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Characterization and Modelling of Stormwater for the City of Calgary

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Characterization and Modelling of Stormwater for the City of Calgary

by

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Abstract

The quantification of pollutant loading from nonpoint pollution sources is very challenging but crucial. Statistical analyses were performed for identifying differences of stormwater quality among different types of land use and among catchments of same land use in three types of flow (baseflow, snowmelt and stormwater runoff). Results indicate water quality parameters present variations among different types of land use and among catchments of same land use. In addition, Stormwater Management Model (SWMM) was calibrated and verified for industrial and residential land uses. The modeling results clearly demonstrate distinct coefficient values for pollutant build-up and wash-off. Rainfall, as the source of stormwater, in the city was also investigated to characterize the spatial and temporal distribution of rainfall. The identified differences in stormwater quality from statistical analysis and modeling suggest the need of quantifying and modeling pollutant loading from different types of land use.

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Chapter One: Introduction

Urbanization alters the natural process of stormwater runoff (Pazwash, 2011). Urbanization could significantly increases stormwater runoff quantity due to the increase of impervious area, such as roads, parking lots, and rooftops. On the other hand, it has also been well acknowledged that urbanization can negatively affect stormwater runoff quality and subsequently water quality of natural receiving water bodies by altering physical, chemical and biological conditions of water (Wang *et al*., 2003; Konard and Booth, 2005). Furthermore, the increases of peak flow, flow volume, flow velocity, as well as event frequency could deteriorate water quality downstream (Burszta-Adamiak and Mrowiec, 2013).

Non-point source pollution (NPS) is contamination that originates from a variety of sources which spread out over land surface and/or subsurface, thus it exists ubiquitously. NPS also enters water bodies from diffuse points of discharge. Urban stormwater and discharge from agricultural, mining and constructions activities are typically NPS (Novonty and Chesters, 1981). In contrast, point source pollution (PS) originates from repetitive operation such as industrial activities and discharges from a designated location such as outfall of a chemical factory or a wastewater treatment plant (WWTP), which can be effectively monitored. Therefore it is more difficult to quantify and control NPS than PS. NPS also differs from PS in terms of flow magnitude and water quality level. PS is often fairly steady in terms of both flow and water quality level whereas NPS is highly dynamic especially with random intermittent interval. In addition, PS is often independent of hydro-meteorological events, such as precipitation. Due to urbanization and consequently the increase in anthropogenic activities, both PS and NPS have been elevated. However, with recent enhancement in reducing pollutant loading from PS, e.g., effluent of WWTP, NPS and its management have attracted more attention in water resources management.

An urban setting or a city always consists of different types of land use. Besides, land use changes in the process of urbanization. For example a typical farmland or open space (e.g., park) is converted to an industrial, residential, or commercial area to accommodate the needs of various anthropogenic activities. As a result, stormwater runoff quantity and quality are land use specific in addition to site specific. The nature of stormwater runoff challenges not only its monitoring but also the quantification and modeling of pollutant loading in stormwater runoff. Therefore the understanding of the association between land use type and stormwater runoff is crucial to better monitor and manage stormwater runoff.

Rain on undisturbed land surfaces, for instance forest and grassland, is intercepted, retained in depression, and also infiltrates and produces overland flow, namely surface runoff. Urbanization, which leads to the increase of impervious surfaces such as roads, parking area, and roofs on building, not only reduces interception and infiltration but also removes depression on land surface to hold water on soil surfaces.

Figure1 shows a systematic diagram of stormwater drainage system in a typical urban setting. In a storm event, a small portion of rain is retained by depression storage and then infiltrates into the subsurface or evaporates into the atmosphere from land surface. Another small portion of rain is intercepted by vegetation. Major amount rainfall generates surface runoff flowing overland if not infiltrate into subsurface. The surface runoff is captured by stormwater drainage system and eventually drains into stormwater management infrastructure, such as retention pond, treatment facility, and overflow point (Kibler, 1982).

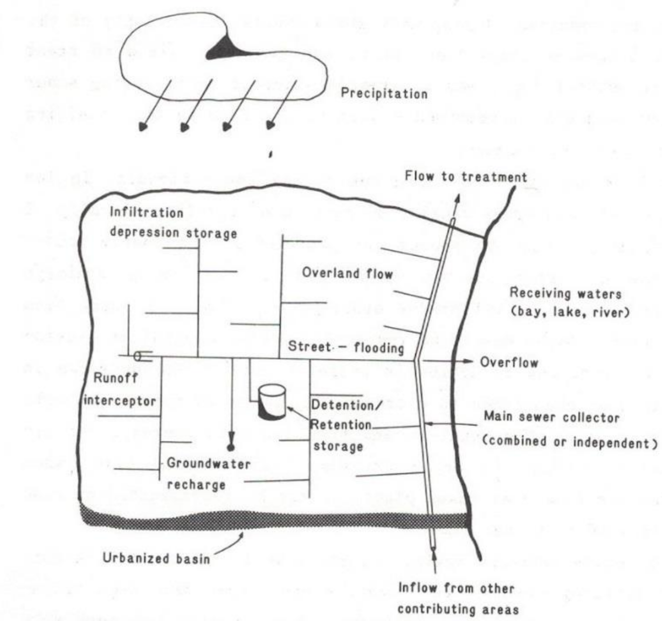


Figure 1: Urban storm drainage system (Kibler, 1982).

The drainage system in urban settings described above can decrease the time of concentration of rainfall. The reduction in the time of concentration attenuates groundwater recharge but significant increases peak flow and total flow volume in a storm event (Fig. 2). As a consequence of urbanization, surface runoff hydrograph from a developed watershed has a sharper peak flow and a lower base flow during dry period. The quick removal of stormwater from land surface to a receiving water body also increases the risk of flooding downstream. Several previous studies by Barco *et al*. (2008), Bai and Li (2013) and Di Modugno *et al*. (2015) have demonstrated the effects of urbanization on stormwater runoff quantity, increases of runoff amount and peak flow rate of runoff. To attenuate peak flow and thus reduce the risk of flooding, detention basins and stormwater ponds have often been placed in urban setting in practice to control outflow hydrograph and to reduce the peak flow as well.

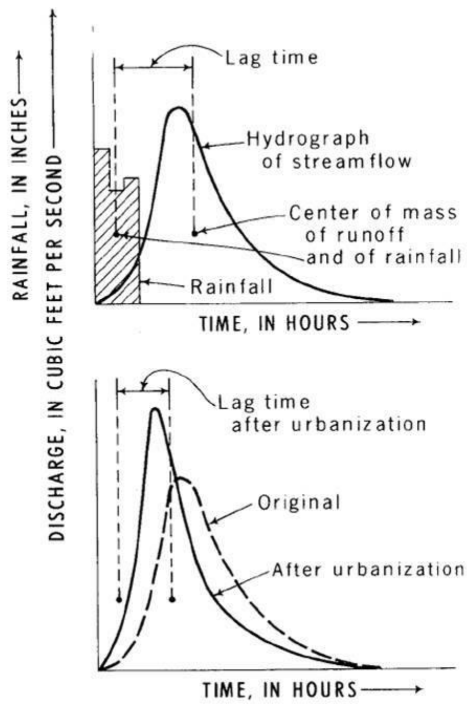


Figure 2: Basin hydrologic response after urbanization (Leopold, 1968).

1.1 Impact of Urbanization on Stormwater Quality

Urbanization affects not only stormwater quantity but also stormwater quality. A variety of pollutant constitutes generated from anthropogenic activities as well as atmosphere deposit on land surface. For instance, lead, chloride and BOD are produced by vehicle exhaust emission (Shaheen, 1975). Application of excess fertilizers and pesticides results in high concentrations of dissolved nitrogen, phosphate and phosphorus (Groffman *et al*., 2004). These pollutants generated from various anthropogenic activities are washed away from land surface by stormwater runoff and then drained into receiving water bodies during rain events (Keiber, 1982). Among a variety of pollutants in stormwater, nitrogen, phosphorus, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) are major pollutants from urban stormwater (Pazwash, 2011; U.S. EPA (1983a)).

The impact of stormwater on the water quality of receiving water bodies has recently attracted more attention. Stormwater has been recognized as one of the most common sources of water pollution by U.S. Environmental Protection Agency (U.S.EPA, 2000). Urbanization, which alters anthropogenic activities, land cover, and consequently urban hydrologic cycle, also has profound effect on stormwater quality (Klein, 1979; Dietz and Clausen, 2008). There are several common negative impacts on receiving water bodies and its aquatic life, e.g., reduction of fish population, unpleasant odour, excessive plant growth (eutrophication), water decolourisation and sediment accumulation at the bottom of the water bodies (Pazwash, 2011). The risk of stormwater on human health is yet to be quantified.

1.2 Stormwater Runoff Monitoring and Modeling

As discussed above, both stormwater quantity and quality are strongly associated with the degree of urbanization. An urban setting typically consists of several different types of land use. Thus the response of stormwater runoff quantity as well as stormwater runoff quality to a rain event would be different across the entire area. To quantify/estimate pollutant loading of various pollutant constituents from an urban area, the behaviour of each type of land use is required to be monitored and then is modeled for prediction. Ideally all sub-catchments are monitored individually and then the monitoring information can be used to quantify total pollutant loading from the entire area. It is however not economically feasible to monitor all sub-catchments in practice. Thus stormwater monitoring of several typical land uses has often been conducted and used to characterize stormwater runoff from different types of land use.

Besides stormwater monitoring, another approach for quantifying pollutant loading is the use of computer model. The modeling approach, however, might be a more preferable approach to quantify pollutant loading considering the cost, resources, and time required by a monitoring program. Tsihrintzis and Hamid (1997) stated that both monitoring and modeling of stormwater runoff from various land use types are needed to develop preventive measures to control the quantity and quality of runoff downstream and to mitigate and reduce the impact of urbanization on stormwater. To present, many models have been developed to simulate stormwater runoff from urban areas. Among various models available, stormwater management model (SWMM) is one of mostly commonly used for simulating pollutants washed off from land surface and conveyed through drainage system.

SWMM is a physically based hydraulic water quality model developed by U.S. EPA (Rossman, 2010) and also available publicly. It is applicable for both urban and sub-urban hydrological modeling and can be used to simulate both quantity and quality of stormwater runoff (Rossman, 2010). SWMM has been applied for efficiently managing stormwater ranging from urban drainage to flood routing (Di Modugno *et al*., 2015; Hsu *et al*., 2000). It has been used in numerous watersheds in Canada, U.S., and other part of the world (Temprano *et al*., 2006; Di Modugno *et al*., 2015; Bhaduri *et al*., 2001).

1.3 Research Background and Objectives

The City of Calgary in Alberta, Canada with more than one million inhabitants, is the most populated municipality in Alberta. The City siting in the watershed of the Bow River, which is an important source of water for both irrigation and drinking water supplies to approximately half of the population of Calgary and many residents in the watershed. The river reaches within and just downstream of Calgary also support a world-class sport fishery. Maintaining water quality in this river, especially in the reach within Calgary, is therefore important not only to ensure high quality drinking water but also to flourish aquatic life in the river.

Calgary, the most populated community in the Bow River Watershed, would largely alter the water quality level of the river due to various anthropogenic activities in the city. Both point (e.g., effluent from wastewater treatment plants (WWTPs)) and non-point source (e.g., stormwater runoff) pollution generated from the city has been claimed to cause water quality degradation in the Bow River. In the last decades, the City has made effort to decrease the nutrient loading from WWTPs by upgrading the plants. The efficiency of the enhancement of WWTPs was observed by Sosiak (2002), which concluded that the upgrade of Bonnybrook WWTP leads to the reduction of biotic factors (e.g., algae and macrophytes). In addition, PS can be easily quantified and managed compared to the NPS, which spreads over on land surface and sub-surface. On the other hand, stormwater, which has been considered to have better quality compared to WWTP effluent, directly discharge into natural water receiving bodies without any treatment. However, the facts are that 90% of the total suspended solids (TSS) entering the Bow River in Calgary is from stormwater and high level of TSS often suggests high level of nutrients, metals and bacteria in the waterways (City of Calgary, 2016). Therefore stormwater quality management has been attracted more attention.

Due to the nature of NPS, it is very challenging to manage, monitor and quantify pollutant loading from stormwater runoff, especially of a large area. Furthermore, an urban setting always consists of different types of land uses, such as residential, industrial, and commercial land uses. In Calgary, NW quadrant of the city is mainly residential and SE quadrant is mainly industrial, while the rest has mixed type of land use. Stormwater carries sediments and many other pollutants from the road, roofs, lawn, pavements and construction sites to water receiving bodies. Stormwater runoff originating from different land use types within the city feeds into the Bow River through a number of stormwater outfalls located along the river. Stormwater quality characteristics are different from a type of land use to another type of land use as it is affected by various anthropogenic activities at different degrees. This poses another challenge for monitoring and quantifying pollutant loading from stormwater.

The City of Calgary is currently moving to develop stormwater management targets, namely, establishing quantitative thresholds for some water quality parameters, to meet provincial guidelines. For example, TSS from a major water body should not be increased more than 25 mg/l from background level for any short term exposure (e.g. 24-hr period) during clear flow and it should not increase more than 25 mg/l at any time when the background level is between 25-250mg/l during high flow according to the Environmental Quality Guidelines for Alberta Surface Water (Alberta, 2014). Due to the growing concern about non-point pollutants, accurate quantification of pollutant loadings (e.g., for total maximum daily loading management) has become crucial, as it provides important information for protecting environment, managing watersheds, identifying pollution problems, and evaluating the efficiency of management techniques and strategies. However, non-point pollutant quantification has been heavily dependent on water quality monitoring, as the use of modeling for the purpose is challenging due to limited understanding on the distribution, behavior and transport of non-point pollutants. To characterize stormwater quality and quantify pollutant loading of stormwater, the City of Calgary has conducted water quality monitoring in different land uses aiming to accurately quantifying non-point pollutant loading released into the Bow River. In the 2001-2005 monitoring program, event-based stormwater runoff was monitored in different types of flow (baseflow, snowmelt, and stormwater runoff), separately; while in the 2007-2013 monitoring program, the monitoring was focused on daily time scale and reported daily flow-weighted pollutants' concentrations without separating different types of flow.

To aid in developing efficient stormwater water monitoring program and modeling approach for accurately quantifying pollutant loading from stormwater in the City of Calgary, this thesis aims to:

1) Revisit the stormwater quantity and quality data collected in the stormwater monitoring program from 2001 to 2005 to investigate the impact of land use on stormwater quality in terms of event mean concentrations (EMCs) of various pollutant constituents.
2) Calibrate and validate SWMM model for two typical types of land uses, namely industrial and residential land uses, for investigating ability of SWMM to reproduce the hydrological and quality behaviour of different types of land use. The calibrated SWMM models would be helpful for the study of pollutant loading quantification at the city-wide scale.
3) Investigate spatial and temporal distribution of rainfall, which generated stormwater runoff. The results are useful to formulate cost effective monitoring program for stormwater runoff in Calgary.

1.4 Thesis Layout

Chapters 3 to 5 cover the results and discussion of characterization of stormwater runoff quality from different land uses, stormwater runoff quantity and quality modeling, and spatial and temporal distribution of rainfall, respectively. In particular, these chapters are structured as individual reports, thus a literature review concerning the subject of each chapter is provided in the "Introduction" section in these chapters. For this reason, there is no a single chapter dedicated as a "Literature Review" in this thesis; however Chapter 1 "Introduction" provides a very general review on the impact of urbanization on stormwater runoff quantity and quality and stormwater runoff monitoring and modeling. Chapter 2 "Study Area and Data" provides an overall view of study area and data that are used in this thesis. Chapter 6 states general conclusions and recommendations for future research.

Chapter Two: Study Area and Data

2.1 Study Area

The City of Calgary is situated on the confluence of Bow River and Elbow River with over one million population and is the most populated city in Alberta, Canada. Besides oil and gas industry, the city has also invested in tourism and high-tech manufacturing. As a result, the population has increased and land use has changed. The city consists of inner city surrounded by suburban communities of various density. A part of NE and major portion of SE represent industrial land use; while the NW part of the city represents residential land use with its highest point at Edgemont. The SW part of the city represents a mix of residential and commercial land use.

Calgary is situated in a semiarid region and at the transition zone between the Canadian Rockies foothills and Canadian Prairies. The city experiences a dry humid continental climate and has warm summer and cold winter. Average summer temperature ranges from 16.5 degree in July to -6.8 degree in December (Environment Canada). During the winter months, dry Chinook winds routinely blow into the city from the mountains and bring the temperature up quickly and result in snowmelt. Calgary receives 418.1 mm of precipitation annually, in average, 78% of that occurring as rain and 22% occurring as snow. The normal annual rainfall amount calculated at the Calgary International Airport (1971 to 2000) is 320.6 mm (Environment Canada, 2007). Rainfall events generally occur in months from May to September, when the average daily temperature is roughly 10ºC or greater.

2.2 Water Quantity and Quality Monitoring

In the past over 10 years, the City has conducted water quantity and quality monitoring in different land uses within the city limit aiming to better understanding stormwater runoff behavior (especially in terms of water quality) and accurately quantifying non-point pollutant loading released into the Bow River by stormwater. Several sub-catchments were selected for different types of land use. In the 2001-2005 monitoring program, stormwater was monitored in baseflow, snowmelt, and stormwater runoff, individually; while the 2007-2013 monitoring program adopted different monitoring scheme to focus on daily pollutant loading combining loading from baseflow and stormwater runoff/or snow melt. As pollutant sources and transport mechanisms would be different in different types of flow, thus water quality characterization and loading quantification are needed to be conducted separately for accuracy assessment. Therefore, this thesis used the data collected from the monitoring program in 2001-2005.

In the monitoring program of 2001-2005, the land use within the city has been classified into four major categories: commercial, industrial, on-going development and residential land uses. From the monitoring program, several sub-catchments were selected from each land use type: two commercial sub-catchments (Eau Claire and Rundle), two industrial sub-catchments (Bonnybrook and Wigmore East), three on-going development sub-catchments (69th St West, Cranston and Crestmont West), and four residential sub-catchments (68th St East, 68th St West, 69th St East and Rocky Ridge Inlet) considering data availability and length.

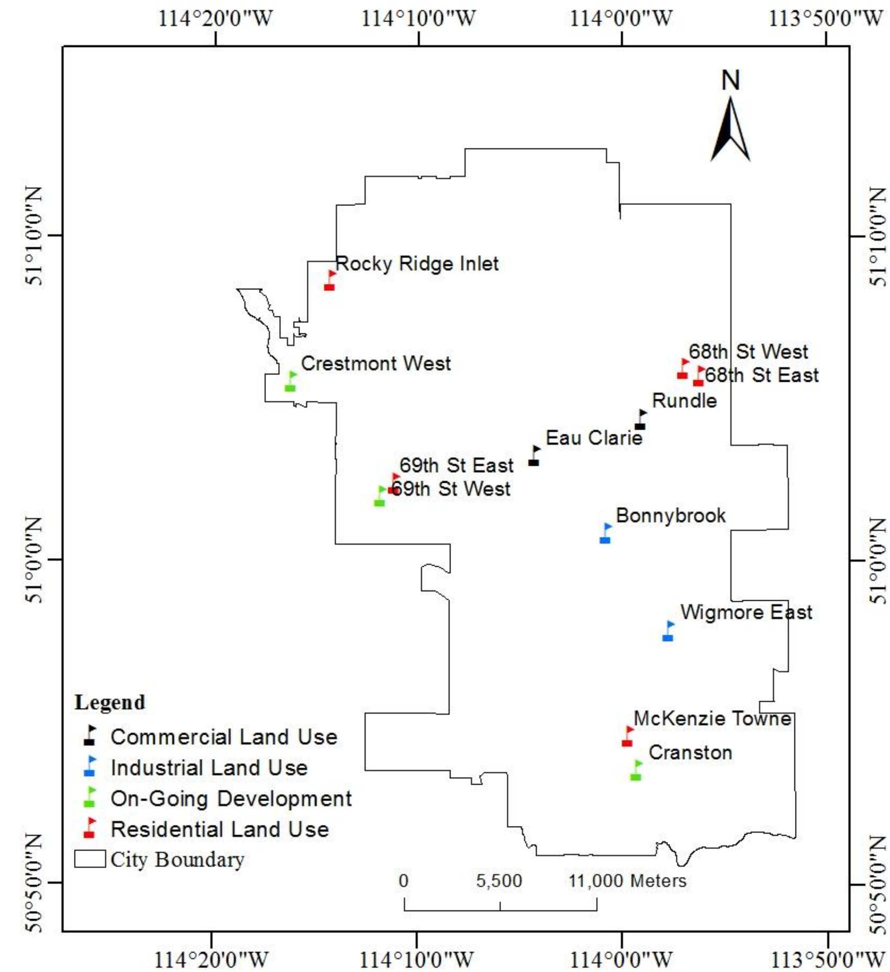


Figure 3: Locations of stormwater monitoring sites used in City of Calgary

The stormwater quantity and quality monitoring was conducted at the outlets of the selected sub-catchments in three different types of flows, which are base flow, snowmelt, and stormwater runoff. The base flow event is defined as an event during dry weather period preceded by a minimum of 72 hours without precipitation or snowmelt. Groundwater infiltration into drainage systems and surface runoff (such as from irrigation and watering practices) primarily contribute to base flow. Snowmelt event is an event in which surface runoff is produced due to snow and ice melting resulting from increased temperature. Storm events is an event with rainfall amount equal to or above 2.0 mm preceded by 72 hours of dry period. In storm events, water samples were collected by automatic water samplers at pre-set time intervals. The water sampling time period was divided into three sub-periods: first flush (FF) which is the initial 30 minutes of stormwater runoff from the beginning of rain, remainder of event 1 (ROE1) which is stormwater runoff in following 135 minutes after FF, and remainder of event 2 (ROE2) which is stormwater runoff in following 135 minutes after ROE1. Thus, a storm event may not have monitoring data in ROE1 and/or ROE2 depending on its duration. In each sub-period, flow weighted pollutant concentrations, namely event mean concentration (EMC), of various pollutants was reported. The temporal distribution and division of water samples in the stormwater sampling is illustrated in Fig. 4.

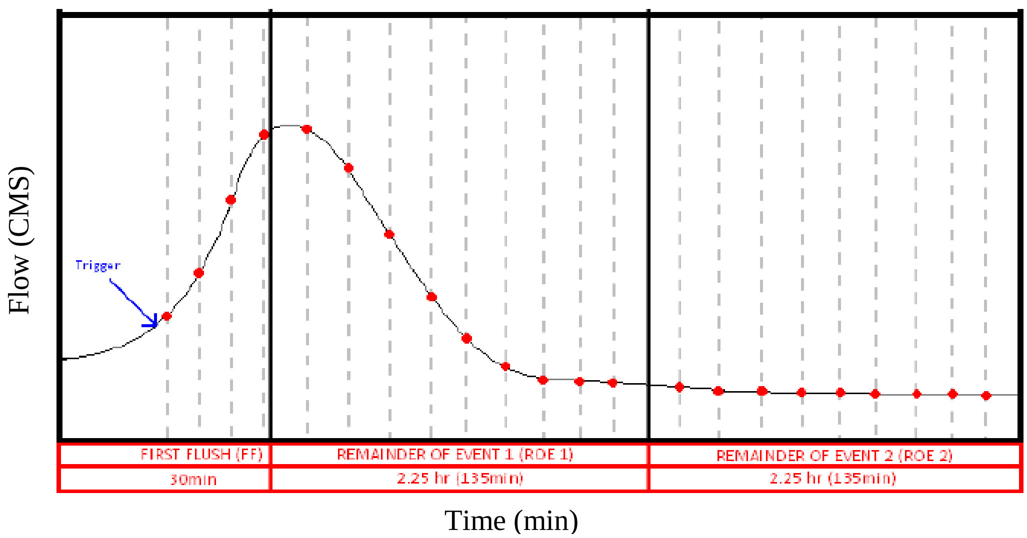


Figure 4: Sketch of temporal distribution ot water samples in stormwater runoff monitoring (City of Calgary, 2013)

Water quality parameters monitored and used in the thesis include TSS, total phosphorus (TP), total dissolved phosphorus (TDP), ammonium (NH_4^+-N), nitrite/nitrate (NO_2^-/NO_3^--N), total Kjeldahl nitrogen (TKN), and 5-day biochemical oxygen demand (BOD). All the above parameters were assayed in the laboratory of the City of Calgary. TSS is one the most crucial parameter for evaluating stormwater commonly monitored water quality parameter, as high TSS can have ecotoxic effects on aquatic organisms and many potentially harmful substances such as heavy metals and organic matter are likely adsorbed onto TSS. Nutrients, which have been attracting more attention in the urban stormwater management at both the municipal and provincial levels of government due to their significant adverse impacts on aquatic environment. Thus, the analyses for water quality were focused on these water quality parameters; while for modeling TSS of stormwater runoff was targeted.

2.3 Rainfall Monitoring

The Calgary's rain gauge network consists of a total of 36 rain gauges. The spatial distribution of these rain gauges and their data length are shown in Fig. 5 and Table 1, respectively. Most of these gauges are located within the city's boundary, but a few (stations 24, 28, 29 and 30) lie outside the city but they are in the proximity to the city's boundary. These rain gauges have commenced to measure rainfall during the rainy season, from May to September, since 1988 or after 1988 and in general recorded rainfall (greater or equal to 0.2 mm) at a five-minute interval; while rainfall data were recorded at irregular intervals between 1988 and 1990.

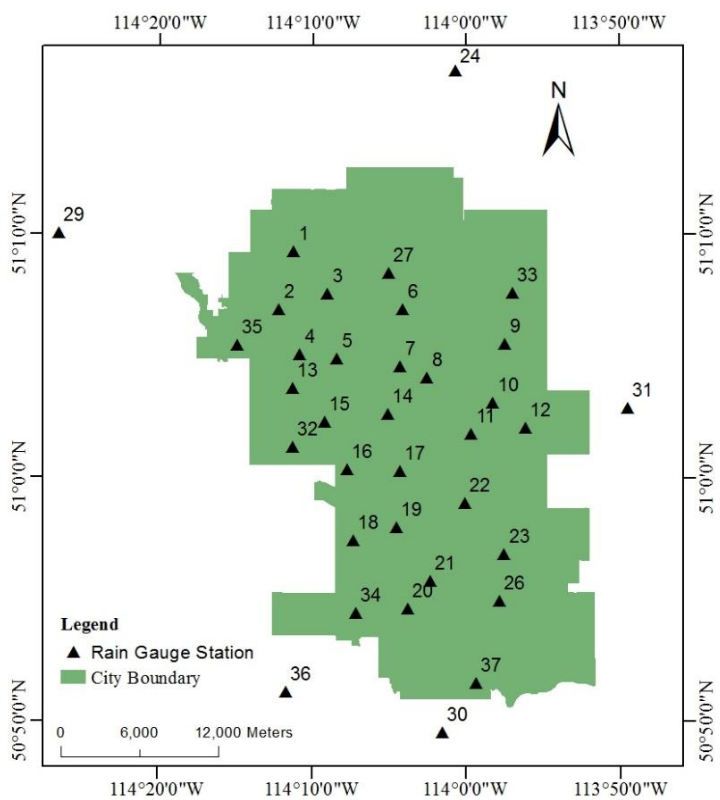


Figure 5: Rain gauge network of the City of Calgary

Table 1: All rain gauge stations of the City of Calgary's rain gauge network

Station	Location	Data length (Year)	Station	Location	Data length (Year)
1	Spyhill	25	19	Haysboro	27
2	Siver Springs	26	20	Mindapore	27
3	Edgemont	24	21	Parkland	27
4	Bowness	27	22	Ogden	27
5	University	26	23	Shepard lagoons	25
6	Huntington Hills	27	24	Airdrie	27
7	Tuxedo	26	26	Mckenzie lake	20
8	Mountview	26	27	Country hills	20
9	Temple	26	28	Crossfield	20
10	Forest Heights	27	29	Coachrane	20
11	West Dover	27	30	Dewinton	20
12	68 th St. Lake	27	31	Chestermere	8
13	Coach Hill	24	32	Bridlewood	7
14	Downtown	27	33	Saddle Ridge	7
15	Rosscarrock	27	34	Signal Hill	6
16	Lincon Park	27	35	Valley Ridge	6
17	Windsor Park	27	36	Pine Creek WTP	5
18	Cedabrae	27	37	Ranch	5

Chapter Three: Characterization of Urban Stormwater

3.1 Introduction

Due to the growing concern about non-point pollutants, accurate quantification of pollutant loadings (e.g., for total maximum daily loading management) has become crucial, as it provides important information for protecting the environment, managing watersheds, identifying pollution problems, and evaluating the efficiency of management techniques and strategies. However, non-point pollutant quantification has been heavily dependent on water quality monitoring, as the use of modeling for these purposes are challenging due to limited understanding on the distribution, behavior and transport of non-point pollutants. Water quality monitoring is any effort to understand the physical, chemical, and biological characteristics of water by statistical sampling (Ward and McBride, 1986). Ideally, water quality monitoring program should be developed based upon its needs; however, the expenses of the monitoring program often constrains the water quality monitoring conducted within limited areas as it is impossible to cover entire monitoring areas.

Environmental systems are complex and water quality always present temporal and spatial variations in an area. These imply that considerable effort and cost are needed for collecting data to capture the statistical characteristics of water quality and consequently interpret its temporal and spatial variations. For this purpose, a water quality monitoring network is required; however, a concise strategy or methodology for designing monitoring networks and monitoring methods are not available. Apart from the choice of targeted variables, the identification of representative sampling site and sampling frequency are critical issues in developing an effective water quality monitoring program (Reinelt *et al*., 1992; Dixon and Chiswell, 1996; Chapman *et al*., 1997; Mei *et al*., 2011), especially when monitoring NPS in urban settings where water quality levels can change rapidly in different land uses. However, Lee *et al*. (2007) did not observe relationship between various types of industrial activity or land use and water quality data. Besides the consideration of spatial distribution of monitoring sites, sampling frequency also plays important roles when making estimates of pollutant loads. Madarang and Kang (2013) assessed several sampling programs, which include random, wet season, antecedent day days-based, monthly, and seasonally weighted sampling, in estimating the annual discharge load. They found that monitoring with equal numbers of storms from the wet and dry seasons best estimated the load. Lee *et al*. (2007) argued that a flow-weighted composite sampling may result in lowing overall cost with improved accuracy, but may be efficient in identifying high-risk dischargers. For storm event sampling, sampling time during storm event would affect results (Lee *et al.*, 2007).

When estimating pollutant loading, the primary objective of water quality monitoring program, the precision of the estimates is of great concern. To obtain accurate estimates of pollutant loading, the monitoring program should be properly designed to collect sufficient samples to characterize the stochastic behavior of water quality, and to capture the statistical association and differences among different land uses, flows, and water quality parameters.

The City of Calgary, Alberta, Canada is moving to develop stormwater management targets, namely, establishing quantitative thresholds for some water quality parameters, to prevent water quality degradation from stormwater runoff. Thus an efficient water quality monitoring program is needed for accurately quantifying pollutant loading at both small scale (e.g., from sub-catchments of different land uses) and large scale (e.g., from the city-wide). The primary objective of this study is to analyse the water quality data obtained from monitoring program adopted during 2001-2005 to assist in developing water quality monitoring program that could better capture the water quality characteristics in the City and consequently improve the quantification of non-point pollutant loading at the city-wide scale. More specifically, this study assessed the necessity of monitoring water quality levels in different land uses and different flows, to answer the question on how to implement water quality monitoring to accurately quantify city-wide pollutant loading. The assessment is a prerequisite in order to develop an efficient water quality monitoring program for this purpose.

3.2 Data Used

As mentioned in Chapter 2, the City of Calgary has conducted stormwater monitoring from 2001-2005 for four major land use types: commercial, industrial, on-going development and residential. The sub-catchment selected for each land use type is shown in Fig. 3. Water quality monitoring was conducted at the outlets of these sub-catchments for three different types of flow including base flow, snowmelt and stormwater runoff. Detailed stormwater quantity and quality monitoring program can be referred to Chapter 2. EMCs of six water quality parameters including TSS, TP, TDP, NH_4^+-N, NO_2^-/NO_3^--N, TKN, and BOD were used for the analyses in the chapter.

3.3 Methodology

Several statistical analyses were adopted to investigate stormwater quality in different types of flows from different types of land use. The Kolmogorov–Smirnov (K-S) test was used to investigate the normality of distributions of water quality data. The analysis was conducted on the pooled data of each water quality parameter collected from each type of land use given a type of flow. Based on the results, non-parametric analyses were selected for comparing the medians of water quality parameters among/between different type flows, among/between different land uses, and among/between sub-catchments classified into same land use type. Wilcoxon rank sum test was applied to compare two samples; while Kruskal-Wallis test followed by multiple comparisons was used to compare more than two samples. In correlation analysis, The Spearman's rank correlation coefficient, which is less sensitive to outliers compared to the Pearson's correlation coefficient, was calculated to evaluate the possible correlation between water quality parameters. All these analyses were performed at the significance level of 5%.

The data points that are reported below detection limits in the monitoring data were replaced with the detection limits in this study. Discussion on the handle of the concentrations that are below detection limits in the statistical analyses are beyond scope of this thesis.

3.4 Analysis and Results

The results form K-S tests (not shown here) indicated that all the water quality parameters (except NO_2^-/NO_3^--N in on-going development land use of ROE2 and TKN in commercial land of snowmelt) are neither normally nor log-normally distributed. Therefore, the non-parametric analysis was applied to compare water quality level and to perform correlation analysis.

3.4.1 Water quality in different flows

Given a type of land use, comparisons of the medians of each water quality parameter among three flow types were conducted. Table 2 summarizes the comparison results. Pooled data of all sites of same land use type were used in the analysis. As demonstrated in this table, in general, the concentration medians of all investigated water quality parameters in base flow are significantly lower than those in both snowmelt and FF, except dissolved constituents including TDP and NO_2^-/NO_3^--N, which are either significantly higher than or equivalent to those in snowmelt and FF, for all four types of land use. When comparing the water quality levels in snowmelt and FF between industrial and on-going development land uses, the concentration medians of most constituents are not significantly different; whereas between commercial and residential land uses, the concentration medians of most constituents in FF are significantly higher than those in snowmelt.

Table 2: Comparison of water quality levels among different flow given same land use type using Kruskal-Wallis test at a significance level of 5% (<, > and = denote significant high, significant low, and no significant difference, respectively.)

Parameter	Results	Parameter	Results
Commercial land use			
TP	Base < Melt < FF	NO_2^-/NO_3^--N	Base > Melt > FF
TDP	Base = Melt > FF	TSS	Base < Melt < FF
NH_4^+-N	Base < Melt = FF	BOD	Base < Melt < FF
TKN	Base < Melt < FF		
Industrial land use			
TP	Base < Melt = FF	NO_2^-/NO_3^--N	Base = Melt = FF
TDP	Base < Melt = FF	TSS	Base < Melt = FF
NH_4^+-N	Base < FF < Melt	BOD	Base < Melt = FF
TKN	Base < Melt = FF		
On-going development land use			
TP	Base < Melt = FF	NO_2^-/NO_3^--N	Base = Melt > FF
TDP	Base = Melt = FF	TSS	Base < Melt = FF
NH_4^+-N	Base < FF < Melt	BOD	Base < Melt = FF
TKN	Base < Melt = FF		
Residential land use			
TP	Base < Melt < FF	NO_2^-/NO_3^--N	Base > Melt > FF
TDP	Base > Melt	TSS	Base < Melt < FF
NH_4^+-N	Base < Melt = FF	BOD	Base < Melt < FF
TKN	Base < Melt < FF		

Note: Base, Melt, and FF denote base flow, snowmelt, and stormwater FF, respectively.

Comparison of water quality levels in stormwater among FF, ROE1, and ROE2 for each site given a flow type (results not shown), elevated concentration medians of TP, TKN, TSS, and BOD were detected in FF; whereas the concentration medians of NO_2^-/NO_3^--N, NH_4^+-N, and TDP have a general tendency to increase towards the end of storm event.

3.4.2 Water quality in different land uses

Given a flow type, the water quality data from sub-catchments, which are classified into same land use type, were pooled together for each type of land use. A comparison of water quality levels among the different types of land uses was conducted. In the analysis, only data of storm FF were used in the analysis. The results are presented in Table 3. TSS concentration medians in on-going development land uses are significant higher than those in other three types of land uses in all types of flow; while in general, equivalent magnitude of TSS concentrations medians were observed in all flows in commercial, industrial and on-going development land uses. For other constituents, the relationships (in terms of order of the magnitude) of their concentration levels appear to vary among different flows.

Table 3: Comparison of water quality levels among land use types given a same flow type using Kruskal-Wallis test at a significance level of 5% (<, > and = denote significant high, significant low, and no significant difference, respectively.)

Flow	Baseflow	Snowmelt	Storm (FF)
TP	Com>Ind=Res	Com=Ind=Res<Dev	Com=Res<Ind<Dev
TDP	Com=Res>Ind=Dev	Ind=Res>Dev	Dev<Res
NH_4^+-N	Com<Res	Com<Ind	Ind<Res
TKN	Com=Ind=Dev=Res	Com=Res<Dev	Dev>Res
NO_2^-/NO_3^--N	Ind<Dev<Res Com>Ind	Com=Res>Ind Com>Dev	Ind>Dev
TSS	Com=Ind=Res<Dev	Com=Ind=Res<Dev	Com=Res<Ind<Dev
BOD	Com=Ind=Dev>Res	Com=Res<Ind	Com=Ind>Dev=Res

Note: Com, Ind, Dev and Res denote commercial, industrial, on-going development and residential land uses, respectively.

3.4.3 Site similarity in each type of land use

Given a flow type, comparison of water quality levels among sub-catchments were performed in each type of land use to investigate whether significant differences in concentration medians among sub-catchments exists. The results are shown in Table 4. In this table, NEQ denotes that at least one data set is significantly difference from the other data set(s); EQ denotes that there are no significant differences between/among the data sets in the analysis. As demonstrated in Table 4, both significant differences and no significant differences were detected in the concentration medians of the constituents between/among sub-catchments in each type of land use.

Table 4: Similarity of water quality levels among sites of same land use and flow type using Kruskal-Wallis test (for more than two samples) or Wilcoxon rank sum test (for two samples) at a significance level of 5%

Flow	Land use	TP	TDP	NH_4^+-N	TKN	NO_2^-/NO_3^--N	TSS	BOD
Baseflow	Com	NEQ	EQ	EQ	NEQ	NEQ	NEQ	NEQ
	Ind	NEQ	NEQ	EQ	NEQ	NEQ	EQ	NEQ
	Dev	NEQ	NEQ	NEQ	NEQ	NEQ	EQ	NEQ
	Res	NEQ	NEQ	NEQ	NEQ	EQ	EQ	EQ
Snowmelt	Com	NEQ	EQ	NEQ	NEQ	NEQ	NEQ	NEQ
	Ind	EQ	EQ	EQ	EQ	NEQ	EQ	EQ
	Dev	EQ	NEQ	NEQ	EQ	EQ	EQ	EQ
	Res	NEQ	NEQ	NEQ	NEQ	NEQ	NEQ	NEQ
Storm (FF)	Com	EQ	EQ	EQ	EQ	EQ	EQ	EQ
	Ind	EQ	EQ	EQ	EQ	NEQ	EQ	EQ
	Dev	EQ	NEQ	EQ	EQ	NEQ	EQ	EQ
	Res	NEQ	NEQ	EQ	NEQ	EQ	NEQ	NEQ
Storm (ROE1)	Com	EQ	EQ	EQ	EQ	NEQ	EQ	EQ
	Ind	NEQ	NEQ	EQ	EQ	EQ	NEQ	EQ
	Dev	EQ	NEQ	EQ	NEQ	EQ	EQ	EQ
	Res	NEQ	EQ	NEQ	EQ	EQ	NEQ	EQ
Storm (ROE2)	Com	EQ	NEQ	EQ	EQ	EQ	EQ	NEQ
	Ind	NEQ	NEQ	EQ	EQ	EQ	NEQ	NEQ
	Dev	--	--	--	--	--	--	--
	Res	EQ	EQ	EQ	EQ	EQ	NEQ	EQ

Note: Com, Ind, Dev and Res denote commercial, industrial, on-going development and residential land uses, respectively.

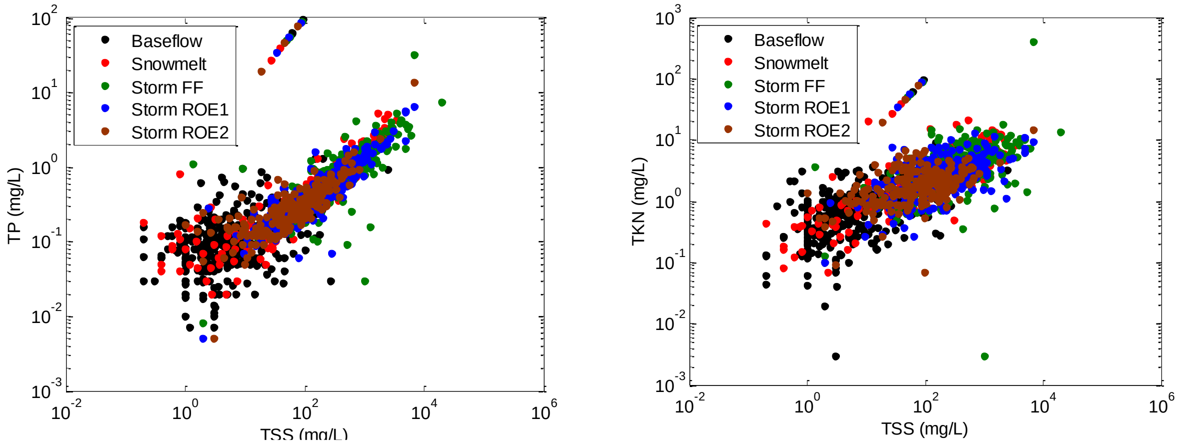
3.4.4 Relationships between TSS and other water quality parameters

Calculated Spearman's correlation coefficients between TSS and other water quality for each flow types, when pooling data collected from same land use types together, are documented in Table 5. Significant correlations were found between TSS and TP and between TSS and TKN (except ROE1 in commercial land use) for all types of land uses given a flow type; while the magnitude of the dependencies of TP on TSS are not consistent in the flows and land uses. Among the four land use types, the correlation coefficients of TSS and TP calculated from baseflow are relatively lower than those calculated from stormwater and snowmelt. In addition as demonstrated in Fig. 6(a), relatively larger variation in the dependence when the concentrations of TSS and TP are low; the dependence is stronger when their concentrations are relatively high; however, the dependence of TKN on TSS appears no prominent change between low and high concentrations (Fig. 6(b)).The associations of TSS and some other parameters, including TDP, NH_4^+-N, and NO_2^-/NO_3^--N, are, in general absent or not strong. BOD presents strong and significant correlations with TSS in both baseflow and snowmelt; while the dependence was only detected in residential areas in FF and ROE1 and commercial areas in ROE2.

Table 6 shows the calculated Spearman's correlation coefficient between TP and TDP, given a flow type and a land use type. Significant and strong correlations were found in all land uses for baseflow. Although significant correlations were calculated in some land use types in snowmelt, and stormwater runoff, which are overall not as strong as the correlations in baseflow. Fig. 7 further demonstrates the scatter plot of TP and TDP for each flow type, in which data from different land uses were pooled together. In baseflow, the ratio of TDP to TP is approximately close to 1; while the ratios in other flow types are below 1, in general.

Table 5: Spearman's correlation coefficients between TSS and other parameter for each type of land use (numbers in bold indicate positive correlations are significant at 5% significance level; numbers in parentheses are the sample sizes)

Flow type	Land use	TP	TDP	NH_4^+-N	TKN	NO_2^-/NO_3^--N	BOD
Baseflow	Commercial	**0.388** (60)	-0.005 (61)	0.104 (61)	**0.754** (58)	**0.388** (59)	**0.720** (61)
	Industrial	**0.391** (93)	0.189 (93)	0.012 (93)	**0.404** (93)	0.058 (92)	**0.517** (93)
	Development	**0.726** (61)	0.205 (62)	**0.415** (62)	**0.621** (59)	-0.173 (60)	**0.420** (60)
	Residential	**0.367** (199)	**0.240** (199)	**0.425** (199)	**0.343** (190)	-0.160 (191)	0.103 (199)
Snowmelt	Commercial	**0.868** (38)	-0.036 (33)	**0.766** (35)	**0.816** (38)	-0.309 (37)	**0.914** (37)
	Industrial	**0.936** (46)	**0.576** (45)	**0.796** (43)	**0.874** (46)	**0.512** (45)	**0.697** (44)
	Development	**0.890** (27)	**0.390** (27)	0.084 (27)	**0.554** (27)	-0.041 (27)	**0.653** (27)
	Residential	**0.932** (76)	**0.396** (70)	**0.759** (73)	**0.895** (77)	-0.057 (74)	**0.858** (74)
Stormwater (FF)	Commercial	**0.718** (55)	**-0.282** (55)	0.050 (55)	**0.364** (56)	**-0.378** (55)	0.124 (54)
	Industrial	**0.774** (89)	-0.014 (87)	-0.008 (87)	**0.539** (89)	-0.261 (86)	0.185 (87)
	Development	**0.898** (49)	0.076 (48)	**0.312** (48)	**0.652** (49)	-0.110 (48)	0.139 (48)
	Residential	**0.918** (127)	**0.264** (121)	**0.256** (121)	**0.592** (127)	**0.195** (121)	**0.413** (122)
Stormwater (ROE1)	Commercial	**0.605** (55)	-0.047 (54)	-0.125 (54)	0.111 (55)	-0.126 (54)	0.100 (54)
	Industrial	**0.774** (87)	-0.019 (85)	-0.003 (85)	**0.251** (87)	-0.196 (85)	-0.038 (85)
	Development	**0.901** (34)	-0.013 (33)	0.215 (33)	**0.619** (34)	-0.248 (33)	0.122 (32)
	Residential	**0.876** (104)	0.186 (100)	**0.302** (99)	**0.647** (104)	**0.202** (101)	**0.390** (99)
Stormwater (ROE2)	Commercial	**0.517** (46)	-0.422 (45)	0.083 (45)	**0.360** (46)	-0.581 (45)	**0.473** (45)
	Industrial	**0.742** (77)	0.202 (75)	0.168 (75)	**0.250** (77)	-0.188 (75)	-0.133 (77)
	Development	**0.826** (19)	-0.136 (19)	-0.010 (19)	**0.551** (19)	-0.485 (19)	-0.208 (19)
	Residential	**0.881** (65)	0.099 (62)	-0.033 (61)	**0.443** (65)	-0.170 (62)	0.167 (62)



(a) TSS and TP (b) TSS and TKN

Figure 6: Relationships of TSS with TP and TKN in each flow type

Table 6: Spearman's correlation coefficients between TP and TDP for each type of land use given a flow type (Numbers in bold indicate positive correlations are significant at 5% significance level; numbers in parentheses are the sample sizes.)

Flow	Baseflow	Snowmelt	Stormwater (FF)	Stormwater (ROE1)	Stormwater (ROE2)
Commercial	**0.658** (63)	0.252 (34)	0.145 (55)	**0.388** (54)	0.265 (45)
Industrial	**0.879** (94)	**0.711** (45)	**0.284** (87)	**0.365** (85)	**0.584** (75)
Development	**0.659** (62)	**0.495** (27)	0.092 (48)	0.136 (33)	0.149 (19)
Residential	**0.916** (118)	**0.607** (74)	**0.348** (121)	**0.366** (100)	**0.328** (45)

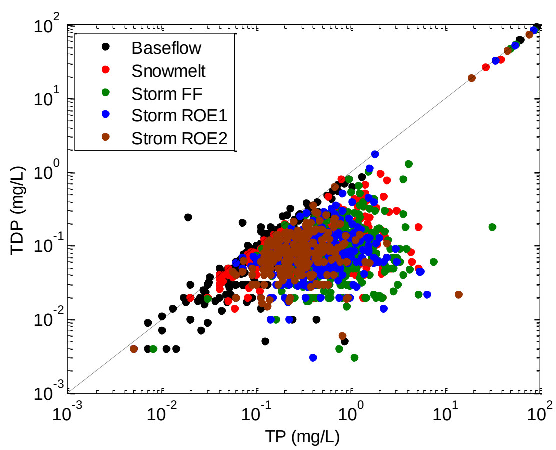


Figure 7: Relationships between TP and TDP in each flow type

3.5 Discussion

3.5.1 Temporal distribution of water quality

The analysis results of water quality levels in different flows (Table 2) demonstrated that significant differences in many water quality parameters among these flows. In particular, the water quality levels (except dissolved constitutes, NO_2^-/NO_3^--N and TDP) in base flow appears to be better than those in snowmelt and FF. The results are under expectation, as different water sources contribute to the flows. In general, groundwater, which is the major source of base flow, has better quality compared to surface runoff (either stormwater or snowmelt). When comparing FF and snowmelt, elevated or equivalent concentration medians of most constituents (except NO_2^-/NO_3^--N and TDP) were found in FF. The results might be explained by the fact that the sources of pollutants in snowmelt and FF are mainly located on land surface and/or subsurface. These significant differences in the flows suggest the different hydrologic responses of water quality, which vary in flows due to different water sources, pollutant sources, and pollutant physical nature. Therefore, an efficient water quality monitoring program should be capable of capturing the temporal variations of water quality, which reflect the different water quality levels in different flow types. Hence, it is necessary to monitor water quality in different types of flow in order to accurately quantifying pollutant loading from urban areas. The daily flow weighted sampling, which ignore the variations of water quality in different flow regimes, likely produces either over- or under-estimation of pollutant loadings.

Regarding water quality monitoring of stormwater runoff, the identified differences in water quality levels among FF, ROE1, and ROE2 imply that the increase of temporal resolution of sampling would enhance the accuracy of the quantification of pollutant loading. To determine appropriate temporal resolution, the investigation on how to divide the time periods for monitoring in storm events is needed and to what degree the accuracy of quantifying can be improved by increasing temporal monitoring resolution can improve the pollutant loading. The trade-off between monitoring cost and the quantification accuracy of loads is needed for further investigation.

3.5.2 Spatial distribution of water quality

As illustrated in Table 3, in general, no particular patterns can be seen can be seen in most constitutes when comparing water quality levels among the land uses given each flow type. Significantly high TSS concentration medians of FF and snowmelt in on-going development land use are under expectation since the construction activities produce and subsequently deposit more particle sediments on land surface. In base flow, the significantly high TSS concentration median in the on-going development land use might be resulted from the re-suspension of sediments deposited in drainage systems after rain events, as construction activities does not directly affect TSS concentrations in groundwater.

Given a flow type, identified significant differences between/among sub-catchments in each type of land use (Table 4) imply the challenge in selecting representative sub-catchment(s) for water quality monitoring to quantify pollutant loading from a type of land use. Therefore besides representation of temporal variations of water quality by the water quality monitoring program, the program should also be capable of capturing the spatial variations of water quality, as differences in water quality levels have been detected not only among different land use types but also between/among sub-catchments for each type of land use. Apart from classifying land use based on the major categories: commercial, industrial, on-going development, and residential land uses, more elaborate classification, such as using the percentage of impervious areas in land use classification, might be necessary to capture the water quality spatial variations between/among sub-catchments in same land use type for quantifying pollutant loading purpose.

3.5.3 Representative parameters in water quality monitoring

Water quality parameters to be measured often are selected based upon the purpose of monitoring and the problem to be answered; however, the cost often constrains the numbers of parameters to be monitored and of samples to be taken. It is often desired to reduce the number of parameters to monitor when designing a water quality monitoring program. Dependency between selected monitoring parameters is not uncommon. If such dependency can be established and verified, then one parameters can act as representative indictors of other parameters and be used to quantify their loading. In this study area, the significant and strong correlations between TSS and TP and between TSS and TKN suggest that TSS might be a suitable representative parameter of particulate constituents in the water quality monitoring. TP consists of both particular form and dissolved form of the constituents; while TKN is the organically bound nitrogen. Their relationships with TSS, however, are needed to be calibrated for the land uses individually before implementing the relationships to quantify pollutant loading. The lack of association between TSS and dissolved constituents, such as TDP and NO_2^-/NO_3^--N, support the fact that the governing transport mechanism and/or sources are different between particulate and dissolved constituents.

Phosphorus management has been one of crucial components in both point and non-point pollution management for protecting the environment in Alberta, Canada, as it has been blamed for low dissolved oxygen and subsequently affect aquatic health. In this study area, the dependence of TP and TDP is strongest in baseflow among all flow types in all land use types (Table 6). The high ratio of TDP to TP in baseflow (Fig. 7) suggest that phosphorus exist largely in dissolved form; while relatively high percentage of particulate form of phosphorus attached to sediments presents in both snowmelt and stormwater. These result further explain a strong relationships between TSS and TP in snowmelt and stormwater (Table 5); whereas their relationship in baseflow is not as strong as that in snowmelt and stormwater. The detected differences in the relationships between TP and TDP in the flows suggest different sources of the pollutants in the flows and these two constituents are needed to be monitored separately.

3.6 Conclusion

In general, the investigated water quality parameters exhibited variations both temporally and spatially. The results show significant differences in the medians of the parameters' concentrations among different flows (baseflow, snowmelt and stormwater); in particular, elevated concentrations were observed in snowmelt and stormwater FF. The different water quality levels suggest that different water sources and pollutant sources in baseflow, snowmelt and stormwater. In stormwater monitoring, differences in the median concentrations detected in FF, ROE1 and ROE2 imply the need of increasing temporal resolution in stormwater event monitoring. Besides the variations among different flows and different time periods in storm events, the spatial variations of water quality levels reflect the differences in water quality among land use types and sub-catchments of a land use type. All these results suggest that an efficient monitoring program needs to represent the spatial and temporal variations for accurately quantifying pollutant loadings. Although measured water quality parameters have often been selected based upon the purpose of monitoring, representative parameters might be able to be identified and used to represent variations of other parameters, and subsequently the number of parameters to be monitored can be reduced. For example, TSS might be a representative parameter of particulate constituents. However, the relationships between TSS and other parameters might be site specific, thus verification of such relationships is needed before implementation.

Chapter Four: Urban Stormwater Runoff Modeling

4.1 Introduction

The increase of impervious area due to urbanization leads to increases of storm water runoff volume, rate and pollutant loading, which pose detrimental impacts to natural receiving water bodies. SWMM (Rossman, 2010) is one of models available and commonly applied to simulate storm water runoff. SWMM developed by the Environment Protection Agency (EPA) of U.S. is a dynamic and physically-based rainfall-runoff model, which can be used to model both quantity and quality of storm water runoff, especially generated from urban areas. SWMM is composed of several modules including an atmospheric module, runoff module, groundwater module and transportation module. Among these modules, the runoff module simulates rain-runoff (both quantity and quality) from catchments; while the routing module transports runoff through drainage network to an outfall. SWMM can be applied to conduct both event-based and continuous simulation. SWMM has been applied for efficiently managing storm water ranging from urban drainage to flood routing (Di Modugno *et al*., 2015; Hsu *et al*., 2000). It has been used on numerous watersheds in Canada, U.S., and other part of the world (Temprano *et al*., 2006; Di Modugno *et al*., 2015; Bhaduri *et al*., 2001).

Compared to modeling of stormwater runoff quantity, modeling of stormwater runoff quality is more challenging due to the fact of the complexity of the processes governing the pollutant buildup and wash-off from land surface and pollutant transport. The wash-off of pollutants deposited on the land surface is primarily dependent on the hydrologic factors (such as rainfall intensity and runoff rate), physical characteristics of pollutants (e.g., size) as well as land surface characteristics (Bai and Li, 2013). The buildup of pollutant is associated with the anthropogenic activities occurring in catchments, thus different function or different function coefficients for describing pollutant deposition on land surface should be applied to different types of land use. In SWMM, water quality modeling (especially for TSS, solids-attached and particulate pollutants) was developed based on the concept of pollutant buildup and wash-off on the land surface. SWMM applies various pollutant buildup functions to express the buildup of pollutant during the dry period. Pollutant buildup is described as mass buildup per unit area of the surface or curve length (Rossman, 2010). The amount of buildup is a function of number of preceding dry days and can be computed either by power function, exponential function or saturation function or external time series function in SWMM. In the literature, the exponential function has been often adopted. The exponential buildup follows an exponential growth curve that approaches a maximum limit asymptotically and it requires only the maximum possible buildup parameter to calculate the pollutant buildup component. Pollutant wash-off during wet weather period from a catchment is also often simulated using an exponential function. When using an exponential function for wash-off, the pollutant load is proportional to the product of runoff raised to some power and to the amount of remaining buildup. The wash-off coefficient and wash-off exponents are two parameters requiring inputs for calculating pollutant load. When using the exponential function, wash-off load of pollutant is directly proportional to the runoff rate hence it is proportional to the runoff volume and hence clearly varied with rainfall intensity. Higher intensity rainfall is expected to produce higher concentration of pollutant load, and vise verse. Di Modugno *et al*. (2015) adopted an exponential function for both buildup and wash-off to simulate storm water runoff quality (TSS) from a residential area in Puglia, Southern Italy. In this study, the wash-off coefficient of 0.18 l/mm and wash-off exponent of 2.35 were determined through model calibration; while the buildup rate of 13.143 kg/ha-day was selected. The coefficient of determination calculated in the model calibration and validation for TSS ranged from 66% to 99%.

In another study by Temprano *et al*. (2006), exponential function was used to model the buildup of pollutants and rating curve function was used to model wash-off of pollutants. In the study, the calibrated maximum build up and build up rate parameters was determined to be 17.5 kg/ha-day and 0.3 respectively.

In addition, Bai and Li (2013) investigated the sediment wash-off from an urban impervious area based on both instantaneous and event based wash-off load. This paper argued that that finite difference numerical models developed based on detailed physical mechanisms outperform empirically based models, such as SWMM.; however, higher cost is associated with the use of such numerical model in which more elaborate mathematical description of physical processes is required. Since the amount of pollutant transported during a storm event can be limited either by the availability of pollutant source deposited in a catchment or by the storm water runoff (transport), However, SWMM only takes into account the pollutant source limitation.

To develop SWMM for a catchment, model parameters (for both quantity and quality modeling) are required to be determined in the model calibration. Model calibration is the process of tuning the parameters used in the model in such a way that the error in observed and simulated results is minimized. When there are multiple parameters needed to be determined in the model calibration, manual calibration is often labor intensive, especially for large catchments; however, manual calibration approach (trial and error approach) has still often been used (e.g., Temprano *et al*., 2006; Di Modugno *et al*., 2015). For event-based simulation, Barco *et al*. (2008) proposed developing SWMM model in three steps (1) calibrating the model “storm by storm” to identify optimal parameters for each individual storm; (2) averaging the optimal parameters of individual storms and using as the optimal parameters for all calibration events; and (3) validating the model using parameters determined in (2). The above method was applied to a large watershed in

California by Barco *et al*. (2008), which reported the error in simulating total runoff volume in the range of 18% ~ 100%, the error in simulating peak flow in the range of 25% ~ 44%, and a smaller error in the model validation compared to the model calibration.

In the model calibration of SWMM, different studies have use different matric(s) for runoff quantity and quality calibration, as there are no systemic rules available for selecting statistics metrics for model validation purpose. Temprano *et al*. (2006) adopted SWMM to predict the quantity and quality of storm water runoff from combined sewer system in a catchment, from a mix type of land use, in Santander, Spain. The model calibration for runoff quantity was conducted based upon the model performance in simulating event peak flows; whereas the calibration for runoff quality was targeted to minimize the error of pollutant concentration.

4.2 Data Used

As mentioned in Chapter 2, the City of Calgary has collected event-based stormwater runoff quantity and quality from four different types of land use. In this chapter, the event-based data collected from two major types of land use: industrial and residential land uses, were selected to investigate the effect of land use on stormwater runoff quality. Among the catchments which were monitored for these two types of land use, Bonnybrook (BB) represents a typical industrial land use in which approximately 60% of catchment is for industry; McKenzie Towne (MK) is a typical residential catchment with approximately 60% area for residential area. Fig. 3 shows the locations of these two catchment within the City of Calgary. The event-based water quantity and quality data are available for BB and MK in 2002-2005 and 2002, respectively. Rainfall data collected at the rain gauges, Odegen and McKenzie Towne, which are in the proximity to these two studied catchments are used. The rain events from April to September were considered in the modeling. At BB, high instrumental error in measurements was suspected, and thus the events observed in 2002 were not included. In a total, 12 and 6 events (Table 7) were selected and used for developing the models for BB and MK, respectively. From statistical point of view analysis of 12 and 6 numbers of rainfall-runoff events seems to be less to provide any conclusion however, comparing to the numbers of rain events used for rainfall runoff modeling on different literatures and given the condition of qualifying rain event, the numbers of rain event considered are appropriate. All the rainfall-runoff monitoring and recording made in the field are sometimes nit useful because of some instrumental errors or any unknown conditions. Among the selected events, two third of the events were used for model calibration and the remaining events were applied to validate the models. At BB, eight events observed during 2003-2004 were used for model calibration and other four events observed in 2005 were used for model validation. At MK, four events in 2002 were adopted to calibrate the model, while the other two events from the same year were used for model validation. The rainfall characteristics of rain events used for both model calibration and validation are also shown in Table 7.

Table 7: Storm events used for model development (both calibration and validation) for BB and MK, respectively.

	Site	Land Use	Date (dd/mm/yy)	Rainfall Duration (hr)	Total ppt (mm)	Runoff Coeff	Return Period
Calibration	BB	Industrial	01/06/03	1.90	2.40	0.20	< 2 yrs
	BB	Industrial	18/06/03	0.50	11.00	0.17	**> 2 yrs**
	BB	Industrial	05/07/03	4.10	9.80	0.12	< 2 yrs
	BB	Industrial	19/08/03	0.66	2.00	0.10	< 2 yrs
	BB	Industrial	06/06/04	13.75	47.60	0.56	**> 5 yrs**
	BB	Industrial	07/07/04	10.60	1.40	0.30	< 2 yrs
	BB	Industrial	04/08/04	1.58	5.60	0.29	< 2 yrs
	BB	Industrial	15/08/04	2.90	16.40	0.03	< 2 yrs
validation	BB	Industrial	19/07/05	1.58	5.60	0.40	< 2 yrs
	BB	Industrial	24/07/05	2.00	5.60	0.37	< 2 yrs
	BB	Industrial	02/08/05	1.50	5.20	0.39	< 2 yrs
	BB	Industrial	23/08/05	3.80	5.80	0.27	< 2 yrs

Calibration	MK	Residential	27/07/02	2	14.20	0.15	**> 2 yrs**
	MK	Residential	02/08/02	1.7	9.40	0.20	< 2 yrs
	MK	Residential	10/08/02	4.7	17.80	0.27	< 2 yrs
	MK	Residential	30/08/02	3.1	13.00	0.32	< 2 yrs
validation	MK	Residential	20/08/02	1.2	2.20	0.27	< 2 yrs
	MK	Residential	30/09/02	5.6	13.60	0.32	< 2 yrs

4.3 Methodology

Due to the popularity of SWMM, it is selected for this study. SWMM conceptualizes a drainage system as a series of water and material flows between several major environment compartments. There are four major compartments in the SWMM model i.e. atmosphere compartment, land surface compartment, ground surface compartment, and transport compartment. Conceptual flow diagram of the SWMM model is shown in Fig. 8. All the compartments are equally important however all the compartments are not required at the same time (Rossman, 2010). The runoff module as well as the transport module of SWMM were used for this study. The runoff module simulates the surface runoff quantity from a catchment during storms. Given a storm, surface runoff quantity is primarily affected by the geophysical characteristics of the catchment, which include area, width, average slope, percentage of impervious area, surface storage of the catchment as well as the soil characteristics (infiltration). The infiltration loss is estimated by using Green-Ampt equation for this study. As there are many parameters in SWMM which can affect storm water runoff quantity from urban catchments, sensitivity analysis is conducted to investigate the response of storm water runoff quantity to the variation of the parameters in order to determine the parameters to be calibrated in the model calibration. Storm water runoff quality is simulated according to runoff volume and the pervious condition of the catchment such as dry weather, cleaning of street and use of the land.

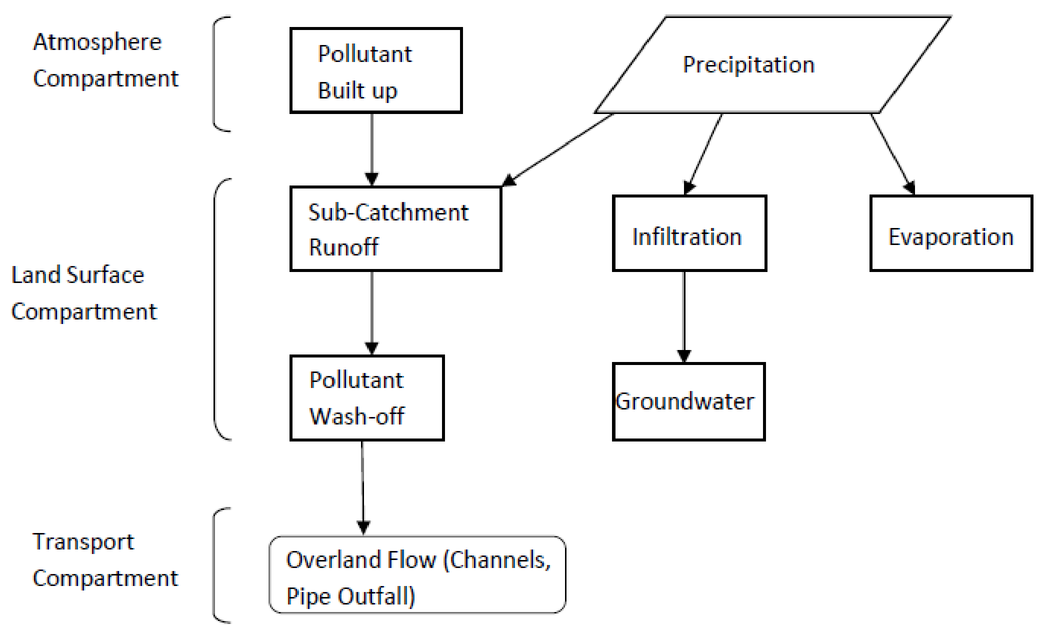


Figure 8: Conceptual flow diagram of SWMM

The calibration for storm water quantity used in this report is based on the study by Barco *et al*. (2010), in which the model calibration for storm water runoff quantity (runoff volume and peak flow) is processed in three steps: 1) calibrating the model by storms individually - for each individual storm, the model parameters are varied manually such that the errors of the observed and simulated runoff volume and peak flow are minimized using manual calibration approach; 2) averaging the calibrated model parameters in all storms; and 3) using the averaged model parameters to simulate all storm events and quantify the errors. The calibrated model parameters are then used for the model validation on the remaining storms which are not used in the model calibration.

After the calibration for storm water runoff quantity, the calibration for storm water runoff quality is proceeded, as water quality modeling is virtually impossible without first accurately modeling runoff (James, 1996). For modeling solids (e.g., TSS), both solids buildup (accumulation) in dry days and wash-off (transport and deposition) by storm water runoff in wet weather are required to be calibrated. Therefore the model parameters associated with pollutant buildup and wash-off are also calibrated manually to minimize the errors in EMC. The rain events that are used for calibrating and validating storm water runoff are used for calibrating and validating water quality, respectively. For water quality modeling, exponential function, which has been often used in the literature, is used to model pollutant buildup and wash-off in this report. The exponential functions for pollutant buildup and wash-off are shown in Equations (1) and (2), respectively.

$$B = C_1(1 - e^{-C_2 t}) \tag{1}$$

where C_1 is maximum possible buildup (mass/area); C_2 is buildup rate constant (1/day); and B denotes pollutant buildup.

$$W = C_{w1} q^{Cw_2} B \tag{2}$$

where Cw_1 and Cw_2 are wash-off coefficient and exponent, respectively; q is runoff rate per unit. All the coefficients for pollutant buildup and wash-off are calibrated in the model calibration.

Besides before developing models using SWMM, local sensitivity analysis, namely only varying one parameter at a time, was performed. The analysis was conducted for all input parameters in SWMM which have potential to affect stormwater runoff quantity. The parameters include catchment width, slope, percentage of impervious area, manning roughness for impervious and pervious area, depth of depression storage for pervious and impervious area as well as suction head, saturated conductivity, and wilting point (in Green-Amp equation modeling infiltration).

4.4 Results and Discussion

4.4.1 Sensitivity analysis

The results of the analysis are shown in Figs. 9 and 10 for a rain event on 06/06/2004 at BB and a rain event on 07/27/2002 at MK, respectively, as examples. As illustrated in the results, percentage impervious is the most sensitive parameter among all parameters followed by depression storage for impervious area and manning roughness for impervious area for both study areas. The result was consistent in all other rain events. Similar result was also reported for urban catchments (e.g., Barco *et al*., 2008; Temprano *et al*., 2006). Therefore, percentage impervious, manning's roughness coefficient, slope, width and depression storage were selected to be determined in the model calibration.

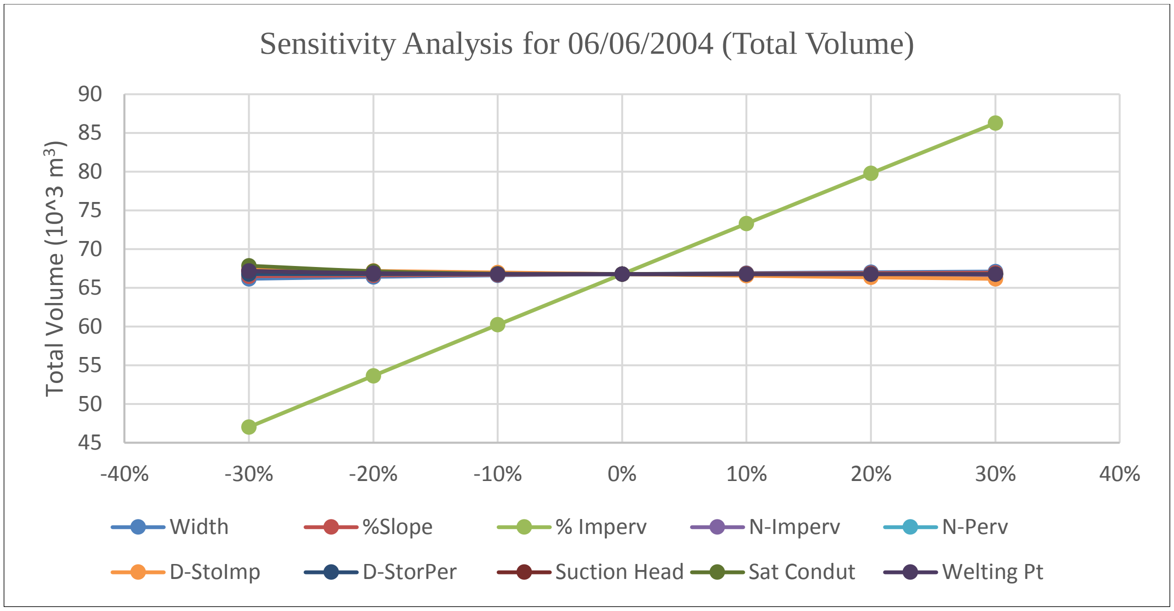


Figure 9: Sensitivity analysis for Bonnybrook in a rain event on 06/06/2004

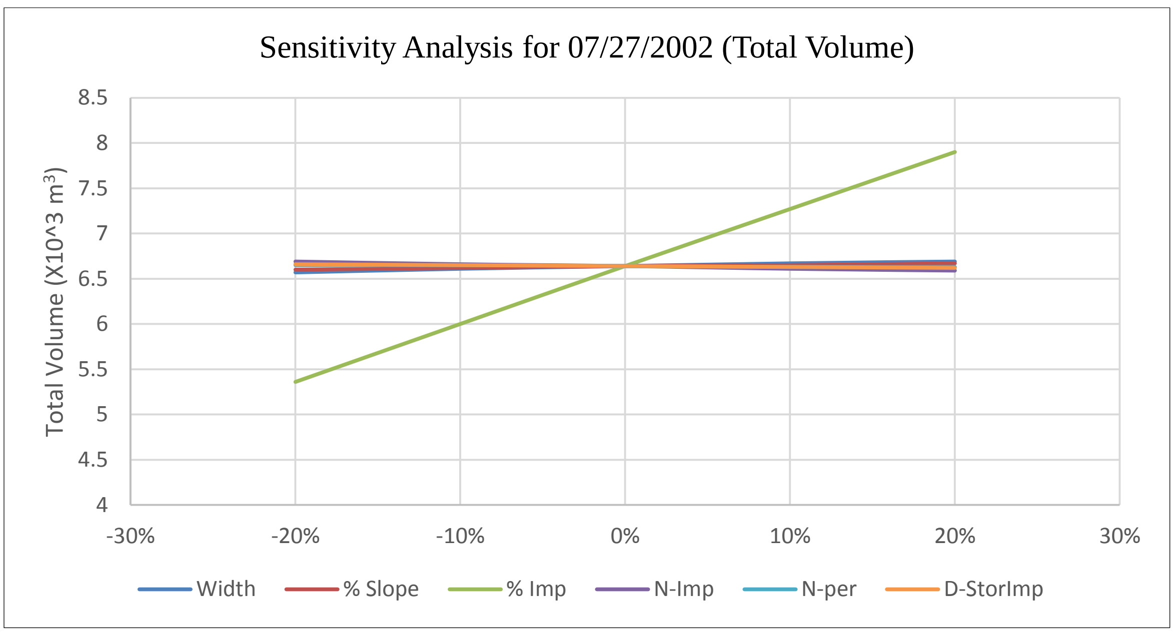


Figure 10: Sensitivity analysis for McKenzie Towne for a rain event on 07/27/2002

4.4.2 Stormwater runoff quantity calibration

The calibrated parameters are listed in Table 8 for BB and MK, respectively. Table 9 shows the observed total volume and peak flow along with simulated results for individual events when the model was calibrated storm by storm and the average calibrated parameters of all calibration events at BB. Table 10 shows the calculated relative error of individual events between observed and simulated of total volume and peak flow at BB. The range of error of total runoff volume is in -19% to 47%; while the error in peak flow varies from -25% to 31% when the average calibrated parameters were used. Figs. 11 and 12 illustrate the observed and simulated total runoff volume and peak flow, respectively, for all calibration events at BB. The coefficient of determination (R^2) (between observed and simulated values) are 99% for total runoff volume and 88 % for peak flow. As examples, the calibrated results for rain events on 07/05/2003 and 07/07/2004 are shown in Figs. 13 and 14, respectively. As illustrated in the figures, the calibrated model is able to predict the shape of the hydrograph, the magnitude of flow and the time to peak fairly well.

Table 8: Calibrated parameters for Bonnybrook and McKenzie Towne

Sites	Bonnybrook	McKenzie Towne
Parameters	Calibrated Value	Calibrated Value
Width (m)	1033.00	506.25
% slope	3.61	3.55
% Impervious	35.67	32.00
N-Impervious	0.01	0.01
N Pervious	0.31	0.24
Dstore-Imper (mm)	0.52	0.23
Dstore-Per (mm)	1.73	2.07

Table 9: Observed and simulated total runoff volume and peak flow at Bonnybrook in the model calibration

Bonnybrook	Observed		Simulation (Storm by Storm)		Simulation (Average all)	
Event Date	V* (m^3)	P**(m^3/s)	V* (m^3)	P**(m^3/s)	V* (m^3)	P**(m^3/s)
06/01/2003	1710.00	0.31	2030.00	0.31	1980.00	0.31
06/18/2003	7503.18	2.81	9200.00	2.15	9430.00	2.16
07/05/2003	8340.00	1.29	11090.00	1.42	12290.00	1.70
08/19/2003	730.00	0.22	1000.00	0.20	850.00	0.17
06/06/2004	75070.00	2.05	78990.00	2.26	61000.00	2.26
07/07/2004	12080.00	2.05	12900.00	2.26	12030.00	2.27
08/04/2004	6250.00	2.05	7100.00	2.15	6410.00	2.15
08/15/2004	12840.00	2.05	11410.00	2.15	12690.00	2.13

* V stands for the total runoff volume.
** P denotes the peak flow.

Table 10: Relative errors between observed and simulated total volume and peak flow at Bonnybrook in the model calibration

Bonnybrook	Simulated (Storm by Storm)		Simulated (Average all)	
Event Date	EV* (%)	EP** (%)	EV (%)	EP (%)
06/01/2003	+18.71	-0.32	+15.79	-1.29
06/18/2003	+22.61	-30.76	+25.68	-23.17
07/05/2003	+32.97	+9.37	+47.36	+31.93
08/19/2003	+36.99	-9.36	+16.44	-24.77
06/06/2004	+5.22	+9.55	-18.74	+10.51
07/07/2004	+6.79	+9.59	-0.41	+10.70
08/04/2004	+13.60	+4.93	+2.56	+5.28
08/15/2004	-11.14	+4.97	+1.17	+3.86

* EV stands for the relative error of total runoff volume.
** EP denotes the relative error of peak flow.

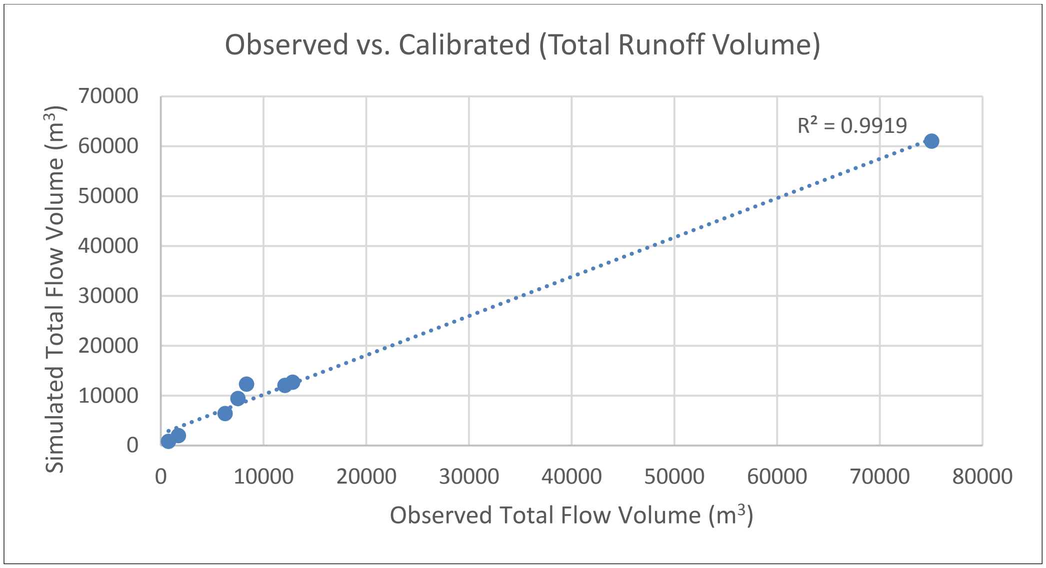


Figure 11: Observed vs. calibrated total runoff volume at Bonnybrook in the model calibration

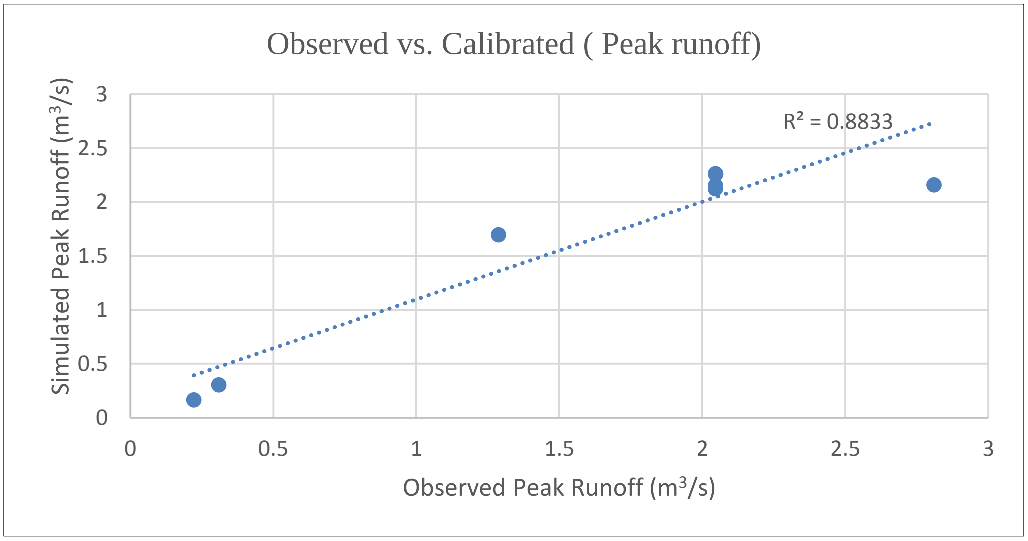


Figure 12: Observed vs. calibrated peak flow at Bonnybrook in the model calibration

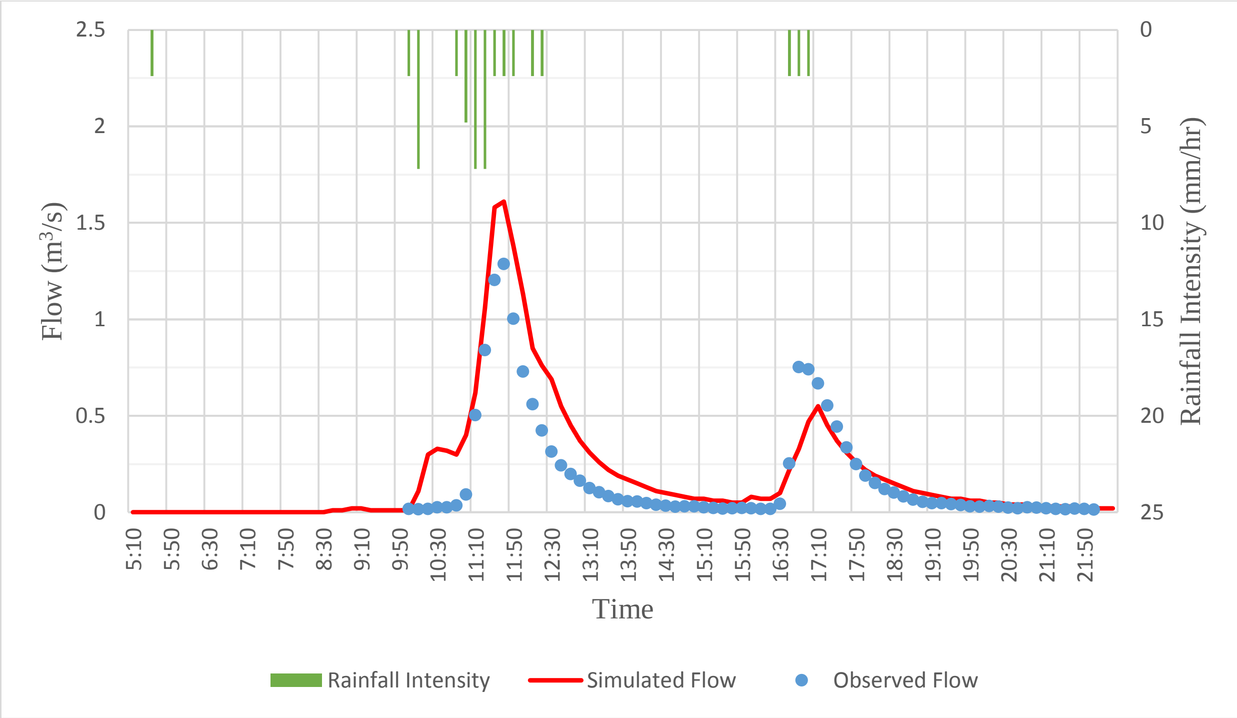


Figure 13: Hyetograph, observed and simulated hydrograph of rain event on 07/05/2003 at Bonnybrook.

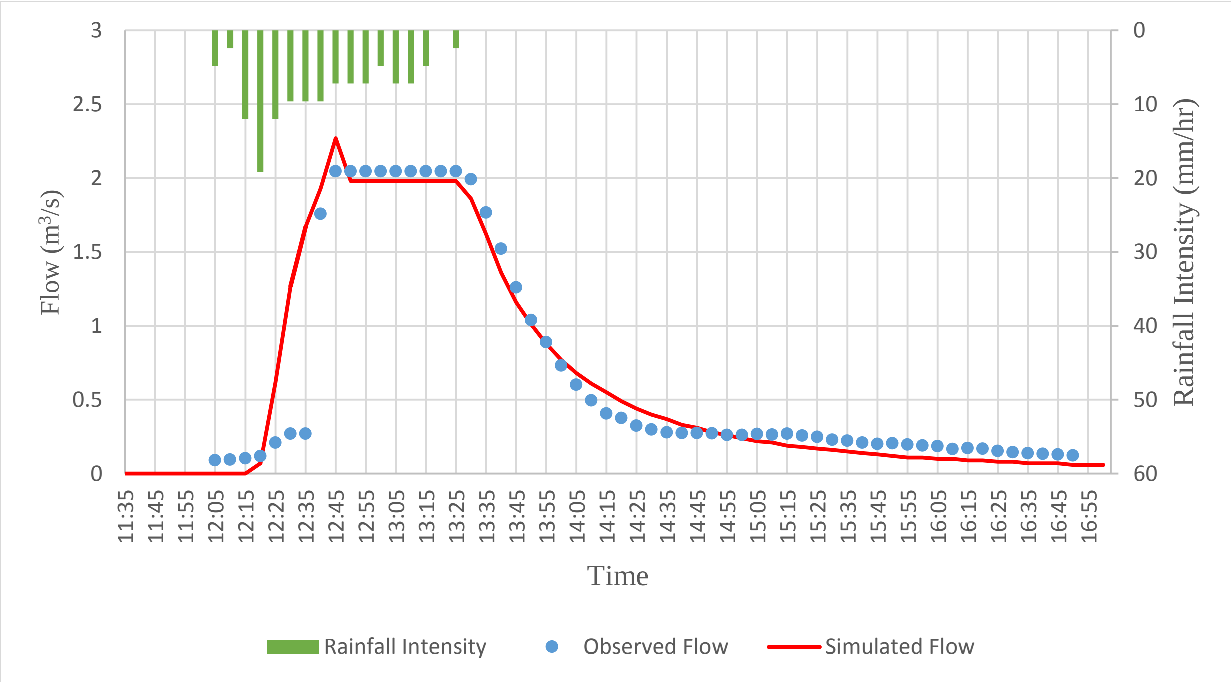


Figure 14: Hyetograph, observed and simulated hydrograph of rain event on 07/07/2004 at Bonnybrook.

Table 11 shows the observed total volume and peak flow along with simulated results for individual events when the model was calibrated storm by storm and the average calibrated parameters of all calibration events were used in the model at MK. Table 12 shows the calculated relative error of individual events between observed and simulated of total volume and peak flow at MK. The range of error of total runoff volume is in -15% to 116%; while the error in peak flow varies from -60% to 72%. Fig. 15 illustrate the observed and simulated total runoff volume for all calibration events at MK. The R^2 is 0.41 for total volume. Low R^2 might be due to the small number of events used in the model calibration compared to BB. As an example, the calibrated results for rain events on 08/10/2002 is shown in Fig.16. As displayed in the figure, the calibrated model is able to predict the shape of the hydrograph, the magnitude of flow and the time to peak fairly well.

Table 11: Observed and simulated total runoff volume and peak flow at McKenzie Towne in the model calibration

McKenzie	Observed		Siml. (Storm by Storm)		Siml. (Average all)	
Event Date	V (m^3)	P(m^3/s)	V (m^3)	P(m^3/s)	V (m^3)	P (m^3/s)
07/27/2002	3010	2.24	4870	2.52	6490	3.856
08/02/2002	3390	1.098	4940	1.13	4270	0.957
08/10/2002	7740	1.96	8210	2.29	8460	2.346
08/30/2002	6910	3.917	6510	1.83	5850	1.547

Table 12: Relative errors between observed and simulated total volume and peak flow at McKenzie Town in the model calibration

McKenzie	Simulated (Storm by Storm)		Simulated (Average all)	
Event Date	EV (%)	EP (%)	EV (%)	EP (%)
07/27/2002	+61.79	+12.50	+115.61	+72.14
08/02/2002	+45.72	+2.91	+25.96	-12.84
08/10/2002	+6.07	+16.84	+9.30	+19.69
08/30/2002	-5.79	-53.28	-15.34	-60.51

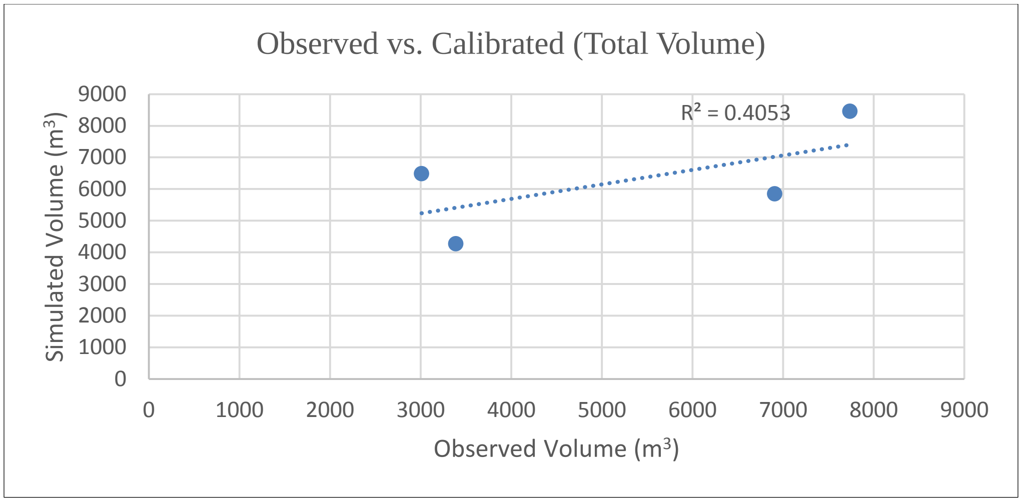


Figure 15: Observed vs. calibrated total runoff volume at McKenzie Towne in the model calibration

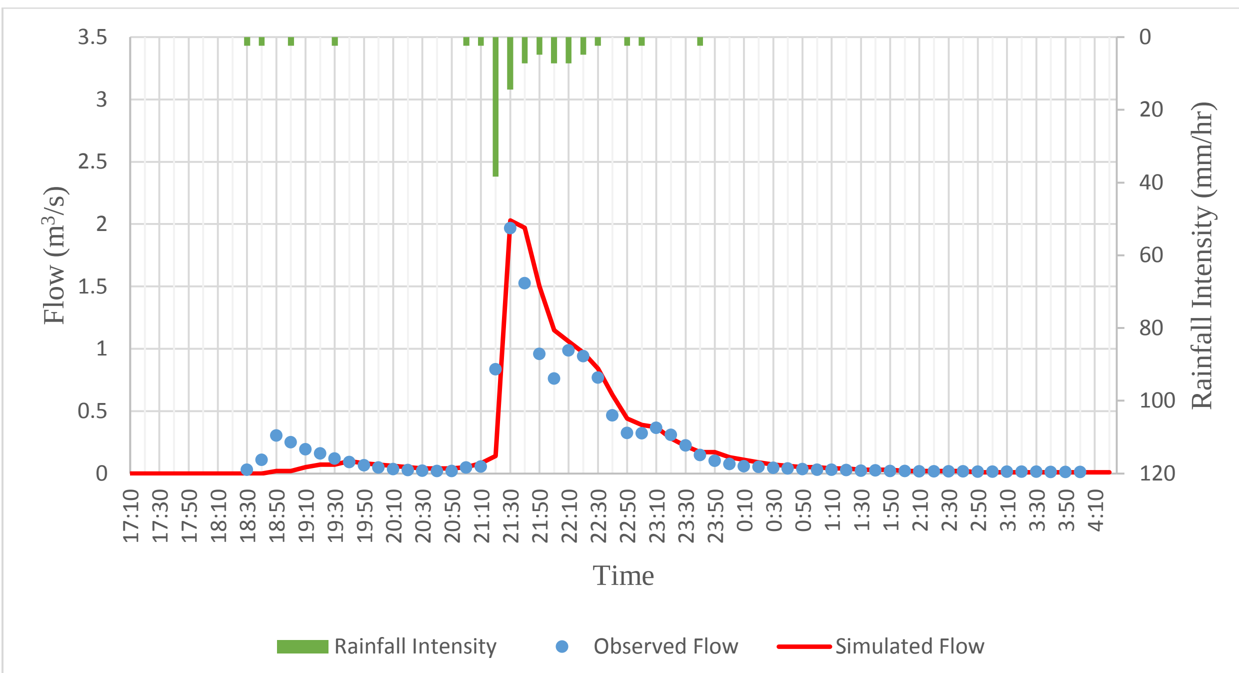


Figure 16: Hyetograph, observed and simulated hydrograph of rain event on 08/10/2002 at McKenzie Towne.

4.4.3 Stormwater runoff quantity validation

At BB, four rain events in 2005 were used to validate the calibrated SWMM model. Table 13 lists the observed and simulated total runoff volume and peak flow as well as their relative errors at BB in the model validation. The error in total runoff volume ranges from -23% to 37%; while the error in peak flow ranges from -43% to -1%. The errors obtained in the model validation for total runoff volume and peak flow are not significantly higher than those in the model calibration. Thus, the calibrated model (for quantity) performs equivalently in both the model calibration and validation. Fig. 17 shows the observed and simulated hydrograph of rain event on 08/23/2005. As illustrated in this figure, the simulated time to the peak (higher peak) is well matched with its observation; whereas there is overall a phrase error (time lag in shape) between the observed and simulated hydrograph and the simulated runoff lasted longer than observed runoff. Thus for this event, the calculated error in peak flow is very small (-0.7%) and while the simulated runoff volume is 36% more than the observed runoff volume (Table 13).

Table 13: Observed and simulated total runoff volume and peak flow as well as their relative errors at Bonnybrook in the model validation

Bonnybrook	Observed		Validation		Validation	
Event Date	V (m^3)	P (m^3/s)	V (m^3)	P (m^3/s)	EV (%)	EP (%)
07/19/2005	9610	2.046	7390	1.78	-23.10	-13.00
07/24/2005	7720	2.046	5600	1.158	-27.46	-43.40
08/02/2005	7140	1.414	5940	1.059	-16.81	-25.11
08/23/2005	4140	1.067	5670	1.06	+36.96	-0.66

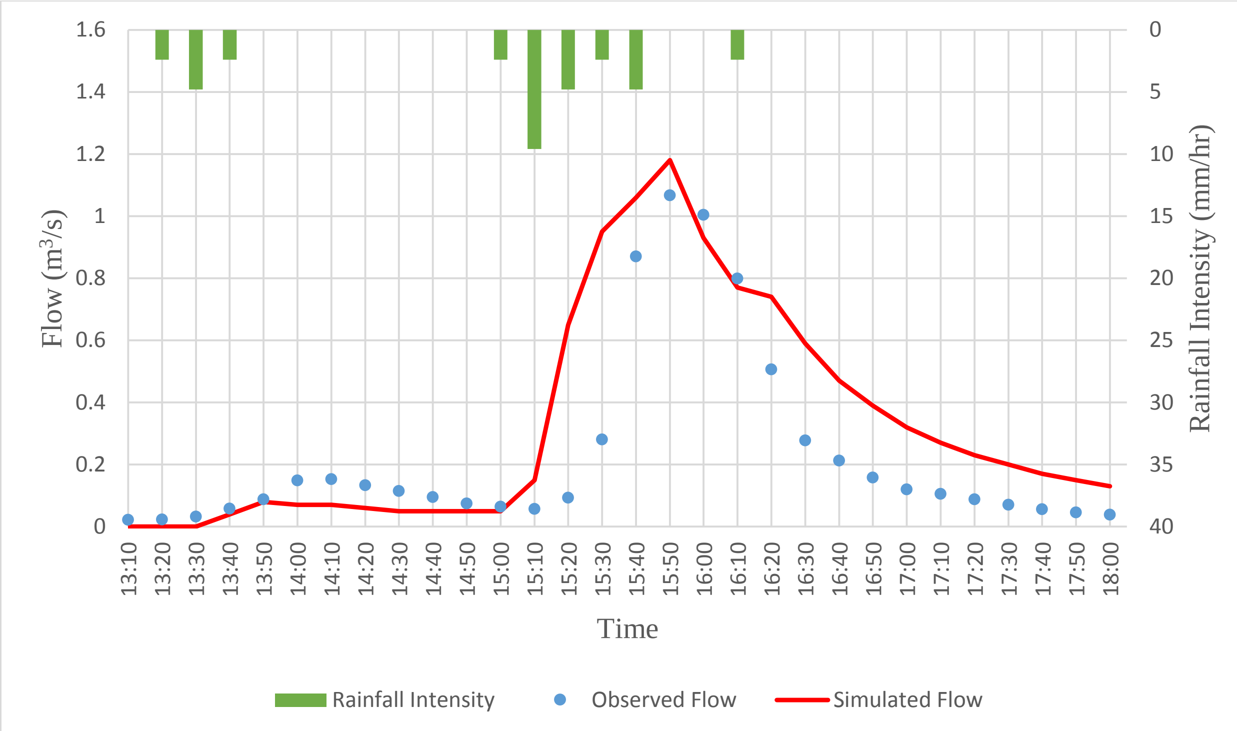


Figure 17: Hyetograph, observed and simulated hydrographs of rain event on 08/23/2005 at Bonnybrook.

Table 14 lists the observed and simulated total runoff volume and peak flow as well as their relative errors at MK in the model validation. The error in total runoff volume ranges from -19% to -9 %; while the error in peak flow ranges from -40% to 5%. The errors obtained in the model validation for total runoff volume and peak flow are located within the ranges reported in the model calibration. Thus, the calibrated model (for quantity) performs fairly well in the model validation. Fig. 18 shows the observed and simulated hydrographs of rain event on 09/30/2002 in the model validation as an example. For this rain event the simulated runoff is more or less equal to observed runoff at the beginning of the rain event but the runoff around the end of the event was underestimated. The peak flow of this event was well predicted.

Table 14: Observed and simulated total runoff volume and peak flow and their relative errors at McKenzie Town in the model validation

McKenzie	Observed		Validation		Validation	
Event Date	V (m^3)	P (m^3/s)	V (m^3)	P (m^3/s)	EV (%)	EP (%)
09/30/2002	7770	0.196	6280	0.206	-19.18	5.10
08/20/2002	880	0.28	800	0.168	-9.09	-40.00

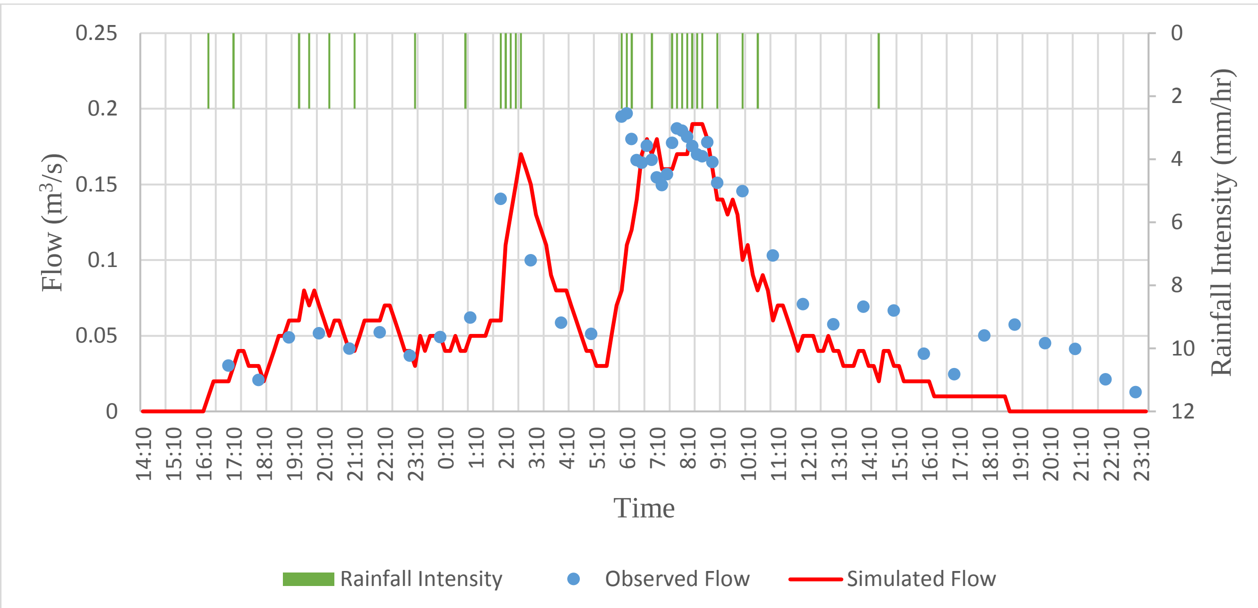


Figure 18: Hyetograph, observed and simulated hydrographs of rain event on 09/30/2002 at McKenzie Towne.

4.4.4 Stormwater runoff quality calibration (for TSS)

Parameters in pollutant (here TSS) buildup and wash-off equations (exponential functions used here) were determined in the model calibration. Initial guess of these parameters were based upon the observed pollutant concentration and literature. The solid buildup rate has demonstrated great variability and generally ranged from 5 kg/ha-day in sparsely populated area to 35 kg/ha-day for industrial area (Sartor *et al*., 1974). The process of model calibration for runoff quality is same as that used for calibrating runoff quantity discussed previously. The rain events selected for model calibration was calibrated individually to match with the observed EMC. Since the pollutograph of TSS are not available, EMCs of rain events were used in the model calibration. The determined buildup and wash-off parameters from individual calibrated events were averaged and then they were used in the calibrated model.

Table 15 presents the calibrated parameters at BB and MK, respectively. The calibrated buildup parameters determined for these two different types of land use (industrial and residential) appear to similar but wash-off coefficient and wash-off exponent are slightly higher for industrial land use (BB) than those for residential land use (MK). TSS EMCs were in general overestimated in most calibration events (except events on 08/04/2004 and 07/05/2003)) at BB, which are shown in Tables 16 and 17. The relative errors in EMC range from -10% to 59%. Among the five rain events at BB, the relative error was less than 10% in two events. R^2 between the observed and simulated EMCs is 0.80 (Fig. 19).

Table 15: Calibrated parameters for Bonnybrook and McKenzie Towne, respectively

Site	Bonnybrook	McKenzie
Parameters	Values used	Values used
Function Used	Exponential	Exponential
Max build up (kg/hec)	56	56
Build up rate (/day)	1	1
Function Used	Exponential	Exponential
Wash off Coefficient	0.098	0.087
Wash off expo	1.79	1.53

Table 16: Observed and simulated EMC at Bonnybrook in the model calibration

Bonnybrook Event Date	Observed EMC mg/l	Simulated EMC Storm by Storm (mg/l)	Simulated EMC Average all (mg/l)
06/01/2003	83.5	91.89	133.21
07/05/2003	345	350.21	311.25
07/07/2004	457	513.10	584.38
08/04/2004	510	491.53	472.16
08/15/2004	451	516.00	595.12

Table 17: Relative errors between observed and simulated EMC at Bonnybrook in the model calibration

Bonnybrook Event Date	Sim (Storm by Storm) Error (%)	Sim (Average all) Error (%)
06/01/2003	10.05	59.53
07/05/2003	1.51	-9.78
07/07/2004	12.28	27.87
08/04/2004	-3.62	-7.42
08/15/2004	14.41	31.96

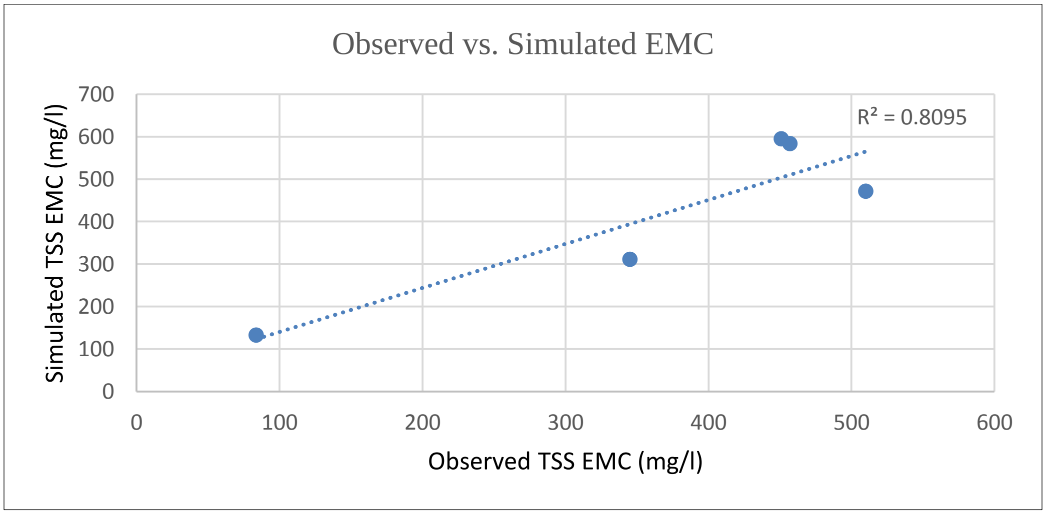


Figure 19: Observed vs. calibrated EMC at Bonnybrook in the model calibration

Tables 18 and 19 display the observed and simulated EMCs and the relative errors at MK in the model calibration. In general, TSS EMC was overestimated in all events for model calibration. The errors in EMC range from 8% to 81%.

Table 18: Observed and simulated EMC at McKenzie Towne in the model calibration

McKenzie Event Date	Observed EMC mg/l	Simulated EMC Storm by Storm (mg/l)	Simulated EMC Calibrated (mg/l)
08/02/2002	301	338	430
08/10/2002	481	482	523
08/30/2002	748	639	1358

Table 19: Relative errors between observed and simulated EMC at McKenzie Towne in the model calibration

McKenzie Event Date	Sim (Storm by Storm) Error (%)	Sim (Average all) Error (%)
08/02/2002	12.29	42.86
08/10/2002	0.21	8.73
08/30/2002	-14.57	81.55

4.4.5 Stormwater runoff quality validation (for TSS)

In the model validation, the observed and simulated EMCs at BB are reported in Table 20. The results demonstrate that the validated model largely underestimated or overestimated the observed EMCs, although its performance is reasonable in the model calibration. The possible causes of the results might lie in the rainfall characteristics and error in observed EMC. For example for the rain event on 07/19/2005 (Table 20), it has a duration of approximately 1.6 hr, rainfall depth of 5.6mm and antecedent dry period of 2 days. The observed TSS EMC is 790 mg/l. However, in the rain event on 08/04/2004 (Table 16), which has a rainfall depth of 5.6mm, a duration of 1.6 hr, and an antecedent dry period of 3 days, the observed TSS EMC is 510 mg/l.

Given similar rainfall duration and rainfall depth, an event of longer antecedent dry period is expected to produce higher EMC since more pollutant can be deposited on the land surface. Similarly, the rain event on 07/24/2005 has 5.6 mm in rainfall depth over 2 hr duration and 4 days of antecedent dry period. The TSS EMC of 159 mg/l was observed. The rain events on 07/19/2005, which is comparable to the event on 07/24/2005 in terms of rainfall amount and duration, has a shorter antecedent dry period compared to that of the event on 07/24/2005. Based upon the concepts of pollutant buildup and wash-off, the event on 07/24/2005 is expected to yield higher TSS EMC compared to that on event of 07/19/2005; however, the observed TSS EMC on 07/24/2005 is much lower than that observed on 07/19/2005 (Table 20). These results might explain the stochastic nature of rainfall, pollutant buildup and/or wash-off on and from land surface (if field observation is reasonably accurate). The other possible explanation is that the pollutant deposited on the land surface is not only dependent on the antecedent dry period before an event but also dependent on the remaining pollutants on the land surface after previous event.

Table 20: Observed and simulated TSS EMCs at Bonnybrook in the model validation

Bonnybrook Event Date	Observed EMC mg/l	Simulated EMC mg/l
07/19/2005	790	368
07/24/2005	159	347
08/02/2005	135	273
08/23/2005	545	372

The errors found during calibration at MK is high whereas the errors during validation at the same site is reasonable. As outlined in Table 21 the relative errors in TSS EMC at MK are in the range of approximately ± 20%. The calibrated model for MK performed better that that for BB. Note that for MK, only four events were used in the model calibration, and two events used in the model validation. More events are required to calibrate and validate the model for MK.

Table 21: Observed and simulated TSS EMCs and relative errors at McKenzie Towne in the model validation

McKenzie	Observed EMC	Simulated EMC	Error
Event Date	mg/l	mg/l	%
08/20/2002	85	68	-19.59
09/30/2002	71.3	86	21.87

4.4.6 Parameterization of the model

The volume and time to peak of runoff from a watershed are functions of several phenomena and parameters, which have varying degree of importance (City of Calgary, 2000). The parameters in the hydraulics model include the depth of depression storage, Manning's roughness coefficient, and impervious area of a catchment as well as the parameters in infiltration equation. The modelling parameters, which have significant impact on the volume and peak of the runoff as identified in the sensitivity analysis, are parameterized (determined in the model calibration) in this study. The ranges of the parameters from literature and the values chosen in this study are shown in Table 22. The values of depression storage (Dstore) for impervious and pervious surface, which are sensitive parameters identified in the sensitivity analysis, were chosen below the lower bound of the range given in literature as the use of low values of the parameters yield good results. The value of manning's coefficient is chosen for smooth concrete surface and for short grasses for impervious and pervious land surface, respectively. Impervious percentage was identified to be the most sensitive parameter thus it was determined with caution and the determined values are below the lower bound to represent the overall land use in these two catchments. Note that the study sites are not 100% for industrial or residential uses. The impervious area was determined such that the developed model can reproduce the observed total runoff volume and peak flow fairly well. The parameters in the Green-Ampt infiltration equation were chosen primarily considering the soil type (silty clay and silty clay loam).

Table 22: Parameters for storm water runoff quantity modeling reported in the literature and used in the models developed in this study for Bonnybrook and McKenzie Towne, respectively

Parameters	Description	Literature Range	Bonnybrook	McKenzie
Dstore-Imperv	Depth of depression storage on the impervious portion of the sub catchment (mm)	1.3-3.8 [1]	0.52	0.23
Dstore-Perv	Depth of depression storage on the pervious portion of the sub catchment (mm)	2.0-12.5 [1]	1.73	2.07
N-Imperv	Manning's coefficient for overland flow over the impervious portion of the sub catchment ($s/m^{1/3}$)	0.01-0.014 [2]	0.01	0.01
N-Perv	Manning's coefficient for overland flow over the previous portion of the sub catchment ($s/m^{1/3}$)	0.03-0.05 [2]	0.031	0.024
% Zero Imperv	Percent of impervious area with no depression storage (%)	-	25	25
% Impervious	Impermeable surfaces (%)	50-85 [1]	35.67	32
Suction Head	Avg. Capillary suction of the soil (mm)	273-292 [3]	270	270
Saturated Hydraulic Conductivity	Saturated Hydraulic conductivity for silty clay to silty clay loam (mm/hr)	1.0-2.0 [3]	1.016	1.016
Welting Point	Initial moisture deficit for soil as a fraction (vol. of air/vol. of void) for dry soil climate	0.229-0.263 [3]	0.26	0.26

[1] City of Calgary (2000), [2] Chow V.T (1986), [3] Maidment D.R (1993)

The parameters for modeling storm water runoff quality were determined in the model calibration to match the simulated TSS EMCs with the observed TSS EMCs. The buildup and wash-off parameters used in the models and commonly used in the literature are summarized in Table 23. The buildup parameters determined in the study for both BB and MK are within the ranges given in the literature whereas the wash-off parameters are below the lower bounds of the ranges given in the literature.

Table 23: Parameters for storm water runoff quality modeling reported in the literature and used in the models developed in this study for Bonnybrook and McKenzie Towne, respectively

Parameters		Literature Range	Bonnybrook	McKenzie
Buildup	Max possible buildup (kg/ha)	5.0-35 [1,2] (kg/ha-day)	56	56
	Rate constant (1/day)	1 [3]	1	1
Wash-off	Wash-off coefficient	0.11-0.19 [2]	0.098	0.087
	Runoff Exponent	0.0-3 [2]	1.79	1.53

[1] Sartor *et al*. (1974), [2] Di Modugno *et al*. (2015), [3] Rossman (2010)

4.5 Conclusion

For these two different types of land use, the percentage of impervious land, manning roughness, and depth of depression storage of a catchment were identified as important factors which largely affect storm water runoff quantity. Other parameters including the width, slope and manning roughness for pervious land of a catchment also affect storm water runoff quantity, but their effects are not as significant as the parameters mentioned above. Overall, the developed models for BB and MK can perform equivalently in both the model calibration and the model validation when simulating storm water runoff quantity. In modeling storm water runoff quality, the developed model at BB (industrial land use) cannot reproduce the observed TSS EMCs reasonably in the model validation although the model performed acceptably in the model calibration. However the calibrated model (for quality) at MK (residential land use) can reproduce the TSS MECs well in both the model calibration and the model validation. These results indicate the stochastic nature of rain event, pollutant buildup and wash-off, especially at BB. At MK, more events are need to further validate the developed model as only two events were used in the model validation.

Although the catchments, BB and MK, are selected as the representative industrial and residential land use in the City of Calgary, these two models developed in the report for these two catchments might not be applicable to other industrial and residential catchments within the city's boundary, if without validation. In order to transfer the model developed for a catchment to other catchments (of same type of land use), the comparison among the catchments in terms of storm water runoff quantity and quality should be conducted beforehand. Note that the interaction between surface water and ground water is not considered in this study.

Chapter Five: Spatial and Temporal Distribution of Rainfall

5.1 Introduction

An urban setting comprises of different types of land use for accommodating various anthropogenic activities. The effects of land use on the quantity and quality of surface stormwater runoff have been well investigated and acknowledged (e.g. Gilbert and Clausen, 2006; Bolstad and Swank, 1997; Valtanen *et al*., 2014). Besides rainfall, the inputs of urban hydrologic parameters like land use, soil types, pollutants etc., are often not homogenously distributed. This would further lead to the complication of the event-based hydrologic response of stormwater runoff in terms of both the quantity and quality to the land use. The understanding and identification of climatological and hydrological homogeneous region is beneficial in managing stormwater, for instance in developing affordable and effective stormwater quantity and quality monitoring program and thus accurately quantifying total pollutant loading generated from an urban setting at a large spatial scale. Many studies have investigated spatial and temporal characterization of rainfall in many areas around the world, however none or a very few have linked rainfall distribution to pollutant loading.

In the existing body of literature, there are many statistical analysis techniques including cluster analysis (CA), principle component analysis, L-moments and factor analysis available for characterizing rainfall spatial distribution. Among the various techniques, CA is one of the most commonly used techniques in the data mining process to discovery groups and identify interesting patterns of datasets (Halkidi *et al*., 2001) and has also been commonly applied to analyze spatial distribution of rainfall. The Ward's method, which is a general criterion applied in hierarchical CA, was proposed by Ward (1963), has often been adopted to investigate the spatial-temporal pattern of rainfall. For instance, Muñoz and Rodrigo (2004) investigated the spatial pattern of seasonal rainfall by grouping stations across Spain into climatologically homogeneous regions. Lyra *et al*. (2014) studied the spatial pattern of rainfall over northeast Brazil state of Alagoas, which is the most populated semiarid region and subject to highly variable weather systems, using 30 years of rainfall data collected from 36 stations. Ramos (2001) analyzed the variability of rainfall distribution pattern at several time scales (annual, seasonal, and daily) in the northeastern of Spain situated in the Mediterranean region. DeGaetano (2001) developed spatial grouping of climate stations using a hybrid clustering approach across the United States. Hybrid clustering is the combination of spearman rank order correlation between stations and grouping of observation sites using complete-linkage method of cluster analysis. Palecki *et al*. (2005) applied the Ward's method and grouped the conterminous United States into nine identical regions based on the characteristics of 15-minute interval precipitation data.

In addition to the Ward's method, many other CA methods have also been applied for analyzing the spatial-temporal pattern of rainfall and compared with the Ward's method. Among a variety of hierarchical methods, several previous works (e.g., Blashfield, 1976; Milligan, 1980; Jackson and Weinand, 1995; Gong and Richman, 1995) concluded that the Ward's method outperforms other methods. Gong and Richman (1995) found that the Euclidean distance appears to generate slightly more accurate results compared with other distance measures. Munoz and Rodrigo (2004) found that the Ward's method performs equivalently as the principal component analysis since these two approaches yield similar results. Ramos (2001) also argued that the K-mean (one of divisive methods) and the Ward's method yield similar classification. Gong and Richman (1995) however concluded that non-hierarchical methods (e.g., the rotated principle method, the nucleated agglomerative method, the K-mean method) outperform hierarchical methods, whereas the K-mean, the Ward's and the nucleated agglomerative methods appear to be superior to other methods when dealing with small sample size by inter-comparing various cluster techniques.

Apart from spatial variation, rainfall also demonstrates temporal variation. On the global scale, it is believed that as the temperature increases, more evaporation takes place leading to more precipitation (Karl *et al*., 1997). However, spatial and temporal non-uniformity across large and small terrain leads to the change of trend in rainfall and temperature. Study conducted by Idso and Balling (1991) across the United States concluded that there is no significant change in precipitation between 1901 and 1954; however precipitation changed by 8.6% between 1955 and 1987. Similarly, a study conducted by Akinremi *et al*. (1999) in three Canadian Prairie Provinces including Alberta, Saskatchewan and Manitoba reported that precipitation increased by about 10% annually between 1921 and 1995. A similar study conducted by Ripley (1986) at three stations in Saskatchewan, Canada concluded that there is a decrease in summer precipitation and an increase in winter and spring precipitation. A more recent study by Akinremi *et al.* (2001) at 140 stations across Canadian prairies detected increases in the rainfall amount (overall increased by 16% of 40-year mean) and the number of rainfall events during the period from 1956 to 1995, although the increases were not uniform, especially the largest increase in rainfall observed in spring (from January to April).

The City of Calgary has been facing challenges to develop efficient water quality monitoring programs and to accurately quantify pollutant loading. The objective of this chapter is to investigate the spatial–temporal distribution pattern of rainfall within the City of Calgary. The results would aid in recommending strategies for enhancing stormwater runoff monitoring and pollutant quantification at the city-scale.

5.2 Data Used

As shown in Fig. 3 and Table 1 in Chapter 2, Calgary rain gauge network consists of 36 rain gauges. Seven stations out of 36 stations (stations 31 to 37) have rainfall records of eight years and less, thus these stations were not included in the analysis. Rainfall station density at the SE quadrant of the city is low, thus the station 30 (Dewinton), which is very close the city limit, was included into the cluster analysis to give better representation of rainfall. The stations lying outside of the city's boundary, stations 24, 28 and 29, are not used in the analysis. Therefore a total of 26 gauges stations were used in the analysis. Rainfall data collected during the time period between 1991 and 2013 were used. The data sets collected from these rain gauges were used to calculate the monthly rainfall and seasonal rainfall (total rainfall from May to September) as well as the average daily rainfall (average over rainy days), average monthly rainfall and average seasonal rainfall over the study time period, which were then used to investigate the spatial and temporal distribution of rainfall in the City of Calgary.

5.3 Methodologies

In this chapter, the cluster analysis (CA) was applied to study the spatial distribution of rainfall; the nonparametric Mann-Kendall (MK) test was used to investigate the temporal monotonic trend in rainfall; and the Kruskal-Wallis (K-W) test was adopted to detect if significant difference in median of rainfall exists among the gauge stations. In the MK and K-W tests, the significance level of 0.05 was chosen.

5.3.1 Cluster analysis

A typical CA groups a set of objects/observations using various algorithms (e.g., distance) and thus possibly leads to empirically useful stratification of data and helps to suggest physical bases for observed structure in the data (Wilks, 1995). The purpose of CA is to place the objects into groups based on the characteristics of the data, so that the objects in a given cluster tend to be similar to each other whereas objects in different clusters tend to be dissimilar in statistical sense (Munoz and Rodrigo, 2004).

Data grouping can be conducted using various algorithms, which largely differ in terms of what constitutes a cluster and how to search them. Among several commonly used notions for clustering such as distance among clusters, density of data space, and particular statistical distribution, distance among clusters is the most commonly used measure to quantify the similarity and dissimilarity between groups. When defining distance, Euclidean distance has often been used. Given an m by n data matrix X, the Euclidean distance between two variables, X_m and X_n, is calculated by

$$d_{mn} = [(X_m - X_n)^T (X_m - X_n)]^{0.5} \tag{3}$$

Cluster technique can be broadly categorized into two different types, namely hierarchical and divisive techniques (Kaufman and Rousseuw, 1990). The divisive technique is a top down approach, in which all objects are initially placed into one single cluster and then they are divided into partitions to ensure highest similarities in groups. Whereas the hierarchical technique is a bottom up approach, which initially starts with single-element groups and then aggregates them into new clusters to replace previous clusters. At the beginning of the procedure there are n number of groups each which contains one observation. Then a new group is formed by combining two closest groups such that the sum of square from each individual cluster to the centroid of the present cluster is minimum. The process is repeated until a single cluster is formed at the end. Comparing these two cluster techniques, the hierarchical technique is more commonly used than the divisive technique (Wilks, 1995) and thus this technique was selected for this study.

Among various hierarchical techniques, the Ward's method or minimum variance method, which minimizes the total within-cluster variance/sum of squares, has been commonly adopted. At each step, the within-cluster variance is minimized over all the partitions obtained by merging two clusters from the previous partitions. Suppose that clusters C_k and C_l are merged to form a new cluster C_m, the combinatorial formula that is used to define the Euclidean distance d_{jm} between the new cluster C_m and another cluster C_j is given by the following equation (Ramos, 2001).

$$d_{jm} = \frac{(n_j+n_k)d_{jk}+(n_j+n_l)d_{jl}-n_j d_{kl}}{n_j+n_m} \tag{4}$$

where n_j, n_k, n_l and n_m are the numbers of objects in clusters C_j, C_k, C_l and C_m, respectively; and d_{jk}, d_{jl} and d_{kl} represent the distances between clusters C_j and C_k, between clusters C_j and C_l, and between clusters C_k and C_l, respectively. The progress and output of a CA are illustrated through a dendrogram or a tree diagram. A dendrogram consists of many U-shaped lines that connect variables in a hierarchical tree. The height of each U represents the distance between the two clusters being connected.

An important practical problem in such a CA is the choice of the final number of clusters. The selection of the number of clusters has often been subjective in practice due to the absence of systemic approach. The selection has been made based on the number of clusters retained; in other words the level of aggregation in the dendrogram needs to be predetermined and is used to stop merging clusters. Ideally, a suitable number of clusters can be identified through multi-objective optimization such that the differences within the clusters are minimized while the differences between different clusters are maximized (Wilks, 1995). In addition, the distance between the merged clusters, which varies with the increase in the stages of the clustering, can be used to determine the number of clusters. Wilks (1995) suggested using a distance plot, which illustrates the distance between merged clusters as a function of the number of clusters, to guide the determination of the number of clusters as the distance continuously increases with the merging of clusters. The distance increases as the dissimilarity increases even when merging similar clusters, which results in a small change in distance. The slope of the plot (the rate of change of the distance) is often not constant. Especially, the merging of unlike clusters that should be distinct results in a remarkable change in the slope/or increase in the distance. Therefore the number of clusters can be determined where the further merging of clusters leads to increase the distance remarkably. When the distance between the combined clusters begins to become noticeably large, it implies that distinct clusters are merged and thus a number of clusters then can be defined at this point (Muñoz and Rodrigo, 2004). However in some cases, a single significant change in the slope does not always appear in CA. Under such circumstance, the selection of the number of clusters primarily relies on subjective judgement.

5.3.2 Mann-Kendall test

The Mann-Kendall (MK) trend analysis, which is a nonparametric analysis technique, was used to investigate the monotonic trends of seasonal rainfall and monthly rainfall. U.S. Geological Survey (USGS) has developed MK analysis program in the 1980s (Hirsch *et al*., 1982). The MK test has been commonly used to analyze trends in surface water quality and also been frequently used in many other fields such as environmental and applied science, biological community structure (Moore, 1987), estuarine salinity (Wiseman *et al*., 1990) and atmospheric chemistry (Cortes and Hites, 2000) since then. The MK test computes Kendall's tau, a non-parametric correlation coefficient, and tests its significance for a pair of variables (Helsel and Hirsch, 2002). If one of variables represents time, the test is to detect the temporal trend of the other variable (Mann, 1945).

5.3.3 Kruskal-Wallis test

To compare more than two samples, Analysis of Variance (ANOVA) and Kruskal-Wallis (K-W) test have often been applied. The null hypothesis assumes the means and medians of all samples are equal in ANOVA and K-W test, respectively. The K-W test, which is a non-parametric alternative to one way ANOVA, is applicable when the samples are not normally distributed, which is often the case in hydrological and environmental data sets. Since K-W test is a nonparametric technique, different from ANOVA the K-W test can also be performed for data sets which do not have equal variances. In this study, the K-W test was adopted to compare the monthly rainfall of the rain gauge stations to investigate whether rainfall from one or more station is significantly different to other stations.

5.4 Results and Discussion

5.4.1 Spatial distribution of rainfall

Figure 20 shows both the dendrogram plot and the distance plot of CA for average monthly rainfall for the month of May as an example. As shown by the distant plot presented in Fig. 20 (b), the distance between the clusters increases prominently after stage 23. At stage 23 the distance between the clusters is 13. Looking back to Fig. 20(a) at distance 13, three cluster are formed. Therefore, three clusters were determined for the average monthly rainfall for the month of May (Fig. 20(a)). The spatial distribution of the three clusters, which contain 15.38%, 42.30%, and 42.30 % of the total number of rain gauge stations, respectively, is shown in Fig. 21(a). As displayed in Fig. 21(a), there is no obvious spatial pattern for the clusters as the stations in each cluster spread widely in the city.

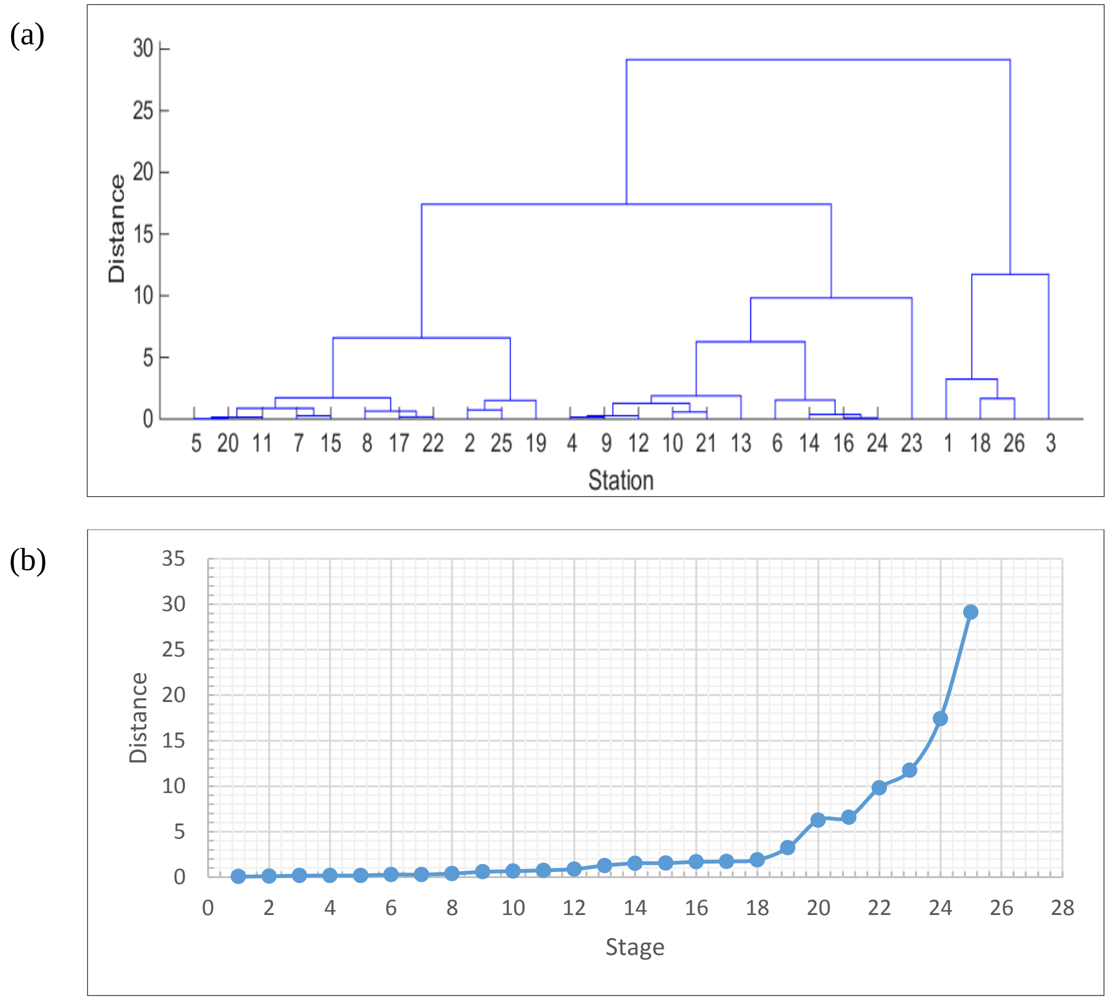
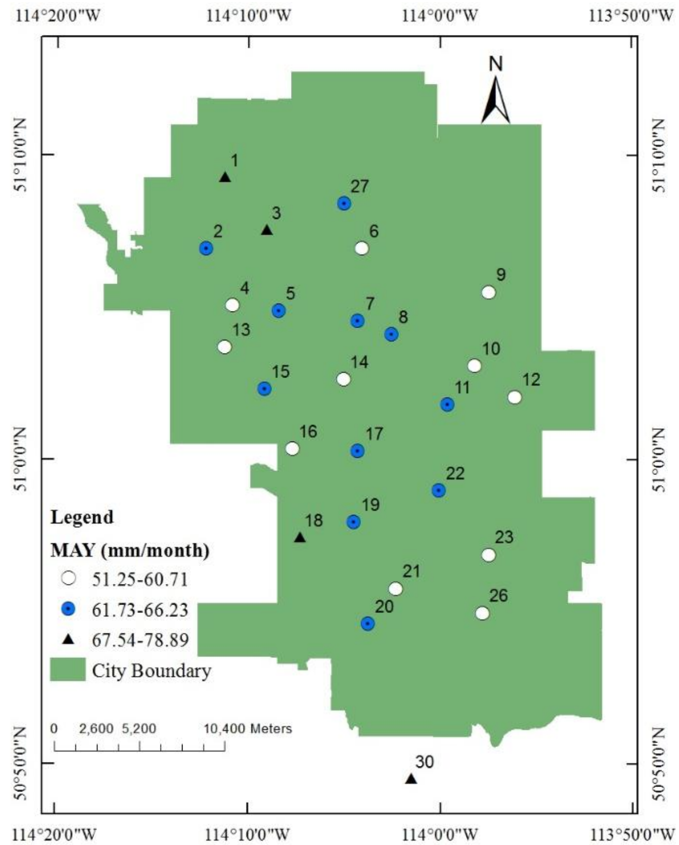


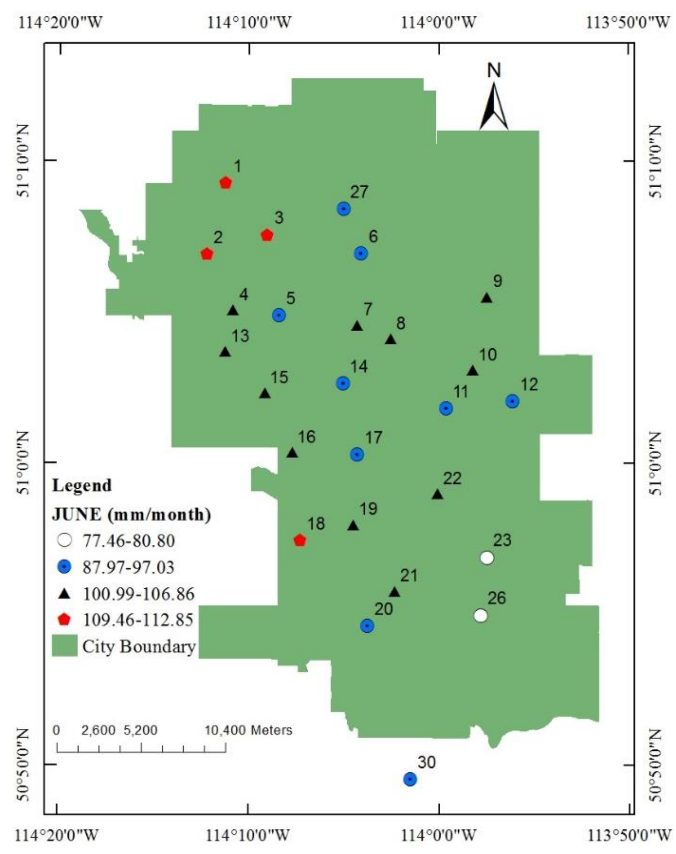
Figure 20: (a) Dendrogram plot and (b) distance plot of the average monthly rainfall for the month of May.

For the average monthly rainfall in other months from June to September, four clusters were determined for each month following the same approach. Their dendrogram plots and distance plots were not presented here. The spatial distribution of the clusters are presented in Fig. 21(b) – 21(e) for the months, respectively. Similar to May, no distinct spatial distribution pattern can be seen for the months from June to September. In addition, the spatial distribution pattern appear to vary in the months. All the results suggest that homogeneous regions for average monthly rainfall cannot be delineated as the spatial distribution pattern of the average monthly rainfall appear to vary among the rainy months in the City of Calgary.

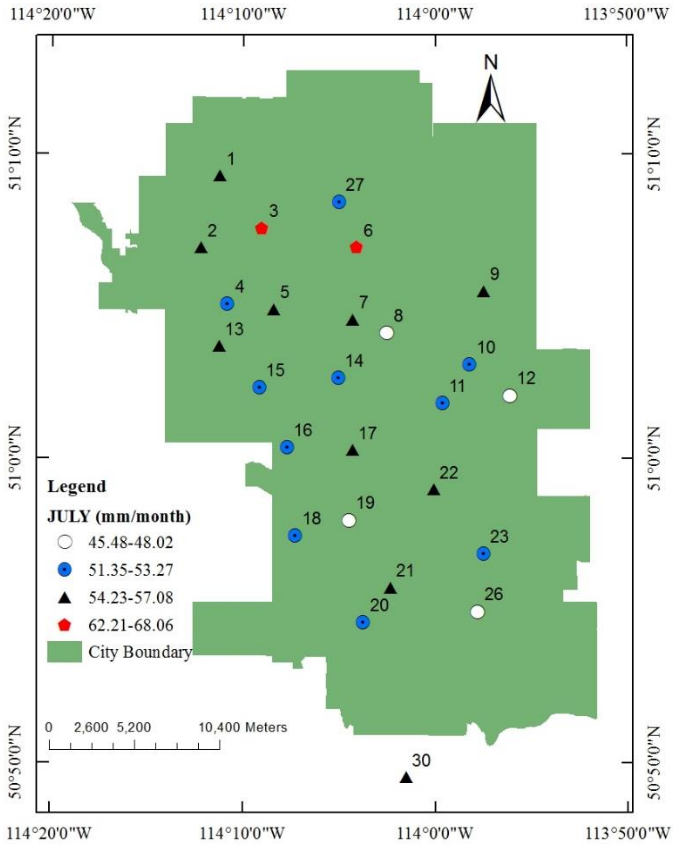
(a)


114°20'0"W
114°10'0"W
114°0'0"W
113°50'0"W
51°10'0"N
51°0'0"N
50°50'0"N
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
26
27
30
Legend
MAY (mm/month)
51.25-60.71
61.73-66.23
67.54-78.89
City Boundary
0 2,600 5,200 10,400 Meters

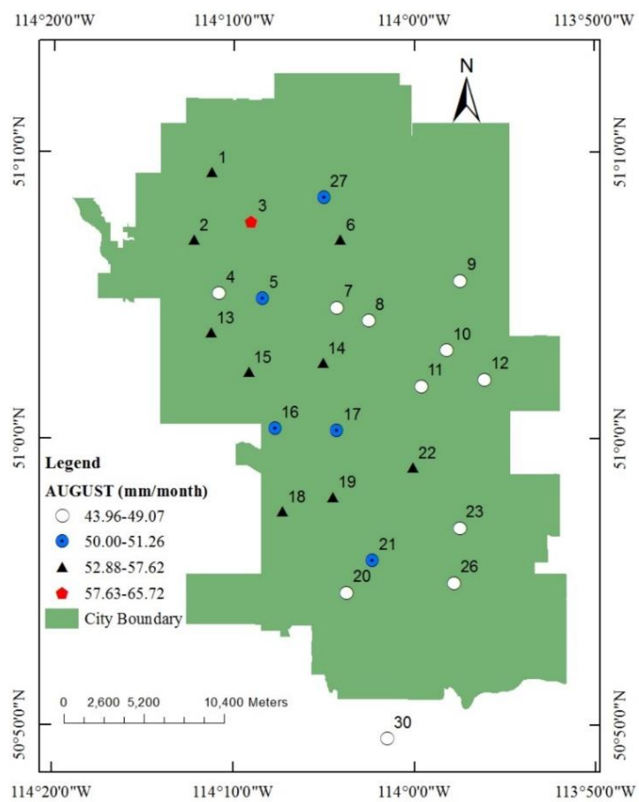
(b)


114°20'0"W
114°10'0"W
114°0'0"W
113°50'0"W
51°10'0"N
51°0'0"N
50°50'0"N
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
26
27
30
Legend
JUNE (mm/month)
77.46-80.80
87.97-97.03
100.99-106.86
109.46-112.85
City Boundary
0 2,600 5,200 10,400 Meters

(c)


114°20'0"W
114°10'0"W
114°0'0"W
113°50'0"W
51°10'0"N
51°0'0"N
50°50'0"N
N
Legend
JULY (mm/month)
45.48-48.02
51.35-53.27
54.23-57.08
62.21-68.06
City Boundary
0 2,600 5,200 10,400 Meters

(d)


114°20'0"W
114°10'0"W
114°0'0"W
113°50'0"W
51°10'0"N
51°0'0"N
50°50'0"N
N
Legend
AUGUST (mm/month)
43.96-49.07
50.00-51.26
52.88-57.62
57.63-65.72
City Boundary
0 2,600 5,200 10,400 Meters

(e)

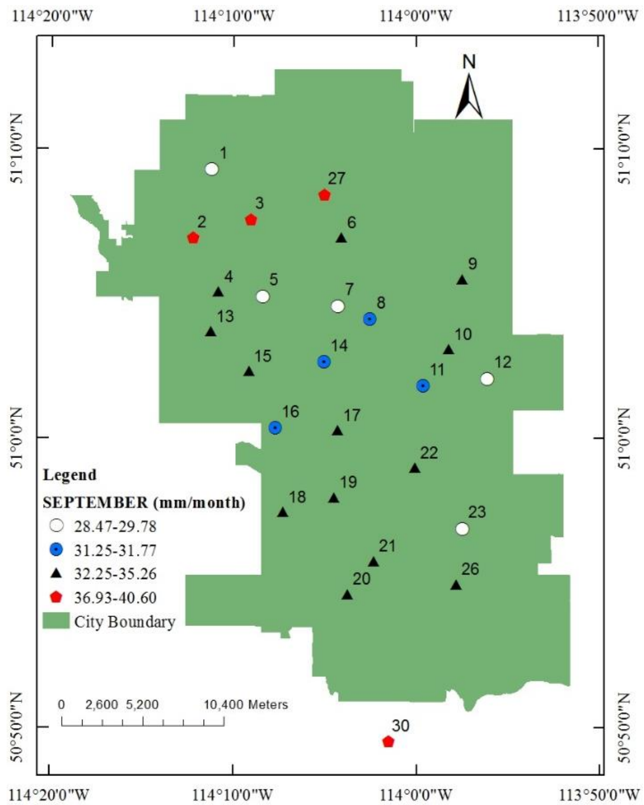


Figure 21: Spatial distribution of the identified clusters for the average monthly rainfall in (a) May, (b) June, (c) July, (d) August and (e) September, respectively.

As illustrated in the box plot of the monthly rainfall for June, as an example, in Fig. 22, variations in the medians and the variances among the gauge stations can be observed. However the K-W test, which was performed to investigate if the monthly rainfall at some stations is statistically different from other stations in the city, did not detected significant difference among the stations, namely the monthly rainfall is statistically homogeneous over space in the month of June. Same results were obtained for all other months (May, July, August, and September). Although the results from the cluster analyses demonstrate the spatial distribution of the average monthly rainfall for each month across of the city (Fig. 21), the statistical homogeneity of the monthly rainfall obtained from the K-W test might be ascribed to small variations over small size of the study region, compared to studies for the prairies and/or the province. In average, there is one gauge station in every 30 km^2 across the city. The weather characteristics represented by the monthly rainfall do not change so significantly that the statistical heterogeneity can be detected.

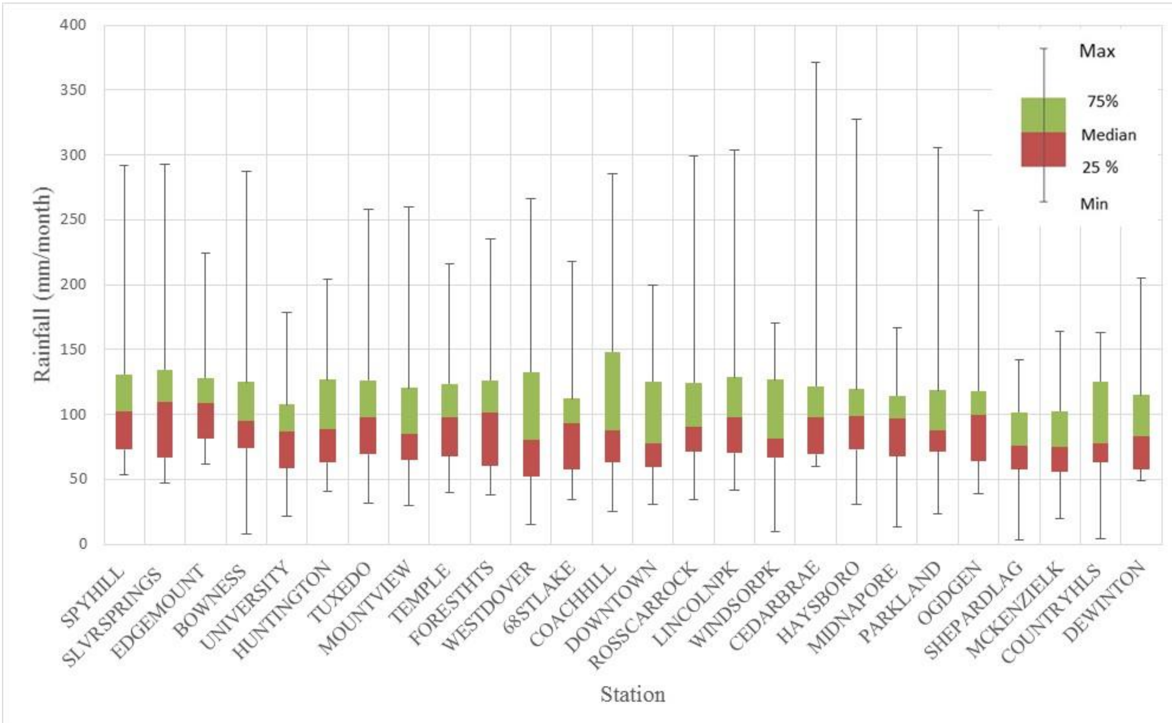
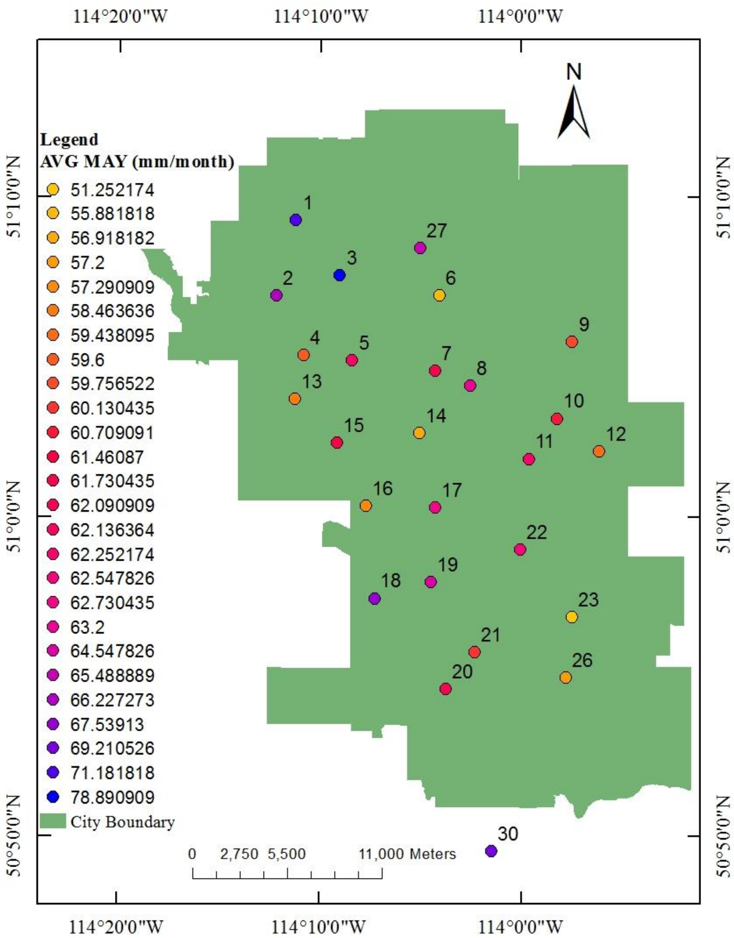


Figure 22: Box and whisker plot of the monthly rainfall for the month of June at all 26 rain gauge stations.

The spatial distributions of the average monthly rainfall for May and June (as examples) are also displayed in Fig. 23. As illustrated in Fig. 23 in both May and June, the rain gauge stations situated on the NW corner of the city, especially station 3 (Edgemont), have high rainfall amount, while the stations located on the SE corner, especially stations 26 (McKenzie) and 23 (Shepard lagoon), receive low rainfall amount compared to all other gauge stations. Similar results can be observed for the monthly rainfall of July, August and September. Although specific spatial distribution pattern was not identified for all the months in rainy season (Fig. 21), Fig. 23 demonstrates that the NW corner of the city always receives large rainfall amount whereas the SE corner of the city receives low rainfall amount compared to the rest of the city. However, relatively small variability in the average monthly rainfall was found at the stations 3 (Edgemont), 26

(McKenzie Lake) and 23 (Shepard lagoon); while the rest of the stations demonstrate more variability in the average monthly rainfall.

(a)



(b)

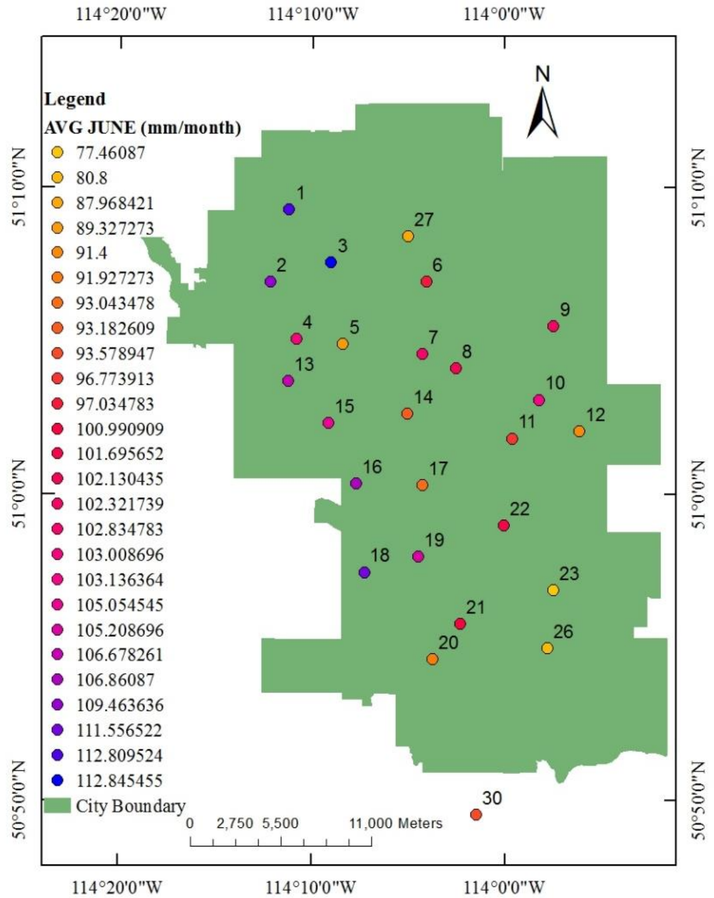
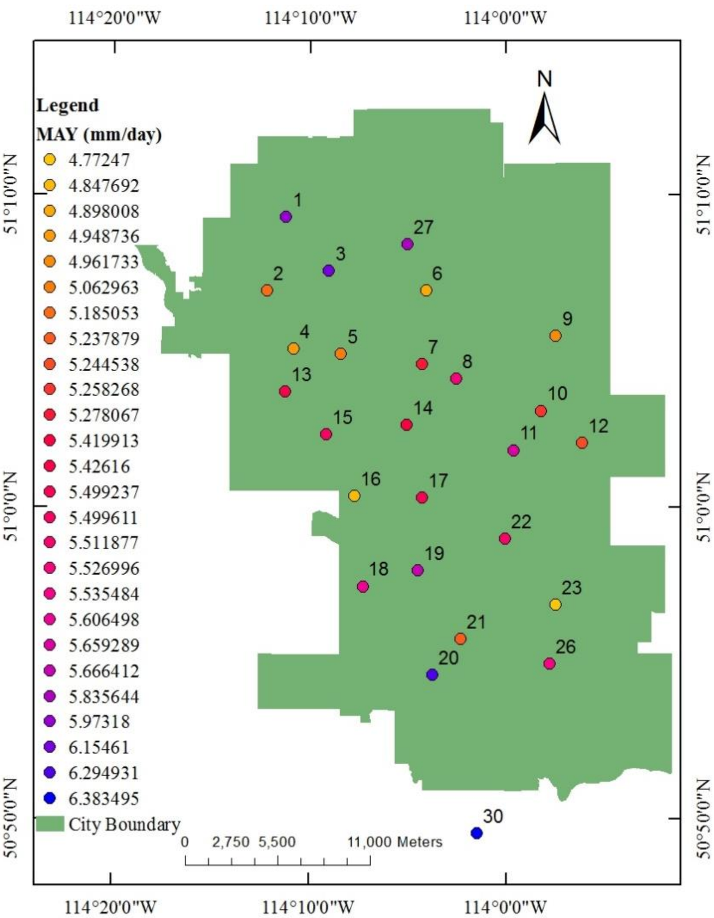


Figure 23: Average monthly rainfall for the month of (a) May and (b) June at all 26 rain gauge stations.

Furthermore, the average daily rainfall, which is the daily rainfall amount averaged over rainy days in each month from May to September, were analysed to investigate if its spatial distribution would differ from that of the average monthly rainfall. The rainy day is defined as the day which has a rainfall amount greater than or equal to 0.2 mm. the spatial distributions of the average daily rainfall for May and June (as example) are displayed in Fig. 24. Similar to the results of the average monthly rainfall, the stations located on the NW corner of the city have relative high average daily rainfall; while the stations situated on the SE corner have low average daily rainfall. Station 3 (Edgemont) situated on the NW corner has the highest daily average rainfall in most of the months; whereas stations 26 (McKenzie) and 23 (Shepard lagoon) on the SE corner have the lowest daily average rainfall. Based on these results along with the results for the average monthly rainfall, it can be concluded that the rainfall in terms of average monthly amount and average daily amount, in general, has a tendency to decrease towards the SE during the rainy season. Similar results can be seen from the months from July to September (results not shown).

(a)



(b)

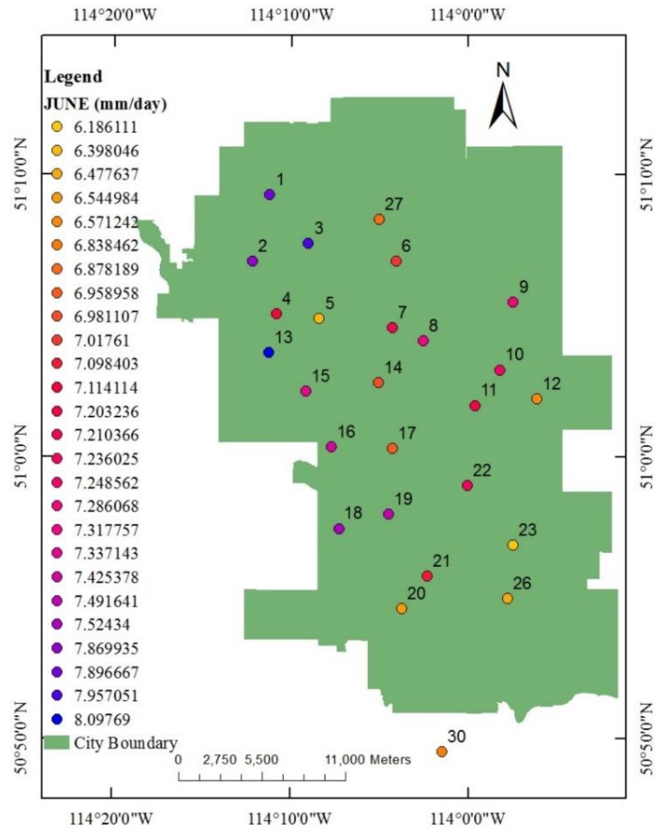


Figure 24: Average Daily rainfall for the month of (a) May and (b) June at all 26 rain gauge stations.

The average number of rainy days over the study time period from 1991 to 2013 in each month at each gauge station are summarized in Table 24. As illustrated in the table, the average number of rainy days appears to slightly increase towards the north of Calgary from the south. Many rain gauge stations located in the NW of the city such as stations 1 (Spyhill), 2 (Silverspring), 3 (Edgemont), and 4 (Bowness) in average have more rainy days than the rest of the stations; whereas stations 23 (Shepard lagoon), 26 (McKenzie Lake), and 30 (Dewinton) situated in the SE of the city have less rainy days compared to other stations. These results as well as the analysis results of the average daily rainfall and average monthly rainfall demonstrate a general pattern of rainfall in the city - both the rainfall amount and the number of rainy days have a tendency to decrease towards SE from NW. The result is supported by the findings of Chakravarti (1972), which concluded that the frontal position at prairies during summer months (June-July) runs diagonally from NW to SE, although the result was obtained from a large spatial scale. A more detailed study on the air circulation pattern within the Canadian prairies and especially at the foothills of Alberta will give more insight into the rainfall distribution pattern within Alberta and Calgary but it is beyond the scope of this study.

Table 24: Average number of rainy days in each month from May to September at all 26 rain gauge stations

Station No.	Station name	May	June	July	August	September
1	Spyhill	11.35	13.04	10.87	9.17	7.74
2	Slvrsprings	12.22	13.30	10.65	8.35	8.39
3	Edgemount	12.26	13.57	11.48	9.96	7.78
4	Bowness	12.04	14.48	11.65	10.09	9.30
5	University	11.74	13.35	10.91	10.22	8.13
6	Huntington	10.91	13.83	11.78	9.09	7.52
7	Tuxedo	11.70	14.26	11.96	9.87	8.22
8	Mountview	11.43	13.96	11.78	9.70	7.52
9	Temple	12.04	14.04	12.30	10.30	7.83
10	Foresthts	11.04	13.61	12.00	10.09	7.74
11	Westdover	11.00	13.43	10.70	9.78	7.52
12	68stlake	10.35	13.30	11.52	10.35	8.22
13	Coachhill	10.30	13.17	11.26	9.83	7.52
14	Downtown	10.04	13.35	11.74	9.87	7.43
15	Rosscarrock	11.17	13.70	11.35	9.91	7.96
16	Lincolnpk	11.30	14.39	12.13	10.04	7.70
17	Windsorpk	11.39	13.35	11.96	10.09	8.43
18	Cedarbrae	12.04	14.83	11.48	10.26	9.00
19	Haysboro	11.39	14.04	11.09	10.13	7.78
20	Midnapore	9.43	13.43	10.70	9.30	8.17
21	Parkland	11.48	13.61	11.52	9.96	8.74
22	Ogdgen	11.35	14.00	11.65	10.39	8.48
23	Shepardlag	10.74	12.52	10.65	9.61	7.57
26	Mckenzielk	8.09	10.30	8.00	7.26	5.83
27	Countryhls	8.78	10.57	9.39	7.91	6.57
30	Dewinton	8.96	11.30	8.52	7.52	6.39

5.4.2 Temporal distribution of rainfall

Table 25 presents the average seasonal rainfall (total rainfall amount from May to September) and the average monthly rainfall of each month on a city-wide scale (average over all 26 rain gauge stations) over the study period from 1991 to 2013. The variation in the monthly rainfall is under expectation. The highest rainfall amount was observed in June; whereas the lowest rainfall amount was measured in September in rainy season. The average seasonal rainfall amount is 284.73 mm during the study time period and 1.22% of rainfall falls in May while about 35% of rainfall falls in June. Rainfall in both July and August contributes about 18% of the seasonal rainfall and September contributes the lowest percentage of seasonal rainfall.

Table 25: Average seasonal and monthly rainfall over the City of Calgary during the study period 1991-2013

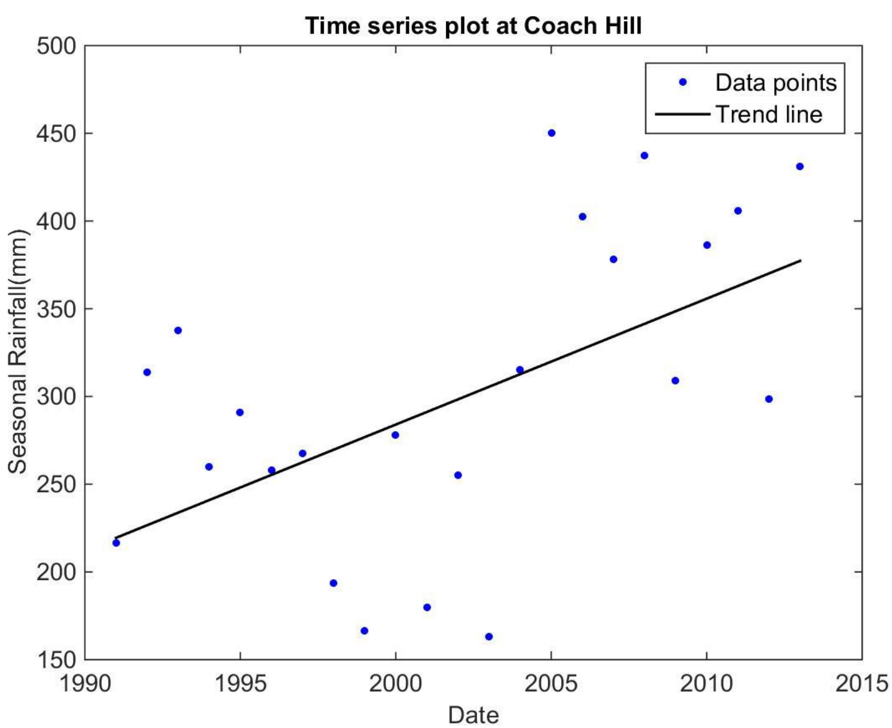
	Amount (mm)	Std. Dev (mm)
Seasonal (May- Sept.)	284.73	31.22
May	62.23	5.47
June	99.20	9.27
July	53.56	4.50
August	51.03	4.86
September	33.18	2.92

The MK test was performed to detect the temporal trend in the monthly rainfall and the seasonal rainfall at each station. The results are summarized and presented in Table 26. As examples, the time series along with the trend line at two stations, station 13 (Coach Hill) and station 27 (Country Hill), are illustrated for the seasonal rainfall and the monthly rainfall for June, respectively, in Fig. 25. As shown in Fig. 25, significant upward trends were detected at these two stations. Across the city, upward trend was detected at 22 stations among of which significant upward trend was found at 4 stations; while downward trend was found in four stations, but no significant downward trend was identified for seasonal rainfall. As for the monthly rainfall, upward trend was detected in majority of the stations, but significant upward trend was demonstrated at very few stations (one or two stations) for May, June and July. However, both insignificant upward and downward trends were found at the stations for the monthly rainfall in August and September.

Table 26: Results of the Mann-Kendall trend analysis for average monthly and average seasonal rainfall amount at 26 stations across the City of Calgary

Rainfall	Stations with upward trends	Stations with significant upward trend	Stations with downward trend	Stations with significant downward trend	No trend
Seasonal	22	4	4	0	0
May	22	1	3	0	1
June	22	2	4	0	0
July	21	1	4	0	1
August	12	0	14	0	0
September	17	0	9	0	0

(a)



(b)

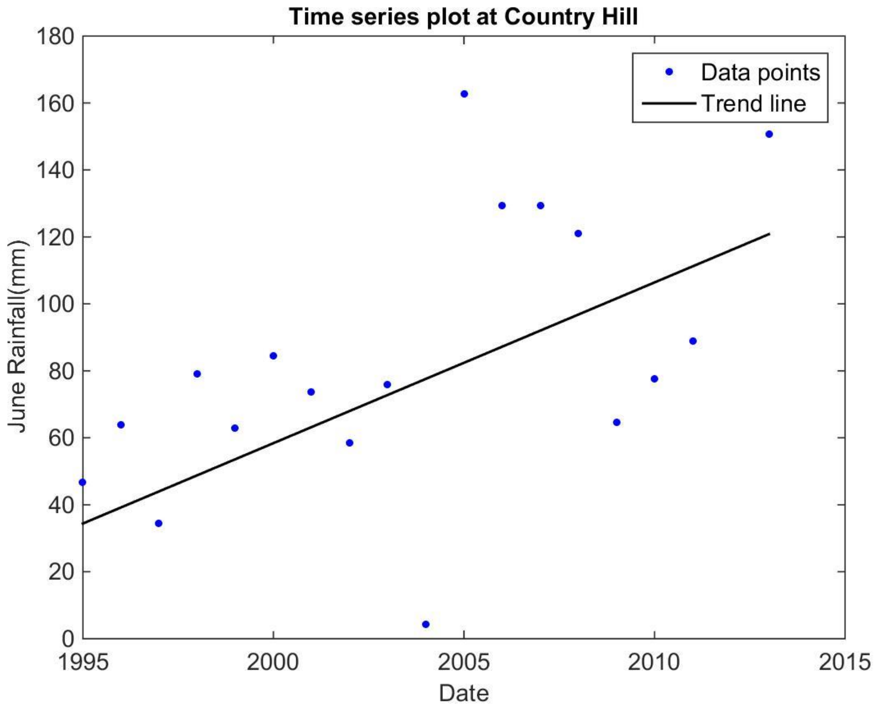
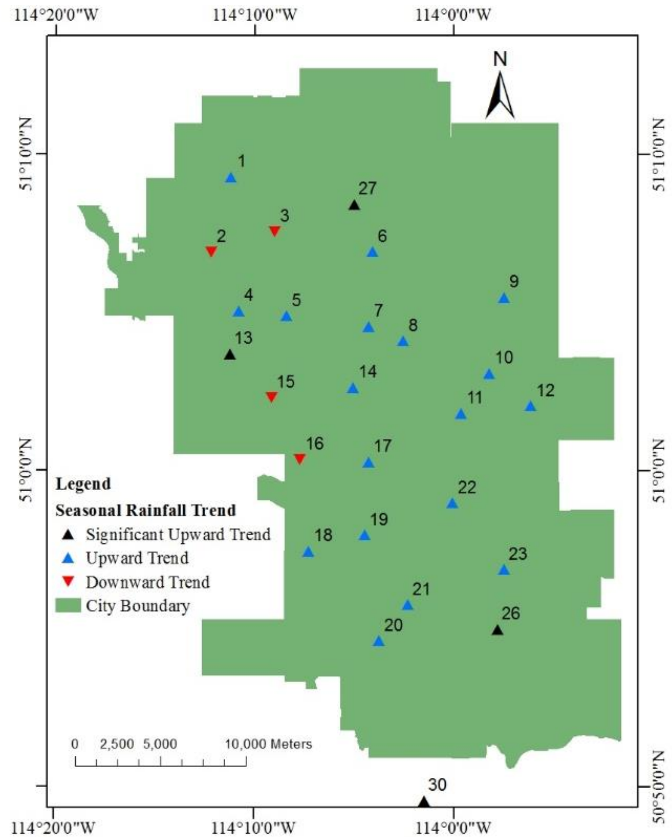


Figure 25: Time series along with Mann-Kendall trend at (a) Coach hill for seasonal rainfall amount and (b) at Country Hill for the monthly rainfall amount in June.

The spatial distributions of the observed trends of the seasonal rainfall and the monthly rainfall are shown in Fig. 26. In general, the seasonal rainfall temporally increases across the city as significant or insignificant upward trends in the seasonal rainfall were found at majority of stations as shown in Fig. 26(a). However, insignificant downward trend in the seasonal rainfall was detected at four stations which are situated in the NW of the city and have relatively high seasonal rainfall (not shown here). In a previous study conducted by Akinremi *et al.* (2001) for the summer rainfall (from May to August) over a large geographical scale across Canadian Prairies, significant positive trend was identified in majority number of stations and argued that the increase in summer rainfall might be ascribed to the increase in convective activities associated with increased soil surface evaporation and evapotranspiration from plants (Raddatz, 1998). Although this study conducted over a much smaller geographical region within Canadian Prairies, the identified significant and insignificant upward trends can be related to the increase convective process and evapotranspiration in the study area.

Figures 26(b) – 26(e) illustrate the spatial distribution of temporal trends identified at each station for each month from May to September. In general, significant and insignificant upward trends were detected at most stations in months from late spring to early summer (May – July) (Figs. 26(b) – 26(d)), which is similar to the seasonal rainfall. During these months (May – July), downward trends were found at three or four stations, which are sparsely distributed across the city. However, different results were observed for the months in later summer (August and September). In August, most stations at which downward trend was observed are located in the west part of the city (Fig. 26(e)). In September, all stations except one station (station 21) in the south part of the city demonstrated upward trend, though insignificant, while both insignificant upward and downward trends were detected at stations in the north part of the city (Fig. 26(f)). Overall, both the monthly rainfall in May, June and July and the seasonal rainfall indicated upward trends across the city; whereas downward trend was observed at many stations in both August and September. Thus it can be concluded that the temporal increase of seasonal rainfall is ascribed to the increased rainfall in springs and early summers.

(a)



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Legend
Seasonal Rainfall Trend
Significant Upward Trend
Upward Trend
Downward Trend
City Boundary
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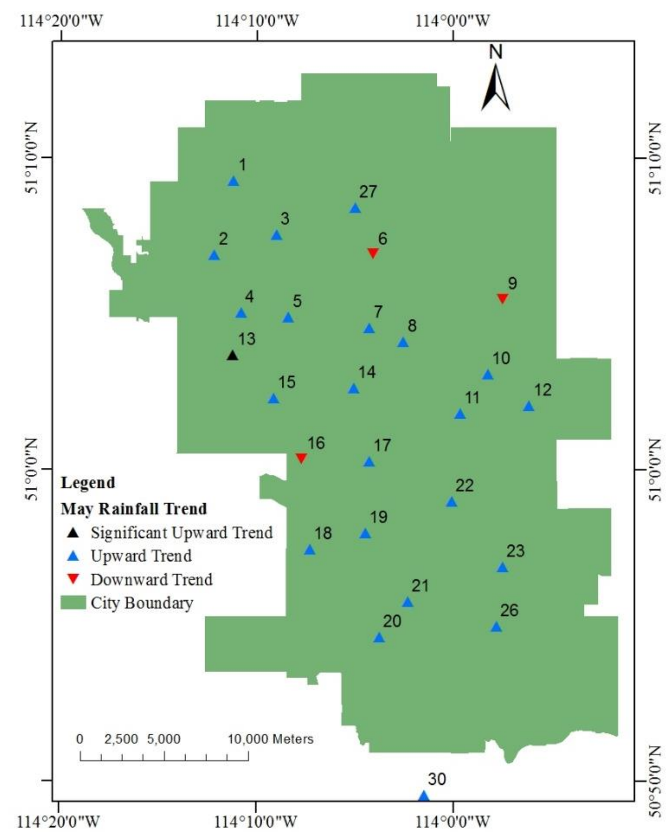
(b)



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May Rainfall Trend
Significant Upward Trend
Upward Trend
Downward Trend
City Boundary
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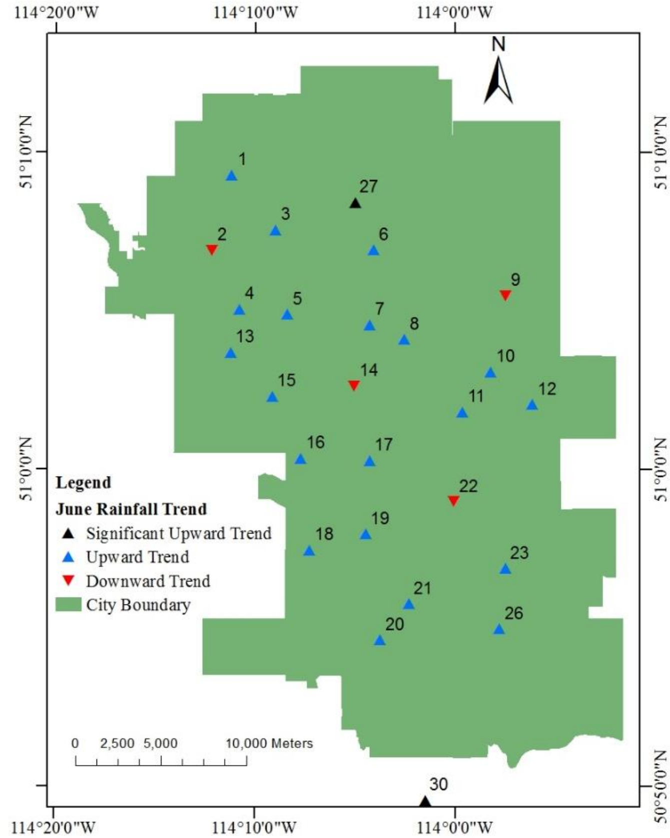
(c)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June Rainfall Trend
Significant Upward Trend
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City Boundary
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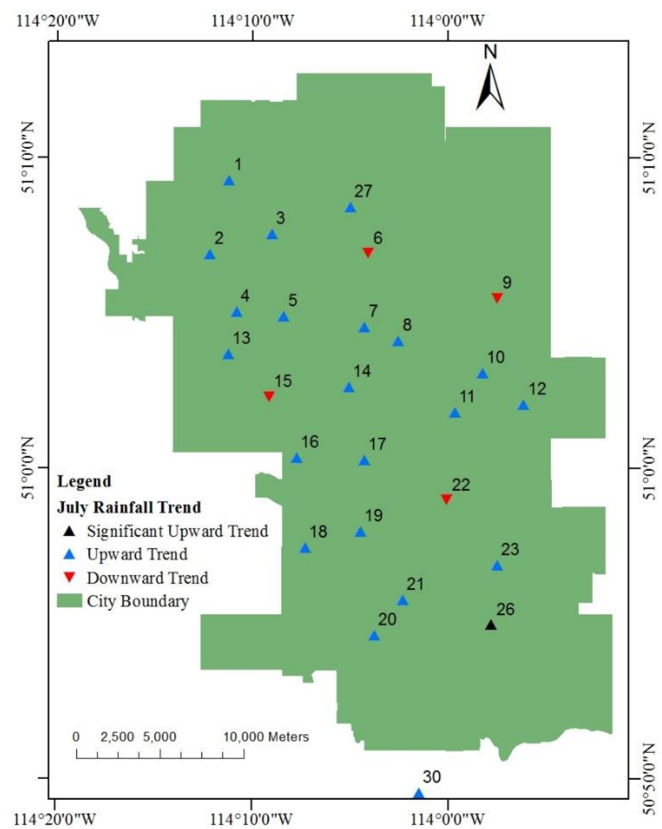
(d)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Legend
July Rainfall Trend
Significant Upward Trend
Upward Trend
Downward Trend
City Boundary
0 2,500 5,000 10,000 Meters

(e)

(f)

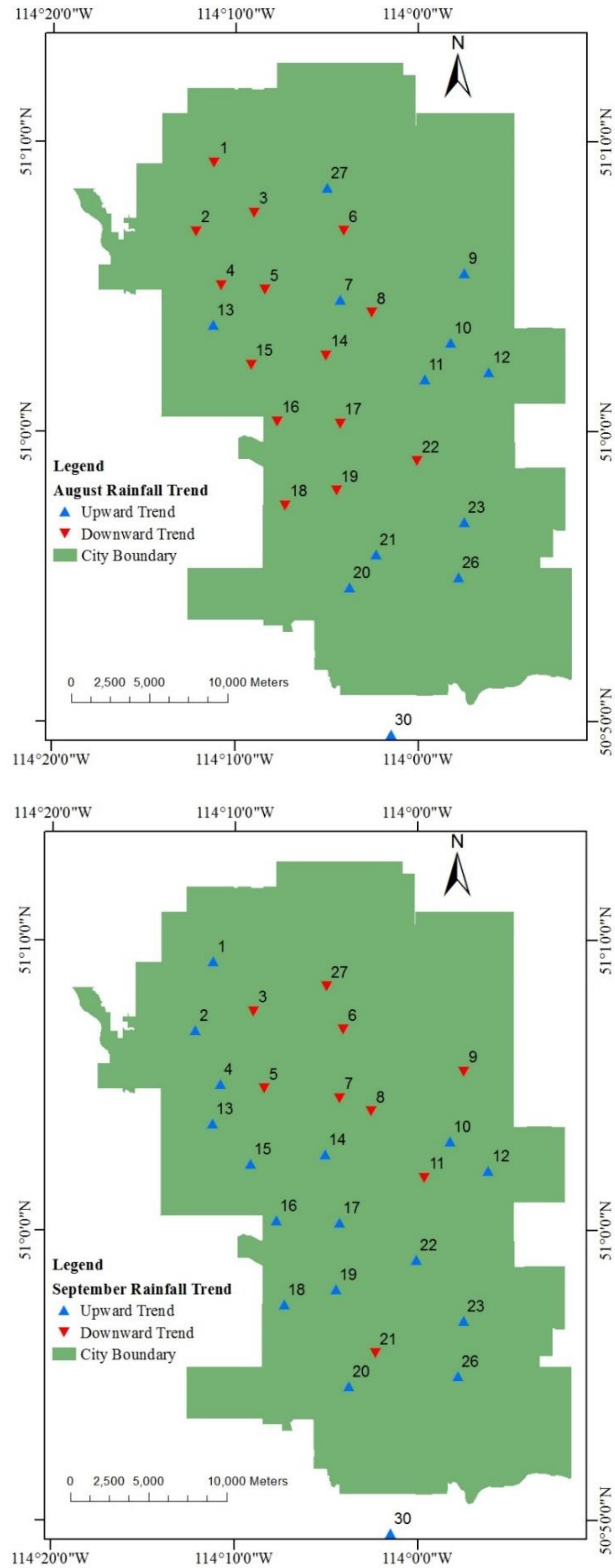

Figure 26: Spatial distributions of observed temporal trends of (a) the seasonal rainfall and the monthly rainfall in (b) May, (c) June, (d) July, (e) August, and (f) September

5.5 Conclusion

The rainfall data collected from 26 stations in Calgary's rain gauge network were applied to investigate the spatial and temporal distribution of rainfall using statistical analyses. As for the spatial distribution of rainfall, no specific spatial distribution pattern was identified for the average monthly rainfall based on the results from CA analysis as the spatial distribution varies among months in rainy season. The results of the K-W test revealed that the monthly rainfall are not statistically different among the stations for each month from May through September. However in general rainfall was found to decrease toward the SE from the NW, since relatively high average rainfall and average daily rainfall were observed in the city's NW part while low rainfall were measured in the SE of the city. This observation is consistent with the results obtained from the previous studies conducted at a large scale (in Prairie Provinces) and the air mass movement in the prairies from the NW to SE during summer. In general, both the seasonal rainfall and the monthly rainfall in each month from May to July indicated upward trends across the city during the study time period; whereas both upward and downward trends were detected in August and September. These results suggest that the upward trend in the seasonal rainfall can be ascribed to the increase of rainfall in late spring and early summer.

The observed variation in the spatial distribution pattern of the average monthly rainfall might challenge the concept to monitor a typical catchment of a type of land use and then apply the monitoring results to all catchments of similar land use type located in different parts of the city when quantifying pollutant loading at the city-side scale. Several water quality pollutants such as dissolved solids and total suspended solids are often strongly associated with stormwater runoff quantity, hence pollutant loading of these pollutants from catchments of same land uses but located in different locations might not be approximately equivalent. In addition, the temporal trends (both upward and downward trends) detected at the stations imply that it is necessary to take the change in meteorological (rainfall) condition into consideration, as it affects stormwater runoff quantity and quality potentially. Thus cautions should be taken when using stormwater runoff quality data collected at one specific location of a particular land use type to interpret stormwater runoff quality of catchments of same land use type but located at different part of the city as rainfall characteristics varies spatially and temporally.

Chapter Six: Conclusions and Recommendations

6.1 Summary of the Thesis

This thesis aimed to provide knowledge for developing more efficient stormwater monitoring network and more accurately quantifying pollutant loading from the City of Calgary, Alberta. More specifically, this thesis made contributions in three aspects: (1) characterizing stormwater quality of different flows, land uses, and catchments; (2) modeling stormwater runoff from two typical types of land use; and (3) investigating spatial and temporal distribution of rainfall. The general conclusions obtained for each aspect are summarized in the following sections.

6.1.1 Characterization of urban stormwater

Statistical analysis was performed for various water quality parameters for three types of flow (base flow, snowmelt and stormwater runoff) from four typical types of land use (residential, industrial, on-going development and commercial). The results show the differences in water quality in different flow types and in different types of land use. As anticipated high pollutant concentrations were generally observed in snowmelt and FF of stormwater runoff for all land use types when compared to base flow. When compared to snowmelt, FF of stormwater runoff has equivalent or higher EMCs for most pollutants investigated in the thesis. In addition, differences in EMCs were also detected among/between catchments of same land use type. Therefore an effective stormwater monitoring program is necessary to be capable of capturing the variations of water quality in different flows, land uses, and catchments (of same land use) to more accurately quantify pollutant loading of stormwater. When formulating a stormwater monitoring program, more detailed characteristics of land surface, for instance percentage impervious, which is another governing factor of stormwater runoff, should also be taken into consideration apart from land use type. On the other hand, although water quality parameters have been selected for monitoring usually based upon the purpose of the monitoring, representative parameters might be able to be identified and used to represent variations of other parameters, and subsequently the number of parameters to be monitored can be reduced. For example, TSS might be a representative parameter of particulate constituents. However, the relationships between TSS and other parameters might be site specific, thus verification of such relationships is needed before implementation.

6.1.2 Urban stormwater runoff modelling

In this thesis, SWMM model was applied to simulate stormwater runoff quantity and quality from two catchments, which represent two typical types of urban land use, namely residential and industrial land uses. The calibration parameters were selected based upon the sensitivity analysis performed for peak flow and total amount of stormwater. The results demonstrate that the percentage impervious is the most sensitive parameter followed by manning roughness coefficient, slope and depression storage of catchment. The models were then calibrated and validated manually using observed storm events. The modeling results show that the models, in general, can accurately reproduce hydraulic behaviour during rainy months (June to August) for both catchments; however the model performance in simulating water quality (TSS) is inferior compared to water quantity simulation, especially for the industrial catchment. The developed model for the industrial catchment was not able to reasonably reproduce TSS EMCs during the model validation although the model performed fairly well during the model calibration. One of the possible reason is that the models cannot fully represent the complexity of the processes governing stormwater runoff quality due to the stochastic nature of rain event, pollutant build up and wash off. More monitoring data can help in improving the understanding of stormwater runoff quality and in turn enhancing model performance.

These two selected catchments represent typical residential and industrial land uses in the City of Calgary. However, the models developed for these two catchments might not be well-justified for other catchments of same land use type, since significant differences exist in water quality parameters among catchments of same land use. To facilitate transferring model among catchments of same land use, stormwater runoff quantity and quality should be linked to geophysical characteristics of land surface, such as percentage of impervious area, depression storage, slope and other factors.

6.1.3 Spatial and temporal distribution of rainfall

Statistical analysis was performed at 26 rain gauge stations to investigate spatial and temporal distribution of rainfall in the City of Calgary. It was found from cluster analysis that there is no obvious spatial pattern for average monthly rainfall, and especially its spatial pattern varies in months during rainy season from May to September. In addition, the K-W tests did not detected significant differences among the stations in all months from May to September. All the results revealed that monthly rainfall is not statistically different across the city. However, in general monthly rainfall was found to be decreasing towards the SE quadrant of the city from the NW quadrant, which were also detected for average monthly rainfall as well as average daily rainfall. In addition, the monthly rainfall in general tends to increase temporally in months from May to July, however both upward and downward trends were observed in August and September across the city.

The variation of spatial distribution of average monthly rainfall within the city poses challenge in monitoring one or more typical catchment of a type of land use to represent stormwater characteristics from all catchments of same land use type. Cautions are needed when transferring observation results to other similar catchments located at different parts of the city to quantify pollutant loading. Some water quality pollutants (such as TSS and dissolved solids) are dependent on flow, hence loading of the pollutants from similar catchments situated in different city quadrants can be different. Furthermore the detected temporal variations in rainfall imply that long-term monitoring program is indispensable to capture the variation. As a results, a stormwater monitoring network which can well capture the spatial and/or temporal variations in stormwater quality and rainfall is needed to accurately quantify pollutant loading from the City of Calgary.

6.2 Recommendation for Future Research

This thesis revisited stormwater data collected from the city's monitoring program during 2001-2005 and used them to develop the models. Since the city is subjected to rapid urbanization and development in the last decade, the validation of the obtained results is needed using most recent monitoring data. In addition to accurately quantify pollutant loading from the entire city, several studies are recommended: (1) investigating the linkage between stormwater quality and more detailed land surface characteristics to facilitate the knowledge transfer between catchments of same land use type; (2) studying the effects of best management practices (BMPs) and low impact developments (LIDs), which have recently been implemented to management stormwater; and (3) investigating the applicability of SWMM model for commercial and on-going development land used.

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