Selection of Low Impact Development Infrastructure Based on Precipitation Regimes and Land Uses in Mosquito Creek, North Vancouver

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MLWS Major Project Report

LWS 548

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Cover Picture Taken by Guowei Li at Mosquito Creek Ln & Marine Dr, July 11th,2020

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Abbreviations Used in This Report

LID = Low Impact Development

WBM = Water Balance Model

EPA = Environmental Protection Agency

MAR = Mean Annual Rainfall

TIA = Total Impervious Area

EIA = Effective Impervious Area

DNV = District of North Vancouver

CNV = City of North Vancouver

QUALHYMO = Quality Hydrologic Model

Executive Summary

Urbanization has introduced incremental changes in impervious surface areas, which reduces the infiltration in the hydrological cycle and poses significant challenges to urban stormwater management in the event of heavy rainfall (i.e., 24h rainfall > 40 mm). Recently, cities around the world have witnessed more frequent urban flooding resulting from increasing impervious surface areas (Jha *et al.*, 2011). Located in the north shore of Burrard Inlet and sprawling east-west across Mount Fromme and Grouse Mountain, City of North Vancouver and District of North Vancouver, have been experiencing the second wave of urbanization in the dominant form of redevelopment of existing housing areas (City of North Vancouver, 2016). A steep gradient for heavy storm event frequencies against elevation has been observed in North Vancouver (Metro Vancouver, 2019), which might cause the failure of mitigation solutions to the negative impacts of increased impervious surface areas if universal standards are set. Modern urban designs have concentrated on the spanning of urban centers, as well as addressing stormwater management. In North America, the concept of Low Impact Development (LID) was proposed to manage urban stormwater through engineering design approaches coupled with landscape planning. The basis of selecting and designing the most appropriate LID practices lies in understanding the characteristics of both the environmental factors (e.g., heavy precipitation frequencies) and anthropogenic factors (e.g., land-use changes).

This case study investigated the frequencies of the 24h precipitation over 40mm events from 2001 to 2020 and presented spatial analyses of land use and imperviousness in 2011 in Mosquito Creek watershed, North Vancouver, based on accessible data. The Water Balance Model (WBM) applied to model the surface runoff discharge rates and direct runoff depths for 2011 surface conditions and 2041 projections without LID practices, as well as performances of selected LID practices (absorbent landscapes, rain gardens, and pervious paving). The modelling results are intended to compare the changes in runoff discharge rates and depths caused by altered surface conditions and the adoption of urban storm runoff mitigation practices.

The implications of conclusions from this case study could be far-reaching. Key findings are listed below:

- The middle watershed experienced more frequent Tier B and Tier C events (24h Precipitation over 40 mm) compared to the lower watershed, indicating that the middle watershed should set higher runoff mitigation targets. The precipitation spectrum analysis demonstrates that communities in the lower watershed should prioritize the management of 24h Precipitation 40 – 50 mm events, whereas the middle watershed needs to consider Tier C events (24h Precipitation over 80 mm) as well as Tier B events (24h precipitation 40 – 80 mm).
- Based on 2011 land use condition, the overall impervious areas account for more land cover in the lower watershed than the middle watershed. However, the 2041 projection on surface runoff discharge rates and direct runoff depths suggest that the middle watershed would be more vulnerable to the negative impacts of increasing impervious surface areas.
- All three selected LID practices would reduce the amount of stormwater that turns into a runoff, thereby reducing the ecologically costly occurrences of urban flooding. In both lower and middle watershed, rain gardens exhibit the most outstanding performance in mitigating the runoff discharge rates and depths, followed by absorbent landscapes and pervious paving. Both rain gardens and permeable landscapes would restore the 2041 projection with no LID practices to pre-development conditions in the middle watershed. In contrast, only rain gardens would achieve the same goal in the lower watershed.

It is recommended that conducting more analyses of runoff (inducing precipitation frequencies over a larger temporal and spatial scale as well as more runoff depth and discharge rate analyses) are necessary to obtain a better understanding of the hydrological processes in a watershed in response to altered land uses and implementation of storm management practices (e.g., LID).

Chapter 1. Introduction

Impervious surfaces refer to surfaces allowing little or no water to pass through them, such as rooftops and driveways (Metro Vancouver, 2019). Current urbanization practices have resulted in an increase in impervious surfaces with several negative disruptions on the hydrological cycle (Line *et al.*, 2011). The shift from natural lands to impervious surfaces changes the infiltration and evaporation processes, which further influences water resource redistribution and runoff interception (Pasimeni *et al.*, 2019). Such disruptions on the hydrological cycle are problematic to urban stormwater management, particularly when an extreme storm event strikes a city. Major issues associated with increases in impervious surface include increases in surface runoff, higher and more rapid streamflow, and increases in-stream erosion. At the same time, there is now sufficient evidence that rainfall intensity is also increasing. Urbanization is projected to be more intense, as higher density and compact block designs have received increasing focus to accommodate the rapidly growing population over the past few decades (Maser, 1997).

The impacts of increasing impervious surface areas have promoted the emergence of innovative urban stormwater management strategies, among which is the Low Impact Development (LID) (Gaitan & Veldhuis, 2015). The LID techniques mainly address excessive urban runoff that should infiltrate into the ground under natural conditions. This technique consists of the decentralized design of stormwater management that reduces the risk of flooding by restoring the pre-development hydrological characteristics and fully utilizing natural infiltration and evapotranspiration processes (Lee et al., 2012). LID techniques have proven to be efficient in reducing runoff volume and peak flow, extending the lag time (LAG) in rainfall-runoff processes and decreasing pollutant loads (Liao et al., 2013). The performance of the LID varies regionally, depending on the meteorological and physiographic characteristics, of which key traits include precipitation regimes and land use/land cover types (City of Saskatoon, 2016). This case study was conducted on Mosquito

Creek in North Vancouver to determine the appropriate LID approaches based on the analyses of heavy precipitation frequencies and land-use projections.

1.1 Benefits of Low Impact Development

1.1.1 Stormwater Reduction through Emphasizing infiltration

The amount of impervious surface area (e.g., parking lots, rooftops, and pavements) grows as the population in a community increases. Generally, the volume of runoffs generated in a storm event is positively correlated to the percentage of impervious surface areas, as the ground could absorb hardly any of the rain falling on impervious surfaces. All this leads to the uptake of pollutants along the way that enters storm drains ends up in local waterways without treatment. The volume of soil erosion and sediment transport also increases, which impacts the stream habitats and aquatic biota (Hvitved-Jacobsen *et al.*, 2010). Typically, in an undeveloped watershed, the vegetation and soil absorb the majority of the rainfall and thus slows the runoff rate over a long duration. In contrast, more intense urbanization causes runoff to accumulate faster over a shorter time, creating an earlier occurrence of a larger peak-flow runoff rate. The shortening of peak flow occurrence time is among the leading contributors to urban flooding and stream erosion (Liu *et al.*, 2014). By installing LID techniques, the disturbed watershed would be able to stimulate the natural infiltration, despite the rising percentage of impervious surface areas. Surface enhancement and storage facilities are commonly adopted LID practices. They are cost- and ecologically effective ways to reduce the frequency of floods and recharge groundwater through mimicking natural infiltration, as well as to filter pollutants carried by the flow (US EPA, 2009).

1.1.2 Environmental and Economic Benefits

The significant environmental benefits include: improved water quality, restored aquatic habitat, and enhanced neighbourhood beauty. Firstly, pollutants such as sediments, pathogens, and heavy metals can be detected in runoff from impervious surface areas, and risks exist that these will be discharged into streams. By delaying the peak flow occurrence time and peak flow volume, LID practices could mitigate pollutant-laden stormwater reaching surface water bodies (Cadavid & Ando, 2013). Secondly, a large quantity of surface runoff also causes stream channel erosion, bringing sediments into the water and obliterating aquatic life habitats. LID practices reduce the percentage of rainfall that becomes discharge into surface water and minimize the disturbances to natural stream channels, protecting the marine life habitat (Credit Valley Conservation, 2018). Thirdly, unlike traditional stormwater management infrastructure using constructed facilities such as pipes, utility holes, and concrete channels that lower the aesthetic value of a community, LID practices introduce more vegetation cover and are more sustainable and friendly conditions to wildlife and enhancing the scenery of the properties (Roseland, 2012).

In addition to the environmental and social benefits commonly accepted by the public, the U.S. Environmental Protection Agency (EPA) has found that considerable economic benefits could be achieved through the incorporation of LID practices. Specifically, LID practices cause less financial commitment than building underground drainage systems and reduce the economic loss from floods (US EPA 2007). Clar (2003) estimated that by retrofitting a conventional subdivision with LID designs, such as abandoning two stormwater ponds, increasing buildable lots, and avoiding removing the land cover, the overall economic benefits (including savings and added property values) was over $450,000. In addition, with increased aesthetic values, the property could potentially be sold at higher prices. A 184-lot community with LID practices was reported to be $7,000 cheaper to develop, 50% faster to sell, and 12 – 16% more to profit compared to conventionally established communities (Mohamed 2006). Some governments implement rebates, cost-sharing, tax credits, and floor to area ratio (FAR) incentives for property owners to incorporate LID practices to their lots. A building with a green roof covering over 50% of the structure can receive a one-year tax credit up to $100,000 in New York City (MacMullan, 2010). The environmental and economic benefits have made the LID an indispensable component in mitigating the impacts of increasing impervious surface areas.

1.2 Typical Low Impact Development (LID) Practices

The goal of LID practices is to "preserve, restore and create green space," utilizing on-site natural features and rainwater harvesting techniques (City of Vancouver, n.d.). Principles employed by LID practices address both functional and aesthetic values such as recreating pre-development landscape and minimizing the impervious surface areas to build useful and attractive drainage systems to recycle stormwater as a resource. Commonly adopted LID practices adhering to these principles include (but are not limited to) absorbent landscapes, pervious paving, infiltration trench, bio-swale, rain gardens, box planters, roof water collection systems, constructed wetlands and soil amendments. Table 1 summarizes the suitability of standard LID practices for multiple land-uses.

Table 1. Summary of LID Practices Suitability for Land Uses

LID Practice	Best Suitable	With Constrains
Absorbent Landscapes	Low/Medium Density Housing	Lanes
Infiltration Swales	Low/Medium Density Housing (Maximum contributing area 2 ha, as cited in Lanarc Consultants Ltd. *et al.*, 2012)	Lanes
Rain Gardens	Low/Medium Density Housing, Commercial	/
Pervious Paving	Low/Medium Density Housing, Commercial	/
Green Roofs	Commercial, Industrial	Low-Density Housing
Infiltration Trench	/	Low/Medium Density Housing
Rainwater Harvesting	/	Low/Medium Density Housing
Constructed Wetlands	Parks & Green Space	Medium Density Housing

The redevelopment/intensification of the existing housing structure is the predominant urbanization trend in Mosquito Creek Watershed (Metro Vancouver, 2011). This case study aims to provide a sub-watershed scale analysis that covers an area over 500 ha. Therefore, absorbent landscapes, rain gardens, and pervious paving will be addressed as practical solutions to mitigate the impacts of increased impervious surface areas.

1.2.1 Absorbent Landscapes

Absorbent landscape mimics the pre-development landscape's hydrologic function to absorb and infiltrate the rainwater. Yet, its capacity to accept runoff is relatively weak compared to other practices. Absorbent landscaping can be applied to treat water from disconnected roof leaders, sidewalks, and driveways. Similar to a rain garden, the dominant functional structure comprises a layer of vegetated soil. Still, absorbent landscapes consist of no reservoirs or sub drains, allowing virtually no ponding to occur. Employing absorbent landscape requires compaction of the surrounding soil and thoughtful selection of the vegetation cover, which might result in reduced infiltration (Lanarc Consultants Ltd. *et al.*, 2012).

1.2.2 Infiltration Rain Garden

The Infiltration Rain Garden is a LID practice through bio-retention of the surface runoff, with the aesthetic appeal of a garden. The Rain Gardens' vegetation cover is dominated by wildflowers, shrubs and rushes that generally have long roots to enhance soil infiltration and maintain soil microbial diversity (Wolverton & McDonald-McCaleb, 1986). Early implementation of rain gardens proves that such practices are efficient in runoff reduction, and the associated economic benefits are significant. The pioneer project in Somerset, England incorporated 28 – 37 m^2 rain gardens to single detached dwellings in a particular district, which reduced 75 – 80% surface runoff in documented precipitation events and saved approximately 0.3 million U.S. dollars by substituting curbs and gutters alongside the walkways with rain gardens (Kassulke, 2003).

1.2.3 Pervious Paving

Pervious paving allows rainfall to percolate into an underlying reservoir where the excessive runoff is stored. Three surface conditions could be categorized as pervious paving: porous asphalt or concrete which provides a large number of void spaces that functions as water passages with no fine materials; concrete or plastic grid pavers where the voids inside the structure are filled with permeable material (e.g., soil or gravel) and may have vegetation growing in the voids; permeable unit pavers constructed with impervious concrete modular pavers which allow the percolation of the runoff between the pavers through gapped joints. The previous paving suggested by this project focuses on the permeable unit pavers, as they are less vulnerable to clogging than other alternatives and have achieved noticeable success in stormwater management (James & Gerrits, 2003).

1.3 Study Site

The development of North Vancouver has dramatically altered the landscape condition beginning at the onset of the 20th Century and again in the 1950s and 1960s (City of North Vancouver, 2016). Urbanization has converted forested lands into impervious surfaces (roads, roofs, parking spaces), and loss of tree cover and absorbent soil has caused changes to the hydrological response of watersheds of North Vancouver. The redevelopment of North Vancouver started in the 1990s, during which the second generation of development aiming for present and future City goals has surpassed the first generation (City of North Vancouver, 2016). To meet the future city needs, the impervious surfaces have been changing on an incremental level that larger houses replace smaller ones, and more impermeable surfaces have been created to support growing transportation needs. Metro Vancouver (2011) predicts that the urban expansion into the remaining semi-rural areas will account for approximately 20% – 25% of projected Metro Vancouver housing growth to the year 2041, suggesting a residential intensification rate of 75% – 80%. This indicates that the intensification within existing housing areas is likely to yield more noticeable impacts than the urban expansion into unused forested regions on the increases in impervious surface areas.

Mosquito Creek watershed (Figure. 1) with a smaller percentage of impervious areas (29%) (City of North Vancouver, 2016) is selected to determine how the surface runoff can be reduced.using LID techniques. Mosquito Creek drains the forested slopes between Grouse Mountain and Fromme Mountain and eventually discharges into the Burrard Inlet (DFO, 1999). The watershed has a history of extensive logging at the turn of the 20th Century and again in the 1960s and 1970s (DFO, 1999). Still, today's second-growth forest can be found throughout the upper watershed (Pacific Streamkeepers, n.d.). For the past 20 years, significant urban development and encroachment into riparian areas have resulted in impervious surface increments (DFO, 1999).

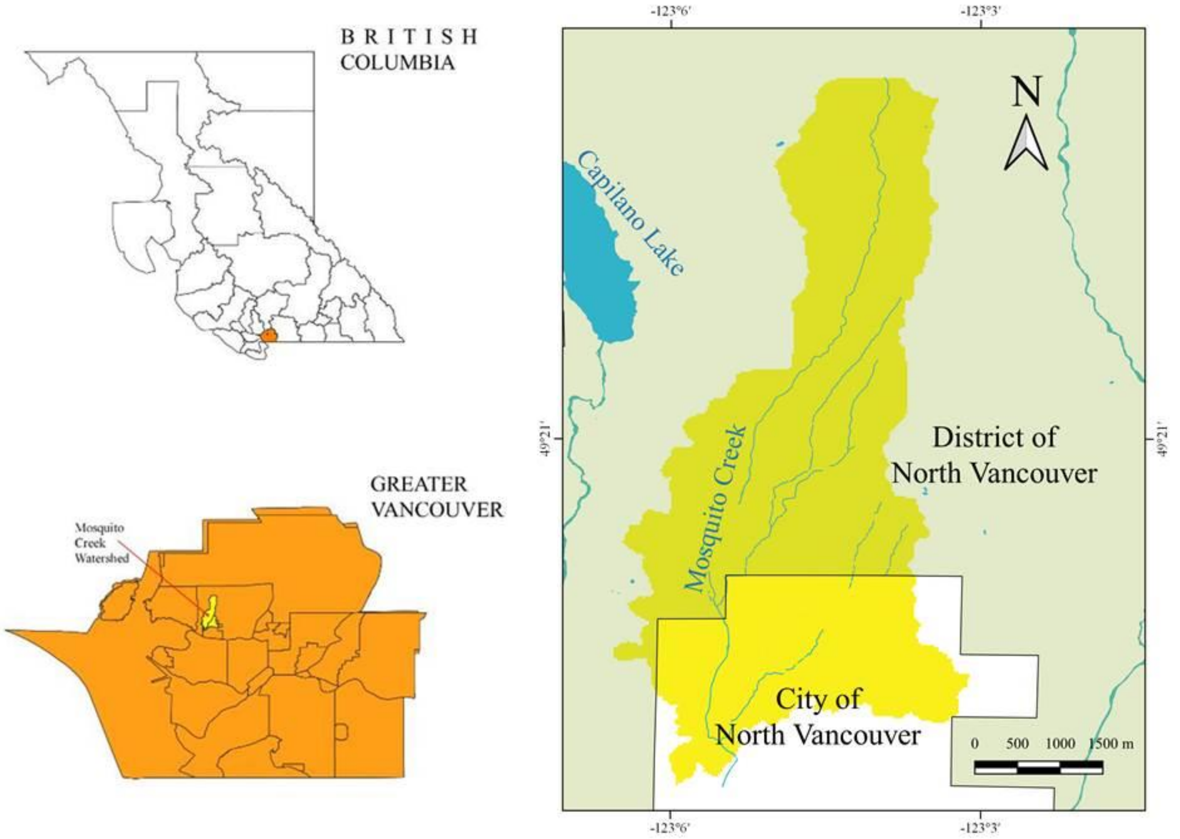


Figure 1. Location map of the study area (Mosquito Creek Watershed, denoted by the yellow polygon)

The elevation of Mosquito Creek Watershed ranges from 0 to 1300 m. The elevation is comparatively low (0 – 80 m) for the lower watershed within the boundary of City of North Vancouver (CNV) where the urban center is located, whereas the elevation of the remaining watershed ranges from 80 to 1300 m, with the developed regions mapped by District of North Vancouver (DNV) covering the lower 300 m elevation. A steep precipitation gradient with elevation has been observed in North Vancouver (Metro Vancouver, 2009), which should be considered when selecting suitable LID practices. Given that the elevation of the watershed in CNV and DNV varies tremendously, precipitation is of noticeable importance to the performance evaluation of the designed LID practices.

1.4 Project Objectives

This project aims to better understand the trends associated with the redevelopment/intensification of single houses within residential landscapes and the expansion of impervious surface areas such as driveways, walkways, and rooftops. By comparing the watershed landscapes before and after surface modification with the application of LID practices, this project helps understand the significance of LID practices in stormwater management in Mosquito Creek Watershed and potentially other urbanizing watersheds. Specifically, the goals of this project include:

(1) Investigating the variability of accumulated winter precipitation (1-day and 3-day precipitation events) at different elevations within or close to Mosquito Creek from 2001 to 2020;

(2) Examining the relationship between different surface conditions and discharge rates and depths to determine the impacts of impervious surface areas in the lower and middle watershed;

(3) Projecting future surface runoff discharge rates and direct runoff depths based on Metro Vancouver's land-use change prediction; and

(4) Providing recommendations to determine the most appropriate LID practice(s) for different precipitation regimes and land uses, with a focus on a) absorbent landscapes, b) rain gardens, and c) pervious paving.

1.5 Report Outline

The entire project report comprises five chapters. Chapter 1 introduces the general background information about this project, including the benefits of LID practices, common LID practice infrastructure, study site introduction, and project objectives. Chapter 2 presents details associated with factors influencing the performances of LID practices, which include the frequency of runoff-generating storm events and changes in the percentage of land use/land cover. Chapter 3 demonstrates the theory and input parameters of the Water Balance Model (WBM). Chapter 4 presents modeling outcomes including surface runoff discharge rates with multiple return periods, peak flows and their occurrence time, as well as direct runoff depths for 2011 land use (base case), 2041 projected land use with and without LID mitigation solutions. Chapter 5 discusses the limitations identified while conducting the project. The report finishes with Chapter 6, presenting the conclusion of this project and future steps required to validate the findings of this case study.

Chapter 2. Prime Factors Affecting Runoff Generation

2.1 Frequency of Runoff-Generating Storm Events

2.1.1 Precipitation Spectrum

LID practices address rainfall capture (source control), runoff control (detention), and flood risk management (contain and convey). Each component requires specific standards or criteria to be met as a target for evaluation of LID practices' performances. The designed targets are derived from a thorough precipitation spectrum analysis. The Mean Annual Rainfall (MAR), estimated as the 2-year, 24-hour duration storm event, is typically adopted to describe the precipitation spectrum. The *Stormwater Planning: A Guidebook for British Columbia* categorized rainfall volumes into Tier A, Tier B and Tier C, as shown in Table 2 for North Shore where the study site is located. Tier A events constitute approximately 90% of all storm events, and Tier B events represent the remaining 10%. Tier C events refer to precipitation exceeding the MAR, which might not occur in a given year (Government of British Columbia, 2002). The guidebook sets the runoff reduction targets as managing large Tier B rainfall events (storing 50% to 100% of MAR runoff and releasing at a rate equivalent to approximately undisturbed forest conditions). Therefore, this project examines the frequencies of 1-day (24-hour) precipitation over 40 mm in meteorological stations to determine the influence of elevation when designing the targets.

Table 2. Summary Tiers A, B and C Events in North Shore

Event	Definition	2-Year 24-Hour precipitation (mm)
Tier A	Less than 50% of MAR	< 40 mm
Tier B	Between 50% of MAR and MAR	40 – 80 mm
Tier C	Greater than MAR	> 80 mm

2.1.2 Precipitation Data

The precipitation data analyzed in this project is collected from Environment Canada's historical climate data. Environment Canada collects precipitation data, but the data collection failed to be monitored in the same time periods. To ensure that adequate data is acquired to demonstrate the relationship between winter precipitation events and elevation, the time series are divided into two groups: 2001 – 2010 and 2011 – 2020, and for each time period, climate stations located at different elevations are selected (Table 3). The frequency of heavy storm events (i.e. 1- day precipitation > 40 mm and 3-day precipitation >100 mm) will be counted and compared. Although some climate stations are out of range from the Mosquito Creek watershed boundaries, it can be assumed that the data are representative due to the proximity of the station to the watershed (i.e., within five km distance).

Table 3. Climate Station Information

Elevation (m)	**Station**	**Time Series**
4	N VANCOUVER 2ND NARROWS	2001 – 2010
7	N VANCOUVER WHARVES	2001 – 2010, 2010 – 2020
170	WEST VANCOUVER AUT	2001 – 2010, 2010 – 2020
183	N VANC SONORA DR	2001 – 2010
1103	N VANC GROUSE MTN RESORT	2001 – 2010, 2010 – 2020

2.1.3 Frequency Analysis

The climatic regime for areas near the selected stations consists of wet winters and dry summers. This is evident in Figure 2, which demonstrates the monthly mean precipitation for all three stations over a thirty-year interval. Between October and April, there was heavier precipitation, as is shown in the graph below. This is consistent with the historical records showing that most of the storm events in North Vancouver occurred through October to April (Natural Resources Canada, 2010). Therefore, the winter precipitation was calculated as the sum of Precipitation from October to April.

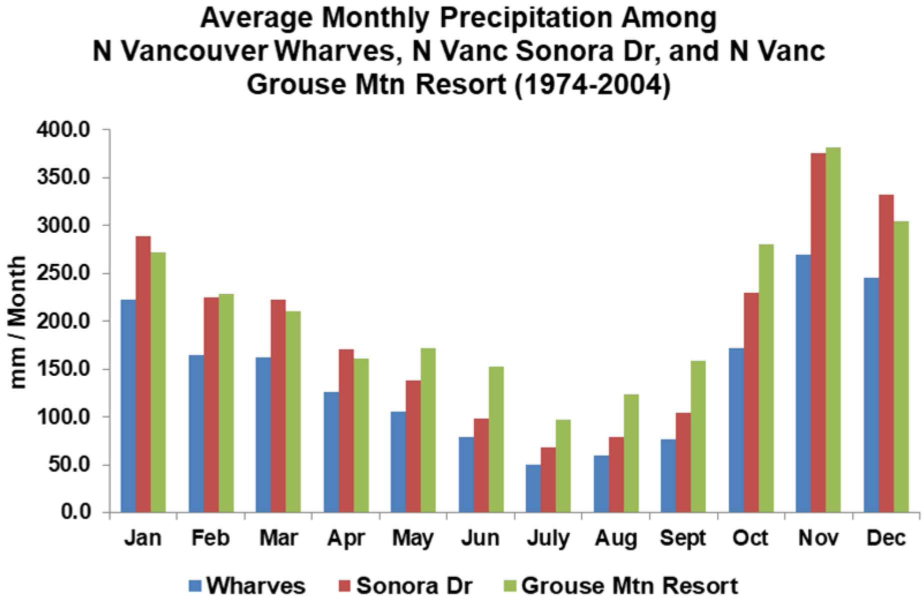


Figure 2. Mean precipitation from 1974 to 2004 retrieved from Station 1105669 "N Vancouver Wharves," Station 110N6FF "N Vanc Sonora Dr," and Station 1105658 "N Vanc Grouse Mtn Resort." Source: Environment Canada Historical Climate Data Archive

Figure 3 compared the documented frequencies of 1-day precipitation events over 40 mm observed in winter (October to April) at climate stations within or in close proximity to the study watershed. Cumulative precipitation patterns exhibited apparent differences for selected stations located at different elevations. In terms of magnitude, data retrieved from selected stations showed that accumulated precipitation increases with rises in elevation, but the relationship is complicated. From the analysis of winter 1-day (24-hour) accumulated precipitation events, it is recommended that communities located between 0 – 200 m elevations should consider the cumulative impacts of 40 – 50 mm/day storms rather than big storms as management priorities to reduce the runoff volume, whereas higher elevation (e.g., Grouse Mtn Resort) would expect the high cumulative events (1-day total precipitation exceeding 100 mm or 3-day total precipitation exceeding 200 mm) for stormwater management. Among communities located below 200 m elevation, lower watershed communities in CNV (elevation < 80 m) are not expected to experience as frequent and heavy precipitation events as communities located at medium elevation, and thus, LID infrastructure should be selected accordingly to be fully functional and cost-effective.

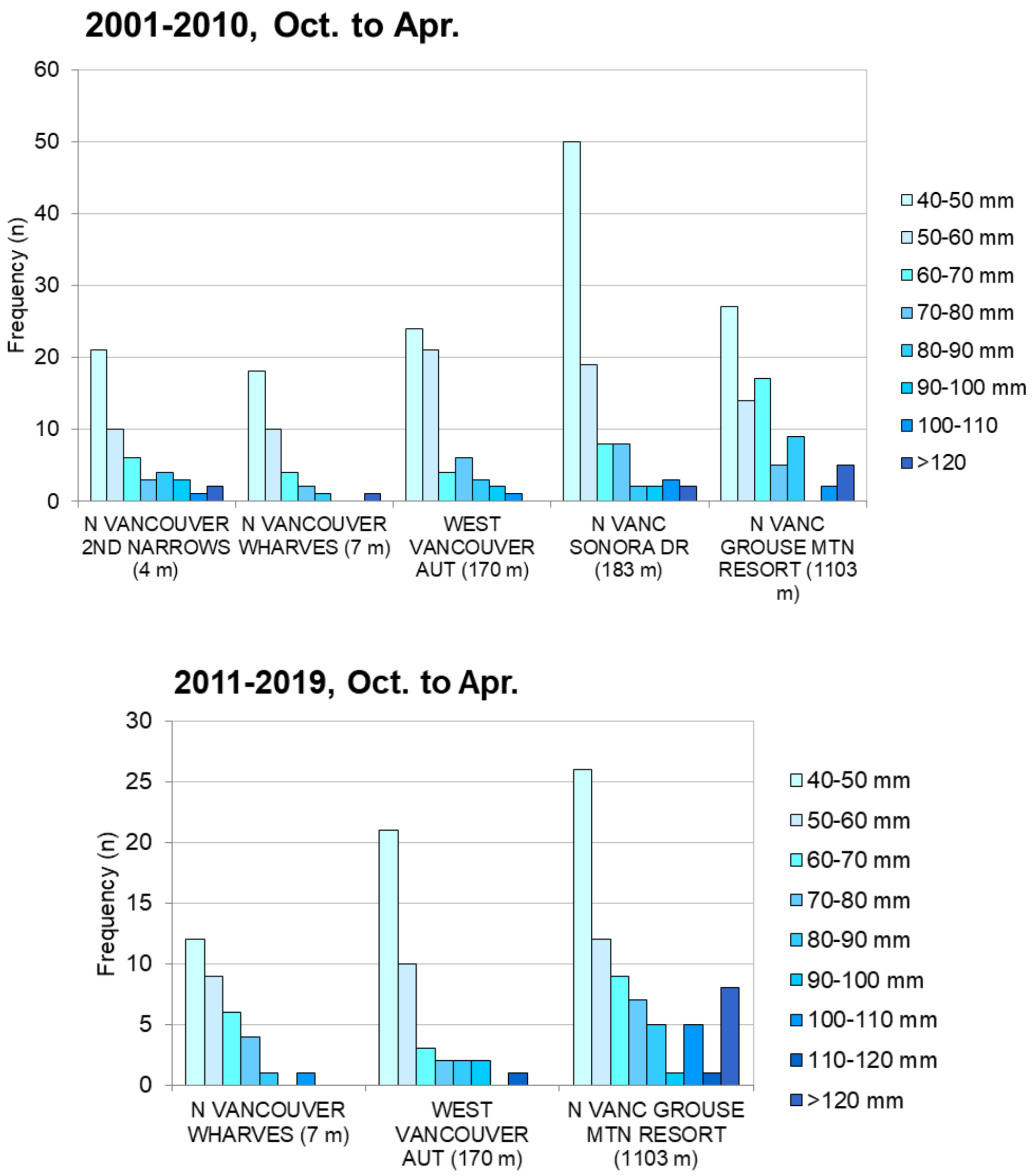


Figure 3. (Top) Frequencies of 1-day Precipitation over 40 mm from 2001 to 2010 and (Bottom) frequencies of 1-day precipitation over 40 mm at different Climate Stations from 2011 to 2019.

2.2 Land Use and Impervious Surface Area

2.2.1 Total Impervious Area (TIA) and Effective Impervious Area (EIA)

The distribution of rainwater experiences a shift from fractional subsurface flow to virtually 100% runoff (Johnson & Sayre, 1973). Low urbanization regions are more sensitive to changes in land use and increases in impervious surfaces (Dudley *et al.* 2001). Total impervious area (TIA) is defined as the sum of all impervious surfaces, and as an important component of TIA, an effective impervious area (EIA) refers to impermeable areas directly connected to a constructed drainage system (e.g., drainage pipes) or a watercourse. EIA is a more accurate parameter to determine the impacts of impervious surface areas, as some land uses yield impermeable surfaces but pose no barriers to the hydrological cycle (Guthrie & Deniseger, 2001). For example, a 10% increase in EIA would cause 2-year storm events in post-development scenarios to generate the same amount of discharge as 10-year pre-development storm events (Booth, 2000). Despite being more accurate, the determination of EIA normally requires access to field survey data, which might not be provided by some municipalities. In contrast, TIA can be determined simply through stereo-photogrammetry (synthesizing of the aerial photos) (Jones *et al.*, 2003). Empirical equations have been developed to estimate EIA based on TIA data (Laenen, 1983). For this project, an assumption is made that Mosquito Creek Watershed is a totally connected basin with linked roofs and no infiltration measures, thus

$$EIA = TIA \tag{1}$$

2.2.2 Land Use in Lower and Middle Mosquito Creek Watershed

The lower watershed located within the boundary of CNV has an elevation ranging from 0 – 80m, and the remaining watershed covers both developed (middle watershed, elevation: 80 – 340 m) and undeveloped areas (elevation: 340 – 1300 m) mapped by the DNV. The projected urbanization process would predominantly take the form of redevelopment/intensification in developed areas and the municipality of CNV. Therefore, the project will focus on low and middle elevation areas (watershed below the city border and developed areas in DNV, see Figure 4).

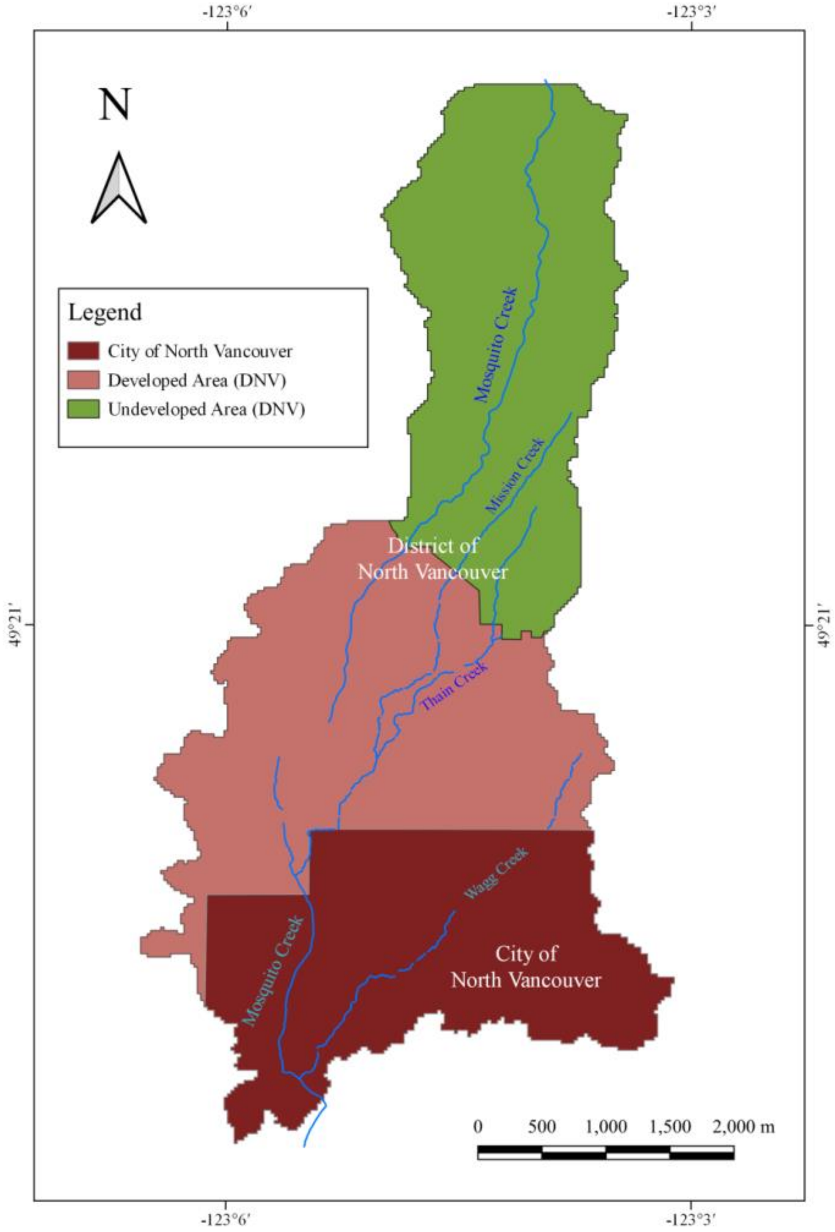


Figure 4. Delineation of Mosquito Creek Watershed and the Different Study Zones (Projected Using WSG84/UTM Zone 10N - EPSG: 32610).

The detailed land use information for each elevation zone in Mosquito Creek Watershed is determined through reference to the 2011 Generalized Land Use Classification Map acquired from Metro Vancouver's Open Data, which is based upon 2011 RapidEye 5m multi-spectral satellite imagery and full feature LiDAR data and thus precise for assessment (Figure 5).

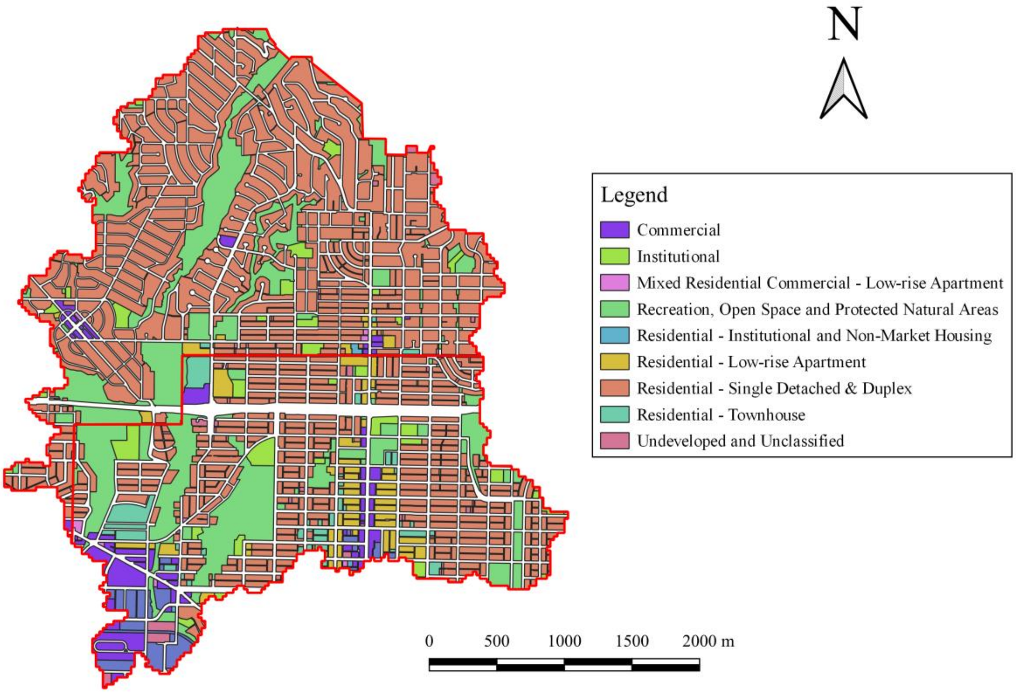


Figure 5. Land Uses in Lower and Middle Mosquito Creek Watershed (Projected Using WSG84/UTM Zone 10N - EPSG: 32610).

The mainland use types in lower and middle watershed contain commercial, institutional, and residential areas. The single-detached houses and duplexes are predominant in both regions. The majority of commercial centers and apartments reside in the lower watershed that belongs to the municipality of CNV. In contrast, over 50% of townhouses are located in the middle watershed governed by the DNV. The 2011 land use mapping results suggest that the extent of urbanization in the lower watershed is moderately greater than the middle watershed, accompanied by structures with greater imperviousness percentage (e.g., commercial buildings).

Land use expansion is usually associated with the imperviousness of a drainage basin. Human-centred land uses such as commercial and residential areas have introduced a massive amount of pavements, parking lots, and rooftops. The first two have resulted in soil compaction and impediment of infiltration. Accurately, CNV's and DNV's zoning bylaws describe the impervious surface coverage ratio (e.g., building and parking coverage) for each land use (Appendix A). Metro Vancouver (2019) has also conducted an analysis of eco-health indicators (i.e., tree canopies and impervious surfaces) by city block covering both municipalities where the watershed is located (Figure 6, modified from *EcoHealth Indicators - Canopy and Imperviousness Map* retrieved from Metro Vancouver's Open Data http://www.metrovancouver.org/data). The block imperviousness map indicates that lower watershed contains more impermeable surfaces compared to the middle watershed.

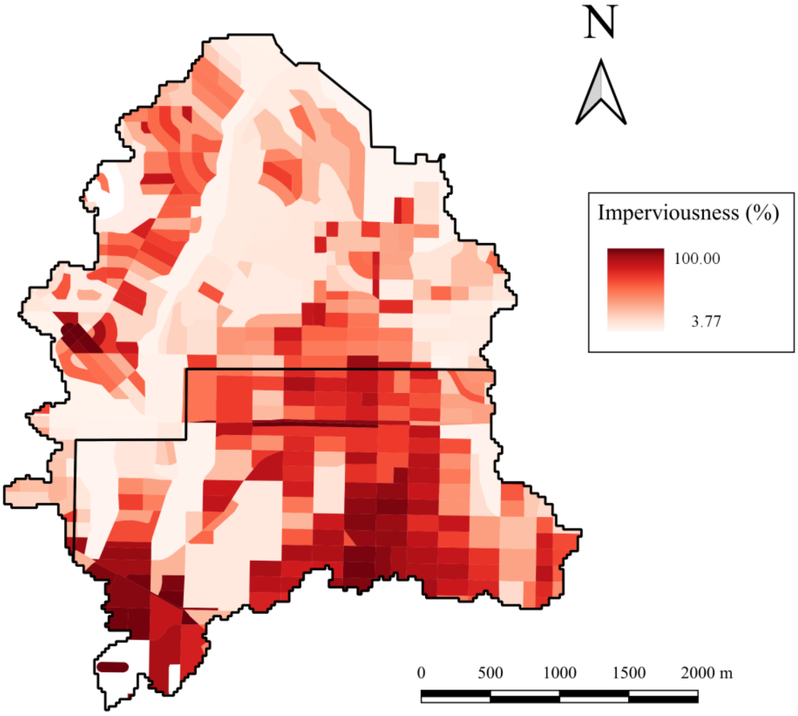


Figure 6. The Imperviousness Percentage in Lower and Middle Watershed (Projected Using WSG84/UTM Zone 10N - EPSG: 32610).

Given the findings of Dudley *et al*. (2001) stated in 2.2.1, such differences in land use and imperviousness result are sensitivity towards increasing impervious surfaces, including runoff rate and volume, which further influence the selection and performances of LID practices.

Chapter 3. Introduction to Water Balance Methodology

3.1 Theories behind Water Balance Methodology

In hydrology, the water balance refers to the cyclical movement of water between the land and atmosphere, which encompasses precipitation, loss (mainly through evaporation), discharge (surface runoff, aquifer recharge/discharge, and interflow), and infiltration (Whittow, 1984) (Figure 8). It can be expressed in equation (2):

$$P = D + L + I \tag{2}$$

where P is Precipitation (mm); D is discharged (mm) equivalent to the amount of rainwater entering into the stream through three flow paths: surface runoff, aquifer recharge/discharge, and interflow; L is loss (mm) through evapotranspiration; and I is infiltration (mm) to the soil. Putting it into a watershed context, the water balance of a watershed involves processes that add or subtract water from the watershed and include all the components mentioned above.

The Water Balance Model (WBM) was developed to illustrate the impacts of urbanization on surface runoff discharge rates and direct runoff depths as well as performances of development alternatives that result in fewer disturbances to the natural surface condition (Partnership for Water Sustainability in BC, 2014). This methodology mainly comprises of two modules: a streamflow duration analysis indicating the impacts of land uses on the flow paths of rainfall, and a rainfall mass balance analysis that quantitatively demonstrates the processes that add or subtract water from the watershed. The built-in simulation of water balance in the tool is conducted by the Quality Hydrologic Model (QUALHYMO) about multiple years of recorded climate data (including hourly precipitation, hourly temperature and monthly evaporation) and stream discharge for establishing the scenarios. The QUALHYMO model allows users to compare multiple development scenarios based on land uses through managing hydrological calculation results on a web-based decision support interface.

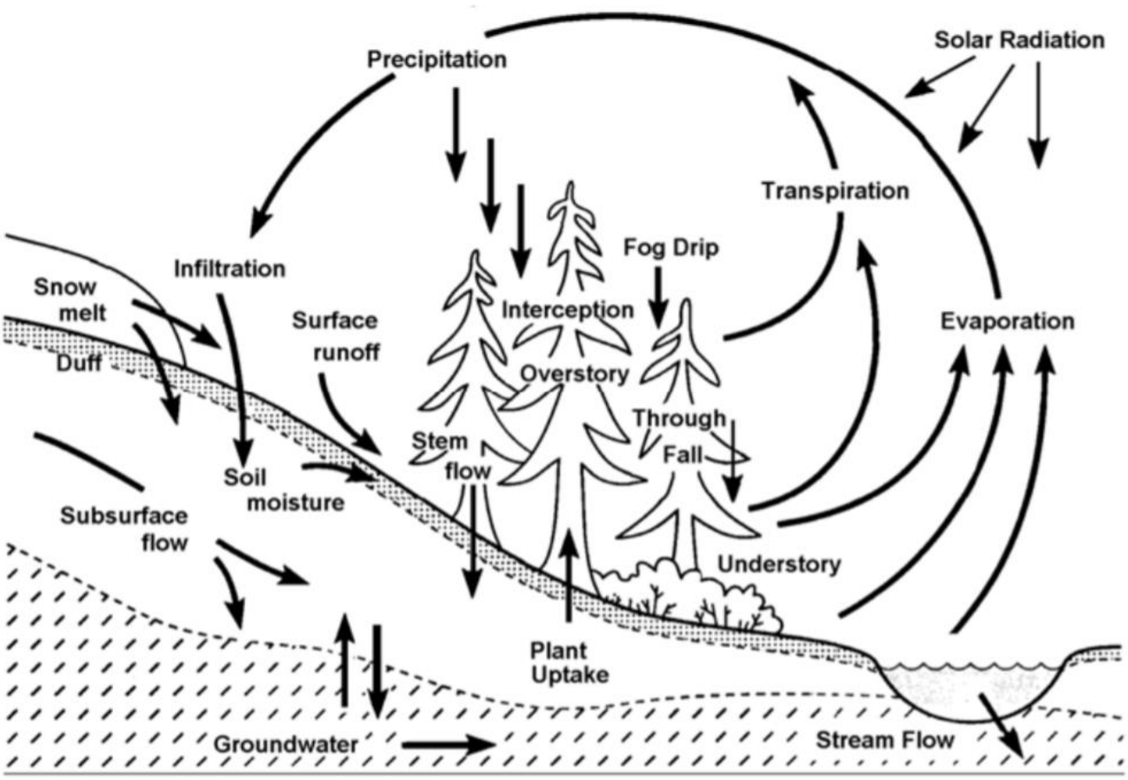


Figure 7. Water Balance Depicted in Hydrological Cycle Diagram (Partnership for Water Sustainability in BC, 2014)

The assessment of the Mosquito Creek watershed was performed based on hydrometric and the weather series based on climate stations that are nearest to the project location. Observed changes in precipitation and temperature in recent decades indicate that the effects of climate change are not negligible to predict future scenarios (City of North Vancouver, 2013). Therefore, climate change factors were considered for this case study based on the work by the Pacific Climate Impacts Consortium at the University of Victoria that adopted fifteen Global Climate Models to generate the average multiplicative factors.

3.2 Data Inputs

The developed methodology is dependent on historical hydrological and climate data, drainage characteristics information (area, length, elevation, and slope), native soil types, and land uses. Once the location of a project is determined, the WBM will allow users to select retrieved climate and hydrological data from climate stations that are nearest to the project site. In order to analyze and visualize geographic information of Mosquito Creek Watershed, the free and open-source cross-platform desktop geographic information system software QGIS was used.

Soil type information in the study site is obtained from *Soils of the Langley-Vancouver Map Area. Report No. 15, British Columbia Soil Survey* (Luttmerding, 1980). However, part of the urban center was not surveyed due to the level of soil disturbance & alteration (Figure 8). An assumption was made that the undocumented area shares the same soil profile with the adjacent field. The soil was identified as Buntzen and Steelhead, whose soil classification is Duric Ferro-Humic Podzol. Soil depth was set as 89 cm and 70 cm separately for the lower and middle watershed (Luttmerding, 1980b). The soil texture is determined by referring to the particle size percentage listed in *The Soil Landscapes of British Columbia*. In general, Podzol soils over 65 cm deep comprise 59.9% sand, 37.7% silt and 2.4% clay (Table 4). Conforming to the soil texture triangle (Figure 9), the "Sandy Loam" texture is deduced for setting up the model (Partnership for Water Sustainability in BC, 2014).

Table 4. Physical Analyses of a Podzol Soil

Horizon	Depth (cm)	Particle Size (%)		
		Sand	**Silt**	**Clay**
Ae	0 – 10	66.9	30.1	3.0
Bfcc	10 – 25	53.0	45.4	1.6
Bm	25 – 65	65.6	32.3	2.2
C	65+	59.9	37.7	2.4

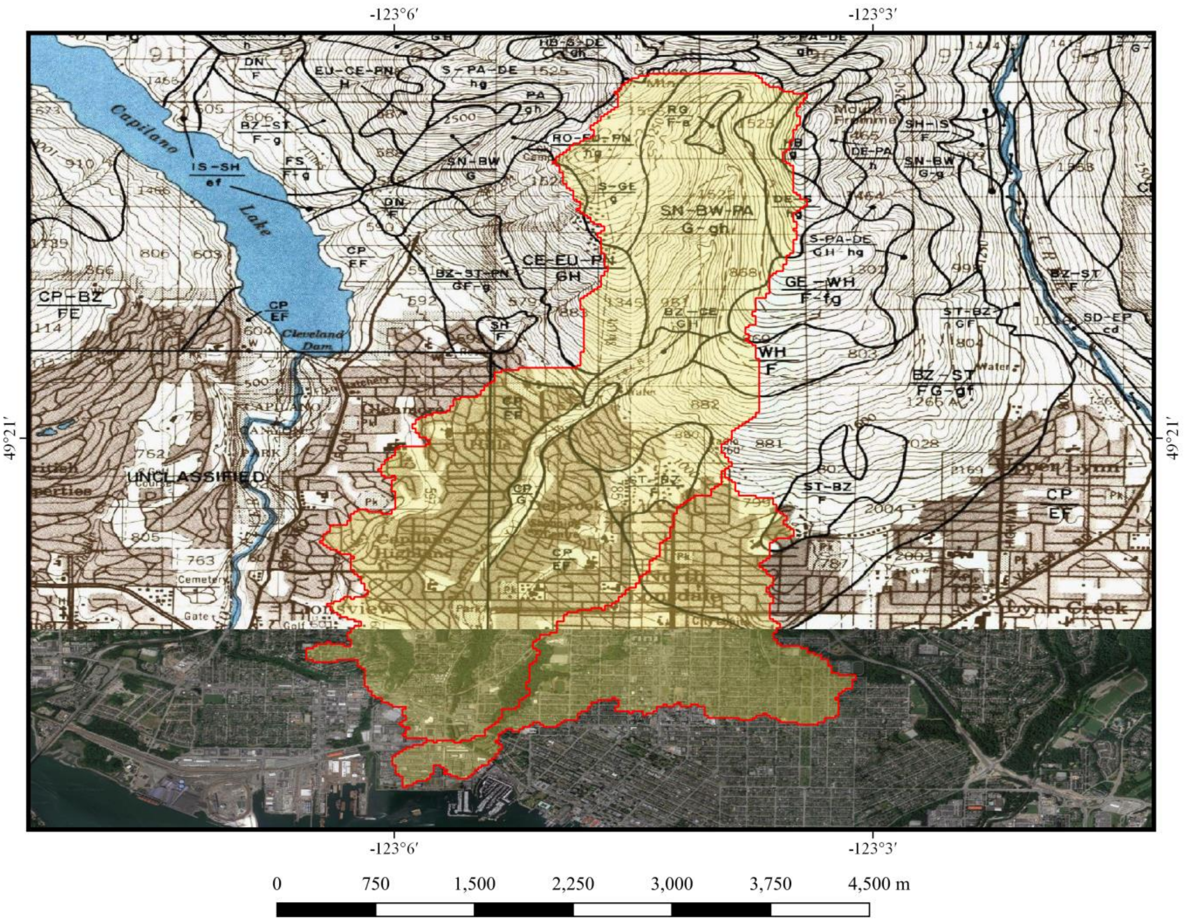


Figure 8. Soil types defined by *Soils of the Langley-Vancouver Map Area*. Red lines denote the boundary of Mosquito Creek Watershed, and it's tributary - Wagg Creek Watershed. The map is created in QGIS by georeferencing page 10 in *Soils of the Langley-Vancouver Map Area*, projected using WSG84- EPSG:4326.

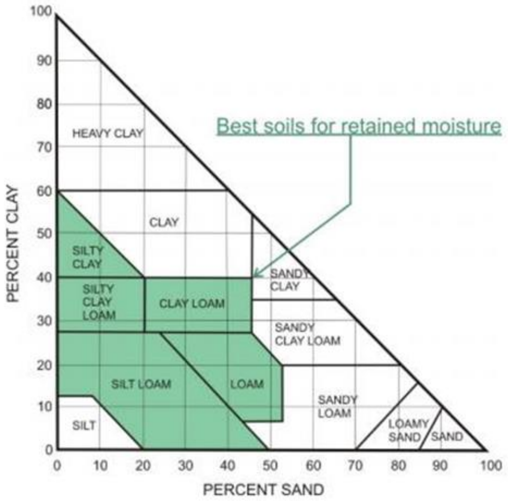


Figure 9. Soil Texture Triangle (Partnership for Water Sustainability in BC, 2014)

Temporarily, two-time series was set for the project: 2010s (based on 2011 land use) and 2040s (based on Metro Vancouver's land use projection in 2041). The year 2011 and 2041 were chosen based on the information available and accessible to the public. Metro Vancouver (2011) projected the dwelling units by structure type; to convert the unit projection to areas, the values for average lot size (width × length) were taken from *Infrastructure Costs Associated with Conventional and Alternative Development Patterns* (Canada Mortage and Housing Corporation, 1995).

Practically all LID practices form a symbiotic relationship between vegetation cover, soils and the constructed facilities, which makes parameters such as growing medium depths and crop coefficients essential in selecting the most appropriate option. In order to assess LID practices' performances using WBM, a prerequisite before applying them to the drainage area is the designing of source controls, of which the regulations are listed in *Stormwater Source Control Design Guidelines 2012* (Lanarc Consultants Ltd. *et al.*, 2012). The required data inputs and their sources are summarized in Table 5.

Table 5. Summary of Data Inputs for the WBM

Inputs	Outputs	Data Sources
Climate Data	Rainfall Mass Balance & Exceedance Table (Based on 2011 Land Use)	Environment Canada Historical Climate Data https://climate.weather.gc.ca/
Model Area		Calculated in QGIS using shapefile created from ASTER Global Elevation Model V003, Earthdata
Length		
Elevation, Slope		Topographic Data of Canada - CanVec Series - 250K BC Elevation
Soil Types		Soils of the Langley-Vancouver Map Area. Report No. 15, British Columbia Soil Survey (Luttmerding, 1980)
Land Uses		2011 Generalized Land Use Classification Map http://www.metrovancouver.org/data
2041 Land Use Projection	Rainfall Mass Balance & Exceedance Table (Based on 2041 Land Use Projection)	Regional Growth Strategy Projections: Population, Housing and Employment 2006 – 2041 Assumptions and Methods; Infrastructure Costs Associated with Conventional and Alternative Development Patterns
LID Designing	Rainfall Mass Balance & Exceedance Table (After Application of LID Practices)	Stormwater Source Control Design Guidelines 2012

3.3 Model Calculation Equations

All the calculations by the WBM are powered by the QUALHYMO Engine. The conceptual framework of quantitative runoff analysis is illustrated in Figure 10. Two procedures are adopted in the QUALHYMO to determine the direct runoff depth: Soil Conservation Service (SCS) method for pervious areas and the volumetric coefficient approach for small impervious areas (Rowney and Wisner 1984). The SCS method was derived from empirical analyses of runoff in small drainage basins monitored by the USDA and is widely used as an efficient approach for estimation of direct runoff generated by a rainfall event in a specific area. The volumetric coefficient approach requires input of configuration of the impervious areas, and it is assumed that the volumetric coefficient is temporarily constant.

The SCS method for calculating excess runoff in pervious areas is expressed in equation (4):

$$Q = \frac{(P - ABSPER)^2}{(P - ABSPER + SSTAR)} \tag{4}$$

where, Q = cumulative depth of runoff (mm),

P = cumulative depth of precipitation (mm),

$ABSPER$ = initial abstraction (mm), and

$SSTAR$ = loss parameter (mm).

Runoff volume in configured impervious areas is calculated using equation (5):

$$Q = (P - ABSIMP) \times RIMP \tag{5}$$

where, Q = cumulative depth of runoff (mm),

P = cumulative depth of precipitation (mm),

$RIMP$ = a constant volumetric runoff coefficient, and

$ABSIMP$ = the impervious area initial abstraction.

Precipitation data is retrieved from Environment Canada's historical records. In contrast, *ABSPER*, *SSTAR*, *RIMP*, and *ABSIMP* values are adjusted for each rainfall event.

The runoff rate is then determined through either The Williams or Nash unit hydrographs. Williams *et al.* developed the Williams unit hydrograph (as cited in Rowney and Wisner 1984), which comprises three phases:

$$q = \begin{cases} q_p \left[t/t_p\right]^{(n-1)} e^{(1-n)\,(t/t_p-1)} & (0 \le t < t_0) \\ q_0\, e^{(t_0-t)/K} & (t_0 \le t \le t_1) \\ q_1{}^{(t_1-t)/K_1} & (t > t_1) \end{cases} \tag{5}$$

where, q = flow rate (cfs),

q_p = peak flow rate (cfs),

t_p = time to reach peak flow (hrs),

n = dimensionless parameter,

t_0 = time to reach inflection point,

K = recession constant (hrs),

$t_1 = t_0 + 2K$,

q_1 = flow rate at t_1, and

$K_1 = 3K$ = second recession constant (hrs).

The Nash unit hydrograph assumes that "n" linear reservoirs exist in the drainage basin and it estimates the outflow from the last reservoir with time using equation 6:

$$q_t = \frac{1}{K_n GAMMA} e^{-t/K_n} (t/K_n)^{n-1} \tag{6}$$

where, q_t = the outflow rate of the last reservoir (cfs),

n = number of reservoirs,

K_n = the storage coefficient of each reservoir, and

$GAMMA$ = the gamma function.

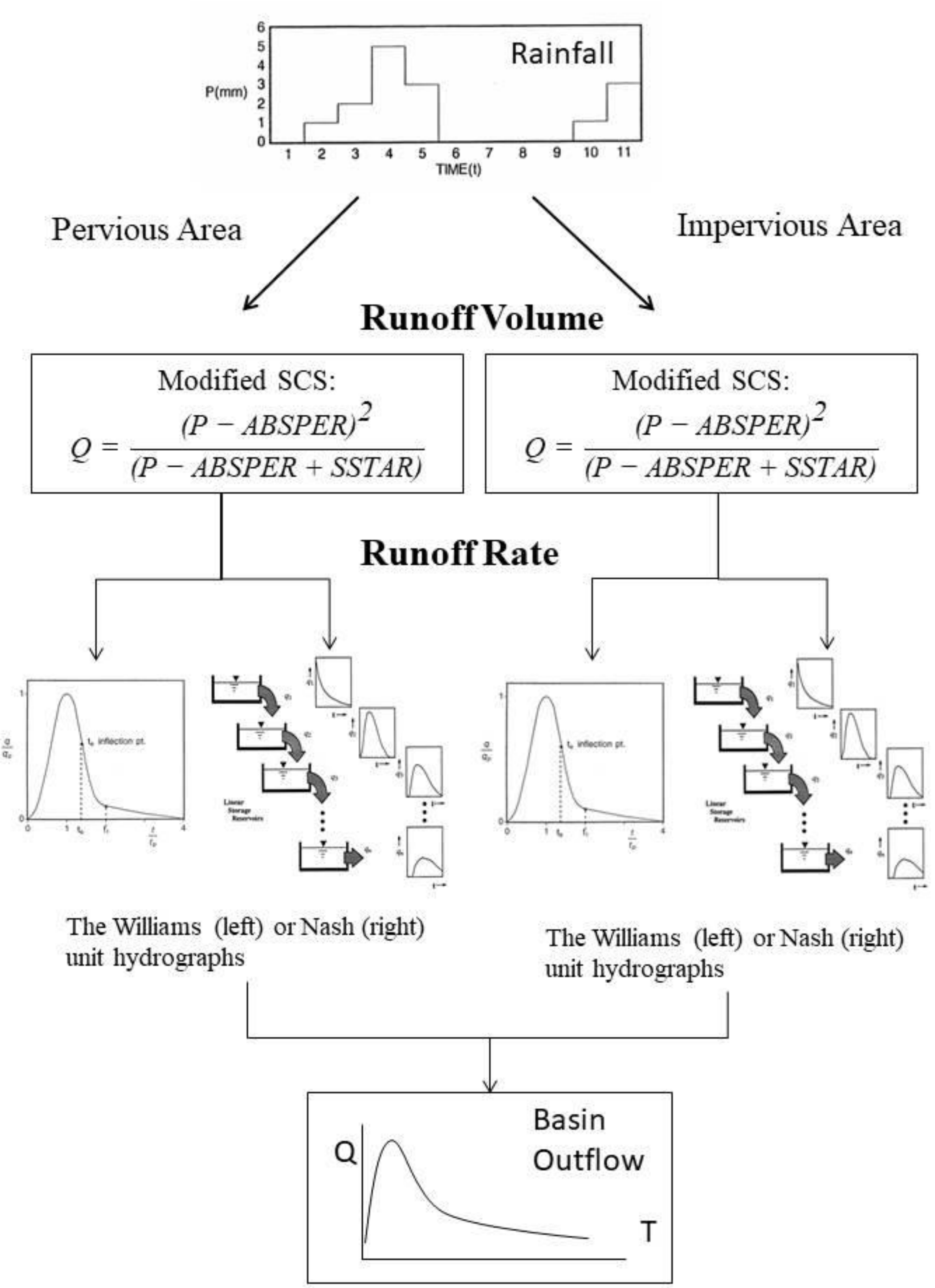


Figure 10. Conceptual framework of the quantitative runoff analysis in WBM powered by QUALHYMO (modified from Rowney and Wisner, 1984)

Chapter 4. Application of WBM to Study Area

4.1 Model Calibration

No recent climate data (i.e., 2000 – 2020) had been recorded for North Vancouver Mosquito Creek climate station (1105663); therefore, precipitation data retrieved from West Vancouver AUT (1108824) and North Vancouver Sonora Drive (110N6FF) were adopted as climate inputs for lower and middle watershed as they are located in proximity to the study area. As the streamflow data was also unavailable for Mosquito Creek watershed, a regional analysis of streams with recorded flow data was conducted to verify the performances of the model. The following criteria were set in selecting the most appropriate data series:

- Situated in CNV or DNV;
- Minimum of 10 years of available maximum instantaneous discharge data;
- Undisturbed discharges (unregulated discharges); and
- No possible attenuation of the peak discharge (e.g., large lakes).

Seymour River near North Vancouver (08GA030) and Mackay Creek at Montroyal Boulevard (08GA061) were found to meet these criteria for the lower and middle watershed. Thus the recorded streamflow data was compared to the modelled values to complete the calibration, as presented in Tables 6 and 7. Figure 11 illustrates the graphical presentations of the comparison results. The model estimated that discharges show a near-perfect match to the recorded data for Mackay Creek. Thus the outputs would accurately represent the existent watershed situations.

Table 6. Comparison of Measured and Modelled Discharge in Lower Watershed.

Return Period (years)	**Measured Discharge (L/s/ha)**	**Modelled Discharge (L/s/ha)**	**Percentage Error (%)**
200	18.10	18.86	4.01
100	17.70	17.90	1.09
50	14.86	15.66	5.11
10	13.79	15.19	9.21
5	12.02	13.42	10.45
3	10.19	11.19	8.90
2	8.90	8.95	0.54

Table 7. Comparison of Measured and Modelled Discharge in Middle Watershed.

Return Period (years)	**Measured Discharge (L/s/ha)**	**Modelled Discharge (L/s/ha)**	**Percentage Error (%)**
200	21.70	21.00	-3.33
100	19.06	18.96	-0.54
50	16.52	16.92	2.35
10	14.18	14.88	4.68
5	11.48	12.18	5.72
3	9.64	10.14	4.89
2	8.6	8.63	0.36

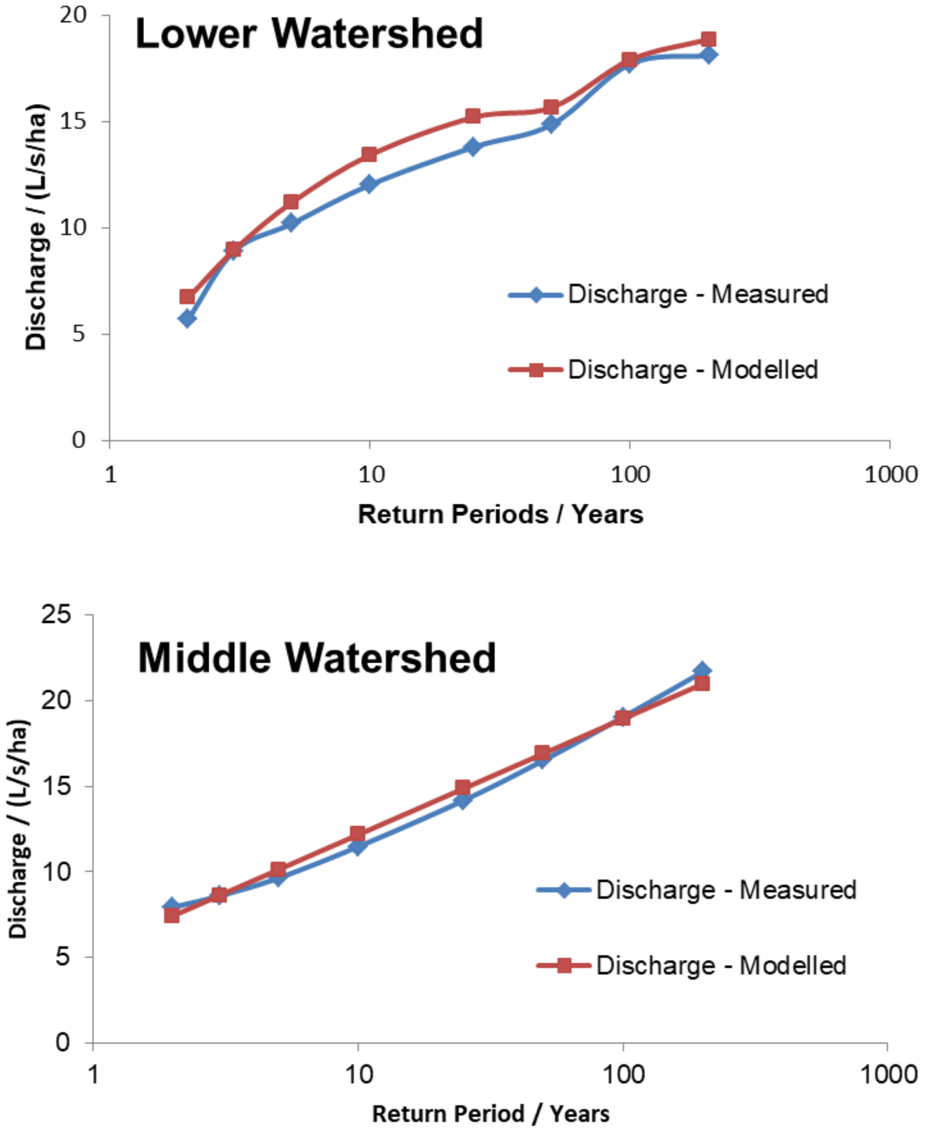


Figure 11. (Top) Model Verification Comparison for Lower Watershed and (Bottom) and Model Verification Comparison for Middle Watershed.

4.2 Model Application to Land Use Scenarios

The 2010s land use conditions were determined in Chapter 2 using accessible land use maps in the study area provided by Metro Vancouver. To run the simulation for future scenarios (2041), Metro Vancouver's regional housing growth projection report (2011) was used for reference. The total dwelling units in CNV and DNV are estimated to be 30,200 and 45,000, respectively, with the composition of 53% apartments, 31% multi attached, and 16% single-detached houses. The study area covers neither of the municipalities; therefore the percentage of each housing area to total area is more practical in estimating the house composition in the study area, which is calculated by using the following equation:

$$\textit{Housing Area Percentage} = (\textit{Units} \times \textit{Lot Size}) / \textit{Total Area} \quad (7)$$

The determination of each parameter in equation seven is explained in Chapter 3 Data Inputs sections. Table 8 presents a summary of house composition in 2011 and 2041.

Table 8. House Composition for the WBM Inputs

Variable	Lower Watershed		Middle Watershed	
	2011	2041	2011	2041
Land Use Percentage (%)				
Single Detached Dwellings	41	6	59	24
Attached Houses	4	13	1	8
Apartments	16	59	0.2	37
Land Use Area (ha)				
Single Detached Dwellings	221	32	374	152
Attached Houses	19	70	5	52
Apartments	86	317	1	235
Total Area (ha)	538	538	634	634
Residential Area (ha)	326	419	380	439
Other Land Use (ha)	212	119	254	195

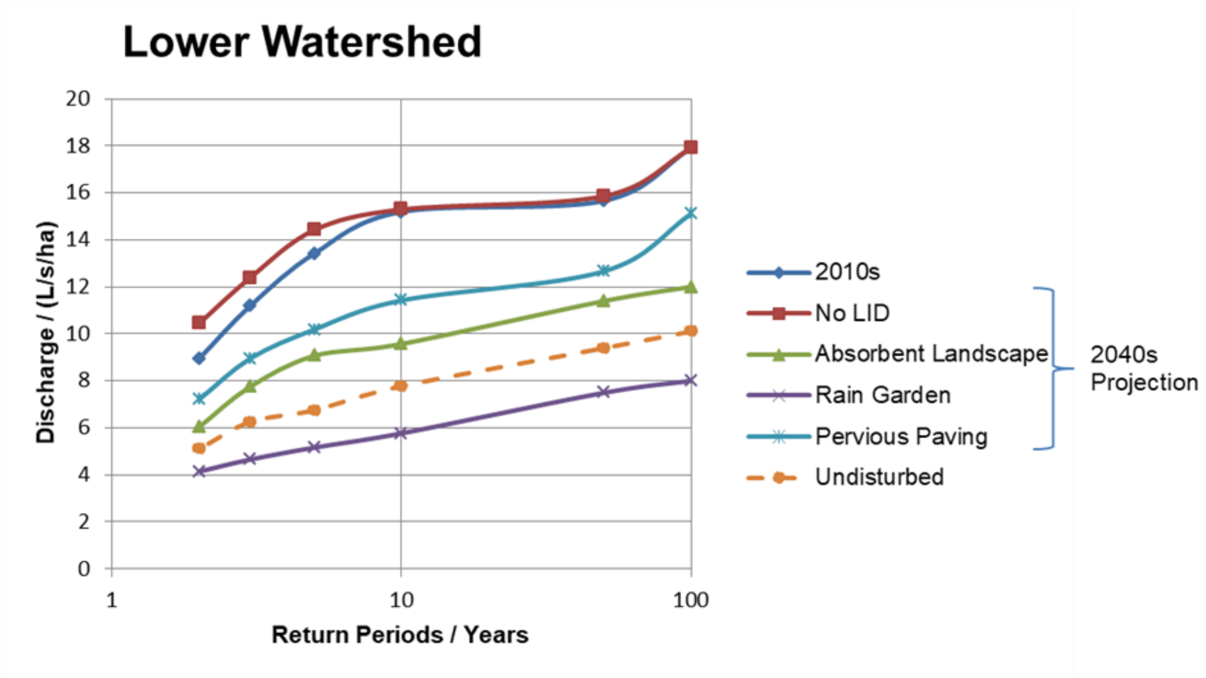
This case study also examined three LID practices that could potentially mitigate the negative impacts (i.e., urban flooding) resulting from increases in impervious surface areas. All of the aforementioned LID practices in Chapter 1 could reduce the runoff volume effectively, thereby reducing the monetarily and ecologically costly occurrences of stream erosion and waterlogging. As the intensification of existing housing is the predominant development trend in the study area, absorbent landscapes, rain gardens, and pervious paving were selected, and their performances were assessed using the WBM. Each of the three mitigation practices could be applied separately or in unison with other methods. For the purpose of comparison, the performance of each method was examined separately. Detailed scenario design variables are listed in Table 9. All scenarios keep the original projected building structures (house, garage etc.) in 2041, as those are unrealistic and costly to modify.

Table 9. LID Scenario Design Variables

No.	Description	Surface Condition LID Applied to	Area (ha)	
			Lower Watershed	Middle Watershed
1	Absorbent Landscape	Divided and Undivided Roads, Parking Areas, Disconnected Roof Leaders, Sidewalks, Driveways	189.85	287.35
2	Rain Garden	Divided and Undivided Roads, Parking Areas, Disconnected Roof Leaders, Sidewalks, Driveways	189.85	287.35
3	Pervious Paving	Impervious Paving	26.05	65.25

4.2.1 Frequency of Different Surface Runoff Discharge Rates

Historical flood discharge frequency analysis serves as practical criteria to both examine the impacts of increase of impervious surface areas and assess the performances of mitigation practices. Increases in certain discharge rates (e.g., discharge rate with two year return periods that has a probability of occurrence of 50% in any given year) might result in larger floods and consequently introduce more runoff that leads to more property damage. The WBM assumes that the interflow and groundwater discharges were ignorable compared to surface runoff, and thus the modelled discharge values equal to surface runoff discharge rates. The frequency analysis of surface runoff is demonstrated in Figure 12.



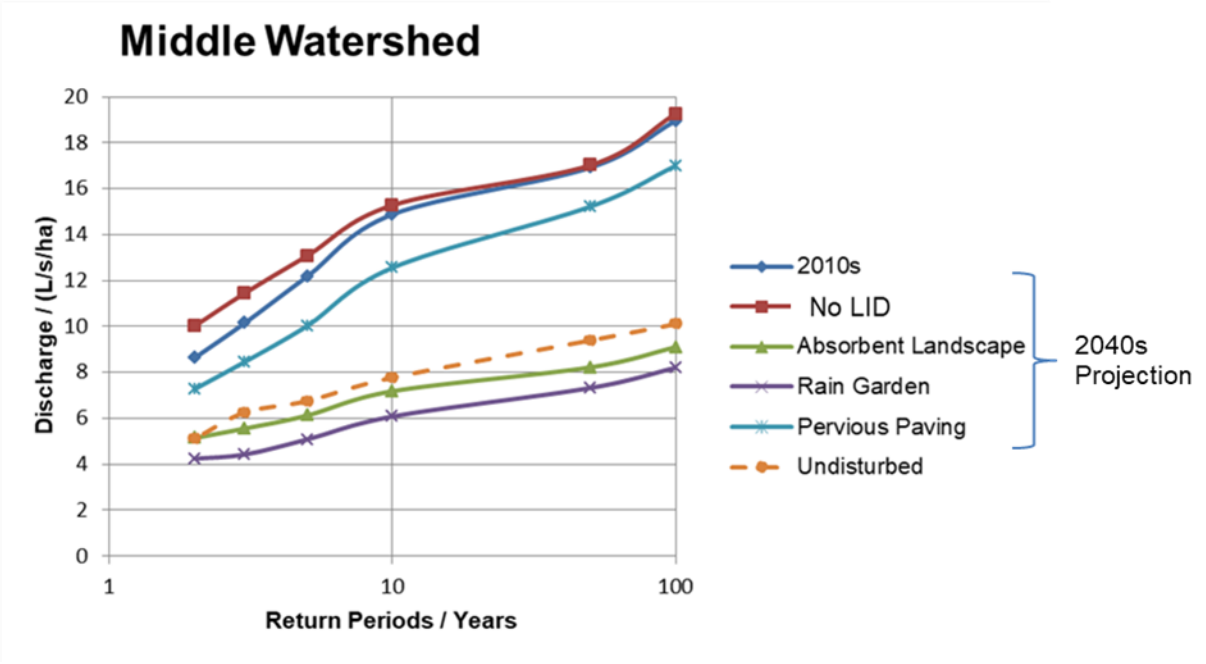


Figure 12. (Top) Frequency Analysis of Surface Runoff in Lower Watershed and (Bottom) Frequency Analysis of Surface Runoff in Middle Watershed.

The above graphs illustrate that as the intensification continues, the magnitude of smaller surface runoff discharges (i.e., < 5 year return period) will increase. In contrast, the value of infrequent surface runoff discharges (i.e., > 100 year return period) is not likely to increase as significantly as smaller surface discharges. For instance, the WBM predicted that the two-year discharge that has a probability of occurrence of 50% in any given year would increase from 8.95 L/s/ha for the 2010s watershed condition to a possible 10.45 L/s/ha in the 2040s projection in lower watershed and from 8.63 L/s/ha in the 2010s to 10.02 L/s/ha in the 2040s in the middle watershed. A plausible explanation is that runoff is correlated to impervious surface area changes, and the magnitude of larger flood events is more likely to be influenced when urbanization expands to the undisturbed natural surface condition. However, in this case, study, the majority of the projected development takes the form of redevelopment/intensification, which shifts the composition of impervious surface areas (i.e., percentage of driveways, rooftops and buildings) but only introduces little or no new impervious surface areas.

Compared to the middle watershed, the discharge rates are slightly lower watershed for both the 2010s and 2040s surface conditions. Only through the application of rain gardens would the values be restored to calm conditions, whereas both absorbent landscapes and rain gardens would reduce the discharge rates to values in the vicinity of the pre-development level. However, in the middle watershed, absorbent landscapes would more likely be preferred if developers were presented with both absorbent landscapes and rain gardens, as it would incur a lesser financial commitment (capital costs $31,973 – 41,476/unit for absorbent landscapes compared to $31,973 – 41,476/unit for rain gardens, Toronto and Region Conservation Authority, 2013).

4.2.2 Peak Flow Rates (L/s/ha) and Related Occurrence Time

The WBM was set up as a planning tool to compare changes to the lower and middle watershed due to altered land uses and implementation of mitigation practices. The model generated a summary table of discharge rates listing several values over a range determined by the surface conditions for each area, including peak flow rates and the related occurrence time. The modelled results under the 2010s, 2040s, and future scenarios with LID practices are listed in Table 10.

Table 10. Modelled Peak Flow Rates and Occurrence Time

Surface Conditions		**Lower Watershed**		**Middle Watershed**	
		Peak Flow Rate (m^3/s)	**Occurrence Time (h)**	**Peak Flow Rate (m^3/s)**	**Occurrence Time (h)**
2010s		52.06	2.03	58.19	3.51
2040s	No LID	59.50	1.65	65.46	2.23
	Absorbent Landscape	37.18	2.85	43.64	3.56
	Rain Garden	29.75	5.81	36.37	7.28
	Pervious Paving	44.63	2.02	50.91	2.53

It can be observed from Table 10 that if no LID practices are applied to the study area, the peak flow rates in both lower and middle watershed will increase. Intensification will shorten the peak flow occurrence time, which is potentially due to shifts in impervious surface areas (e.g., percentage changes in driveways and sidewalks). All three selected LID practices resulted in a reduction in peak flow rates and delays in the occurrence time, among which rain gardens exhibited the most compelling performance in both the lower and the middle watershed, followed by absorbent landscapes and pervious paving. The plausible explanation for the differences in peak flow rates and returns of selected LID practices is that lower watershed experiences less frequent runoff-causing precipitation events (i.e. Tier B and Tier C events) and due to more impervious surface area in the lower watershed, the soil water holding capacity has decreased significantly (Abu-hashim et al., 2015); thus solely enhancing the surface condition (e.g., adopting absorbent landscapes) might fail to effectively retain the excessive rainwater and LID practices with storage (e.g. rain gardens) would be preferable.

4.2.3 Direct Runoff Depths

In comparison with the above modelling results, more apparent changes can be observed in the direct runoff depths in both lower and middle watershed. Table 11 lists the direct runoff depths calculated in each scenario simulating 24h rainfall over 40 mm events (Tier B and Tier

C events). Similar to trends in peak flow and the relevant occurrence time, intensification/redevelopment would result in increases in direct runoff depths. As middle watershed experiences more frequent runoff-causing precipitation events, consequently, the area would be subjected to a greater extent of runoff; meanwhile, the intensification/redevelopment processes would result in more significant increases in runoff depths in middle watershed than lower watershed (29.61% increase in the middle watershed compared to 21.49%. increase in the lower watershed). Mitigation effects are most significant when rain gardens are applied in both lower and middle watershed, followed by absorbent landscapes and pervious paving.

Table 11. Modelled Direct Runoff Depths in Study Area

Sub-watershed / **Surface Condition**			**Lower Watershed**	**Middle Watershed**
2010s		Runoff (mm)	147.97	190.64
2040s	No LID	Runoff (mm)	179.77	247.09
		Increase[1] (%)	21.49	29.61
	Absorbent Landscape	Runoff (mm)	168.02	214.96
		Decrease[2] (%)	6.53	13.01
	Rain Garden	Runoff (mm)	118.59	182.92
		Decrease[2] (%)	34.04	25.97
	Pervious Paving	Runoff (mm)	175.18	229.95
		Decrease[2] (%)	2.55	6.94

[1] Compared to Runoff Depth in 2011

[2] Compared to Runoff Depth in 2041 (No LID)

Chapter 5. Case Study Limitations

Limitations exist pertaining to the analysis of Mosquito Creek Watershed. For instance, some of the selected climate stations are outside the boundary of Mosquito Creek watershed. Ideally, the precipitation data would have been collected from within the watershed.

Additionally, several stations devoid of recent precipitation data (i.e. 2015 – 2020) and time series vary for each station, which poses a challenge to interpolate the differences among all stations using the same time scale. Climate stations were chosen with the highest care, but due to the unavailability of recent climate records, two stations examined for 2001 – 2010 period (North Vancouver 2nd Narrows and North Vancouver Sonora Drive) were eliminated in the 2011 – 2020 analysis. For the purposes of setting up the WBM, soil depths and soil type values were deduced based upon soil map relevant to the site of interest; however, part of the urban center was not surveyed due to the level of soil disturbance and alteration. Only by conducting a field visit could more accurate and detailed inputs be acquired, replacing those well-informed speculations.

Besides disadvantages on data sources, the evaluation method adopted by this project, the Water Balance Model (WBM), possesses several limitations, including:

- No surface flow has been modelled within the WBM, leading to the default setting of rain gardens as flat layouts. Such design would retain rainwater longer, resulting in higher surface water ponding durations.
- No groundwater flow has been modelled in the WBM, leading to the ignorance of groundwater and interflow entering the local streams as discharge.

Chapter 6. Concluding Remarks

The goal of this project is to provide suggestions on the selection of LID practices based on implications from runoff-causing precipitation event frequency analysis and sensitivity to land-use changes. It can be inferred that runoff-causing storm event frequencies increase with elevation, yet the relationship is not merely linear. A quantitative analysis on Tier B and Tier C events indicates that higher elevation zones not only experience more frequent runoff-causing Tier B and Tier C events, but also receive greater depths of precipitation. When designing the LID practices, developers should meet the mitigation targets set by individual municipalities as well as surviving the less frequent extremes. The frequency of runoff-causing precipitation events and precipitation amounts are vital factors to consider when designing and selecting the LID practices, as the mitigation targets are influenced by the frequencies of runoff-causing storm events. Normally greater precipitation amounts and larger surface discharge rates are correlated (Stephenson, editor, 2000).

Water Balance Model (WBM) was used to facilitate the assessment of impervious surface areas' impact on hydrological processes. Analyses on lower watershed and middle watershed support Dudley *et al.* 's conclusion (2001) that the sensitivity towards impervious surface area changes is positively correlated to the extent of imperviousness. Among the three LID practices recommended in this project, middle watershed's discharge rates with multiple return periods would be restored to pre-development standards through absorbent landscapes and rain gardens. However, considering the financial commissions, absorbent landscapes might be preferred by developers. In contrast to the performances of selected LID practices in the middle watershed, only rain gardens' 2040s projection meets the target to reduce discharge rates to pre-development levels in the lower watershed. Given that the lower watershed is more urbanized than the middle watershed, it can be inferred that rain gardens in the representation of LID practices with storage facilities perform better in highly developed areas potentially due to the loss of soil water holding capacity, whilst the surface enhancement such as absorbent landscapes is more likely to be favoured in comparably less developed areas regarding development budgets.

The results yield far-reaching implications. It would be of great value to conduct more runoff inducing precipitation frequencies analyses over a larger temporal and spatial scale as well as more runoff discharge rate, and depth analyses to acquire not only a thorough understanding of how the frequencies are related to elevation but also how the hydrological processes in a watershed will change due to altered land uses and implementation of runoff reduction practices (e.g., LID). Mostly, the intents of Low Impact Development (LID) practices are to alleviate hydrological challenges (e.g., urban flooding) resulting from urbanization.

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Appendix A

Table A-1. Land Use in City of North Vancouver (CNV) and District of North Vancouver (DNV) Zoning Bylaws

Land Use	Description		Gross Floor Area (times total lot area)	Building Coverage (%)			Parking Coverage (%)		Other Coverage (%)		Total Impervious Coverage	
	CNV	DNV	CNV	DNV	CNV	DNV	CNV	DNV	CNV	DNV	CNV	DNV
Commercial	Commercial Zones (Neighbourhood, General, Local, Service, and Lower Lonsdale): C1-A, C1-B, C-2, C-3, CS-1, CS-2, CS-3, LL-1, LL-2, LL-3, LL-4, LL-5	General, Tourist, Entertainment, Public House, and Business Commercial: C1, C1L, C1A, C2, C3, C3A, C4, C5, C6, C7, C8; Minimum Lot Size: C4 2787 m^2; C5 1858 m^2	1.0 - 2.3	0.55 - 1.75	35 - 90%	30% - 60%	≤ 10%	≤ 35%	≤ 5%	--	--	60% - 90%
Institutional	Public Use and Assembly (School and Institution Zones): P1, P2; Minimum Lot Area per Classroom: 1100 m^2	School and Institution Zones: PA, PA1, PA3, PA4	--	≥ 0.4	≤ 40%	25% - 50%	≤ 35%	≤ 40%	≤ 5%	--	≤ 75%	50% - 90%
Park	Public Use and Assembly (Park, Recreation, and Open Space Zones): P1, P2; Minimum Lot Area: 1100 m^2	Park, Recreation, and Open Space Zones: PRO, SP, CP, NP, NPL	--	--	--	≤ 5%	--	≤ 5%	--	--	--	≤ 10%
Residential Level 1	One-Unit Residential Zones: RS-1, RS-2, RS-3	Single-Family Residential： RS1, RS2, RS3, RS4, RSMH, RSN, RSD, RSKL, RSMF, RSNQ, RSPH, RSSG, RSK, RSH, RSEW, RSCH, RSE, RSQ	≤ 0.5	0.35 - 0.55	≤ 30%	35% - 45%	≤ 10%	≤ 15%	≤ 5%	--	≤ 42%	≤ 50%
Residential Level 2	Two-Unit Residential Zones: RT-1, RT-2	Multi-Family Residential: RM1, RM2, RM4, RM5	0.35 - 0.67	--	35% - 50%	≤ 40%	≤ 10%	≤ 15%	≤ 5%	--	≤ 60%	≤ 50%
Residential Level 3	Cedar Village Residential Zones: RC-1, RC-2		--		≤ 35%		≤ 10%		≤ 10%		≤ 55%	
Residential Level 4	Garden Apartment Residential Zones: RG-1	Multi-Family Residential, Attached Zones: RM3, RM6, RM7	≤ 0.49	≤ 0.8	≤ 35%	≤ 60%	≤ 10%	≤ 20%	≤ 10%	--	≤ 55%	≤ 70%
Residential Level 5	Medium-Density Apartment Residential Zones: RM-1	Multi-Family Residential, Medium Density, Low-Rise Apartment: RL1, RL2, RL3, RL4; Minimum lot size: 929 m^2	≤ 1.0	≤ 1.3	≤ 50%	≤ 50%	≤ 5%	≤ 25%	≤ 5%	--	≤ 55%	≤ 75%
Residential Level 6	High Density Apartment Residential Zones: RH-1	Multi-Family Residential, High Density, High-Rise Apartment Zones: RH1, RH2, RH3; Minimum lot size: 1300 sq.m	≤ 1.2	--	≤ 50%	≤ 33%	≤ 5%	≤ 40%	≤ 5%	--	--	≤ 75%

* Note: Surface Conditions are based on maximum values where ranges are shown. For zone specific values refer to the City of North Vancouver and District of North Vancouver zoning bylaws.

** Zones with similar surface conditions are combined for modeling purposes.

Source: Zoning Bylaw, 1995, No. 6700 (City of North Vancouver); District of North Vancouver Zoning Bylaw, 1965