Simulating the impact of water infrastructure on groundwater and surface water within the Laurel Creek Watershed

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

As the urbanization of the City of Waterloo, the infrastructure system expanded fast in the last couple decades. The increased population gave a higher load to the Laurel Creek Watershed. At the same time, the aged infrastructures have fractures and cracks, which result in the leakage of watermain and groundwater infiltration into the sewer pipelines. Those waste drinking water and additional sewer water increased the water bill of the citizens. Therefore, the City of Waterloo needs a municipal infrastructure asset management to keep the water supply and drainage system sustainable in the future.

Part of the municipal infrastructure asset management is to establish an integrated natural water cycle model of the Laurel Creek Watershed. This surface water-ground water simulation model was built up using HydroGeoSphere (HGS). Then, insert the watermain, sewer pipeline, and the storm water pipeline (GIS data was from the City of Waterloo) into this natural water cycle model. The subsurface geology of the model is based on the multi-aquifer Waterloo Moraine system created by Martin and Frind (1998). The updated hydraulic conductivities, the land use condition, and the evapotranspiration pattern have been added into the Laurel Creek Watershed model. In the HGS model, there are a total of 46 layers. The 20 upper layers were generated based on the shape of the topography. The bottom 17 layers were created based on the bedrock layer. In between the upper layers and the bottom layers, there are 8 sublayers to refine the information of hydro-stratigraphic units. There is an additional layer for the municipal infrastructure to input the pipelines' elevations. Due to the time limitation, only the sewer trunk lines have been inserted into the model.

The Laurel Creek Watershed model was first run to steady state using only the nature water cycle system driven by rainfall and evapotranspiration. Next, the model was then to run steady state again but now containing the sewer drainage pattern. The stream flow in both models was measured to compare the difference between the model with the sewer drainage pattern and the model without the sewer system. Also, the stream flow simulated data is compared with the real word measurement data.

This thesis concludes that the municipal infrastructure is possible to be simulated in the natural water cycle HGS model. The simulated results are reasonable matching the real hydraulic condition in the Laurel Creek Watershed.

Acknowledgements

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I would like to thank everyone at Aquanty Inc. Specifically, I wish to thank Young-Jin Park for his technical advice and support, and for those weekly meetings that provided me with a deeper understanding of HydroGeoSphere. I am also grateful to Jason Davison for his technical guidance.

To all the members of the SWIFT research group, thank you for this great opportunity to work on part of this municipal asset management project. I had so many harvests from all your presentations during those group meetings. You make me believe municipal asset management is incredibly valuable for the city.

I would also like to thank the University of Waterloo and the Department of Earth Sciences for the scholarships that were awarded to me: the Science Graduate Student Award, the Science Graduate Experience Award, and the International Master Student Award.

Finally, I must express my very profound gratitude to my parents and to my wife for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

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1 Introduction

Due to the continued urban development of the City of Waterloo, the financial sustainability of municipal water supply and drainage system is of ever increasing importance for all residents' daily life. Municipal pipelines are the life lines of cities. Watermains provide potable water to its residents and business developments. Sanitary sewers collect and transport wastewater to the treatment plant. There is also another pipe system collect and transport storm water. To keep this municipal pipeline system working and in good condition, financial expenses are incurred for capital and operational expenses which subsequently can cause affordability issues for the municipal governments and the residents of the cities. The water (from river or ground water source) needs to be treated to make it potable. Then, the potable water is supplied to the residents through watermains. After that, sanitary sewers collected waste water to treatment plant to treat the water again to discharge it safely back into the natural water body. All these municipal water treatment and distribution processes consume labour, material and energy resources.

The City of Waterloo is located in the Laurel Creel Watershed, and obtains its potable water mostly from the groundwater wells and also in part from the Grand River. After treatment, the potable water is sold to consumers living in the City of Waterloo. These customers then pay to discharge their wastewater, which is then treated to comply with Ontario Ministry of the Environment standards. Finally, the wastewater can be discharged back into the Grand River. As the municipal infrastructure ages, those pipes deteriorate and exhibit cracking and breaking. Therefore, another cost of the water distribution system is to maintain and repair those leaking municipal pipelines. At the same time, the leaking drinking water costs money at the drinking water treatment plant, and the infiltrated groundwater into the sewer pipelines costs money at the wastewater treatment plant. As the development of the urban area in the City of Waterloo, to maintain the water supply and drainage system sustainable, it is essential to develop infrastructure asset management strategies.

1.1 BACKGROUND

Due to growing water demand needed to support urban development, a quantitative understanding of the hydrological cycle is imperative. For this purpose, numerical models are inevitable tools. A wide range of numerical models of different complexity have been developed for this purpose that range from simple lumped parameter models to more complex physically based models. The foundation of physically-based models is the blueprint paper by Freeze and Harlan (1969), and many physically based models have been developed following this blueprint. HydroGeoSphere is one of them.

The origin of HGS is the code FRAC3DVS, developed by Therrien at the University of Waterloo (Therrien, 1992). This code was designed to simulate variably saturated groundwater flow and advective-dispersive solute transport in fractured and porous media. VanderKwaak (1999) created the Integrated Hydrology Model (InHM) based on FRAC3DVS. InHM is an integrated physically-based numerical model, which can simulate surface and subsurface hydrologic response to precipitation and chemical transport within coupled hydrologic system (VanderKwaak, 1999).

Then, the InHM led to the development of HydroGeoSphere . A two-dimensional surface water flow and transport component were incorporated in FRAC3DVS and the code was renamed HydroGeoSphere (Therrien et al., 2003). The most important feature of HGS is its ability to simulate water flow in a fully integrated model, thus allowing precipitation to partition into all key components of the hydrologic cycle.

To implement Ontario Ministry of the Environment's financially sustainable water infrastructure legislation (Rehan et al., 2011), the water utility requires a knowledge-based hydrological simulation model to quantify the interaction of groundwater and surface water flow with engineered structures representing the water and the wastewater infrastructure systems. Given the approximately 80% of the Laurel Creek watershed is comprised of the urban expanse of the City of Waterloo, a HydroGeoSphere model representation of the Laurel Creek Watershed is necessary to assess issues of suitability.

The Laurel Creek Watershed has been studied by the hydrology group of the University of Waterloo for a long time. The sub-surficial geological and hydrostratigraphy data, as well as numerous precipitation, climate data collected over the years, makes a good condition to build up the numerical modeling for the Laurel Creek Watershed. At first, the InHM model of the Laurel Creek Watershed has been done by Professor John Jones at the University of Waterloo. Then, during the period of updating, the InHM model has been translated into HydroGeoSphere with the addition of fully integrated evapotranspiration parameters.

However, due to the urbanization of the City of Waterloo, the urban area has been extended during last few years, which influences the evapotranspiration pattern a lot (Guo, 2014). Therefore, part of my undergraduate thesis work was updating the land use of the City of Waterloo to get latest values of different parameters of the evapotranspiration. Then, Lindsay Bowman, the master student working on this project at that time, updating the new evapotranspiration pattern into this Laurel Creek Watershed hydrological model (Bowman, 2016).

1.2 RESEARCH OBJECTIVES

The objective of this thesis is to include the sanitary sewer network into the hydrologic model of the Laurel Creek Watershed. This hydrologic model can then simulate the interaction between the natural hydrologic cycle and municipal pipelines within the watershed, and their influence on groundwater and surface water flows. This objective will be achieved in three steps. Firstly, the hydrologic model of Laurel Creek Watershed needs to be rebuilt with the modified soil layers. Secondly, the pipeline GIS data will be transferred into Grid Builder, which has the same two-dimensional mesh surface as the three-dimensional mesh layer in the HGS model. The third step is to insert the two-dimensional pipe layer into the Laurel Creek Watershed model, and the model will be rerun with sanitary sewer network. The final Laurel Creek Watershed model with the water infrastructure of the City of Waterloo will be used to assess the water interaction between city's water infrastructure system and the natural hydrological cycle.

2 Site Description

The Laurel Creek Watershed is a subwatershed located within the Grand River Basin in Southern Ontario. It covers an area of 75km^2 with the main drainage going into the Grand River at the eastern boundary of the watershed. There are six streams within the Laurel Creek Watershed, all of them tributaries of the Grand River. Figure 2.1 shows the geographical location of the Laurel Creek Watershed within the Grand River Watershed. Figure 2.2 shows the boundary of Laurel Creek Watershed within a GIS map.

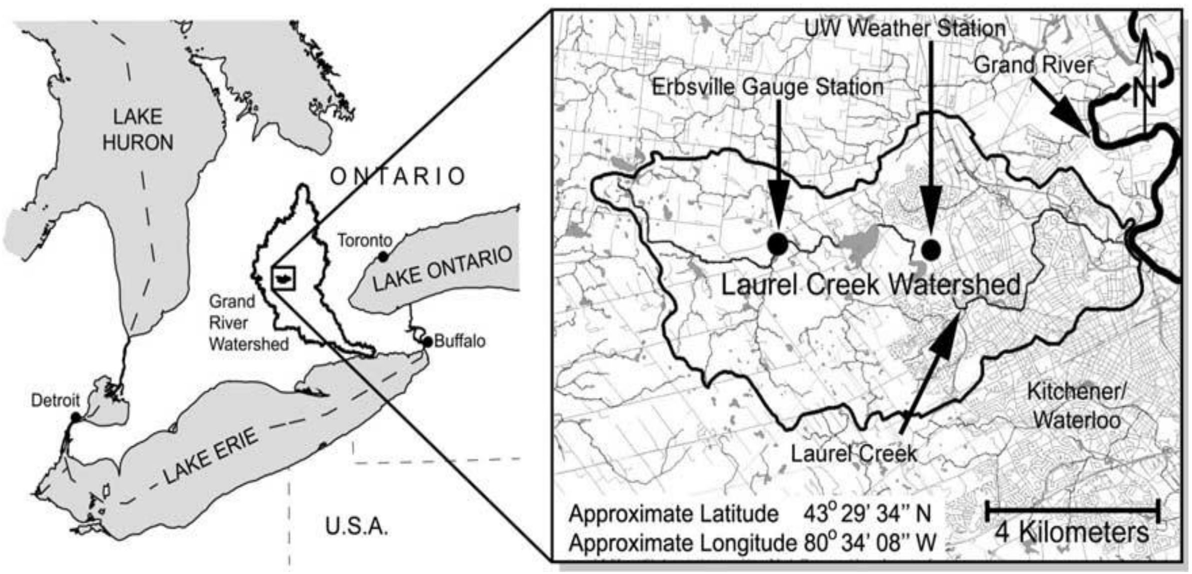

Figure 2.1: Location of the Laurel Creek Watershed within the Grand River Watershed (Jones et al. 2008)

Surface elevation ranges from 410m above sea level to 300m at the discharge to Grand River. The climate in southern Ontario is sub-humid; the annual average precipitation on the Laurel Creek watershed is 908mm between 1871-2000.

Surface geology consists of complex overburden till that ranges in thickness from 20 to 100m, and hosts all of the surface and groundwater interactions pertinent to the Laurel Creek watershed in the context of the urban water infrastructure system. Geology of the overburden is quite complex, with areas of sandy till, clay, drumlins, and kame moraines. Several types of hydrostratigraphic units were observed from the core logs varying from gravelly clay to silty clay to sandy silt. Overland flow can be measured from the discharge at the six streams at the boundary of the watershed, as well as at the Grand River.

Land cover in the Laurel Creek Watershed is quite varied. The majority of the watershed is temperate grasslands due to nature conservation, agricultural, pasture and golf courses. Temperate deciduous trees grow in forested areas. Broad leaf vegetation is common in farmlands. Different types of vegetation have different rates of evapotranspiration. The second largest portion of land cover in the watershed is urban developed areas covered by city streets, buildings and some soil and vegetation. In these regions, most of the precipitation ends up as overland flow; however, there is transpiration as well due to the variety of vegetation within the urban environment.

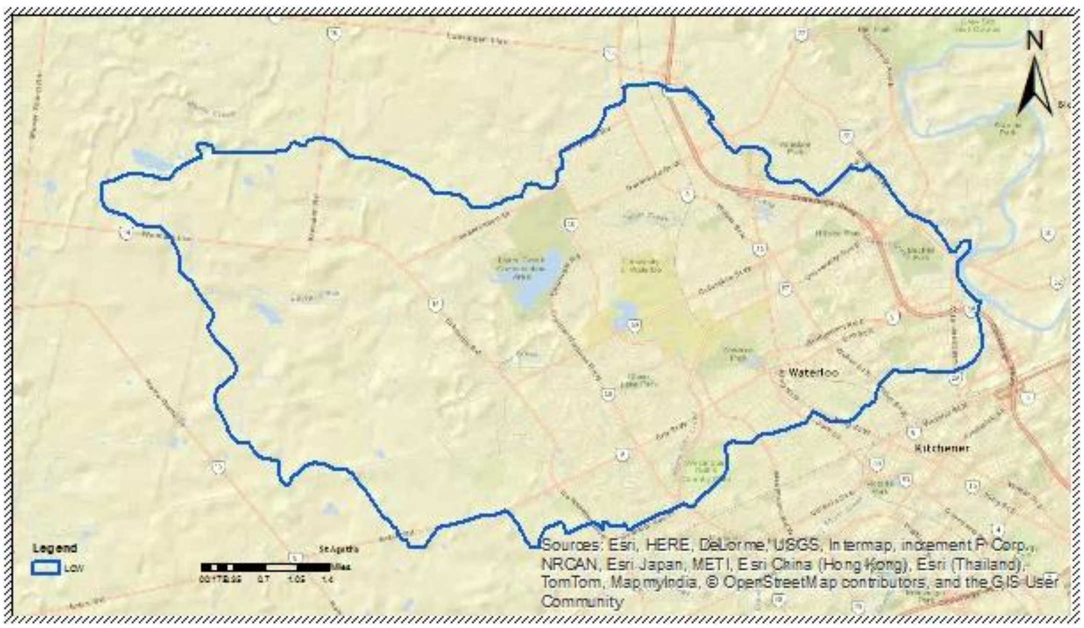

Figure 2.2: The boundary of Laurel Creek Watershed with the GIS map

3 Methodology

3.1 The Laurel Creek Watershed mesh

The hydrologic model of Laurel Creek Watershed from Jones (2005) was rebuilt to accommodate the sanitary sewer infrastructure. The surface of the model conforms to the topography of the land surface, while the bottom of the model conforms to the topography of the impermeable bedrock. An additional surface was inserted into the model to accommodate the plane on which sanitary sewer pipes lie and undergo gravity drainage to the wastewater treatment plant. This section describes the methodology to insert layers into this model that conform to the hydrogeological units.

The two-dimensional surface mesh was created using Grid Builder. Grid Builder is a useful tool to generate a two-dimensional, finite-element grid. The boundary of the mesh was defined by the Laurel Creek Watershed boundary. Inside this boundary, the triangular grids were generated automatically by Grid Builder. Nodes that are adjacent to the streams were refined to a maximum length scale of 25m, while the remainder of the nodes within the watershed has a length scale of 100m. Figure 3.1 show the final two-dimensional Laurel Creek Watershed mesh in Grid Builder.

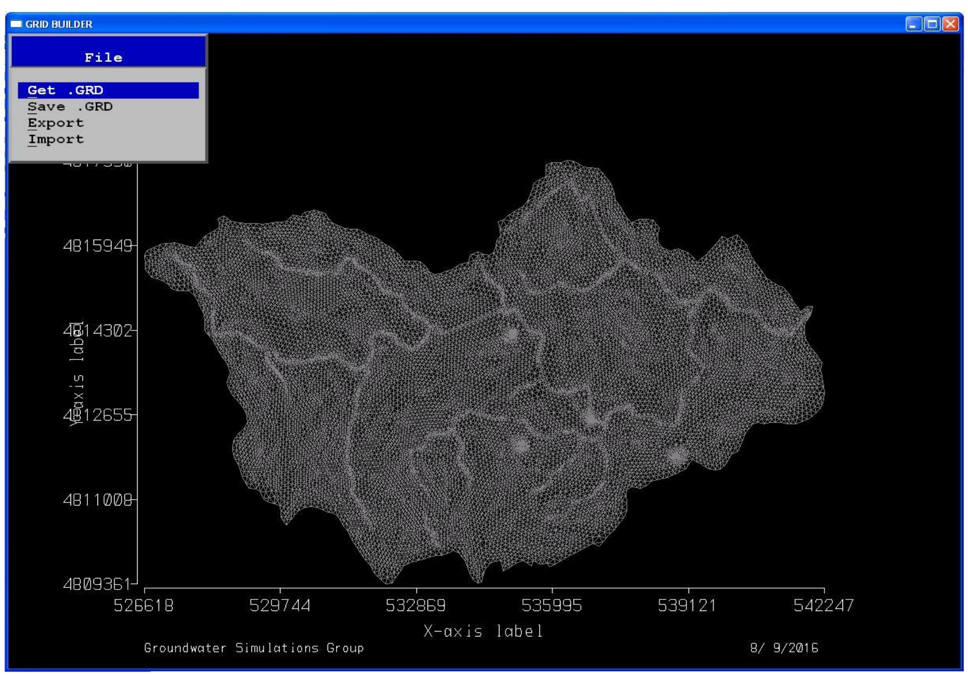

Figure 3.1: The 2-D Laurel Creek Watershed mesh in Grid Builder

Next, the two-dimensional (2-D) mesh was used to generate the three-dimensional (3-D) mesh. The topography of the 3-D mesh was generated using a 10m digital elevation model (DEM). There are 46 layers in total, which are listed in Table 3.1 and Table 3.2.

Table 3.1 itemizes the 21 upper layers that extend from the surface to a depth of 10 meters. These layers constitute the root zone, host the water infrastructure pipe network, and conform to the shape of the surface topography. Among those layers, the first layer is the surface layer, followed by the second layer at 0.1 meter depth. Between the 0.1-m deep layer and the 1-m deep layer, there are additional 7 sublayers with the same interval in between, hosting the shallow root zone. At a depth between 1-m to 2-m, there are three sublayers. The layer at 2-m depth is a sanitary sewer pipe layer containing the sewer pipeline structures. Along the sanitary sewer pipelines, the elevations were remodified using those pipelines' elevations. From 2-m to 10-m depth, there are another 6 sublayers, which establish the root zone and hydro-stratigraphic condition around the sewer pipe layer.

Table 3.1 Upper layers table

Upper Layers Table		
Layer	**Sublayer**	**Depth from surface(m)**
surface layer	-	0
0.1m layer	-	0.1
-	7	-
1m layer	-	1.0
-	3	-
sewer pipe layer	-	2.0
-	6	-
10m layer	-	10.0
-	8	-

The bottom layer of the 3-D mesh conforms to the top surface of the bedrock layer from Waterloo Moraine Model created by Sousa (2013). Between the bottom of the root zone and the top of the bedrock are additional 16 layers as itemized on Table 3.2. These layers capture the different hydro-stratigraphic layers of the moraine.

Table 3.2 Lower layers table

Lower Layers Table	
Layer	Depth from bottom(m)
bottom layer	0
2	4.6
3	5.1
4	5.5
5	13.4
6	21.1
7	29.2
8	34.4
9	39.7
10	44.9
11	45.8
12	46.7
13	47.5
14	48.4
15	49.3
16	50.9
17	52.4

In between the 21 upper layers and the bottom 17 layers, there are an additional 8 sublayers to refine the information of hydro-stratigraphic units. Therefore, there are 46 layers in total in the 3-D HGS mesh. After the regeneration of the 3-D mesh, Figure 3.2 shows the comparison of original mesh and updated mesh. Table 3.3 summarizes the layers, nodes and elements in 2-D Mesh and 3-D Mesh.

Table 3.3: The layers, Nodes & Elements in 2-D Mesh and 3-D Mesh

	2-D Mesh	3-D Mesh
Layers	1	46
Nodes	15,525	714,150
Elements	30,661	1,410,406

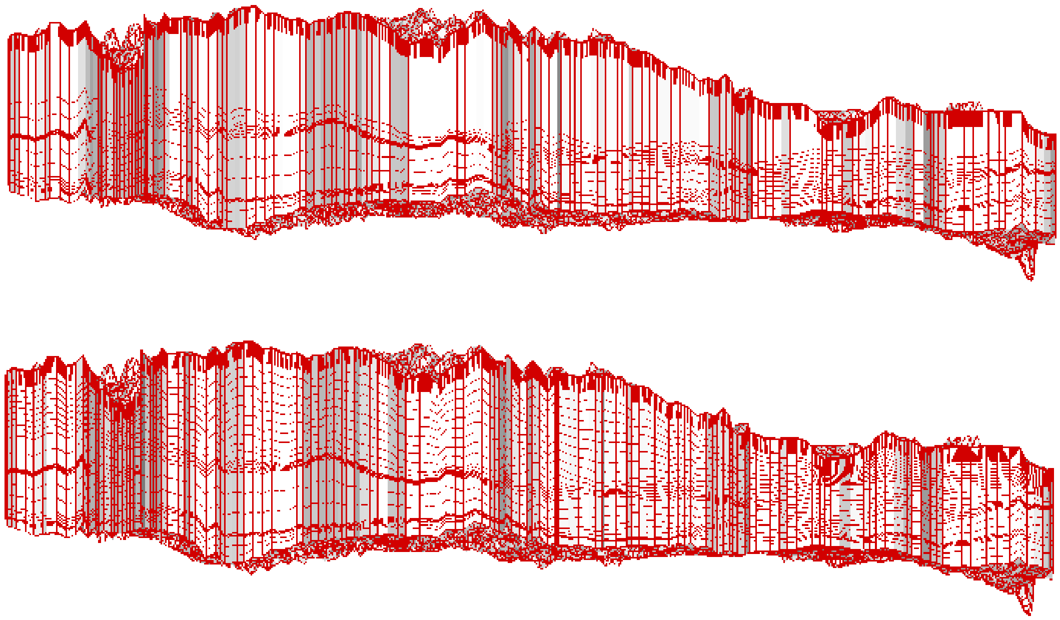

Figure 3.2: The comparison of original mesh (upper) and updated mesh (lower)

3.2 SURFICIAL LAND USE IN THE LAUREL CREEK WATERSHED

The original land use map describing the Laurel Creek Watershed was provided by Grand River Conservation Authority. The urban area in this map was a unique zone, containing no detailed information about the land-use. The urban zoning map was published by the City of Waterloo. This map was then modified to conform to the Laurel Creek Watershed land-use map. Then, the land use map and the zoning map were combined to use in this model by constraining the usages into eight categories shown in Figure 3.3. These eight categories include: agriculture; green zone; forest; residential, university, and institutional; commercial, industrial, and service station; road cover; landfill; and water body. After merging the zoning map into the Laurel Creek Watershed land use map, the urban area contains much more detail information, and the evapotranspiration pattern based on this land-use map can be spatially attributed to the varying land usages within the watershed.

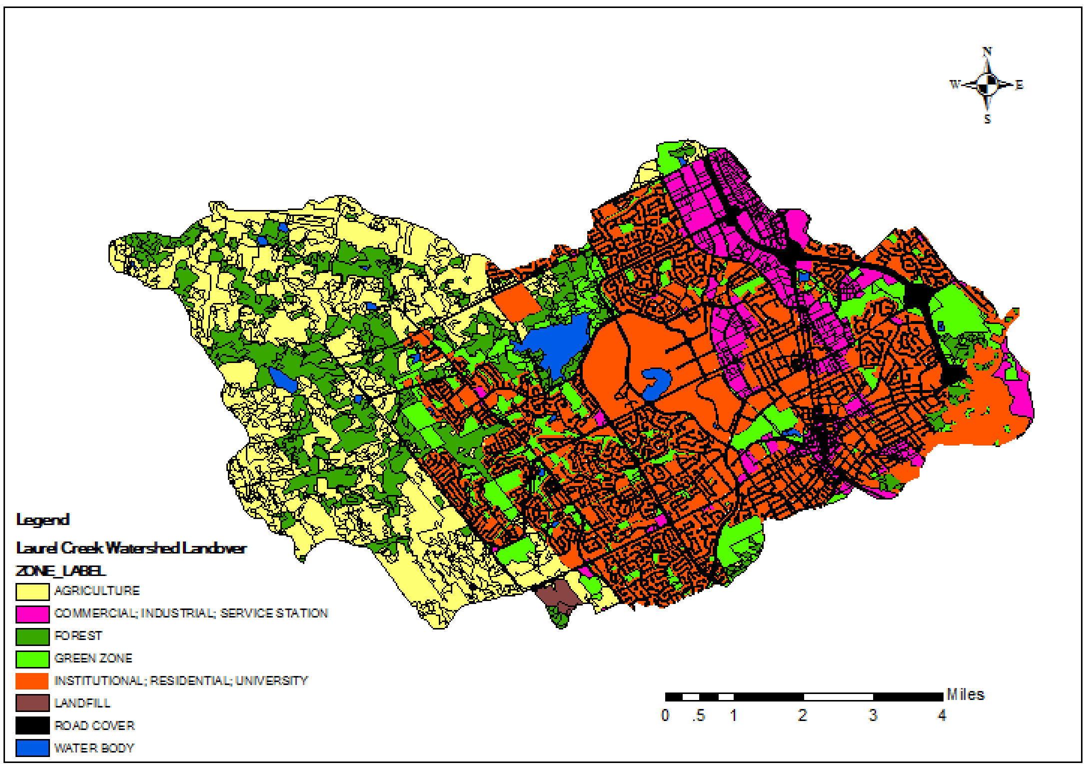

Figure 3.3: Land use in the Laurel Creek Watershed

3.3 SUBSURFACE GEOLOGY

In 1998, the multi-aquifer Waterloo Moraine system was created by Martin and Frind (1998). This Waterloo Moraine model has eight hydrostratigraphic layers. From Figure 3.4, we can see there are three aquifers, four aquitards, and a bedrock layer. This conceptual hydrogeological model was the blueprint for all other Water Moraine hydrogeological models.

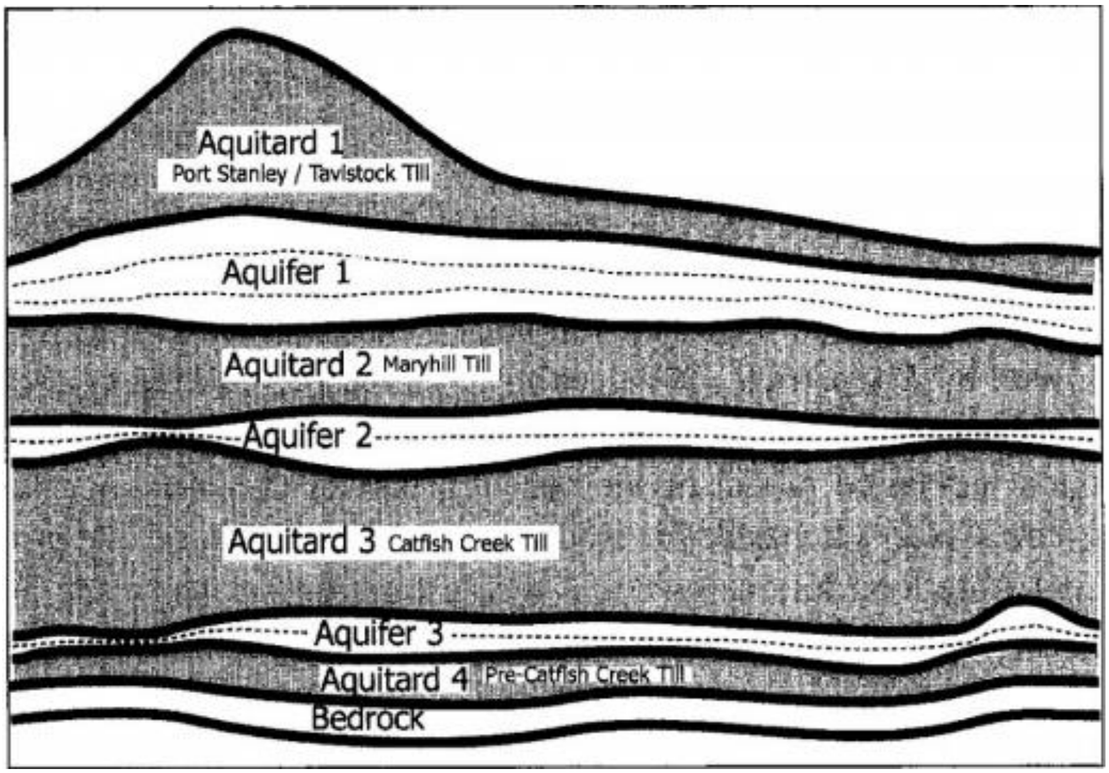

Figure 3.4: Hydrostratigraphic layers of the Waterloo Moraine (Martin and Frind, 1998)

To simulate the Laurel Creek Watershed subsurface geology condition, three parameters need to be used. They are hydraulic conductivity, specific storage, and porosity. In the Laurel Creek Watershed model constructed by Bowman (2016), the hydraulic conductivity values from Sousa (2013) were directly mapped, while porosity and specific storage were based on Jones (2005).

The hydraulic conductivities values within the Bowman (2016) were modified (reduced in value) in order to better replicate the shape of the known water table. Specifically, the hydraulic conductivity values in the current model are listed on Table 3.4 and were obtained from Lappala (1978) as well as Schwartz and Zhang (2003).

Table 3.4: Hydraulic Conductivity of Unconsolidated Materials (Lappala, 1978)

	Hydraulic Conductivity (m/day)					
	Degree of Sorting			Silt Content		
Grain-Size Class	Poor	Moderate	Well	Slight	Moderate	High
1. Fine-grained Materials						
Clay	0.0003					
Silt, clayey	0.3–1.2					
Silt, slightly sandy	1.5					
Silt, moderately sandy	2.1–2.5					
Silt, very sandy	2.7–3.5					
Sandy silt	3.4					
Silty sand	4					
2. Sands and Gravels						
Very fine sand	4	6	8	7	6	4
Very fine to fine sand	8	8	—	7	6	4
Very fine to medium sand	11	12–14	—	10	8	6
Very fine to coarse sand	15	—	—	12	9	7
Very fine to very coarse sand	18	—	—	16	12	9
Very fine sand to fine gravel	23	—	—	20	16	12
Very fine sand to medium gravel	30	—	—	24	20	15
Very fine sand to coarse gravel	39	—	—	33	26	20
Fine sand	8	12	16	10	8	6
Fine to medium sand	16	20	—	15	12	9
Fine to coarse sand	17	20 – 22	—	16	13	10
Fine to very coarse sand	21	—	—	18	14	11
Fine sand to fine gravel	27	—	—	23	18	13
Fine sand to medium gravel	35	—	—	29	23	17
Fine sand to coarse gravel	44	—	—	33	27	22
Medium sand	20	24	29	20	16	12
Medium to coarse sand	23	29	—	22	17	13
Medium to very coarse sand	26	30–34	—	22	19	15
Medium sand to fine gravel	31	—	—	26	21	16
Medium sand to medium gravel	40	—	—	35	25	20
Medium sand to coarse gravel	50	—	—	41	33	25
Coarse sand	24	33	41	29	23	16
Coarse to very coarse sand	29	41	—	29	23	17
Coarse sand to fine gravel	35	41–48	—	33	27	21
Coarse sand to medium gravel	45	—	—	35	29	23
Coarse sand to coarse gravel	56	—	—	41	30	28
Very coarse sand	33	45	57	35	29	23
Very coarse sand to fine gravel	41	65	—	37	32	27
Very coarse sand to medium gravel	52	61–69	—	45	37	30
Very coarse sand to coarse gravel	63	—	—	49	40	32
Fine gravel	49	65	81	69	43	33
Fine to medium gravel	61	102	—	61	51	41
Fine to coarse gravel	75	88–102	—	71	58	44
Medium gravel	73	70	122	73	61	49
Medium to coarse gravel	90	143	—	90	74	58
Coarse gravel	102	143	183	102	87	71

Upon further calibration, these hydraulic conductivity values were further decreased by half-an-order-of-magnitude to further cause the simulated groundwater table to match the estimated groundwater table. Finally, the hydraulic properties using in the current version Laurel Creek Watershed model are summarized in Table 3.5.

Table 3.5: Hydraulic Properties of Different Soil Type

Soil Type	Hydraulic Conductivity (K) [m/s]	Specific Storage (Ss) [m^{-1}]	Porosity (Φ) [-]
Silty clay	6.94×10^{-7}	9.75×10^{-4}	0.45
Clayey silt	1.16×10^{-6}	2.30×10^{-4}	0.45
Sandy clay	1.74×10^{-6}	9.75×10^{-4}	0.43
Gravelly clay	2.78×10^{-6}	9.75×10^{-4}	0.42
Silt	3.48×10^{-6}	2.30×10^{-4}	0.43
Sandy silt	5.32×10^{-6}	2.30×10^{-4}	0.41
Gravelly silt	7.18×10^{-6}	2.30×10^{-4}	0.41
Clayey sand	7.88×10^{-6}	1.62×10^{-4}	0.39
Silty sand	9.26×10^{-6}	1.62×10^{-4}	0.37
Fine sand	2.78×10^{-5}	1.62×10^{-4}	0.38
Medium sand	5.56×10^{-5}	1.19×10^{-4}	0.36
Coarse sand	7.64×10^{-5}	7.45×10^{-4}	0.37
Gravel	8.10×10^{-4}	1.10×10^{-5}	0.28

3.4 MEASURED HYDRAULIC HEAD DATA IN THE LAUREL CREEK WATERSHED

Comparison of measured and simulated hydraulic head values is a necessary step to check the accuracy of a simulated model. However, only limited measured hydraulic data were obtained in time for this analysis.

Bowman (2016) used measured hydraulic head data from Sousa (2013) to compare with the Laurel Creek Watershed simulated hydraulic head data. The same hydraulic head measurements were used in this study. However, all the measured hydraulic head values only varied by a few meters because measurement locations were obtained within a 4 km^2 area. This is a very small area compared to the entire area of the Laurel Creek Watershed.

Jones (2005) used hydraulic head data potentially from Martin (1994) to calibrate his Laurel Creek Watershed model. However, I was unable to obtain the same data set. Potentially the data could also be obtained from the Region of Waterloo with their permission.

Given that the presentation of this model does not include a groundwater hydraulic head calibration exercise, the model presented herein simply serves as a prototype demonstrating the efficacy of including sanitary sewer pipes within an integrated hydrologic model.

3.5 EVAPOTRANSPIRATION

Evapotranspiration is an important component in the natural water cycle system, and is a combination of evaporation and transpiration. Evaporation is water changing from liquid to vapor phase. Transpiration occurs when plants absorb water from subsurface for respiration as water vapor is transferred from the leaf stomata into the atmosphere. To study and simulate the evapotranspiration process in the model, potential evapotranspiration and actual evapotranspiration are two parameters that are required. Potential evapotranspiration (E_p) is the amount of water that can be transferred to the vapor phase given an unlimited water source supply. Actual evapotranspiration is the amount of evapotranspiration occurring given the actual availability of water to support plant respiration. Given typical limitations in available water, potential evapotranspiration is greater than or equal to actual evapotranspiration.

Potential evapotranspiration is calculated using Hargreaves equation. Hargreaves equation is based on the climate of the region and independent to vegetation types. The E_p assumes the ideal condition and gives maximum amount of evapotranspiration that takes place for a region.

$$E_p = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} \times Ra \quad (1)$$

Where T_{mean}, T_{max}, and T_{min} are the daily mean, maximum and minimum air temperatures [˚C], and R_a is the daily water equivalent of the extraterrestrial radiation [L/T in mm/day]. Daily temperature data were provided by the UW weather station, while monthly extraterrestrial radiation values were obtained from Food and Agriculture Organization of the United Nations (Guo, 2014). These data are used to construct daily estimates of the potential evapotranspiration using Hargreaves formulae. Results are shown in Figure 3.5.

Actual evapotranspiration is modeled as the sum of plant transpiration E_T and evaporation from the surface and subsurface domains E_{SG}. Plant transpiration E_T [L/T] is estimated using a largely empirical relationship that distributes the net capacity for transpiration among various factors, and is given as:

$$E_T = f_1(LAI)f_2(\theta)RDF(L_r)[E_p - E_{can}] \tag{2}$$

where E_{can} is the canopy evaporation [L/T] of water held in interception storage.

The vegetation term $f_1(LAI)$ [–] is a function of the leaf area index and is given as:

$$f_1(LAI) = \max(0, \min[1, C_2 + C_1\mathrm{LAI}]) \tag{3}$$

The moisture content term$f_2(\theta)$ [–] is defined as:

$$f_2(\theta) = \begin{cases} 0 & for\ 0 \le \theta \le \theta_{wp} \\ 1 - \left[\frac{\theta_{fc}-\theta}{\theta_{fc}-\theta_{wp}}\right]^{\frac{C_3}{E_p}} & for\ \theta_{wp} \le \theta \le \theta_{fc} \\ 1 & for\ \theta_{fc} \le \theta \le \theta_o \\ 1 - \left[\frac{\theta_{an}-\theta}{\theta_{an}-\theta_o}\right]^{\frac{C_3}{E_p}} & for\ \theta_o \le \theta \le \theta_{an} \\ 0 & for\ \theta_o \le \theta \end{cases} \tag{4}$$

where C_1, C_2, and C_3 are dimensionless fitting parameters; θ_{fc}, θ_{wp}, θ_o, and θ_{an} are the soil moisture contents at field capacity, wilting point, oxic limit and anoxic limit, respectively.

Additional evaporation of water E_{SG}[L/T] from the surface and subsurface process is given by:

$$E_{SG} = \alpha^*[\mathrm{Ep} - E_{can}][1 - f_1(LAI)]EDF(B_{soil}) \tag{5}$$

where α^* is a wetness factor given as:

$$\alpha^* = \begin{cases} (\theta_1 - \theta_{e2})/(\theta_{e1} - \theta_{e2}) & for\ \theta_{e2} \le \theta \le \theta_{e1} \\ 1 & for\ \theta > \ \theta_{e1} \\ 0 & for\ \theta < \ \theta_{e2} \end{cases} \tag{6}$$

Evapotranspiration parameters obtained by Li (2008) when applying the HGS model to the Duffins Creek Watershed are adopted here for the Laurel Creek Watershed given their close geographic proximity. These values are itemized on Table 3.6 below.

Table 3.6: Fitting parameters for evapotranspiration process

	The Name of Parameters	Value [-]
C_1	Fitting parameter	0.31
C_2	Fitting parameter	0.20
C_3	Fitting parameter	1.00
θ_{wp}	Moisture content at wilting point	0.20
θ_{fc}	Moisture content at field capacity	0.32
θ_o	Moisture content at oxic limit	1.00
θ_{an}	Moisture content at anoxic limit	1.00
θ_{e1}	Moisture content above which evaporation can occur	0.20
θ_{e2}	Moisture content below which evaporation is zero	0.32

The leaf area index and the maximum rooting depth of each zone are calculated based on the area ratio of different vegetation types within them. For example, in the forest zone, the area ratio of deciduous trees (4,431,645.14 m^2) and coniferous trees (371,648.85m^2) is about 12. Therefore, the 92.3 percentage area is deciduous trees, and the 7.7 percentage area is coniferous trees. Assume deciduous tree's value is A, and coniferous tree's value is B. Then, the weighted arithmetic mean value is 92.3%A+7.7%B.

Leaf area index values were further modified using data from the global synthesis of leaf area index observations (Asner, 2003) shown in Table 3.7. These values follow from the mean data within the Inter-Quartile Range (IQR) analysis. Based on the vegetation types living in Laurel Creek Watershed, the leaf area indexes of grasslands, crops, temperate coniferous and temperate deciduous are used to calculate the leaf area index of different land use zones.

Table 3.7: Statistical distribution of leaf area index by biome for the original data compilation and after removal of statistical outliers using Inter-Quartile Range (IQR) analysis. (Asner, 2003)

	Original data					Data after IQR analysis				
Biome	Observations	Mean	Standard deviation	Min	Max	Outliers Removed	Mean	Standard deviation	Min	Max
All	931	5.2	4.1	0.01	47.0	53	4.5	2.5	0.01	18.0
Crops	88	4.2	3.3	0.2	20.3	5	3.6	2.1	0.2	8.7
Desert	6	1.3	0.9	0.6	2.8	0	1.3	0.9	0.6	2.8
Forest/BoDBL	58	2.6	1.0	0.3	6.0	5	2.6	0.7	0.6	4.0
Forest/BoENL	94	3.5	3.3	0.5	21.6	8	2.7	1.3	0.5	6.2
Forest/BoTeDNL	17	4.6	2.4	0.5	8.5	0	4.6	2.4	0.5	8.5
Forest/TeDBL	187	5.1	1.8	0.4	16.0	3	5.1	1.6	1.1	8.8
Forest/TeEBL	58	5.8	2.6	0.8	12.5	1	5.7	2.4	0.8	11.6
Forest/TeENL	215	6.7	6.0	0.01	47.0	16	5.5	3.4	0.01	15.0
Forest/TrDBL	18	3.9	2.5	0.6	8.9	0	3.9	2.5	0.6	8.9
Forest/TrEBL	61	4.9	2.0	1.5	12.3	1	4.8	1.7	1.5	8.0
Grasslands	28	2.5	3.0	0.3	15.4	3	1.7	1.2	0.3	5.0
Plantations	77	8.7	4.3	1.6	18.0	0	8.7	4.3	1.6	18.0
Shrublands	5	2.1	1.6	0.4	4.5	0	2.1	1.6	0.4	4.5
Tundra	13	2.7	2.4	0.2	7.2	2	1.9	1.5	0.2	5.3
Wetlands	6	6.3	2.3	2.5	8.4	0	6.3	2.3	2.5	8.4

Professor John C. Semple, from the Department of Biology at the University of Waterloo, provided root depth information regarding the most common species living in the Laurel Creek Watershed using data from Canadell et al (1996). The most common crops are wheat, zea mays, soy bean and oats. The temperate coniferous trees are mostly pinus strobus. The temperate deciduous trees are mostly acer saccharum and quercus macrocarpa. For the grassland, several types living in South Canada have been concerned, and the arithmetic mean value has been used. Finally, the leaf area index and maximum rooting depth of each zone shown in Figure 3.3 are calculated based on the area ratio of different vegetation types occupying their respective zone. All results are summarized in Table 3.8.

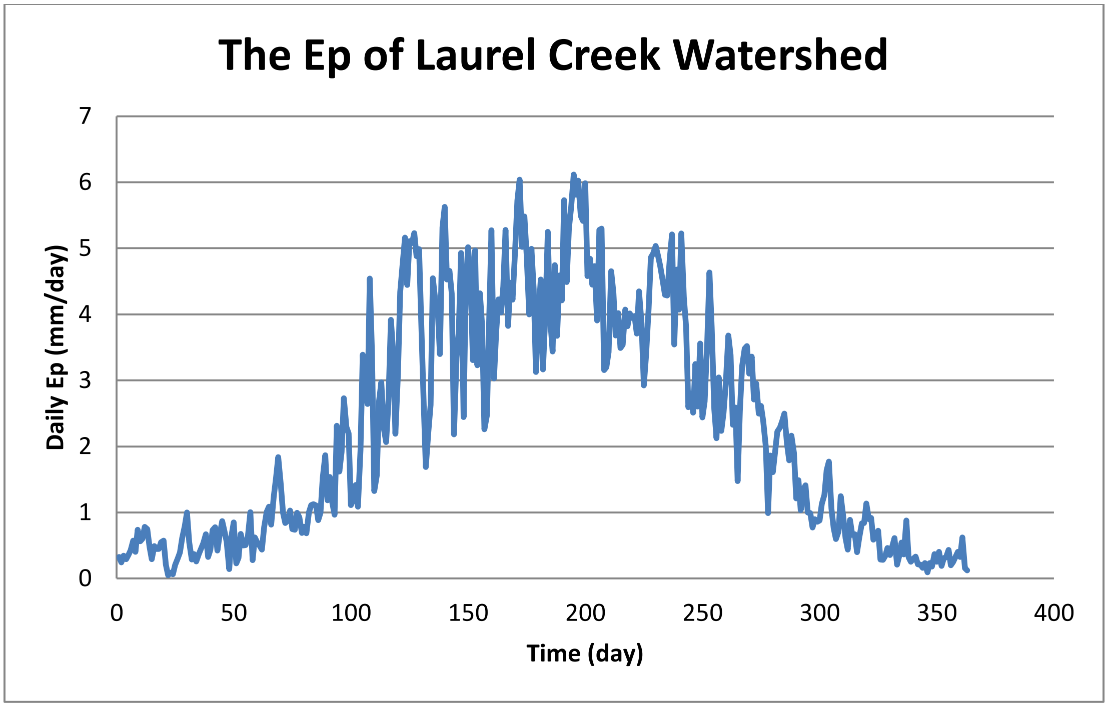

Figure 3.5: The daily potential evapotranspiration of Laurel Creek Watershed

Table 3.8: The leaf area index & maximum rooting depth of different land use zones in Laurel Creek Watershed

Land use zones	Leaf area index	Maximum rooting depth (m)
Agriculture	3.60	2.13
Forest	5.15	3.93
Green zone	3.77	3.16
Residential	1.55	1.49
Commercial	0.00	0.00
Road cover	0.00	0.00
Landfill	0.00	0.00
Water body	0.00	0.00

3.6 INFRASTRUCTURE

Figure 3.6 shows the sanitary sewer pipeline network for the City of Waterloo obtained using a GIS database. Information includes the location, the depth, the pipe material, the diameter, the construction year and all other information of the watermain, sanitary sewer and storm sewer. The GIS data was then used to construct a layer within the mesh to accommodate a subsection of the pipe network. In this initial attempt to include water distribution infrastructure, the watermain pipes were neglected. Given that the sanitary sewer and storm sewer are both gravity drainage systems, their elevation decreases from the periphery of the municipal pipeline system to the wastewater treatment plant.

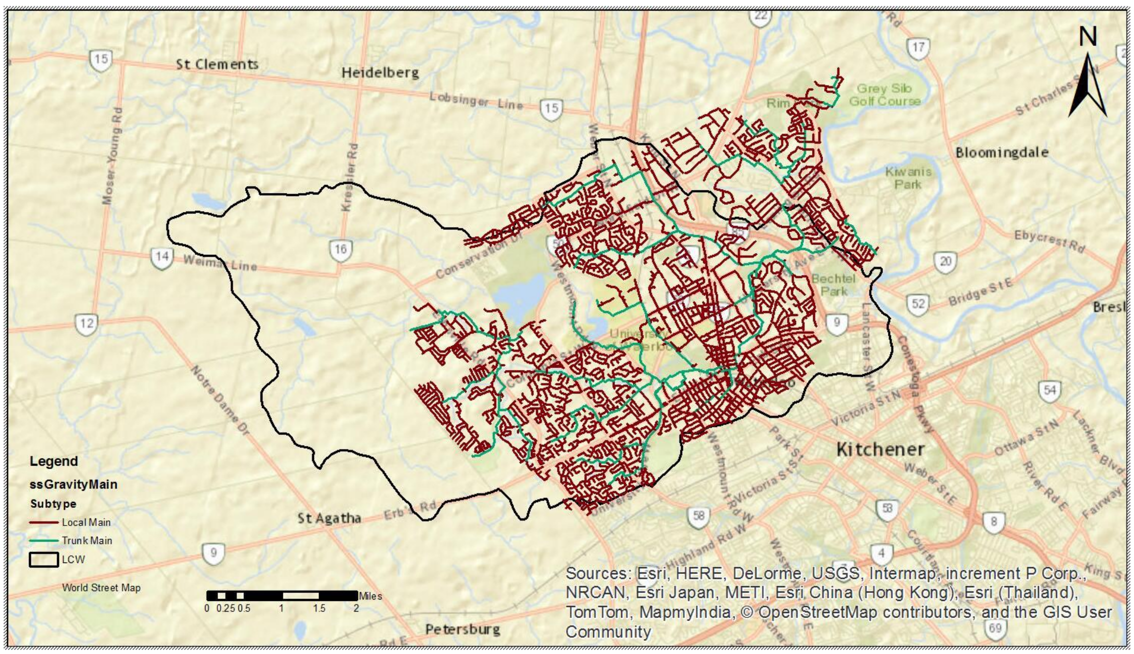

Figure 3.6: The Sewer Pipelines of The City of Waterloo

3.6.1 Select the Infrastructure to simulate in the HGS model

In Figure 3.6, there are two types of sewer pipelines: sewer trunk lines and smaller-sized sewer pipeline which are colored in green and orange, respectively. The sewer trunk lines collect wastewater from the sewer pipelines, and transport the wastewater to corresponding treatment plant. In Figure 3.6, it is clear that not all of the sewer trunk lines are connected together; the sewer trunk lines at the southwest and northeast parts of the sewer pipeline system are separated from the main sewer trunk lines (middle part) in the City of Waterloo. In this case, only the wastewater from the main sewer trunk lines is drained to the Waterloo Wastewater Treatment Plant while the wastewater in other pipelines drains to separate locations.

The above mentioned circumstances can be explained by the surface topography of the City of Waterloo. The northeast part of the sewer pipelines is beyond the boundary of the Laurel Creek Watershed. Because the boundary of a watershed is defined by surface water drainage resulting from topography, sanitary sewer pipes outside of the watershed boundary drain by gravity to locations outside the watershed. In terms of the southwest part of the sewer pipelines, they are located at the downhill side, where gravity drives the flow towards the opposite direction to the Waterloo Wastewater Treatment Plant.

The measured municipal sewage flow data is obtained from the Waterloo Wastewater Treatment Plant. Therefore, only the sewer pipelines connected to the plant are included in the model simulation. Figure 3.7 illustrates the sewer pipelines selected in the model.

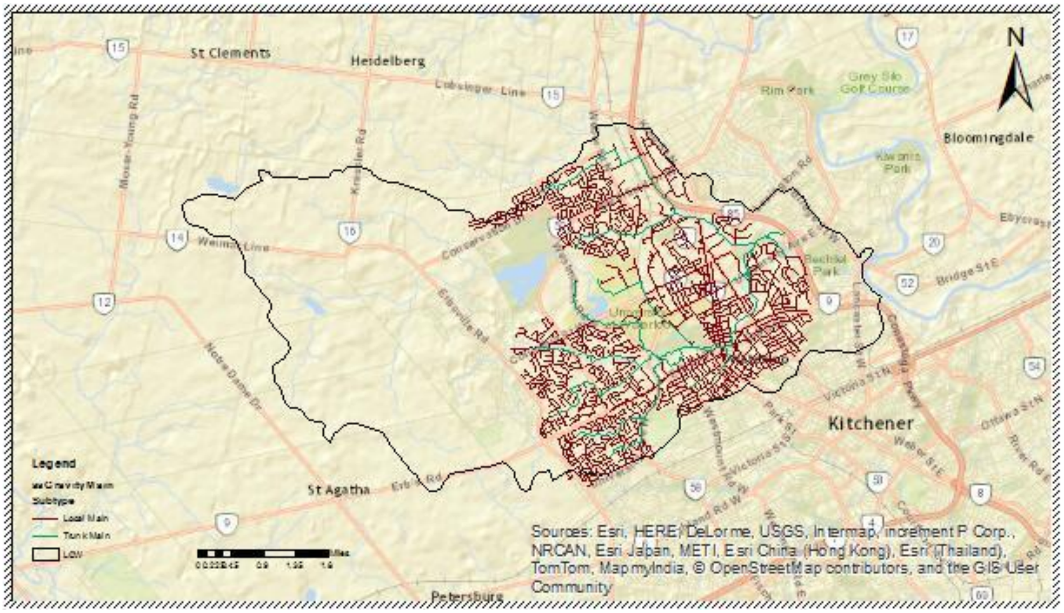

Figure 3.7: Sewer pipelines selected in the model simulation

Given the complexity of the sanitary sewer pipe network, and the need to include it within a specific layer of the hydrological model, only a subset of the pipes consisting of trunk lines that drain the broad region of the city towards the wastewater treatment plant were included for this analysis. Finally, the subset of sanitary sewer pipes was used in this model shown in Figure 3.8.

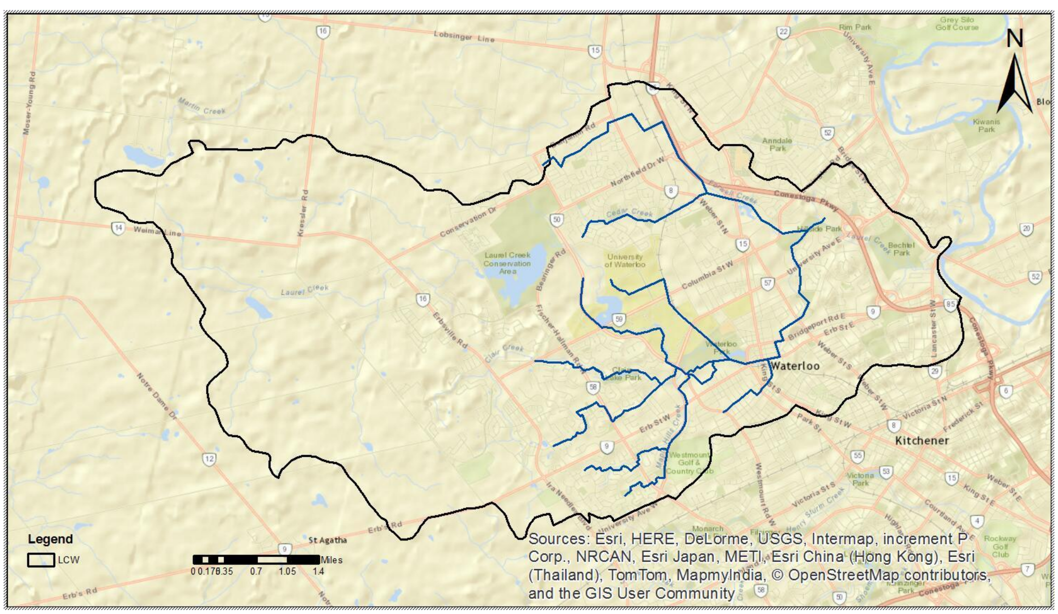

Figure 3.8: The Selected Sewer Trunk Lines in the Laurel Creek Watershed

Table 3.9 Dimensions and Approximate Mass of Concrete Pipe

CSA A257.2M - Reinforced Concrete Culvert, Storm Drain, Drain and Sewer Pipe, Bell and SpigotWALL				
	Wall B		Wall C	
Nominal Internal Diameter mm	Minimum Wall Thickness mm	Approx. Mass kg/m	Minimum Wall Thickness mm	Approx. Mass kg/m
300	50	162		
375	57	216		
450	63	253		
525	69	327		
600	75	430	94	545
675	82	500	100	625
750	88	598	107	708
825	94	695	113	821
900	100	832	119	973
975	113	923	125	1090
1050	117	1057	132	1207
1200	125	1324	144	1504
1350	138	1589	157	1798
1500	150	1927	169	2192
1650	163	2295	182	2582
1800	175	2695	194	2998
1950	188	3125	207	3586
2100	200	3585	219	3958
2250	213	4078	232	4494
2400	225	4598	244	4993
2550	238	5179	257	5595
2700	250	5752	269	6190
3000	279	6344	298	7401
3600	330	9921	349	9117

The material of those sewer trunk lines is concrete, and the average diameter is 900mm. The relations between nominal internal diameters of concrete pipes and minimum wall thickness are listed on the Table 3.9 and were obtained from OCPA Concrete Pipe Design Manual (Ontario Concrete Pipe Association, 1997). For the 900mm concrete pipes, the minimum wall thickness is 100mm in the wall B list and 119mm in the wall C list. For the City of Waterloo, the loading on the sewer trunk lines is relatively low according to the urban scale. Therefore, the wall thickness of sewer trunk lines is using 100mm in the model.

Table 3.10 shows the measured sewer water balance for the City of Waterloo. Metered water is the amount of water supplied to the customers. Non-consumptive water is typically used for washing the car or watering the lawn/garden. Treated sewer water is the amount of water received by the waste water treatment plant. I&I is the Inflow & Infiltration between the subsurface water and the sewer water in the sewer pipelines.

The following equation summarized the relationship between those parameters.

$$\text{Treated Sewer Water} = \text{Metered Water} - \text{Non– consumption Water} + \text{I\&I} \qquad (7)$$

Table 3.10: Measured Water Demand

Demand	m^3/year
Metered Water	11,043,299
Treated Sewer Water	14,350,000
Non-consumption Water	1,104,330
I & I	4,422,032
I & I Percent	30.82%

Boundary conditions for the sanitary sewer pipe network include injecting waste water into the upstream ends of the pipeline network, and imposing a constant head boundary condition of 311.81m at the wastewater treatment plant. The volumetric rate of injected is the metered water less the non-consumptive water which is 9,938,969 $m^3/year$, divided equally between the 9 ends of sewer trunk lines, and is calculated yielding an injection rate of 0.035018 m^3/s. In the model, flow of waste water Q is simulated using the Manning equation with a roughness coefficient (n) of 0.013.

$$Q = \frac{1}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad (8)$$

Calibration is achieved by adjusting the HGS coefficient that controls the flow of water between the adjacent porous media and a pipe segment, thereby changing the interaction between the adjacent porous media and pipe segment, and hence groundwater I&I into the sanitary sewer pipes. Wastewater received at the treatment plant is the sum of injected water plus the cumulative I&I that has occurred along their entire network length.

The percentage of I&I in treated sewer water is calculated using the following equation:

$$I\ \&\ I\ Percent = \frac{I\ \&\ I}{Treated\ Sewer\ Water} \times 100\% \qquad (9)$$

The calculated I&I percent will be applied to check the calibration results. Comparing the I&I percent of the simulated sewer water balance to that of the measured sewer water balance is a calibration target for the sewer pipeline model.

3.6.2 Using GB to transfer the infrastructure from GIS data into HGS

The original Laurel Creek Watershed HGS model contains 46 soil layers in total. Among those layers, the geometry of the upper 29 layer meshes are established based on the surface geomorphology, whereas the geometry of the lower 17 layer meshes are derived based on the bedrock geomorphology. In addition, wastewater flow within the sanitary sewer pipelines is dominated by gravity. Because the elevation of the sanitary sewer pipelines is from 311.81m to 373.13m, these sewer pipelines will intersect with some soil mesh layers. However, the one-dimensional sanitary sewer pipelines must all reside in the same layer due to restrictions within the HGS code. Therefore, a two-dimensional sewer mesh layer containing corresponding pipelines was first constructed to contain the sewer network.

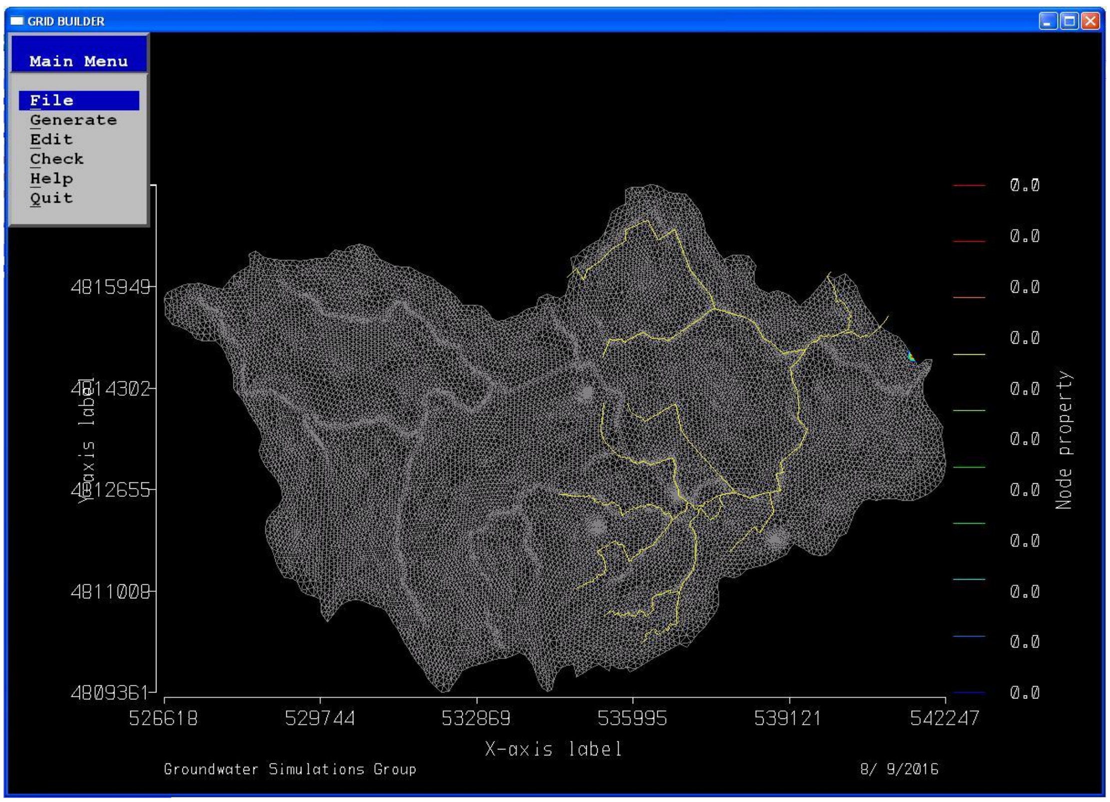

Figure 3.9: Sanitary sewer trunk line GIS data and the 2-D Grid Builder mesh surface

The sewer mesh layer was created using Grid Builder. Figure 3.9 shows the relationship between the GIS sanitary sewer trunk lines (yellow lines) and the 2-D Grid Builder mesh surface. The GIS sewer trunk lines were added on top of the two-dimensional Grid Builder mesh as a separate layer. Then, the nodes beside the sewer pipeline were selected, and node property was set as the ‘Elevation’ of the sewer pipeline beside it. Each pipeline is a few hundred meters long and contains several nodes, and the elevation of each node was determined according to their distance from the origin and termination of each pipeline. By doing this to all of the pipelines, they are transferred to the two-dimensional mesh layer, and the elevation property of the mesh layer is shown in Figure 3.10. It should also be noted that the elevation of all other nodes of the mesh layer is set as 355.5m.

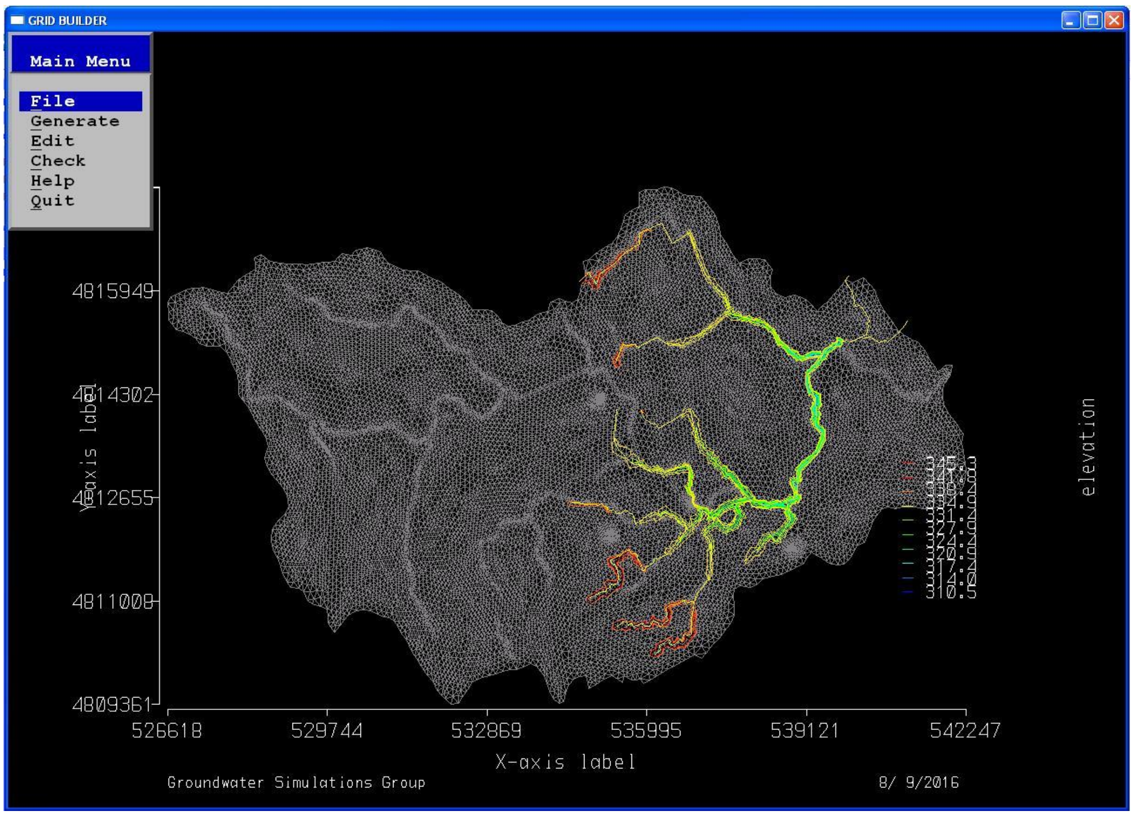

Figure 3.10: The converted pipelines in the 2-D Grid Builder mesh surface

In order to insert the sewer mesh layer into the 3-D Laurel Creek Watershed model, the geometry of the sewer mesh layer should follow that of the 3-D surface geomorphology. Because the elevations of the sewer pipelines are generally around 2 meters below the land surface, the geometry of the sewer mesh layer is also set as 2 meters below the 3-D HGS mesh surface geomorphology. Then, the elevations of the sewer pipelines from the sewer mesh layer were combined into this sewer mesh layer (Figure 3.11). Finally, this 2-D mesh layer created by Grid Builder was inserted into the 3-D Laurel Creek Watershed model. After inserting the sewer mesh layer, the upper root zone mesh layers were refined, and the lower hydro-stratigraphic layers were rebuilt. Then, the hydro-stratigraphic units of this new 3-D mesh were reestablished.

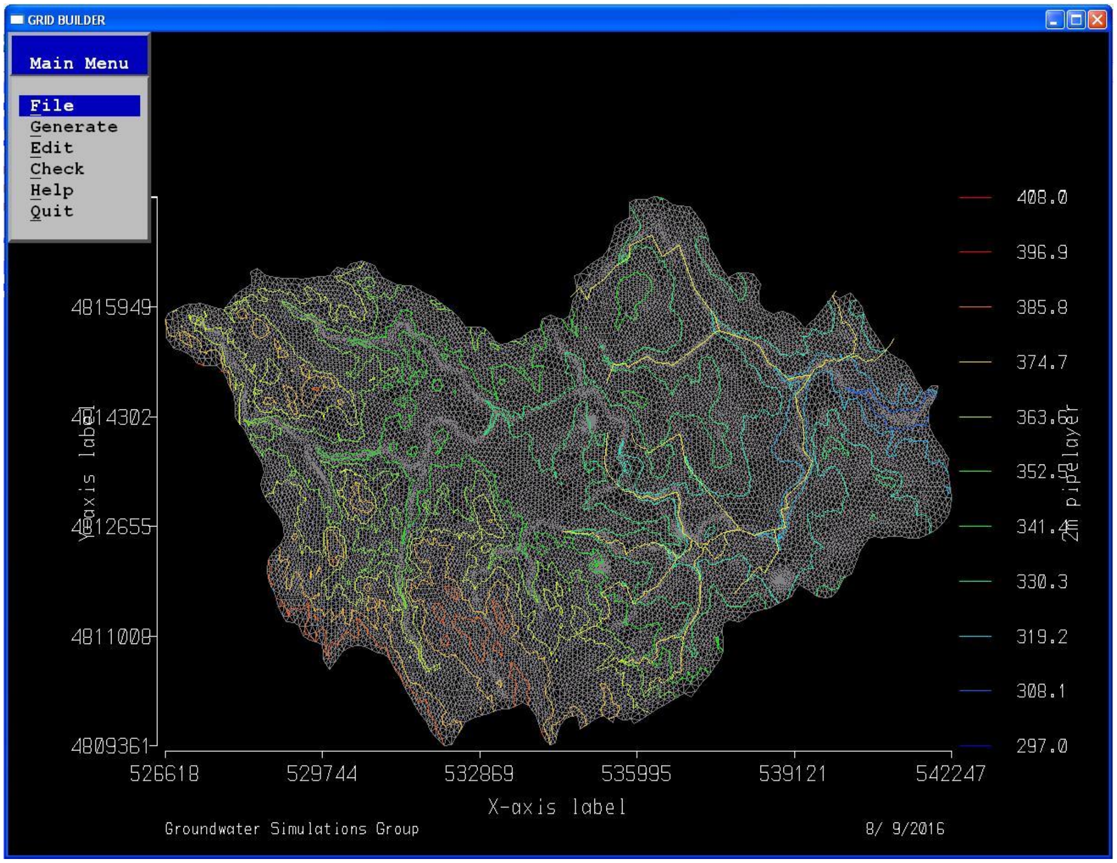

Figure 3.11: The Sewer Mesh Layer

The pipelines were inserted into the model using the "well" function in a manner analogous to tile drains, which means that they trace horizontally along nodes within the 2-D sewer mesh layer surface. Therefore, the locations and elevations of those pipeline nodes in the Grid Builder mesh need to be picked up and converted to be the well function in the HGS code. By inserting the sewer pipe layer into the Laurel Creek Watershed hydrologic cycle model and rerunning the model, the HGS model can simulate flow through sanitary sewer pipelines, and the water interaction between the sewer pipelines and the natural water system can be checked.

3.7 MEASUREMENT OF THE STREAM FLOW IN THE LAUREL CREEK WATERSHED

Two versions of the Laurel Creek Watershed model exist: one with, and one without the sanitary sewer pipe network. A key hypothesis of this work is that the sanitary sewer pipe network will impact stream flows due to the fact that excessive groundwater inflows contribute I&I that is redirected towards the wastewater treatment plant. To examine this issue, both versions of Laurel Creek watershed model are run to steady state. Resulting differences in stream flows between these versions therefore reflect the long-term impact of this infrastructure. Finally, the simulated stream flow values are compared to actual stream flow measurements within the watershed.

This data was obtained from Dr. Mike Stone at the University of Waterloo, Department of Geography. Weekly stream flows measurements were obtained at 10 locations as shown in Figure 3.12. The resulting annual average values are then listed on Table 3.11.

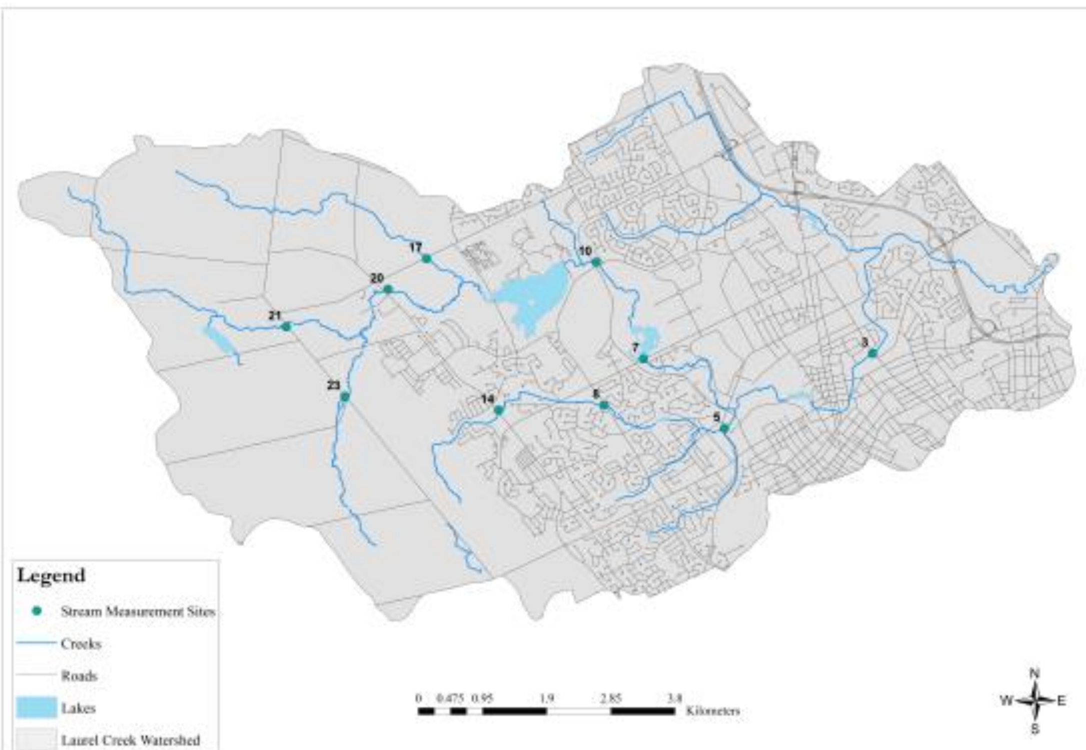

Figure 3.12: Stream Flow Measurement Sites in Laurel Creek Watershed

Table 3.11: Measured Stream Flow from 2010 to 2014

Site NO.	Measured Stream Flow (m3/s)				Average measured Stream flow (m3/s)
	2010	2011	2012	2014	
3	0.234	0.415	0.142	0.150	0.261
5	0.508	0.0683	0.0312	0.0367	0.128
7	0.192	0.222	0.0739	0.0948	0.173
8	0.0259	0.0584	0.00750	0.0114	0.027
10	0.256	0.0311	0.0674	0.123	0.189
14	0.0414	0.0365	0.00700	0.0142	0.0265
17	0.0379	0.0517	0.0191	0.0198	0.0386
20	0.0994	0.198	0.103	0.123	0.133
21	0.0349	0.0546	0.0261	0.0328	0.0357
23	0.0244	0.0292	0.00730	0.00760	0.0455

4 Results

4.1 THE STEADY STATE MODEL WITHOUT SEWER PIPELINE

The mesh layer that hosts the sanitary sewer "wells" is imbedded within the model whether the sanitary sewer pipes are there or not. The steady state model in this section is applied to simulate the natural water cycle. Therefore, the sanitary sewer pipeline "wells" are omitted from the mesh layer. Hereafter, this model will be denoted as the natural water cycle model.

The steady state model has been calibrated to match the measured groundwater table and the natural surface water saturation condition. The fluid balance for the steady-state model is shown in Table 4.1. In this table, the total annual average rainfall and ET in Laurel Creek Watershed, simulated by the aforementioned model, are 2.258 m^3/s (939.42mm/yr) and -1.275 m^3/s (-530.45mm/yr), respectively. The total annual average ET accounts for 56.5% of rainfall.

In terms of the real measurement data, the annual average annual rainfall and ET are 940 mm/year and 510 mm/year, respectively, where the annual ET accounts for 54.3% of the annual rainfall. Therefore, the fluid balance results from the simulating model match perfectly with the practical measurement data.

Table 4.1: Fluid Balance Table

Fluid Balance			
Rate Of Fluid Exchange [m^3/s]; (LCW: Laurel Creek Watershed)			
Boundary Condition Name	**IN**	**OUT**	**NET**
LCW_outlet		-0.971	-0.971
LCW_non_outlet		-0.0122	-0.0122
Rain	2.26		2.26
PotET		-1.28	-1.28
TOTAL	2.26	-2.26	0.000
RATE OF FLUID ACCUMULATION [m^3/s]			
Porous medium	3.26×10^{-7}		
Overland	4.36×10^{-7}		
NET2 ACCUMULATION RATE			7.62×10^{-7}

FLUID BALANCE ERROR			
Absolute: (NET1-NET2)			-2.09×10^{-6}
Relative: (NET1-NET2)/(abs(NET1)+abs(NET2))/2.0			2
Percent: abs(NET1-NET2)/NET1(+ve)*100.0d0			9.26×10^{-5}
FLUID EXCHANGE BETWEEN SURFACE AND SUBSURFACE DOMAIN [m^3/s]			
Infiltration	2.00		2.00
Exfiltration	-0.756		-0.756
Total			1.25
ET COMPONENTS [m^3/s]			
Surface water evaporation	-0.0269		
Subsurface evaporation	-0.323		
Subsurface transpiration	-0.925		
TOTAL ET	-1.28		

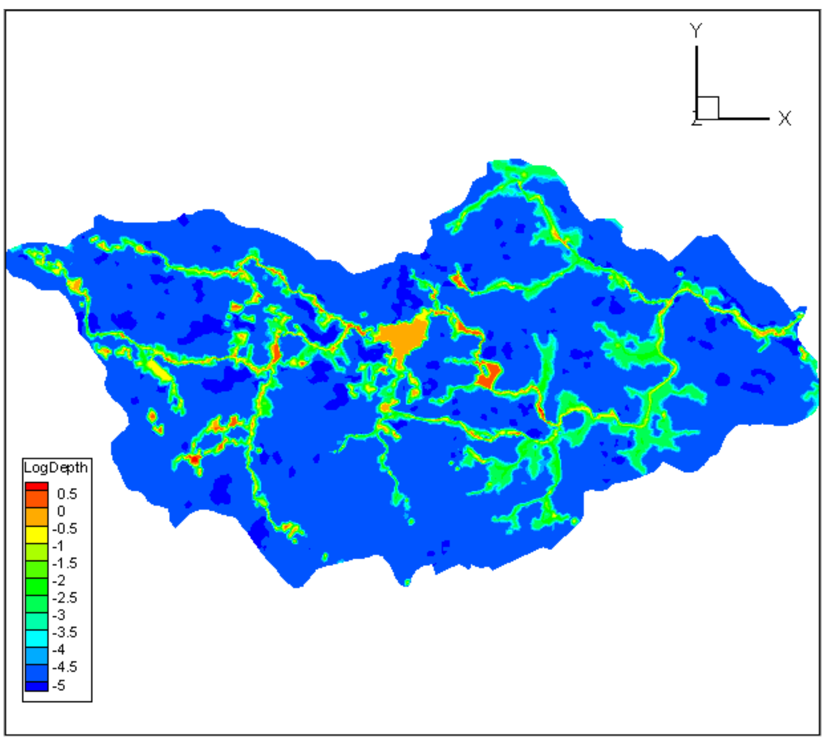

Figure 4.1: Surface flow pattern in $\log_{10}\{depth\ in\ [m]\}$

The surface water depth condition is shown in Figure 4.1 and shown as $\log_{10}\{depth\ in\ [m]\}$. From Figure 4.1, it is evident that all of the creeks are connected to the Columbia Lake, which is distinguished in orange in the center of the map. The deepest depth of the lakes and creeks is around 3.16 m ($10^{0.5}$ m), and that of the shallow parts is around 0.01 m (10^{-2} m). The surface water depth for the areas colored in blue is around 10^{-5} m, which indicates that these areas are not water bodies. Instead, they are commercial, industrial, residential, and agriculture regions with minor overland flow due to runoff from precipitation.

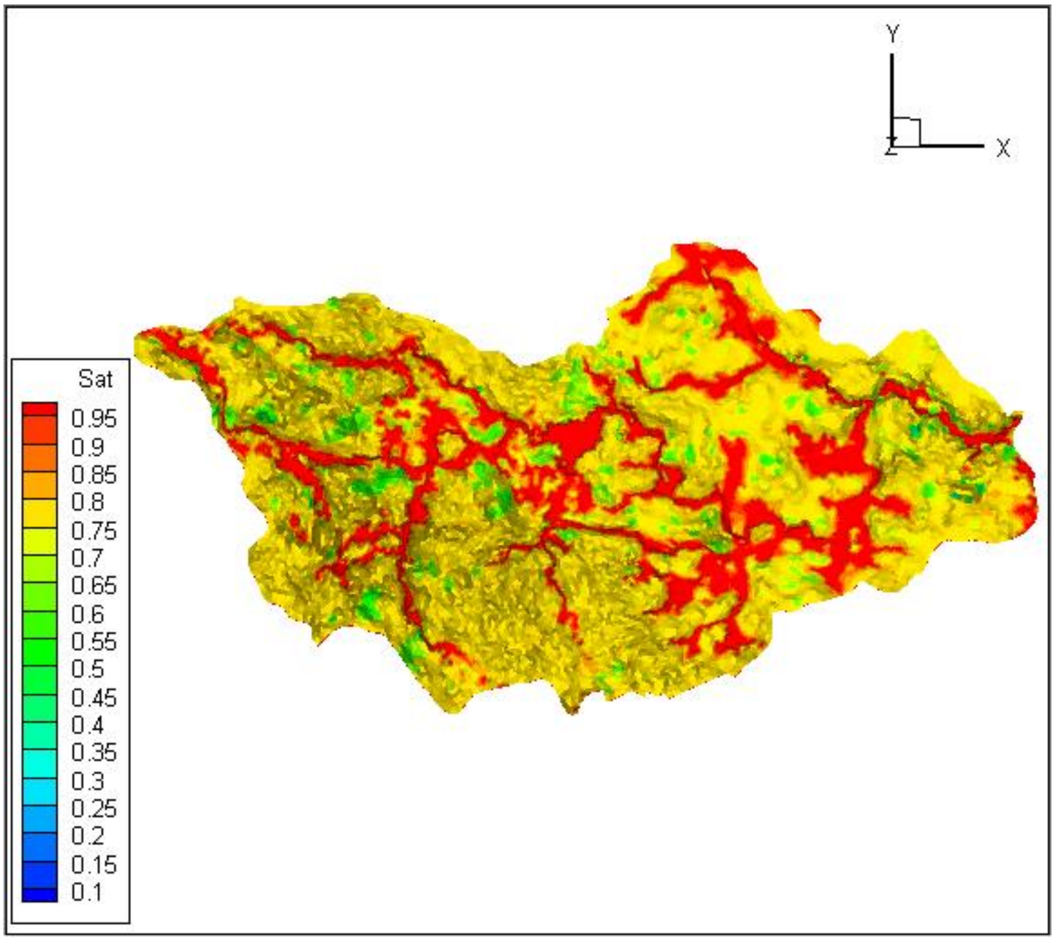

Figure 4.2: Surface water saturation

The surface water saturation map (Figure 4.2) has the similar pattern with the surface water depth map (Figure 4.1). As shown in Figure 4.2 in red, the lakes and creeks are fully saturated. The other areas are shown in dark green to bright yellow color, which represent around 50% to 80% saturation. In addition, the surface water saturation map clearly shows that the locations of all water bodies coincide with those from the surface water depth map.

Figure 4.3 shows the groundwater saturation condition along the west-east orientation. The areas between the bottom layer and around 30 m below the land surface are fully saturated (colored in red), and the areas within 30 m to the land surface are not fully saturated (colored in yellow and green). The boundary between saturated zone and unsaturated zone is the location of the water table, and its pattern has the similar trend with that of the land surface. In addition, as the surface elevation rises from east to west, the water table elevation also increases; similarly, the depth between the water table and the land surface also increases from east to west.

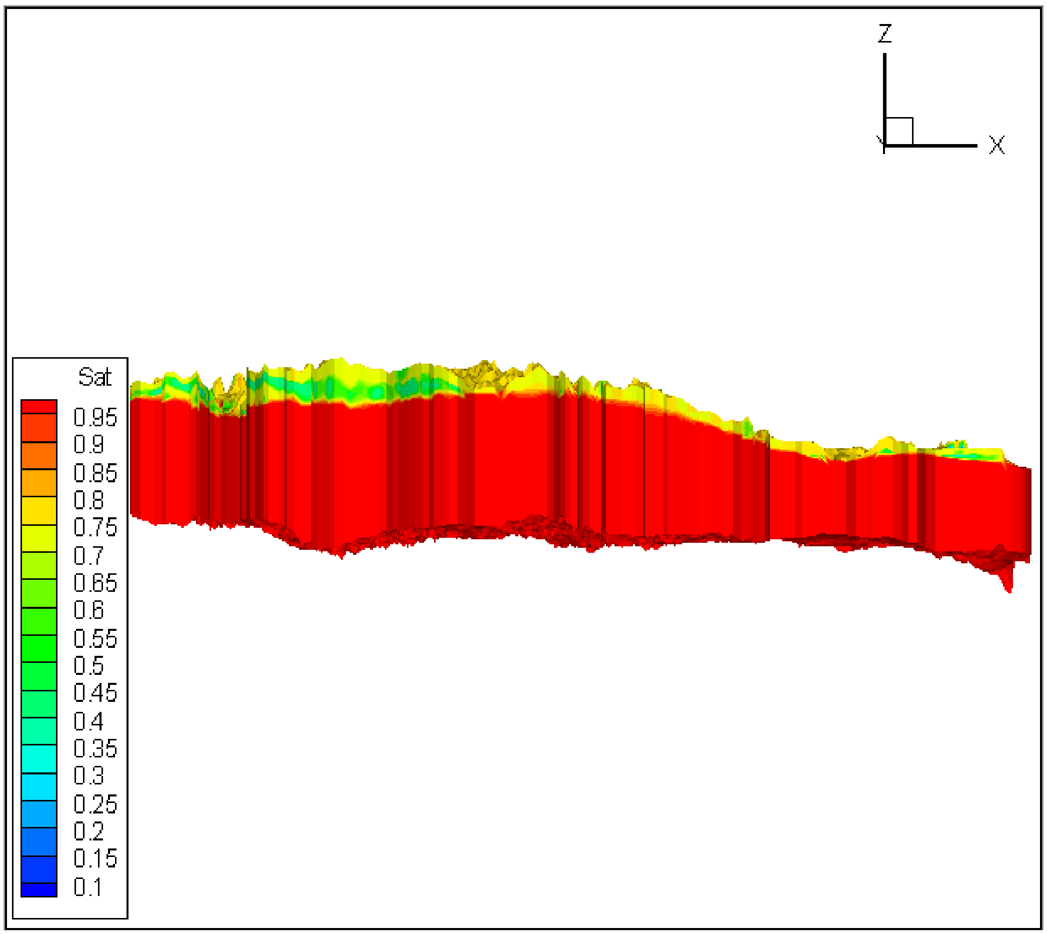

Figure 4.3: Groundwater saturation along the west-east direction

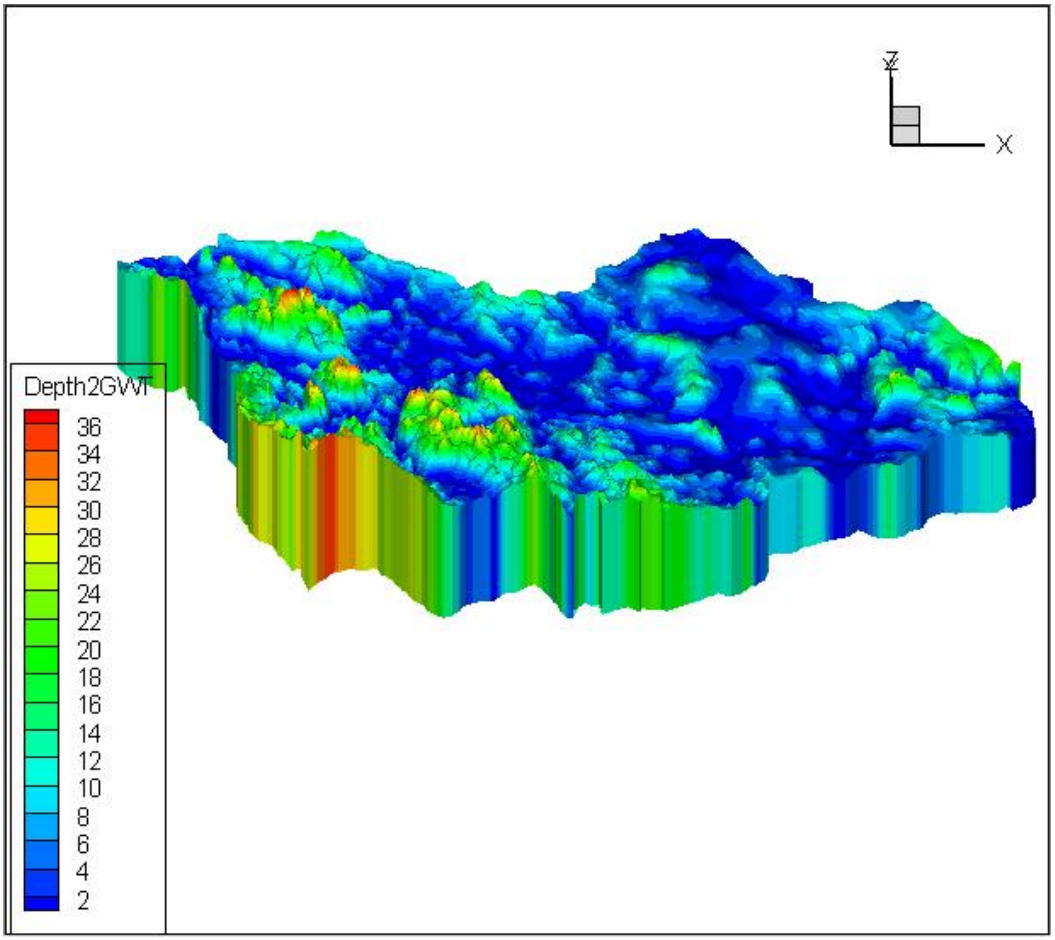

Figure 4.4: Depth to ground water table (m)

Figure 4.4 shows the depth from the land surface to the groundwater table, which supplements the information shown in Figure 4.3. In Figure 4.4, the southwest areas of the watershed have the highest surface elevation, and these areas coincide with the highest depth from the groundwater table to the land surface (shown in green to red color). In addition, for the Laurel Creek Watershed, the groundwater table depth is from 0 m (the surface water body) to 36 m (the highest surface elevation location).

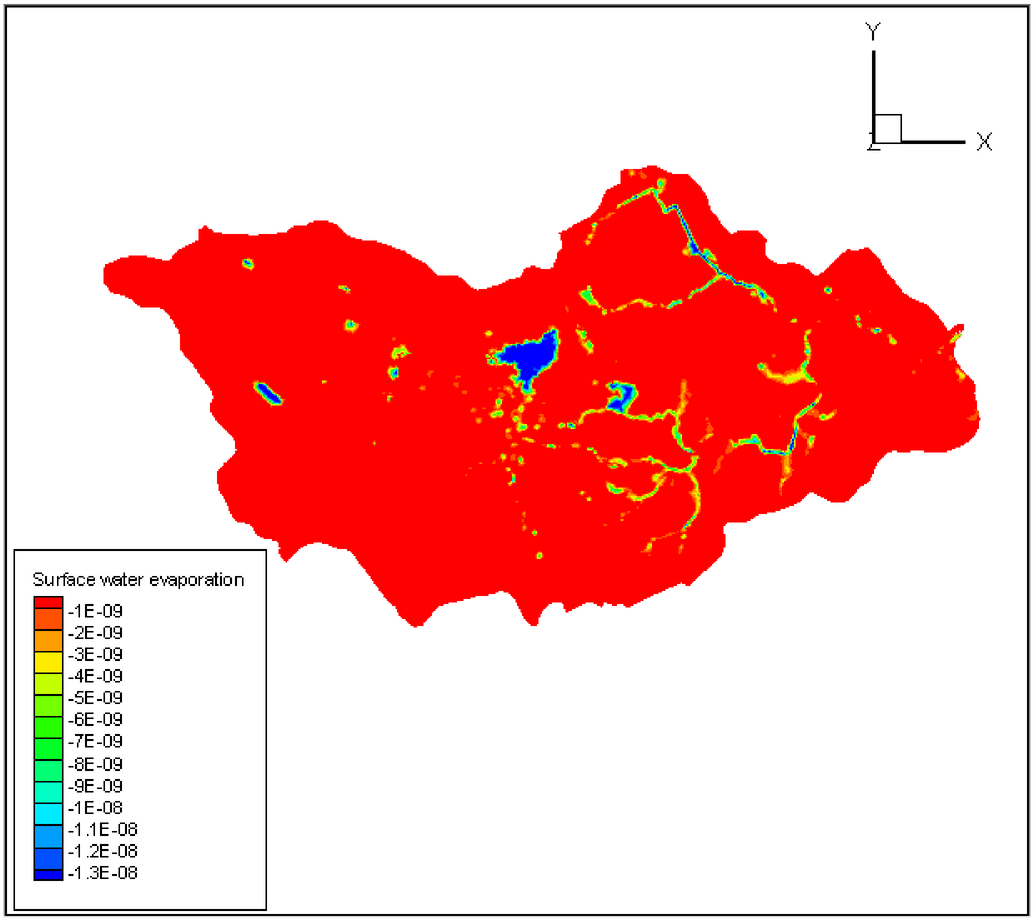

Figure 4.5: Surface water evaporation (m^3/s)

The total evapotranspiration contains three parts: surface water evaporation, subsurface evaporation, and subsurface transpiration. Among them, surface water evaporation is the phase change from liquid to water vapor from surface water. Subsurface evaporation has the same phase change condition, but the focus is on the subsurface water. The subsurface transpiration is the process where moisture is absorbed by the plants, transferred to vapor, and released to the atmosphere by leaves through respiration.

The surface water evaporation condition is shown in Figure 4.5. The areas in blue and green represent the water bodies with higher evaporation rates comparing to other red-colored zones. The results are further supported by Figure 4.2, where the areas with high surface water evaporation (Figure 4.5) are all within the saturated water bodies with sustainable surface water source for evaporation. Meanwhile, the area with low surface water evaporation is unsaturated zone, and there is less surface water for evaporation.

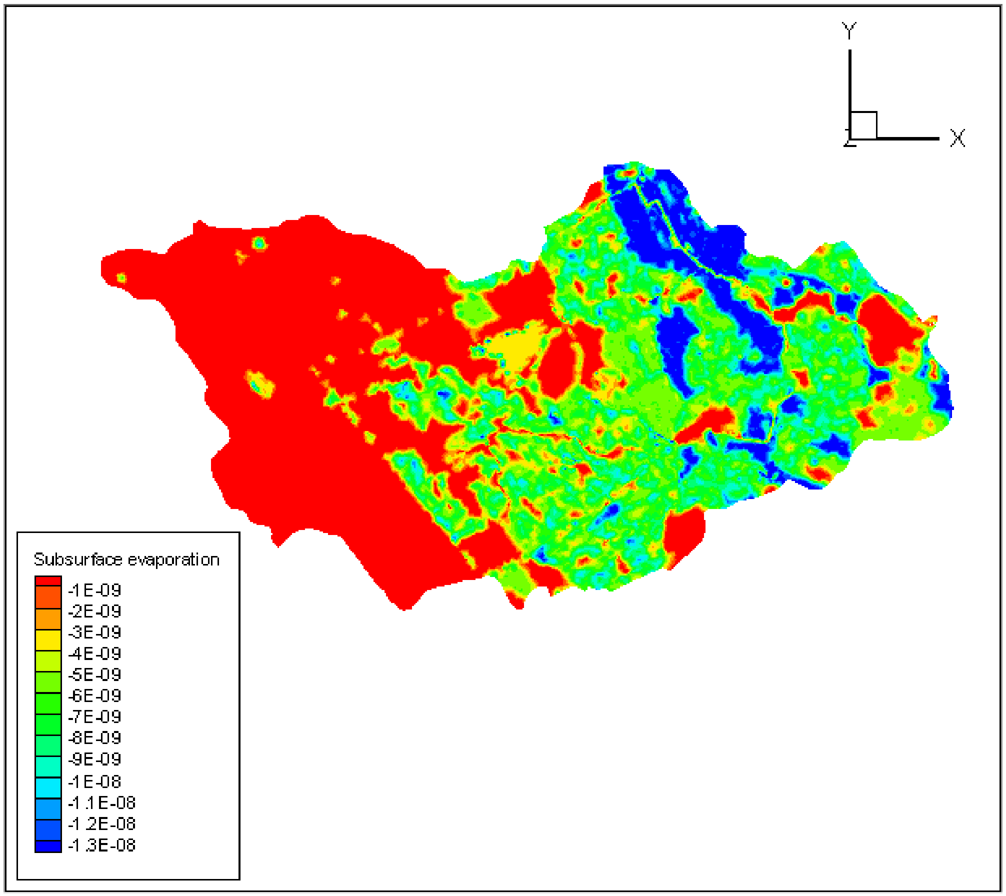

Figure 4.6: Subsurface evaporation (m^3/s)

The pattern for subsurface evaporation is shown in Figure 4.6, which shares similarity with the land use map (Figure 3.3). In Figure 4.6, the commercial and industrial areas have the highest subsurface evaporation value; the residential areas also have relatively high subsurface evaporation comparing to the agricultural and forest areas. This is due to the fact that the subsurface evaporation in a region is largely dependent on the amount of plants within that area. If there are a lot of plants growing in that area, such as the forest and agricultural areas, those plants will shade the surface preventing the sun from inducing subsurface evaporation. On the contrary, areas that paved will have high subsurface evaporation, such as the commercial and industrial areas.

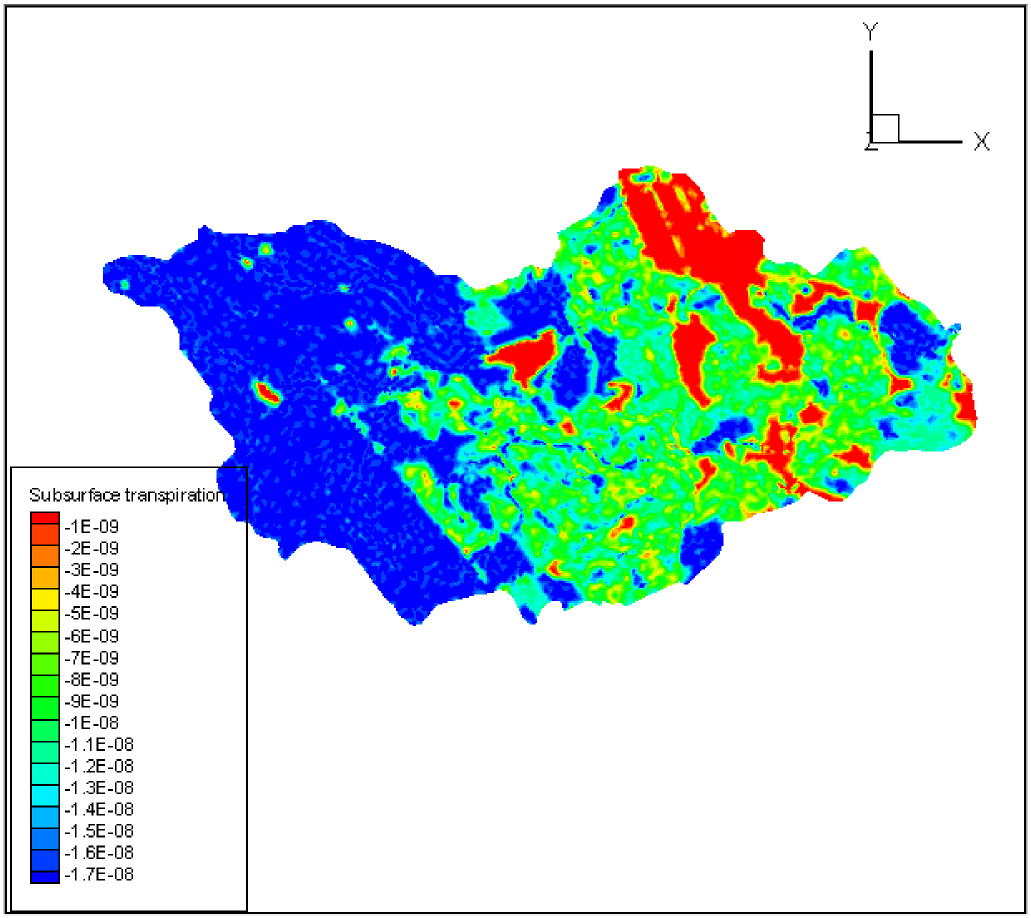

Figure 4.7: Subsurface transpiration (m^3/s)

Last but not the least, the pattern for the subsurface transpiration is shown in Figure 4.7. Comparing Figure 4.7 to Figure 4.6, the patterns are exactly reverse. This can be explained by the fact that an increase in the density of plants increases subsurface transpiration from their root zone. Therefore, the magnitude of subsurface transpiration for forest and agricultural areas is higher than that for the residential areas, with the commercial and industrial areas being the lowest within the Laurel Creek Watershed.

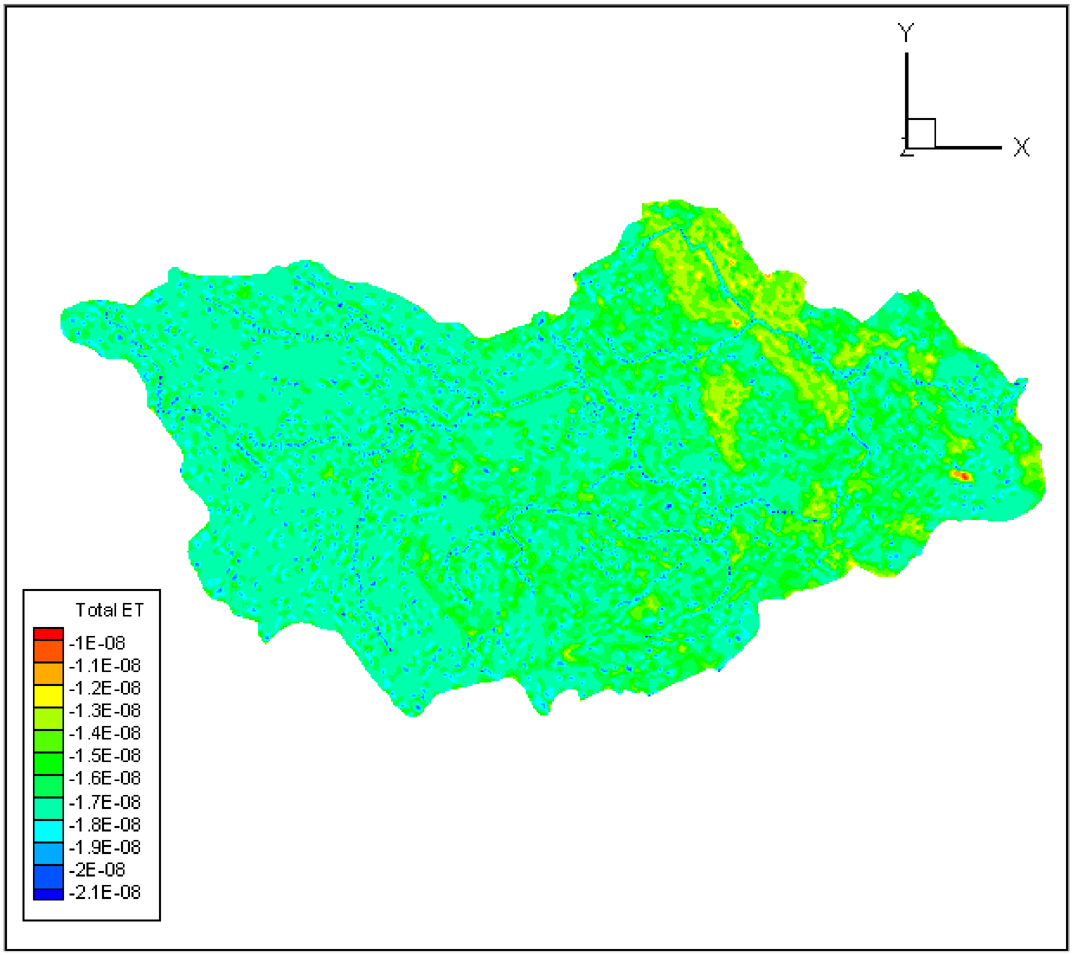

Figure 4.8: Total evapotranspiration pattern (m^3/s)

Figure 4.8 shows the total evapotranspiration which combines the surface water evaporation, subsurface evaporation, and subsurface transpiration. In this map, the forest and agricultural zones have the highest evapotranspiration, followed by the residential areas, whereas the commercial and industrial zones have the lowest evapotranspiration. The results are supported by the fact that more plants will absorb and store more surface and subsurface water, which is used for evapotranspiration.

4.2 THE STEADY STATE MODEL WITH SEWER PIPELINE

This section will focus on the situation where sewer trunk line system (City of Waterloo) is incorporated in the Laurel Creek Watershed. The information related to the sewer trunk line system can be found in the Section 3.5. There are 9 ends of the trunk lines, and they are named as Pipe002 to Pipe010 in the HGS model. These ends represent the locations where the wastewater is injected into the sanitary sewer trunk line system. The wastewater then eventually drains to the treatment plant from Pipe001. The input values of rainfall and evapotranspiration parameters remain the same as those in the model without the sewer trunk lines. In addition, the initial head condition in this model is set to be the same as the steady-state condition of the natural water cycle model.

Table 4.2: Measured Water Demand & Simulated Water Demand

	Measured	Simulated
Demand	**m3/year**	**m3/year**
Metered Water	11,043,299	
Non-consumption Water	1,104,330	
Injected Sewer Water		9,938,969
Treated Sewer Water	14,350,000	15,598,588
I & I	4,422,032	5,662,226
I & I Percent	30.82%	36.30%

The comparison between measured and simulated sewer water balance data (City of Waterloo) is shown in Table 4.2. The definition of the parameters in the measured sewer water balance section, namely metered water, treated sewer water, non-consumption water and I&I, is listed in Section 3.5.1. Also, the percentage of I&I in treated sewer water is calculated according to Equation 8. From Table 4.2, the I&I Percent by the simulated model (36.30%) is very close to the I&I Percent from the measurement data (30.82%). Therefore, the simulated sewer flow results are reasonable following the I&I calibration. The value for the permeability of the pipe wall that controlled this calibration is using $10^{-9}m^2$.

Table 4.3: Fluid Balance Table

Fluid Balance			
Rate Of Fluid Exchange [m³/s]; (LCW: Laurel Creek Watershed)			
Boundary Condition Name	**IN**	**OUT**	**NET**
LCW_outlet		-0.792	-0.792
LCW_non_outlet		-0.0120	-0.0120
Rain	2.26		2.26
PotET		-1.27	-1.27
Pipe001		-0.495	-0.495
Pipe002	0.0350		0.0350
Pipe003	0.0350		0.0350
Pipe004	0.0350		0.0350
Pipe005	0.0350		0.0350
Pipe006	0.0350		0.0350
Pipe007	0.0350		0.0350
Pipe008	0.0350		0.0350
Pipe009	0.0350		0.0350
Pipe010	0.0350		0.0350
TOTAL	2.57	-2.57	0.000
RATE OF FLUID ACCUMULATION [m³/s]			
Porous medium	-7.48×10^{-10}		
Overland	2.48×10^{-10}		
NET2 ACCUMULATION RATE			-5.00×10^{-10}
FLUID BALANCE ERROR			
Absolute: (NET1-NET2)			1.68×10^{-4}
Relative: (NET1-NET2)/(abs(NET1)+abs(NET2))/2.0			2
Percent: abs(NET1-NET2)/NET1(+ve)*100.0d0			6.52×10^{-3}
FLUID EXCHANGE BETWEEN SURFACE AND SUBSURFACE DOMAIN [m³/s]			
Infiltration	2.06		2.06
Exfiltration	-0.626		-0.626
Well+	-0.179		-0.179
Well-	0.000		0.000
Total			1.25
ET COMPONENTS [m³/s]			

Surface water evaporation	-0.0242		
Subsurface evaporation	-0.321		
Subsurface transpiration	-0.930		
TOTAL ET	-1.27		

The steady-state fluid balance results, run by the Laurel Creek Watershed model with the sewer trunk line, are summarized in Table 4.3. In this model, rainfall as an input parameter (2.258 m^3/s, which is 939.42mm/yr) is equal to that in the natural water cycle model. The total ET (PotET: -1.274 m^3/s, which is -530.04mm/yr) accounts for 56.4% of the total rainfall, which shares the same values as that in the natural water cycle model. However, the amount of outflow (LCW_outlet: -0.792 m^3/s) is lower than that in the natural water cycle model (-0.971 m^3/s). The reason is that the sewer pipelines are gaining subsurface groundwater through fractures and joints between pipe segments. In addition, as more surface water infiltrates into the subsurface to accommodate drainage into the sanitary sewer pipes, the surface water depth will decrease. The amount of wastewater draining to the treatment plant is 0.495 m^3/s, which is equivalent to 62.5% of the total streamflow within Laurel Creek as it discharges into the Grand River. Also, wastewater flow is equivalent to 38.9% of total ET. Therefore, there is a significant amount of wastewater flow in the sewer trunk lines, of which 36.3% is I&I. I&I decreases the streamflow by 0.179 m^3/s, which is 18.4% of the streamflow in the natural water cycle model. However, I&I decreases total ET from 1.2751 m^3/s to 1.2744 m^3/s which is only by 0.055%.

The abovementioned results are clearly illustrated in Figures 4.9, 4.10 and 4.11. Among them, Figure 4.9 and 4.10 summarize the comparison of the surface water depth and surface water saturation before and after inserting sewer trunk lines. It is evident that the surface water depth and surface water saturation both decrease after the sewer trunk lines were added (shown in circles). Figure 11 also indicates that the depth to groundwater table increases when the sewer trunk lines are added.

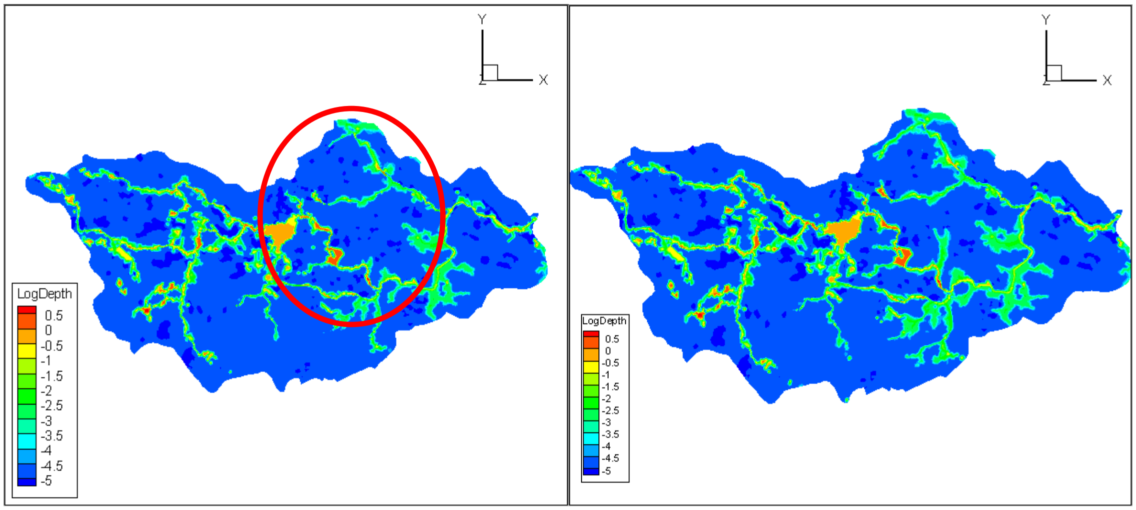

Figure 4.9: Surface water depth pattern with(left) and without(right) sewer trunk lines

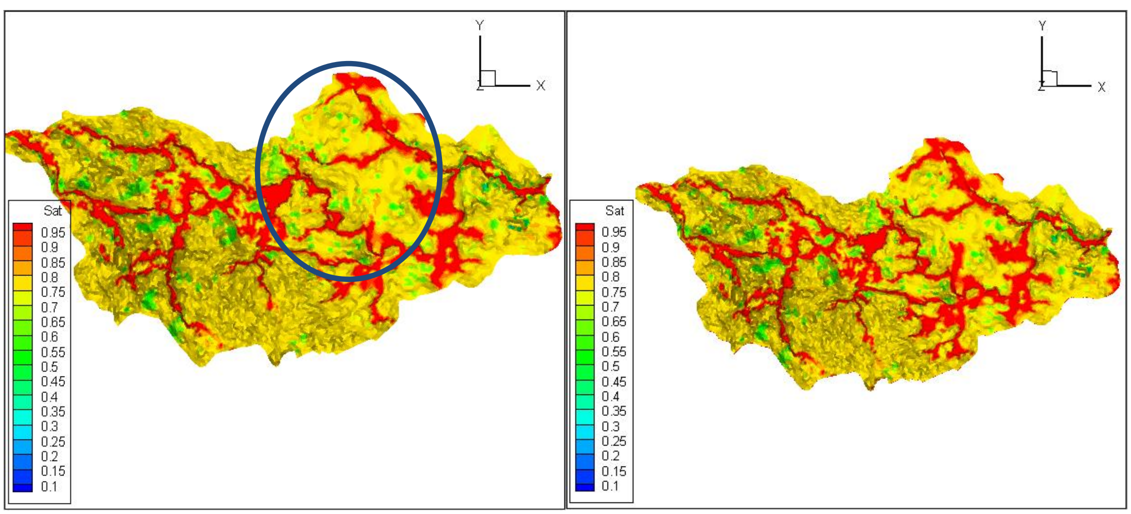

Figure 4.10: Surface water saturation with(left) and without(right) sewer trunk lines

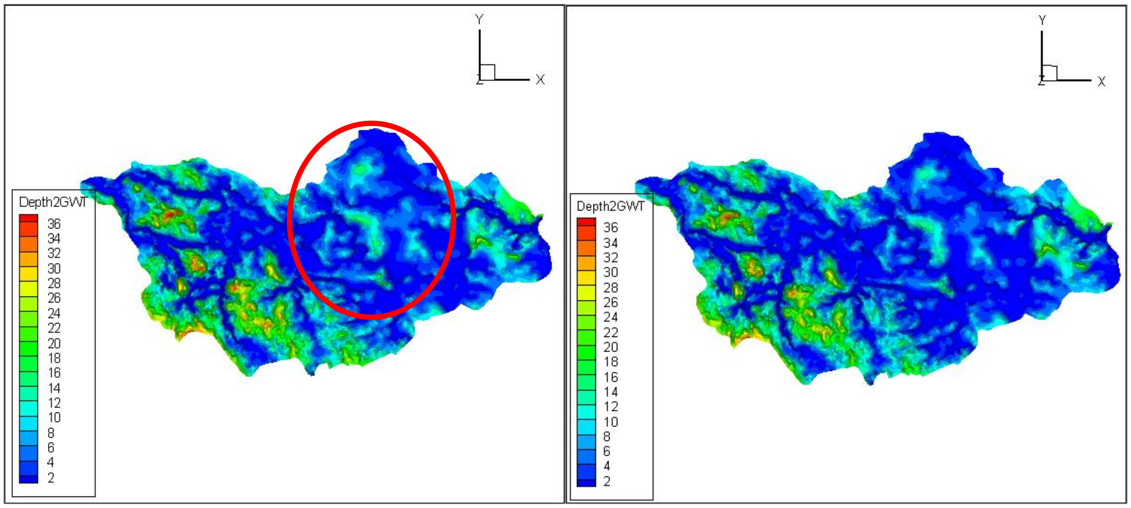

Figure 4.11: Depth to GWT with(left) and without(right) sewer trunk lines (m)

In terms of the fluid exchange between surface and subsurface domain (Table 4.3), the value of infiltration by the model with sewer trunk lines is higher than that in the natural water cycle model. However, exfiltration exhibits has the opposite result. In addition, the total amount of fluid exchange between surface and subsurface domain is 1.250197 m^3/s (Table 4.3), which is higher than the 1.248147 m^3/s from the natural water cycle model (Table 4.1). The higher fluid exchange rate indicates that there is more surface water infiltrating into the subsurface to accommodate the sewer trunk lines gaining groundwater.

When sanitary sewer pipes are included in the model, surface water and subsurface evaporations are lower because the amount of surface and subsurface water is diminished. However, subsurface transpiration is higher. Overall, the total evapotranspiration value is lower, because the sewer trunk lines drains water from the hydrogeology system. The comparisons of ET components between the results from the model with and without sewer trunk lines are shown from Figure 4.12 to Figure 4.15.

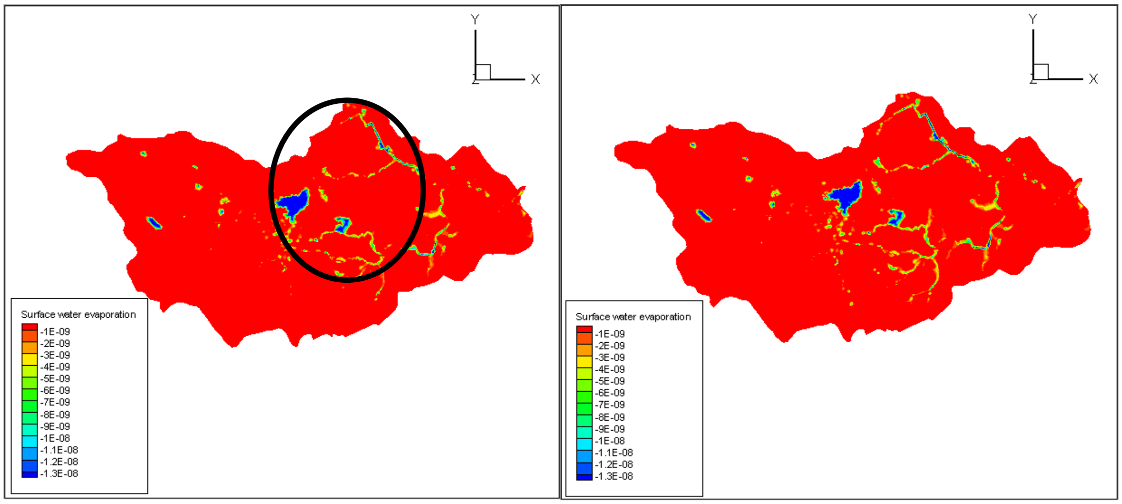

Figure 4.12: Surface water evaporation with(left) and without(right) sewer trunk lines (m^3/s)

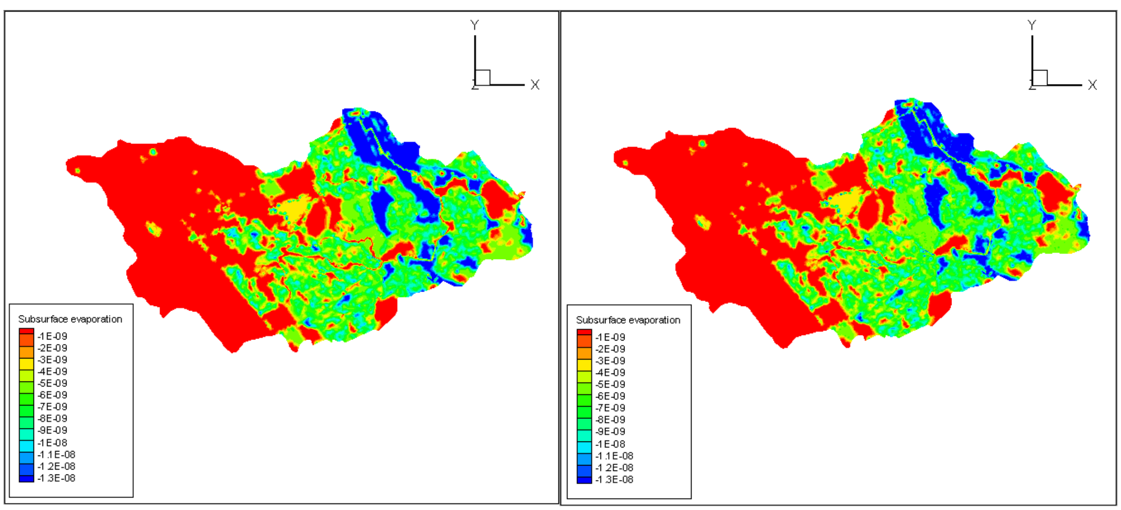

Figure 4.13: Subsurface evaporation with(left) and without(right) sewer trunk lines (m^3/s)

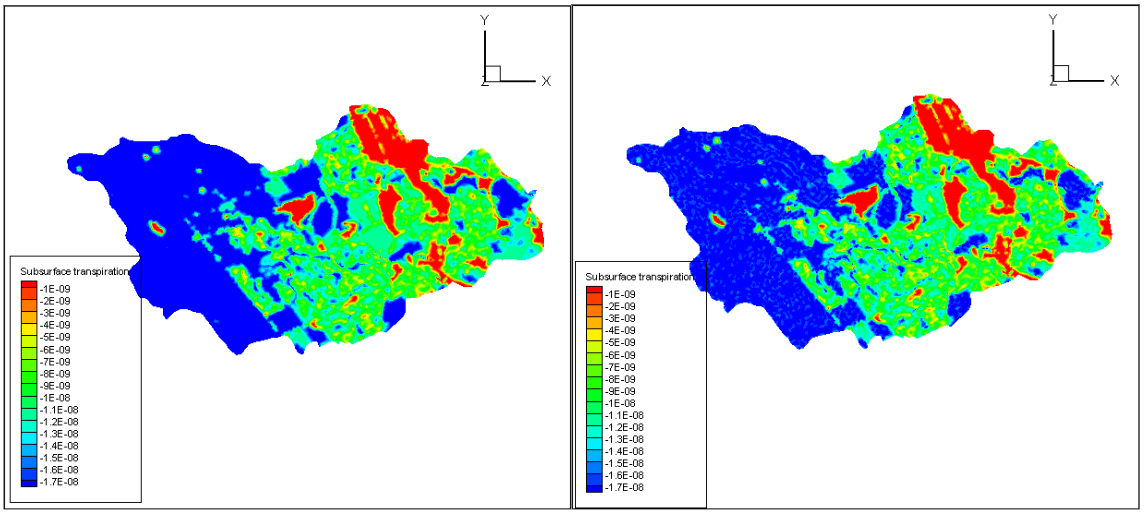

Figure 4.14: Subsurface transpiration with (left) and without (right) sewer trunk lines (m^3/s)

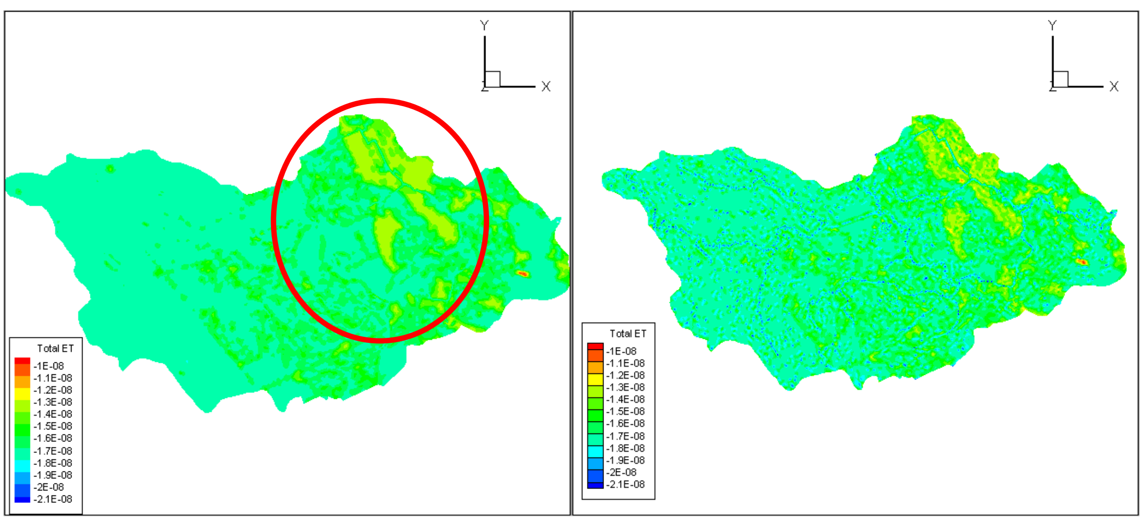

Figure 4.15: Total ET with(left) and without(right) sewer trunk lines (m^3/s)

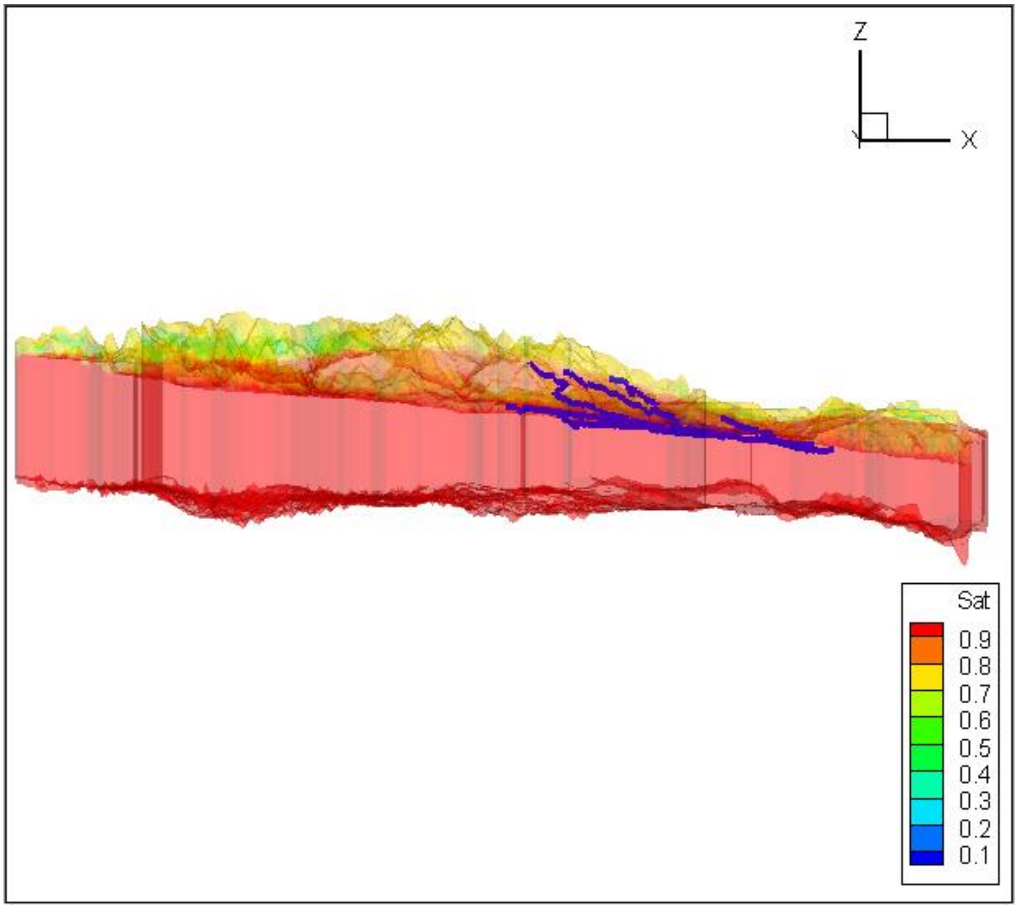

Figure 4.16: The sewer pipeline in HGS along the west-east direction

Figure 4.16 is the side view of the sewer trunk lines along the west-east direction in the Laurel Creek Watershed saturation map. The 9 different ends of the sewer trunk lines are located at higher elevations. Because waste water drainage is gravity driven, flow originates at the high-elevation ends of the trunk lines and drains towards the low-elevation wastewater treatment plant.

Figure 4.17 illustrates the water saturation condition of the sewer trunk lines. Because the sanitary sewer pipe does not flow completely full with waste water, its water saturation is relatively low. Figure 4.18 represents the velocity of the sewer water in the sewer trunk lines. The velocity increases from the ends of sewer pipelines towards the wastewater treatment plant given gravity drainage.

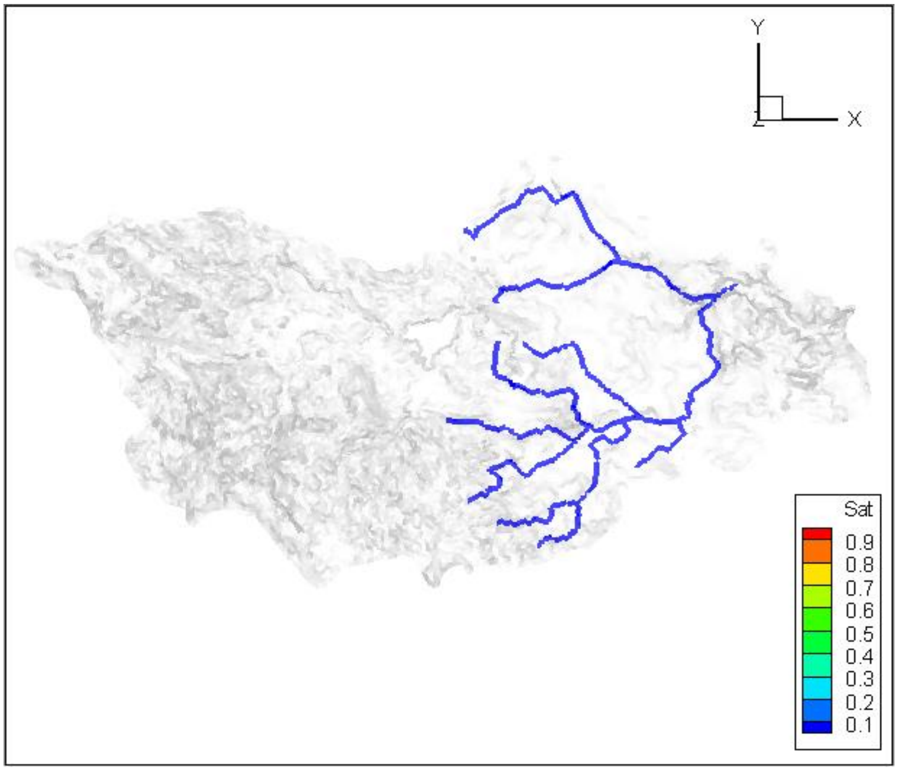

Figure 4.17: The saturation of sewer pipeline

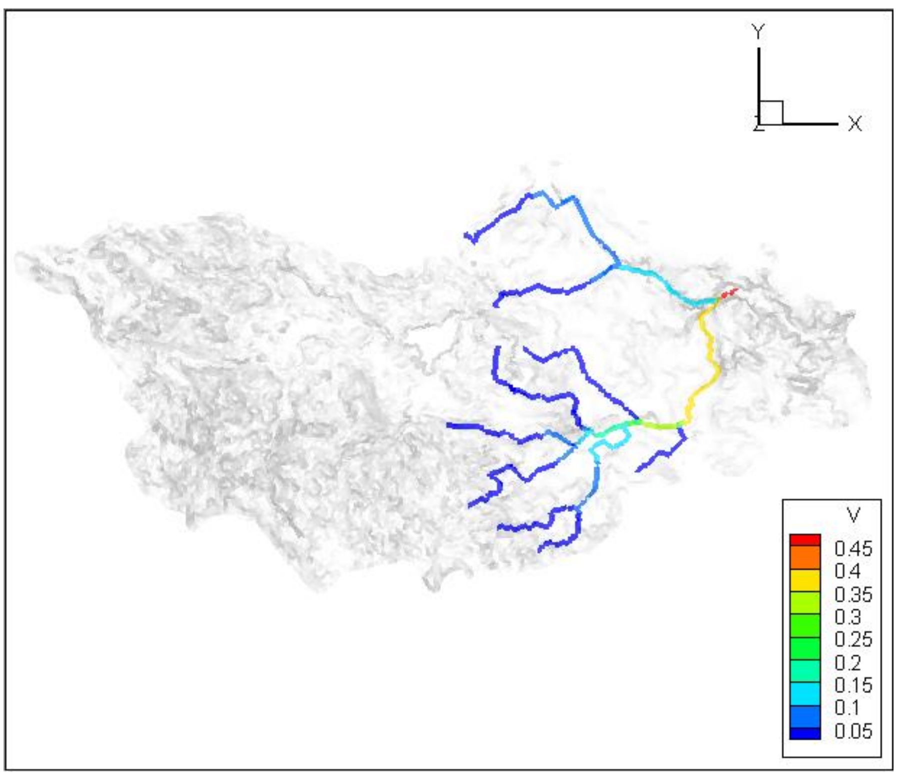

Figure 4.18: The velocity of sewer pipeline (m/s)

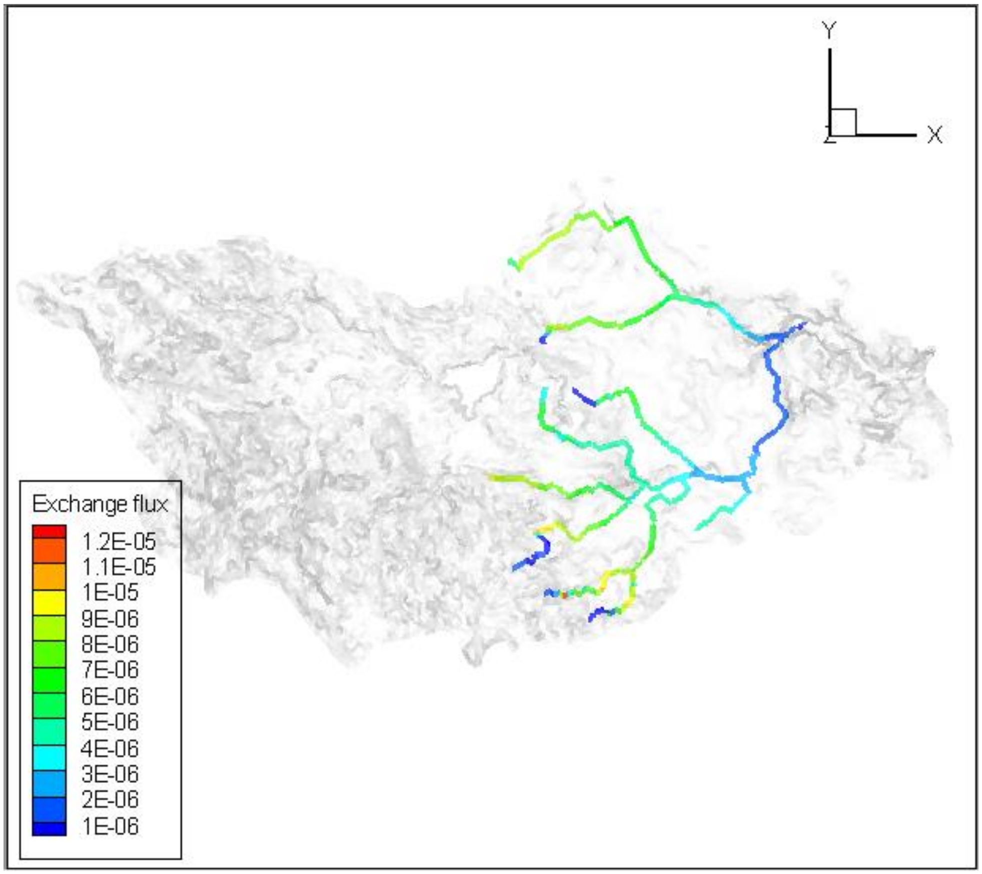

Figure 4.19: Exchange flux (m^3/s)

Figure 4.19 demonstrates the exchange flux between the waste water in the sanitary sewer trunk lines and the surrounding groundwater. All values are positive, which means the groundwater is flowing into the sewer trunk lines. This occurs in all regions of the model, including where the sewer pipelines are above the water table. One would expect that infiltration would only occur when the pipelines are below the groundwater table. In the context of the HGS model, the sewer pipelines are one-dimensional elements. Given their capillary pressure relationship and low water saturation, the pipes have a simulated negative pressure that is lower than the surrounding porous media. Thus, the pipelines above the groundwater table gain water. In reality, we would expect that the water pressure within these pipelines to be positive due to the depth of water within the pipe. Prescribing a water saturation and capillary pressure curve to a pipe element is a fictitious concept. Note that sanitary sewer pipes above the water table could gain inflow of water from leaking watermain located above them. However, the current model does not include watermain flow at this time.

From Figure 4.19, the different colors stand for different flux rates. The flux rate of the pipelines beneath groundwater table is higher than that of the pipelines above the groundwater table. From Figure 4.20, the background light blue color represents the groundwater table, and the dark blue pipelines indicate the locations of those sewer trunk lines above the groundwater table. If elevations of sewer trunk lines are higher than elevation of groundwater table, the dark blue pipelines can show up on top of the groundwater table. Comparing to the Figure 4.19, we can clearly see the lower exchange flux rate of those pipelines above the groundwater table.

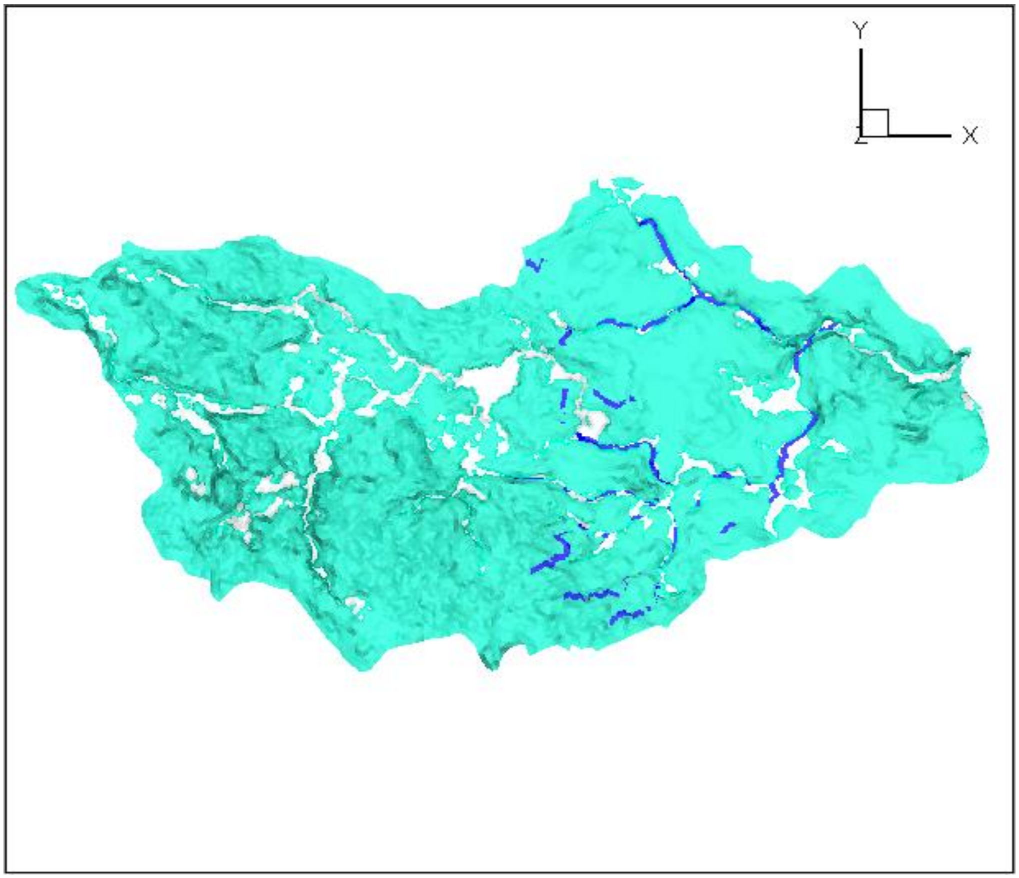

Figure 4.20: The elevation comparison between sewer trunk lines and groundwater table

4.3 STREAM FLOW MEASUREMENT COMPARISON

Figure 4.22 shows 10 locations where the stream flow is measured within the Laurel Creek Watershed. Measurement sites 3, 5, 7, 8, 10, 14 are in the urban area, and sites17, 20, 21, 23 are in the rural area. Table 4.5 summarizes the stream flow at the 10 sites for the year 2010, 2011, 2012, and 2014. It also includes the average stream flow for these four years.

Table 4.5 shows the comparison between the measured stream flow and the simulated stream flow with or without sewer trunk lines. Figure 4.23 depicts a bar graph that compares the simulated streamflow values without and with sanitary sewer pipes versus measured streamflow's. It is evident that the simulated stream flow (with or without sewer pipes) is a better match at the low stream flow locations such as sites 8 and14. As the stream flow values increase, the difference between the simulated stream flows and measured stream flow also increases. In addition, the values of simulated stream flows are constantly higher than those of the measured stream flows. A possible reason is that the rainfall in the model is constant throughout the entire simulation process; however, the measured stream flow values are derived when there is no rainfall. Therefore, the simulated results are always higher than the corresponding measured results.

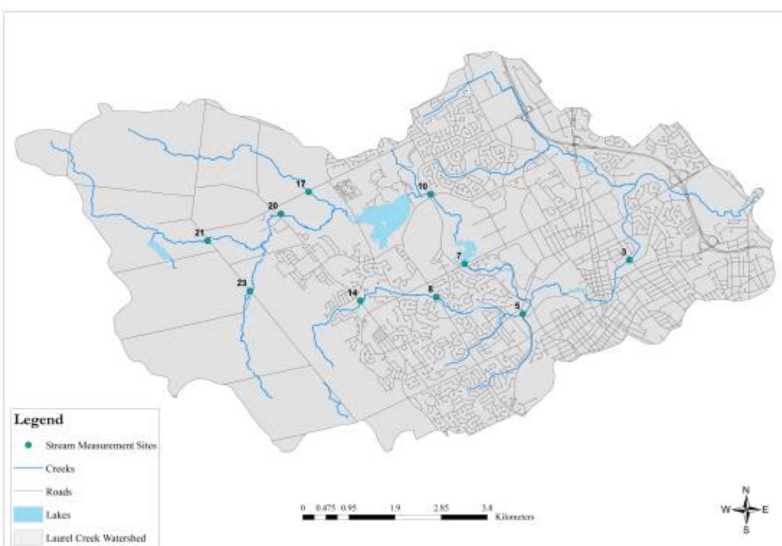

Figure 4.21: Stream Flow Measurement Sites in Laurel Creek Watershed

Table 4.4: Measured Stream Flow from 2010 to 2014

Site NO.	Measured Stream Flow (m3/s)				Average measured Stream flow (m3/s)
	2010	2011	2012	2014	
3	0.234	0.415	0.142	0.150	0.261
5	0.508	0.0683	0.0312	0.0367	0.128
7	0.192	0.222	0.0739	0.0948	0.173
8	0.0259	0.0584	0.00750	0.0114	0.027
10	0.256	0.0311	0.0674	0.123	0.189
14	0.0414	0.0365	0.00700	0.0142	0.0265
17	0.0379	0.0517	0.0191	0.0198	0.0386
20	0.0994	0.198	0.103	0.123	0.133
21	0.0349	0.0546	0.0261	0.0328	0.0357
23	0.0244	0.0292	0.00730	0.00760	0.0455

Table 4.5: Comparison of the stream flow

Site NO.	Average measured stream flow (m3/s)	Simulated flow without pipe (m3/s)	Simulated flow with pipe (m3/s)	% changing without and with pipe
3	0.261	0.726	0.607	16%
5	0.128	0.144	0.0760	47%
7	0.173	0.618	0.603	2%
8	0.0273	0.0490	0.0410	16%
10	0.189	0.418	0.414	1%
14	0.0265	0.0290	0.0260	10%
17	0.0386	0.0822	0.0822	0%
20	0.133	0.219	0.219	0%
21	0.0357	0.0917	0.0917	0%
23	0.0455	0.132	0.132	0%

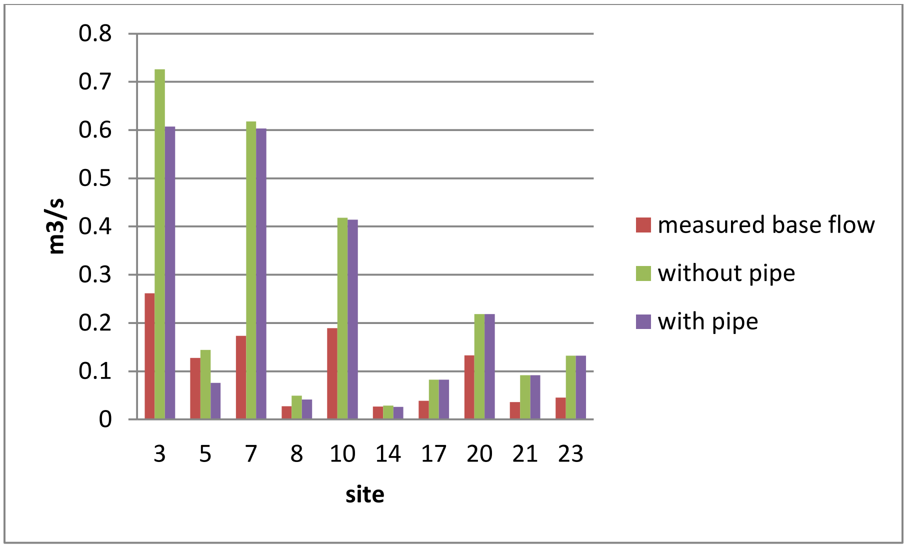

Figure 4.22: Comparison of the stream flows

Simulated stream flows with the sanitary sewer trunk lines are consistently lower than without the pipes. The difference is caused by defects in the pipe wall as well as imperfectly sealed connections between pipe segments. This promotes groundwater infiltration into the sewer pipelines as I&I. Infiltration occurs because flow in the sewer pipelines is gravity driven and with the pipes only being partially full. As the amount of groundwater decreases, the surface water will infiltrate into the subsurface. Therefore, the amount of stream flow will decrease.

The difference for the simulated stream flow with or without sewer trunk lines is site dependent. Specifically, sites 3, 5, 7, 8, 10, 14 are the locations close to the sewer trunk lines, and site 14, 17, 20, 21, 23 are the locations far away from the sewer trunk lines. It is clear that the percent of difference with or without the pipelines is much higher in terms of the locations close to the sewer trunk lines, ranging from 1% to 47% (Table 4.6). However, for the locations far away from the sewer trunk lines, percent of difference is much lower, with four locations sharing the same stream flow values with or without pipelines. This further suggests that the sewer trunk lines gain groundwater and therefore decrease the surface stream flow around those pipelines. In specific, the largest difference (47%) occurs at location 5, where four small-sized streams converge above the corresponding sewer trunk lines. The stream flows in all those four streams decrease; therefore, the percent of difference at site 5 is the largest among all locations.

5 Conclusions

As the urbanization of the City of Waterloo, the infrastructure system expanded fast in the last couple decades. The increased population gave a higher load to the Laurel Creek Watershed. At the same time, the aged infrastructures have fractures and cracks, which result in the leakage of watermain and groundwater infiltration into the sewer pipelines. Those waste drinking water and additional sewer water increased the water bill of the citizens. Therefore, the City of Waterloo needs a municipal infrastructure asset management to keep the water supply and drainage system sustainable in the future.

Part of the municipal infrastructure asset management is to establish an integrated nature water cycle model of the Laurel Creek Watershed. This surface water- ground water simulation model was built up using HydroGeoSphere (HGS). Then, insert the sewer pipeline (GIS data was from the City of Waterloo) into this natural water cycle model. The subsurface geology of the model is based on the multi-aquifer Waterloo Moraine system created by Martin and Frind (1998). The updated hydraulic conductivities, the land use condition, and the evapotranspiration pattern have been added into the Laurel Creek Watershed model.

The two-dimensional surface mesh was created based on the topography of the Laurel Creek Watershed. Nodes that are adjacent to the streams were refined to a maximum length scale of 25m, while the remainder of the nodes within the watershed has a length scale of 100m. In the 3-D HGS model, there are a total of 46 layers. The 20 upper layers were generated based on the shape of the topography. The bottom 17 layers were created based on the bedrock layer. In between the upper layers and the bottom layers, there are 8 sublayers to refine the information of hydro-stratigraphic units. There is an additional layer for the municipal infrastructure to input the pipelines' elevations. Due to the time limitation, only the sewer trunk lines have been inserted into the model.

The Laurel Creek Watershed model was first run to steady state using only the nature water cycle system driven by rainfall and evapotranspiration. Next, the model was then to run steady state again but now containing the sewer drainage pattern.

The steady state nature water cycle model has been calibrated to match the measured groundwater table and the natural surface water saturation condition. The total annual average rainfall and ET in Laurel Creek Watershed, simulated by the aforementioned model, are 2.258 m^3/s and -1.275 m^3/s, respectively. The total annual average ET accounts for 56.5% of rainfall. In terms of the real measurement data, the average annual rainfall and ET are 940 mm/year and 510 mm/year, respectively, where the annual ET accounts for 54.3% of the annual rainfall. Therefore, the fluid balance results from the simulating model match perfectly with the practical measurement data.

For the steady state sewer trunk line model, the amount of sewer water flow into the treatment plant has been calibrated to match the measurement data. In this model, rainfall as an input parameter (2.258 m^3/s) is equal to that in the natural water cycle model. However, the amount of outflow (LCW_outlet: -0.792 m3/s) is lower than that in the natural water cycle model. The reason is that the sewer pipelines are gaining subsurface groundwater through the fractures and joints between pipe segments. This amount of groundwater gaining by the sewer pipelines is defined as I&I. The simulated result of I&I Percent is 36.30%, which is close to the real measurement result 30.82%. Therefore, the simulated sewer flow results are reasonable.

Then, the stream flow in both models was measured to compare the difference between the model with the sewer drainage pattern and the model without the sewer system. Simulated stream flows with the sanitary sewer trunk lines are consistently lower than without the pipes. The difference is caused by defects in the pipe wall as well as imperfectly sealed connections between pipe segments. This promotes groundwater infiltration into the sewer pipelines as I&I. The infiltration occurs since the flow in the sewer pipelines is gravity flow, so the pipes are only partially filled. As the amount of groundwater decreases, the surface water will infiltrate into the subsurface. Therefore, the amount of stream flow will decrease.

Also, the stream flow simulated data is compared with the real word measurement data. The values of simulated stream flows are constantly higher than those of the measured stream flows. A possible reason is that the rainfall in the model is constant throughout the entire simulation process; however, the measured stream flow values are derived when there is no rainfall. Therefore, the simulated results are always higher than the corresponding measured results.

This thesis concludes that the municipal infrastructure is possible to be simulated in the natural water cycle HGS model. The simulated results are reasonable matching the real hydraulic condition in the Laurel Creek Watershed. The Laurel Creek Watershed model with the water infrastructure of the City of Waterloo can be used to assess the water interaction between city's water infrastructure system and the natural hydrological cycle. The model can be used to simulate and forecast the future condition with an uncertain natural hydrologic condition or deteriorated water infrastructure conditions, in order to protect the safety of drinking water in the future.

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