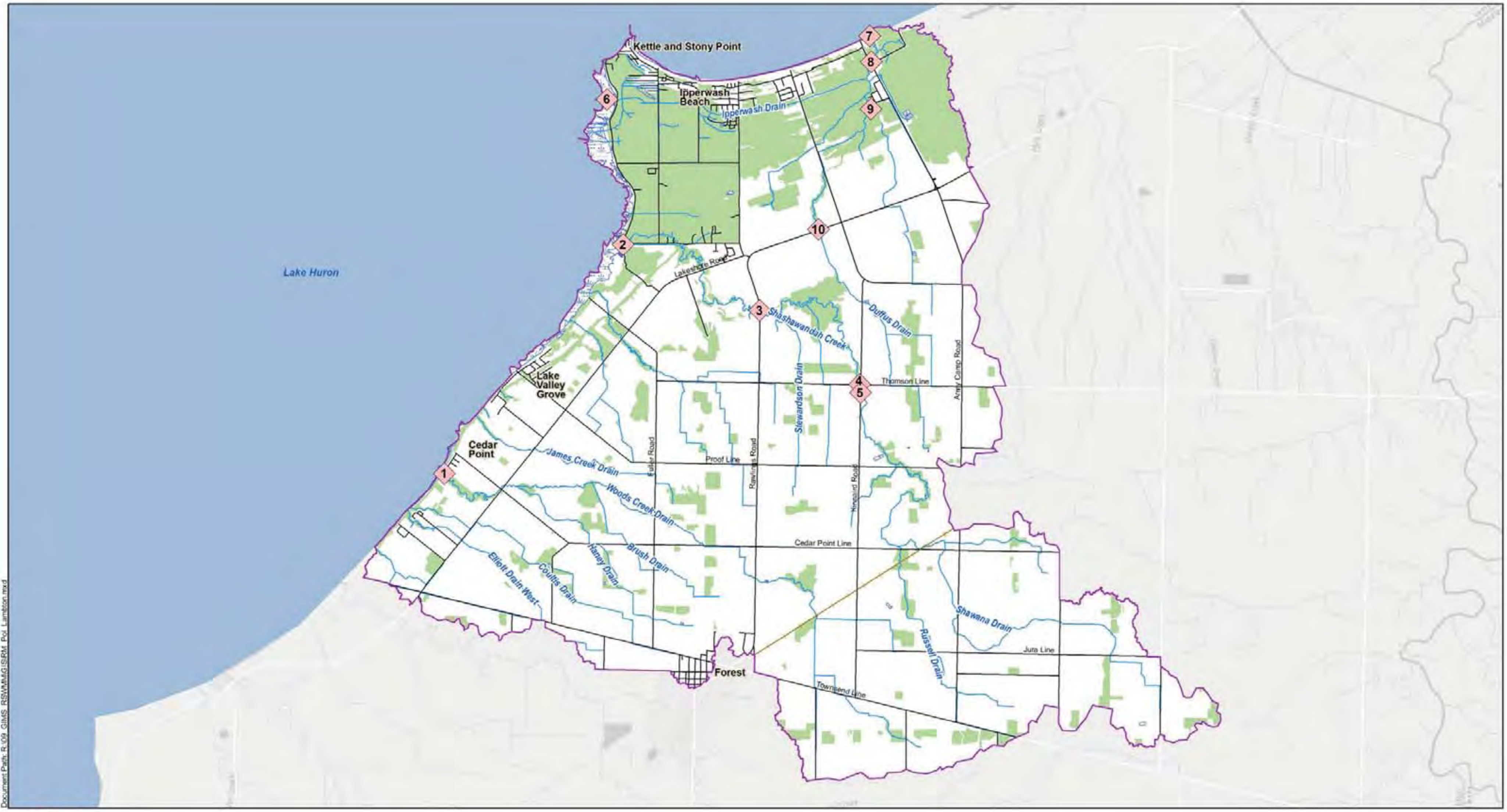


Figure A.19: Main Bayfield Watershed Points of Interest

EOR water ecology community

Date: 8/25/2014 Time: 4:04:32 PM Author: ejensen
Document Path: R:\09 GIMS RSWMMG\SRM_PoI_MainBayfield.mxd

Date: 8/25/2014 Time: 4:06:47 PM Author: ejensen
Document Path: R:\09_GIMS_RSWMM\GIS\RM_PoI_Lambton.mxd



EOR water ecology community

Figure A.20:
Lambton Shores Watershed
Points of Interest

APPENDIX B LOOKUP TABLES AND AUTO-EXPRESSIONS

Appendix B.1 Lookup Tables

Table 38: Subcatchment Infiltration Parameterization by Soil Type

TEXTURECODE	FieldCap	Wilting	Conduct	SuctionHead	InitDeficit	*Description*
S	0.062	0.024	120.4	49.02	0.413	*Sand*
LS	0.105	0.047	29.97	60.96	0.39	*Loamy Sand*
SL	0.19	0.085	10.92	109.98	0.368	*Sandy Loam*
L	0.232	0.116	6.6	169.93	0.366	*Loam*
SIL	0.284	0.135	3.3	88.9	0.347	*Silty Loam*
SCL	0.244	0.136	1.52	219.96	0.262	*Sandy Clay Loam*
CL	0.31	0.187	1.02	210.06	0.277	*Clay Loam*
SICL	0.342	0.21	1.02	270	0.261	*Silty Clay Loam*
SC	0.321	0.221	0.51	240.03	0.209	*Sandy Clay*
SIC	0.371	0.251	0.51	290.07	0.228	*Silty Clay*
C	0.378	0.265	0.25	320.04	0.21	*Clay*
Units	*fraction*	*fraction*	*mm/hr*	*mm*	*fraction*	

Table 39: Subcatchment Erosion Parameterization By Soil Type

TEXTURECODE	ER_Clay	ER_Silt	ER_Sand	KUSLE	*Description*
S	0.05	0.07	0.88	0.003	*Sand*
LS	0.05	0.15	0.8	0.005	*Loamy Sand*
SL	0.1	0.25	0.65	0.016	*Sandy Loam*
L	0.2	0.4	0.4	0.038	*Loam*
SIL	0.15	0.65	0.2	0.049	*Silty Loam*
SCL	0.25	0.15	0.6	0.026	*Sandy Clay Loam*
CL	0.35	0.35	0.3	0.037	*Clay Loam*
SICL	0.35	0.55	0.1	0.04	*Silty Clay Loam*
SC	0.4	0.1	0.5	0.026	*Sandy Clay*
SIC	0.45	0.45	0.1	0.034	*Silty Clay*
C	0.5	0.25	0.25	0.028	*Clay*
Units	*fraction*	*fraction*	*fraction*	$\frac{t*ha*hr}{(ha*MJ*mm)}$	

Table 40: Subcatchment Parameterization By Land Use

Unique_LU	NPerv	DSPerv	Imperv
BUILT UP/URBAN AREA	0.11	2.07	100
CANOLA	0.19	2.71	0
CONTINUOUS ROW CROP	0.19	2.71	0
CORN	0.19	2.71	0
CORN CONSERVATION	0.11	2.07	0
CORN CONVENTIONAL	0.19	2.71	0
CORN NO TILL	0.07	1.74	0
CORN NO-TILL	0.07	1.74	0
CORN SYSTEM	0.19	2.71	0
CORN UNKNOWN	0.19	2.71	0
DITCH	0.4	4.4	0
DITCHES	0.4	4.4	0
EDIBLE BEANS	0.19	2.71	0
EXTENSIVE FIELD VEGETABLES	0.19	2.71	0
EXTRACTION PITS (PITS/QUARRIES)	0.11	2.07	0
FALLOW	0.05	1.58	0
FARMSTEAD	0.4	4.4	50
FENCEROW	0.4	4.4	0
FIELD	0.19	2.71	0
FIELDS	0.19	2.71	0
FORAGES	0.235	3.07	0
FRUIT	0.4	4.4	0
GRAIN SYSTEM	0.19	2.71	0
GRASS WATERWAY	0.4	4.4	0
GRASSED WATERWAY	0.4	4.4	0
GRASSLAND	0.4	4.4	0
HAY	0.11	2.07	0
HAY SYSTEM	0.11	2.07	0
IDLE AGRIC LAND > 10 YEARS	0.07	1.74	0
IDLE AGRIC. LAND 5-10 YEARS	0.07	1.74	0
MARKET GARDEN/TRUCK FARM	0.4	4.4	50
MIXED SYSTEM	0.11	2.07	0
NOT FARMED	0.4	4.4	0
NURSERY	0.4	4.4	0
ORCHARD	0.4	4.4	0
OTHER	0.19	2.71	0
PASTURE	0.13	2.23	0
PASTURE SYSTEM	0.13	2.23	0
PASTURED WOODLOT	0.13	2.23	0
PITS AND QUARRY	0.11	2.07	72
PLANTATION	0.8	7.62	0
QUARRY	0.11	2.07	72
RECREATION	0.4	4.4	0
REFORESTED WOODLOT	0.4	4.4	0
RIPARIAN	0.4	4.4	0
ROAD	0.015	1.3	100
ROUGH LAND	0.13	2.23	0
ROUGHLAND	0.13	2.23	0
SOYBEANS	0.19	2.71	0
SOYBEANS CONSERVATION	0.11	2.07	0
SOYBEANS CONVENTIONAL	0.19	2.71	0
SOYBEANS NO TILL	0.07	1.74	0
SOYBEANS NO-TILL	0.07	1.74	0
SOYBEANS UNKNOWN	0.19	2.71	0
SPECIALITY CROPS	0.19	2.71	0
SPRING CEREAL	0.19	2.71	0
TOBACCO SYSTEM	0.19	2.71	0
UNKNOWN	0.19	2.71	0
URBAN	0.11	2.07	38
URBAN/WOODED	0.4	4.4	50
VEGETABLE	0.19	2.71	0
VINEYARD/ORCHARD	0.4	4.4	0
WATER	0.011	1.27	100
WETLAND	0.8	7.62	0
WHEAT	0.19	2.71	0
WINTER WHEAT	0.19	2.71	0
WINTER WHEAT CONSERVATION	0.11	2.07	0
WINTER WHEAT CONVENTIONAL	0.19	2.71	0
WINTER WHEAT NO TILL	0.07	1.74	0
WINTER WHEAT NO-TILL	0.07	1.74	0
WINTER WHEAT UNKNOWN	0.19	2.71	0
WOODLAND	0.4	4.4	0
WOODLANDS	0.4	4.4	0
WOODLOT	0.4	4.4	0

Table 41: Subcatchment Land Use Percentage

CUSLE	LU_CANOLA	LU_CORN	LU_EDIBLEBE	LU_ESTFORAG	LU_FALLOW	LU_FRUIT	LU_IDLEGRAS	LU_IDLEWEED	LU_NURSERY	LU_PASTURE	LU_PASTWOOD	LU_Quarry	LU_SOYBEAN	LU_SPRGRAIN	LU_TOBACCO	LU_URBAN	LU_VEGETABL	LU_WATER	LU_WINTERWH	LU_WOODLAND
EDIBLEBEAN	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESTFORAGE	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FALLOW	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FRUIT	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IDLEGRASS	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0
IDLEWEEDS	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0
PASTURE	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0
QUARRY	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0
SPRGRAIN	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
URBAN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0
WATER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0
WOODLAND	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
CANOLA	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NURSERY	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0
PASTWOOD	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0
TOBACCO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0
VEGETABLE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0
CORNCONV	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CORNCONS	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CORNCONSCC	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CORNNOTILL	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SOYCONV	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0
SOYCONS	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0
SOYCONSCC	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0
SOYNOTILL	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0
WWCONV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0
WWCONS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0
WWCONSCC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0
WWNOTILL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0

Table 42: Transect Manning's n

Material	Equivalent	Center
Asphalt	Road overtop	0.016
CDT	Concrete	0.012
CIP	Cast Iron Pipe	0.012
Clay	Clay	0.014
CMP	Corrugated metal	0.024
CMP_G	Corrugated metal good condition	0.023
CMP_P	Corrugated metal poor condition	0.025
Concrete	Concrete	0.013
Concrete drain tile	Concrete	0.013
CPP	Corrugated plastic (smooth inner walls)	0.013
CSP	Corrugated metal	0.024
Field tile	Clay	0.014
Grassed waterway	With short grass, few weeds	0.027
HDPE	Corrugated plastic (smooth inner walls)	0.013
Natural	Main channel (clean)	0.035
Open	Excavated Channel	0.027
Overland	Conventional tillage	0.019
RCP_G	Reinforced concrete pipe good cond	0.012
RCP_P	Reinforced concrete pipe poor cond	0.013
RCSP	Corrugated metal	0.021
SPDT	Corrugated plastic (smooth inner walls)	0.013
Wood	Wood - Unplaned	0.013

Appendix B.2 Auto-Expressions

Table 43: Auto-Expressions for Fields Layer

Parameter	Auto-Expression
Field Characteristics	
Area (ha) [AREA]	`[GIS_Area]/10000`
Base Parameters	
Base LS Factor [LS_BASE]	`(([LUSLE_BASE]/22.1)^(0.6*(1-EXP(-35.835*([SLOPE_BASE]/100)))))*(65.41*SIN(ATAN([SLOPE_BASE]/100))^2+4.56*SIN(ATAN([SLOPE_BASE]/100))+0.065)`
Modified Parameters	

Land Use [LANDUSE]

```
CONDITION([AGFIELD]
="True":    CONDITION([CONSCOVER]
      ="True":     CONDITION([BASE_LU]
            ="Corn": "Established Forage"
            ="Soybeans": "Established Forage"
            ="Winter Wheat": "Established Forage")
      ="False":    CONDITION([BASE_LU]
            ="Corn":            CONDITION([TILLAGE]
                                ="Conventional":    "Corn, Conventional"
                                ="Conservation":    CONDITION([COVERCROPS]
                                                    ="True": "Corn, Conservation, Cover Crop"
                                                    ="False": "Corn, Conservation")
                                ="No Till":         "Corn, No Till")
            ="Soybeans":        CONDITION([TILLAGE]
                                ="Conventional":    "Soybeans, Conventional"
                                ="Conservation":    CONDITION([COVERCROPS]
                                                    ="True": "Soybeans, Conservation, Cover Crop"
                                                    ="False": "Soybeans, Conservation")
                                ="No Till":         "Soybeans, No Till")
            ="Winter Wheat":    CONDITION([TILLAGE]
                                ="Conventional":    "Winter Wheat, Conventional")
                                ="Conservation":    CONDITION([COVERCROPS]
                                                    ="True": "Winter Wheat, Conservation, Cover Crop"
                                                    ="False": "Winter Wheat, Conservation")
                                ="No Till":         "Winter Wheat, No Till"))
="False":   [BASE_LU])
```

Slope (%) [SLOPE]

```
IF([AGFIELD]="True",
MIN(
IF([CONTFARM]="True",IF([CONTSLOPE]=-99,[SLOPE_BASE]/2,[CONTSLOPE]),[SLOPE_BASE]),
```

Parameter	Auto-Expression

```
  IF([TERRACING]="True",[TERRSLOPE],[SLOPE_BASE])
  ),
  [SLOPE_BASE])
```

Roughness [NPERV]

```
IF([AGFIELD]="True",
      MAX(
      IF([CONSCOVER]="True", ;Adjust value for Est. Forage to reflect calibration
            ([NPERV_BASE]/0.19)*0.235,
            [NPERV_BASE]),
      IF([GRASSEDWW]="True",
            CONDITION([GWWLENGTH]
                  =100: [NPERV_BASE]*1.1
                  =200: [NPERV_BASE]*1.2
                  =300: [NPERV_BASE]*1.3
                  =400: [NPERV_BASE]*1.4
                  =500: [NPERV_BASE]*1.5
                  =600: [NPERV_BASE]*1.63),
            [NPERV_BASE]),
      CONDITION([TILLAGE]
            ="Conservation":    [NPERV_BASE]*1.5
            ="No Till":         [NPERV_BASE]*3.5
            ="Conventional":    [NPERV_BASE]
            ="N/A" :            [NPERV_BASE])),
      [NPERV_BASE])
```

Dep. Storage (mm) [DSPERV]

```
IF([NPERV_BASE]<>0,[DSPERV_BASE]*([NPERV]/[NPERV_BASE]),[DSPERV_BASE]) ;Varies linearly with Manning's roughness
```

P Factor (index) [PUSLE]

```
IF([AGFIELD]="True",
MIN([CONTPFACT],[TERRPFACT],[GWWPFACT]),
1.0)
```

C Factor [CUSLE]

```
CONDITION([CONSCOVER]
="True": CONDITION([BASE_LU]
            ="Corn": "ESTFORAGE"
            ="Soybeans": "ESTFORAGE"
            ="Winter Wheat": "ESTFORAGE"
            default: [BASE_LU])
="False":   CONDITION([BASE_LU]
            ="Corn":            CONDITION([TILLAGE]
                                ="Conventional":    "CORNCONV"
                                ="Conservation":    CONDITION([COVERCROPS]
                                                    ="True": "CORNCONSCC"
                                                    ="False": "CORNCONS"
                                                    )
```

Parameter	Auto-Expression

```
                                ="No Till":         "CORNNOTILL"
                                )
            ="Soybeans":        CONDITION([TILLAGE]
                                ="Conventional":    "SOYCONV"
                                ="Conservation":    CONDITION([COVERCROPS]
                                                    ="True": "SOYCONSCC"
                                                    ="False": "SOYCONS"
                                                    )
                                ="No Till":         "SOYNOTILL"
                                )
            ="Winter Wheat":    CONDITION([TILLAGE]
                                ="Conventional":    "WWCONV"
                                ="Conservation":    CONDITION([COVERCROPS]
                                                    ="True": "WWCONSCC"
                                                    ="False": "WWCONS"
                                                    )
                                ="No Till":         "WWNOTILL"
                                )

            ="Canola": "CANOLA"
            ="Edible Beans": "EDIBLEBEAN"
            ="Established Forage": "ESTFORAGE"
            ="Fallow": "FALLOW"
            ="Fruit": "FRUIT"
            ="Idle Grass": "IDLEGRASS"
            ="Idle Weeds": "IDLEWEEDS"
            ="Nursery": "NURSERY"
            ="Pasture": "PASTURE"
            ="Pastured Woodland": "PASTWOOD"
            ="Quarry": "QUARRY"
            ="Spring Grains": "SPRGRAIN"
            ="Tobacco": "TOBACCO"
            ="Urban": "URBAN"
            ="Vegetables": "VEGETABLE"
            ="Water": "WATER"
            ="Woodland": "WOODLAND"
            default: [BASE_LU])
)
```

Length (m)
[LUSLE]

```
IF([AGFIELD]="True",
MIN(  IF([TERRACING]="True",IF([TERRSPACE]>0,[TERRSPACE],[LUSLE_BASE]),300),
IF([CONTFARM]="True",IF([CONTLENGTH]>0,[CONTLENGTH],[LUSLE_BASE]),300),
CONDITION([FIELDLENGTH]
=-99   : IF([LUSLE_BASE]<>0,MIN([LUSLE_BASE],300),300)
<=0   : IF([LUSLE_BASE]<>0,MIN([LUSLE_BASE],300),300)
```

Parameter	Auto-Expression

(continued)

```
>0   : [FIELDLENGTH])
),
[LUSLE_BASE])
```

LS Factor (index) [LSUSLE]

```
(([LUSLE]/22.1)^(0.6*(1-EXP(-
35.835*([SLOPE]/100)))))*(65.41*SIN(ATAN([SLOPE]/100))^2+4.56*SIN(ATAN([SLOPE]/100))+0.065)
```

Tillage [TILLAGE]

```
CONDITION([AGFIELD]
="True": [CONSTILLAGE]
="False": "N/A")
```

Intermediate Variables

Contour Max. Length (m) [CONTMAXL]

```
CONDITION([SLOPE_BASE]
>25  : 0
>=21 : 15
>=17 : 18
>=13 : 24
>=9  : 37
>=6  : 61
>=3  : 91
>=1  : 122
<1   : 0
default: 0)
```

Contour P Factor [CONTPFACT]

```
IF([CONTFARM]="True",
IF([CONTLENGTH]=-99, ;Use LUSLE_BASE
IF([LUSLE_BASE]<=[CONTMAXL],;Else use user-defined CONTLENGTH
CONDITION([SLOPE_BASE]
>25  : 1.0
>=21 : 0.9
>=17 : 0.8
>=13 : 0.7
>=9  : 0.6
>=6  : 0.5
>=3  : 0.5
>=1  : 0.6
<1   : 1.0
default: 1.0),
1.0),
IF([CONTLENGTH]<=[CONTMAXL],
CONDITION([SLOPE_BASE]
>25  : 1.0
>=21 : 0.9
>=17 : 0.8
>=13 : 0.7
>=9  : 0.6
```

Parameter	Auto-Expression

```
>=6   : 0.5
>=3   : 0.5
>=1   : 0.6
<1    : 1.0
default: 1.0),1.0)),1.0)
```

Terrace P Factor [TERRPFACT]

```
IF([TERRACING]="True",IF([TERRSPACE]<122, IF([TERRSLOPE]<=0.9,CONDITION([SLOPE_BASE]
<1    : 1.0
<=2   : 0.6
<=8   : 0.5
<=12  : 0.6
<=16  : 0.7
<=20  : 0.8
<=25  : 0.9
>25   : 1.0
),1.0),1.0),1.0)
```

Grassed WW P Factor [GWWPFACT]

```
IF([GRASSEDWW]="True",
     CONDITION([GWWLENGTH]
     =100: 0.82
     =200: 0.75
     =300: 0.68
     =400: 0.61
     =500: 0.54
     =600: 0.46
     default: 1.0),1.0)
```

Agricultural Field? [AGFIELD]

```
CONDITION([BASE_LU]
="Corn": "True"
="Soybeans": "True"
="Winter Wheat": "True"
="Canola": "False"
="Edible Beans": "False"
="Established Forage": "False"
="Fallow": "False"
="Fruit": "False"
="Idle Grass": "False"
="Idle Weeds": "False"
="Nursery": "False"
="Pasture": "False"
="Pastured Woodland": "False"
="Quarry": "False"
="Spring Grains": "False"
="Tobacco": "False"
="Urban": "False"
="Vegetables": "False"
="Water": "False"
```

Parameter	Auto-Expression

```
 ="Woodland": "False"
 default: "False")
```

Table 44: Auto-Expressions for Junction and Outfall Treatment Parameters

Parameter	Auto-Expression
Treatment	

NO2 Treatment [TE_NO2]

```
;In-stream NO2 treatment
CONDITION([INSTREAM]
      ="True":      "R=1-(exp(((-
("&[B0]&"*NO3^("&[B1]&"))*((DEPTH*DT)^("&[B2]&"))))*"&[US_TRAVTIME]&"))"
      ="False":     "")
```

NO3 Treatment [TE_NO3]

```
;In-stream NO3 treatment
CONDITION([INSTREAM]
      ="True":      "R=1-(exp(((-
("&[B0]&"*NO3^("&[B1]&"))*((DEPTH*DT)^("&[B2]&"))))*"&[US_TRAVTIME]&"))"
      ="False":     "")
```

SRP Treatment [TE_SRP]

```
;In-stream SRP treatment
CONDITION([INSTREAM]
      ="True":      "R = R_NO3 *0.69"
      ="False":     "")
```

Parameter	Auto-Expression
InStream Treatment	
US Travel Time [US_TRAVTIME]	`IF( [US_AVEVEL]<>0 , [US_IRR_LEN] /[US_AVEVEL]/60/1440, 0)`

Table 45: Auto-Expressions for Storage Treatment Parameters

Parameter	Auto-Expression
Treatment	

Clay Treatment [TE_CLAY]

```
;Clay Treatment Expression
CONDITION([TREAT_TYPE]
      ="Pond":            "C = (Clay) * EXP(-"&[CLAY_RATE]&"/3600/DEPTH*DT)"
      ="Wetland":         "C = (Clay) * EXP(-"&[CLAY_RATE]&"/3600/DEPTH*DT)"
      ="Bioreactor": "")
```

NO2 Treatment [TE_NO2]

```
;NO2 Treatment Expression
CONDITION([TREAT_TYPE]
="Bioreactor": "R=1"
="Wetland": "R=1"
 ="Pond": CONDITION([INSTREAM]
      ="True":                                                    "R=1-(exp(((-
("&[B0]&"*NO3^("&[B1]&"))*((DEPTH*DT)^("&[B2]&"))))*"&[US_TRAVTIME]&"))"
      ="False": ""))
```

Parameter

Auto-Expression

NO3 Treatment [TE_NO3]

```
;NO3 Treatment Expression
CONDITION([TREAT_TYPE]
="Bioreactor": "C=(NO3+NO2)*EXP(-"&[DENIT_RATE]&"*HRT)"
="Wetland": "C=(NO3+NO2+TKN*R_TKN)*EXP(-"&[DENIT_RATE]&"*HRT)"
 ="Pond": CONDITION([INSTREAM]
      ="True":                                                   "R=1-(exp(((-
("&[B0]&"*NO3^("&[B1]&"))*((DEPTH*DT)^("&[B2]&"))))*"&[US_TRAVTIME]&"))"
      ="False": ""))
```

Sand Treatment [TE_SAND]

```
;Sand Treatment Expression
CONDITION([TREAT_TYPE]
      ="Pond":            "C = (Sand) * EXP(-"&[SAND_RATE]&"/3600/DEPTH*DT)"
      ="Wetland":         "C = (Sand) * EXP(-"&[SAND_RATE]&"/3600/DEPTH*DT)"
      ="Bioreactor": "")
```

Silt Treatment [TE_SILT]

```
;Silt Treatment Expression
CONDITION([TREAT_TYPE]
      ="Pond":            "C = (Silt) * EXP(-"&[SILT_RATE]&"/3600/DEPTH*DT)"
      ="Wetland":         "C = (Silt) * EXP(-"&[SILT_RATE]&"/3600/DEPTH*DT)"
      ="Bioreactor": "")
```

SRP Treatment [TE_SRP]

```
;SRP Treatment Expression
CONDITION([TREAT_TYPE]
="Bioreactor": ""
="Wetland": ""
 ="Pond": CONDITION([INSTREAM]
      ="True": "R = R_NO3 *0.69"
      ="False": ""))
```

TKN Treatment [TE_TKN]

```
;TKN Treatment Expression
CONDITION([TREAT_TYPE]
="Bioreactor": ""
="Wetland":        "C=TKN*"&[AMMONIUM]&"*exp(-"&[NIT_RATE]&"*HRT)"
 ="Pond": "")
```

Treatment BMP Design

Footprint [FOOTPRINT]

```
CONDITION([TREAT_TYPE]
      ="Bioreactor":      [Constant]/([BIOPOROSITY]*[EFFICIENCY])
      ="Wetland":         [Constant]/[EFFICIENCY]
      ="Pond":            [Constant]/[EFFICIENCY]
      default: [CONSTANT])
```

Denitrification Rate [DENIT_RATE]

```
CONDITION([TREAT_TYPE]
      ="Pond":            0
      ="Wetland":         0.024
      ="Bioreactor":      5.2)
```

Nitrification Rate [NIT_RATE]

```
CONDITION([TREAT_TYPE]
      ="Pond":            0
      ="Wetland":         0.010
```

Parameter	Auto-Expression
	`="Bioreactor":      0)`
InStream Treatment	
US Travel Time [US_TRAVTIME]	`IF( [US_AVEVEL]<>0 , [US_IRR_LEN] /[US_AVEVEL]/60/1440, 0)`

APPENDIX C PARAMETERIZATION

Table 46: Subcatchment Attributes

Attribute/Category	Value/Description
Rain Gauge	For watersheds with more than one precipitation gauge, set by proximity using Set Outlet Tool in a copy of the model.
Outlet	Use the Set Outlet tool after rim elevations of all junctions are set.
Area	Delineate subcatchments based on DEM, watercourse layer, and road/crossings layers using ArcSWAT process. Verify manually in PCSWMM compared to contours and aerial photos.
Width, Slope, and Length	Use ArcMap Spatial Analyst Tool to create DEM of surface slope. Use ArcMap Zonal Statistics to calculate slope of each subcatchment based on DEM of surface slope. Use ArcMap Zonal Statistics to calculate subcatchment max/min elevations and elevation range based on DEM of surface elevation. Use results to calculate subcatchment length and width.
Imperv, N Perv, Dstore Perv	Area weight using Land Use layer using lookup table (Table 40). Lookup table creation is described in 6.3.1
N Imperv	0.01
Dstore Imperv	1.75
Zero Imperv	25%
Subarea Routing	OUTLET
Curb Length	0
Snow Pack	n/a
LID Controls	0
Groundwater	YES
Erosion	YES
Groundwater and Groundwater2	
Setup Methodology for all parameters except A1COEFF	• Create Aquifers using Tools > Subcatchments > Groundwater Component Creator • Parameterization discussed in Section 5.6.
A1 Coefficient	Auto-expression using subcatchment conductivity, LATCONDFACT, and GW1CALIB
Land Uses	
All land uses	Land use percentages calculated using area weighting of Fields layer and lookup table (Table 41).
Erosion	

Setup Methodology	- C factor time series:
	  o Open C factor time series **.tsb* file – this includes a time series of C factors for each land use type
	  o Add time series to fields layer (Attribute: C Factor CUSLE): In the Graph tab, plot all the C factor time series. Go to Menu > Add to Layer > Fields layer / TSB / Add current.
	  o Calculate CUSLE for each subcatchment using Tools > Area Weight Time Series > Fields layer to Subcatchments.
	- Enable erosion using File > Erosion:
	  o Obtain C from Subcatchment time series described above
	  o Route TSS: Clay, Sand, Silt

K [KUSLE]	Area weight using Soils layer and lookup table (Table 39)
P [PUSLE] and LS [LSUSLE]	Area weight using Fields Layer (no lookup table)
CFRG	Obtain from Subcatchment time series when erosion is enabled
Clay, Sand, and Silt Fractions [ER_Clay, Silt, and Sand]	Area weight using Soils layer and lookup table (Table 39)
Seasonal Variations	
Setup Methodology	Open the Time Pattern Editor and add five time patterns with the names below. These are all set to 1 initially and are revised during the calibration process as needed.
N Perv Pattern	NPerv
Dstore Perv Pattern	DSPerv
Suction Head Pattern	Suction
Conductivity Pattern	Conduct
Initial Deficit Pattern	InitDeficit
Land Uses	
Setup Methodology	Area weight using Fields layer and lookup table (Table 41). Abbreviated land use type is saved in the CUSLE attribute of the Fields layer.
Infiltration: Green-Ampt	
Suction Head, Conductivity, Initial Deficit	Area weight using Soils layer using lookup table (Table 38). Lookup table creation described in 6.3.1
Other	
Porosity, Field Capacity [FIELDCAP], Wilting	Area weight using Soils layer and lookup table (Table 38)
MAXELEV, MINELEV, ELEVRANGE, MEANSLOPE	Calculate using DEM in ArcMap Zonal Statistics to determine subcatchment length and width
Gauge	First downstream flow monitoring station name
LATCONDFACT	1.5
GW1CALIB	Varies based on calibration

Table 47: Conduit Attributes

Attribute/Category	Value/Description
Length	Automatically calculated by setting Auto-Length on. Short conduits were merged with upstream conduits (i.e. CSP's at the outlet of municipal drains) to prevent numerical instability.
Roughness	Set roughness based on material and lookup table. Roughness of bridges with very wide spans were set to a natural channel roughness where appropriate
Inlet Elevation	Set conduit and node elevations by extracting elevation from DEM in RSWMM. For municipal drains, use the attribute for depth below surface to determine the conduit invert. Elevations were adjusted in some cases to reverse negative slopes. This was a common issue in models with a low-resolution DEM. In some models, invert elevations were adjusted so that culverts and bridges had a slope of 2%. The elevation of overflow conduits where a road could overtop at a culvert or bridge was determined using the DEM. When the resolution of the DEM was too low, it was assumed that the road was 0.3 m above the culvert/bridge obvert.
Outlet Elevation	Set conduit and node elevations by extracting elevation from DEM in RSWMM. For municipal drains, use the attribute for depth below surface to determine the conduit invert.
Initial Flow	0
Flow Limit	0
Entry Loss Coefficient	Set based on culvert/bridge type
Exit Loss Coefficient	Set based on culvert/bridge type
Average Loss Coefficient	0
Seepage Rate (mm/hr)	0
Flap Gate	Set to Yes manually where appropriate
Cross Section	Dummy – Manually for conduits representing unknown structures or to separate a common outlet node. Irregular – Manual default for all conduits that are open or natural watercourses. Trapezoidal – Set manually when municipal drain drawings include dimensions of open ditch. Also used to represent drainage pathway when road overtops. Circular – Manual default for all closed conduits. Arch, Rect_Closed, etc. – Set other closed conduit shapes when importing culvert and bridge information provided by CAs. File > Import > Microsoft Excel > Conduits.
Geom1	Height of closed conduits set when importing culvert and bridge information provided by CAs.
Geom2	This is the width of box, trapezoidal, arch, and elliptical conduits or the depth of sediment in filled circular conduits. Set when importing culvert and bridge.
Geom3 and Geom4	Left and right side slope of trapezoidal conduits
Barrels	Default value is 1. Changed when multiple structures exist at crossing as provided by CAs (e.g. Twin culvert).

Transect	Automatically refers to transect determined using DEM in Transect Creator tool (Named based on conduit).
Culvert Code	Set based on culvert/bridge type
Other	
DRAINSYSTEM	Name of drainage system or municipal drain set manually.
MATERIAL	Set manually based on details in municipal drain drawings or for open/natural conduits. For culverts and bridges, import based on information provided by CAs.
INELEV_M, OUTELEV_M, DIAMETER_MM, LENGTH_M, UP_STATION, DN_STATION, SLOPE_CHECK	Set manually based on details in municipal drain drawings

Table 48: Transect Attributes

Attribute/Category	Value/Description
Bank Stations	0
Modifiers	0
Right Bank	Set using average roughness for each conduit material type (Table 42).
Transect	Cross sections of watercourses were created using DEM and Transect Creator tool that generates a representative transect for each conduit based on multiple transects along the conduit. After running the models, the transect lengths were increased where necessary to capture the available storage in the overbank areas. In some cases, a representative transect was used to replace the average calculated in RSWMM.

Table 49: Junction Attributes

Attribute/Category	Value/Description
Treatment	Yes (see treatment attributes below)
Invert Elev	Set node elevations by extracting elevation from DEM.
Depth	10 (or more if conduit upstream or downstream of junction has a height greater than 10 m)
Initial Depth, Surcharge Depth, Ponded Area	0
Inflows	
	Automatically defined by PCSWMM after erosion simulation.
Other	
DRAINSYSTEM	Name of drainage system or municipal drain set manually.
TYPE, DEPTH_BGS_M, & STATION	Set manually based on details in municipal drain drawings
Treatment	
Treatment auto-expressions for dissolved pollutants	Defined in Appendix B.2
InStream Treatment	
US Channel Length (m)	Sum of upstream Irregular conduit Length
Avg. Velocity (m/s)	Average of upstream Irregular conduit mean velocity
US Travel Time (day)	Upstream Mean Water Travel Time (See in Appendix B.2)
Nitrate Coeff.	Default = -0.786 (user defined)
Hydrology Coeff	Default = -0.309 (user defined)

Model Intercept Coeff	Default = 0.336 (user defined)
US Conduit Type	Upstream conduit Cross-section type

Table 50: Outfall Attributes

Attribute/Category	Value/Description
Inflows	Yes
Treatment	Yes
Invert Elev	Set node elevations by extracting elevation from DEM.
Rim Elev	10 m above invert
Tide Gate	NO
Type	FREE
Inflows	
	Automatically defined by SWMM.
Treatment	
Treatment auto-expressions for dissolved pollutants	Defined in Appendix B.2
InStream Treatment	
US Channel Length (m)	Sum of upstream Irregular conduit Length
Avg. Velocity (m/s)	Average of upstream Irregular conduit mean velocity
US Travel Time (day)	Upstream Mean Water Travel Time (See in Appendix B.2)
Nitrate Coeff.	Default = -0.786 (user defined)
Hydrology Coeff	Default = -0.309 (user defined)
Model Intercept Coeff	Default = 0.336 (user defined)
US Conduit Type	Upstream conduit Cross-section type

Table 51: Storage Attributes

Attribute/Category	Value/Description
Inflows	Yes
Treatment	Yes
Invert El	Set invert elevations by extracting elevation from DEM.
Depth	10
Initial Depth	0
Ponded Area	0
Evap Factor	Set to zero to prevent numerical instability in pollutant concentration calculations when the volume of water in the dry pond approaches zero.
Storage Curve	Set as Tabular for storage areas with known stage/storage relationship. Set as Functional when calibration used to estimate storage.
Coefficient	Varies
Exponent	Varies
Constant	Estimated as 1000, used as calibration parameter
Infiltration	
Suction Head	0
Conductivity	0
Initial Deficit	0
Inflows	
	Automatically defined by SWMM.
Treatment	

Treatment auto-expressions	Defined in Appendix B.2
Treatment BMP Design	
Treatment Type	Pond, Wetland, or Bioreactor
Media Porosity (cm^3/cm^3)	Default = 0.65 for woodchips (user defined)
Footprint (m^2)	Auto-expressed
Denitrification Rate (1/hour)	Varies based on BMP type (user defined)
Efficiency Coefficient	User defined; between 0 and 1
Nitrification Rate	Varies based on BMP type (user defined)
Ammonium Fraction	Default = 0.8 (user defined)
Sand Settling Rate (m/hr)	Default = 0.204 (user defined)
Silt Settling Rate (m/hr)	Default = 0.00154 (user defined)
Clay Settling Rate (m/hr)	Default = 0.00000884 (user defined)
InStream Treatment	
US Channel Length (m)	Sum of upstream Irregular conduit Length
Avg. Velocity (m/s)	Average of upstream Irregular conduit mean velocity
US Travel Time (day)	Upstream Mean Water Travel Time (See in Appendix B.2)
Nitrate Coeff.	Default = -0.786 (user defined)
Hydrology Coeff	Default = -0.309 (user defined)
Model Intercept Coeff	Default = 0.336 (user defined)
US Conduit Type	Upstream conduit Cross-section type

Table 52: Land Use Attributes

Attribute/Category	Value/Description
Street Sweeping Interval, Street Sweeping Availability, Last Sweep	0
Buildup (Set for each soil and pollutant for each land use)	
Buildup Function	None
Max Buildup, Buildup Rate Constant (Scaling Factor), Buildup Power/Sat Constant	0
Buildup Normalizer	Area
Washoff (Set for each soil and pollutant for each land use)	
Washoff Function	EMC for all except RC for SRP
Washoff Coefficient	Varies based on calibration.
Washoff Exponent	1 for all except SRP. Varies based on calibration.
Washoff Cleaning Effic. and Washoff BMP Effic.	0

APPENDIX D MODEL RESULTS

Table 53: Pine River Points of Interest

Point of Interest	PCSWMM Object ID
1	J10-03O
2	1
3	J12-03J
4	J13-02J
5	J13-12J
6	58
7	76
8	J18-04J
9	J01-01O

Table 54: Garvey-Glenn Points of Interest

Point of Interest	PCSWMM Object ID
1	JUN30-01O
2	JUN01-01O
3	CB-10
4	CB-20
5	CB-19
6	CB-50
7	CB-40
8	CB-70
9	CB-80
10	CB-90
11	CB-100
12	CB-110

Table 55: Bayfield North Points of Interest

Point of Interest	PCSWMM Object ID
1	OF_GODM
2	OF_GODL
3	OF_GODJ
4	OF_GODI
5	OF_GODH
6	OF_GODG
7	OF_GODF
8	OF_GulyC
9	OF_GODD
10	OF_GODA
11	CH-G188
12	CH-G189

Table 56: Main Bayfield Points of Interest

Point of Interest	PCSWMM Object ID
1	OUT01-02
2	BW-B82
3	BW-B80
4	CH-B76
5	CH-B74

Table 57: Lambton Shores Points of Interest

Point of Interest	PCSWMM Object ID
1	J21-01O
2	J34-01O
3	C16
4	C13
5	C12
6	J02-01O
7	J58-01O
8	A9
9	J62-01J
10	A5

Appendix D.1 Hydrographs

Appendix D.1.1 Pine River

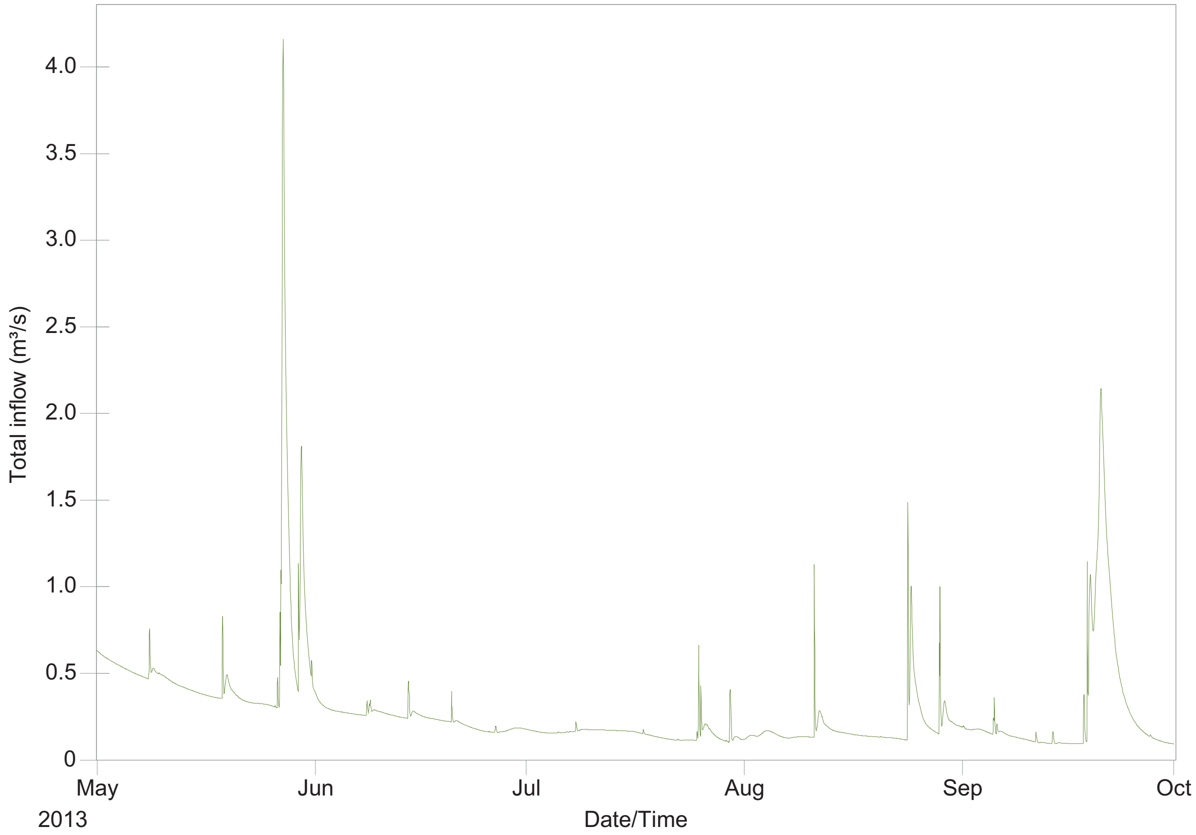


Figure 69: Pine River Hydrograph at Point of Interest 1, Outfall J10-03O

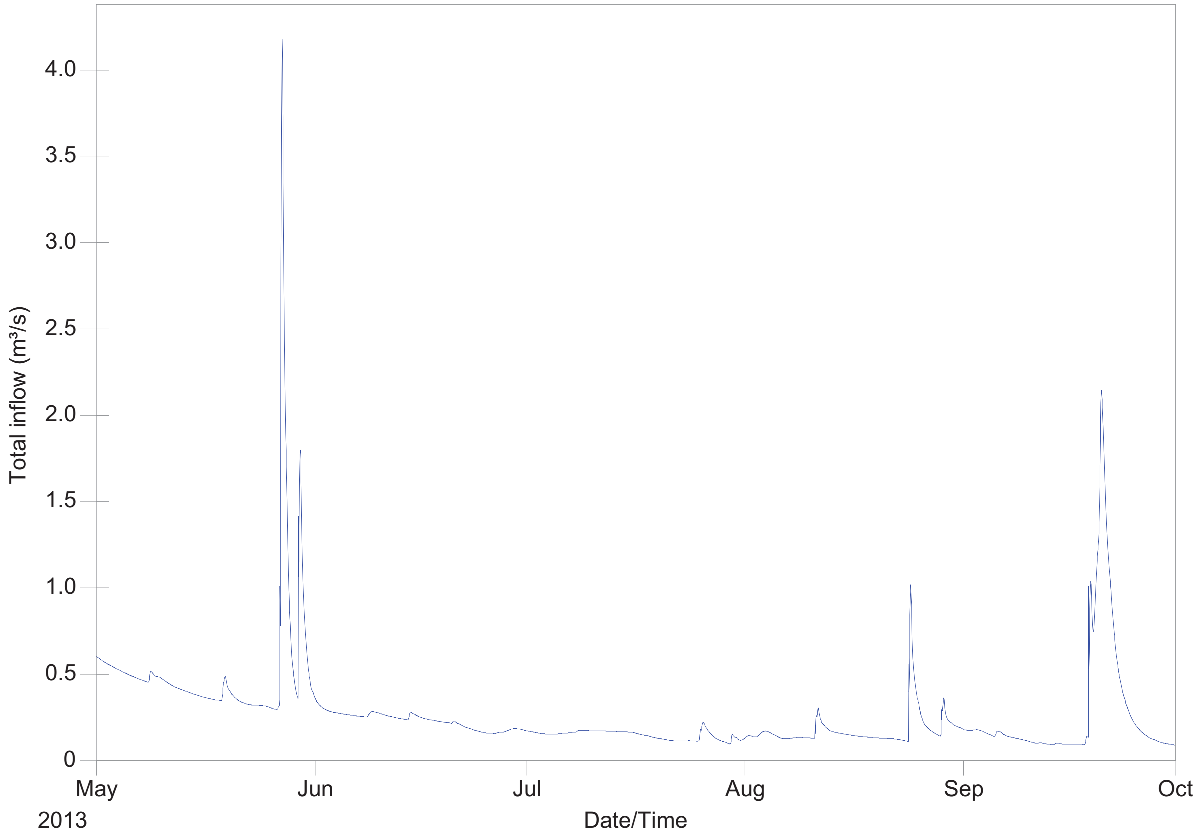


Figure 70: Pine River Hydrograph at Point of Interest 3, Junction J12-03J

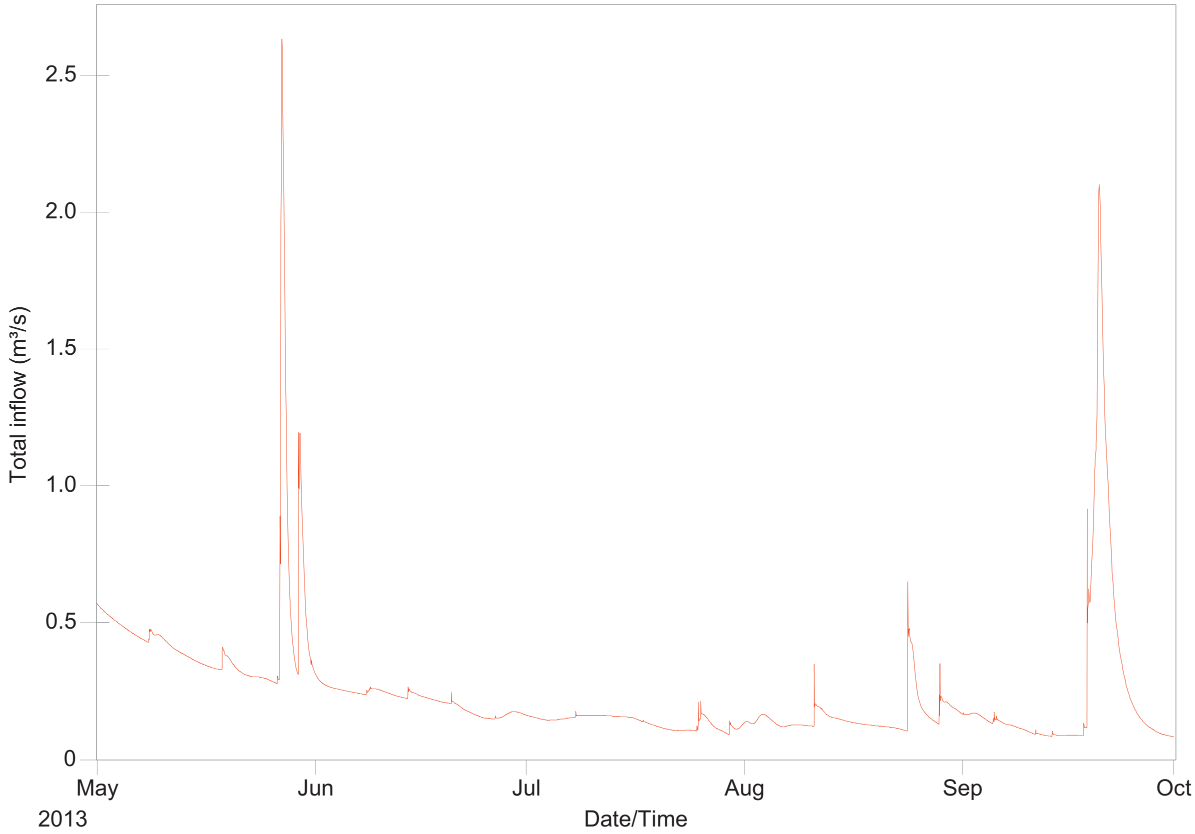


Figure 71: Pine River Hydrograph at Point of Interest 4, Junction J13-02J

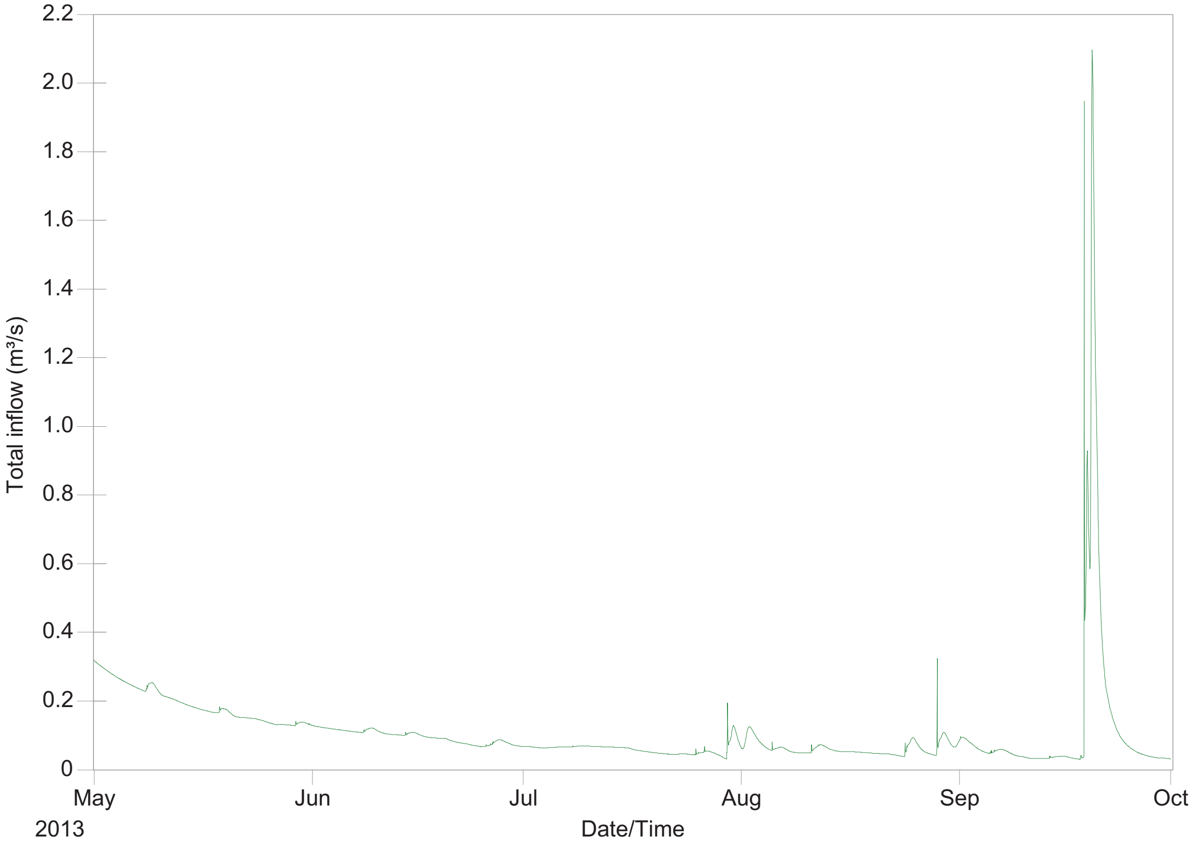


Figure 72: Pine River Hydrograph at Point of Interest 5, Junction J13-12J

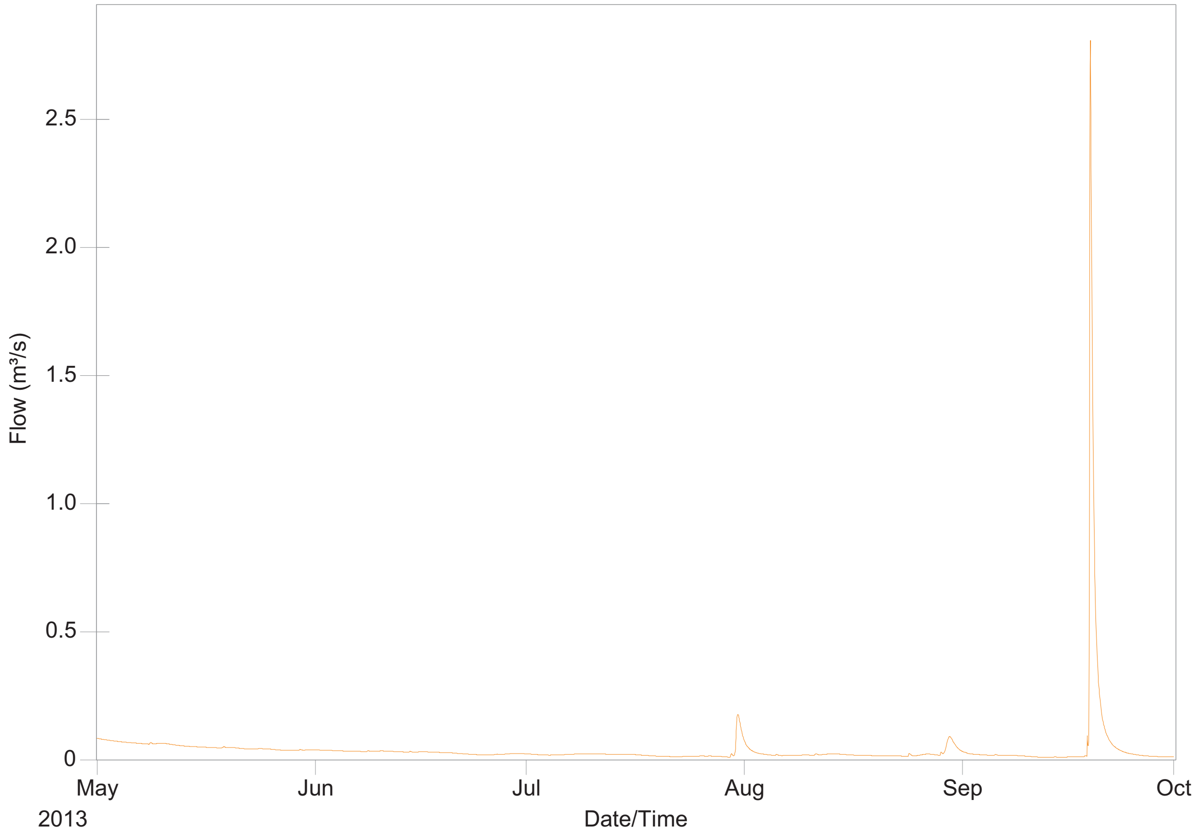


Figure 73: Pine River Hydrograph at Point of Interest 6, Conduit 58

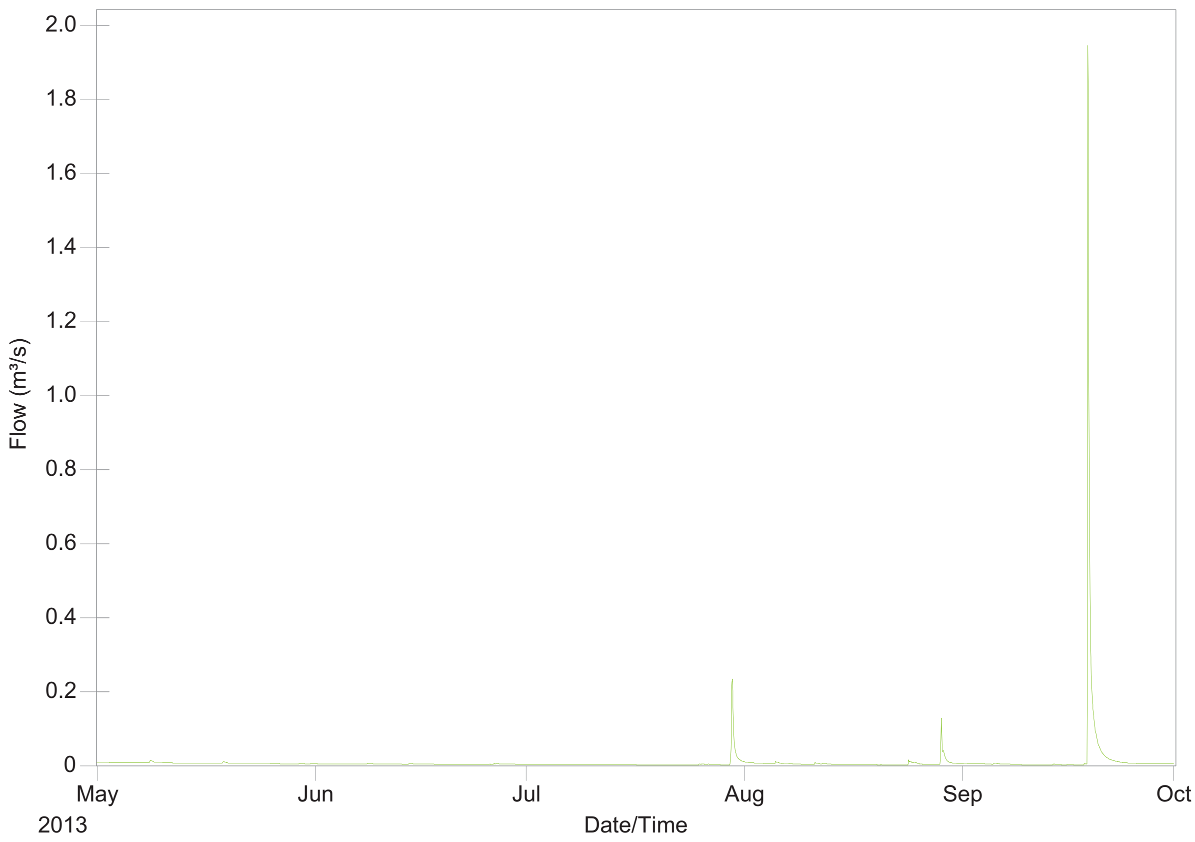


Figure 74: Pine River Hydrograph at Point of Interest 7, Conduit 76

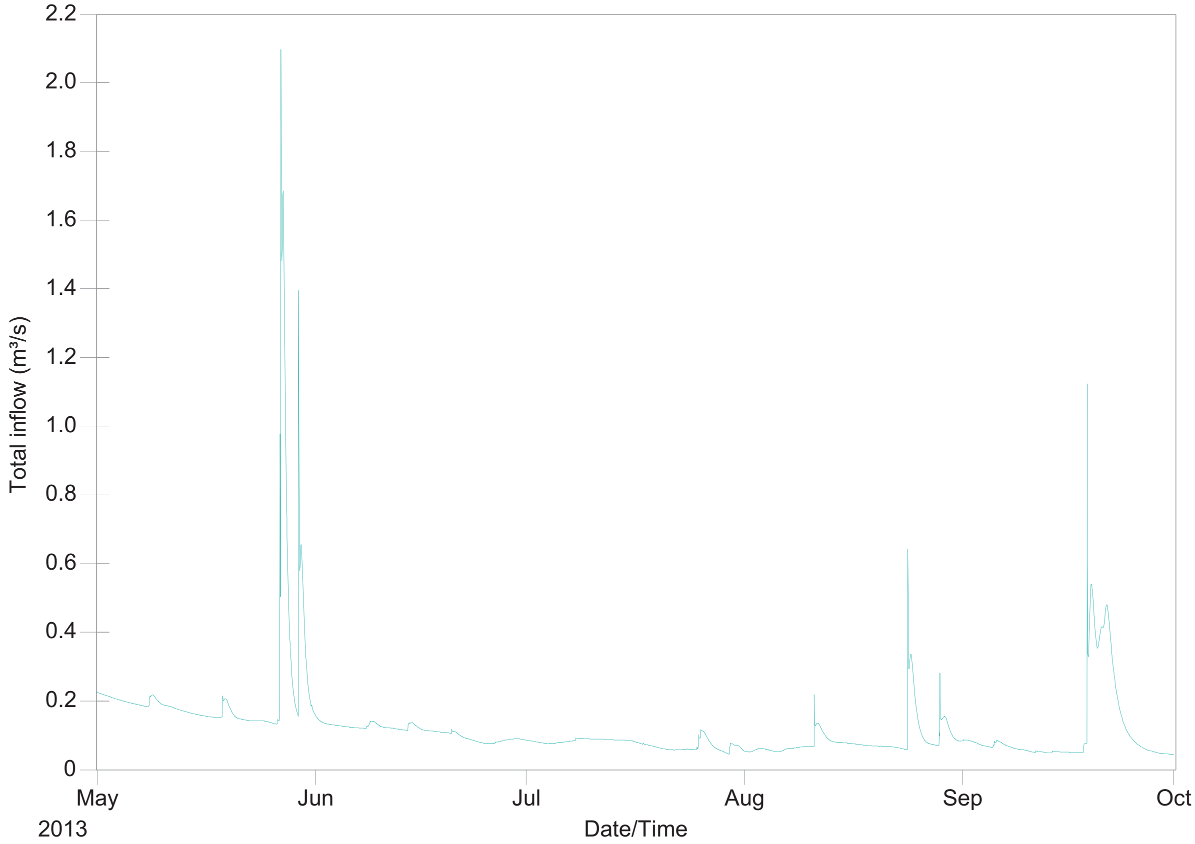


Figure 75: Pine River Hydrograph at Point of Interest 8, Junction J18-04J

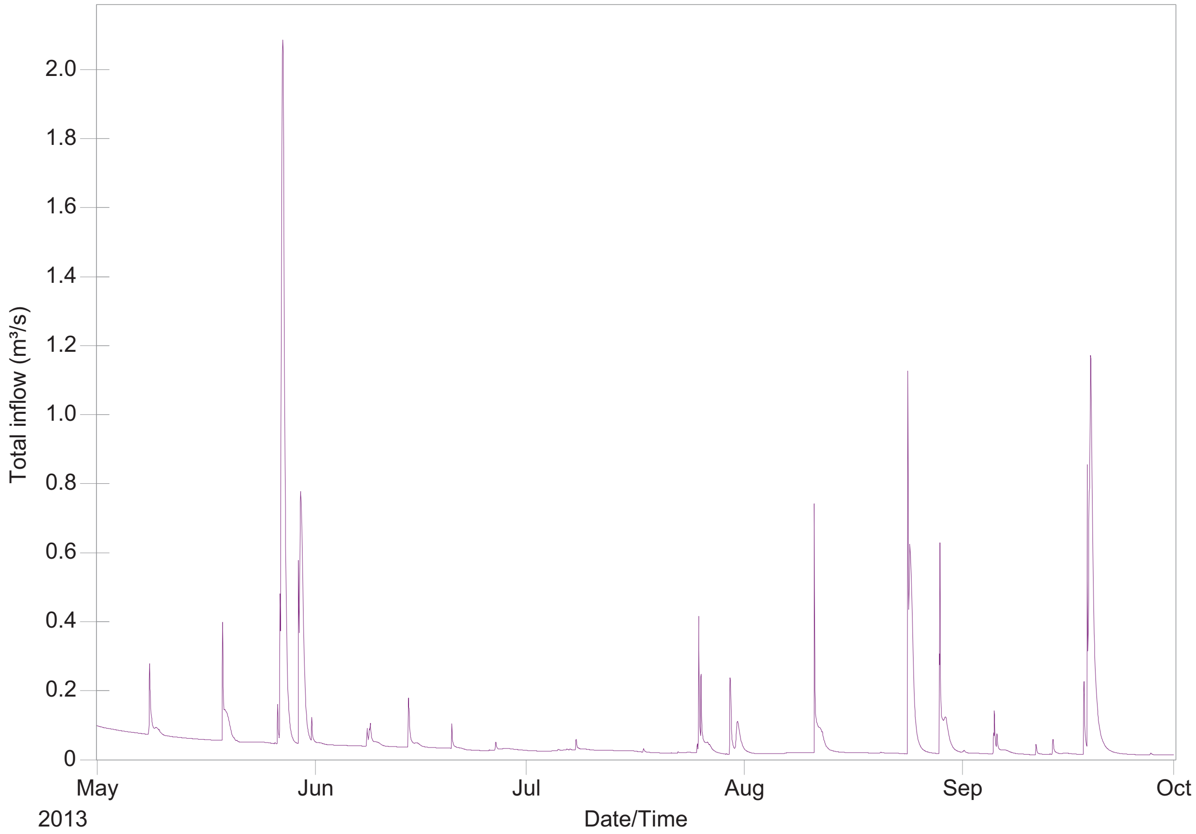


Figure 76: Pine River Hydrograph at Point of Interest 9, Junction J01-01O

Appendix D.1.2 Garvey-Glenn

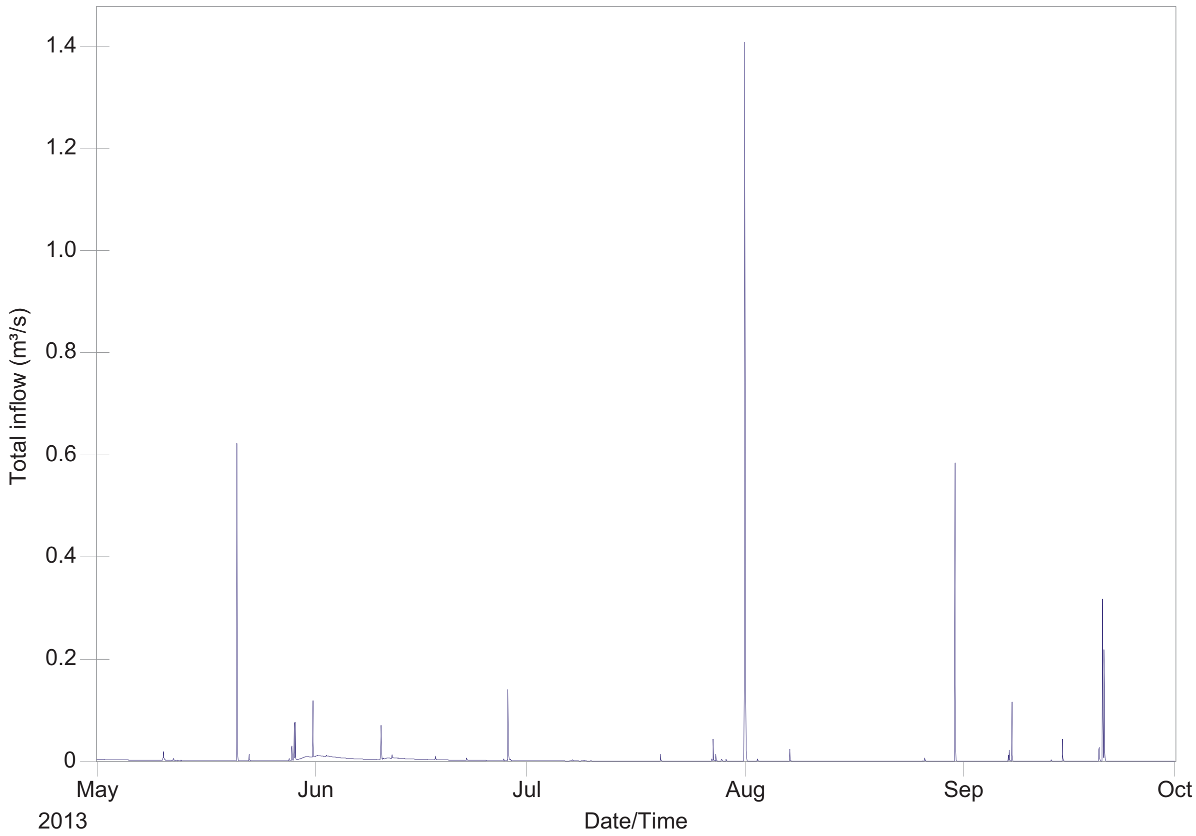


Figure 77: Garvey-Glenn Hydrograph at Point of Interest 1, Outfall JUN30-01O

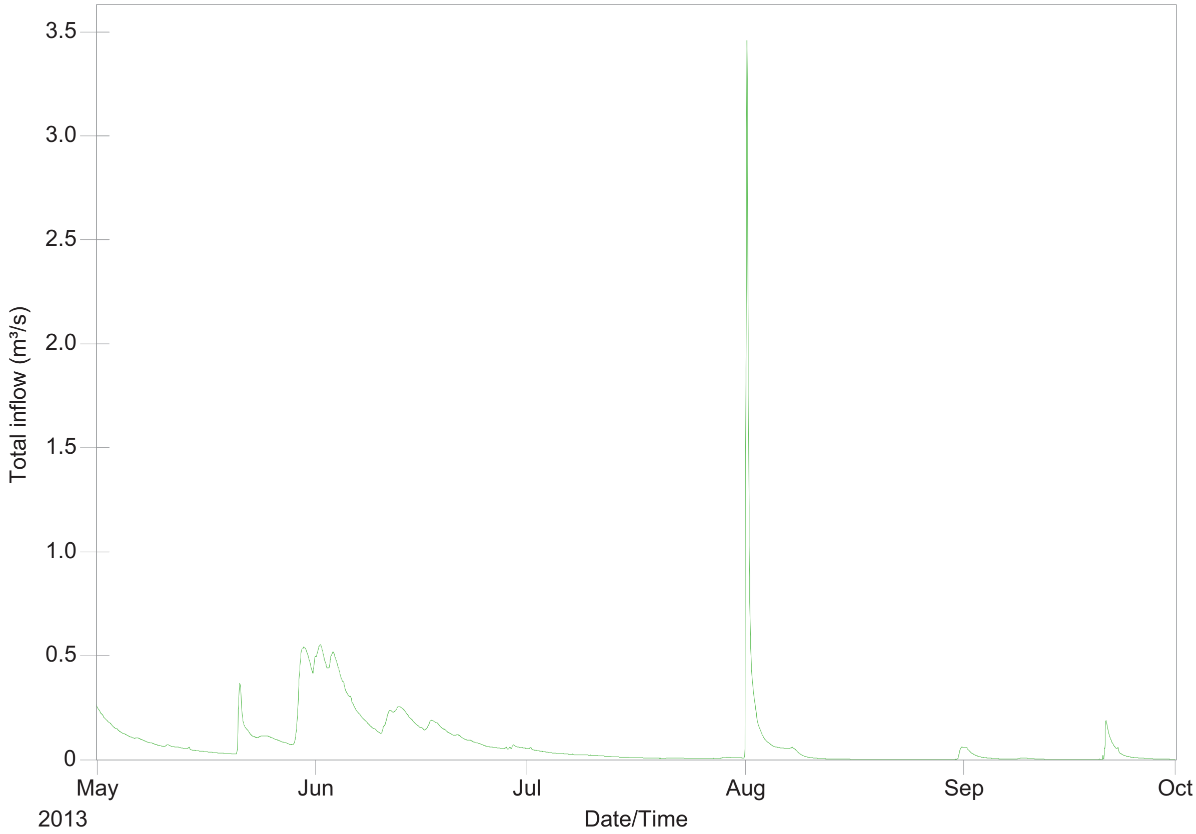


Figure 78: Garvey-Glenn Hydrograph at Point of Interest 2, Outfall JUN01-010

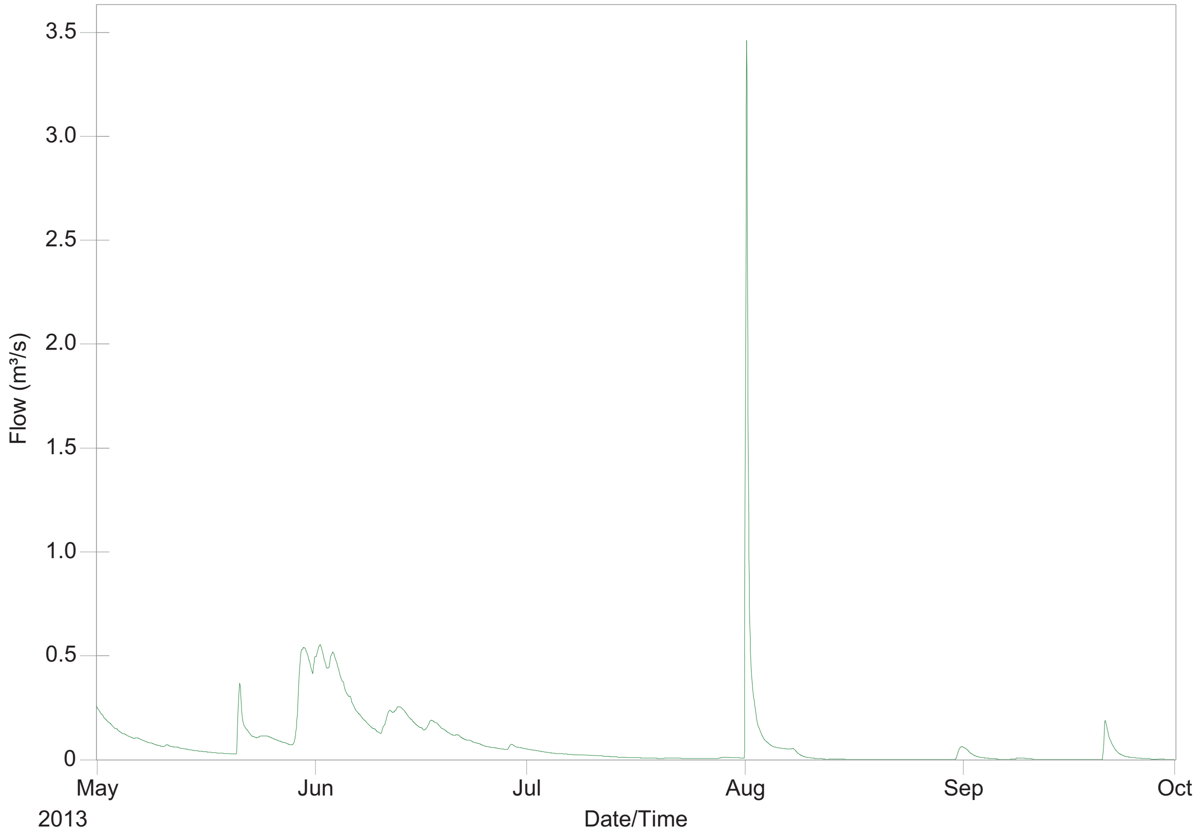


Figure 79: Garvey-Glenn Hydrograph at Point of Interest 3, Conduit CB-10

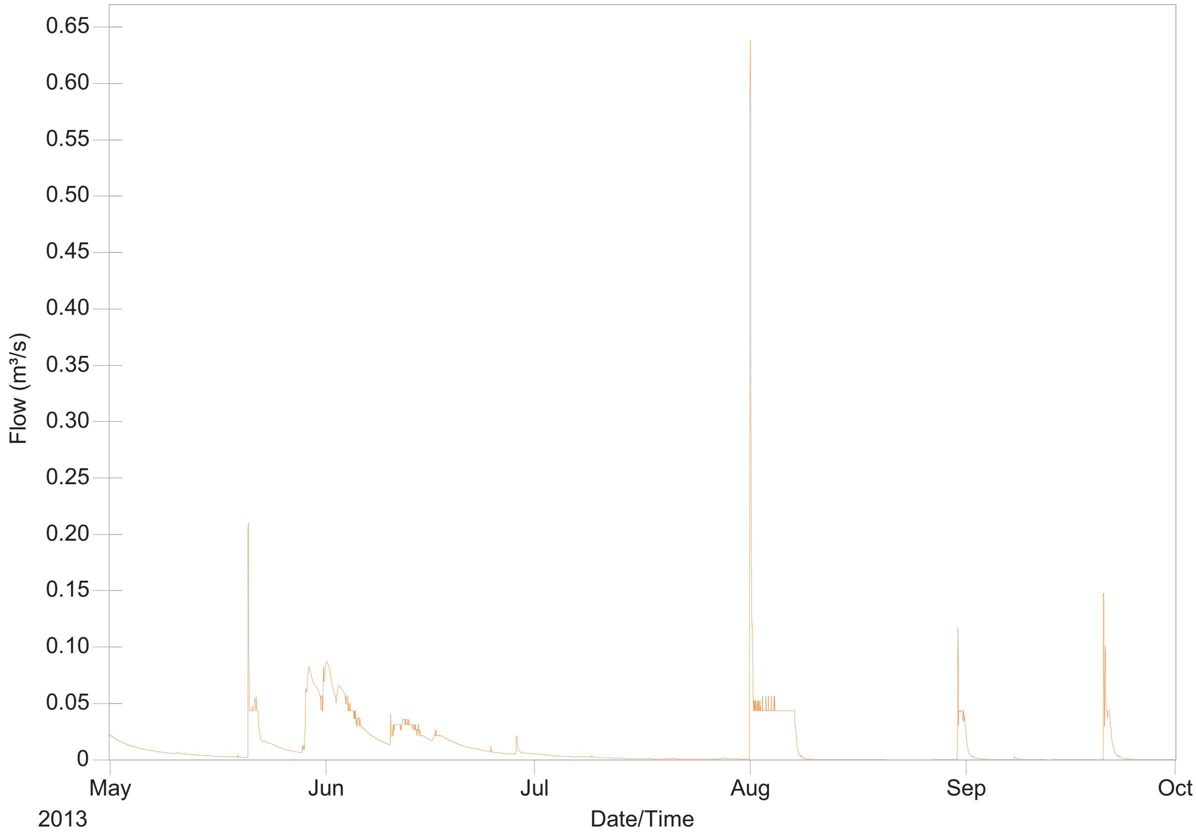


Figure 80: Garvey-Glenn Hydrograph at Point of Interest 5, Conduit CB-19

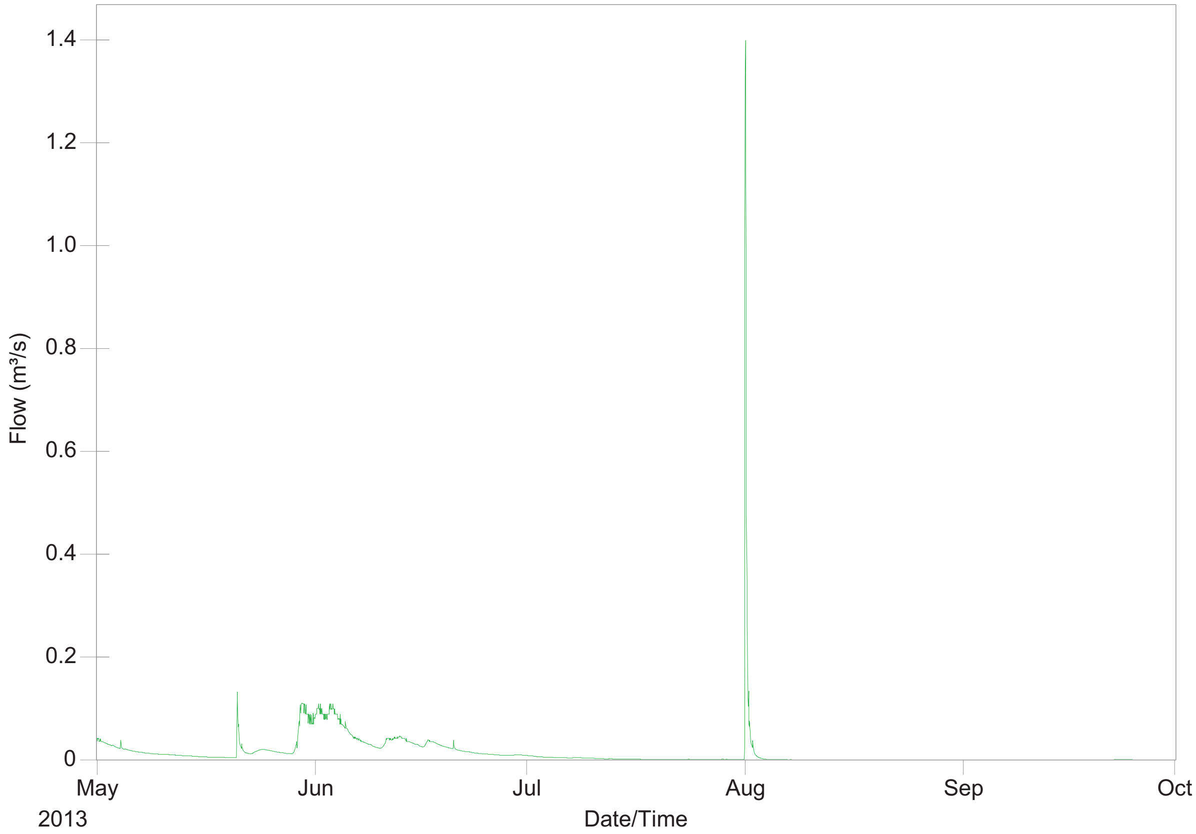


Figure 81: Garvey-Glenn Hydrograph at Point of Interest 6, Conduit CB-50

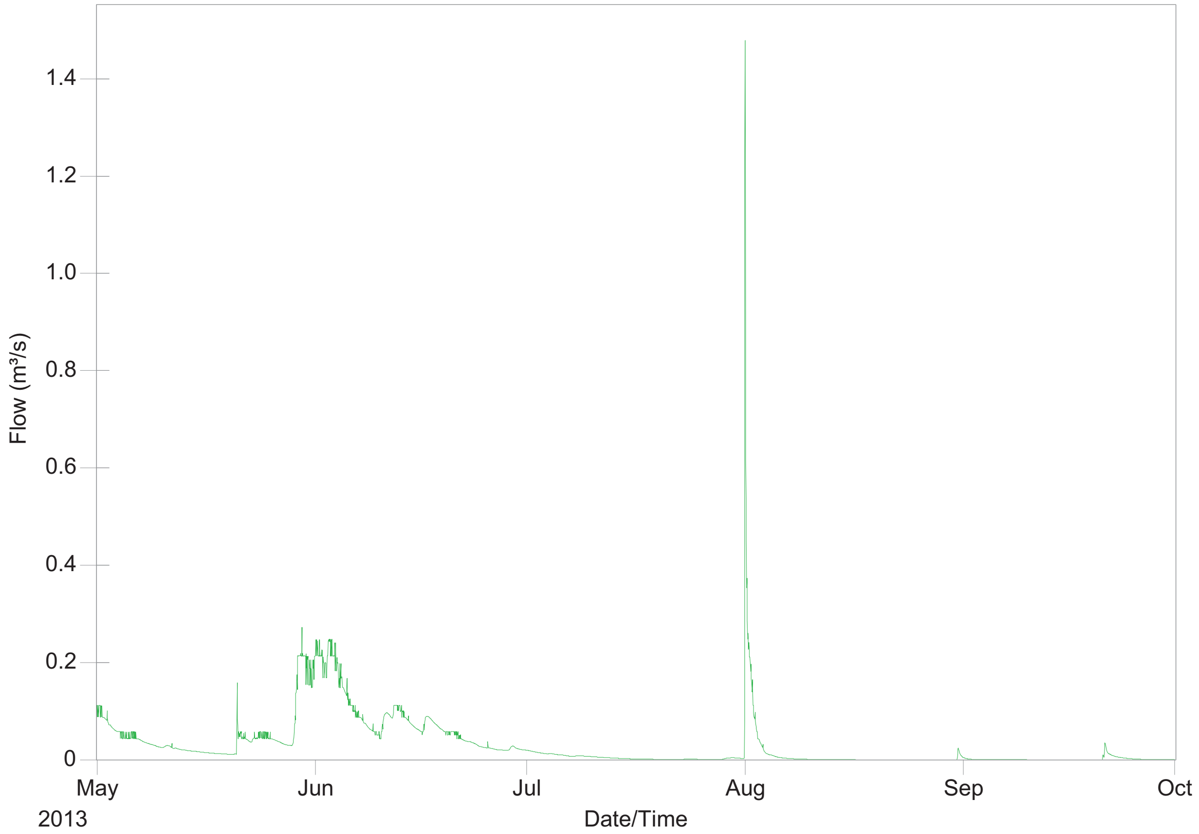


Figure 82: Garvey-Glenn Hydrograph at Point of Interest 7, Conduit CB-40

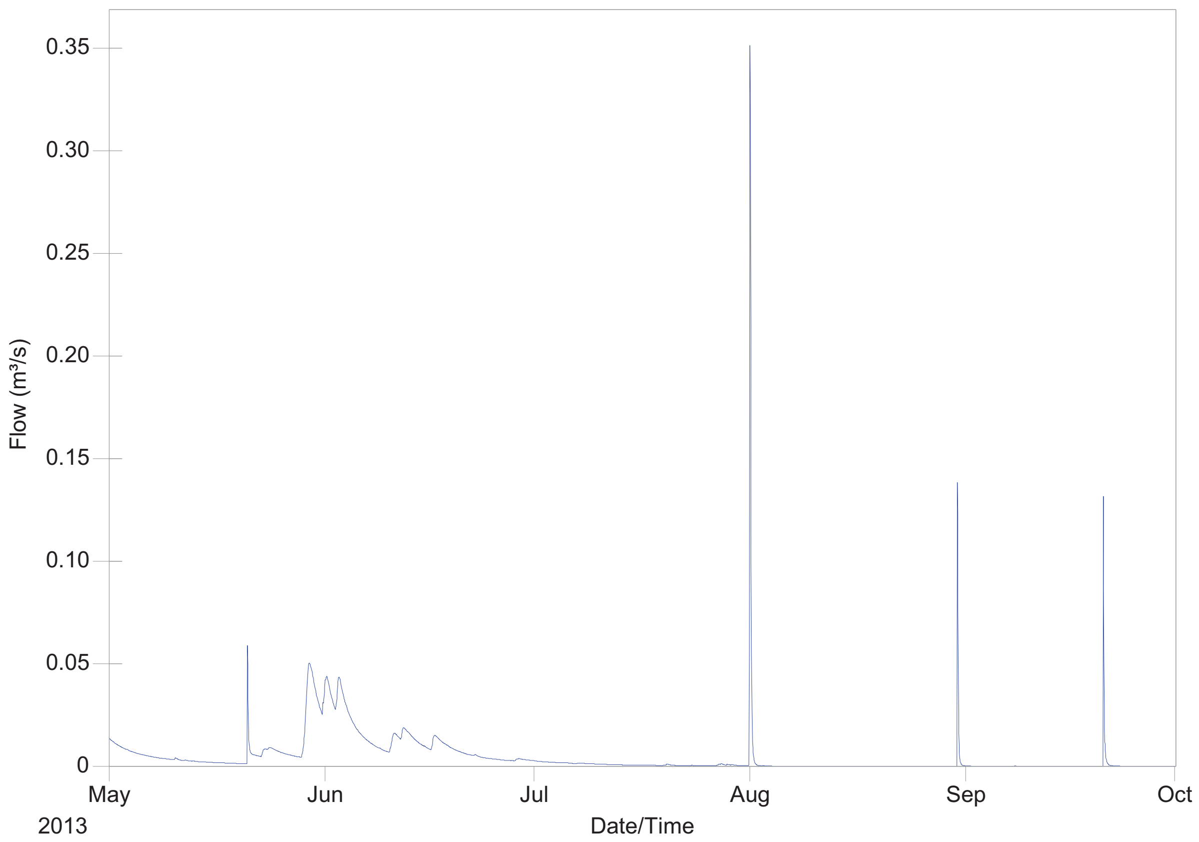


Figure 83: Garvey-Glenn Hydrograph at Point of Interest 8, Conduit CB-70

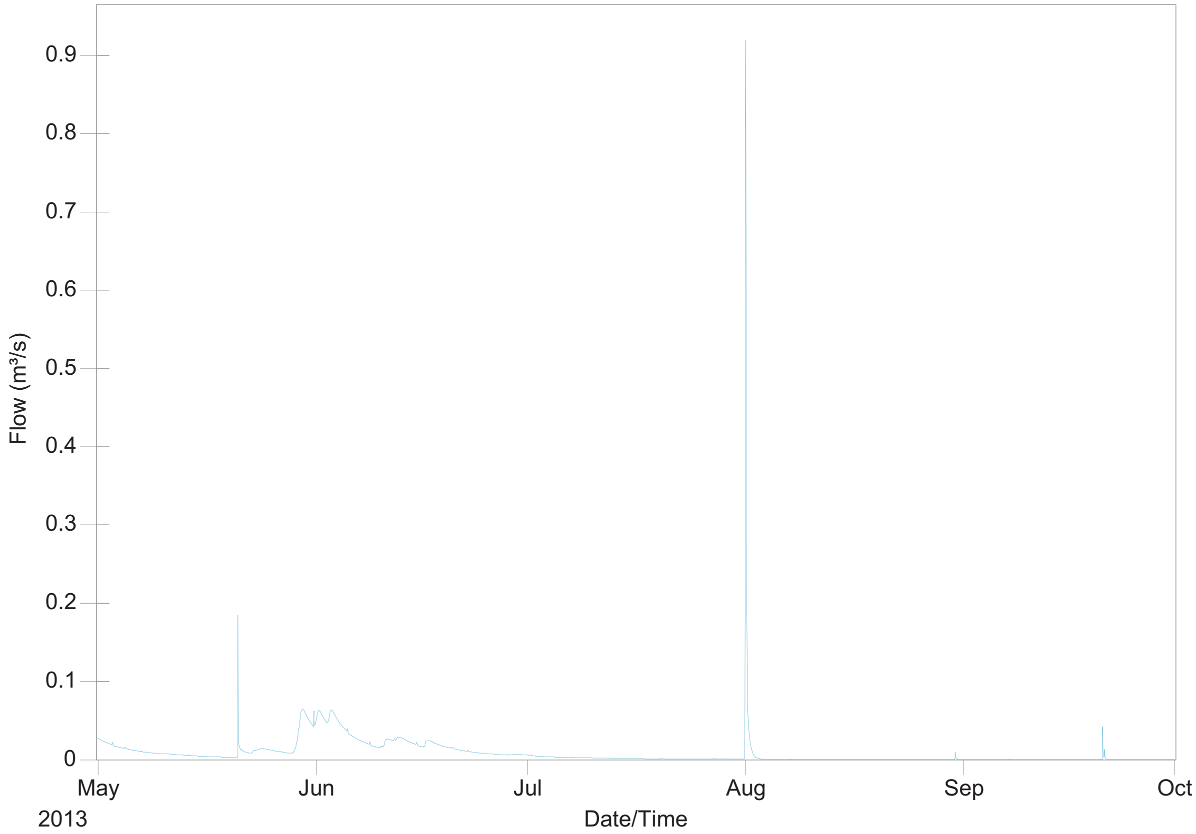


Figure 84: Garvey-Glenn Hydrograph at Point of Interest 9, Conduit CB-80

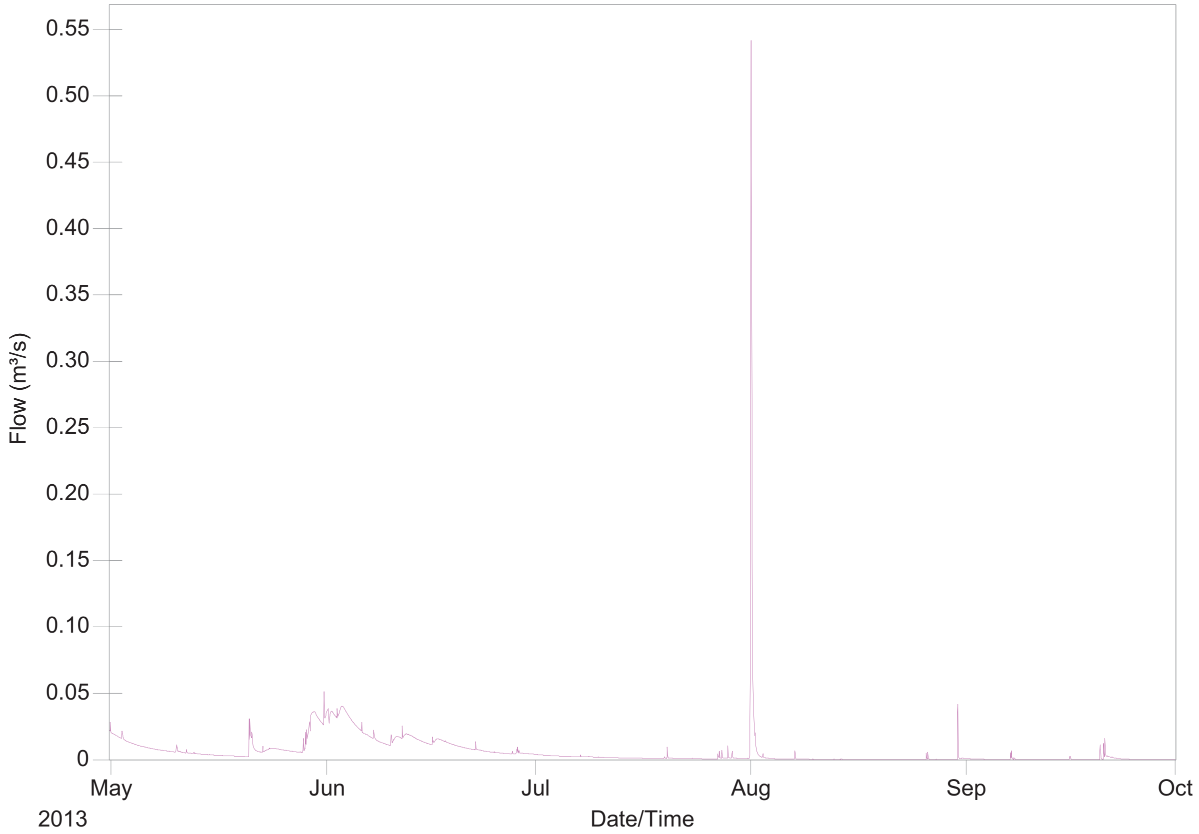


Figure 85: Garvey-Glenn Hydrograph at Point of Interest 10, Conduit CB-90

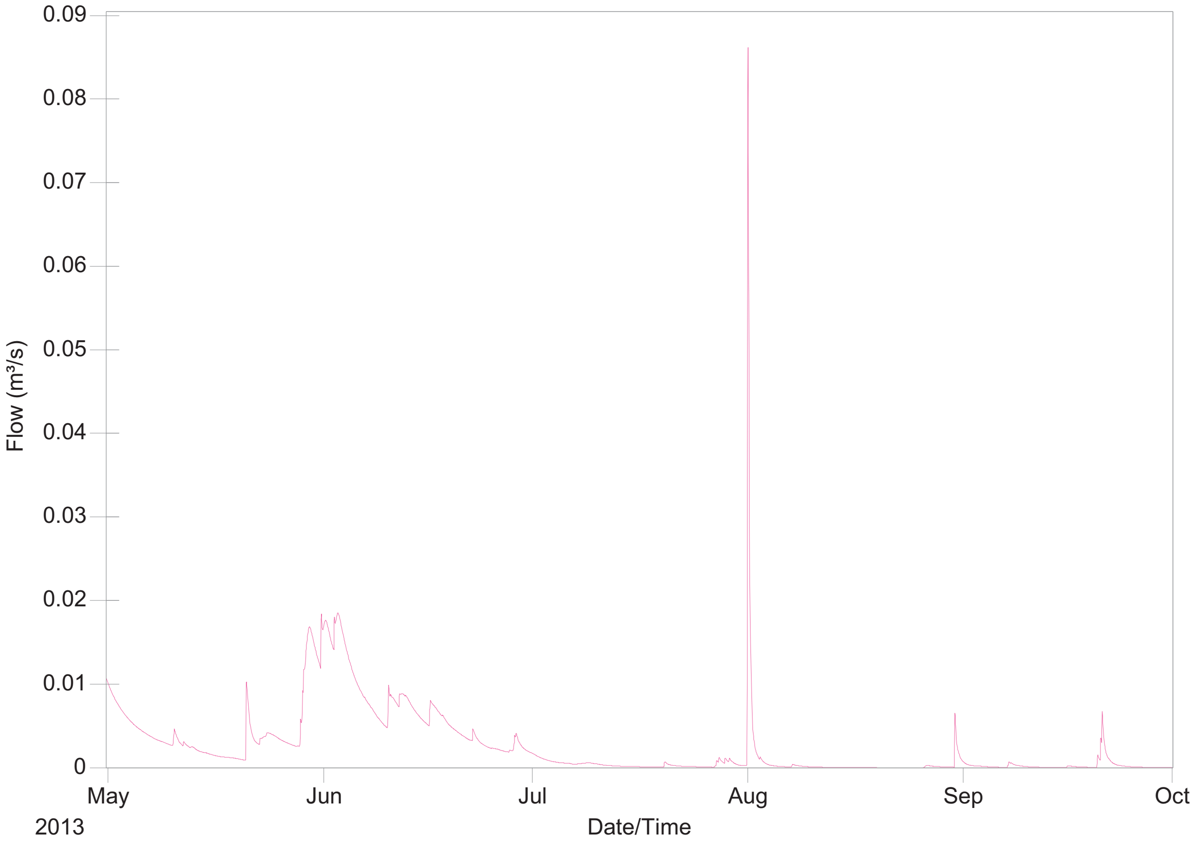


Figure 86: Garvey-Glenn Hydrograph at Point of Interest 11, Conduit CB-100

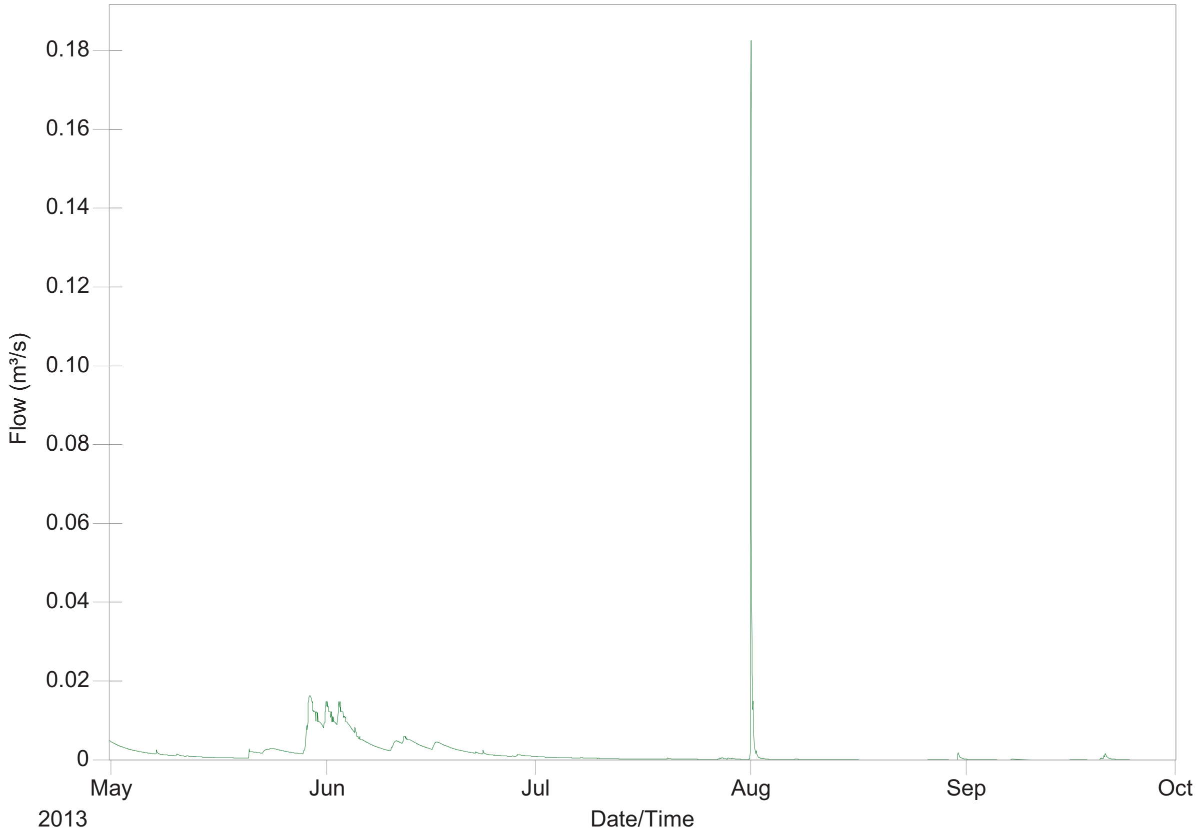


Figure 87: Garvey-Glenn Hydrograph at Point of Interest 12, Conduit CB-110

Appendix D.1.3 Bayfield North

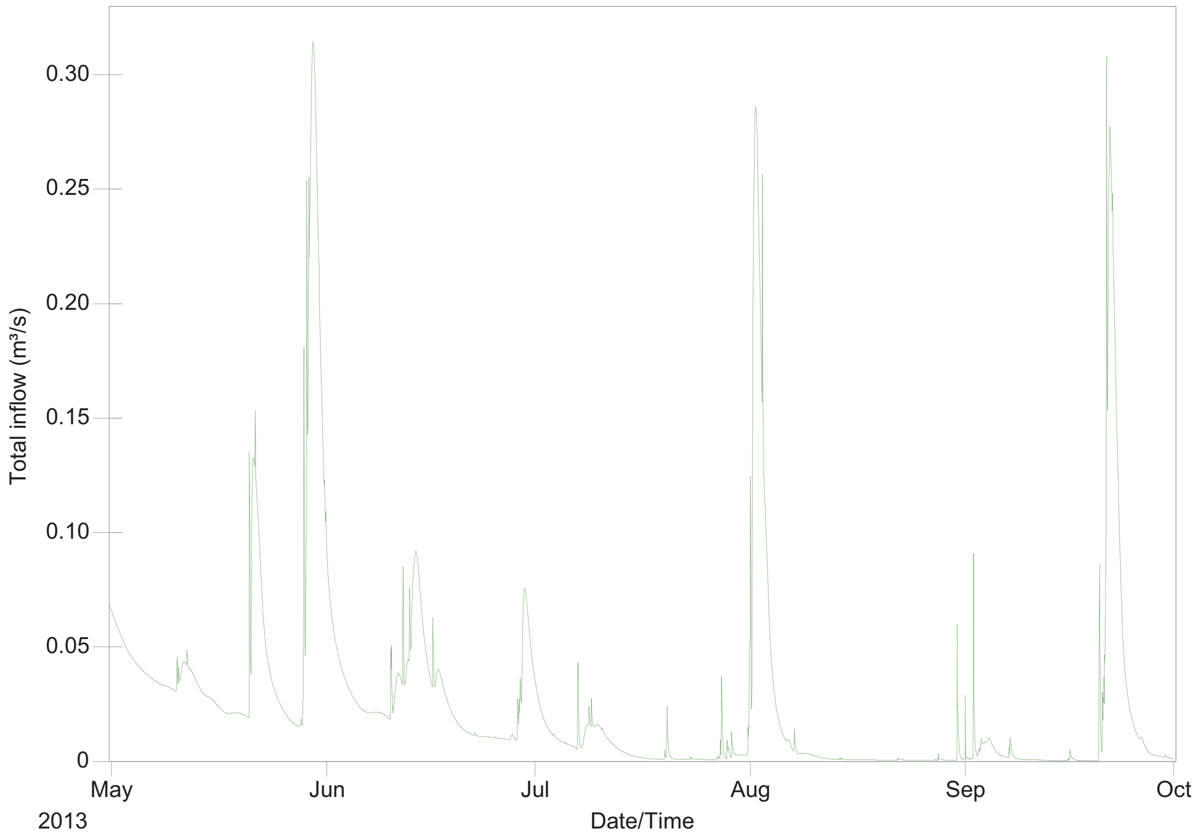


Figure 88: Bayfield North Hydrograph at Point of Interest 1, Outfall OF_GODM

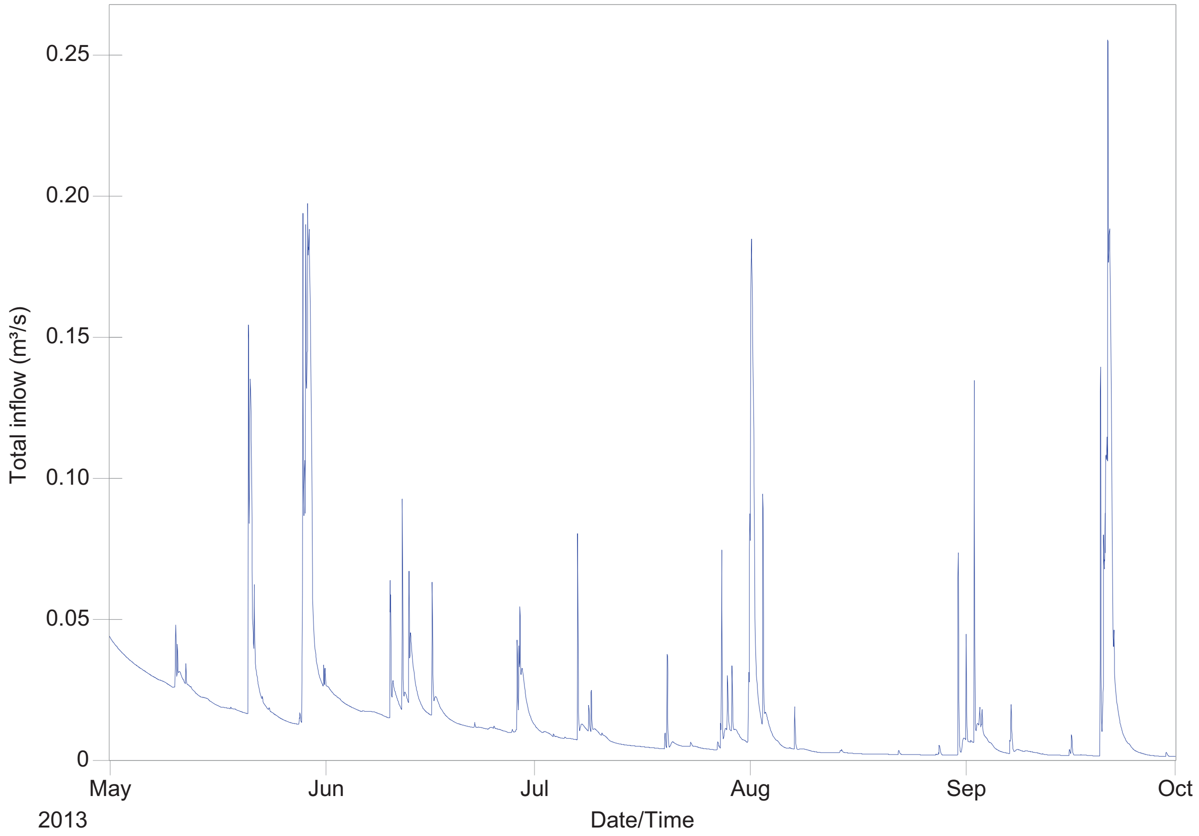


Figure 89: Bayfield North Hydrograph at Point of Interest 2, Outfall OF_GODL

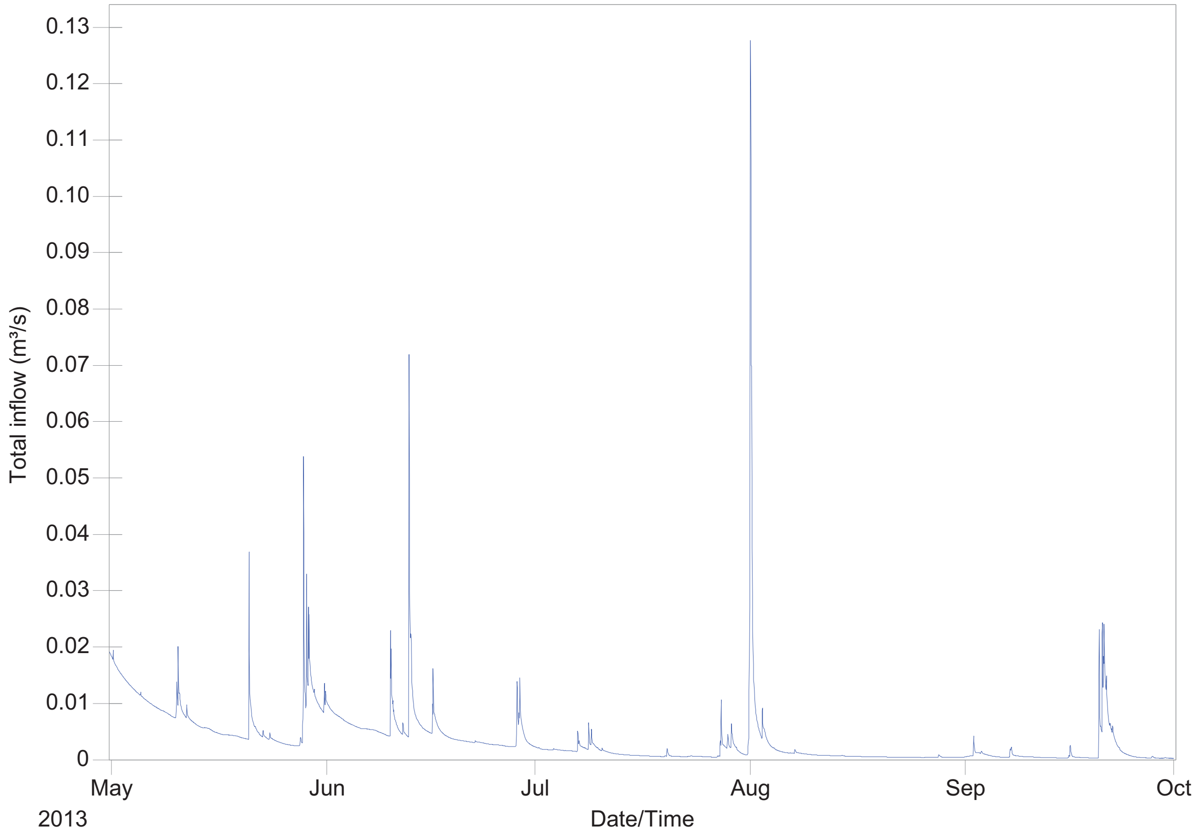


Figure 90: Bayfield North Hydrograph at Point of Interest 3, Outfall OF_GODJ

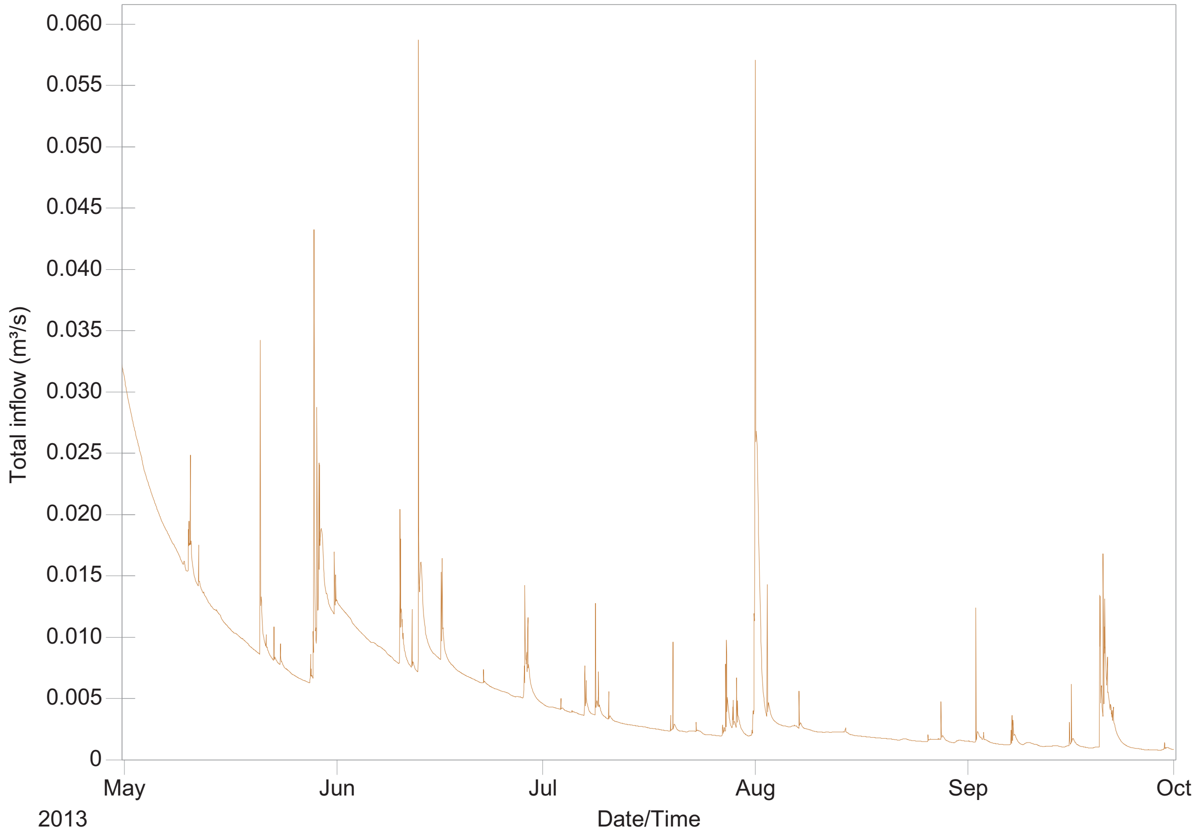


Figure 91: Bayfield North Hydrograph at Point of Interest 4, Outfall OF_GODI

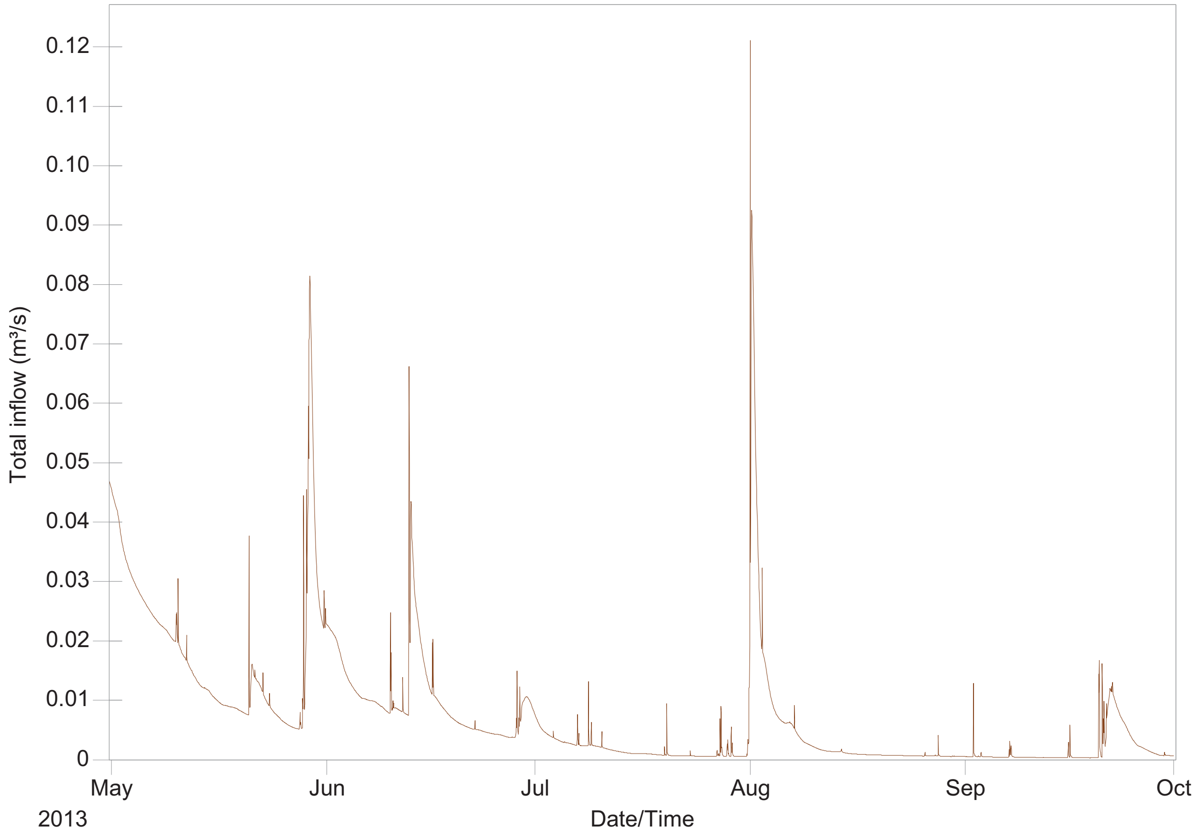


Figure 92: Bayfield North Hydrograph at Point of Interest 5, Outfall OF_GODH

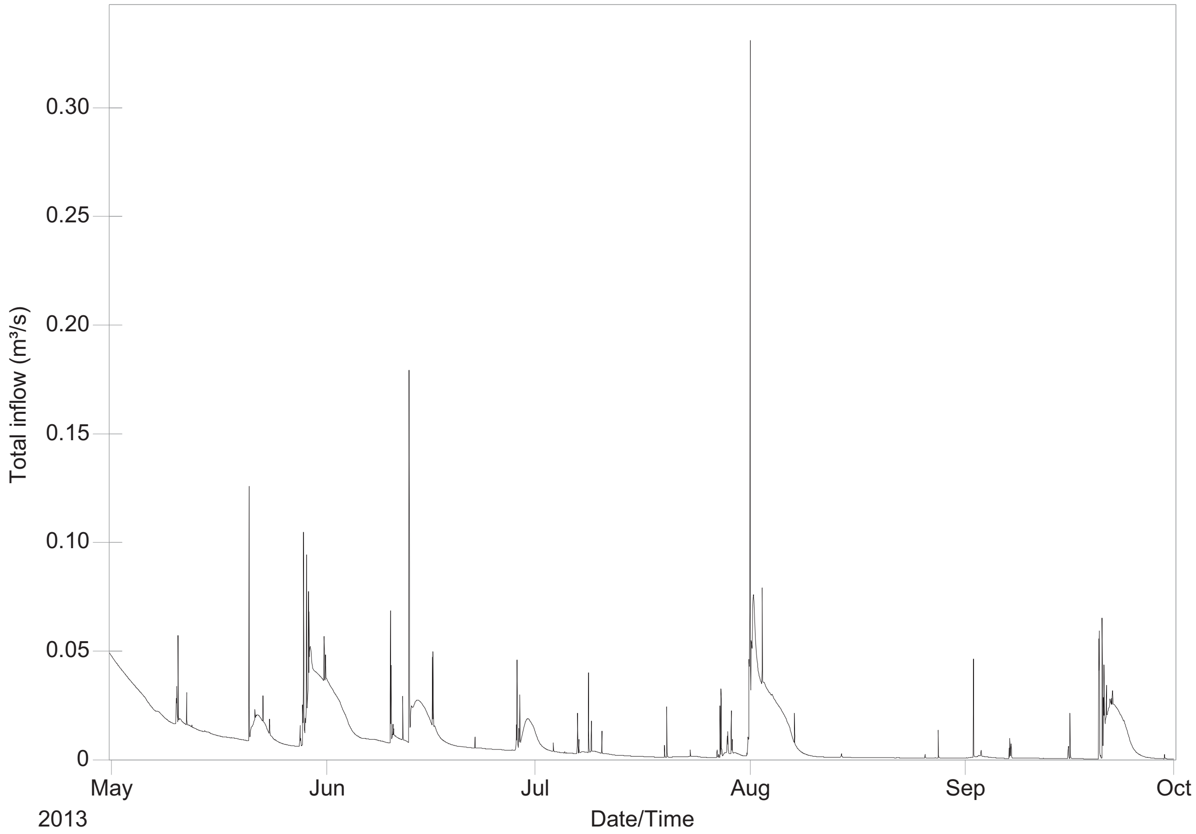


Figure 93: Bayfield North Hydrograph at Point of Interest 6, Outfall OF_GODG

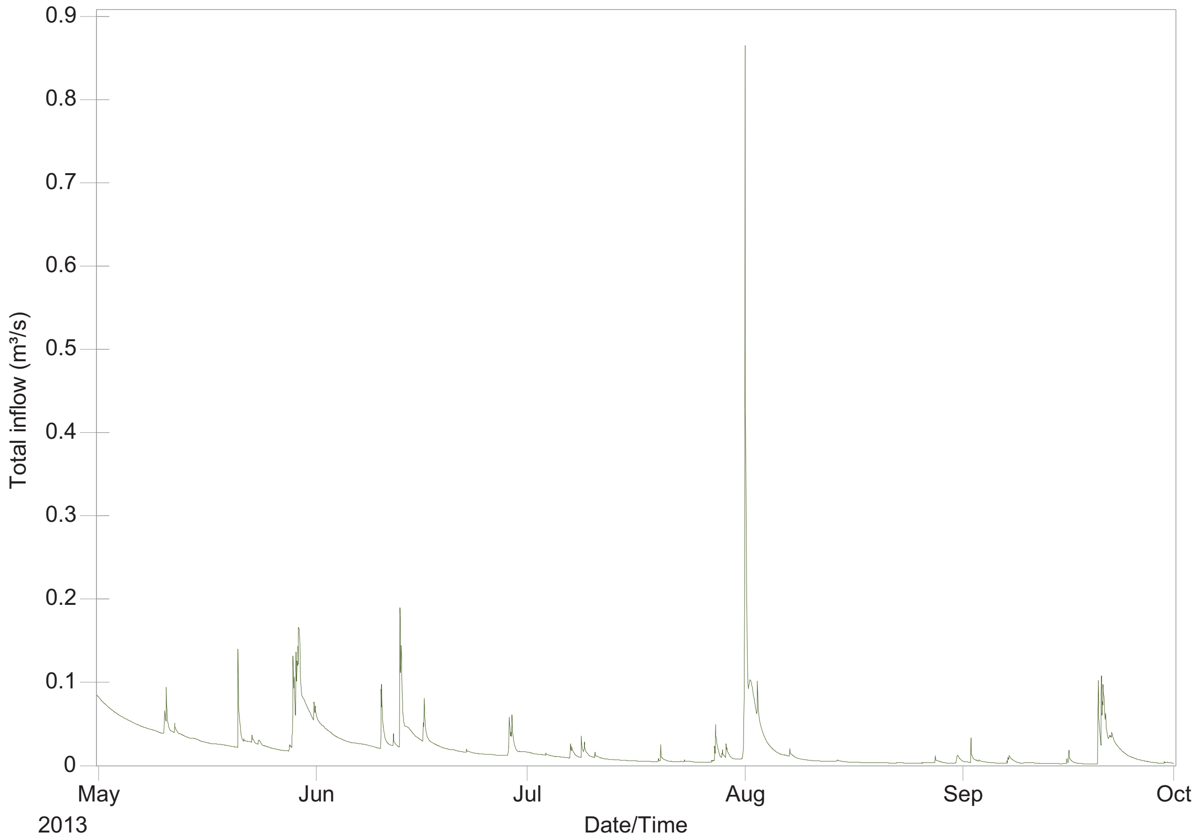


Figure 94: Bayfield North Hydrograph at Point of Interest 7, Outfall OF_GODF

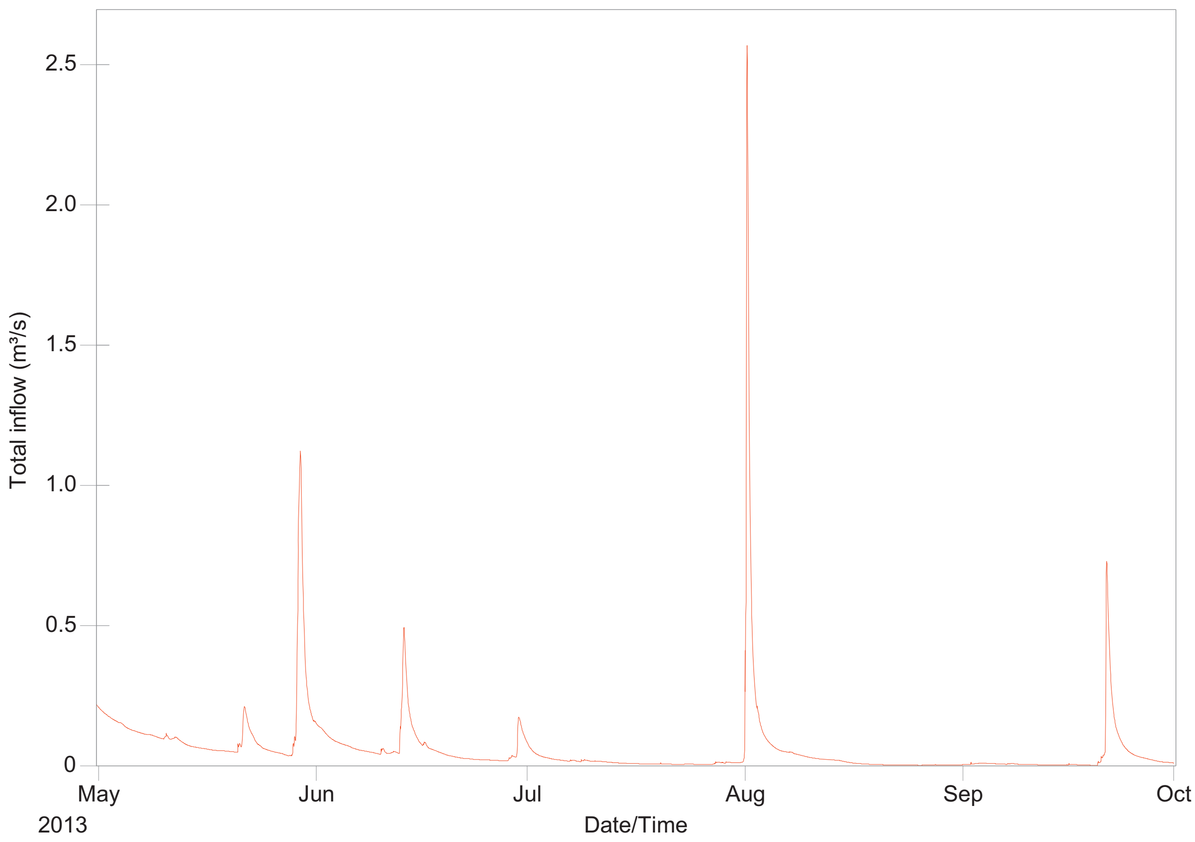


Figure 95: Bayfield North Hydrograph at Point of Interest 8, Outfall OF_GulyC

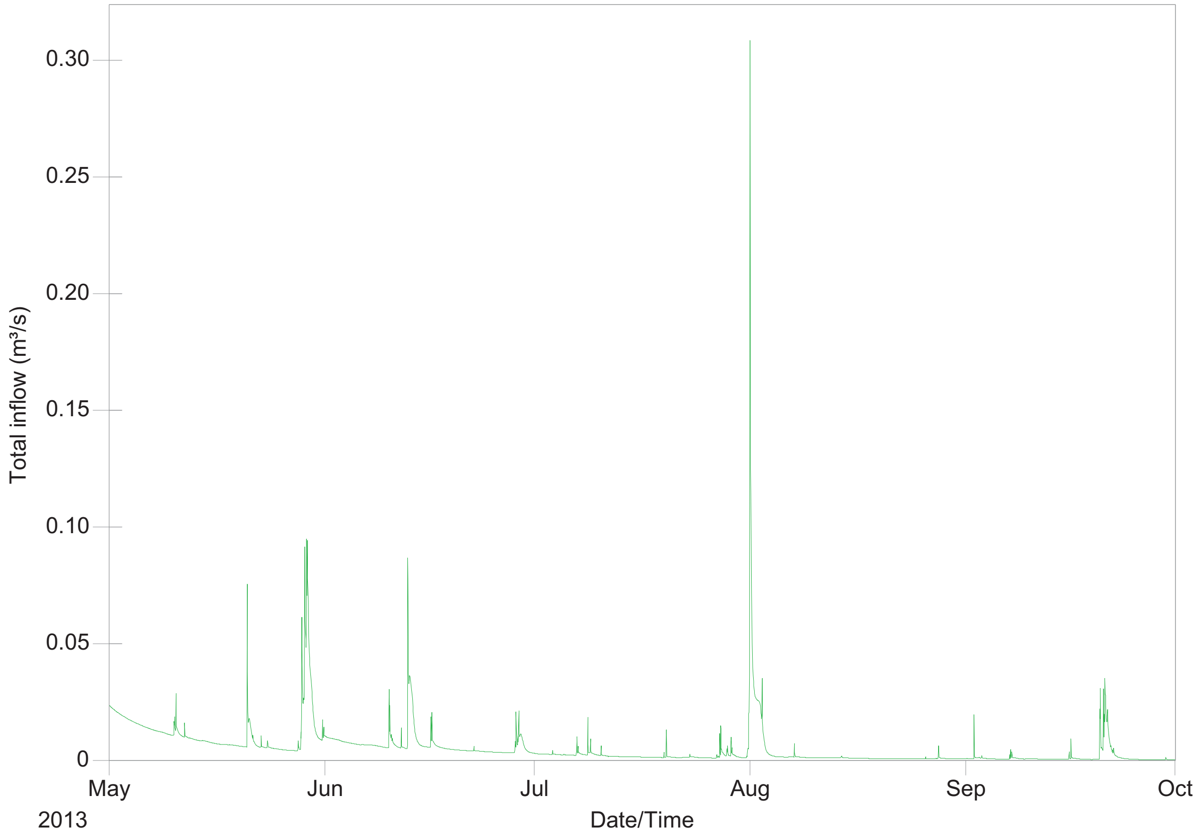


Figure 96: Bayfield North Hydrograph at Point of Interest 9, Outfall OF_GODD

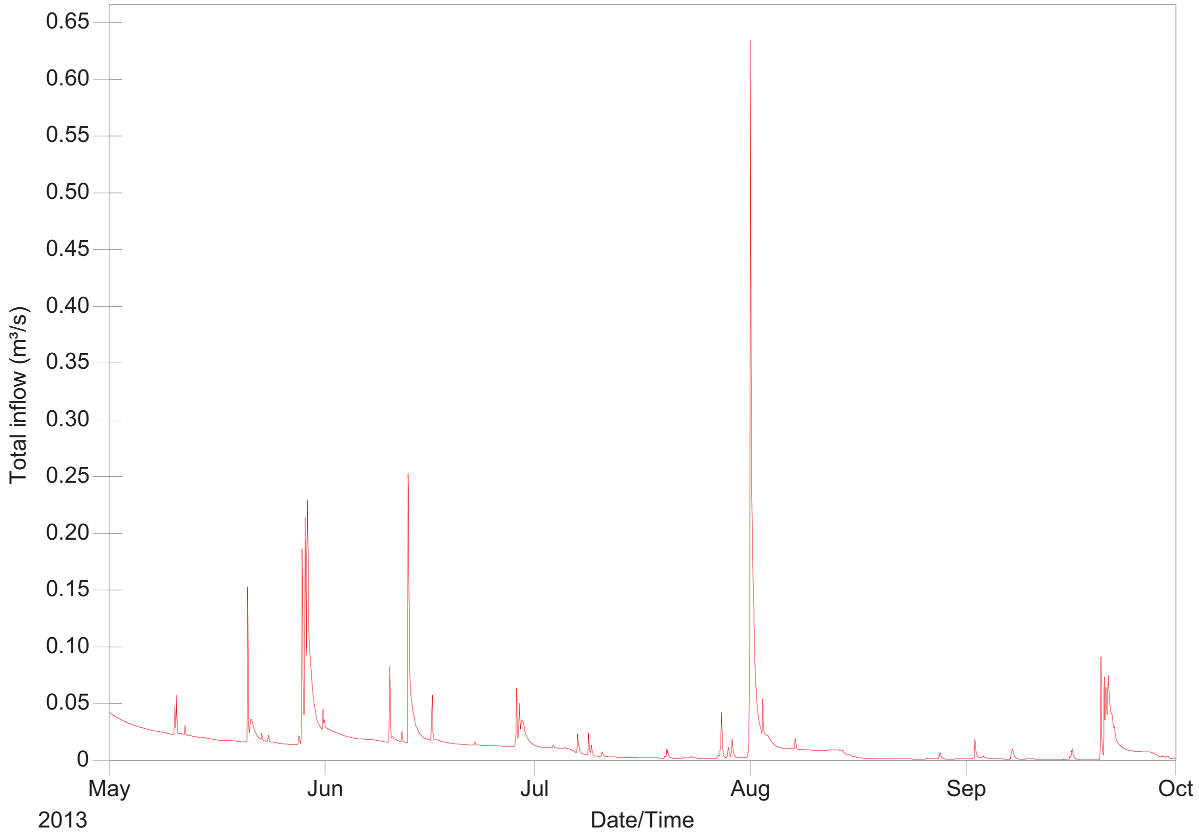


Figure 97: Bayfield North Hydrograph at Point of Interest 10, Outfall OF_GODA

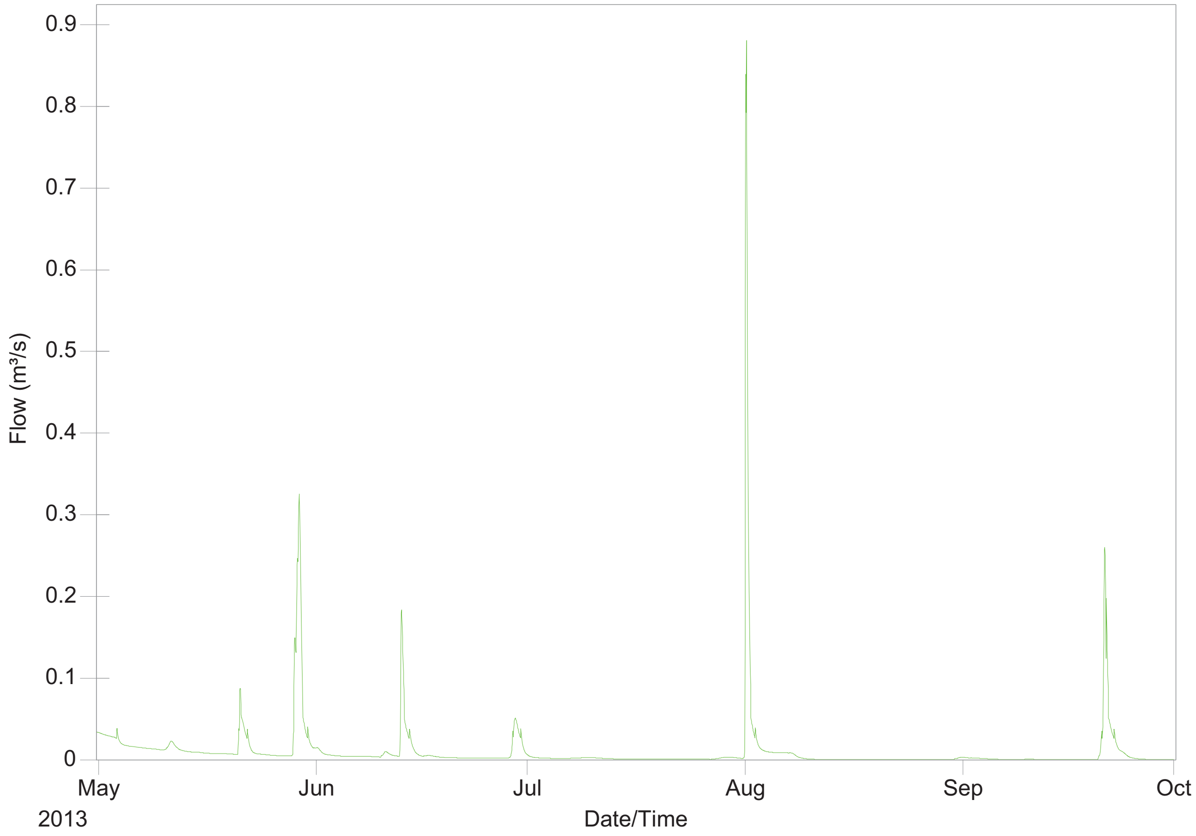


Figure 98: Bayfield North Hydrograph at Point of Interest 11, Culvert CH-G188

Appendix D.1.4 Main Bayfield

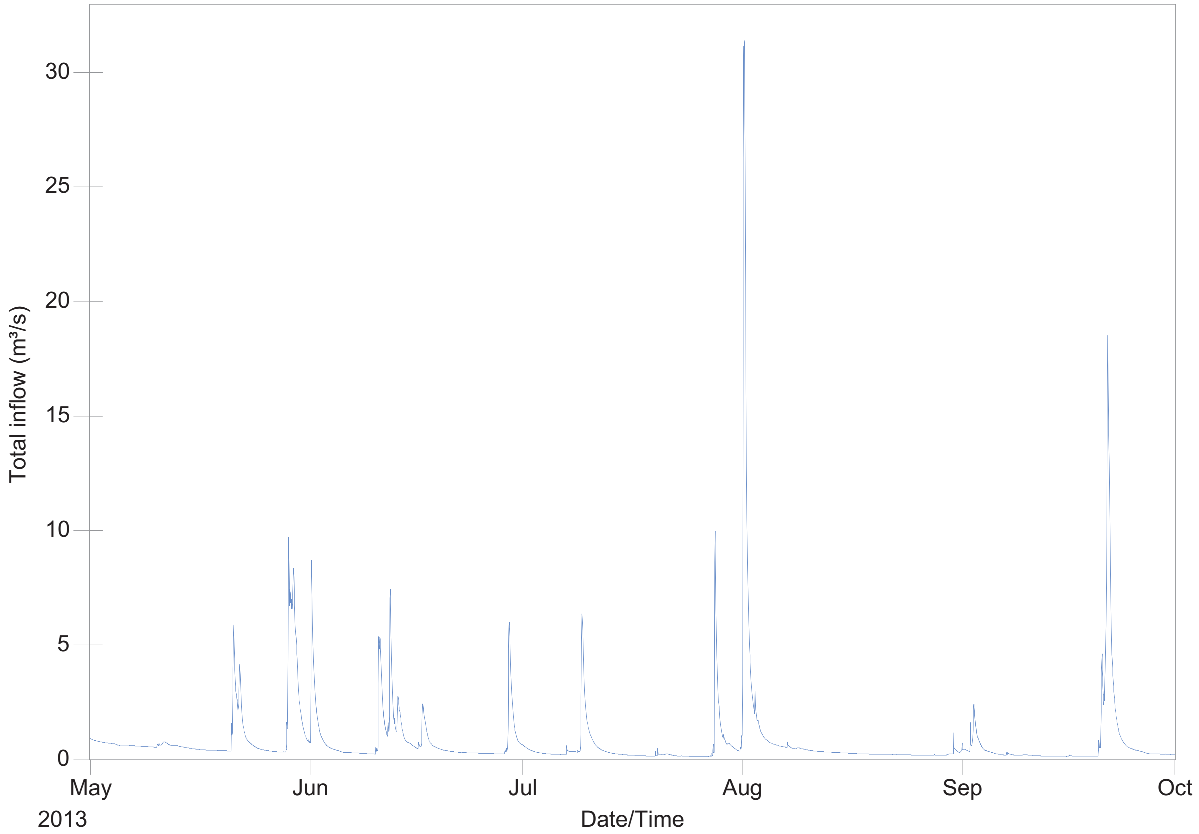


Figure 99: Main Bayfield Hydrograph at Point of Interest 1, Outfall OUT01-02

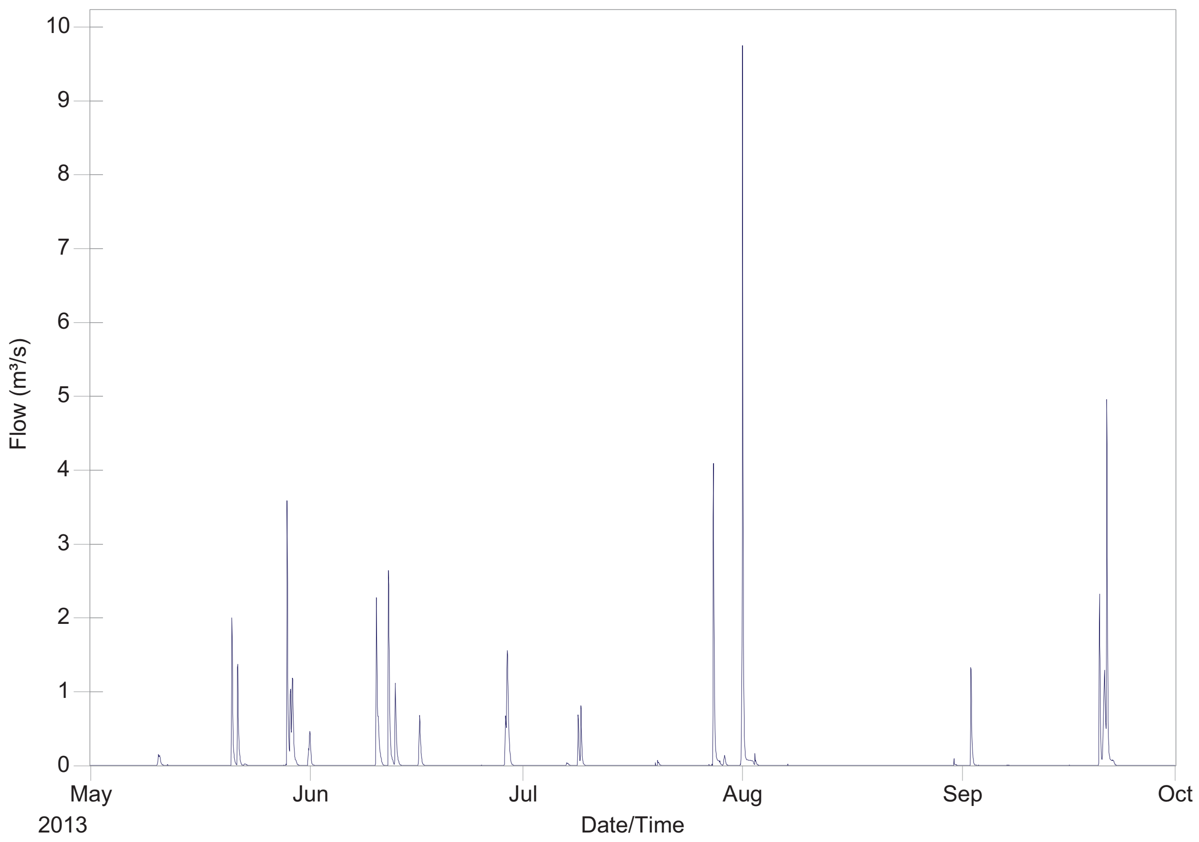


Figure 100: Main Bayfield Hydrograph at Point of Interest 2, Conduit BW-B82

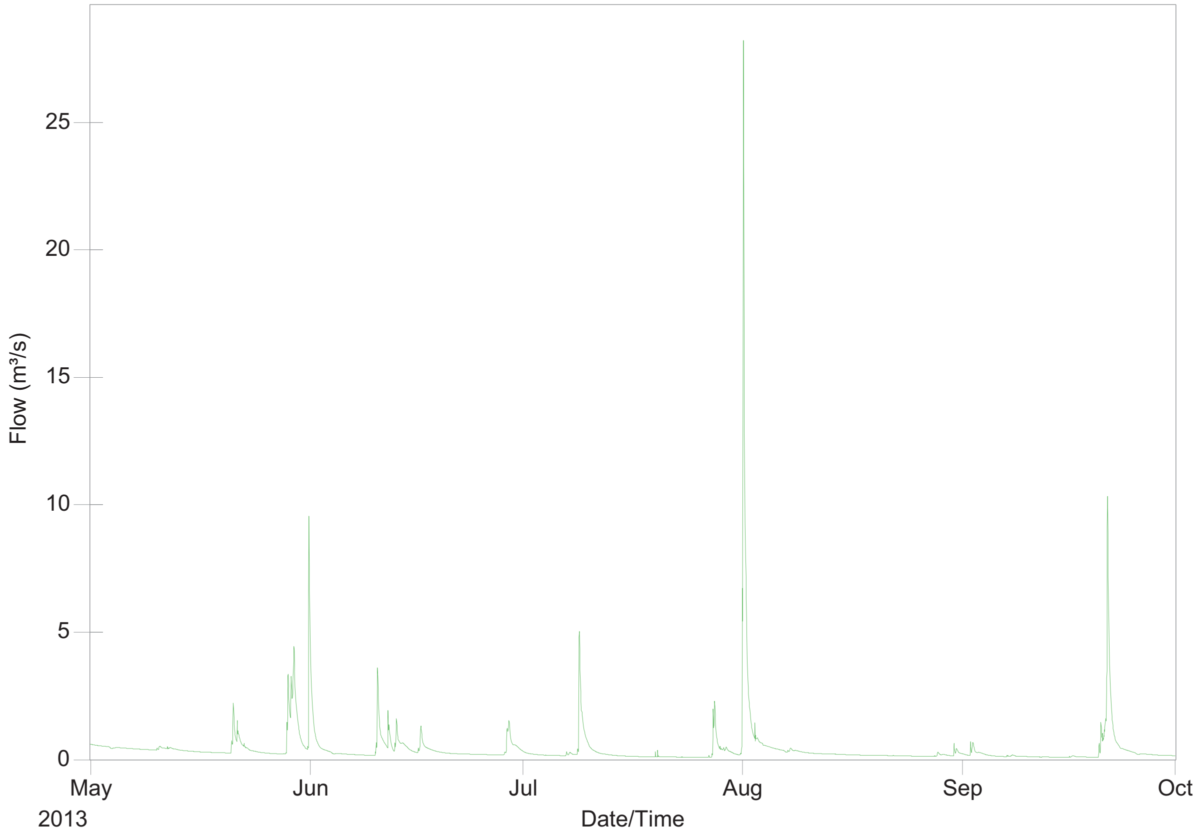


Figure 101: Main Bayfield Hydrograph at Point of Interest 3, Conduit BW-B80

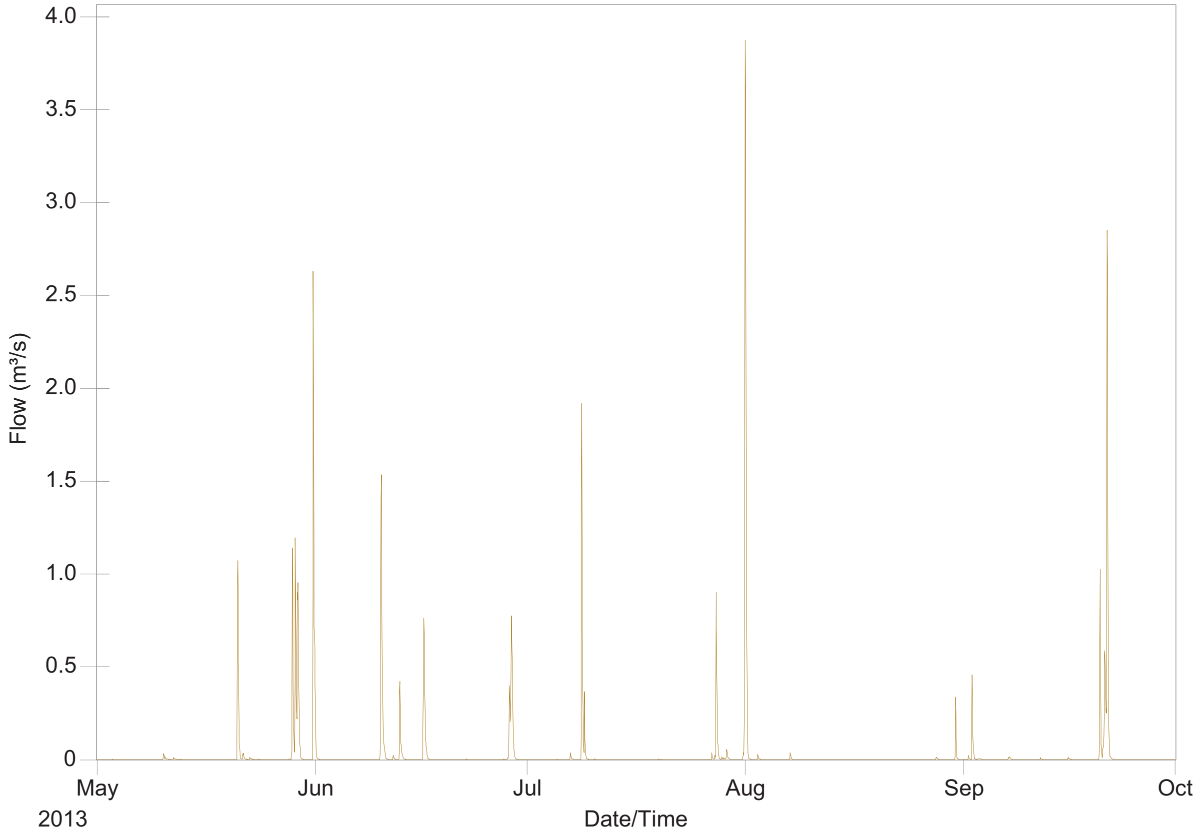


Figure 102: Main Bayfield Hydrograph at Point of Interest 4, Conduit CH-B76

Appendix D.1.5 Lambton Shores

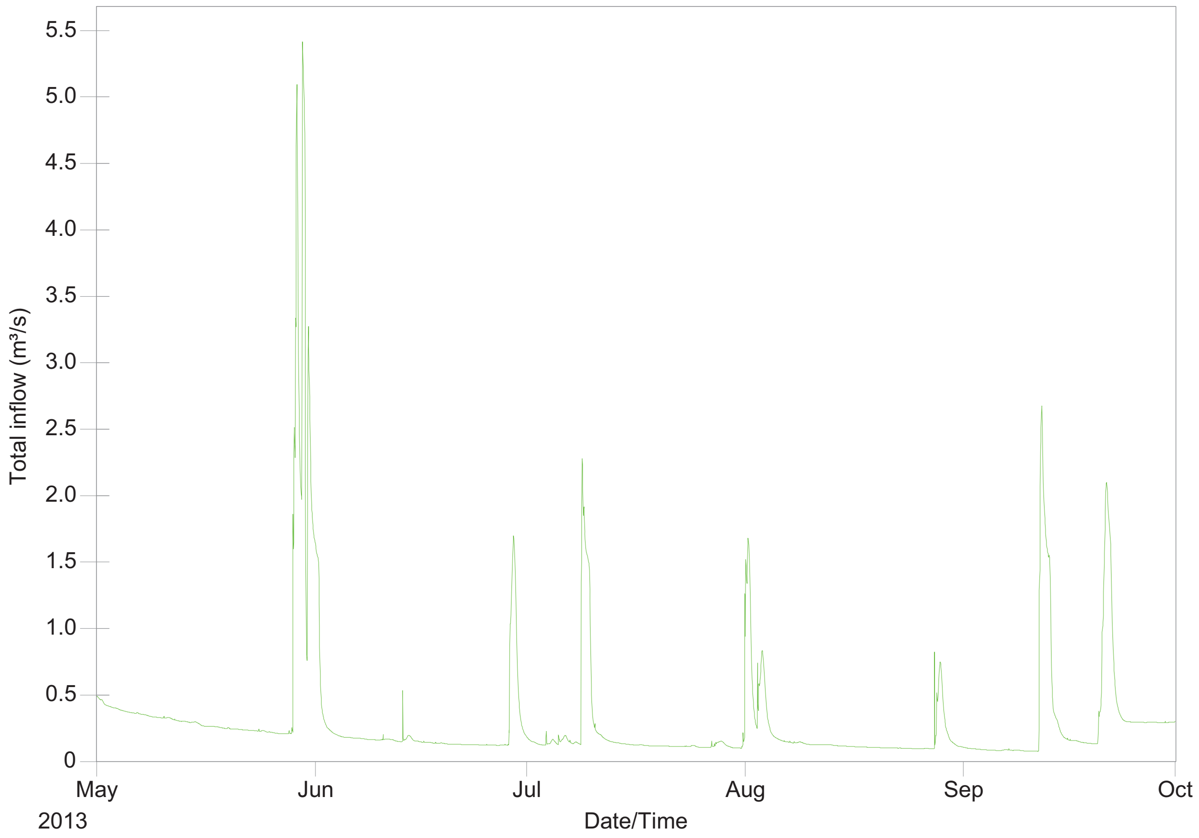


Figure 103: Lambton Shores Hydrograph at Point of Interest 1, Outfall J21-01O

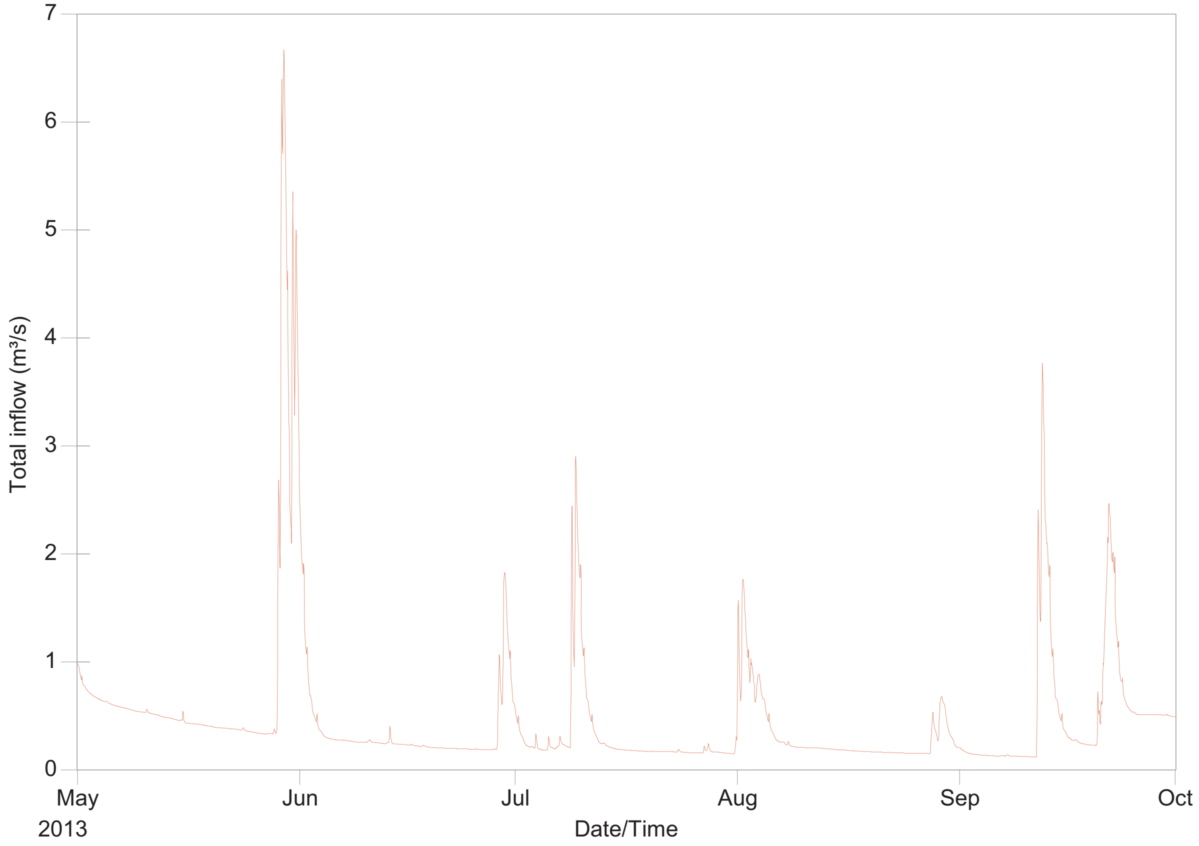


Figure 104: Lambton Shores Hydrograph at Point of Interest 2, Outfall J34-01O

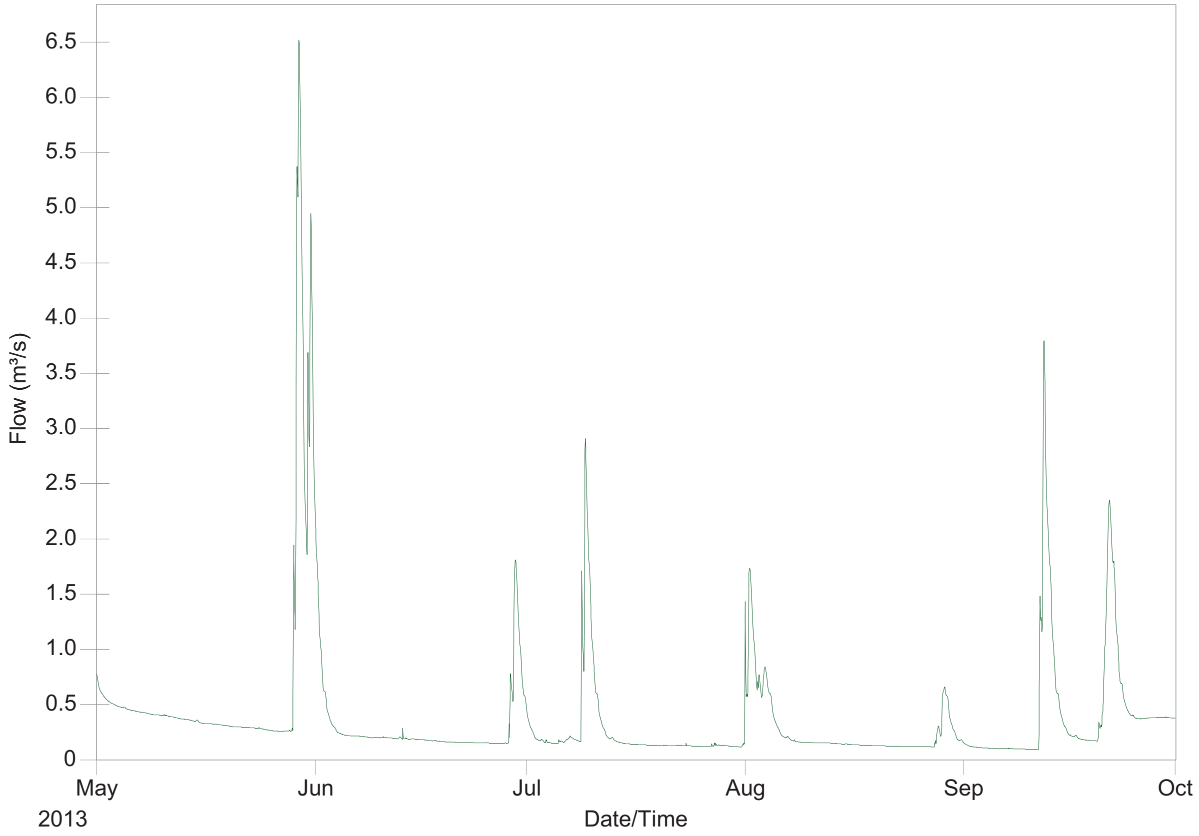


Figure 105: Lambton Shores Hydrograph at Point of Interest 3, Conduit C16

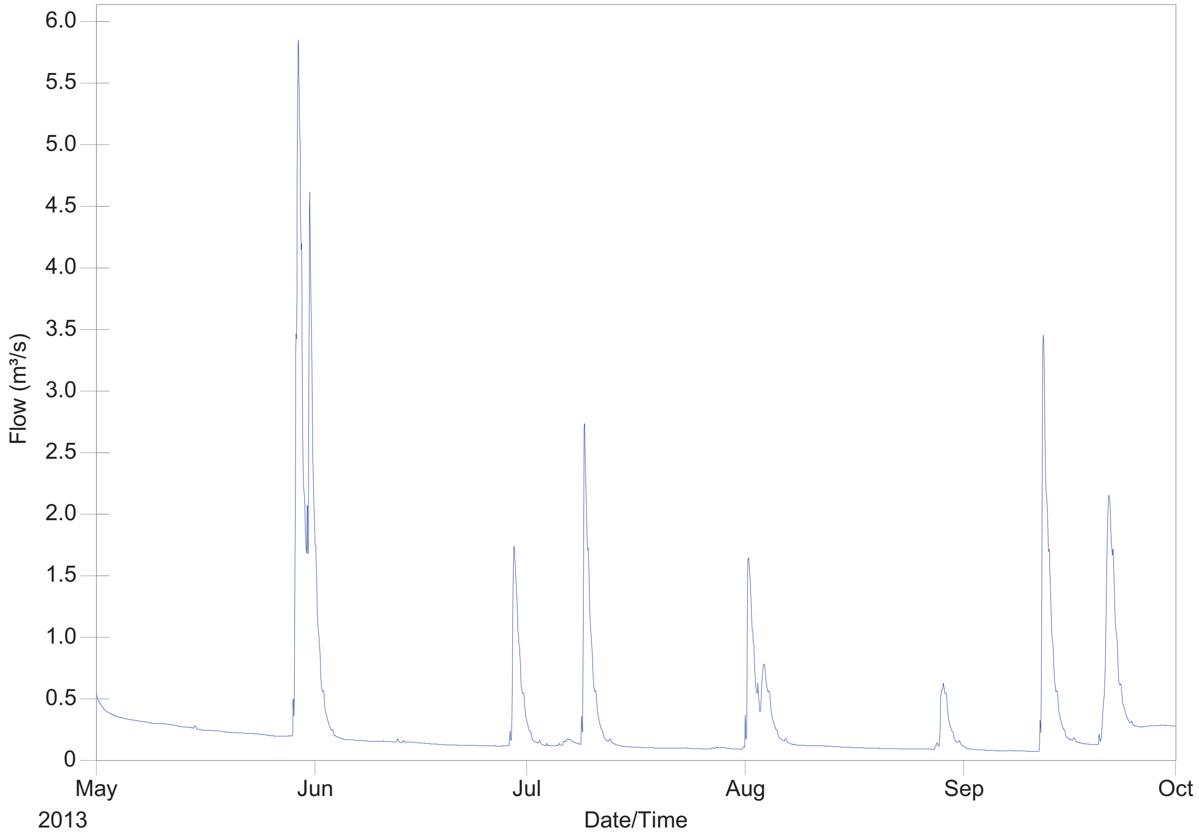


Figure 106: Lambton Shores Hydrograph at Point of Interest 4, Conduit C13

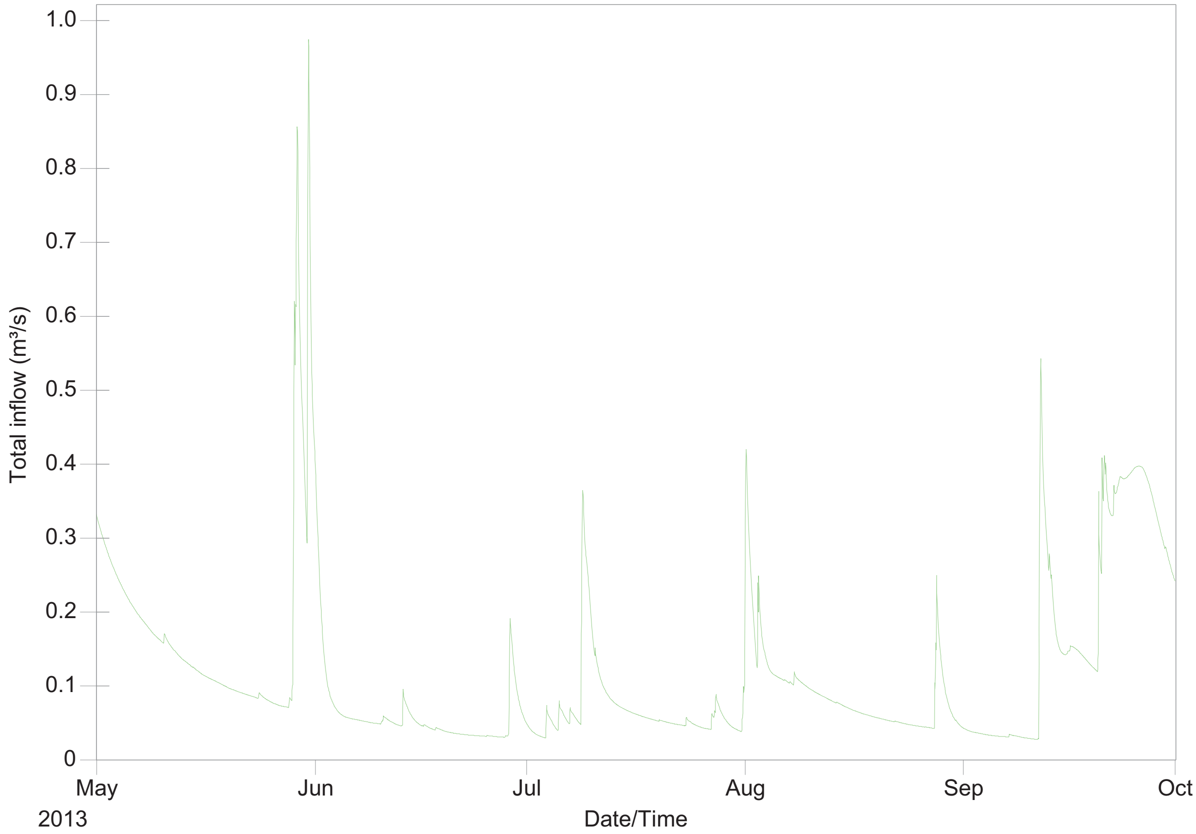


Figure 107: Lambton Shores Hydrograph at Point of Interest 6, Outfall J02-01O

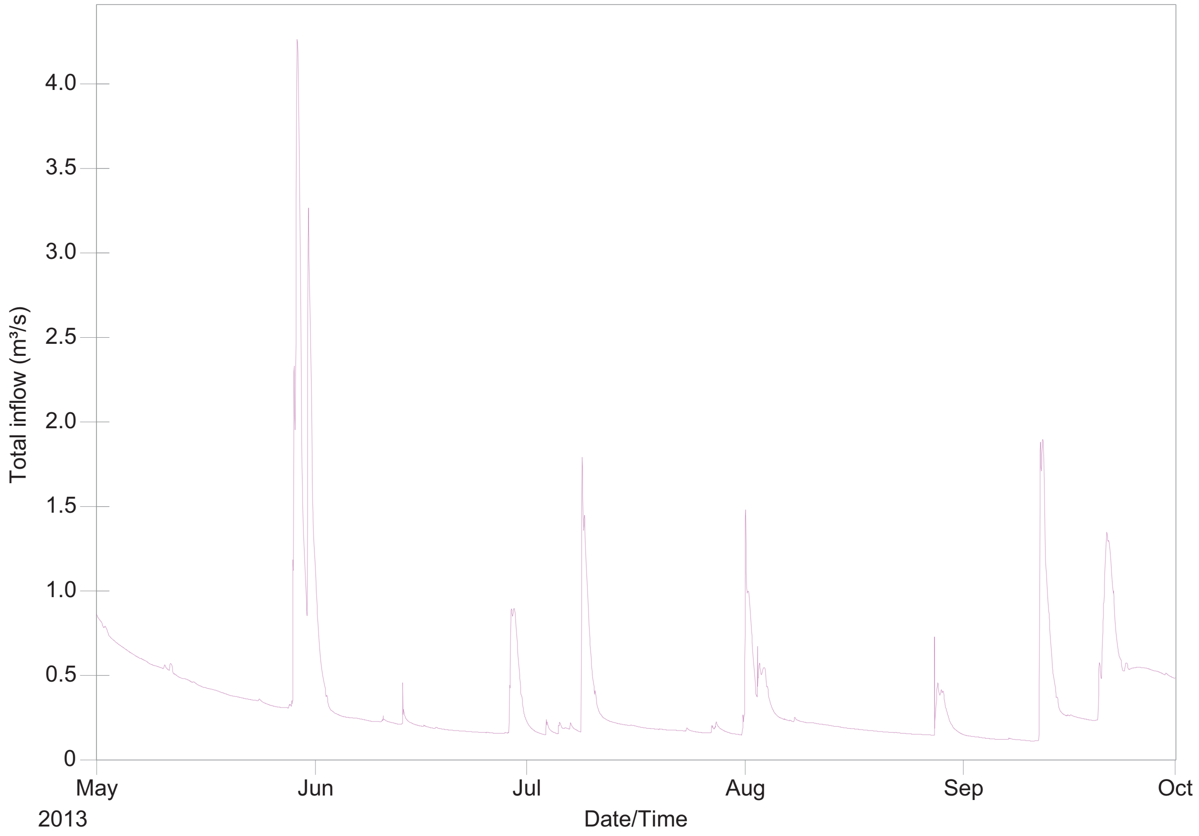


Figure 108: Lambton Shores Hydrograph at Point of Interest 7, Outfall J58-01O

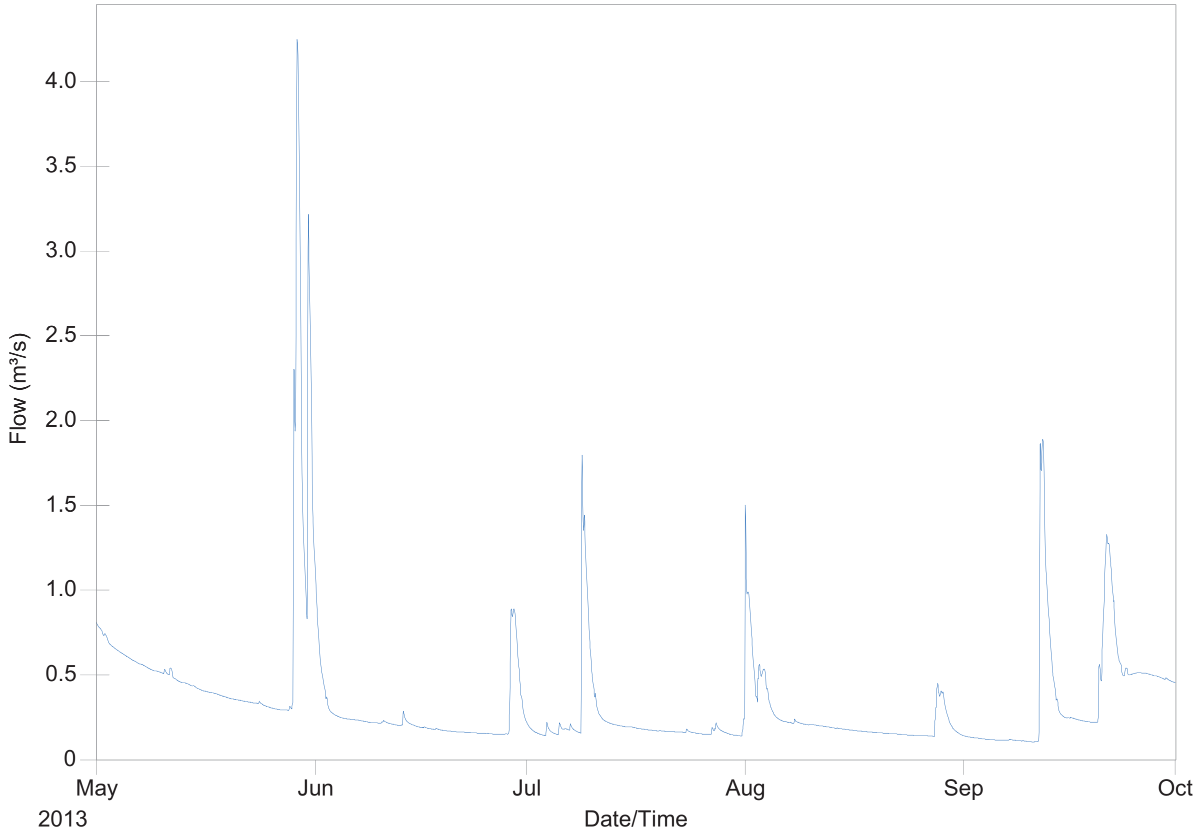


Figure 109: Lambton Shores Hydrograph at Point of Interest 8, Conduit A9

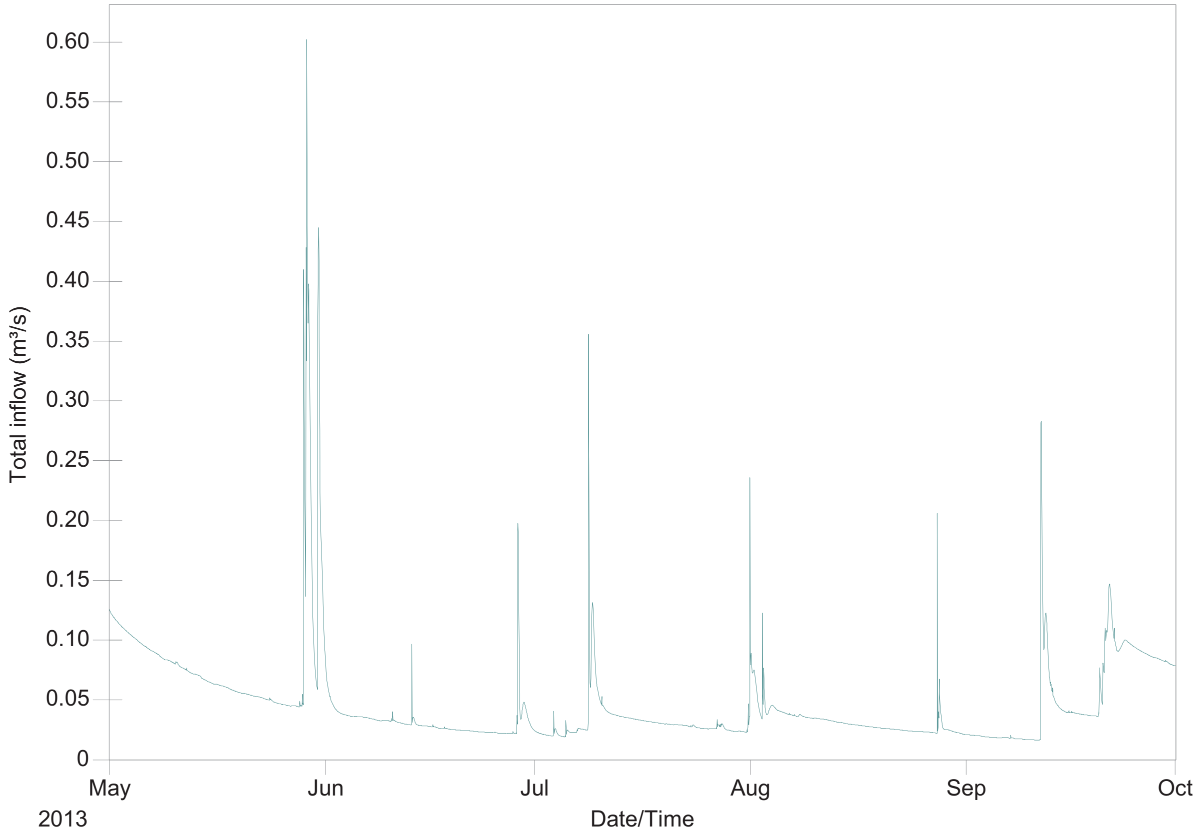


Figure 110: Lambton Shores Hydrograph at Point of Interest 9, Junction J62-01J

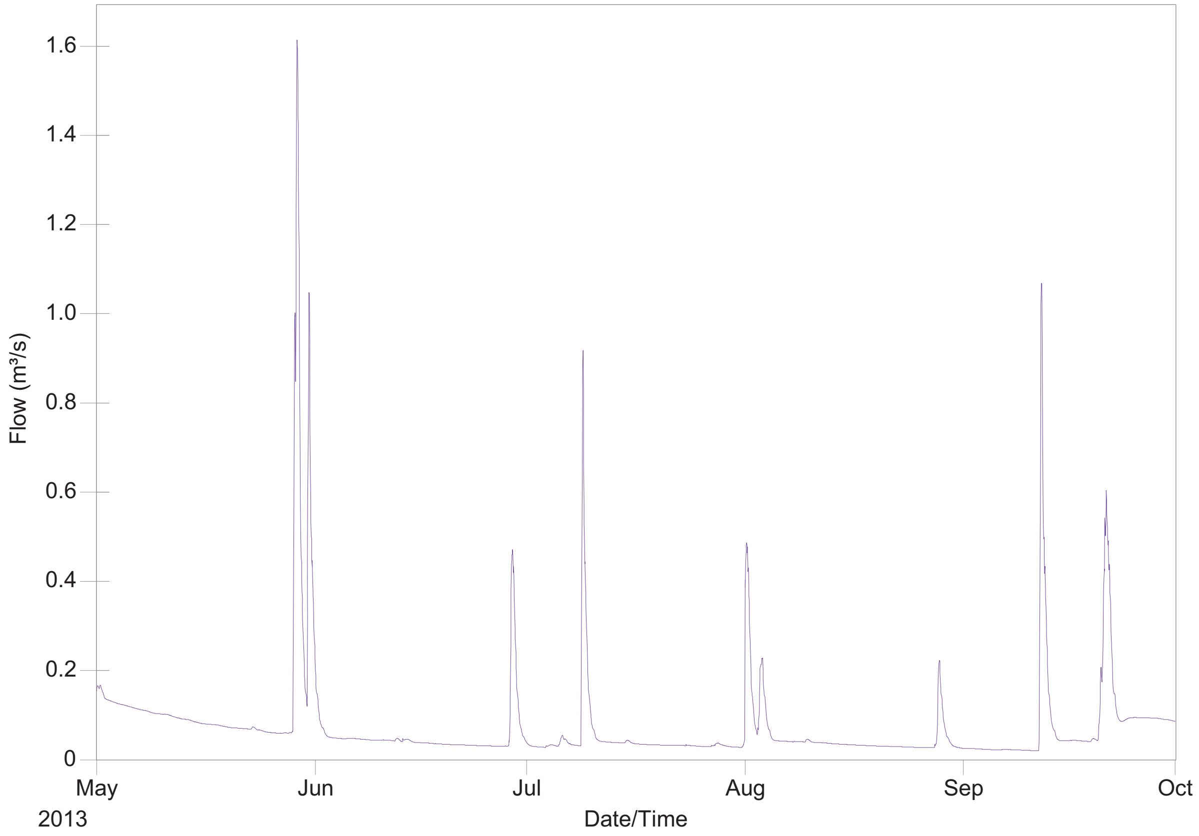


Figure 111: Lambton Shores Hydrograph at Point of Interest 10, Conduit A5

Appendix D.2 Pollutographs

Appendix D.2.1 Pine River

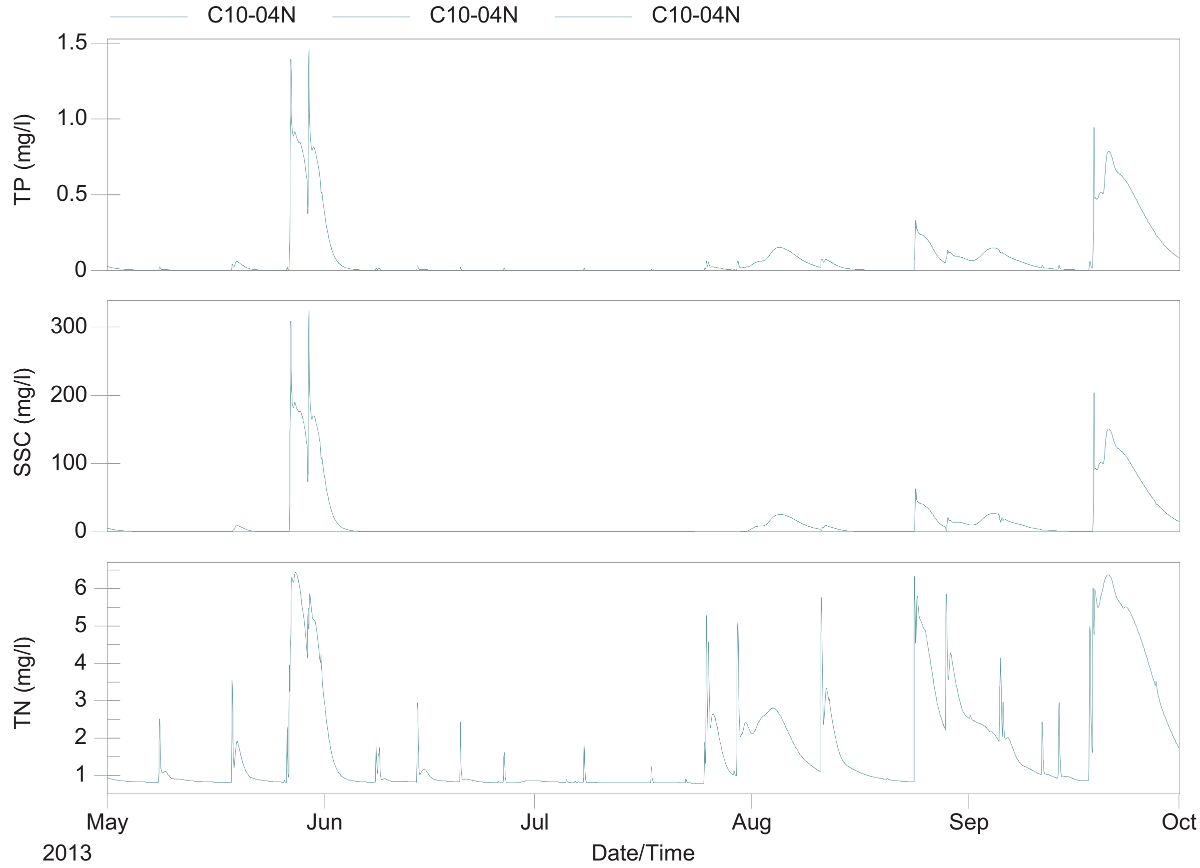


Figure 112: Pine River Pollutograph at Point of Interest 1, Outfall J10-03O

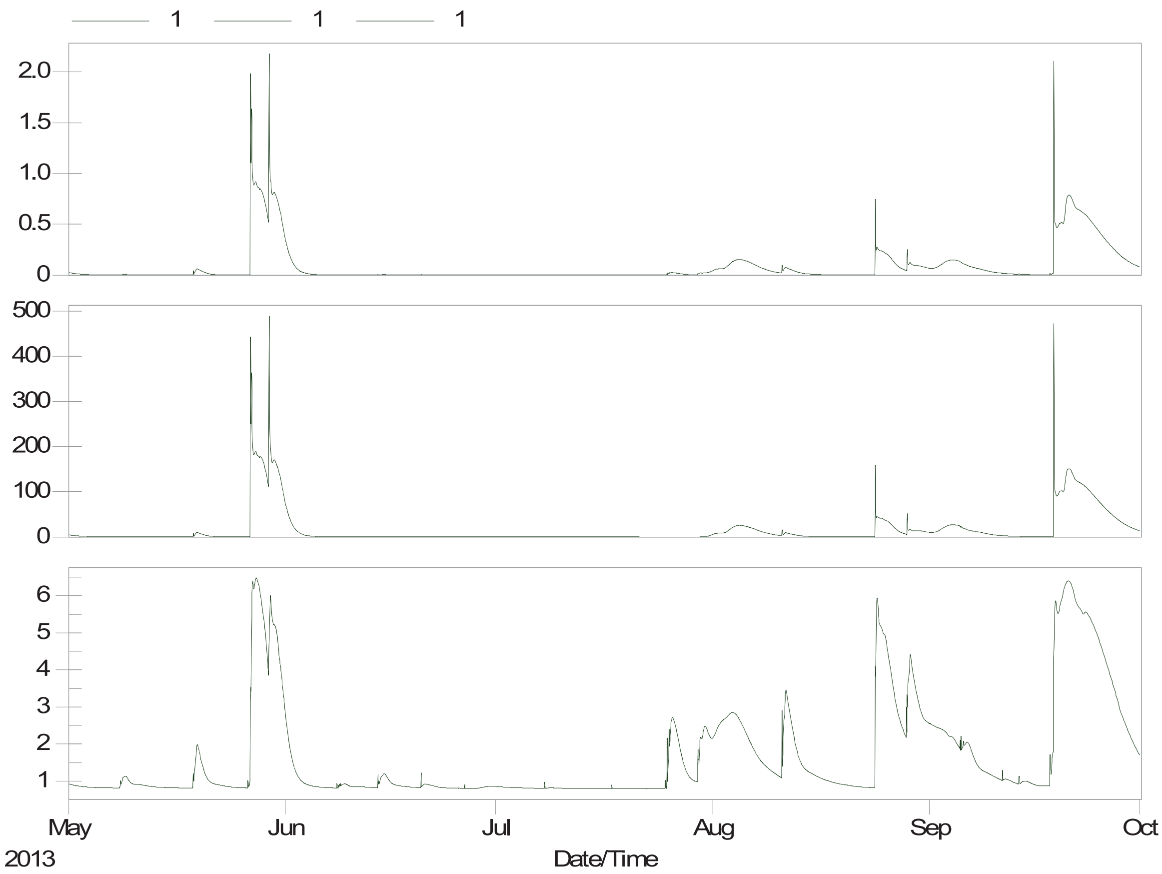


Figure 113: Pine River Pollutograph at Point of Interest 2, Conduit 1

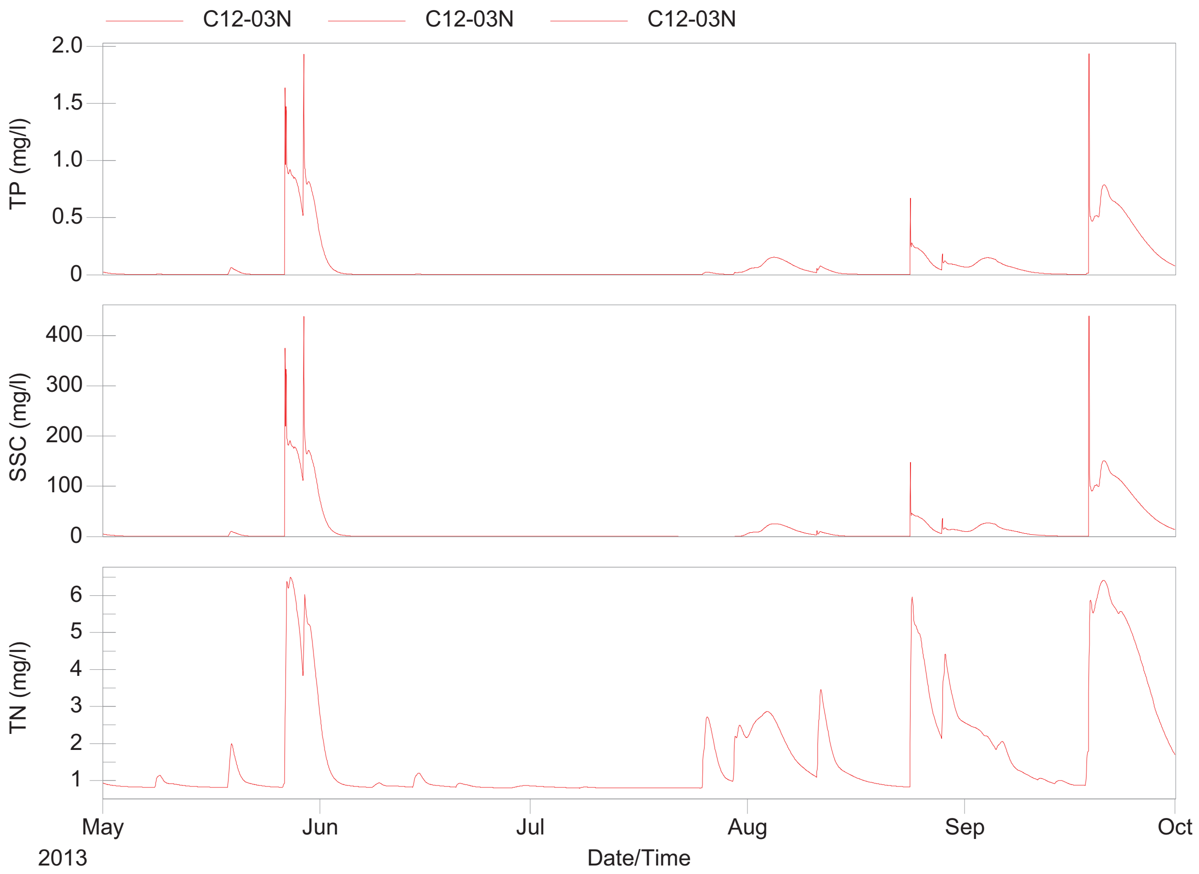


Figure 114: Pine River Pollutograph at Point of Interest 3, Junction J12-03J

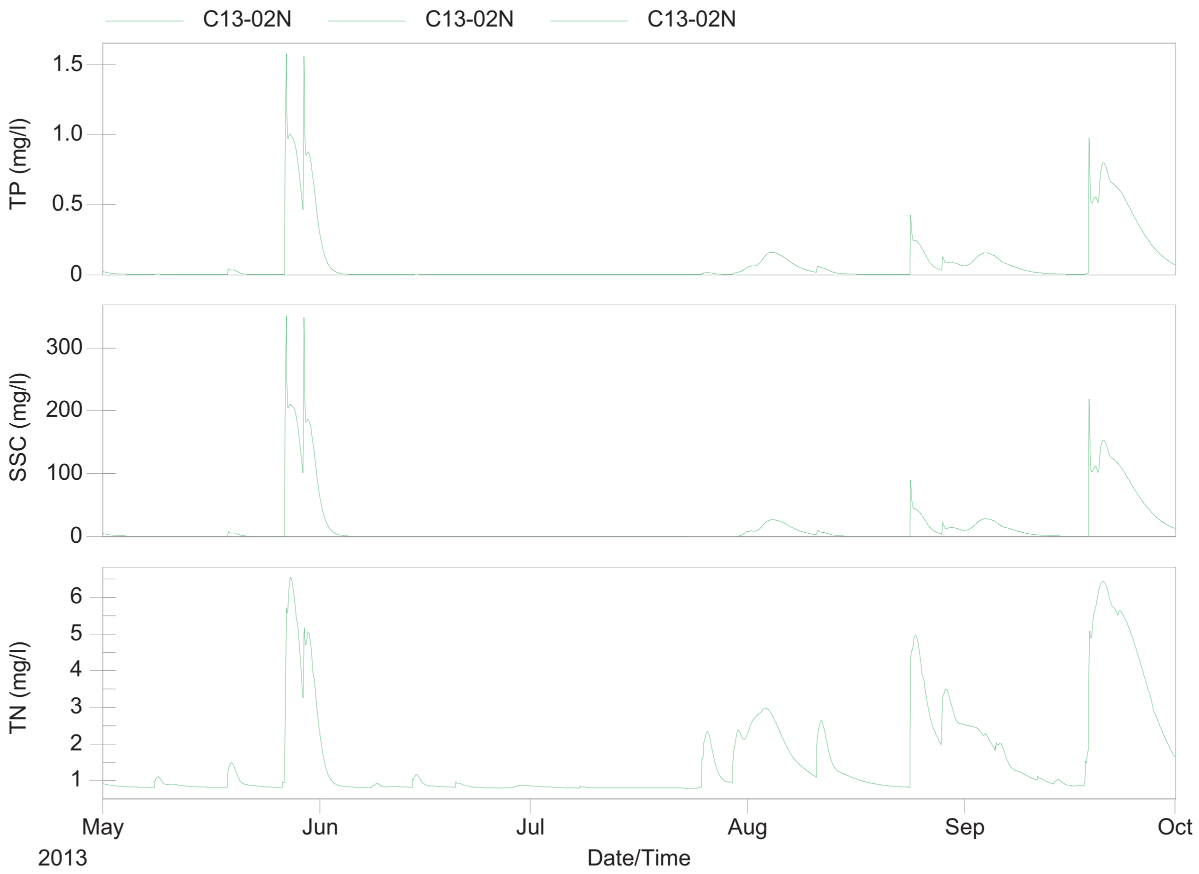


Figure 115: Pine River Pollutograph at Point of Interest 4, Junction J13-02J

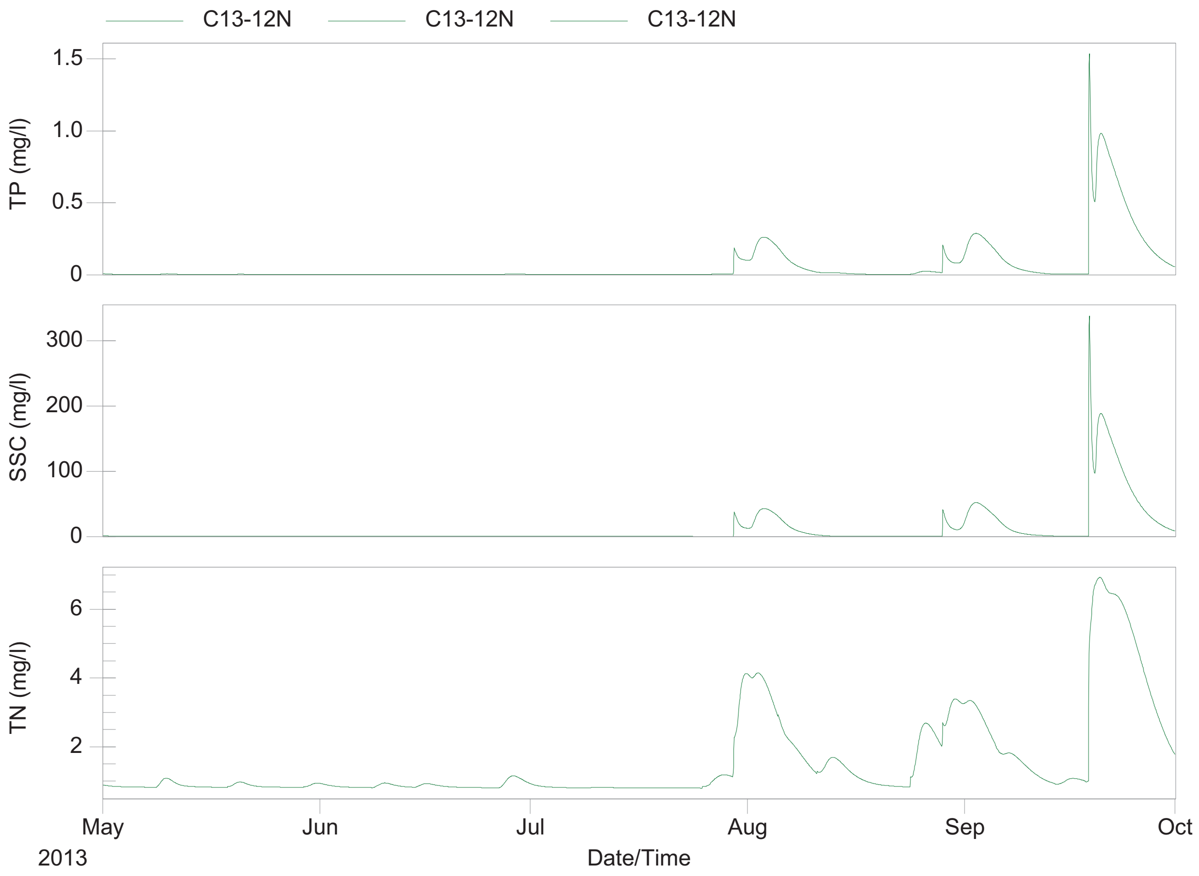


Figure 116: Pine River Pollutograph at Point of Interest 5, Junction J13-12J

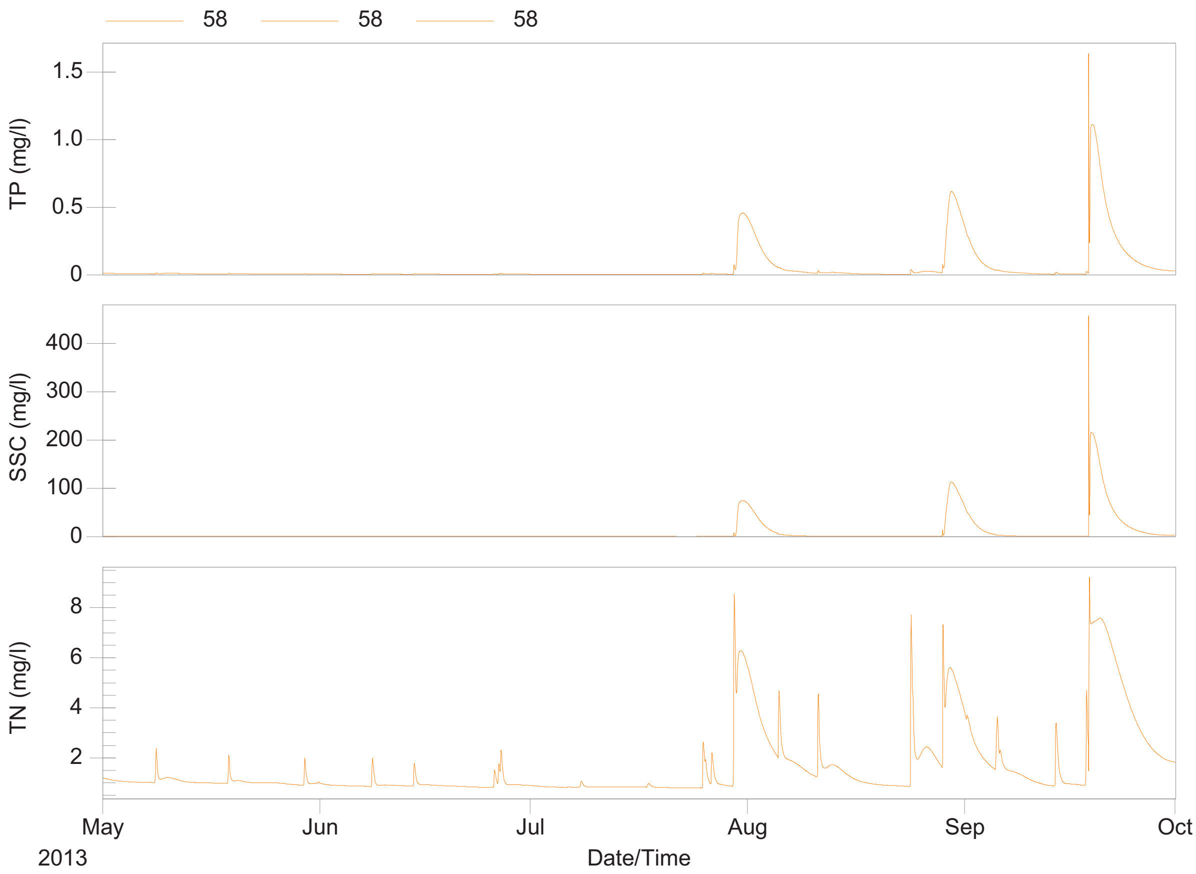


Figure 117: Pine River Pollutograph at Point of Interest 6, Conduit 58

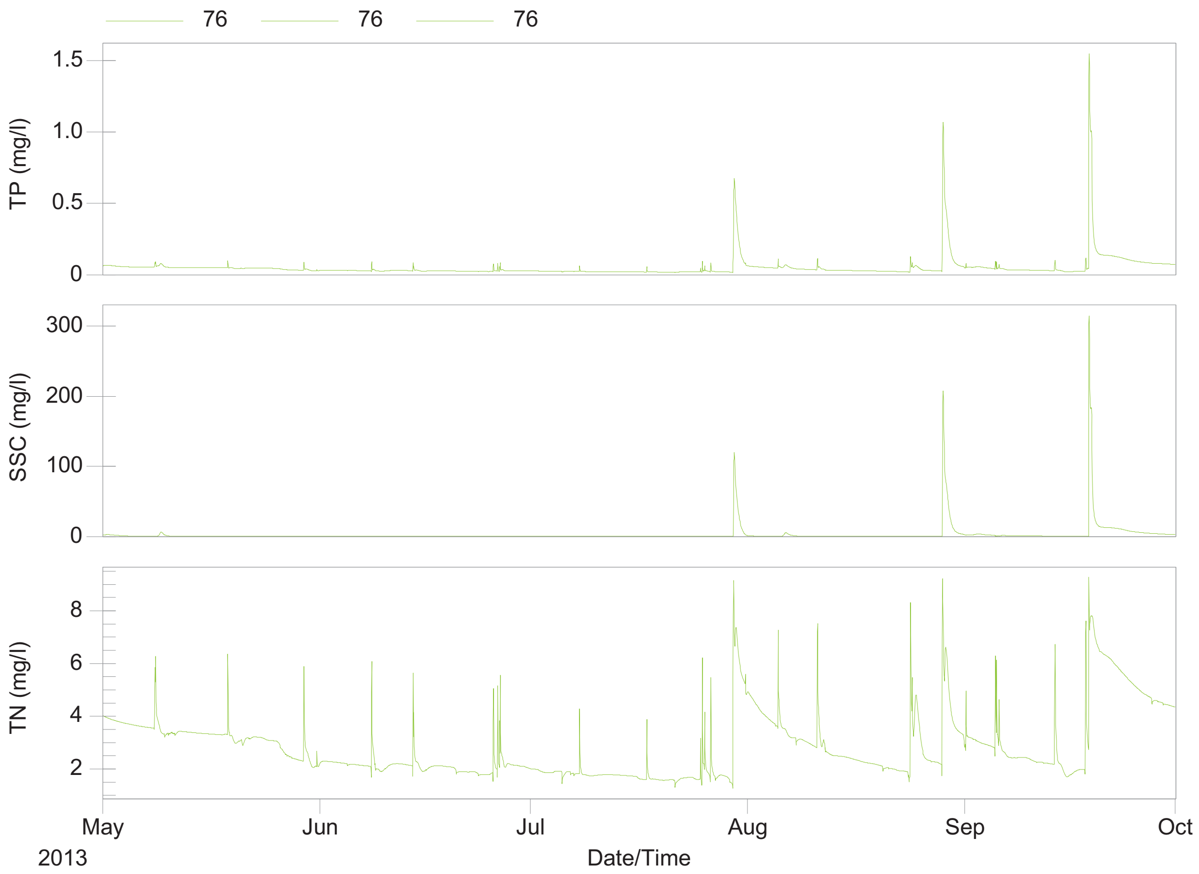


Figure 118: Pine River Pollutograph at Point of Interest 7, Conduit 76

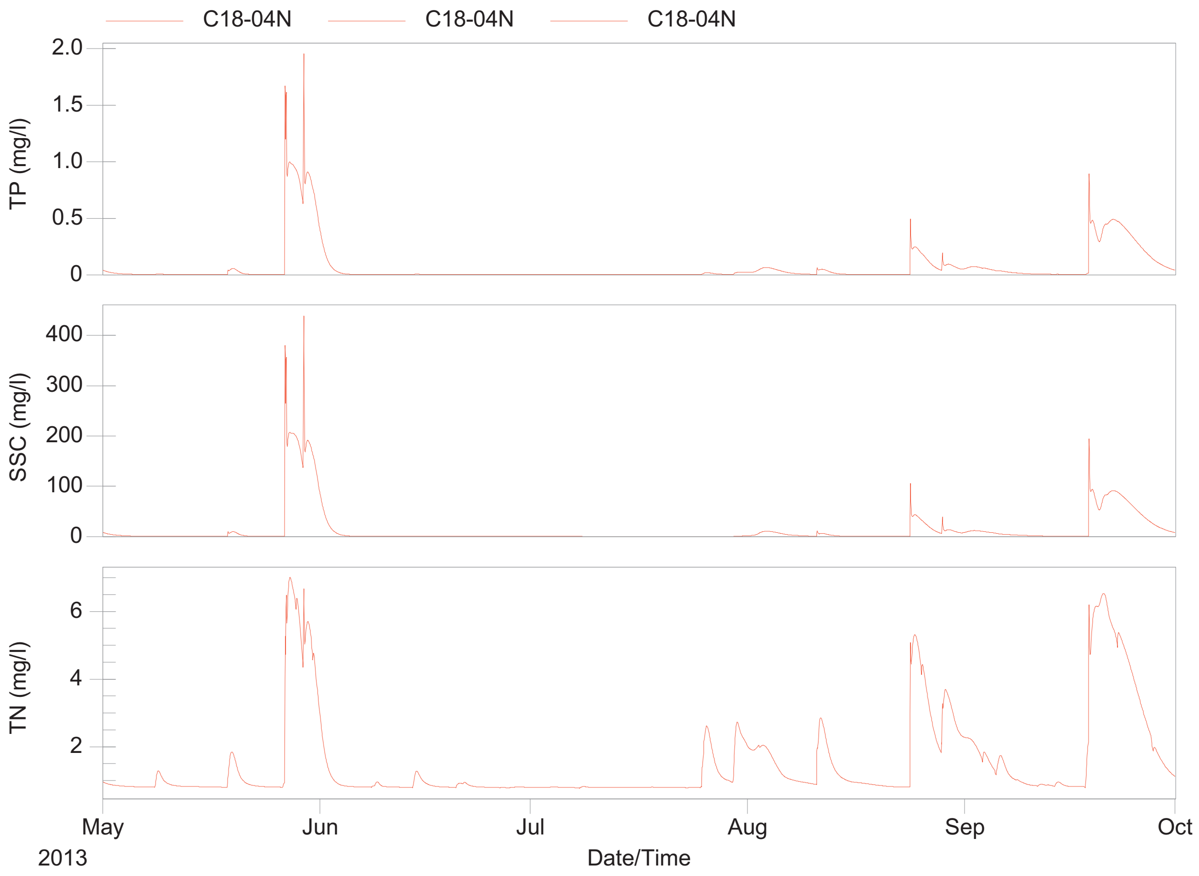


Figure 119: Pine River Pollutograph at Point of Interest 8, Junction J18-04J

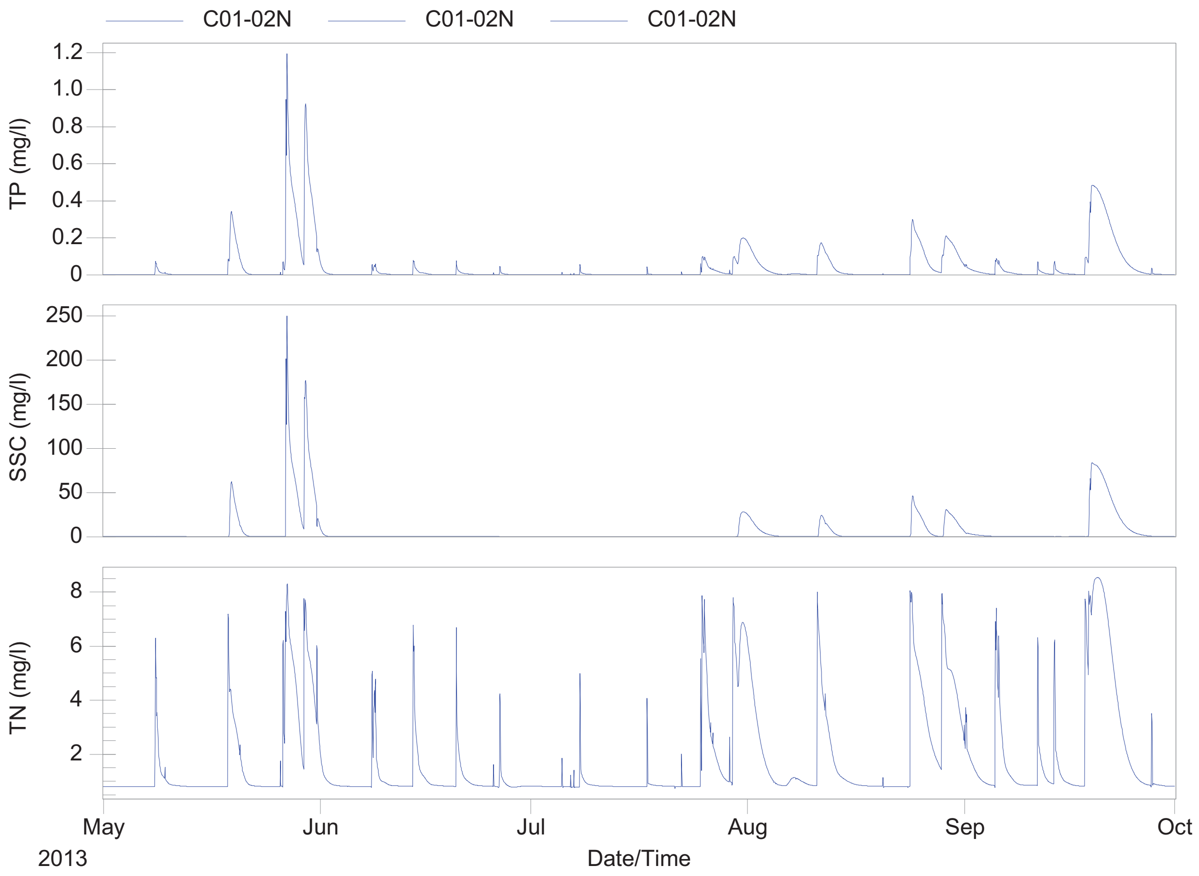


Figure 120: Pine River Pollutograph at Point of Interest 9, Junction J01-010

Appendix D.2.2 Garvey-Glenn

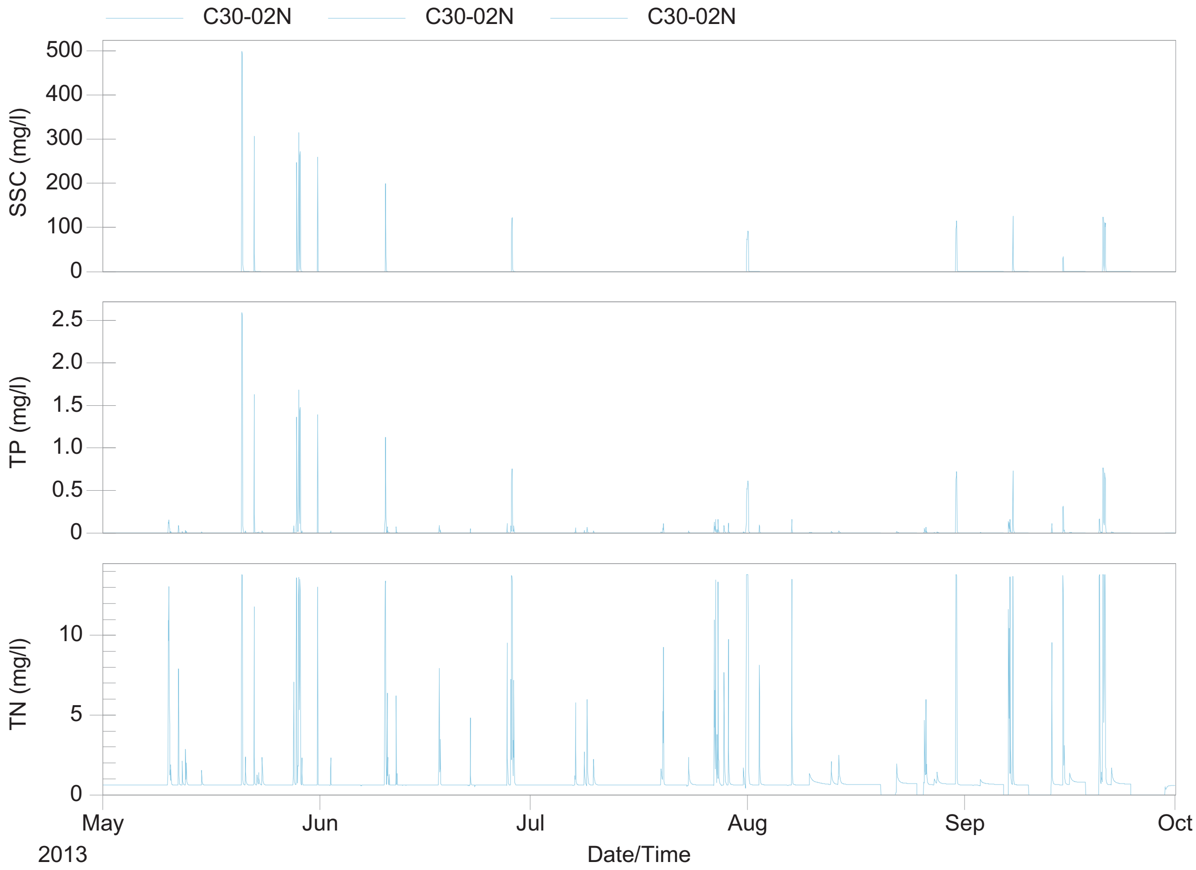


Figure 121: Garvey-Glenn Pollutograph at Point of Interest 1, Outfall JUN30-01O

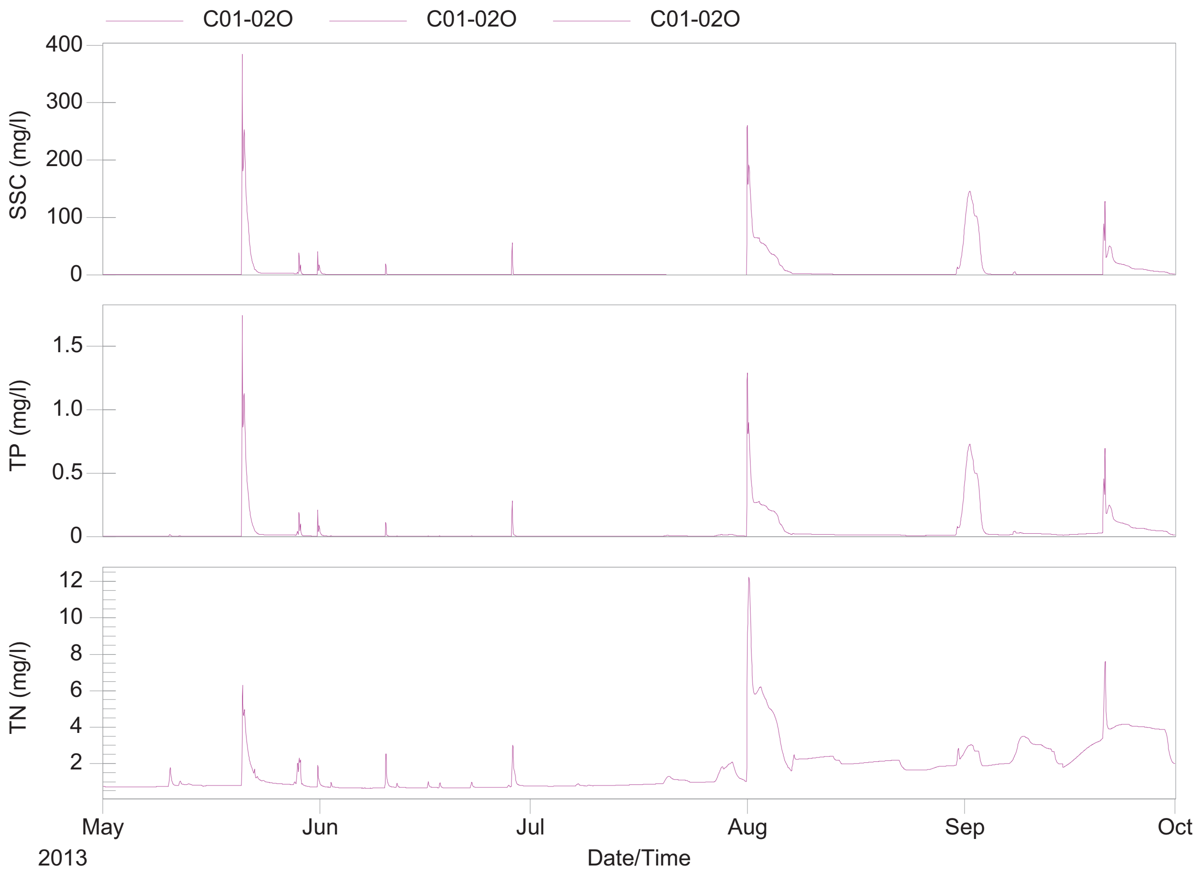


Figure 122: Garvey-Glenn Pollutograph at Point of Interest 2, Outfall JUN01-01O

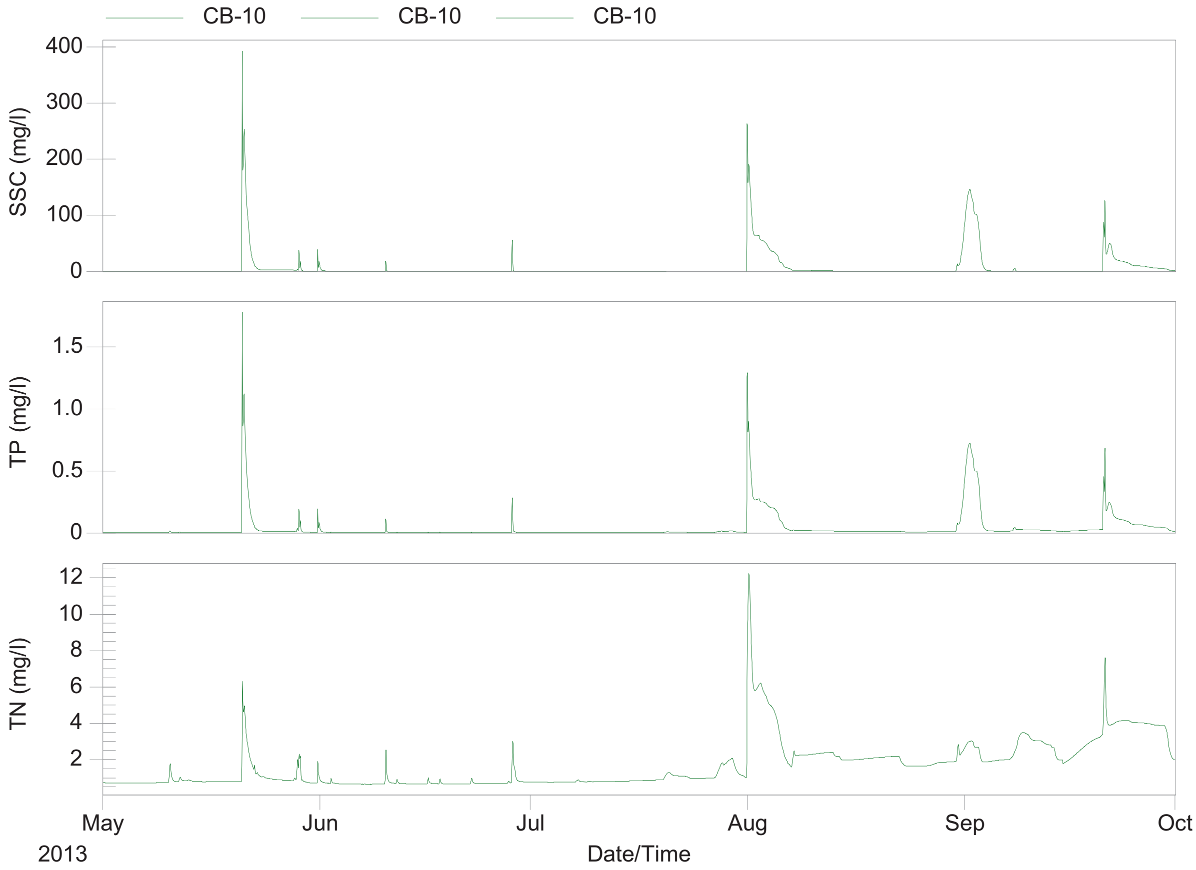


Figure 123: Garvey-Glenn Pollutograph at Point of Interest 3, Conduit CB-10

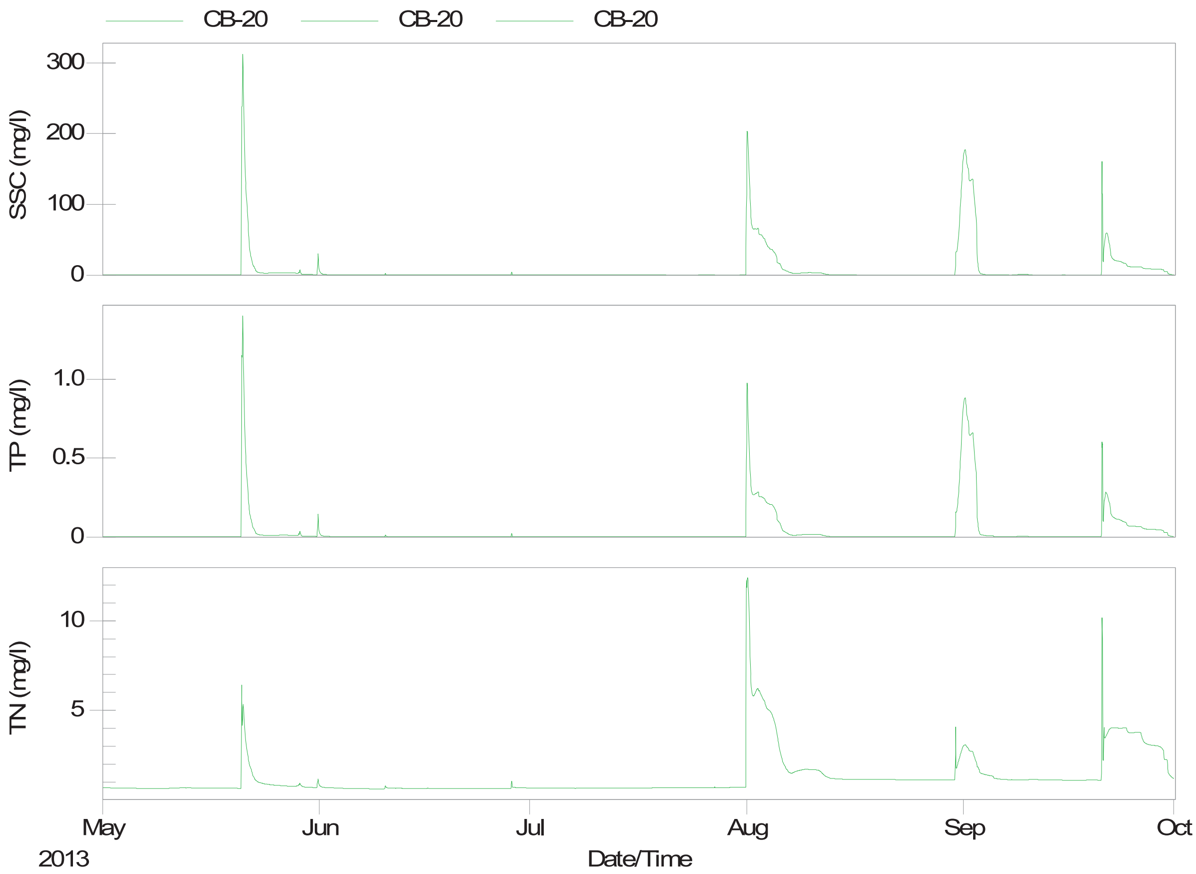


Figure 124: Garvey-Glenn Pollutograph at Point of Interest 4, Conduit CB-20

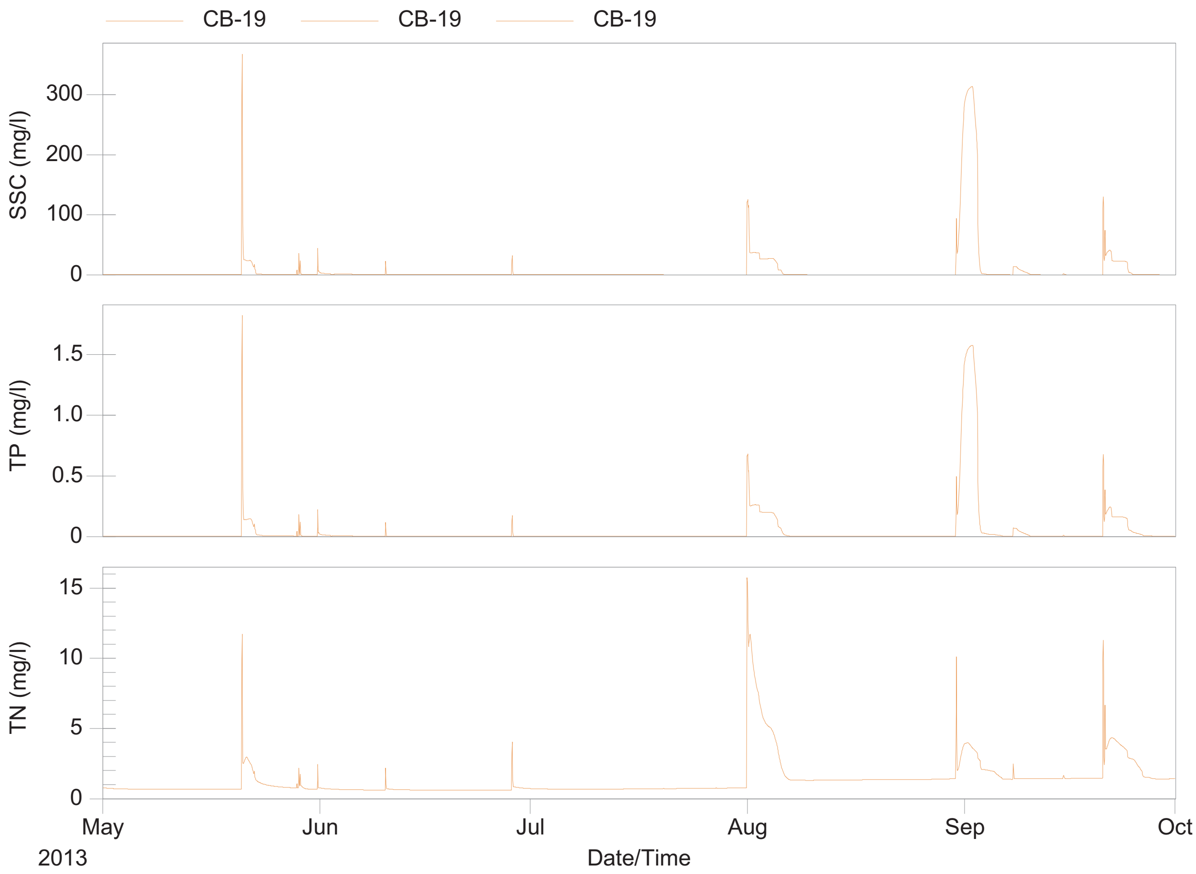


Figure 125: Garvey-Glenn Pollutograph at Point of Interest 5, Conduit CB-19

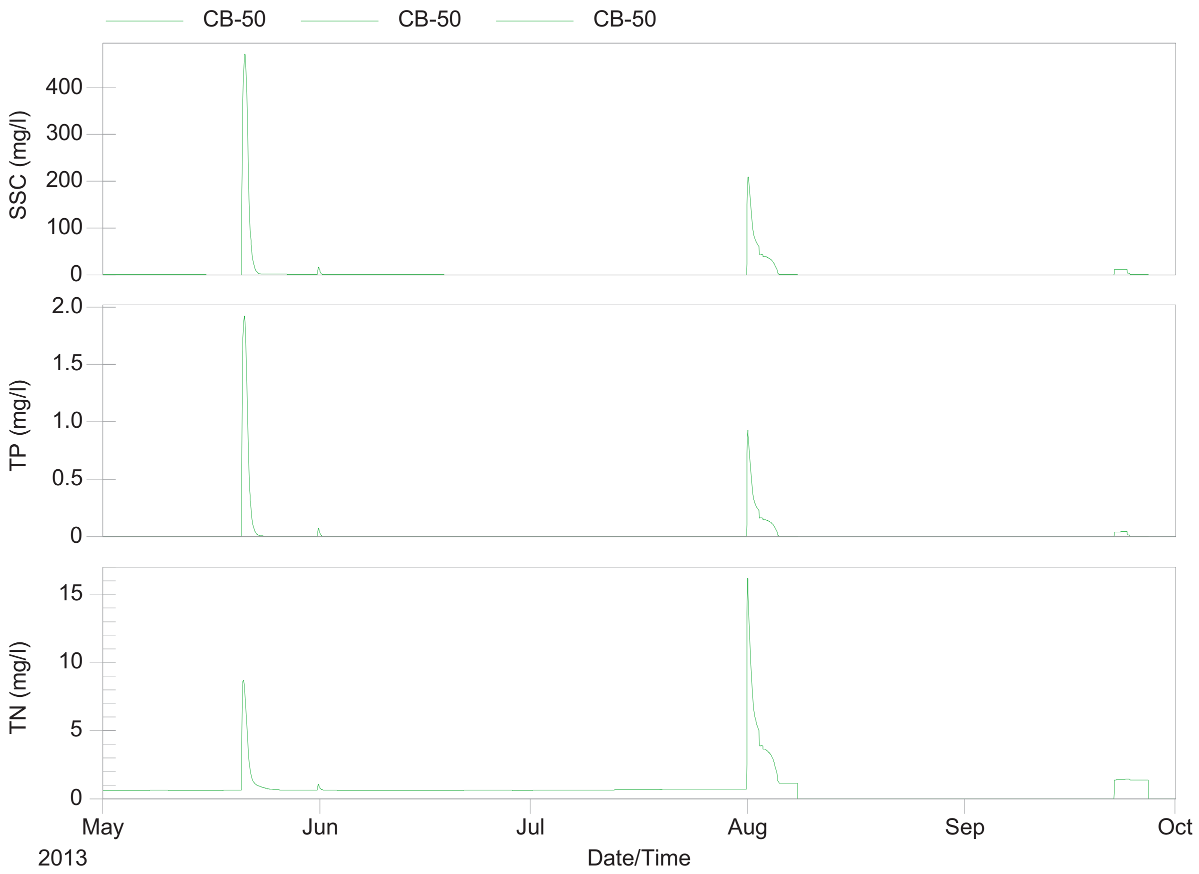


Figure 126: Garvey-Glenn Pollutograph at Point of Interest 6, Conduit CB-50

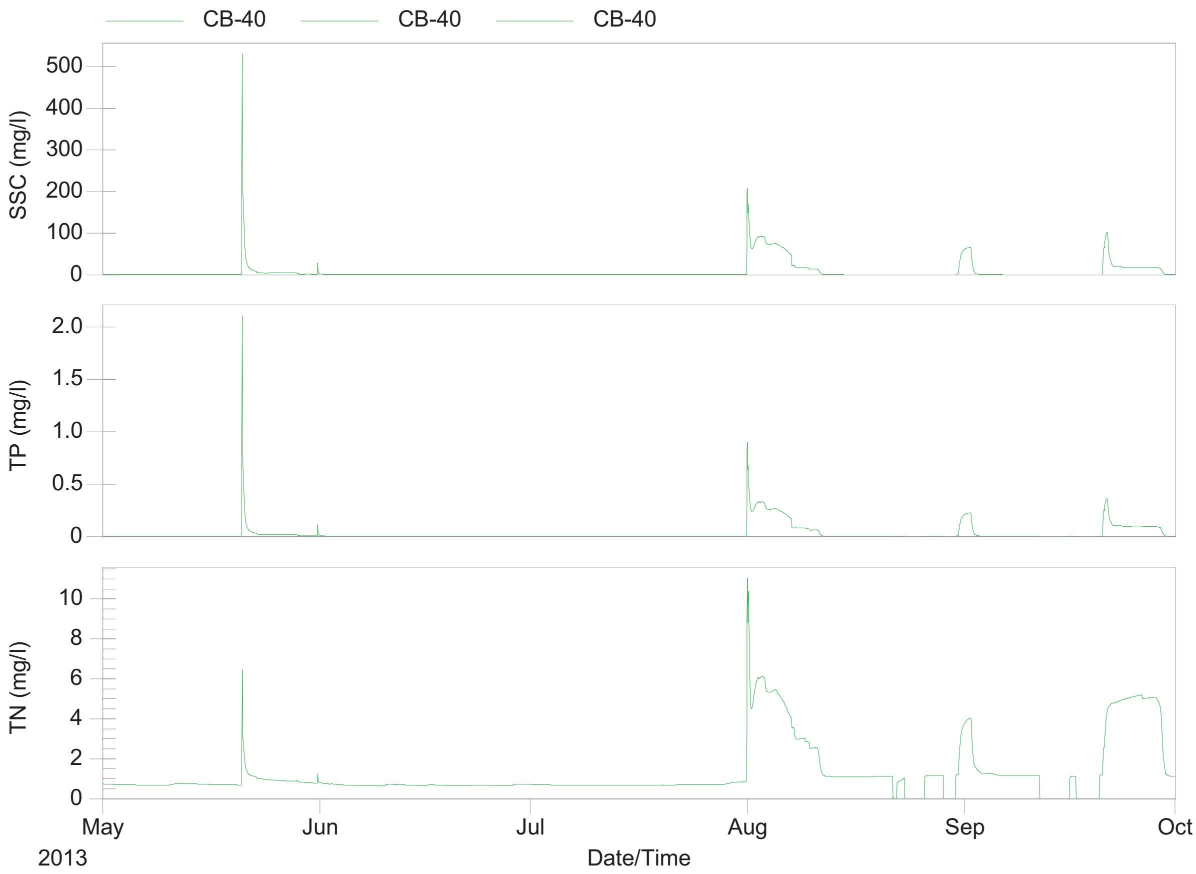


Figure 127: Garvey-Glenn Pollutograph at Point of Interest 7, Conduit CB-40

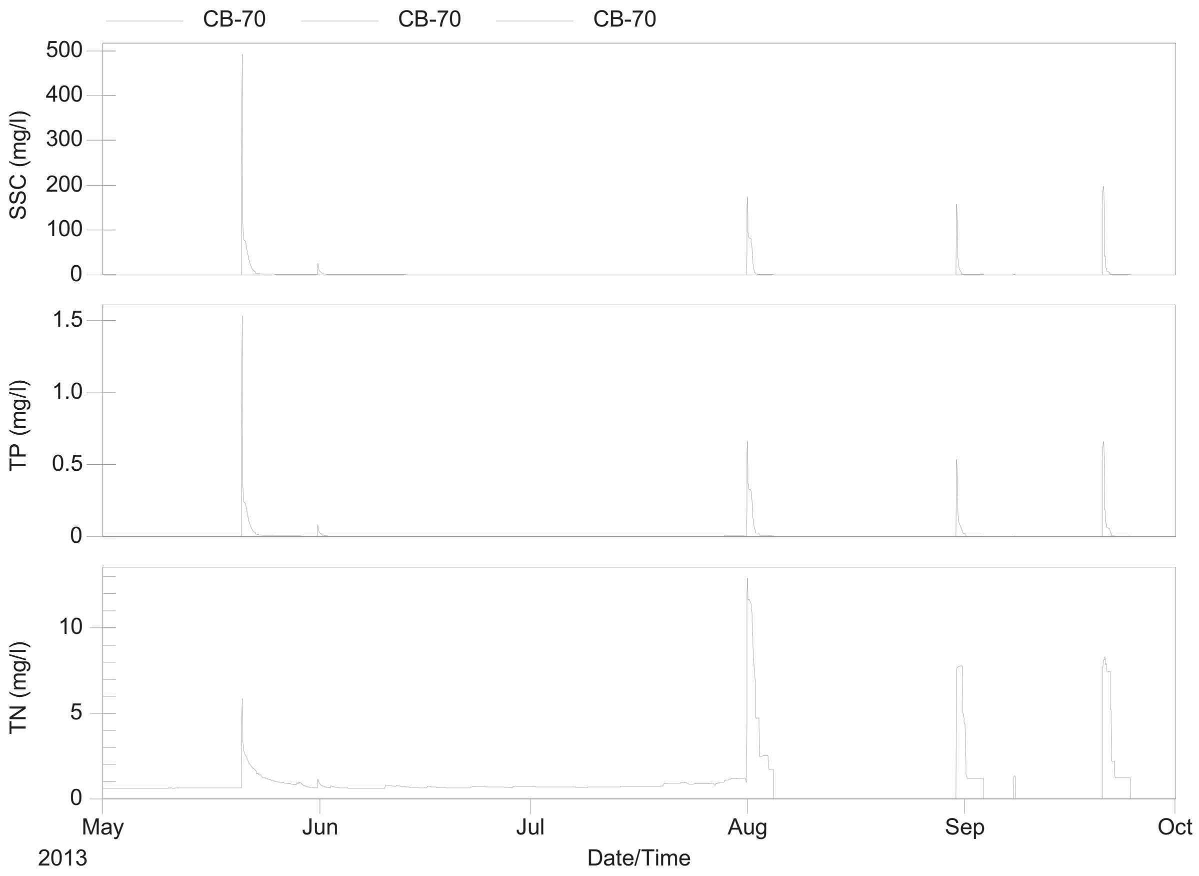


Figure 128: Garvey-Glenn Pollutograph at Point of Interest 8, Conduit CB-70

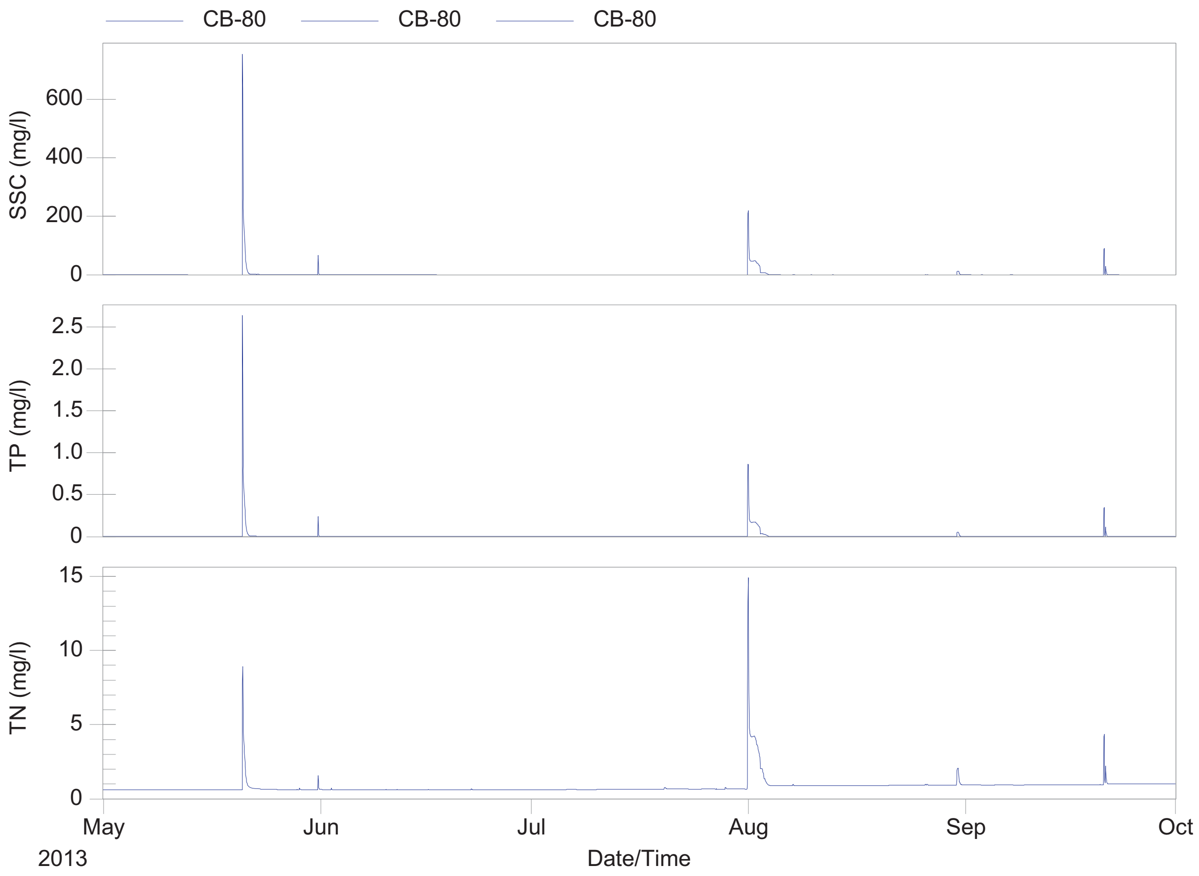


Figure 129: Garvey-Glenn Pollutograph at Point of Interest 9, Conduit CB-80

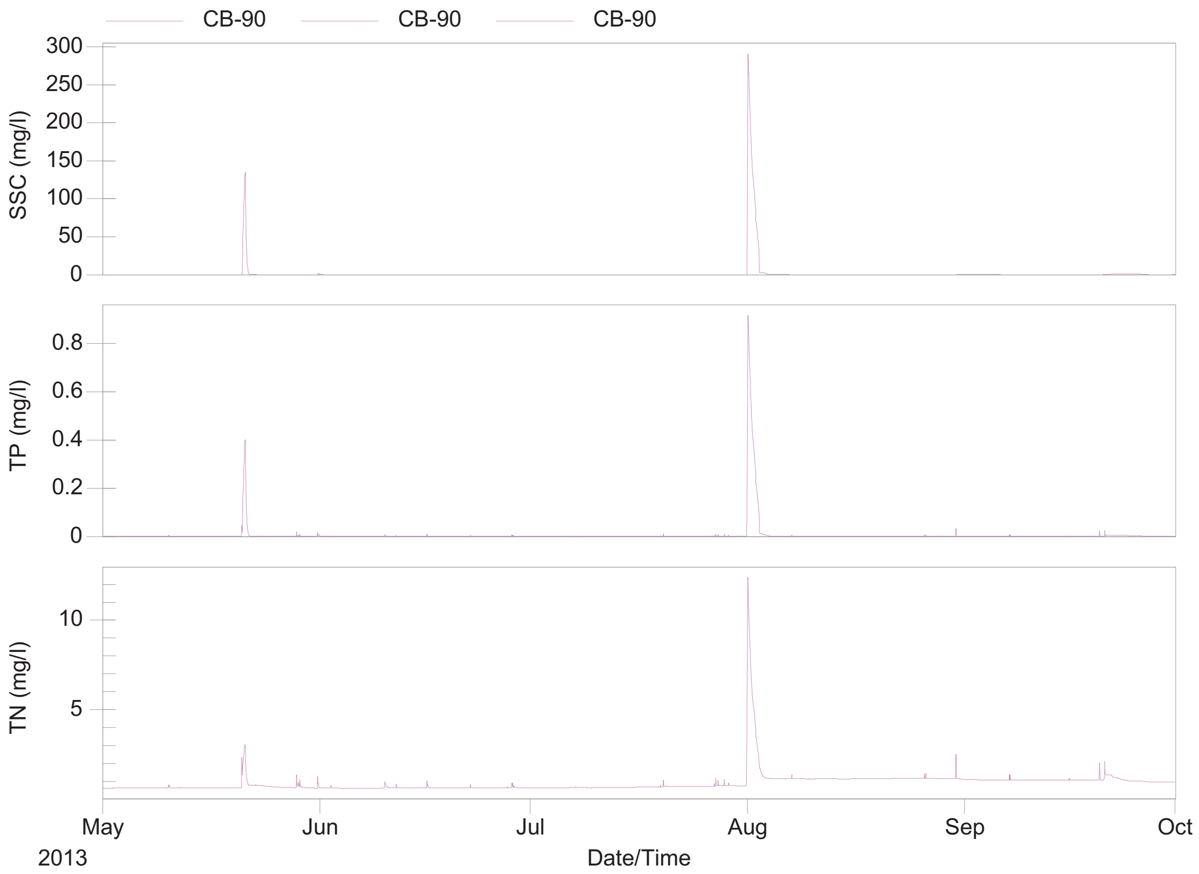


Figure 130: Garvey-Glenn Pollutograph at Point of Interest 10, Conduit CB-90

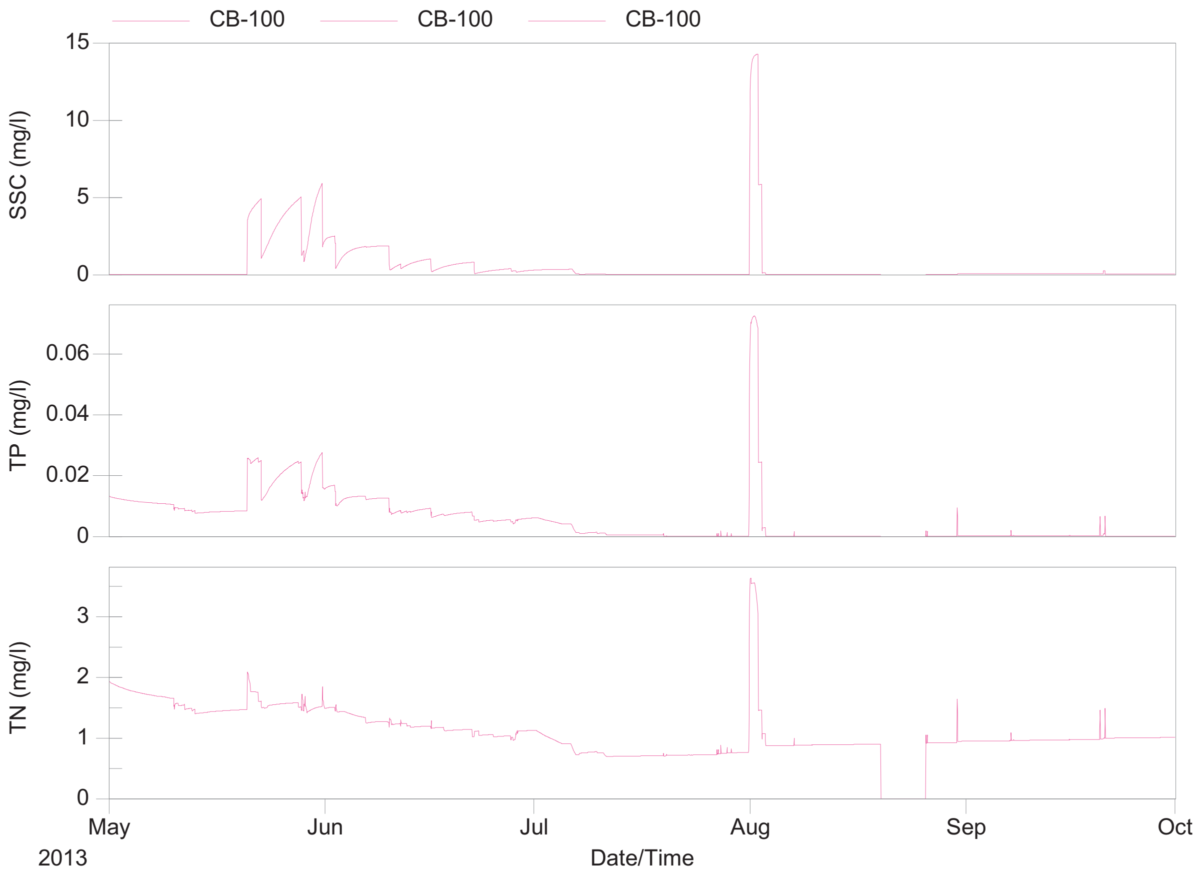


Figure 131: Garvey-Glenn Pollutograph at Point of Interest 11, Conduit CB-100

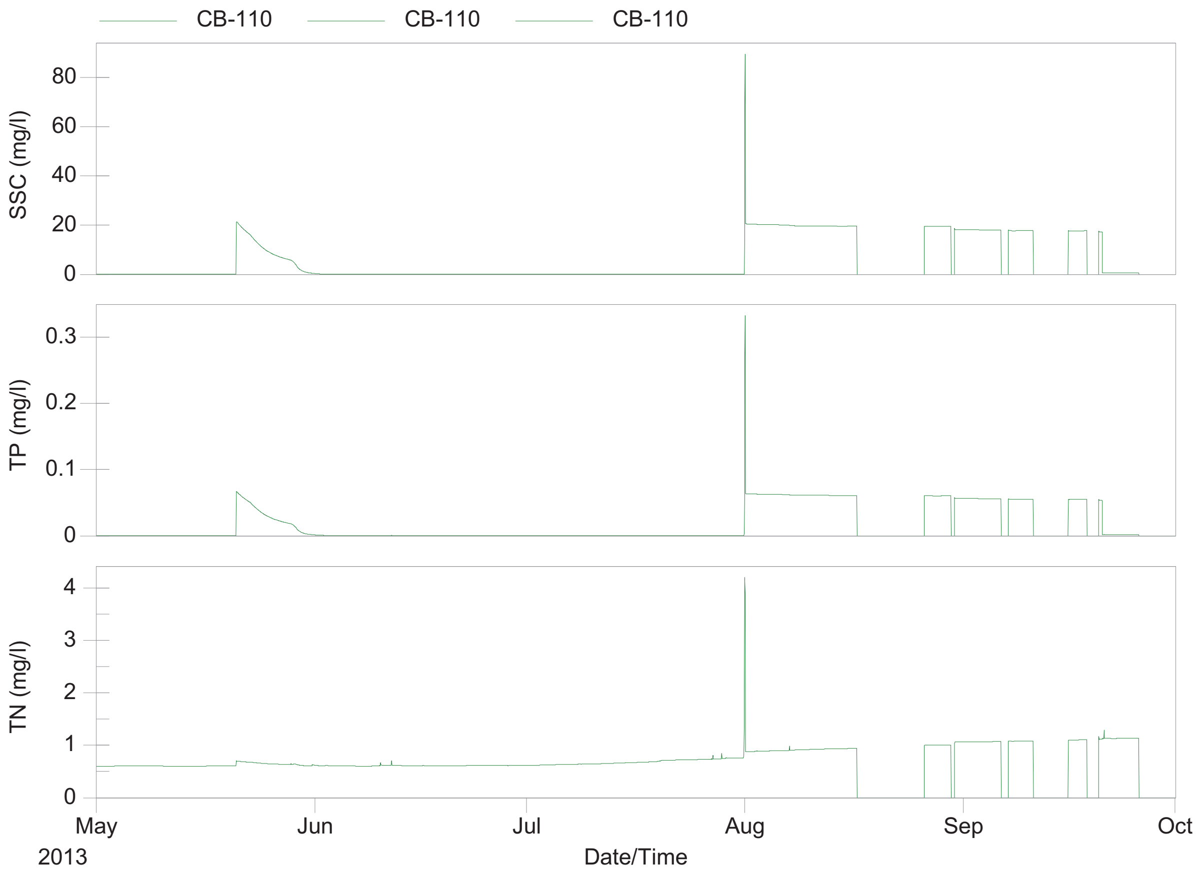


Figure 132: Garvey-Glenn Pollutograph at Point of Interest 12, Conduit CB-110

Appendix D.2.3 Bayfield North

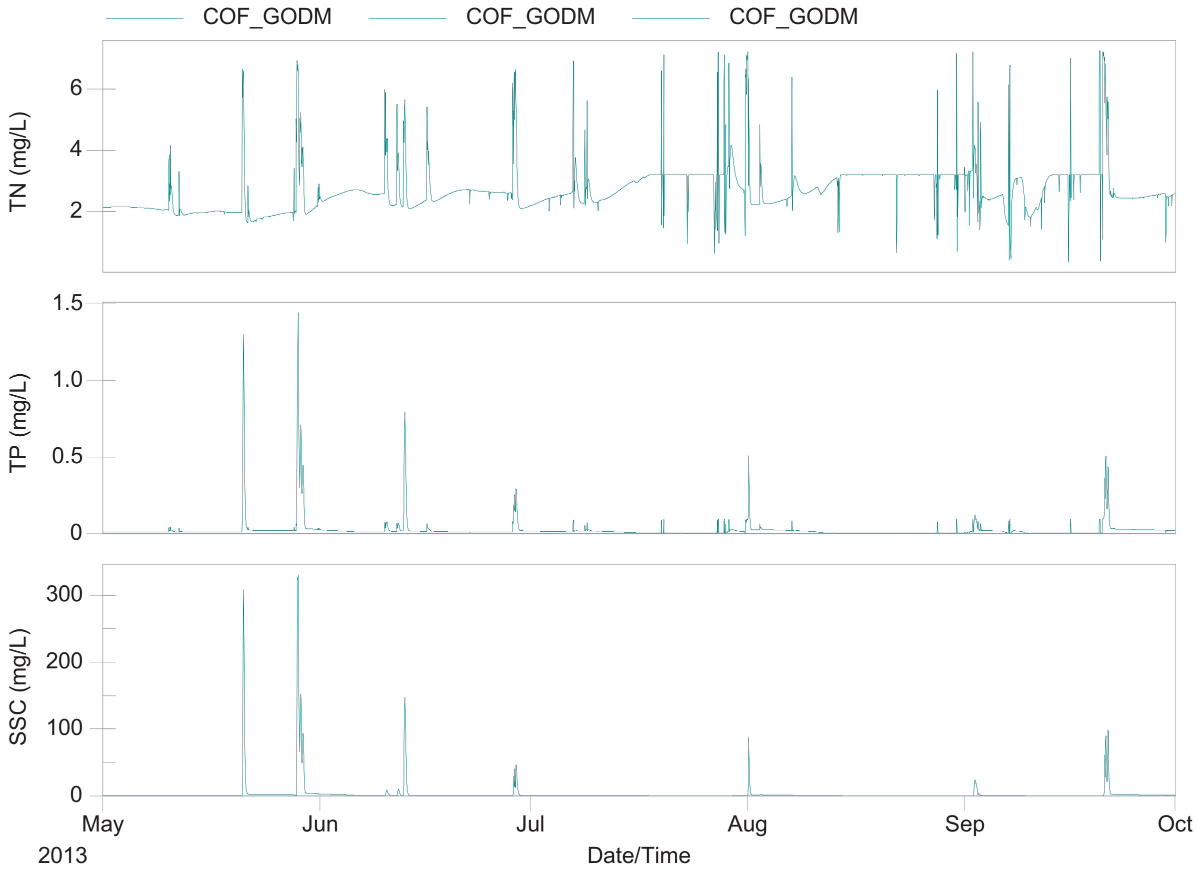


Figure 133: Bayfield North Pollutograph at Point of Interest 1, Outfall OF_GODM

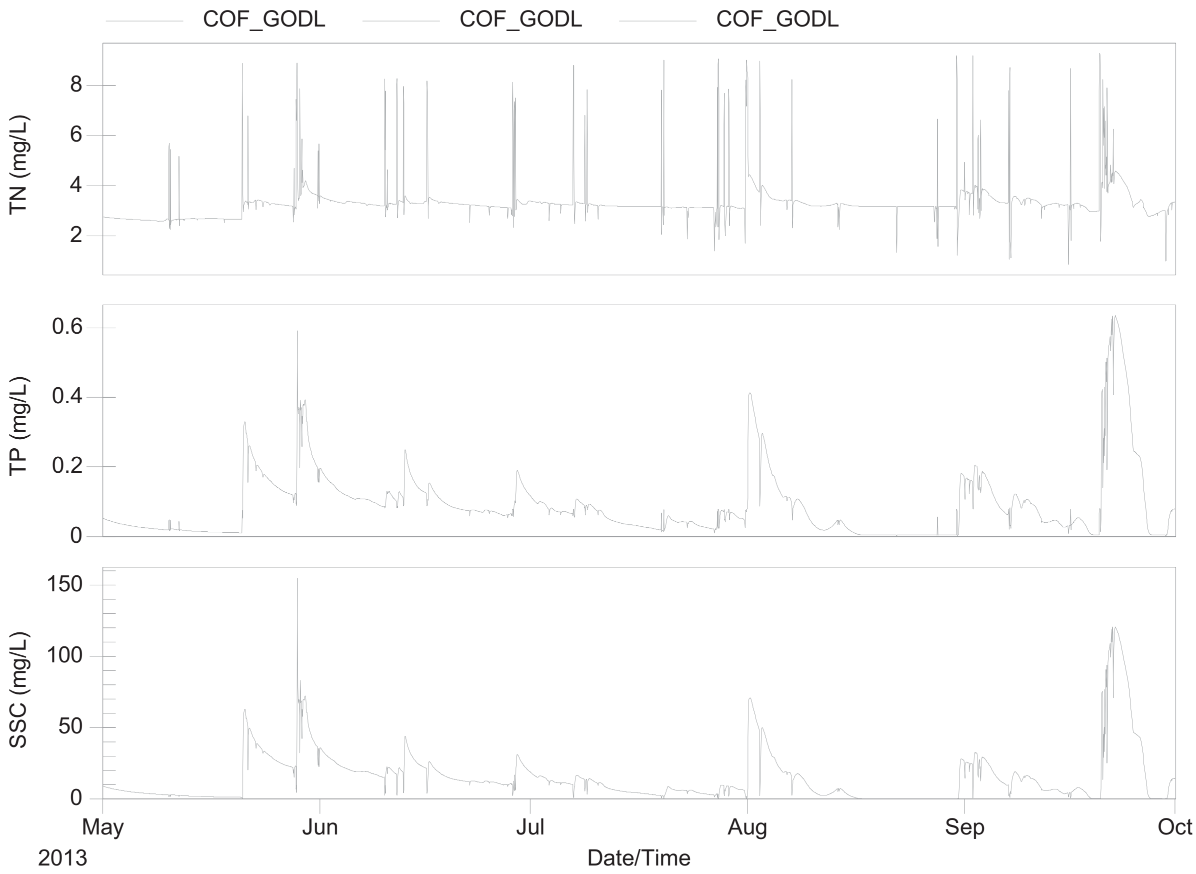


Figure 134: Bayfield North Pollutograph at Point of Interest 2, Outfall OF_GODL

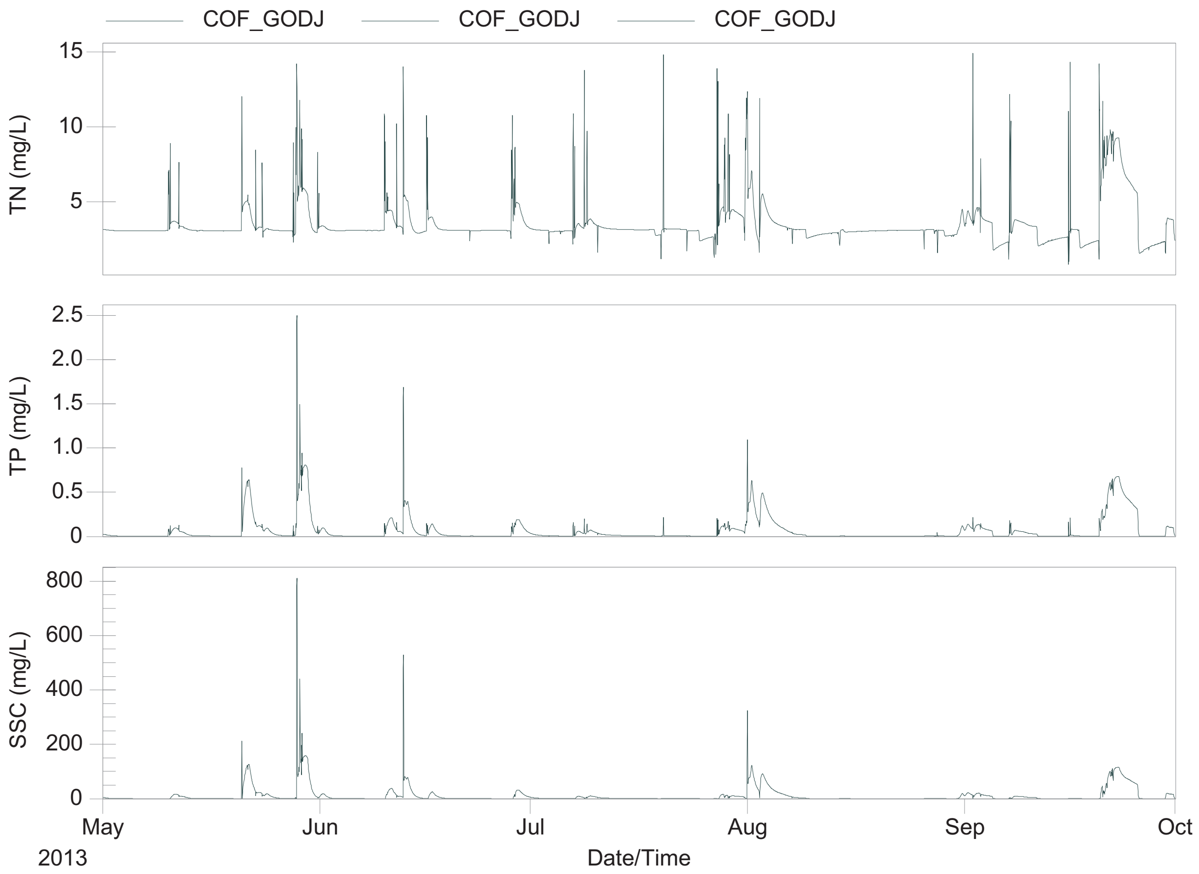


Figure 135: Bayfield North Pollutograph at Point of Interest 3, Outfall OF_GODJ

Figure 136: Bayfield North Pollutograph at Point of Interest 4, Outfall OF_GODI

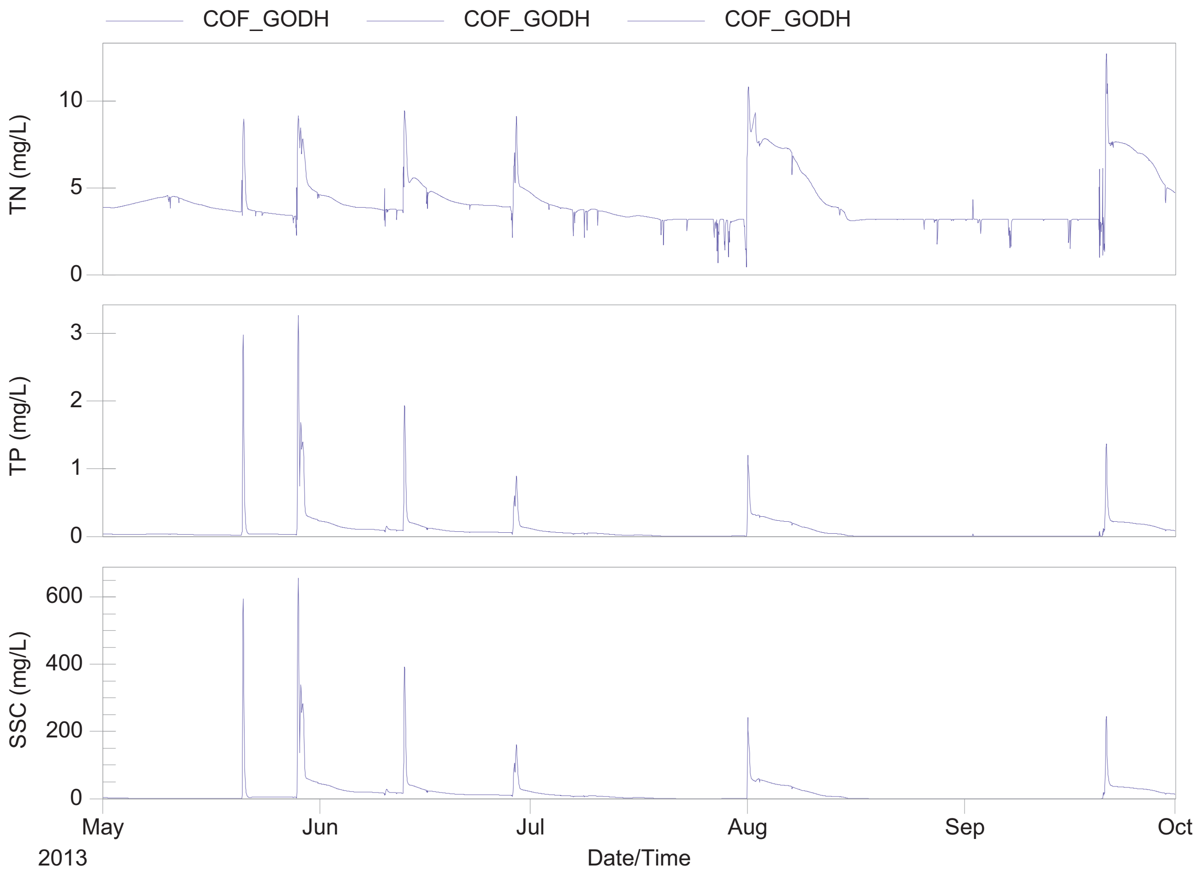


Figure 137: Bayfield North Pollutograph at Point of Interest 5, Outfall OF_GODH

Figure 138: Bayfield North Pollutograph at Point of Interest 6, Outfall OF_GODG

Figure 139: Bayfield North Pollutograph at Point of Interest 7, Outfall OF_GODF

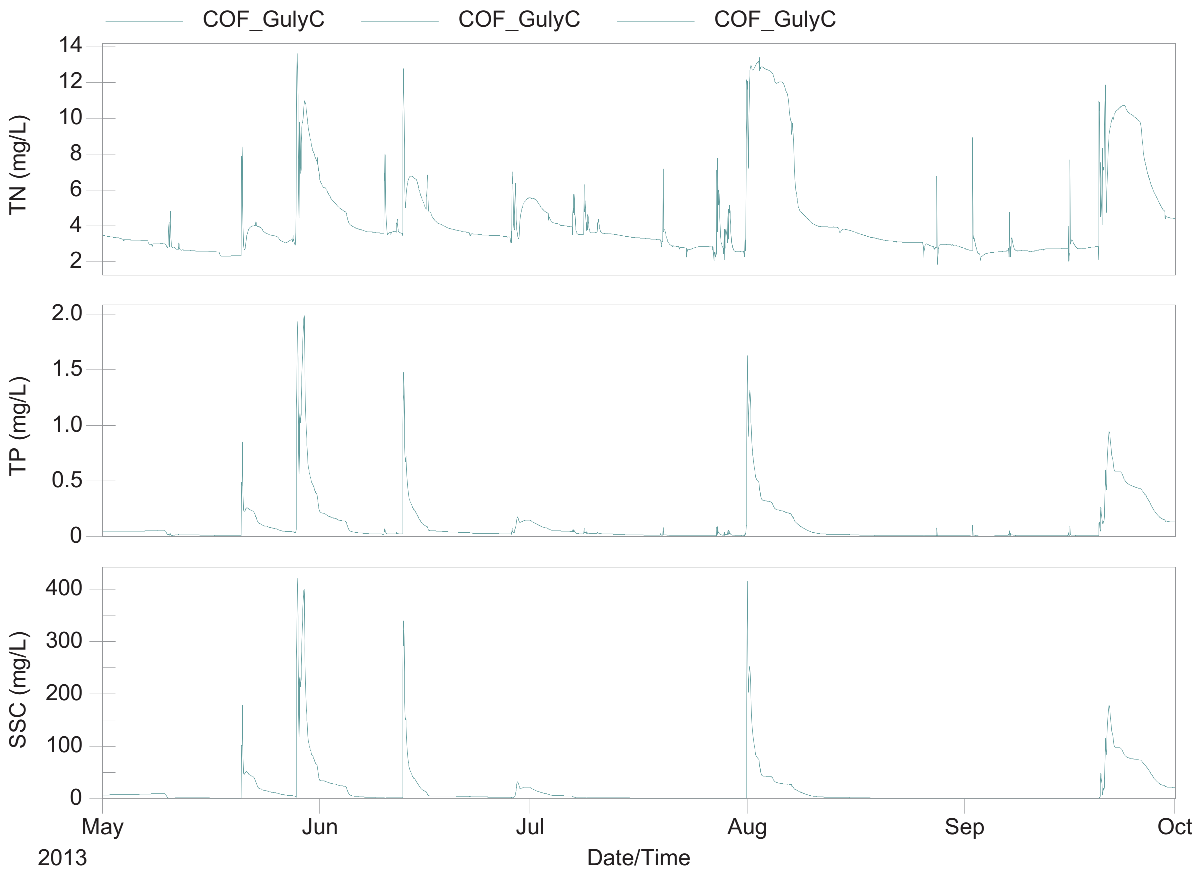


Figure 140: Bayfield North Pollutograph at Point of Interest 8, Outfall OF_GulyC

Figure 141: Bayfield North Pollutograph at Point of Interest 9, Outfall OF_GODD

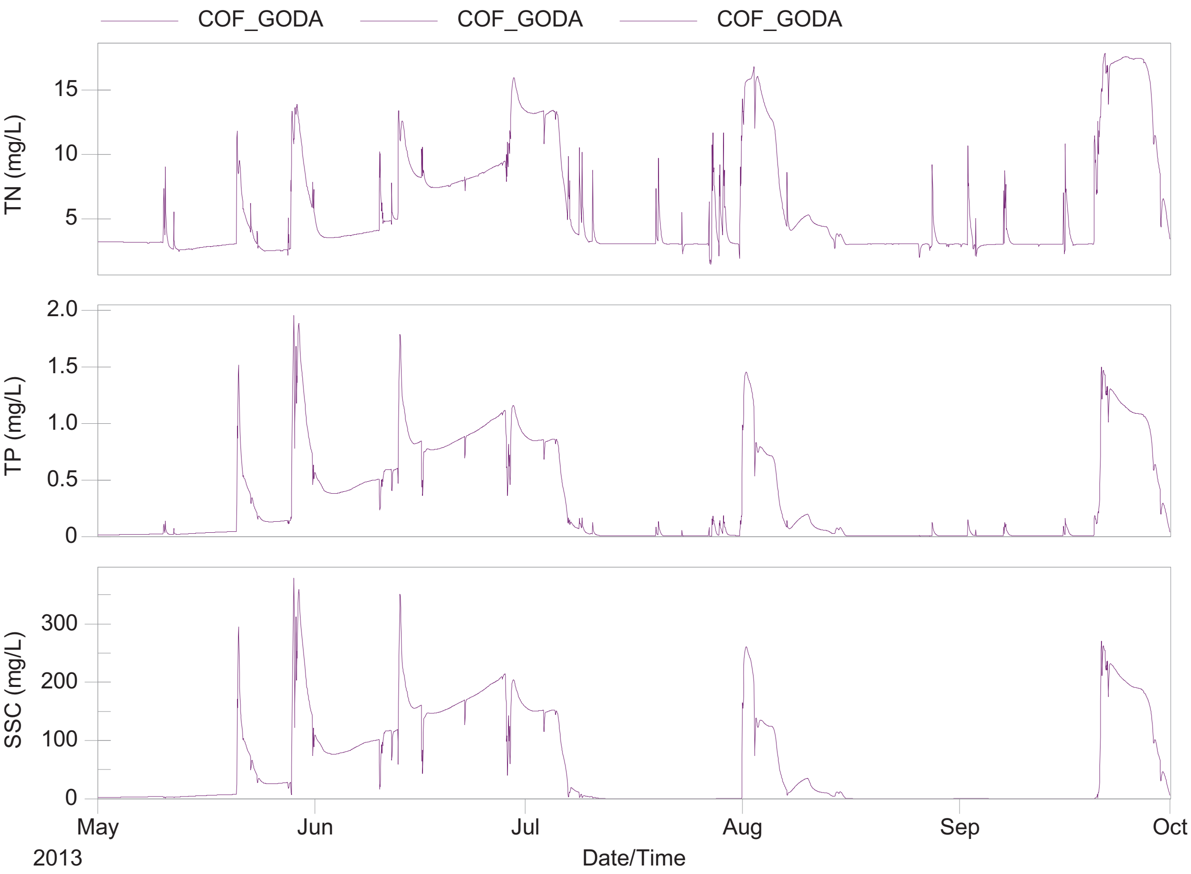


Figure 142: Bayfield North Pollutograph at Point of Interest 10, Outfall OF_GODA

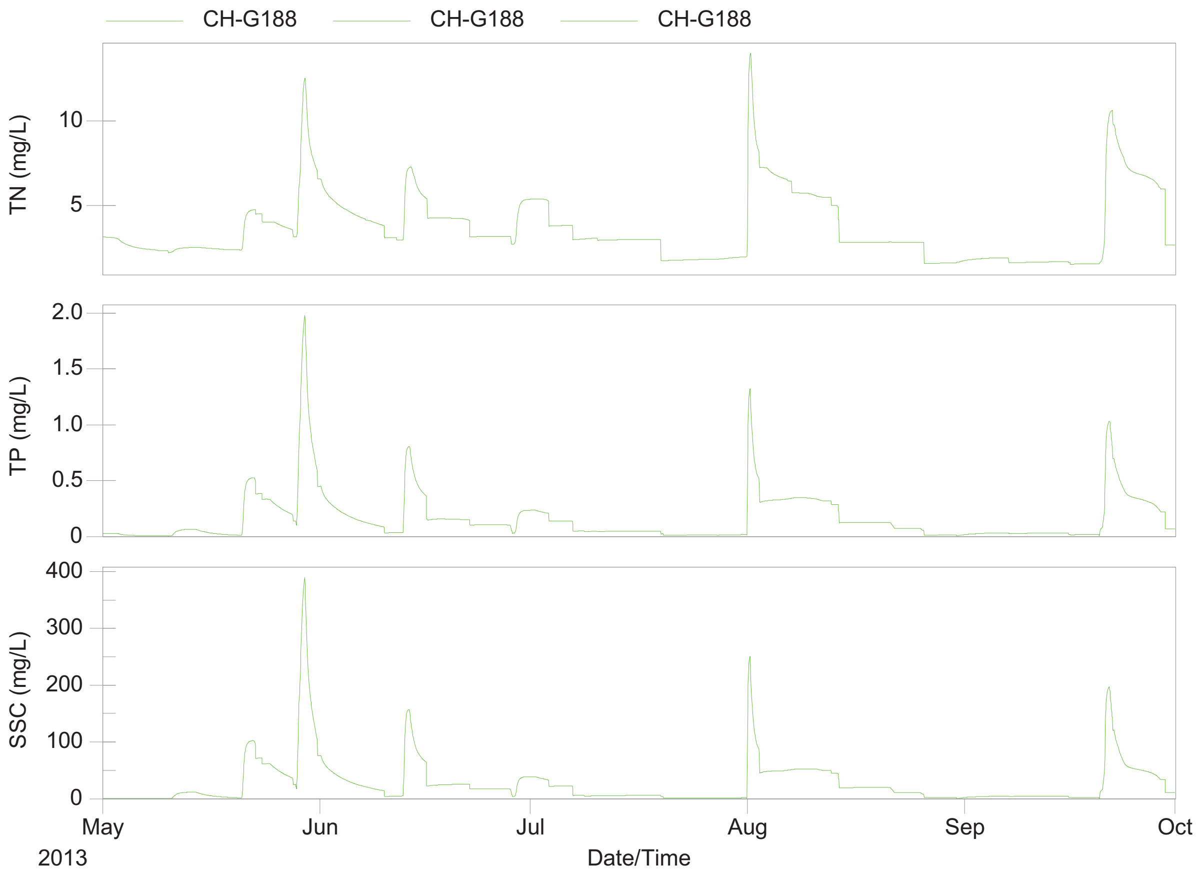


Figure 143: Bayfield North Pollutograph at Point of Interest 11, Culvert CH-G188

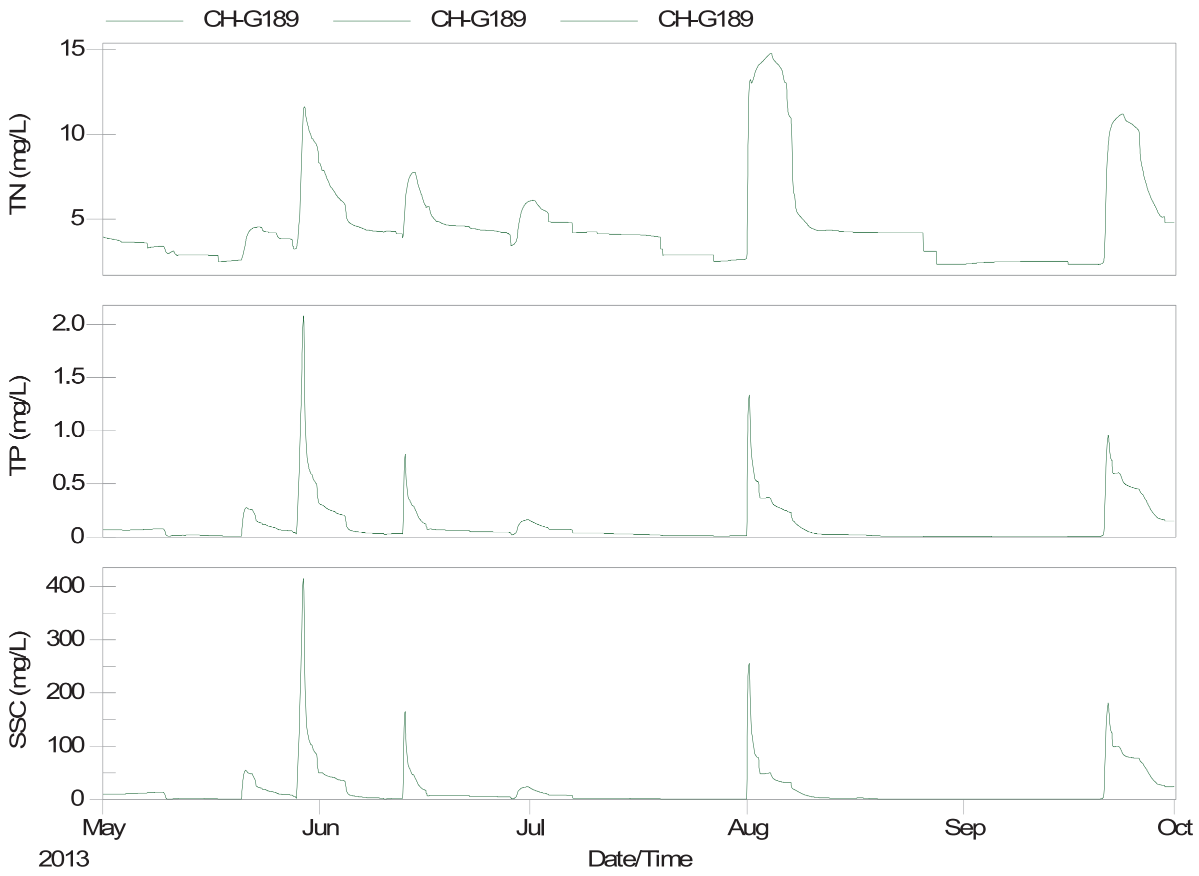


Figure 144: Bayfield North Pollutograph at Point of Interest 12, Culvert CH-G189

Appendix D.2.4 Main Bayfield

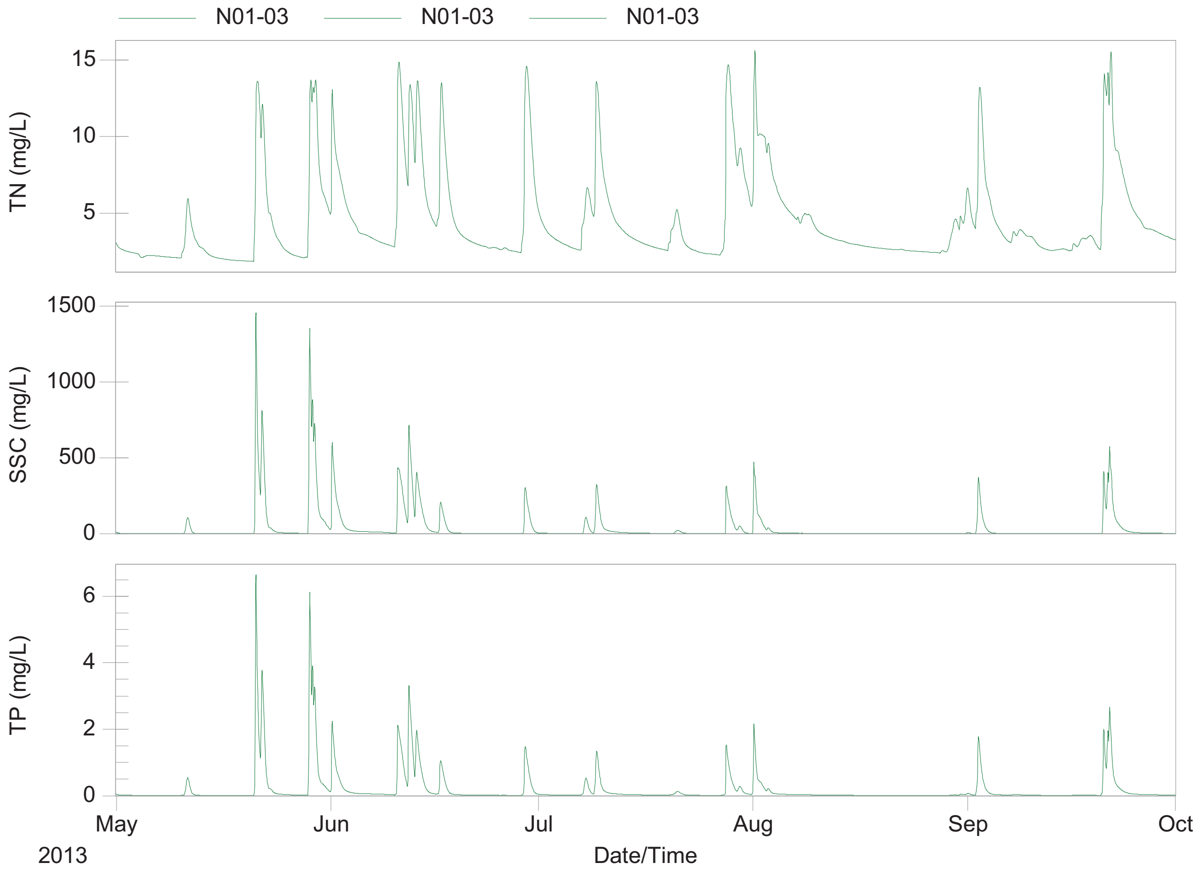


Figure 145: Main Bayfield Pollutograph at Point of Interest 1, Outfall OUT01-02

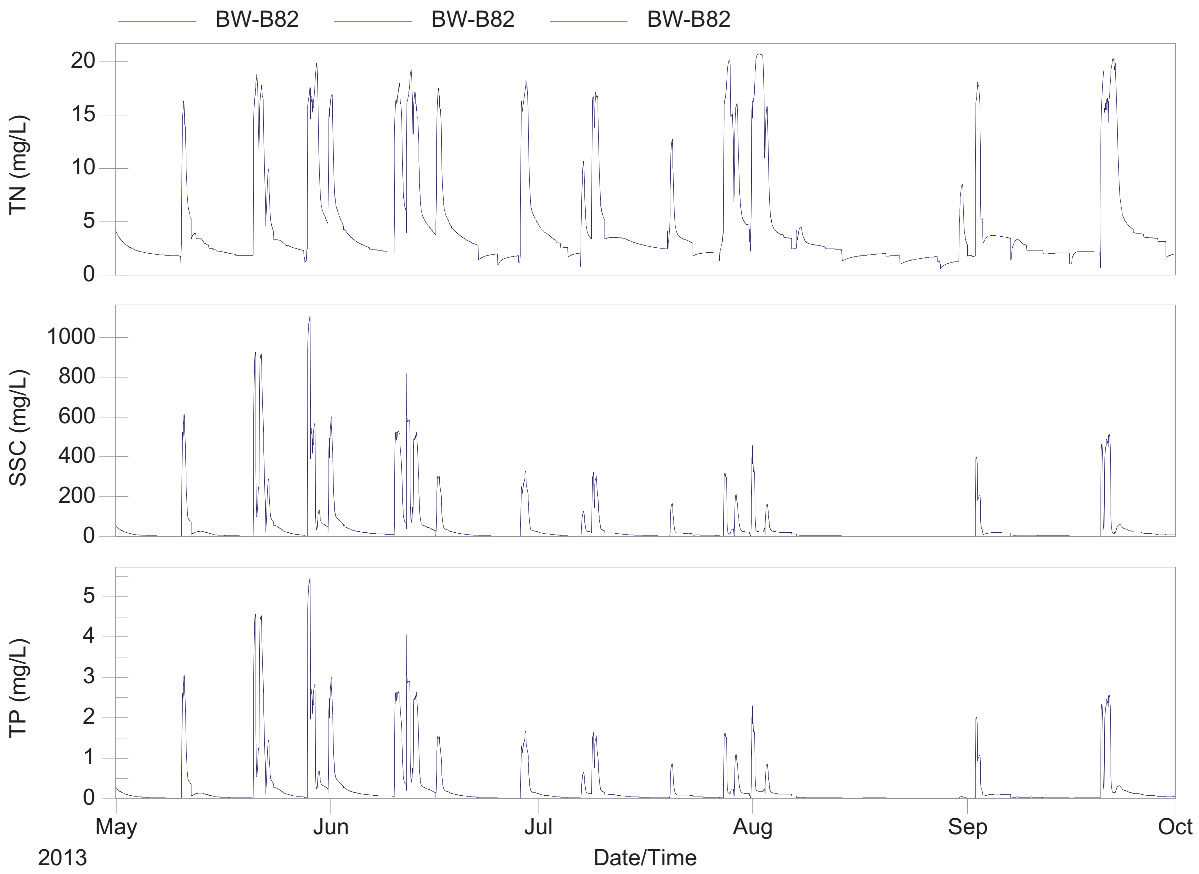


Figure 146: Main Bayfield Pollutograph at Point of Interest 2, Conduit BW-B82

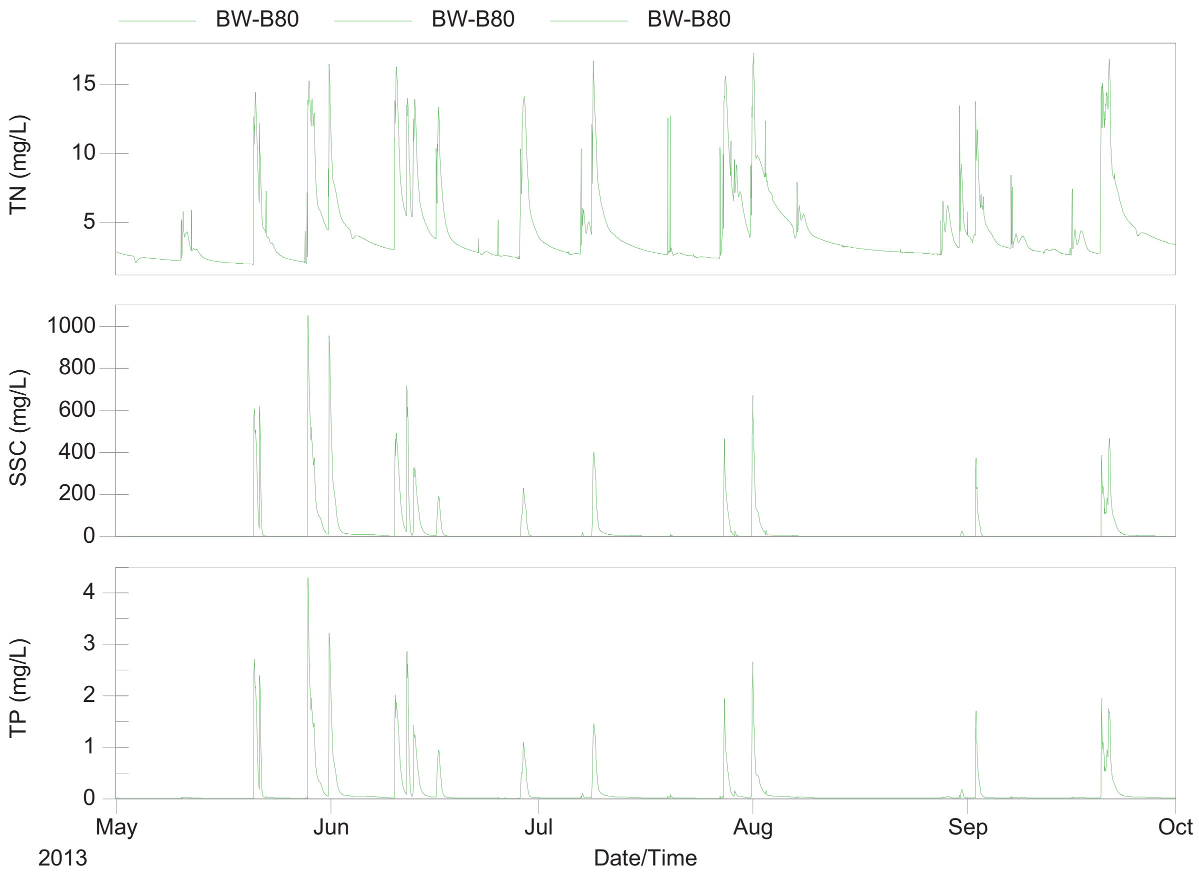


Figure 147: Main Bayfield Pollutograph at Point of Interest 3, Conduit BW-B80

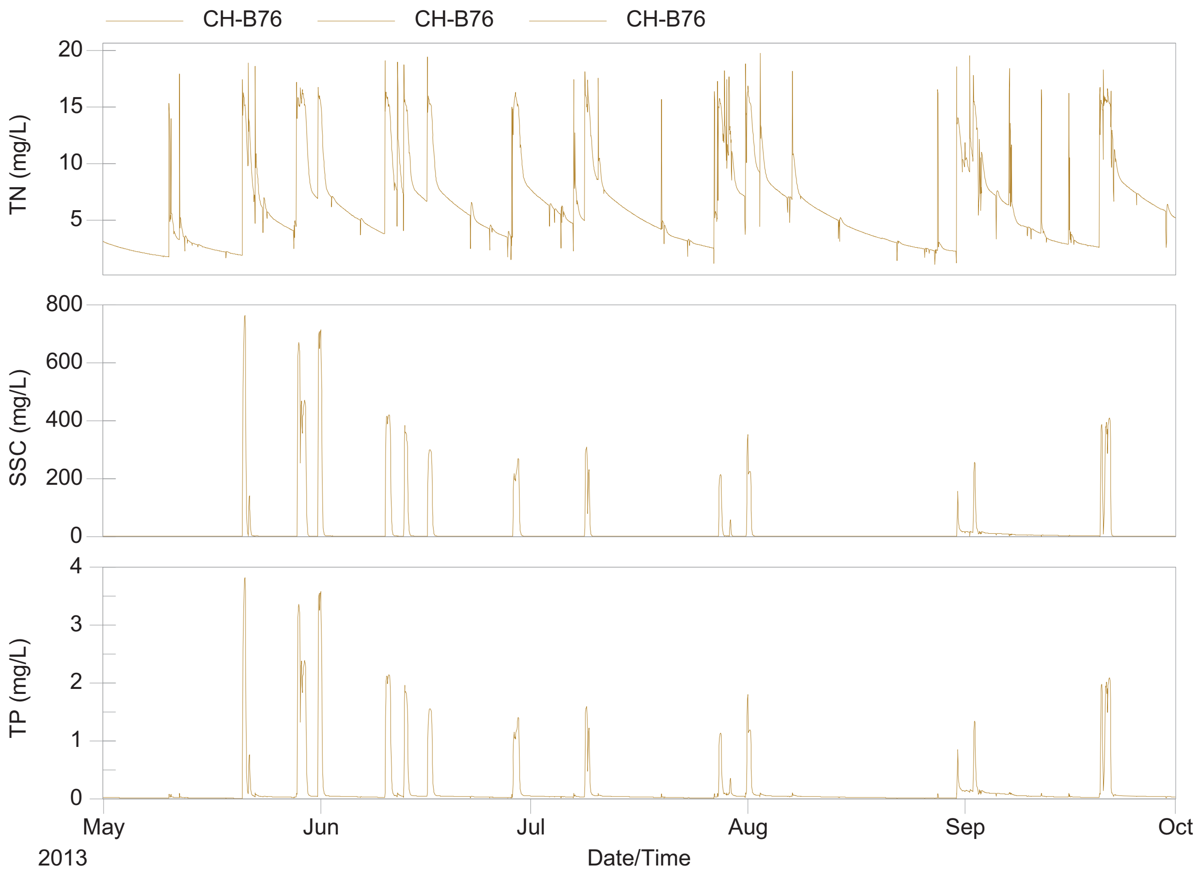


Figure 148: Main Bayfield Pollutograph at Point of Interest 4, Conduit CH-B76

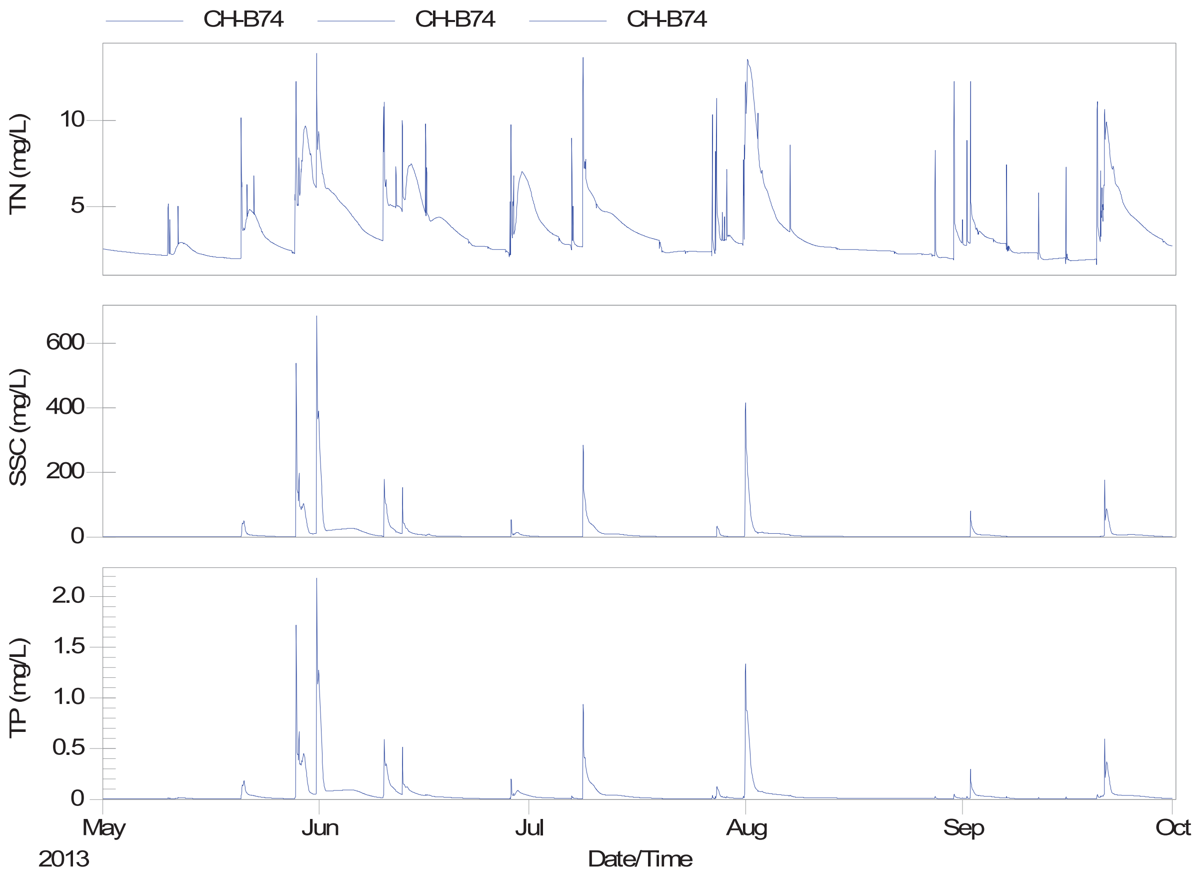


Figure 149: Main Bayfield Pollutograph at Point of Interest 5, Conduit CH-B74

Appendix D.2.5 Lambton Shores

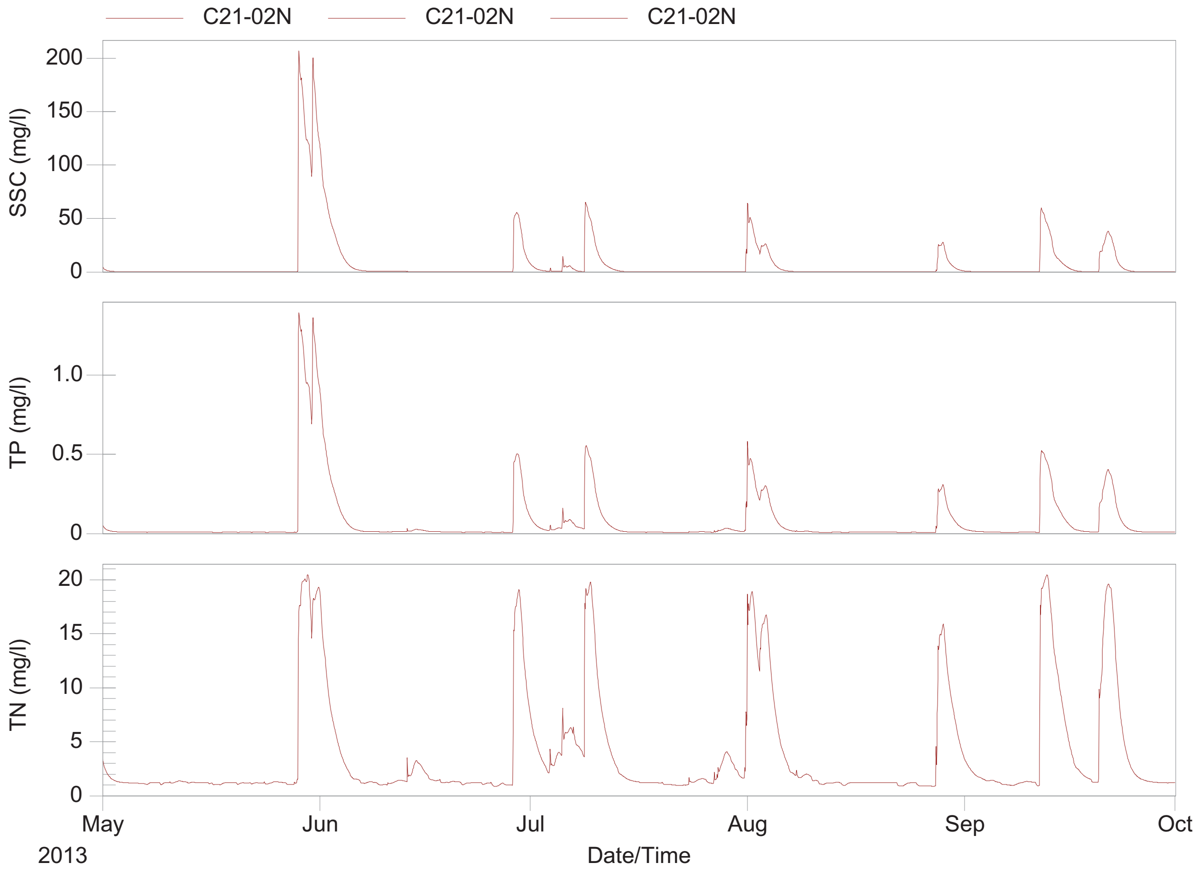


Figure 150: Lambton Shores Pollutograph at Point of Interest 1, Outfall J21-01O

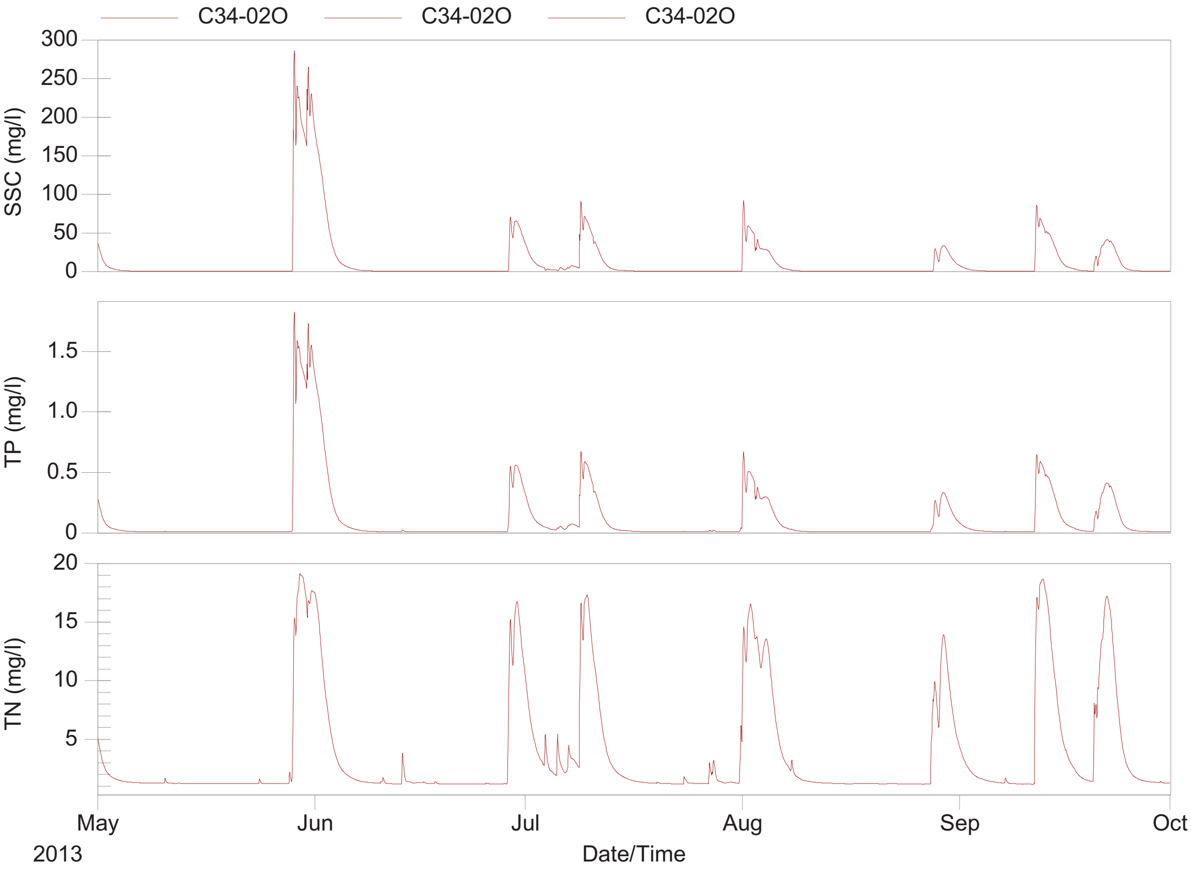


Figure 151: Lambton Shores Pollutograph at Point of Interest 2, Outfall J34-01O

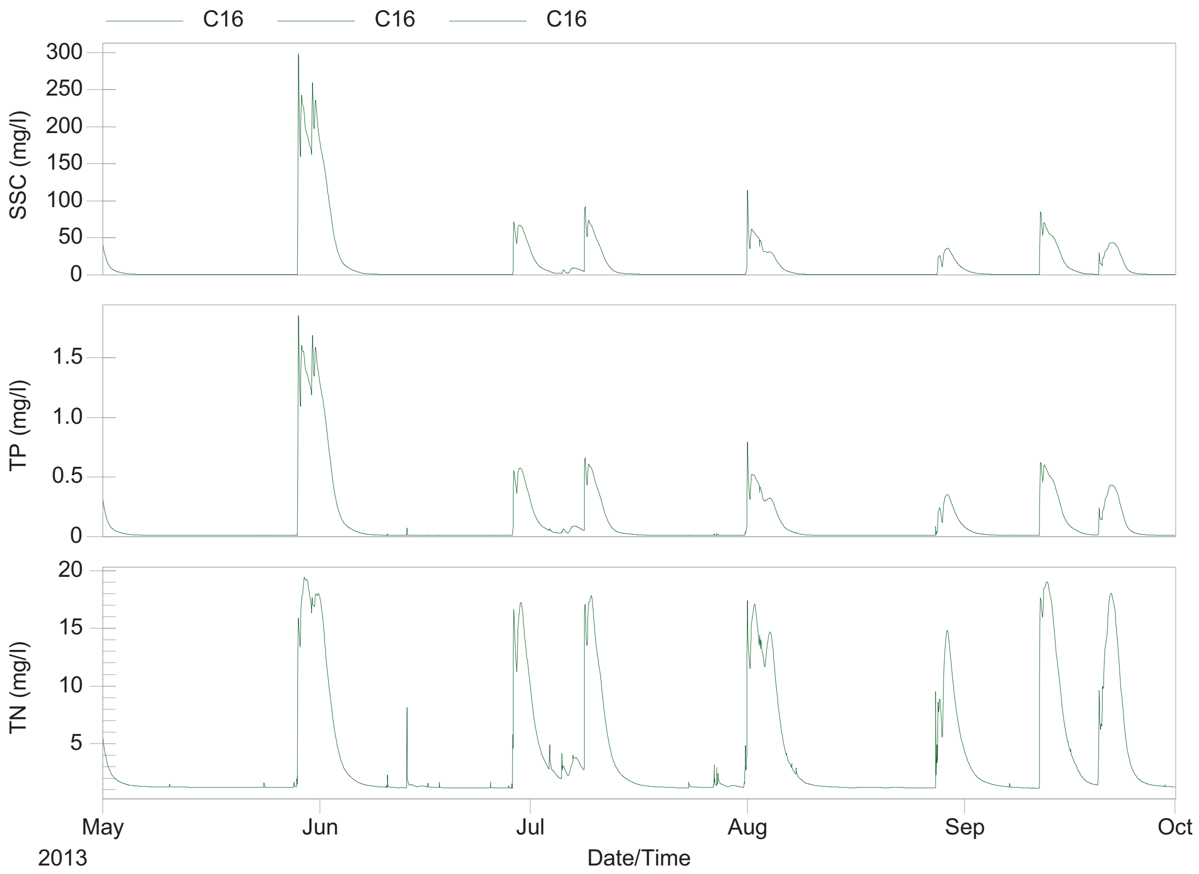


Figure 152: Lambton Shores Pollutograph at Point of Interest 3, Conduit C16

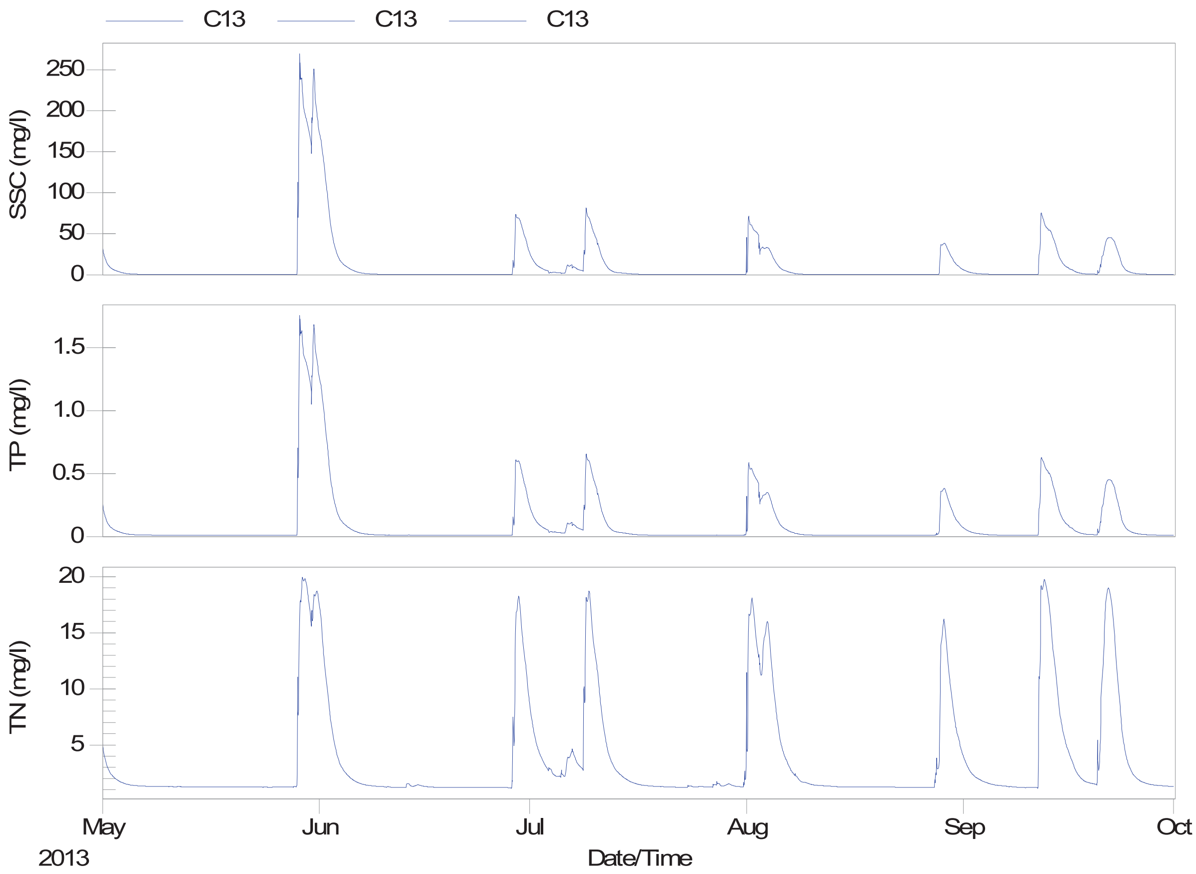


Figure 153: Lambton Shores Pollutograph at Point of Interest 4, Conduit C13

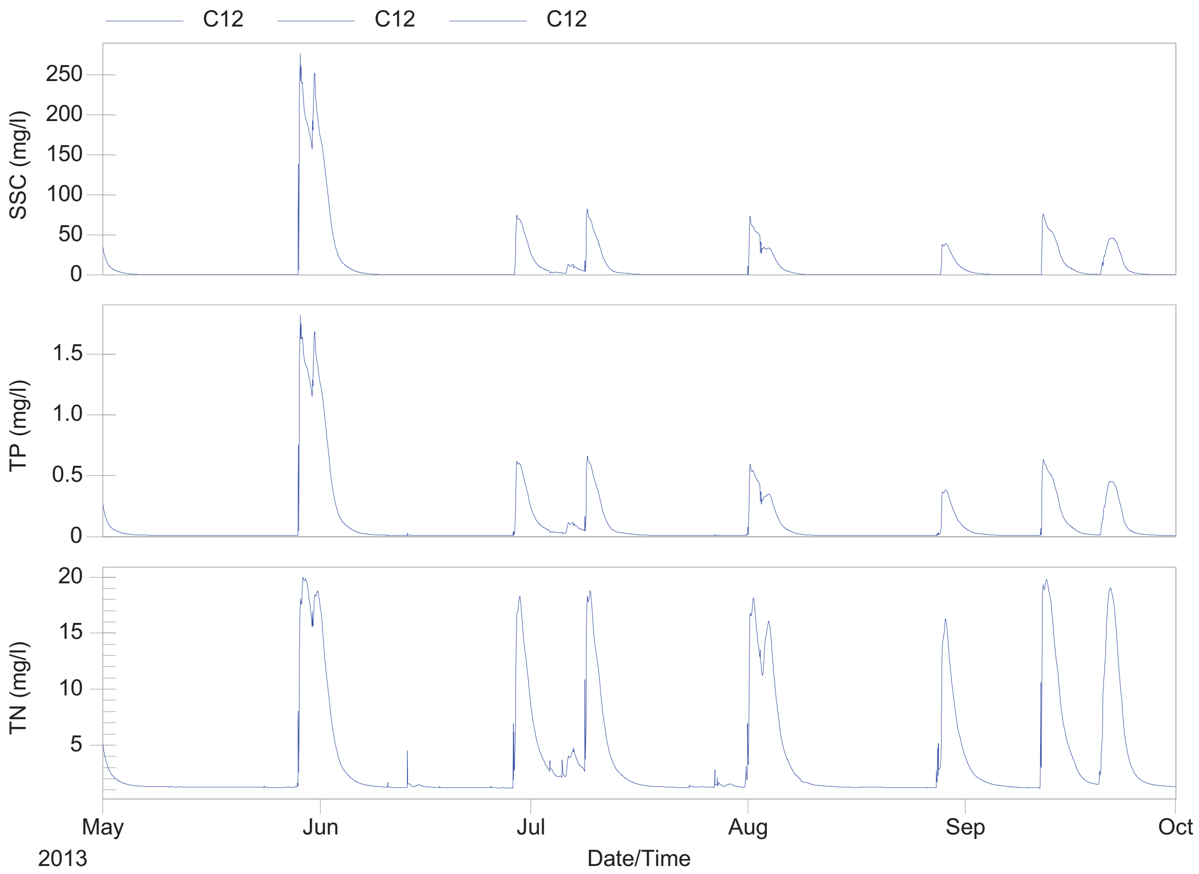


Figure 154: Lambton Shores Pollutograph at Point of Interest 5, Conduit C12

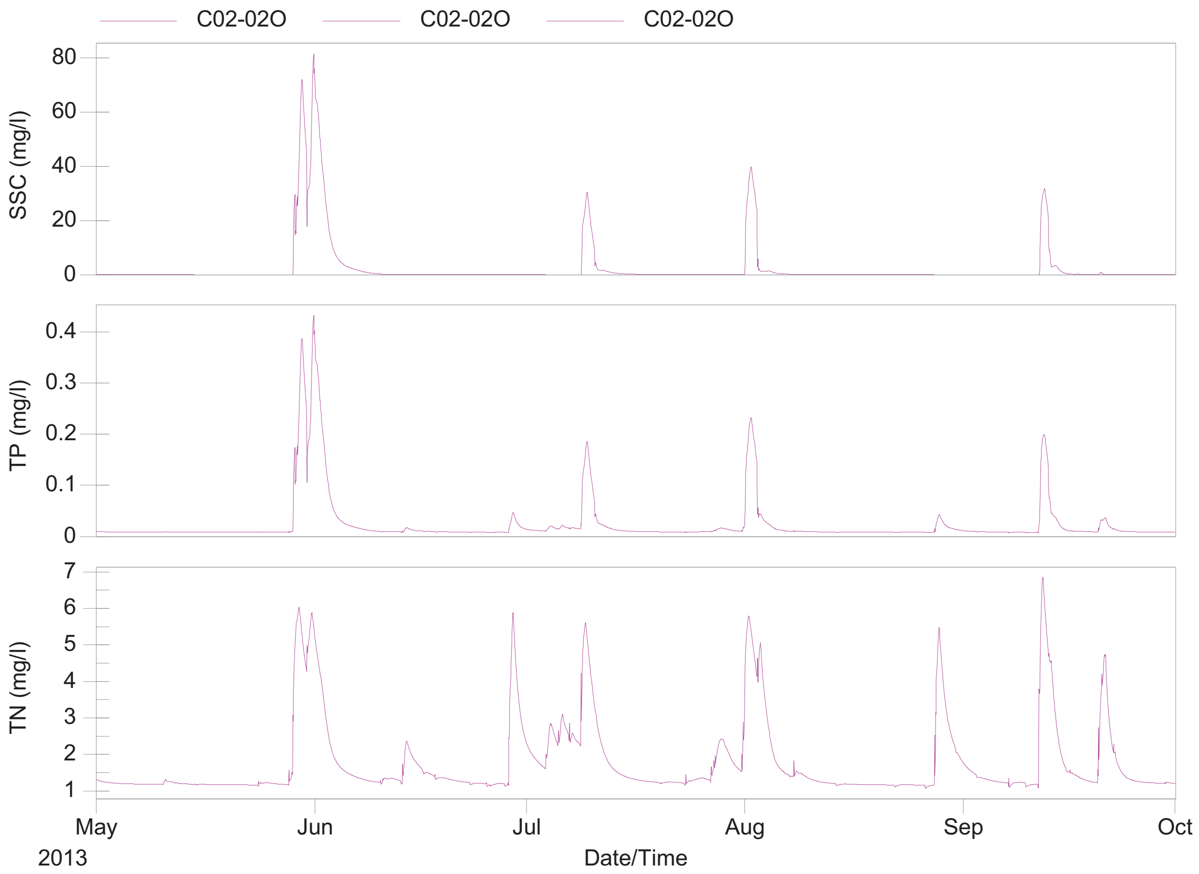


Figure 155: Lambton Shores Pollutograph at Point of Interest 6, Outfall J02-01O

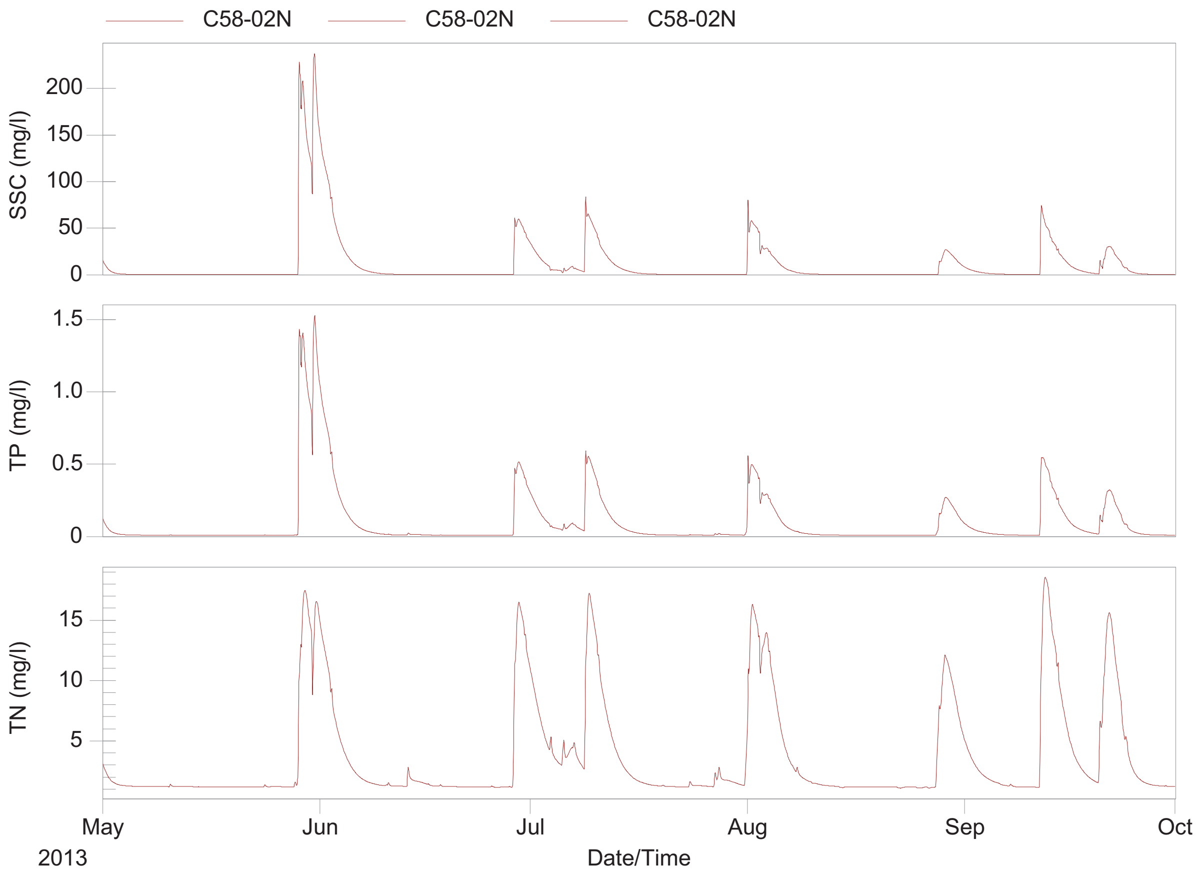


Figure 156: Lambton Shores Pollutograph at Point of Interest 7, Outfall J58-01O

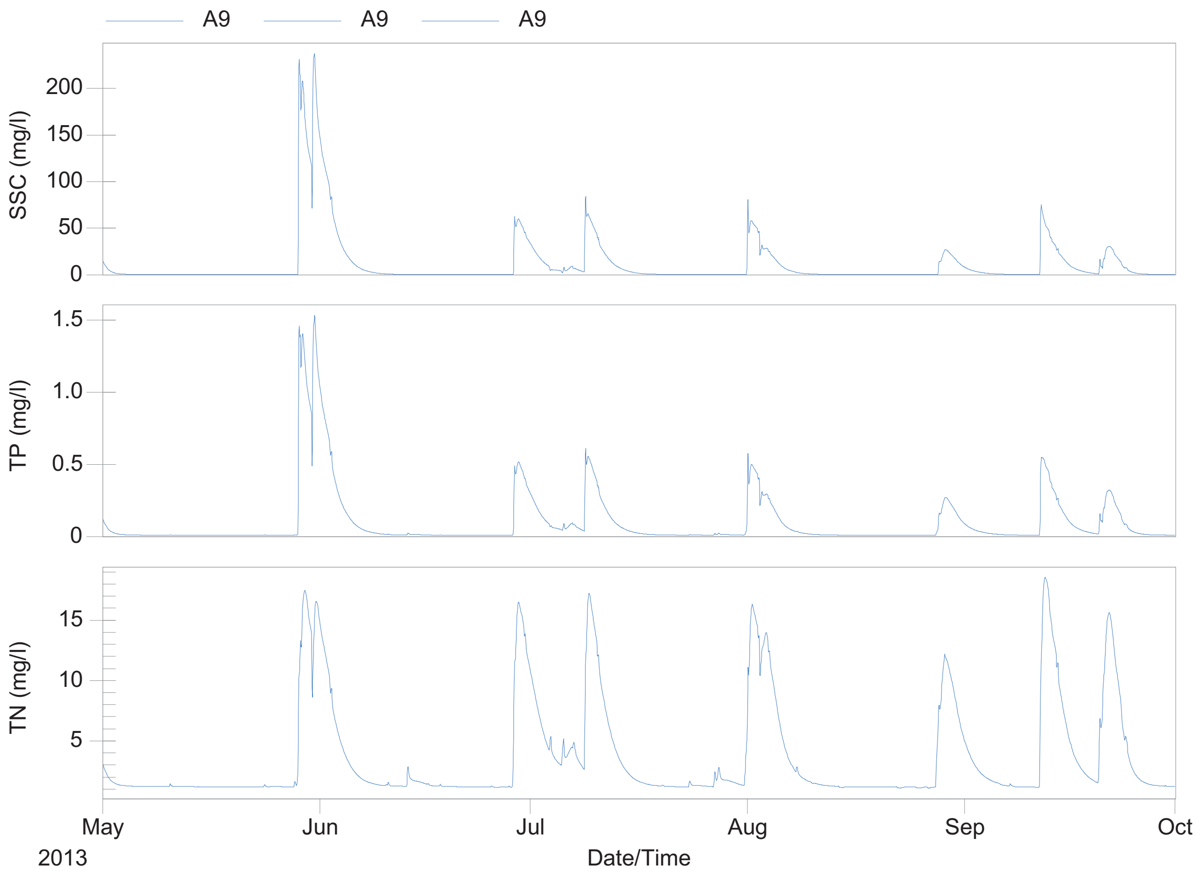


Figure 157: Lambton Shores Pollutograph at Point of Interest 8, Conduit A9

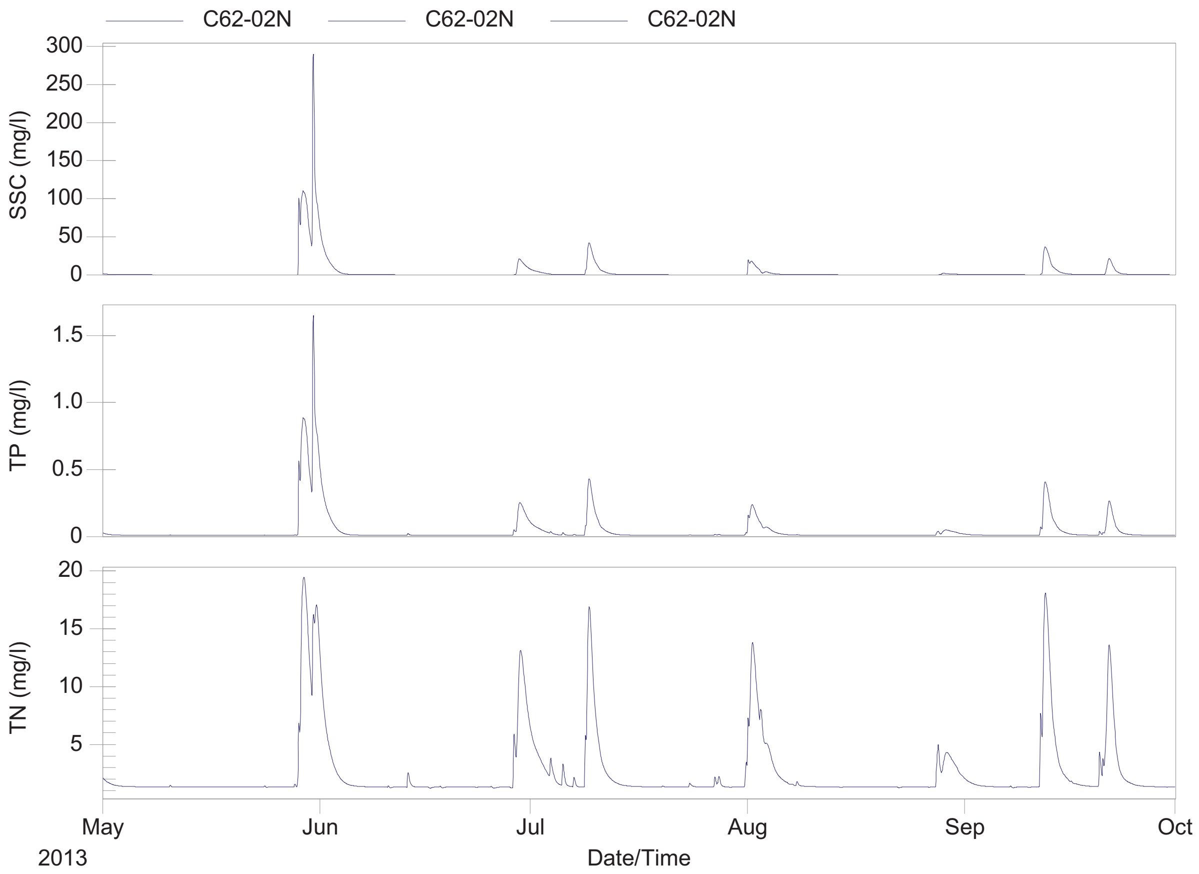


Figure 158: Lambton Shores Pollutograph at Point of Interest 9, Junction J62-01J

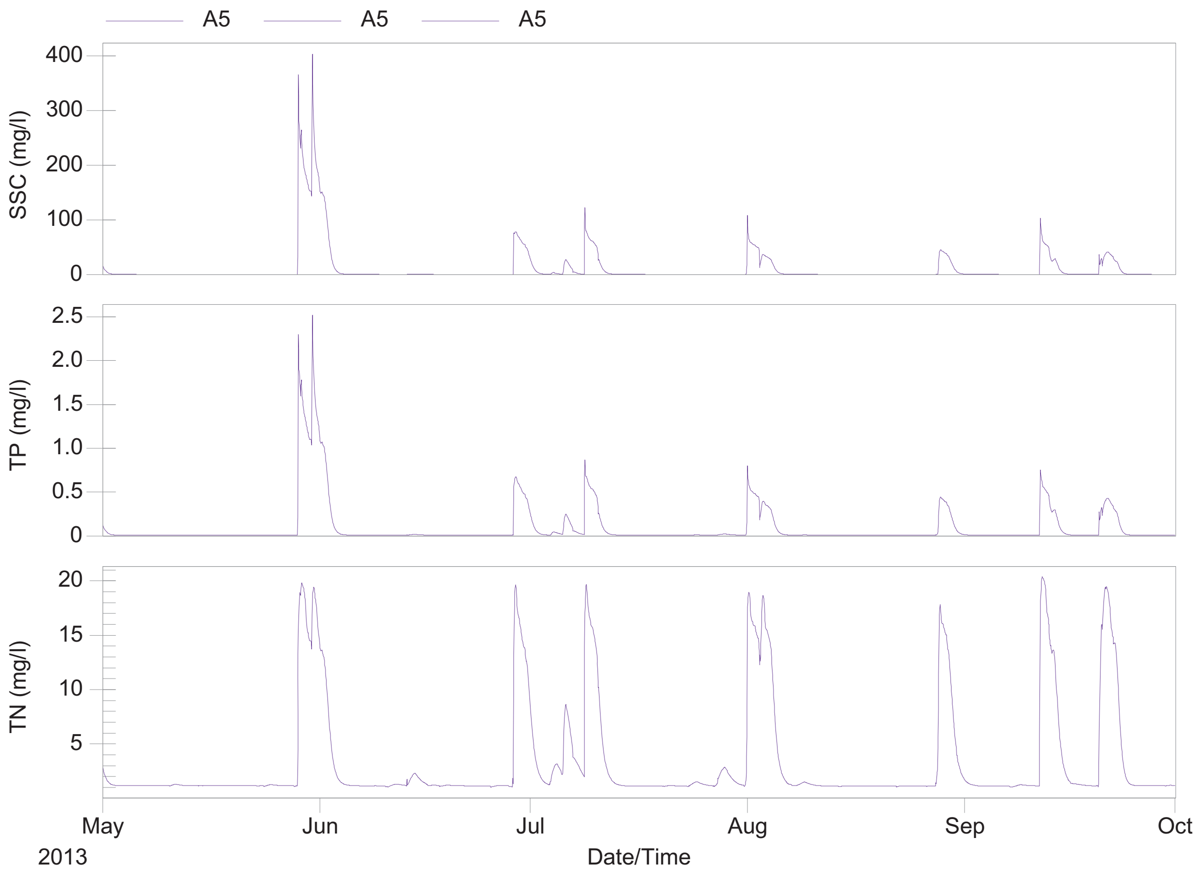


Figure 159: Lambton Shores Pollutograph at Point of Interest 10, Conduit A5