A THEORETICAL STEMFLOW MODEL FOR URBAN TREES

WITH AN EVALUATION OF CURRENT STREET TREE PIT DESIGN AND PRACTICES

By **Anne Day**

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This project would not have been possible without the support of many people. First, I would like to thank my supervisor, Les Lavkulich, for his support and feedback, which pushed me to meet and exceed my own expectations. Special thanks to Dr. Andy Black and Dr. Rachhpal Jassal for their ongoing feedback, their support and generosity in helping me throughout this project. I would also like to extend my thanks to Dr. Carlyle-Moses and Julie Schooling who generously shared their stemflow study data with me.

EXECUTIVE SUMMARY

Cities across the world are dealing with new issues such as stormwater runoff and its management as urbanization leads to urban densification. The use of urban forestry has become widely accepted as a more resilient means to address stormwater management problems in the face of densification and climate change. Trees can help mitigate stormwater runoff by intercepting rainfall and diverting rainwater along the trunk. Most research on tree rainfall partitioning has focused on interception, however because stemflow is a concentrated volume of water that reaches a very limited area on the ground it should be studied further.

In this project I develop a theoretical stemflow model that works to predict the volume of stemflow on an event basis for several common tree species that are used in the Metro Vancouver area as street trees. The model is based on a linear relationship between stemflow volume (L) and precipitation depth (mm) in relation to tree diameter at breast height (DBH) (cm). The model performed well and was able to reasonably predict stemflow volumes based on inputs of DBH and precipitation. Based on two modeling approaches, it was found that modeling stemflow based on grouping all trees together is more accurate in comparison to modeling stemflow based on grouping the trees by genus.

In an application of the model I evaluate current street tree pit specifications to determine whether current practices allow for sufficient stemflow infiltration and storage within the pit. Results indicate that current street tree pit building materials allow for sufficient stemflow infiltration and water storage volumes. However, based on previous studies, street tree pit practices in Metro Vancouver do not provide sufficient below ground volume for root development and this may be limiting tree health and the supply of ecosystem services such as stormwater management. I also investigate the impacts of climate change and found that as tree DBH increases the percent increase in stemflow volume decreases. This may be attributed to several different factors impacting stemflow such as the stemflow initiation threshold (P’’) and changes in the effective surface area of the trunk, which may impact evaporation rates. Further research into the mechanisms behind this phenomenon is required.

I found that stemflow volume can be a significant proportion of incident rainfall and as a concentrated source of water at the base of the trunk should not be ignored when practitioners consider the stormwater management benefits of urban trees. The theoretical stemflow model was developed to be as simple as possible and rely on the least amount of field measurements. As such this model can provide a first pass estimate of stemflow volumes but for more accurate predictions further research and multiple regression analysis involving more predictive parameters such as canopy cover and bark roughness should be included. That is not to say that this model cannot be improved upon as more research and measurements are collected and the model is refined.

List of symbols and abbreviations

c = fraction of canopy cover (dimensionless)
$\bar{E}_{\boldsymbol{c}}$ = mean rate of evaporation from the tree during saturated conditions (mm h^{-1})
ϵ = fraction of evaporation rate from the saturated tree that comes from the trunk (dimensionless)
p_d = drainage portioning coefficient (dimensionless)
P_G = gross rainfall for a single rainfall event (mm)
P_g = gross rainfall required to saturate the canopy (mm)
P'' = threshold rain depth required to initiate stemflow (mm)
q = the number of events where the stemflow initiation threshold has been reached
Q_{SF} = Stemflow flow rate once threshold depth has been satisfied (L mm^{-1})
R = mean rate of rainfall during saturated canopy conditions (mm h^{-1})
S_t = saturation storage of the trunk (mm)

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1 INTRODUCTION

1.1 Context

Urbanisation and the associated increase in land cover conversion from natural and undisturbed landscapes to city is a phenomenon that can be traced back to the Industrial Revolution, when the global population began to grow at an exponential rate and cities across the world began to experience significant amounts of expansion (Korotayev and Grinin, 2006). Now as cities reach sizes too large densification must take place to accommodate the continued increase in urban population. Urbanisation originally resulted in a transformation from natural landscapes to small, dense city centers surrounded by suburban housing areas. This change effectively decreased the amount of pervious surfaces, surfaces that can infiltrate water, covering the land from 100% down to approximately 50-60%. Densification requires more transformation by further developing those less crowded suburban areas with denser infrastructure such as high rises. This change is evident in cities such as Vancouver in British Columbia, Canada, where plans such as the Cambie Corridor Planning Program have been put forth in order to guide development and densification (City of Vancouver, 2017). Unfortunately, changes in land cover from forest to suburbia to dense metropolis result in changes to the ecosystem such as changes to the water cycle. By paving large areas for parking lots and roads and by developing large condo complexes closely spaced together, cities are decreasing the amount of green space and therefore pervious ground surface present in an area. Thus, urbanisation has changed the way water flows through a landscape towards a watershed outlet.

Streets are designed to drain stormwater runoff into catch basins.

Stormwater occurs when the rainfall intensity of a storm is greater than the infiltration rate of the ground cover. In natural areas where the ground is often made of porous soil and covered by vegetation, rainfall generally soaks into the ground and very little overland runoff occurs. In urban areas where the ground has been covered by an impervious surface such as concrete, the water from a storm event cannot infiltrate into the ground and therefore quickly flows over the surface to drains where it is routed towards the nearest water body. In undisturbed natural watersheds streamflow is predominantly driven by a constant influx of baseflow. Baseflow is water that feeds a stream that comes from a groundwater source. In contrast, urban watershed streams become increasingly driven by surface runoff which has a different timing and magnitude compared to baseflow. Urban watersheds that are dominated by surface runoff display patterns of earlier peak flow during rain events and also higher discharge volumes (Figure 1). At the end of the event, flow decreases more quickly and to a lower volume in comparison to watersheds driven by baseflow inputs.

There are many issues associated with changes in the water cycle that come from creating large areas of impervious surface. Changes in peak flows and increases in overland runoff have important impacts on stream ecology as streams experience greater variation in flow and temperatures (Poff et al., 1997). In addition, changes to urban hydrology increase the frequency of flooding (Schooling, 2015). Because water runs over many surfaces in the city where pollutants may be introduced, this may also cause water quality issues. These issues may impact aquatic life further downstream, but can also lead to higher costs for people dwelling in cities, especially when stormwater runoff requires water treatment.

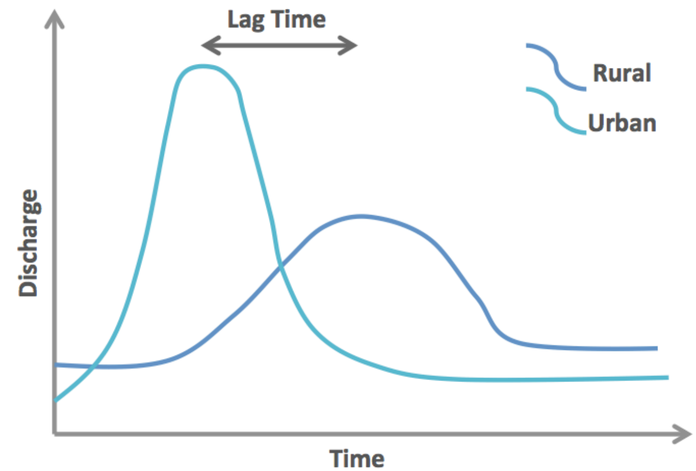

Figure 1. Typical hydrograph for urban and rural runoff.
This example hydrograph demonstrates how streamflow volume discharged throughout a rain event changes with time. The peak flow occurs at the time when there is the highest amount of discharge volume. The lag time is the time difference between the largest amount of rainfall and the largest amount of discharge. The recession limb is the part of the curve where the discharge decreases after the peak flow. The curves show the comparison between typical streamflow discharge from a rural watershed and an urban watershed. The total discharge from the urban area is higher, and the peak flow is significantly higher. The peak flow also has a shorter lag time compared to natural conditions. However, the baseflow in rural areas is higher than the baseflow in urban areas.

1.1.1 Green Infrastructure and Trees

Many scholars have recognized that trees and the urban forest, defined as trees and vegetation that are present in an urban landscape, can help to mitigate the negative impacts associated with stormwater runoff that is a product of urbanisation and densification (Girling and Kellett, 2005; McPherson et al. 2005; Soares et al., 2011; Livesley et al. 2014; Xiao and McPherson, 2015). Not only can trees mitigate stormwater issues, but they also offer many other benefits such as urban heat island mitigation (Kleerekoper et al., 2012), carbon sequestration, and air quality control (McPherson et al., 2016), not to mention the social benefits derived from the urban forest (Maller et al., 2006).

Trees and plants have been widely recognized as a useful tool in urban stormwater management. Trees reduce stormwater runoff by delaying rainfall through interception and evaporation, funnelling water through preferential pathways along the stem and roots, and by evapotranspirating some of the water that reaches the ground back into the atmosphere. The results of these mechanisms taking place at the tree scale results in a reduction in the likelihood of flooding and a decrease in the speed and volume of water that may wash pollutants into nearby water bodies.

Although trees can provide countless benefits such as contributing to soil moisture and groundwater recharge (Návar, 1993; Tanaka et al., 1996), trees and the stemflow (SF) they produce may lead to issues in areas where soil instability, pavement, or compaction can lead to localized runoff, which can exacerbate water quality and quantity issues. Therefore, the trade-offs between tree benefits and costs require further research and a better understanding of certain processes such as SF in urban areas is needed in order to improve urban planning and management.

1.1.2 Stemflow

Rainfall falling on a tree canopy is partitioned three ways: (1) into interception loss, which is the portion of rainfall that does not reach the ground but is directly evaporated from the leaf and wood surfaces of the tree; (2) throughfall (TF), which is the portion of rainfall that reaches the ground directly by falling through gaps in the canopy or by dripping from the canopy; and (3) stemflow (SF), which is the portion of rainfall that is intercepted by the tree canopy and subsequently funnelled to the base of the tree along branches and the stem (Helvey & Patric, 1965; Valente et al., 1997, Schooling, 2015) (Figure 2).

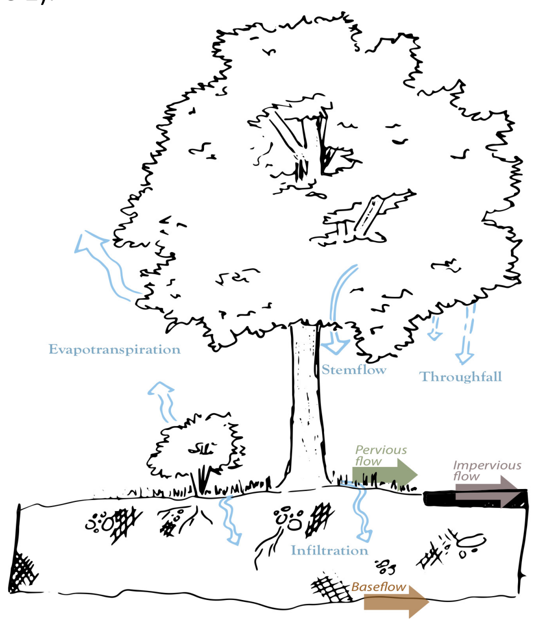

Figure 2. Green infrastructure stormwater management
Urban vegetation intercepts rainfall with the foliage and branches. Some of it will then be released to the ground through SF and TF but over an extended period of time, which allows for more infiltration. Evapotranspiration will also take place and reduce the volume of runoff. Image from LeFrançois (2012).

Historically SF has received far less global research attention in comparison to throughfall and interception due to its relatively small proportion at the stand scale (Levia & Forest, 2003). Throughfall in broadleaf forests has been found to average around 70-80% of incident rainfall in comparison to stemflow which averages around 3-10% of incident rainfall (Llorens & Domingo, 2007; Van Stan et al., 2011). Recently, more studies have focused on SF in urban environments (Xiao & McPherson, 2011; Livelsey et al., 2014), singletree processes (David et al., 2006; Guervara-Escobar et al., 2007; Levia et al., 2015), meteorological effects (e.g. Van Stan et al., 2014; Schooling, 2015), and seasonal influences (Levia, 2004; Staelens et al., 2008).

These recent studies focusing on SF demonstrate that there is a growing recognition of the importance of SF not only hydrologically, but also biogeochemically and ecologically. In comparison to TF, which reaches the ground as a dispersed source of water, SF is funnelled to a small area at the base of the tree and this leads to a concentration of water, nutrients, and possibly pollutants. The significance of this concentrated input results in a relatively volumetrically minor amount of water having a disproportionate impact on the hydrological cycle at the interface between tree trunk and ground (Levia & Forest, 2003; Staelens et al., 2007; Germer et al., 2010; Levia et al., 2010). The implications of this concentrated flux of water are compounded in urban areas where the landscape is often covered by impervious surfaces or compacted soils (Xiao & McPherson, 2011). Therefore, a small amount of SF can strongly impact the spatial distribution of rainfall in the understory of a tree. The hydraulic implications of concentrated SF have received very little attention. As one exception, Herwitz (1986) studied SF in relation to soil hydraulic properties and calculated the overland flow at the base of trees.

There are numerous biotic and abiotic factors that influence stemflow volume. Biotic factors, such as tree morphology, include tree density, canopy structure, species composition, and the phenophase (for deciduous trees) (Herwitz, 1987; Návar, 1993, Staelens et al., 2008, Schooling, 2015). Biotic factors, such as meteorological factors and seasonal effects, may affect stemflow volume. These include rainfall volume, intensity, wind speed, and evaporation rates (Tang, 1996; Crockford and Richardson, 2000; Kuraji et al., 2001, Schooling, 2015). In addition, there are many factors that influence the storage capacity of a tree and therefore its threshold before stemflow initiation value (P’’). These factors may include species-specific characteristics such as bark roughness, size, texture, and the arrangement of leaves (Herwitz, 1985; Levia and Frost, 2003; Levia and Herwitz, 2005, Schooling, 2015). The stemflow threshold initiation value also depends upon the antecedent moisture of the tree (Crockford and Richardson, 1990; Pypker et al., 2006a, b).

Stemflow is an interesting component of rainfall partitioning because it is a concentrated amount of water that is being funnelled along the stem from the canopy towards the ground. This component may not be as important in a forest environment, but in an urban environment it may require consideration. For example, if the materials used in tree pit construction are too fine, dense, or compacted then the intensity of stemflow may be greater than the infiltration capacity and thus result in surface runoff, which could easily be avoided by planting with a more appropriate material and reducing the amount of compaction during construction. Likewise, once the stemflow has been infiltrated, a tree pit has the capacity to store water for tree use that also reduces the amount of stormwater runoff. In addition, not only do tree pits have the capacity to store stormwater but these pits may also hinder tree health and performance if they are too small and limiting tree root growth.

Although trees can help mitigate issues around stormwater management, the current standards and practices for urban forestry may not be specific enough and trees may be currently limited in how they provide stormwater mitigating ecosystem services. Evaluating current practices and making recommendations for improved urban forestry requires predicting the performance of trees to intercept and funnel water through stemflow. Huang et al. (2017) previously developed and calibrated an analytical model for predicting urban tree interception for the Metro Vancouver area. They did not address SF generation in their study, citing that less than 5% of incident rainfall is partitioned into stemflow. However, their model was calibrated using evergreen trees, which generally produce less stemflow compared to deciduous trees. Because most street trees in Vancouver are deciduous, it is important to investigate and further research this component of rainfall partitioning.

1.2 Climate Change Considerations

Not only has human activity changed the landscape, but human growth and development has also changed the atmosphere, which has led to global climate change. The Pacific Climate Impacts Consortium (PCIC) have predicted that climate change in the Pacific Northwest will result in increased temperatures throughout the year and more variable changes to precipitation that nevertheless will result in more frequent large storm events (2011). Changes in the frequency and magnitude of precipitation events as a result of climate change will have impacts on stormwater management and trees have the potential to aid in efforts to help evolve stormwater management as the climate changes. Many scholars have argued that building resilient cities will require the adoption of more green urban infrastructure, which many believe provides a level of resilience that cannot be achieved using grey infrastructure (Demuzere et al., 2014; Foster et al., 2011; Newman et al., 2009; Kazmierczah and Carter, 2010).

1.3 Project Objectives

The objectives of this study are to

(1) Develop a theoretical stemflow model for several common tree species used as street trees in the Metro Vancouver area.

(2) Evaluate current tree pit building standards in Metro Vancouver to establish whether these standards are sufficient to provide conditions that allow for stemflow infiltration and storage while providing enough volume to promote healthy tree growth.

(3) Predict how modeled changes in climate for Metro Vancouver will change stemflow volumes and whether current tree pit standards are sufficient to provide conditions that allow for changes in stemflow volumes.

2 METHODS

In this section I explain my process of developing and validating a stemflow model. I also explain my process of evaluating current street tree pit specifications for infiltrating stemflow at the ground and storing the water for later evapotranspiration.

2.1 Model Theory

By definition stemflow is the part of rain that falls on the vegetation and subsequently is funnelled to the base of the trunk. There currently already exists an empirical equation (see Equation 1) developed by Valente et al. (1997) for calculating the amount of stemflow for an individual tree on an event basis. However, the use of this equation requires that the user go into the field and make several measurements or else use default values based on previous research. The parameters that require measurement (or derivation) include the drainage partitioning coefficient (p_d), the fraction of canopy cover (c), the fraction of evaporation rate from the saturated tree that comes from the trunk (ϵ), the mean rate of evaporation from the tree duration saturated conditions (E_c), the mean rate of rainfall during saturated canopy conditions (R), the gross rainfall required to saturate the canopy (P_g), and the gross rainfall required to saturate the trunk (P_g'), and the saturation storage of the trunk (S_t). The coefficient q is the number of storms that saturate the trunk, where the gross amount of rainfall (P_G) is greater than the amount of rainfall required to saturate the trunk ($P_G > P_g'$).

$$SF = p_d c\left[1 - \frac{(1-\epsilon)E_c}{R}\right]\sum_{j=1}^{q}\left(P_{g,j} - P_g'\right) - qS_t \quad (1)$$

Because this model takes into account several factors that impact SF, theoretically it should be more rigorous and accurate. However, this empirical equation must be supported by a large amount of data collection. The calibre of data required to use this equation requires large amounts of time and money. To simplify the SF prediction process and provide an initial estimate of typical SF values for the Metro Vancouver region a theoretical stemflow model was developed. This model allows for an initial SF prediction while reducing the amount of measurements that must be taken in the field.

Although stemflow is affected by all of the above factors mentioned in Section 1.1.2, this project explores the possibility of estimating stemflow volumes based on one tree characteristic – diameter at breast height (DBH) - to explore whether stemflow can be reasonably and accurately modelled without requiring extensive field measurements. There are many studies that have related precipitation depth and stemflow volume to tree DBH (e.g., Brown and Barker 1970; Brinson et al. 1980; Hanchi and Rapp 1997; Manfroi et al. 2004). These and other studies have demonstrated that DBH can be a strong predictor of SF production (Deguchi et al., 2006; André et al., 2008; Šraj et al., 2008; Germer et al., 2010; Van Stan and Levia, 2010). For example Germer et al. (2010) found that DBH in two tropical tree species is positively related to SF volume. In a study of Japanese deciduous trees Park and Hattori (2002) found that greater basal area, BA, which is directly related to DBH, was linked to higher SF volume yields. In addition, Schooling (2015) found that DBH was significantly correlated with canopy width, tree height, projected canopy area (PCA), canopy volume, wood cover, and bark relief index. These other tree characteristics may impact SF yield and by using DBH as the key parameter, we can approximate other characteristics of the tree.

2.2 Theoretical Stemflow Model

When rainfall begins, before stemflow can occur the canopy and trunk must become saturated. Water that falls on the canopy can be temporarily stored on the canopy and may evaporate into the atmosphere. Once the storage capacity of the canopy and trunk is reached, stemflow will be initiated. Park and Hattori (2002) have suggested that the slope, *a*, and the intercept, *b*, associated with the linear relationship between stemflow depth (mm) and rainfall depth (mm) [i.e. SF = *a* x Rainfall + *b*] for a single tree or an entire stand may be related to the tree/stand DBH in the form of power relationships:

$$a = A \times D_{BH}^{\beta 1} \quad (2)$$

$$b = B \times D_{BH}^{\beta 2} \quad (3)$$

Where A, B, β_1, and β_2 are regression coefficients, and D_{BH} represents the diameter at breast height.

Linear regression equations (Figure 3) were developed between stemflow volume (L) and rainfall depth (mm) for individual trees where data for all valid events during which rain depths equal to or greater than the first event that yielded SF (even if some events with greater precipitation depths produced no SF) were plotted. This data was obtained from Schooling (2015). Although Schooling previously measured SF for over 30 trees, the relationship between P and SF was plotted for a selected 11 trees from the dataset that were representative of common street trees used in Metro Vancouver: *Quercus palustris* (Pin Oak), *Quercus rubra* (Red Oak), *Acer platanoides* (Norway Maple), *Acer platanoides 'Crimson King'* (Crimson King Maple), and *Fraxinus pennsylvanica* (Green Ash). Linear relationships between tree SF volume and rainfall depth have been previously reported in several studies for various species (Reynolds and Henderson, 1967). Other studies have utilized semi-logarithmic and power functions (White and Carlisle, 1968). However for this project, based on a visual inspection of the data, a simple linear regression was used.

The slope of the linear regression (*a* in Equation 2) represents the amount of stemflow generated from each millimeter of rain; this is the stemflow rate, Q_{SF} (L mm^{-1}). The intersection of the regression line with the x-axis (*b* in Equation 3) corresponds to the minimum amount of rainfall depth required for stemflow initiation at the place where DBH is measured, this is the stemflow initiation threshold, P'' (mm). The derived Q_{SF} and P'' values were then plotted against the DBH of the individual trees sampled for stemflow. Q_{SF} versus DBH and P'' versus DBH were first plotted by grouping trees by genus. However, it was found that the most accurate results were obtained when these two parameters were plotted with all the trees grouped together. According to Park and Hattori (2002) the relationship between Q_{SF} and DBH and P'' and DBH should produce power relationships (see Equation 2 and 3). For this project it was found that the relationship between Q_{SF} and DBH and P'' and DBH produced a weak linear relationship (Figure 4 and Figure 5).

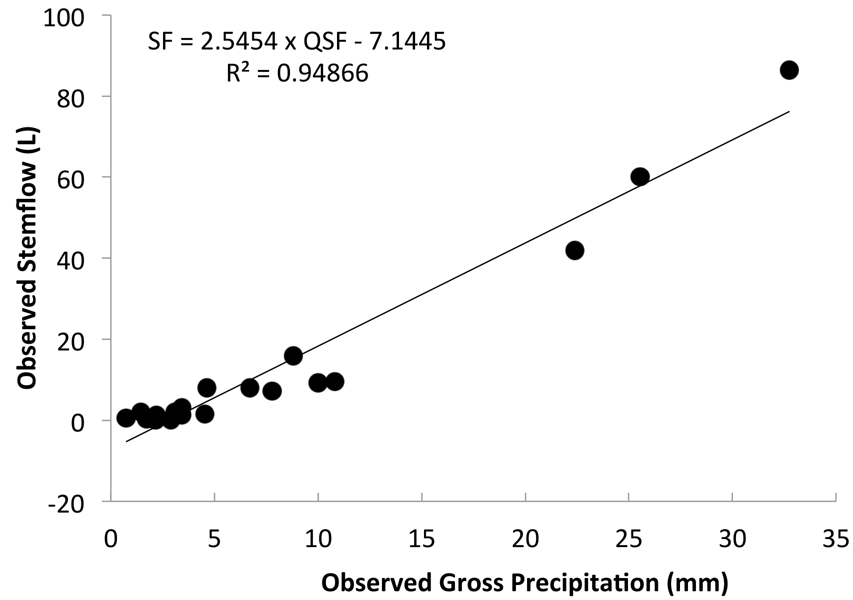

Figure 3. Observed stemflow volume (SF, L) versus observed gross precipitation (GP, mm).
Example plot of observed stemflow volume versus observed gross precipitation data to determine the stemflow initiation threshold (mm) and the stemflow rate (L mm^{-1}). The data shown is the stemflow of a single Green Ash tree obtained by Schooling (2015).

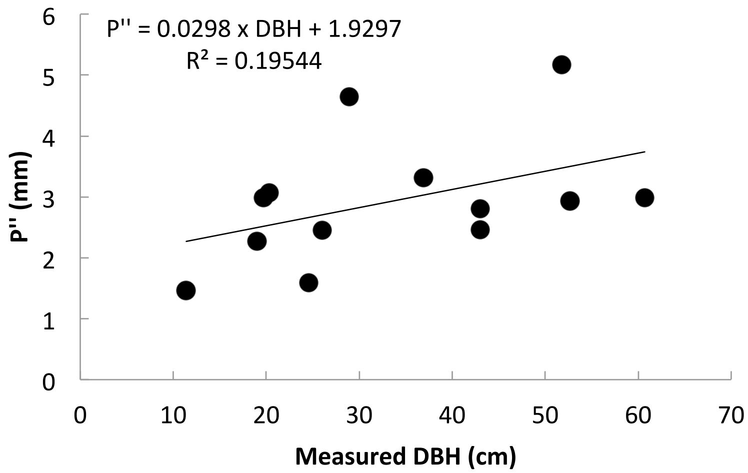

Figure 4. Stemflow initiation threshold (P'', mm) versus observed diameter at breast height (DBH, cm) for all trees.
Intercept values (P'') versus DBH showing a weak linear relationship and not the power relationship shown by Park and Hattori (2002), more similar to the relationship shown by McKee and Carlyle-Moses (2017)

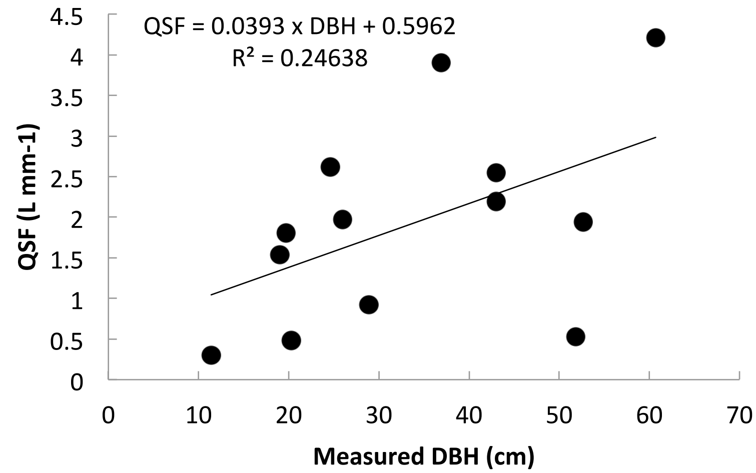

Figure 5. Stemflow rate (Q_{SF}, L mm-1) versus observed diameter at breast height (DBH, cm) for all trees.
Slope values (Q_{SF}) versus DBH showing a weak linear relationship and not the power relationship shown by Park and Hattori (2002) or by McKee and Carlyle-Moses (2017).

By establishing the linear relationship between P'' and DBH (Figure 4) and Q_{SF} and DBH (Figure 5), the P'' and Q_{SF} parameters may be calculated for any tree if the DBH has been measured. Therefore, by measuring the tree DBH and taking precipitation measurements for rainfall events, it is possible to simply and quickly predict stemflow by using Equation 4. Where Q_{SF} represents the quantity of water intercepted by the canopy that is diverted to stemflow and P'' is the amount of water retained in the canopy and on the trunk as storage that does not become stemflow.

$$SF = Q_{SF} * P_G - P'' \quad (4)$$

Stemflow volume was not differentiated between the growing and dormant season as no significant difference was found in Q_{SF} and P'' that could be attributed to seasonality. Park (2000) also reported similar results in Japan where seasonality did not appear to change the Q_{SF} or P'' value.

2.2.1 Stemflow Model Performance

Before applying the model to evaluate tree pit design and specifications, the next stage of the analysis was to determine the performance of the SF model in simulating observed versus predicted SF volumes (Piñeiro et al. 2008). The model was applied on an event basis using both the "by genus" estimated P'' and Q_{SF} and the P'' and

Q_{SF} estimated based on grouping all of the trees in the sample set together.

Figure 6 shows the two approaches of predicting stemflow and observed stemflow for one sample tree from the genera Quercus, Acer, and Fraxinus. Overall the model performs relatively well. For the sample tree from the genus Quercus (Figure 6a) the calculated SF based on a genus estimated P'' and Q_{SF} overestimates SF, while the estimation using the regression based on all trees grouped together to calculate P'' and Q_{SF} leads to a underestimation. For the sample tree from the genus Acer (Figure 6b) both methods of estimating P'' and Q_{SF} led to an overestimation of SF. Finally, for the sample tree from the genus Fraxinus (Figure 6c) estimating P'' and Q_{SF} with all the trees grouped together led to an overestimation whereas the genus grouping method led to an underestimation. Overall, the methodology for estimating P'' and Q_{SF} with all the trees grouped together appears to be more accurate in comparison to the methodology for estimating P'' and Q_{SF} by grouping the trees by genera. Similarly, Deguchi et al. (2006) found that because there is no clear seasonal trend in SF volume and because SF volume is highly dependent on precipitation depth, SF volume for each tree may not be strongly related to species or seasonal changes in canopy structure, which makes SF approximation based solely on DBH possible. Figure 6 serves to demonstrate that the model performs well but the model does not consistently over- or under- predict SF volumes. Nevertheless, the pattern of modelled and measured stemflow mimics each other quite well.

Many factors could cause differences between modelled and measured data. Differences in crown shape and leaf morphology or branching pattern between the genera Quercus, Acer, and Fraxinus lead to variations in rainfall distribution patterns and the total amount of stemflow being funnelled to the ground. Any discrepancy

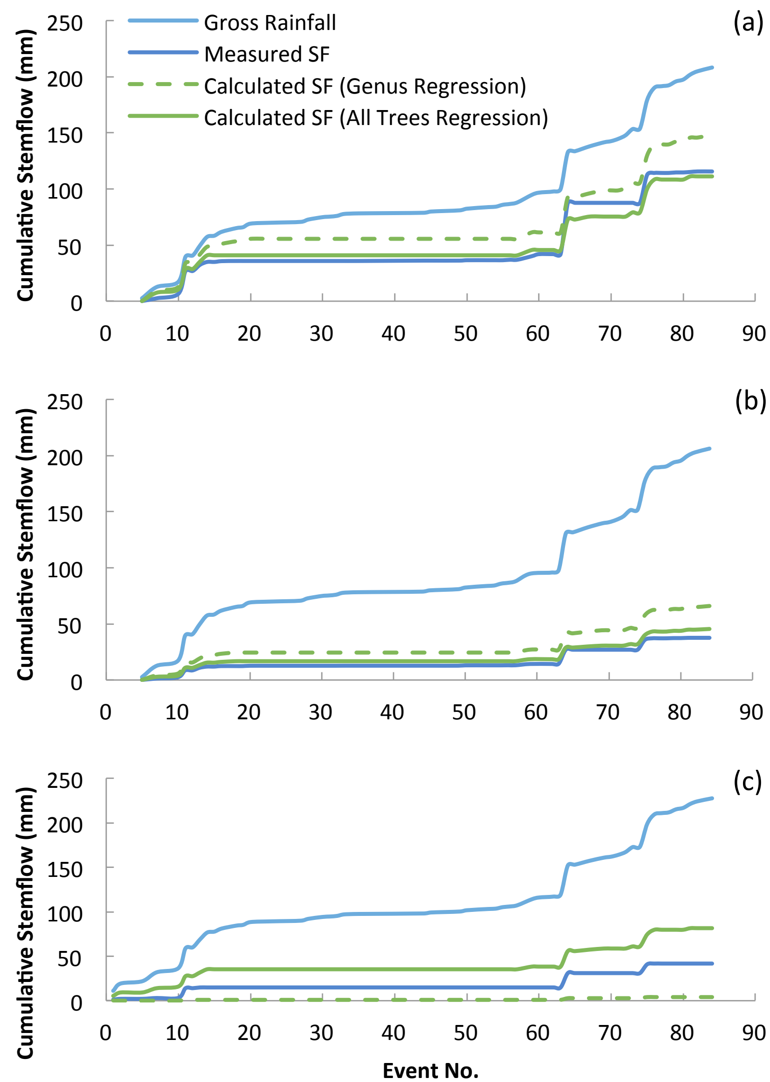

Figure 6. Cumulative rainfall (mm) and stemflow (SF, mm) for three genera: a) Quercus; b) Acer; and c) Fraxinus. Both observed and modelled SF is presented.

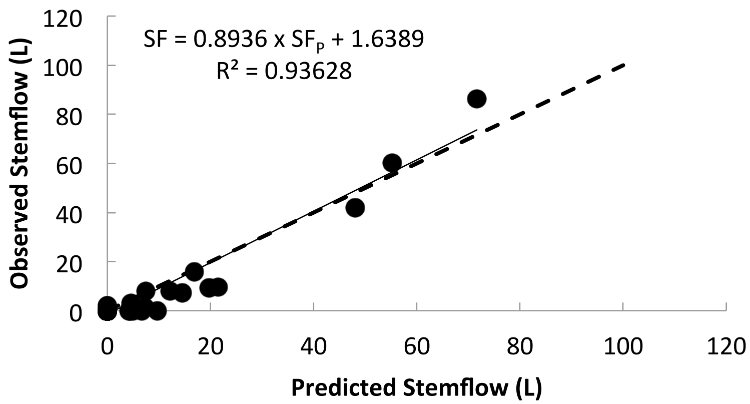

Figure 7 - Observed stemflow volume (SF_O, L) versus predicted stemflow volume (SF_P) derived by employing the stemflow theoretical model (solid line) and the 1:1 line (dotted line).

between modelled and measured stemflow losses derived from uncertainty, not only of the canopy and bark characteristics, but also of the variations in rainfall rates and other meteorological factors such as wind direction and speed which play into evaporation rates and storage capacity. The P'' and Q_{SF} are treated as constants throughout the duration of event, but in particular Q_{SF} may change over time as conditions change. Carlyle-Moses and Schooling (2015) found that the threshold rainfall depth for SF initiation, P'', was directly related to DBH but only for single leader trees. An increase in P'' with increasing DBH could reflect the increase in surface area and therefore water storage capacity. On the other hand, they found that the bark roughness index (BRI) was positively related to P'' for both single-leader and multi-leader trees. They note that this result intuitively follows since smoother bark was generally associated with a lower P'' based on the idea that rougher bark provides a larger amount of surface area that increases the effective surface area and thus the water storage capacity of the trunk.

Because this theoretical model endeavours to summarize conditions minor disagreements between observed and predicted stemflow is reasonable, it was determined that the stemflow model could accurately calculate SF with an average R^2 of 0.86 and a p-value of 0.05. In addition, analysis of the slope and intercept for plotted predicted SF volumes versus observed SF volumes (Figure 7) shows that they do not differ significantly from unity and zero, respectively.

2.2.2 Theoretical Model Assumptions

One objective of this project was to develop a simple stemflow model that could be easily used after minimal field measurements to predict tree stemflow. By reducing the amount of parameters used in the model, some of the complexity inherent in the physical stemflow system is lost and therefore some accuracy is also lost. This model assumes that DBH is the most significant parameter for predicting other tree characteristics such as canopy cover and branch morphology as Schooling (2015) found that most tree parameters are significantly correlated with tree DBH. Levia et al. (2001) also found that DBH is an important predictive parameter because tree characteristics such as leaf area, tree height, crown diameter, crown length, and crown volume are all strongly correlated with DBH. In creating this model I have assumed that DBH is the most significant tree parameter that is a predictor of P'' and Q_{SF}. Based on a comparison between model results calculated using the two above mentioned relationships when grouped by tree genus versus model results calculated using the above mentioned relationships when all trees were taken into account, I have determined that SF can be predicted by using a relationship that is based on data from all trees when grouped together. Therefore, this decision assumes that all trees are similar enough that apart from changes in DBH, no other parameters must be distinguished in order to calculate SF. In addition, the estimation of apparent storage capacity or P'' using this process relies on three assumptions: a) that the stemflow rate is constant during the full duration of the event; b) that no drip occurs from sloping branches; and c) that any evaporation from the stem during the event is negligible (André et al., 2008).

2.3 Model Application to Evaluate Tree Pit Design

In order to evaluate the current practices of tree pit design and implementation, a methodology was followed to determine the types of materials and pit volume required to allow for full stemflow infiltration and storage. SF was calculated for a range of trees where DBH was varied from 6 to 60 cm. SF was calculated based on the intensity-duration-frequency (IDF) curves provided by Environment Canada for the Vancouver Airport weather station based on historically collected weather data (Environment Canada, 2014). Overall there are 54 possible IDF scenarios that include any combination of the following return period and event duration where the return periods are for every 2, 5, 10, 25, 50, and 100 years and the event durations are for 5, 10, 15, and 30 minutes and 1, 2, 6, 12, and 24 hours. The equivalent depth of SF (mm) was calculated based on the basal area (m^2) of the tree. Using the derived P'' value and rainfall intensity from the IDF curve, the number of hours to reach saturation were calculated and based on the remaining amount of time during the event for which SF occurred after P'' was reached; the average SF intensity (mm h^{-1}) was calculated.

Based on the SF intensity, it is possible to distinguish which soil types would allow for full SF infiltration given average infiltration rate capacities supplied by (FAO, n.d.). For any IDF scenarios where the average SF intensity is greater than the infiltration rate, runoff occurs. Runoff amounts are calculated as the difference between the SF intensity and the infiltration rate multiplied by the number of hours when SF occurred after P'' was satisfied. This analysis provides insight into the materials necessary to allow infiltration given different tree sizes.

To evaluate tree pit volumes, the water holding capacity of the tree pit was estimated based on the dimensions of the pit and the average water storage capacity (AWSC) (mm m-1) for a given soil type (FAO, n.d.). Appendix A includes a schematic of the average area and depth specifications for a tree pit in Vancouver and based on these specifications a volume can be calculated (City of Vancouver, 2011). The rootball depth was estimated based on a linear regression between DBH and rootball depth data from the Canadian Standards for Nursery stock 8th edition (2017). Once the AWSC of the pit was established, the amount of SF (mm) was compared to the AWSC of the pit to evaluate whether current pit design specifications provide sufficient water storage volume given predicted SF volumes.

2.3.1 Infiltration and Storage Evaluation Assumptions

Several assumptions were made during the course of the tree pit design evaluation. In the field infiltration occurs along a complex wetting front mechanism (Mays, 2010) so that in field conditions, infiltration rate changes over time as a rainfall event progresses. For simplicity it was assumed that if SF intensity was greater than the infiltration rate that runoff occurred. This first assumption allows for a rough calculation of the amount of runoff, which is the difference between SF intensity and infiltration rate multiplied by the number of hours for which SF occurred during the event. By using one fixed infiltration rate this also assumes that the soil in question is homogeneous throughout the pit and therefore the infiltration rate is also uniform throughout. In addition it was assumed that the infiltration rates attained from the FAO are representative of the typical soil types when all other factors are kept equal. Finally, the SF model was developed based on measurements taken in Kamloops. This infiltration and water storage evaluation assumed that it is possible to extrapolate the SF model to trees of the same species but different meteorology in Vancouver in order to make an evaluation of Vancouver street tree pits.

3 FINDINGS AND IMPLICATIONS

In this section I discuss the results from the stemflow model predictions. The findings of my evaluation of current street pit specifications are detailed and discussed in relation to stormwater management, tree health, and future climate change predictions.

3.1 Stemflow Model Results

Schooling (2015) found in their research that contrary to previous studies that indicated SF accounts for on average less than 10% of incident rainfall, for isolated trees in an urban park SF accounted for up to 10% of incident rainfall. Because the stemflow model closely predicts SF based on data provided by Schooling, the model also predicts that SF accounts for up to 14% of incident rainfall. These results indicate that SF is not a negligible component of rainfall partitioning in urban settings for deciduous species and should be accounted for in future rainfall partitioning studies and in future stormwater management plans that rely on urban forestry strategies.

3.2 Tree Pit Evaluation

For all of the modeled IDF scenarios and soil types the pit volume was sufficient to supply adequate water storage capacity to hold the total amount of infiltrated stemflow. Under current design specifications for street tree pits in Metro Vancouver, the area of the pit remains constant regardless of tree size while the depth of the pit depends upon the size of the rootball. The largest tree evaluated had a DBH of 60 cm - that translates into a tree pit volume of approximately 6.2 m^3. According to the City of Vancouver Street Tree Guidelines for the Public Realm (2011 Revision), deciduous street trees must have a calliper (DBH) greater than or equal to 6 cm. Based on recommendations by Diamond Head Consulting Ltd (2017), a tree requires 0.6 cubic metres (m^3) of soil for every square meter (m^2) of projected canopy area (PCA). Based on a linear relationship between DBH and PCA, a tree with a minimum DBH of 6 cm would have a canopy with a PCA of approximately 10 m^2. Based on a 10m^2 PCA the ideal soil volume for the smallest allowable tree is 6 m^3. Therefore, although there is theoretically enough water holding capacity of any given soil type to store potential stemflow for up to the 1 in 100 year 24-hour storm for the largest calliper tree in this study, the volume of the pit does not meet the requirements to provide adequate growing space for roots.

For the evaluation of the soil type infiltration rate versus stemflow intensity, the number of IDF scenarios for which SF intensity was greater than the theoretical infiltration rate increased as DBH increased (**Figure 8**). For a pit with sand fill runoff began at a DBH of 34 cm for one event, the 1 in 2 year 5-minute storm. The amount of runoff from this event would be approximately 0.09 mm. For the largest tree with a DBH of 60 cm, 20 IDF scenarios have calculated SF intensities greater than the average theoretical sand infiltration rate. The smallest amount of runoff, 0.86 mm, occurred during the 1 in 25 year 30-minute storm and the greatest amount of runoff, 5.70 mm, occurred during the 1 in 100 year 15-minute storm.

For a pit with a loam fill, runoff began at a DBH of 26 cm for one event, again the 1 in 2 year 5-minute storm. The amount of runoff from this event would be approximately 0.002 mm. This amount of negligible, however, the next largest tree with a DBH of 30 cm has 7 IDF scenarios with calculated SF intensities greater than the average infiltration rate. For the largest tree with a DBH of 60 cm, 33 IDF scenarios have calculated SF intensities greater than the average theoretical loam infiltration rate. The smallest amount of runoff, 1.36 mm, occurred during the 1 in 2 year 1-hour storm. The greatest amount of runoff, 12.89 mm, occurred during the 1 in 100 year 2-hour storm.

For a pit with a clay fill, runoff began at a DBH of 14 cm for 9 events, the least intense being the 1 in 100 year 15-minute storm. The smallest amount of runoff, 0.003 mm, occurs during the 1 in 5 year 5-minute storm. The greatest amount of runoff, 0.04 mm, occurs during the 1 in 100 10-minute storm. At and above a DBH of 50 cm a pit filled with clay soil would lead to surface runoff for all the IDF storms proposed by Environment Canada. For the largest tree with a DBH of 60 cm, all 53 IDF scenarios have IDF intensities greater than the average theoretical clay infiltration rate. The smallest amount of runoff, 2.61 mm, occurred during the 1 in 5 year 5-minute storm. The largest amount of runoff occurred during the 1 in 100 year 24-hour storm.

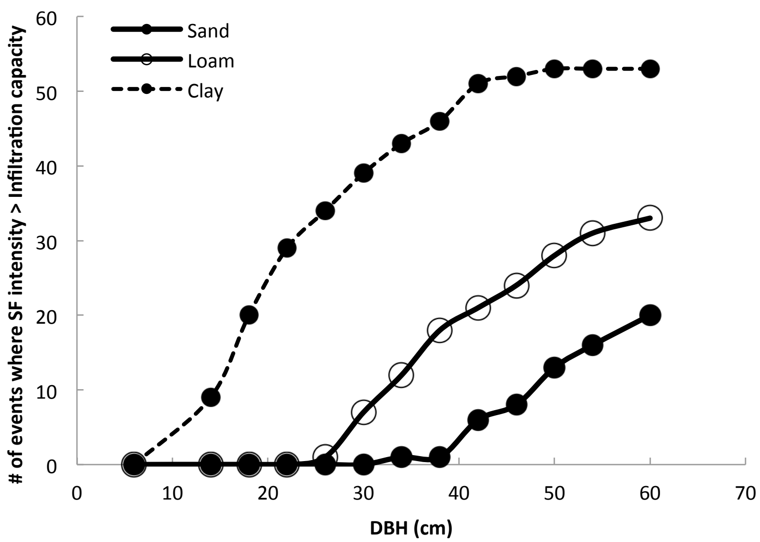

Figure 8. Number of IDF scenarios where stemflow intensity is greater than infiltration capacity versus diameter at breast height.
As the coarsest material, sand produces the least number of events where SF intensity is greater than infiltration capacity. As the material becomes finer, the infiltration capacity decreases and more IDF scenarios result in a predicted SF intensity greater than infiltration capacity, which would lead to stemflow water generated runoff.

In the Street Tree Guidelines from the City of Vancouver a standard soil texture is mandated which should follow the following guidelines: the mixture should be made up of 0 - 1% coarse gravel and up to 5% all gravel. 83-85% of the mixture should be sand, 12-17% should b silt, 0-5% should be clay. In total the clay and silt content should be between 12-16%. Based on these specifications, this soil would be classified as loamy sand. Loamy sand is predominately sand with trace amounts of silt and clay. A theoretical average infiltration rate for a loamy sand would be between 25 - 30 mm/hr. Assuming an infiltration rate of 27.5 mm/hr, it would be expected that the number of IDF scenarios where SF intensity is greater than infiltration rate for a pit filled with this regulation soil mix would be the same as for a pit filled with sand. The amount of runoff occurring would however change slightly (possibly increasing slightly as the amount of trace textures increases). Given that certain rainstorm events will result in overland flow for even the most coarse material of sand, using a loamy sand amendments in street tree pits is the best possible action to reduce the number of IDF scenarios under which surface runoff occurs.

3.3 Climate Change Implications

Climate projections from the Pacific Climate Impact Consortium (PCIC) indicate that Metro Vancouver will experience an increase in total annual precipitation of approximately 5% by the 2050s, and approximately 11% by the 2080s (Metro Vancouver, 2016). This total annual increase will not be distributed evenly throughout the year. The PCIC predicts that increases in rainfall will favour the wetter months of the year while there may be a decline in precipitation during the drier summer months. PCIC notes that the models indicate only a range of possible changes but that overall the models mostly agree upon the direction of change for each season.

As noted above, a modest increase (5%) in total annual precipitation is expected by the 2050s. Models project that the increase will be concentrated into the wettest days. Significantly more precipitation is expected to fall during the 1 in 20 wettest day extreme storm events in the near future. Larger 1 in 20 wettest day events could mean up to 50% more rain in low-lying areas by the 2050s, and 86% by the 2080s (see **Table 1**). In addition to more precipitation during future 1 in 20 year events, the climate models also indicate that what was previously characterized, as a 1 in 20 event will happen more often.

Table 1. 1 in 20 year wettest day predicted changes. Adapted from Metro Vancouver (2016)

	Past (mm)	2050s Change (mm)		2080s Change (mm)	
		Average	(Range)	Average	(Range)
Region	105	30	(7 to 43)	46	(24 to 70)
Low elevations	89	31	(9 to 50)	51	(30 to 86)
High elevations	121	23	(7 to 38)	38	(16 to 60)

Because temperature is not modeled in the stemflow model, it is difficult to predict how changes in temperature throughout Metro Vancouver will impact stemflow. Temperature impacts evaporation, which is related to a tree's potential water storage. Increasing temperatures should theoretically lead to increasing evaporation, which could increase the amount of water required to fill up storage before stemflow may occur. Therefore increasing temperatures will likely result in higher stemflow initiation thresholds and therefore potentially smaller SF volumes. The balance between increasing temperatures and increasing precipitation volumes and their impacts on SF yield requires further research and consideration.

The stemflow model was applied based on the regional 1 in 20 year minimum, average, and maximum climate projections for the 2050s and 2080s. Based on these possible changes in precipitation, runoff begins to occur for trees with a DBH of 38 cm or greater (**Figure 9**). Under current conditions the 1 in 20 year 24-hour storm is expected to produce approximately 1.24 mm of runoff. During predicted average conditions in 2050 runoff will increase to 8.20 mm and further increase to 11.93 mm given predicted averages conditions for 2080. This equates to a 560% increase in SF between now and 2050 and an 861% increase in SF between now and 2080. Interestingly, the increase in SF between current and future climate predictions decreases as DBH increases. For a tree with a DBH of 60 cm SF is predicted to increase by only 39% by 2050 and by 60% by 2080. A possible reason for this decrease in impact with increasing DBH may be related to the relationship between DBH and P''. As DBH increases the surface area of the trunk also increase and therefore is partly responsible for the increase in P''. This mechanism may act as a dampener on the effect of increasing precipitation with climate change. Further research into this phenomenon is required.

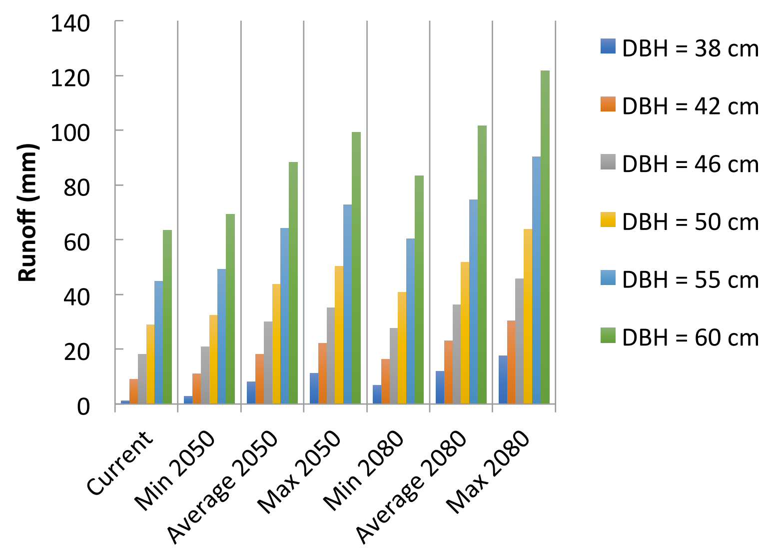

Figure 9. Predicted rainfall runoff (mm) from excess stemflow for current, minimum, average, and maximum climate predictions for 2050 and minimum, average, and maximum climate predictions for 2080.

3.4 Further Model Applications

3.4.1 Implications of Model Findings for Urban Forestry

The evaluation of current street tree pits suggests that the soil types used in street tree pits are appropriate and provide adequate infiltration capacity and water storage capacity. This finding tells us that trees planted in these tree pits can funnel water down their stems that can subsequently be stored and evapotranspirated by the tree. This is useful information to know, especially for during the summer months when water scarcity rather than stormwater runoff is a problem. By providing a direct volume of storage to which the trees may use this reduces the amount of water that trees should potentially require as additional irrigation.

The evaluation of the current street tree pits design, however, also suggests that current pit specifications do not provide enough volume to provide adequate space for root growth. By limiting root growth this effectively also limits whole tree growth and therefore reduces the effectiveness of a tree and the number and quality of potential ecosystems services offered by a given tree. To promote tree growth and increase the stormwater services associated with trees it is essential that enough below ground volume be provided.

3.4.2 Model Limitations and Potential Improvements

This stemflow model seeks to provide professionals with a tool to produce initial estimates of stemflow and to comprehend its relative importance for certain trees in the urban environment. However, there are some limitations that have been identified that should be considered in the context of future model use for urban forest planning. First, the utility of this model may also be its biggest limitation: by simplifying the mechanism of SF down to a relationship that can be determined based solely on DBH this creates an opportunity for practitioners to easily and affordably estimate SF based on very few measurements made in the field. However, it has been argued that the use of multiple predictor variables (e.g. canopy cover, bark relief, etc.) in such a model would increase model accuracy (McKee and Carlyle-Moses, 2017; Park and Hattori, 2002). Second, this model was developed based on observed data for a limited subset of tree species and the model itself was built to model SF for those tree that falls within this species subset, assuming that any tree within this subset will reasonably share characteristics of these species. The model will benefit from further research and studies that quantify the relationships explored in this project.

4 Conclusion

In conclusion, according to my findings stemflow is an important component in rainfall partitioning that should not be immediately dismissed.

By utilizing the developed stemflow model, an evaluation was conducted to determine whether current street tree pit specifications allow for stemflow infiltration given the predicted stemflow volumes and whether these pits provide adequate below ground volumes for water storage and root growth. The results show that loamy sand is adequate for providing infiltration capacity and soil water storage space. However, based on current specifications, street tree pits are not big enough to provide enough volume for root growth and this issue should be addressed in order to provide enough growing space so that trees are healthy and can provide stormwater management services.

Based on climate change projections from the PCIC, trees over a calliper of 38 cm can expect to experience varying degrees of increasing stemflow yield as precipitation increases during the 1 in 20 year wettest day. The feedback between temperature and precipitation due to climate change is unknown and may impact stemflow volumes. In addition trees with larger DBH were less impacted compared to trees with smaller DBH. This may possibly be attributed to the relationship between DBH and P'' but further research is required to investigate this possibility.

One goal of this project was to provide a theoretical model on rainwater stemflow funnelling performance of a selection of common urban street trees in the Metro Vancouver area, given a series of climatic conditions and a range of tree sizes. A simple linear regression model was developed to relate stemflow volume at the base of the tree to its trunk circumference and rainfall depth. Overall, the model performed with a reasonable capacity to simulate the stemflow and results mimicked observed stemflow values, given limited data inputs and with the stated assumptions. The discrepancy between modelled data and observed data could be the result of a series of factors, and better accuracy could be achieved by conducting multiple regression analysis with more predictor variables. The results from the model demonstrate that while interception loss by urban trees is still larger in comparison to SF, SF can no longer be dismissed as insignificant. Therefore, urban foresters and planners should be encouraged to utilize tools such as this stemflow model to better understand and quantify stemflow in order to support any work related to urban forestry and stormwater management planning.

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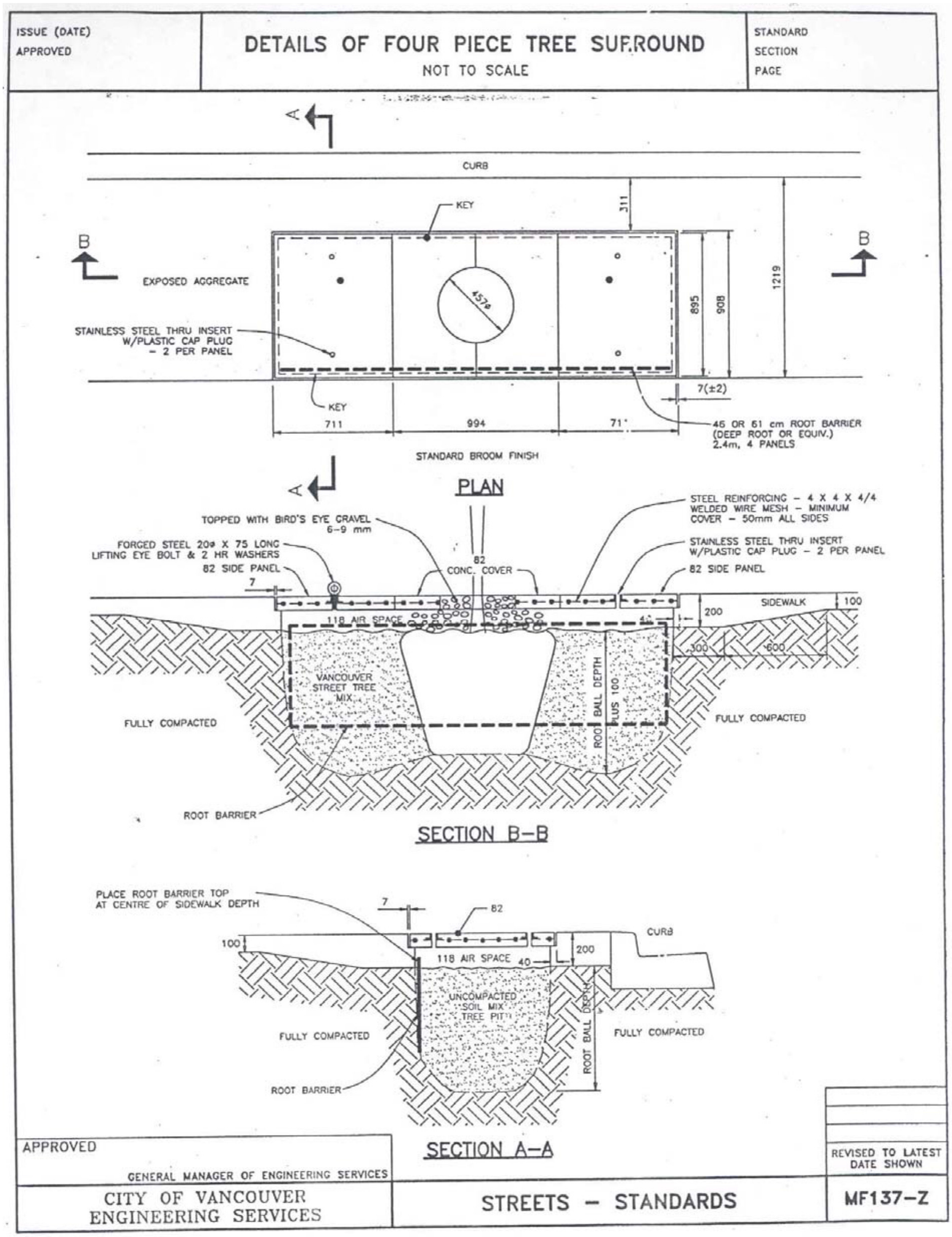
APPENDIX A


ISSUE (DATE)
APPROVED
DETAILS OF FOUR PIECE TREE SURROUND
NOT TO SCALE
STANDARD
SECTION
PAGE
CURB
KEY
311
1219
895
908
EXPOSED AGGREGATE
STAINLESS STEEL THRU INSERT W/PLASTIC CAP PLUG - 2 PER PANEL
457ø
KEY
7(±2)
711
994
711
46 OR 61 cm ROOT BARRIER (DEEP ROOT OR EQUIV.) 2.4m, 4 PANELS
STANDARD BROOM FINISH
PLAN
TOPPED WITH BIRD'S EYE GRAVEL 6-9 mm
FORGED STEEL 20ø X 75 LONG LIFTING EYE BOLT & 2 HR WASHERS
82 SIDE PANEL
82
CONC. COVER
STEEL REINFORCING - 4 X 4 X 4/4 WELDED WIRE MESH - MINIMUM COVER - 50mm ALL SIDES
STAINLESS STEEL THRU INSERT W/PLASTIC CAP PLUG - 2 PER PANEL
82 SIDE PANEL
SIDEWALK
100
200
118 AIR SPACE
40
300
600
VANCOUVER STREET TREE MIX
ROOT BALL DEPTH PLUS 100
FULLY COMPACTED
FULLY COMPACTED
ROOT BARRIER
SECTION B-B
PLACE ROOT BARRIER TOP AT CENTRE OF SIDEWALK DEPTH
7
82
CURB
100
200
118 AIR SPACE
40
UNCOMPACTED SOIL MIX TREE PIT
ROOT BALL DEPTH
FULLY COMPACTED
FULLY COMPACTED
ROOT BARRIER
APPROVED
GENERAL MANAGER OF ENGINEERING SERVICES
SECTION A-A
REVISED TO LATEST DATE SHOWN
CITY OF VANCOUVER ENGINEERING SERVICES
STREETS - STANDARDS
MF137-Z