ROLE OF URBAN FORESTS ON HYDROLOGICAL CYCLE IN METRO VANCOUVER

LWS 548 Major Project

By

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Executive summary

With increasing urbanization, more and more trees are removed from forested landscapes. With the increasing climate change, trees become more important to mitigate the impact of climate change. Urban forests become more important as urban forests have many benefits mitigating air pollution, increasing oxygen and decreasing the heat island effect. More important, urban forests help regulate the hydrological cycle, because trees control stormwater, increase infiltration and decrease runoff. However, although there are many studies on the effect of urban forests on the hydrological cycle, the methods to implement the urban forests in cities are lacking. The objective of this study was to analyze the effects of an urban forest on the hydrological cycle in Metro Vancouver and make recommendations on sustaining the urban forest to regulate the hydrological cycle.

A comparative analysis was conducted. The study site was Pacific Spirit Regional Park (PSRP) and its adjacent urban city (Vancouver) in Metro Vancouver. The study compared the effects of urban forests on the hydrological cycle encompassing PSRP with non-disturbed old-growth forests and PSRP with disturbed areas (second-growth forests and trails) to the adjacent urban residential areas of Vancouver in terms of runoff and evapotranspiration. The literature was used for the calculation of runoff and evapotranspiration.

The results showed that the areas of trails and off-trails have the lowest evapotranspiration and highest runoff in PSRP, as the trails are impervious and the water cannot infiltrate into the soil. As there is no tree cover to intercept rainfall, the evapotranspiration on trails is quite low. In contrast, runoff is the same for both old-growth and second-growth forests, but evapotranspiration is different. The evapotranspiration is higher in old-growth forests compared to second-growth forests, so old-growth forests without disturbances are better to control and decrease runoff. In Vancouver, the impervious areas, such as roads, buildings and pavement cover most of the surface areas of Vancouver, with only a few areas of parks. Therefore, the runoff in Vancouver is very high and the evapotranspiration is very low.

Based on the results, several recommendations are suggested for implementing urban forests. First, it is important to maintain as much as old forests as possible. Second, it is beneficial to minimize the amount of trails and roads. Third, everyone in cities needs to maintain as much green space as possible, and fourth, it is useful to plant trees in cities for future development. In conclusion, urban forests are important and should not be ignored in future urban developments.

Introduction

Benefits of urban forests

Urban forest is a common term and has been accepted recently by many cities nowadays. The 2019-2024 Canadian Urban Forest Strategy (CUFS) developed a new definition for urban forests, "trees, forests, greenspace and related abiotic, biotic and cultural components in areas extending from the urban core to the urban-rural fringe.". Therefore, urban forests has become an important part and a key green infrastructure system in our lives (Wolf *et al*., 2020). There are many benefits of sustaining urban forests, and many scientists have demonstrated the advantages of urban forests. For social aspects benefits, urban forests can create a beautiful outdoor environment for cities and provide a space for recreation (Mytton *et al*., 2012; Price, 2003; Tyrväinen *et al*., 2005). For environmental aspects benefits, urban forests can mitigate air pollution and increase oxygen, because trees can absorb greenhouse gases by carbon storage (Wolf *et al*., 2020). Urban forests can eliminate the urban heat island effect and reduce the temperature in cities (Brandt *et al*., 2016; Sinnett, 2020; Rahman *et al*., 2015; Edmondson *et al*., 2016), as trees reduce heat stress by providing a cooling effect from evapotranspiration and shade (Ontario coalition, n.d.). Because of the cooling effect from evapotranspiration and shade, the surface and air temperatures will be reduced and lower compared to the peak temperatures of unshaded materials (EPA, 2019). In addition, evapotranspiration and shading will lower the peak summer temperatures (EPA, 2019). Trees are useful as a mitigation strategy that is planted around buildings and pavement to reduce the heal island effect (EPA, 2019).

More importantly, urban forests help regulate the extremes within the hydrological cycle, protect water resources and improve water quality. The hydrological cycle, also known as the water cycle, illustrates the water exchange among oceans, atmosphere, land surface, biosphere, soils, groundwater systems and solid Earth (Marshall, 2014). Five main processes make up the hydrological cycle: condensation, precipitation, infiltration, runoff and evapotranspiration (Dunbar, 2009), which makes the hydrological cycle very important in our lives (consider a hydrological image). Urban forests can affect hydrological by improving water infiltration, storing water and reducing stormwater runoff (Berland *et al*., 2017; Bartens *et al*., 2008). More specifically, urban forests can control stormwater by intercepting rainfall (Zoë Hoyle, 2016), and larger trees have a greater ability to intercept rainfall because of larger canopy sizes (Ontario coalition, n.d.). Urban forests can also regulate the flow of water, decrease runoff and increase water storage (Zoë Hoyle, 2016) because trees can slow the rate of water flow and reduce the volume of rainwater by retaining water by a canopy, stemflow, throughfall, infiltration and transpiration (Ontario coalition, n.d.). Urban soils without trees are often compacted, which means the water can easily run off from these urban soils. Runoff picks up pollutants from urban streets which make their way into waterways, so runoff may contribute to water pollution and erosion in waterways. However, tree roots can reduce the impact of impervious surfaces, increase the penetration of water into compacted soil, and thus help to increase water infiltration under tree canopies (Ontario coalition n.d. & Song *et al*., 2020). It is estimated that an urban forest can reduce the 9.85% volume of total runoff and intercept 9.69% of total rainfall by the trees' canopies (Song *et al*., 2020). It has been shown that the urban forest reduced about 17% to 23% of rainfall annually in Beijing from 2000 to 2010 (Song *et al*., 2020). In Santa Monica, California, the urban forests were estimated that can intercept 1.6% of total precipitation annually (Song *et al*., 2020). The different amount of interception of rainfall is due to various tree species and tree size (Song *et al*., 2020).

The reasons for sustaining urban forests

The trend of the global population shows that the urban population has increased consistently during the past several decades (Kundu & Pandey, 2020), with the increasing phenomenon of urbanization globally. Increasing urbanization affects the hydrological cycle because the land cover changes from natural pervious surfaces to manmade impervious surfaces and the tree cover is removed and changed to compacted soil (Song *et al*., 2020). The removal of trees will decrease the ability of trees to intercept, infiltrate and store water, in other words, surface runoff will increase especially, the peak runoff, and the possibility of urban flooding will increase (Song *et al*., 2020). Climate change is a serious problem because climate change will increase temperature, increase the fluctuation of precipitation and increase extreme weather conditions. Therefore, climate change will further decrease the ability of the land to infiltrate, store water and affect the hydrological cycle. China has experienced serious urbanization since the 1980s (Song *et al*., 2020). The dramatic urbanization in China increased the frequency of urban flooding and increased extreme weather conditions from climate change which has further exacerbated urban flooding (Song *et al*., 2020). The rainfall events from climate change have also increased in Canada (Ontario coalition). Therefore, it is important to conserve and maintain the urban forests to protect extreme events in the hydrological cycle from urbanization and climate change.

Project objectives

Although there are many studies on the effect of urban forests on the hydrological cycle, established methods to sustain the urban forests in cities are lacking. It is important to analyze how to sustain the urban forest in cities to achieve the optimal effect of the hydrological cycle, as a result of urbanization and the impacts of climate change. Research can also increase people's knowledge about urban forests and increase motivation to protect urban forests. The objective for my project was to analyze the effects of an urban forest on the hydrological cycle in Metro Vancouver and make recommendations for better sustaining the urban forest to regulate the extremes within the hydrological cycle.

Study area

The study site for the project was Pacific Spirit Regional Park (PSRP) and adjacent urban city Vancouver (Figure 1) in Metro Vancouver.

Figure 1. The map shows the area of Vancouver and PSRP in Metro Vancouver.

Pacific Spirit Regional Park (PSRP)

The park was initially a part of the Province of British Columbia. UBC Endowment Lands was established in 1923 by the BC Government (Hewitt, 2020). The provincial government-specified part of the UBC Endowment Lands as an ecological reserve in 1975 and PSRP was established in 1989 (Hewitt, 2020). The new park is located on the western edge of Vancouver, right up against the University of British Columbia (UBC) (Figure 2) (Pacific spirit REGIONAL Park: Tourism Vancouver, n.d. & Pacific Spirit Park Society, n.d.). The park is a dense forest that covers over 750 hectares (Pacific spirit REGIONAL Park: Tourism Vancouver, n.d.). The forest contains many varieties of trees, mostly second-growth trees evergreen trees including cedar, hemlock, Douglas fir and Sitka spruce and deciduous trees including vine maple, big leaf maple, red alder and bitter cherry (Pacific Spirit Park Society, n.d.). There are over 50km of trails in the park for usages like walkers, runners and bicyclists (Pacific Spirit Park Society, n.d.). The vegetation and soils in PSRP function to reduce runoff when precipitation occurs (Reynolds, 2017). This is because the vegetation can intercept precipitation, and increase the water storage in the watershed and increase the potential evapotranspiration from leaves. Vegetation can also protect the soil from precipitation by a canopy, and then increase the infiltration of water into the soil (Reynolds, 2017).

Figure 2. The map shows the area of PSRP in Metro Vancouver. The black line shows the boundary of PSRP. The green area shows the area of PSRP (Edited from Google Earth).

Vancouver

The City of Vancouver is located in the southwestern of British Columbia, Canada (Davis, 2021) (Figure 3). Vancouver lies between Burrard Inlet to the north and the Fraser River delta to the south, and east of Vancouver Island (Davis, 2021). The boundary of Vancouver is adjacent to the PSRP to the west, Stanley Park to the north, with boundary road to the east and Fraser River to the south. It is the major urban center of western Canada and is one of the cities with the highest population in Canada (Davis, 2021). The land is necessary for City's development. With the economic and social development and population growth, land use is changing in response to socioeconomic patterns and increasing population (Reynolds, 2017). However, the land is limited, as only about 5% of BC is available for development (Reynolds, 2017). The urban areas developing in Vancouver results in more pervious land transferred to impervious land. The increased imperviousness will increase stormwater runoff, decrease infiltration and negatively influence the ability of vegetation and soils to reduce runoff (Reynolds, 2017). Within Vancouver, many large urban parks include Stanley Park, Queen Elizabeth Park, Killarney Park, John Hendry Park, Jericho Beach Park, Vancouver Botanical Garden, Charles, Rupert, Thunderbird, Captain Cook, Champlain Heights and Everett Crowley Parks. These areas of urban parks are pervious, and the rest of Vancouver like roads and buildings are imperious areas.

Figure 3. The map shows the area of Vancouver. The black line shows the boundary of Vancouver. The grey colour shows the urban residential areas in Vancouver. The other colours show the main large parks in Vancouver. The red lines show the main roads in Vancouver.

Climate of Metro Vancouver

The climate in Metro Vancouver is a moderate oceanic climate (Wikipedia, 2020). The summers are usually warm and dry, often resulting in moderate drought especially in July and August. The winters are mild and rainy (World climate guide, n.d.). The average annual temperature is 9.5 °C, the average temperature is above freezing even in winter, and the average annual rainfall is 2351 mm (CLIMATE-DATA.ORG, n.d. & World climate guide, n.d.). Precipitation is abundant, especially from November to March (World climate guide, n.d.). Summer is the driest season with less precipitation in Metro Vancouver (World climate guide, n.d.).

Methods

As stated earlier, urbanization leads to large increases in precipitation runoff as a result of the increased impervious surfaces compared to undeveloped areas such as forests. Increased urban surface runoff is a growing problem to mitigate, largely the result of climate change, more extreme weather effects, including an increase in precipitation, and increasing impervious surfaces in urban areas due to urbanization development. This study conducted a comparative analysis of the relative increase in surface runoff of urban development by assessing the runoff from the urban areas and an adjacent forest in the Metro Vancouver area. A systematic review of the existing literature was conducted of the study site PSRP and Vancouver, and the impact on the hydrological cycle in terms of precipitation interception, potential evapotranspiration and runoff. Government reports and Statistics Canada were used to obtain data for precipitation interception, potential evapotranspiration and runoff. After that, a comparison of the effect on the hydrological cycle includes three aspects of non-disturbed areas (old-growth forests) in PSRP, disturbed areas (trails and second-growth forests) in PSRP and urban residential areas in Vancouver. The data focused on runoff, potential evapotranspiration and precipitation interception, and which allowed comparing the result to assess the effects of urban forest on the hydrological cycle. Based on the previous information and data, make the recommendations on maintaining urban forest in Vancouver.

Hydrological cycle

Figure 4 shows the hydrological cycle and the main components. Precipitation is the primary source of water of the hydrological cycle and affects the land surface (Riya, 2018). Precipitation interception is the amount of rainfall that is intercepted by a vegetative canopy and then evaporates (Yang *et al*., 2019). When rainfall occurs, some raindrops will pass through the foliage and gaps between branches, and then reach the ground, this is called throughfall (Yang *et al*., 2019). The other raindrops that are intercepted by leaves and branches will be stored on their surfaces temporarily and finally evaporate into the atmosphere after rainfall (Yang *et al*., 2019). Except for the rainfall that infiltrates into soil or evapotranspires by leaves, the excess rainfall moves over the land surface and is known as runoff (Riya, 2018). There are three different kinds of runoff. The first one is called surface runoff, which means the part of rainfall enters the stream immediately after the rainfall (Riya, 2018). This occurs because the rainfall rate is greater than the infiltration rate and evapotranspiration rate, which makes the excess water flow over the ground surface (Riya, 2018). This water moves over the ground surface following the land gradient, and reaches streams, channels or oceans, and is named surface runoff (Riya, 2018). The second type is called sub-surface runoff, which means the part of rainfall that infiltrates into the soil and then moves laterally without reaching the water-table to the streams, channels or oceans (Riya, 2018). The third runoff type is called base flow, which is the part of rainfall that infiltrates into the soil and reaches the water table to the streams, channels or oceans (Riya, 2018). However, the time for the water in this type of runoff is very slow, so it takes a long time for the water to reach streams, channels or oceans (Riya, 2018). In this study, only surface runoff was considered, largely because there is limited data for the sites selected. The calculation that follows focuses on surface runoff and evapotranspiration.

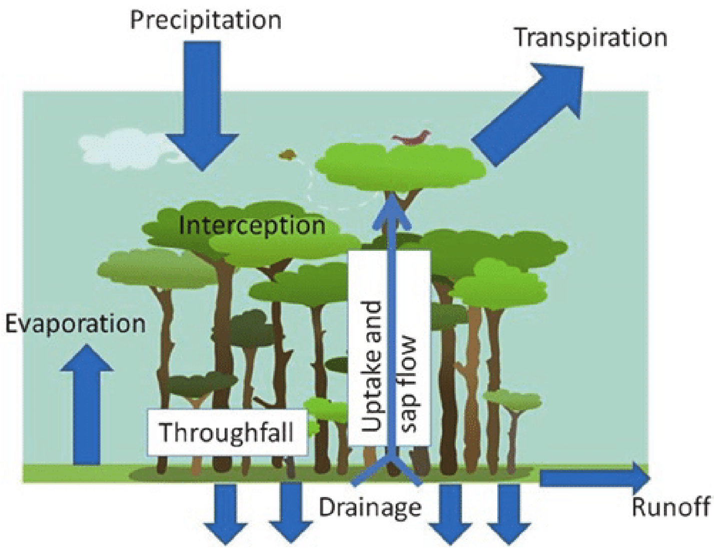

Figure 4. The hydrological cycle in forests and the main components (Centritto *et al.,* 2010).

Calculation of runoff and potential evapotranspiration

Reynolds (2017) mentioned in his study that when there are 0% impervious areas and 100% pervious areas, there will be approximately 10% runoff and 50% infiltration (Reynolds, 2017). Based on the study from Reynolds (2017), evapotranspiration can be calculated by one minus percentage of runoff and minus a percentage of infiltration (Evapotranspiration = 1 - % runoff - % infiltration). Therefore, if the area has 0% impervious surfaces, it will have approximately 10% runoff, 50% infiltration, and 40% potential evapotranspiration (Reynolds, 2017). Aa s framework, water balance equation $P = R + ET + \Delta S$ (P is precipitation, R is streamflow, ET is evapotranspiration, ΔS is the change in storage (in soil or the bedrock/groundwater) (Zhang et al., 1999). As no direct measurements or data are readily available a number of assumptions were made. These assumptions are reasonable in this study, as in a comparative study factors of the water balance equation may be assumed to be constant within the same geographical region. The first assumption is the R and ΔS are seemed as constant, as is P within Metro Vancouver. The one factor, which is dependent on impervious vs pervious surface. In this comparative study, impervious surfaces were; roads, trails, sidewalks (E) and rooftops and pervious surfaces were the areas that were vegetated. The second assumption is all of the pervious areas have 0% surface runoff because all of the precipitation infiltrates into soil except those that are evapotranspired. As there is no data in the region where rainfall intensity exceeds soil infiltration rates of vegetative surfaces it was also assumed that these surfaces lost water to evapotranspiration. And all of the impervious areas have 100% surface runoff because water cannot infiltrate into impervious surfaces. The calculation of evapotranspiration is based on the study of Moore, Bond and Jones (2011), and the evapotranspiration of impervious areas is based on the study of Herrera Environmental Consultants, Inc. (2008).

By definition, the percentage of pervious areas is equal to the number of pervious areas divide by the amount of total area and multiplied by 100% (% pervious areas = (amount of pervious areas/amount of total areas) * 100%. The percentage of impervious areas is equal to the number of impervious areas divide by the amount of total area and multiplied 100% (% impervious areas = (amount of impervious areas/amount of total areas) * 100%. The percentage of runoff is equal to the percentage of impervious areas. In the study of Moore, Bond and Jones (2011), the average annual evapotranspiration in old-growth mixed forests is 101.5mm per year, the average annual evapotranspiration in second-growth mixed forests is 86.5mm per year, the average annual evapotranspiration in evergreen forests is 101.5mm per year, and the average annual evapotranspiration in deciduous forests is 104mm per year. The potential evapotranspiration of impervious surfaces is 5%, and the potential evapotranspiration of the same amount of second-growth forests is 15% (Herrera Environmental Consultants, Inc., 2008). Therefore, the potential evapotranspiration of pervious surface with second-growth forest cover is 3 times higher than the impervious surface. The total water volume of surface runoff may be calculated by summing the areas of impervious areas and multiplying the precipitation. The precipitation is 2351mm per year in PSRP and Vancouver.

Non-disturbed areas (old-growth forests) in PSRP

PSRP is a natural forest, which contains old-growth forests, dominated by Douglas-fir, western hemlock and western red cedar (Soilx, n.d.). According to Table 1 and Figure 5 (GVRD Parks, 1991), the association 8-13 and 15-18 are old-growth forests, which means these areas are natural without disturbances. The impervious areas are 0% and pervious areas are 100%. Therefore, the runoff is 0% in non-disturbance areas in PSRP. An edited table (Table 2) from Table 1 of GVRD Parks (1991) shows the tree types in each association. In terms of old-growth forests which are association 8-13 and 15-18, the total area of old-growth forests is 361.6 hectares, in other words, the area is about 48.2% (361.6 / 750 * 100% = 48.2%) in PSRP (Table 1). There are ten associations in total, and seven associations are evergreen forests and three associations are old-growth mixed forests (Table 2). The potential evapotranspiration in evergreen forests is 101.5 * (7/10) = 71.05mm per year. The potential evapotranspiration in old-growth mixed forests is 101.5 * (3/10) = 30.45mm per year. Therefore, the total potential evapotranspiration in non-disturbance old-growth forests in PSRP is 71.05 + 30.45 = 101.5mm per year, which is about 101.5mm / 2351mm * 100% = 4.3%. The total water volume of runoff is 0 * 750 hectares * 2351mm = 0 m^3/hectare.

Table 1 The association and related tree types and area in PSRP (GVRD Parks, 1991).

Association	Title	Area (ha)	Percent
1	Hardhack - Salmonberry - Fireweed	30.9	4.3
2	Red Alder - Salmonberry	74.6	10.2
3	Bitter Cherry - Willow - Trailing Blackberry	20.9	2.9
4	Bigleaf Maple - Spiny Wood Fern	27.7	3.8
5	Cascara - Mountain Ash - Deer Fern	4.6	0.6
6	Vine Maple - Red Elderberry	97.5	13.4
7	Red Alder - Western Red Cedar - Red Huckleberry	109.7	15.0
8	Douglas-fir - Bracken - *Stokesiella oregana**	5.9	0.8
9	Douglas-fir - Salal - *Plagiothecium undulatum*	135.9	18.6
10	Western hemlock - *Mnium glabrescens*	62.1	8.5
11	Western Red Cedar - English Holly	46.6	6.4
12	Western hemlock - Douglas-fir - *Stokesiella praelonga*	23.4	3.2
13	Western Red Cedar - Western hemlock - Sitka Spruce	68.4	9.4
14	Pacific Crabapple - Hardhack - False Lily-of-the-Valley - Skunk Cabbage	1.0	0.1
15	Shore Pine - White Birch - Western hemlock - Salal	0.9	0.1
16	Western hemlock - Salmonberry	6.4	0.9
17	Western hemlock - Red Huckleberry - *Plagiothecium undulatum*	11.2	1.5
18	Western hemlock - Salal - Labrador Tea	0.8	0.1
19	Pond Association	0.9	0.1
20	Salal - Labrador Tea - Bracken - False Lily-of-the-Valley	0.2	0.03
		729.6	100.0

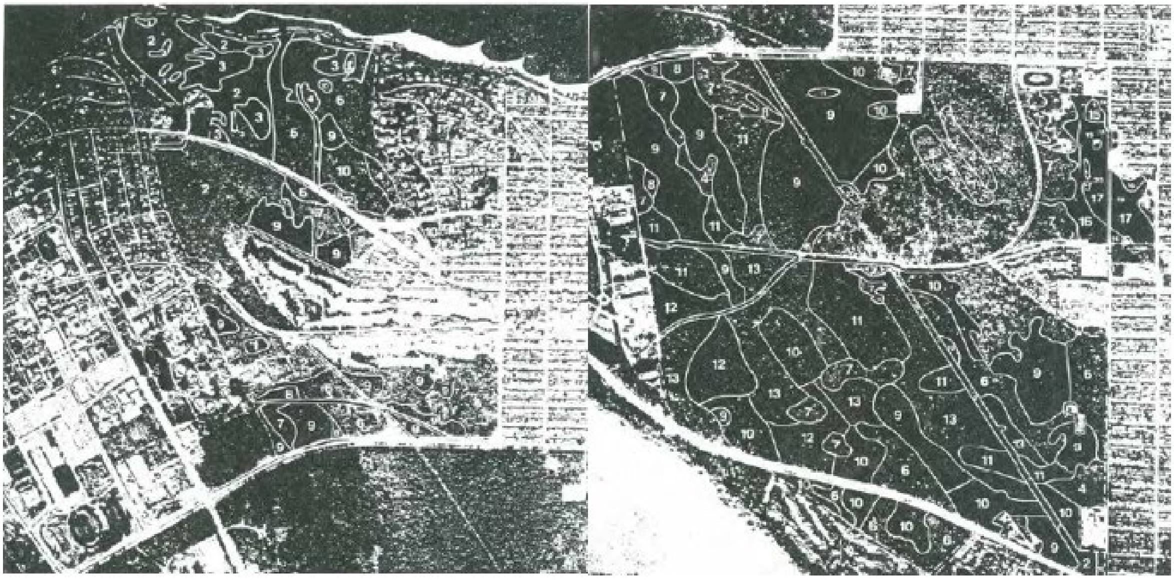

Figure 5. The two maps show the different associations in PSRP. The left map shows the north PSRP. The right map shows the south PSRP. (GVRD Parks, 1991)

Table 2 The different tree types and percentage of area in different associations (Edit from GVRD Parks, 1991, Table 1)

Association	Name of Tree	Tree type	Tree type in an association	Percentage of area
1	Hardhack	Deciduous	Mixed (include both deciduous and evergreen)	4.3%
	Salmonberry	Deciduous & Evergreen		
	Firewood	Evergreen		

2	Red Alder	Deciduous	Mixed	10.2%
	Salmonberry	Deciduous & Evergreen		
3	Bitter Cherry	Deciduous	Deciduous	2.9%
	Willow	Deciduous		
	Trailing Blackberry	Deciduous		
4	Bigleaf Maple	Deciduous	Deciduous	3.8%
5	Cascara	Deciduous	Deciduous	0.6%
	Mountain Ash	Deciduous		
6	Vine Maple	Deciduous	Deciduous	13.4%
	Red Elderberry	Deciduous		
7	Red Alder	Deciduous	Mixed	15.0%
	Western Red Cedar	Evergreen		
	Red Huckleberry	Deciduous		
8	Douglas-fir	Evergreen	Evergreen	0.8%
9	Douglas-fir	Evergreen	Evergreen	18.6%
	Salal	Evergreen		
10	Western hemlock	Evergreen	Evergreen	8.5%
11	Western Red Cedar	Evergreen	Evergreen	6.4%
	English Holly	Evergreen		
12	Western hemlock	Evergreen	Evergreen	3.2%
	Douglas-fir	Evergreen		
13	Western Red Cedar	Evergreen	Evergreen	9.4%
	Western hemlock	Evergreen		
	Sitka Spruce	Evergreen		
14	Pacific Crabapple	Deciduous	Deciduous	0.1%
	Hardhack	Deciduous		
15	Shore Pine	Evergreen	Mixed	0.1%
	White Birch	Deciduous		
	Western hemlock	Evergreen		
	Salal	Evergreen		
16	Western hemlock	Evergreen	Mixed	0.9%
	Salmonberry	Deciduous & Evergreen		

17	Western hemlock	Evergreen	Mixed	1.5%
	Red Huckleberry	Deciduous		
18	Western hemlock	Evergreen	Evergreen	0.1%
	Salal	Evergreen		
	Labrador tea	Evergreen		
19	Pond Association	-	-	-
20	Salal	Evergreen	Evergreen	0.03%
	Labrador tea	Evergreen		

Disturbed areas (trails and second-growth forests) in PSRP

However, PSRP is not all covered by non-disturbance forests. It also has disturbance areas like trails and second-growth forests. Thus, the hydrological cycle in PSRP will be affected by trails. There is over 50km of trails in the park for different usages like walkers, runners and bicyclists (Pacific Spirit Park Society, n.d.). Trails that are created by removing trees will have compacted surfaces with lower permeability than forest surfaces (Winkler *et al.,* n.d.), which results in lower infiltration and higher surface runoff. PSRP is scenic and includes a range of vegetation, which attracts many park visitors such as environmentalists, dog walkers, cyclists and so on, so trails are heavily explored and used by park visitors (Super *et al.,* 2013). In addition, the park is near the campus of UBC, so it attracts numerous students to the park for courses and research purpose, which further increase the pressure and compaction on the trails and affect the infiltration of trails (Super *et al.,* 2013). The length of trails in PSRP is approximately 50 km. The average width of trails is estimated as 2.5 m. The estimated areas of trails are equal to the length of trails multiply the average width of trails, which is 50 km * 2.5 m = 125,000 m^2 = 12.5 hectares.

In addition, there is disturbance from unauthorized, off-trail use (Super *et al.,* 2013). The unauthorized use includes mountain bike use is more frequent along trails, which will result in negative effects (Super *et al.,* 2013). Not only unauthorized use but also increasing park visitors will lead to negative effects on the vegetation near and even farther away from trails (Super *et al.,* 2013). Therefore, this is also called trail disturbance (Super *et al.,* 2013). However, the trail disturbance on vegetation will be different depending on the place and intensity of usage, so there is a conservative estimate that approximately 3m off-trail vegetation will be affected (Super *et al.,* 2013). The estimated areas of affected off-trail vegetation are equal to the length of trails multiply the estimated width of off-trail vegetation, which is 50 km * 3 m = 150,000m2 = 15 hectares. Therefore, the areas of trails and affected off-trail vegetation, in other words, the areas of impervious areas in PSRP are equal to 12.5 hectares plus 15 hectares, which are 27.5 hectares.

The hydrological cycle is also affected by disturbed areas which are second-growth forests now. The disturbance includes two ways, one is natural disturbance and the other is human disturbance. Natural disturbance includes wildfire, flooding, large-scale disease outbreaks, and major windstorms (Hewitt, 2020). Wildfire will burn the forests and the large windstorms will blow the tree down, which will disturb the forests areas. Human disturbance includes harvesting forests for wood production or other land uses. The other associations, except 8-13 and 15-18 are the disturbed areas in PSRP (Table 1 & Figure 3). The total area of second-growth forests in PSRP is 368 hectares, which is about 49% based on Table 1.

The percentage of areas of trails and off-trails is (27.5 hectares / 750 hectares) * 100% = 3.7%. The percentage of disturbed areas is 49%. Therefore, the total percentage of impervious areas is 3.7%, and pervious areas are 49%. The percentage of runoff is 3.7%. There are nine associations in total, and one association is evergreen forests, three associations are second-growth mixed forests and five associations are deciduous forests (Table 2). Therefore, the potential evapotranspiration in evergreen forests is 101.5 * (1/9) = 11.28mm per year. The potential evapotranspiration in old-growth mixed forests is 86.5 * (3/9) = 28.83mm per year. The potential evapotranspiration in deciduous forests is 104 * (5/9) = 57.78mm per year Therefore, the total potential evapotranspiration in second-growth forests in PSRP is 11.28 + 28.83 + 57.78 = 97.89mm per year. The areas of trails and off-trail are 13 times (49% / 3.7% = 13) smaller than the areas of second-growth forests. Because the potential evapotranspiration of pervious surface with second-growth forest cover is 3 times higher than the impervious surface, the potential evapotranspiration for the impervious areas of trails and off-trail is equal to 97.89mm / 3 / 13 = 2.51mm per year. Therefore, the total potential evapotranspiration in disturbed areas is 97.89mm + 3.63mm = 101.52mm per year, which is about 101.52mm / 2351mm = 4.3%. The total water volume of runoff is 3.7% * 750 hectares * 2351mm = 6.5e+5 m^3/hectare.

Urban residential areas in Vancouver

For the urban residential areas in Vancouver, assume there are no trees along the roads. The imperious areas include roads and buildings, and the pervious areas include large urban parks. The area of Vancouver is 11,500 hectares. The total area of large urban parks in Vancouver is 631.12 hectares (Table 3). The percentage of pervious areas is (631.12 hectares / 11,500 hectares) * 100% = 5.5%. The areas of impervious areas, including roads and buildings, are 11,500 – 631.12 = 10,868.88 hectares. The percentage of impervious areas is 1 – 5.5% = 94.5%. Therefore, the percentage of runoff in Vancouver is 94.5%. Assumed that the parks in Vancouver are covered by second-growth mixed forests. The second-growth mixed forests take up 5.5% of areas in Vancouver, so the potential evapotranspiration is 86.5 * 5.5% = 4.76mm per year. The impervious areas are 17 (94.5% / 5.5% = 17) times larger than the areas of second-growth forests, so the potential evapotranspiration in impervious areas is equal to 4.76mm / 3 * 17 = 27mm per year. Therefore, the total potential evapotranspiration in Vancouver is 4.76mm + 27mm = 31.76mm per year, which is about 31.76mm / 2351mm = 1.4%. The total water volume is 94.5% * 11,500 hectares * 2351mm = 2.6e+8 m^3/hectare.

Table 3 The main large urban parks in Vancouver and their areas (City of Vancouver)

Parks	Areas (hectares)
Stanley Park	404.9
Queen Elizabeth Park	52
Killarney Park	13.36
John Hendry Park	27
Jericho Beach Park	46.71
Vancouver Botanical Garden	22
Charles, Rupert and Thunderbird Parks	13.82
Captain Cook, Champlain Heights and Everett Crowley Parks	51.33

Total areas	631.12

Effects of tree types

Except for urbanization and land-use effects, climate and tree species will also affect the hydrological cycle. Deciduous trees are trees that will lose their leaves at the end of their growing season (BD Editors, 2019). The falling leaves from deciduous trees will occur in the fall in temperate forests, while in dry seasons in tropical and subtropical forests (BD Editors, 2019). Evergreen trees are trees that will not lose their leaves during any season of the year (BD Editors, 2019). PSRP contains both evergreen trees and deciduous trees. The deciduous trees will not have their leaves during fall and winter, so the water will directly hit the soil surface without canopy interception when there is precipitation. In addition, the precipitation is less in summer, while it is abundant in fall and winter in Vancouver. Different tree types have different abilities of precipitation interception in different seasons. Evergreen trees can intercept 46.6% precipitation in winter and 64.5% precipitation in summer, while deciduous trees can intercept 25.1% precipitation in winter and 42.4% in summer (Reynolds, 2017).

Based on the association and trees' species (Table 2), the data shows that the area of deciduous forests is about 20.8%, the area of evergreen forests is 47.03%, and the area of mixed forests is 32% in PSRP (Table 4). The precipitation interception of deciduous forests is 20.8% * 25.1% = 5.2% in winter, and is 20.8% * 42.4% = 8.8% in summer in PSRP. The precipitation interception of evergreen forests is 47.03% * 46.6% = 21.9% in winter, and is 47.03% * 64.5% = 30.3% in summer in PSRP. It is assumed that the amount of deciduous forests and evergreen forests is equal in mixed forests, so the area of deciduous forests and evergreen forests is 32% / 2 = 16% for each. Within mixed forests in PSRP, the precipitation interception of deciduous forests is 16% * 25.1% = 4% in winter, and is 16% * 42.4% = 6.8% in summer. The precipitation interception of evergreen forests is 16% * 46.6% = 7.5% in winter, and is 16% * 64.5% = 10.32% in summer. Therefore, the total precipitation interception of deciduous forests is 5.2% + 4% = 9.2% in winter, and is 8.8% + 6.8% = 15.6% in summer. The total precipitation interception of evergreen forests is 21.9% + 7.5% = 29.4% in winter, and is 30.3% + 10.32%

= 40.62% in summer.

Table 4 The percentage of the total area of deciduous, evergreen and mixed forests in PSRP is based on table 2.

Tree type	Total area (%)
Deciduous	20.8
Evergreen	47.03
Mixed	32

Discussion

Framework

The framework shows the process of the project (Figure 6). It starts from the objective of the project, which is analyzing the effects of current forests on the hydrological cycle. The hydrological cycle is evaluated by two factors: runoff and potential evapotranspiration. The comparison among non-disturbance areas in PSRP, disturbed areas in PSRP and urban residential areas in Vancouver in terms of runoff and potential evapotranspiration to see the effects on the hydrological cycle based on different circumstances. In addition, provided the analysis showed how different tree types and different seasons affect the hydrological cycle in terms of precipitation interception. Finally, the results concluded a framework to conduct on the comparison.

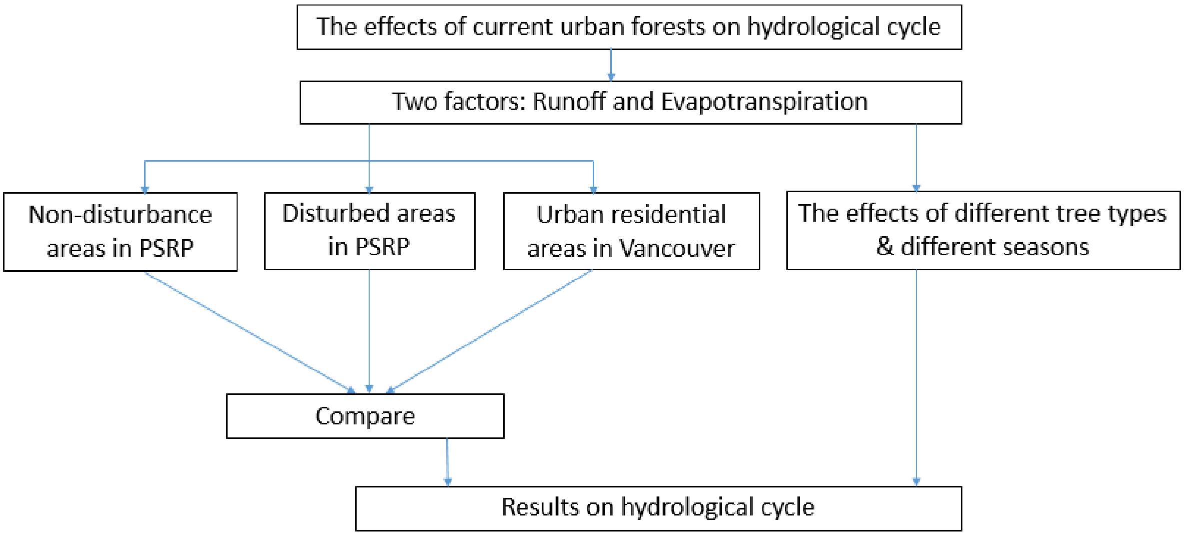

Figure 6. The general framework of the project's processes.

Hydrological cycle in PSRP

The data provided an analysis of the precipitation, evapotranspiration, area and total runoff in non-disturbed areas, disturbed areas and urban Vancouver (Table 5). The precipitation was assumed constant within the area. The evapotranspiration was calculated based on the different kinds of trees. The total runoff was calculated by the area of impervious areas multiplied by precipitation. PSRP is a natural-growth forest, so it has a large amount of old-growth forests, in other words, non-disturbance and native areas originally, which is about 361.6 hectares (Table 5). However, with development, some areas were harvested, so the area of second-growth forests is about 368 hectares (Table 5). In addition, the trails were built for human uses and with off-trail damages, which accounted for about 27.5 hectares (Table 5). In PSRP, the areas of trails and off-trail damage have the lowest evapotranspiration which is 2.51 mm per year and the highest runoff which is 6.5e+5 m^3 per hectare compared to the areas of old-growth forests and second-growth forests (Table 5). This is because trails without tree cover allow the rainfall to directly hit the surface without canopy interception and evapotranspiration. Also, the trails are impervious, so the rainfall cannot infiltrate, all precipitation becomes surface runoff. Although both old-growth forests and second-growth forests are covered by trees and pervious with no runoff, the evapotranspiration is different. The evapotranspiration of old-growth forests at 101.5 mm per year is higher than second-growth forests which is 97.89 mm per year, even the areas of old-growth forests are lower than second-growth forests (Table 5). Therefore, the non-disturbance areas covered by old-growth forests in PSRP have a very good effect on the hydrological cycle with no runoff and the highest evapotranspiration. However, natural disturbances like wildfires, windstorms will transfer areas to second-growth forests. Although there is no runoff, the evapotranspiration will be lower. Human disturbance, like harvesting and trail construction, will also contribute to the disturbances in forests in PSRP. Because of the disturbance, large surface runoff occurs, and evapotranspiration decreases a lot.

Hydrological cycle in Vancouver

In terms of an adjacent urban city in Vancouver, the evapotranspiration of parks is 4.76 mm per year, and 27 mm per year in the impervious areas resulting from roads, buildings and so on (Table 5). The reason that the evapotranspiration of impervious areas is larger than parks is that the area of impervious areas which is 10868.88 hectares is much larger than the area of parks like 631.12 hectares (Table 5). If the area of parks and impervious areas are seemed equal, the parks will have higher evapotranspiration than impervious areas. In addition, the impervious areas lead to a huge amount of surface runoff, which is about 2.6e+8 m^3 per hectare. Vancouver City has very low evapotranspiration but very high surface runoff. Therefore, the evapotranspiration is lower and surface runoff is higher in Vancouver compared to PSRP with disturbances.

For the effects of current urban forests on the hydrological cycle, the urban forest in PSRP contribute low runoff and high potential evapotranspiration. However, with the increase of disturbed areas in PSRP, the runoff increases and potential evapotranspiration decreases. In terms of Vancouver without urban forests, and although Vancouver still has some parks that can help to control the extreme events of the hydrological cycle in Vancouver, the areas of parks are quite small compared to the rest of urban residential areas. Therefore, the contribution of parks in Vancouver city on the hydrological cycle is quite small.

Table 5 Summary of surface runoff from PSRP and adjacent city development (Vancouver).

PSRP	Precipitation (mm/year)	Evapotranspiration (mm/year)	Area (hectares)	Total runoff (m^3/hectare)
Old-growth Forests	2351	101.5	361.6	0
Second-growth forests	2351	97.89	368	0
Trails and off-trail damage	2351	2.51	27.5	6.5e+5
Urban city				
Parks	2351	4.76	631.12	0
Roads, buildings, etc.	2351	27	10,868.88	2.6e+8

The effects on hydrological cycle from different tree types

Not only land-use effects, but tree types and climate also affect the hydrological cycle. The data shows that the precipitation interception of deciduous forests is lower than evergreen forests both in winter and summer (Table 6). The canopy precipitation interception is related to leaf area indices (LAI) which is the ratio of leaf surface area to crown projection area (Xiao *et al.*, 1998). The evergreen trees commonly have higher LAI than deciduous trees (Xiao *et al.*, 1998), so evergreen trees have a higher ability to intercept precipitation than deciduous trees. The data also shows that the precipitation interception of both deciduous and evergreen forests in winter is lower than in summer. One important reason is climate. Vancouver has mild temperature and little precipitation in summer, so trees do not intercept much rainfall. However, the temperature is low and the precipitation is abundant in winter, so there is a huge impact on trees to intercept rainfall and the trees may not able to intercept a large amount of rainfall in winter. Therefore, the precipitation interception is lower in winter than summer for both deciduous and evergreen forests. In addition, the leaves of deciduous trees will fall in autumn and winter, so the rainfall will hit the surface directly. With the influence of abundant rainfall in winter, the precipitation interception of deciduous forests will be even worse in winter. The precipitation interception is related to the hydrological cycle. The more trees can intercept, the lower pressure on soil and lower surface runoff. Evergreen trees have a higher ability to intercept precipitation and decrease surface runoff compared to deciduous trees.

Table 6 The precipitation interception of deciduous forests and evergreen forests in winter and summer respectively.

Tree types	Winter	Summer
Deciduous	5.2%	8.8%
Deciduous in Mixed	4%	6.8%
Total deciduous	9.2%	15.6%
Evergreen	21.9%	30.3%
Evergreen in Mixed	7.5%	10.32%
Total evergreen	29.4%	40.62%

Recommendations

In recent times, increasing urbanization and disturbed areas have had a marked influence on the natural hydrological cycle, so it is necessary to sustain the urban forests to attempt to maintain the hydrological cycle. The followings are some recommendations on how to better sustain urban forest:

- First, it is important to maintain as much as old forests as possible. Because old forests are native forests without disturbances, the areas are pervious areas that have high infiltration rates and decreased runoff. If the areas are harvested or disturbed, and then transferred into second-growth forests, these areas or soils may not be able to maintain infiltration and decrease runoff, in contrast, the hydrological cycle of these areas may be less efficient in terms of natural balance. Therefore, the more old forests are maintained, the better the hydrological cycle will be regulated.
- Second, it is necessary to minimize the amount of trails and roads. The construction of trails and roads will remove trees and convert the pervious areas to impervious areas. The impervious areas will have lower infiltration and increased runoff. With the overuse of trails and roads, the impervious areas will be compacted gradually, which further

lowers the infiltration and increase runoff, and then decrease the ability to the natural hydrological cycle. Therefore, the lower amount of trails and roads that are constructed, the better balance of the hydrological cycle.

- Third, everyone in cities needs to maintain as much green space as possible. The more forests the cities have, the more benefits for a balanced hydrological cycle because the pervious areas of forests can help to increase infiltration and minimize runoff. If urbanization is necessary to achieve by removing forests, it is important to maintain as many parks as possible. The pervious areas of parks can also help to regulate and improve the hydrological cycle in cities. Therefore, cities should maintain as many forests and parks as possible.
- Fourth, for future development, it is useful to plant trees in cities. Planting trees can transfer impervious areas to pervious areas, and then increase infiltration and reduce.

In terms of planting trees, trees' types and trees' distribution are also important for sustaining the hydrological cycle. Studies show that the canopy interception is highest in mixed forests (Kermavnar & Vilhar, 2017). The highest canopy interception of mixed forests will help to decrease runoff by intercepting runoff and then regulating the hydrological cycle. Another study shows that intermediate tree cover has the highest ability for groundwater recharge (Ilstedt *et al.*, 2016), which is helpful to regulate a balanced hydrological cycle. Therefore, both deciduous trees and evergreen trees should be planted with proper tree distribution.

Conclusions

With the increasing urbanization and climate change, urban forests become more important. This project analyzes the effects of current urban forests on the hydrological cycle based on the comparison among PSRP without disturbances, PSRP with disturbances and the urban residential areas in Vancouver, in terms of runoff and potential evapotranspiration. PSRP without disturbances has the lowest runoff and highest potential evapotranspiration. However, with the development, the PSRP was disturbed by constructing trails, harvesting trees and then changing to second-growth forests with higher runoff and lower potential evapotranspiration compared to PSRP without disturbances. For the urban residential areas in Vancouver, a large number of areas have been transferred to imperious areas like buildings and roads. Although there are some parks in Vancouver, the areas of parks are quite small compared to the impervious areas, so the contribution of parks to the hydrological cycle is small. The urban residential areas have the highest runoff and lowest potential evapotranspiration. Therefore, the effects of current urban forests on the hydrological cycle are best in PSRP without disturbances, moderate in PSRP with disturbances and worst in the urban residential areas in Vancouver.

In addition, there are some recommendations on how to better sustain urban forests. It is important to maintain as many as old-forests (non-disturbed areas) as possible, and necessary to minimize the construction of trails and roads to reduce impervious areas. It is essential to maintain as much green space in cities, like forests and parks to increase pervious areas to enhance a more balanced hydrological cycle. It is also important to plant trees in cities to decrease runoff. The tree types and distribution should be noticed. It is better to implement mixed forests with both deciduous trees and evergreen trees with proper tree distribution and tree interval. Urban forests are beneficial, however, urbanization and climate change are continuing, so a better understanding of the hydrological cycle needs everyone's attention.

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