



Quantification of stemflow in three isolated shrub species in an urban environment

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Rakestraw, E. (2016). Quantification of stemflow in three isolated shrub species in an urban environment [Drexel University]. <https://doi.org/10.17918/etd-6907>
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Quantification of Stemflow in Three Isolated Shrub Species in an Urban Environment

A Thesis Submitted

to the

Faculty of

Drexel University

By

Emma Rakestraw

in partial fulfillment of the

requirements for the degree

of

Master of Science in Environmental Engineering

April 2016



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TABLE OF CONTENTS

LIST OF TABLES	iv
LIST OF FIGURES	v
LIST OF EQUATIONS.....	vi
ABSTRACT	vii
1. INTRODUCTION.....	1
<i>1.1 Background.....</i>	6
<i>1.2 Literature Review.....</i>	1
<i>1.3 Goals.....</i>	6
2. METHODS.....	8
<i>2.1 Location and Shrub Species</i>	8
<i>2.2 Design Setup</i>	9
<i>2.3 Data Collection</i>	11
3. DATA ANALYSIS	13
4. RESULTS	19
5. DISCUSSION.....	32
6. CONCLUSION	35
LIST OF REFERENCES.....	37

LIST OF TABLES

1. Statistically Significant Variables for Each Data Set	17
2. <i>P. laurocerasus</i> Significant Variables	29
3. <i>H. quercifolia</i> Significant Variables	30
4. <i>I. virginica</i> Significant Variables	30
5. All Data Significant Variables	31

LIST OF FIGURES

1. Published Percent Stemflow in Trees	5
2. Published Percent Stemflow in Shrubs	5
3. Published Percent Stemflow in Mixed Species	6
4. Species Studied	8
5. Collar Design	10
6. Stemflow Collection System and HOBO Weather Station	11
7. - ImageJ Area Analysis	14
8. Rain Events Throughout Sampling Period	19
9. Percent Stemflow in Individual Branches in Each Event	20
10. Determined Percent Stemflow Compared to Other Species	21
11. Range in Percent Stemflow Across Growing Season	22
12. Event Depth vs Percent Stemflow for <i>P. laurocerasus</i>	23
13. Event Depth vs Percent Stemflow for <i>H. quercifolia</i>	23
14. Event Depth vs Percent Stemflow for <i>I. virginica</i>	24
15. Small and Large Events for <i>P. laurocerasus</i>	25
16. Small and Large Events for <i>H. quercifolia</i>	25
17. Small and Large Events for <i>I. virginica</i>	26
18. Fit of <i>P. laurocerasus</i> SPSS Model	27
19. Fit of <i>H. quercifolia</i> SPSS Model	27
20. Fit of <i>I. virginica</i> SPSS Model	28
21. Fit of All Data SPSS Model	28

LIST OF EQUATIONS

1. Weight to Depth Equation	15
2. Percent Stemflow Equation.....	15

ABSTRACT

Quantification of Stemflow in Three Isolated Shrub Species in an
Urban Environment
Emma Rakestraw

As precipitation falls on vegetated areas, it is partitioned into throughfall, stemflow and vapor. Stemflow has often been neglected in hydraulic budgeting of both trees and shrubs due to the small volume, and limited number of quantitative studies conducted. Studies of stemflow in shrub species are especially rare, and this study intends to decrease uncertainty of its occurrence. Six shrubs of species *Prunus laurocerasus* 'Otto Luyken', *Hydrangea quercifolia* 'Alice', and *Itea virginica* 'Little Henry' were studied in an urban environment in Philadelphia, PA. During the 2015 growing season, total incident rainfall and measured stemflow were recorded. Stemflow was collected using aluminum collars attached to individual branches of each individual. Vinyl tubing transported stemflow from the collars into collection bottles that were weighed after each rain event.

Canopy areas of each collared branch were calculated. Impact of branch attachment angle and stem circumference on the percent stemflow expected was analyzed. In addition to species characteristics, rain depth, rain intensity, wind speed, gust speed, date of storm, direction of collar, and wind direction were considered. Of the six measured individuals it was found that stemflow averaged 7.6 %, with values ranging from 0 to 58 percent for individual branches across all storms. Species specific averages were found to be 11.4 %, 7.0 %, and 4.4 % for *P.*

laurocerasus, *H. quercifolia*, and *I. virginica* respectively. These results show that there is significant variation in stemflow percent by species. It was also determined that between 55 and 79 percent of variation in stemflow can be defined by the above characteristics. To make prediction models more accurate, more variables should be examined. By understanding how the quantity of stemflow is affected by both meteorological and species characteristics, the partitioning of rainfall can be more accurately calculated.

CHAPTER 1: INTRODUCTION

Background

Green infrastructure has become an increasingly popular stormwater management technique, especially in cities with combined sewer systems. In order to manage stormwater runoff, green infrastructure attempts to intercept and infiltrate runoff before it enters the sewer system. Green infrastructure installments are often planted with trees and shrubs that can withstand pollution and large influxes of water. Since the species planted impact the way the green infrastructure functions, hydrologic information about each species can help designers make informed decisions. Stemflow has not been extensively studied in shrub species. This study intends to increase understanding on how stemflow varies between species and what variables can be used to predict amount of stemflow expected.

Literature Review

As water budgets are developed, stemflow is often neglected. This is because quantification of stemflow has not been extensively studied. As water flows down stems, nutrients concentrate and infiltrate at the base of plants (Garcia-Estringana, Alonso-Blázquez, and Alegre, 2010). In fact, in a study of a holm-oak forest, the funneling ratio was found to be over 30 (Bellot and Escarre, 1998). Observing such an increase in flux in the area around the stem may show that stemflow should not be neglected in calculations (André, Jonard, and Ponette, 2008).

To make water budgets more accurate, more quantification must be done on stemflow.

Stemflow collection on trees has been conducted more extensively than stemflow on shrubs. Stemflow collection on trees is generally collected in the same fashion during most studies, which allows for better comparison of results. Collars are wrapped around trunks in a spiral, sealed with silicone caulking, and connected to a vessel functioning as a collector. Collar materials used do vary slightly between each study. Polyethylene plastic tubing is a common choice as the tubing can easily be cut in half and spiraled around the tree to allow for water collection (Marin, Bouten, and Sevink, 2000; Liu, Wenyao, Fox, Xu, 2002; Farmer, Bates and Bell, 1991). Other studies fashioned a similar collar using vinyl sheeting instead (Levia, Van Stan, Mage, and Kelley-Hauske, 2010; Levia and Herwitz, 2005). Neoprene has been utilized and another, longer-term study used flexible polyurethane foam board to allow for growth of trees (Murakami, 2009; André, Jonard, and Ponette, 2008). In order to collect information on quantity and chemical composition, stemflow was generally collected in plastic containers for collection and measurement (Liu et al, 2002; Farmer et al 1991; Levia and Herwitz, 2005; Murakami, 2009; Silva and Rodriguez, 2000). Several studies used tipping bucket gauges or bottle gauges (Marin et al 2000; Levia et al 2010; André et al, 2008). If stemflow was to be tested for chemical composition or bacteria content, water was run through washed glass wool, buckets were rinsed with deionized and distilled water, or chemically inert bags were used as a lining material (André et al, 2008; Farmer et al 1991; Levia and Herwitz, 2005). During quantification only, no such measures are needed.

There is more variation in the measurement methods of stemflow on shrubs. Similar to trees, some studies used a polyethylene funnel and silicone sealant to collect stemflow (Whitford, Anderson, and Rice, 1996; Li, Liu, Gao, Ma, and Yang, 2008). Other studies used double impermeable rings or folded aluminum foil plates (Zhang, Wang, Hu, Pan, and Zhang, 2013, Garcia-Estringana et al, 2010).

Some studies took special measures to prepare stems of shrubs before application of the funnel. Fine sandpaper was used to treat the stem, or new growth was removed from the lower 10 cm of the plant (Zhang et al, 2013, Garcia-Estringana et al, 2010). Random selection of only several stems on shrubs with a large number of stems was also utilized (Whitford et al, 1996).

Caragana korshinskii stemflow was found to average 0.88 mm, which accounts for 8.8 % of incident rainfall, while *Artemisia ordosica* averaged 0.29 mm, or 2.8 % of total rainfall (Zhang et al, 2013). When six *Larrea tridentate* were studied over the course of 18 rain events, stemflow averaged 16.8 % +/- 1.9 % (Whitford et al, 1996). Stemflow coefficient values for Tamaulipan thorn-shrub forests were found to be greater than 1 (Navar, 2011). Using a rain simulator in an arid climate, stemflow for *Flourensia cernua* was found to have stemflow amounting to 4-45% of total rainfall (Mauchamp and Janeau, 1993). It was found that lower rainfall intensities had a higher percentage of stemflow. A similar study using rainfall simulator found that stemflow ranged from 3.8 % -26.4 % over nine species of shrubs and had an average of 16 % (Garcia-Estringana et al, 2010). *Tamariz ramosissima*, *Caragana korshinskii* and *Reaumuria songorica* were studied in China and found to have stemflow averages of 2.2 %, 2.7 %, and 7.2 %, respectively (Li et

al, 2008). This study found that as depth of rain increased, stemflow did as well until rainfall was greater than 2 mm/h, in which case stemflow decreased and rainfall increased.

When looking at stemflow, studies generally focus on trees, shrubs or a specific area of land that contains a mixture of species types. This allows comparison between species of similar types. In trees that have been evaluated average stemflows ranged from 1.41 % to 11.73 % in *Pseudotsuga mensiesii* and *Phylliorea media* respectively. In shrubs values had a larger range, which spanned between 2.2 % in *Tamarix ramosissima* to 26.4 % in the *Cytisus zeelandia*. In mixed species floodplain species were found to have the lowest percent stemflow with 0.98 %. Highest in the mixed species was Tamaulipan thornscrub species, which had 8.37 % stemflow.

Looking at the ranges of stemflow found for different species of trees, and shrubs, and mixed species in Figures 1, 2, and 3 respectively, it is shown that shrubs have a wider range of percent stemflow than trees or mixed species. This could be due to a wider variation in overall shape and branching patterns. Another possibility is that weather patterns affect stemflow in shrubs more, therefore causing a larger change in stemflow values.

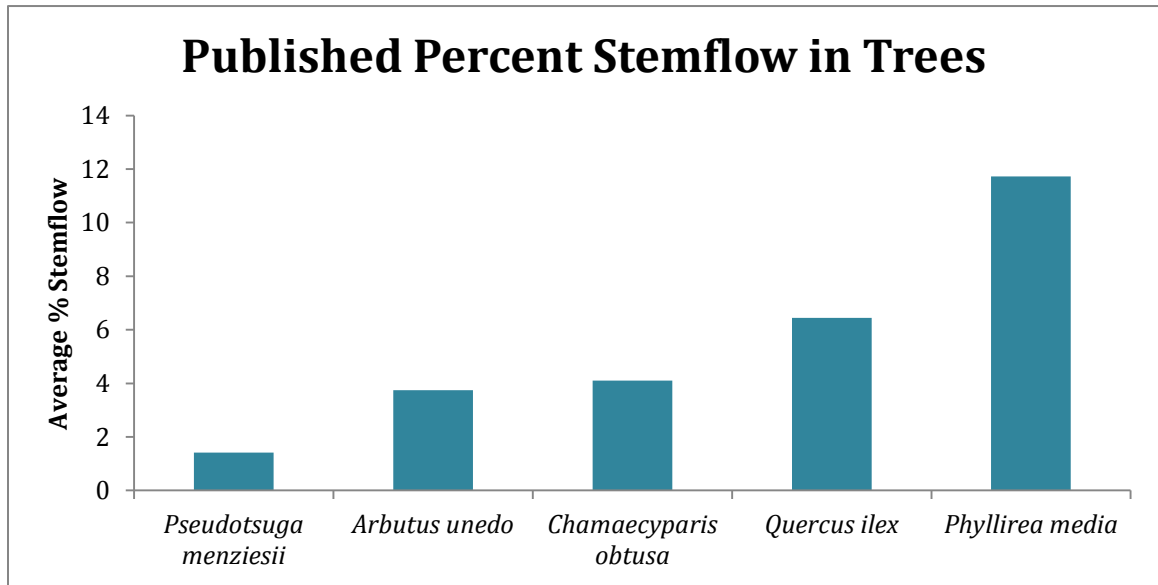


Figure 1-Published Percent Stemflow in Trees, Sources: Bellot and Escarre, 1998; Hutchinson and Roberts, 1981; and Murakami, 2009

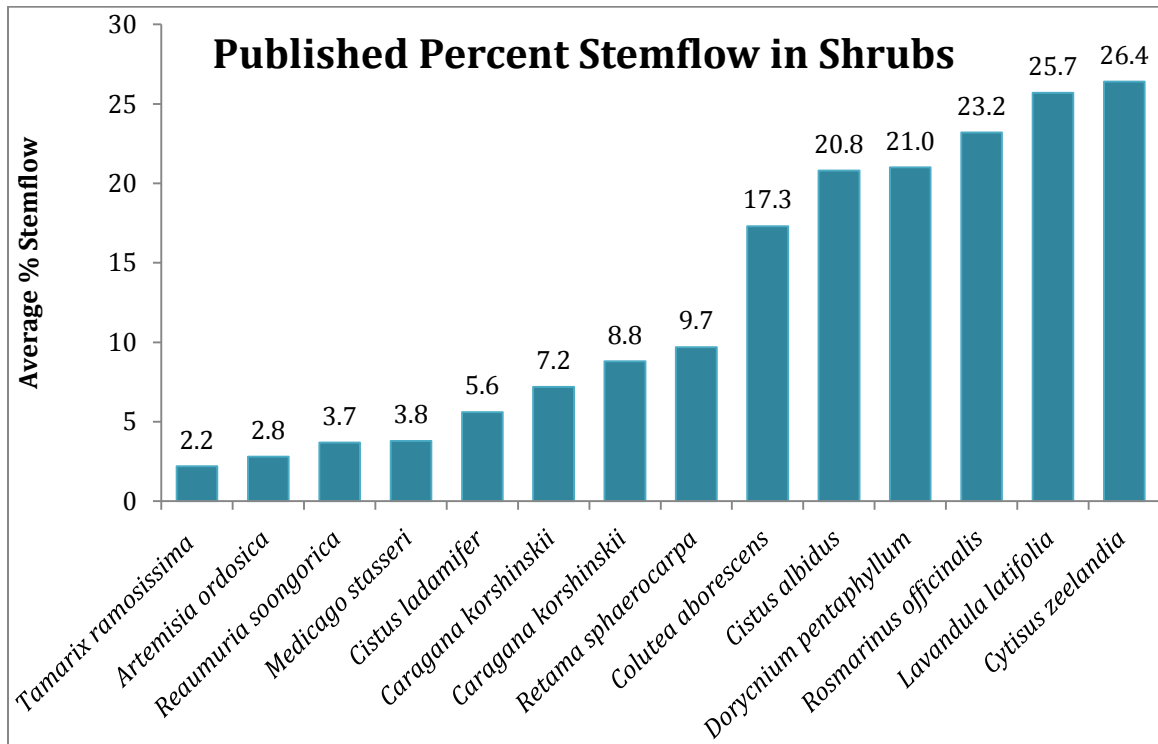


Figure 2- Published Percent Stemflow in Shrubs, Sources: Li et al, 2008; Zhang et al, 2013; and Garcia-Estringana et al, 2010

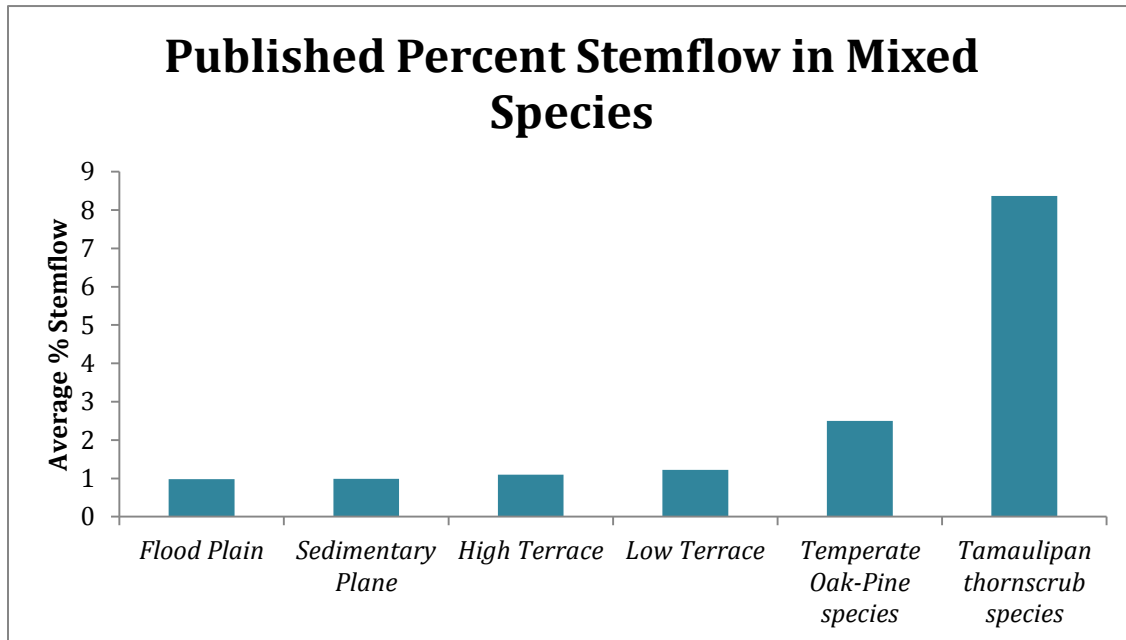


Figure 3- Published Percent Stemflow in Mixed Species, Sources: Navar, 2011 and Marin et al, 2000

Studies are inconclusive on the relationship between rainfall intensity and stemflow amounts. In one study it is found that rainfall intensity and stemflow have an inverse relationship (Mauchamp and Janeau 1993). This contrasts with another study that concludes that with rainfall rates below 2 mm/h, stemflow and rainfall intensity are directly proportional with the inverse relationship only being seen when rainfall is greater than 2 mm/h. This leaves the question of how exactly stemflow of shrubs is affected by rainfall intensity. By recording the intensity of each rainfall event along with the amount of stemflow collected, any patterns between the two may be seen. Another factor to consider is wind direction and speed. A greater wind speed may decrease the amount of stemflow while the direction of wind may change the distribution of stemflow throughout the plant.

Other factors affecting stemflow may be duration of rain, leaf cover and angle of branches. These factors need to be studied in order to increase the understanding of stemflow and its significance.

Goals

This study was intended to quantify stemflow for three different shrub species in an urban area. It was then determined if there was a significant difference in stemflow between shrub species. In addition, factors needed to predict stemflow were identified through linear regression modeling. These significant factors were determined by examining characteristics about the individual, as well as each rainfall event. This allows for greater understanding of what impacts the amount of stemflow expected for certain species and rainfall events. This information can be used to better understand the partitioning of rainfall, which is valuable information in green infrastructure design. When choosing species to include in a green infrastructure installment, a clear understanding of the hydrologic interactions expected will allow for the most informed decisions to be made. This study will begin by examining stemflow for three shrub species that are candidates for green infrastructure design.

CHAPTER 2: METHODS

Location and Shrub Species

This study was conducted in Philadelphia, PA at 32nd and Winter Streets. Three different species were used in this study: *Prunus laurocerasus* 'Otto Luyken', *Hydrangea quercifolia* 'Alice', and *Itea virginica* 'Little Henry'. A top view of these species can be seen below in Figure 4. Two individuals were of each species were studied. All individuals were received in 12 quart pots, except the *P. laurocerasus* which were in 28 quart pots upon arrival. *H. quercifolia* were replanted in 28 quart pots shortly after purchasing to ensure they remained healthy.

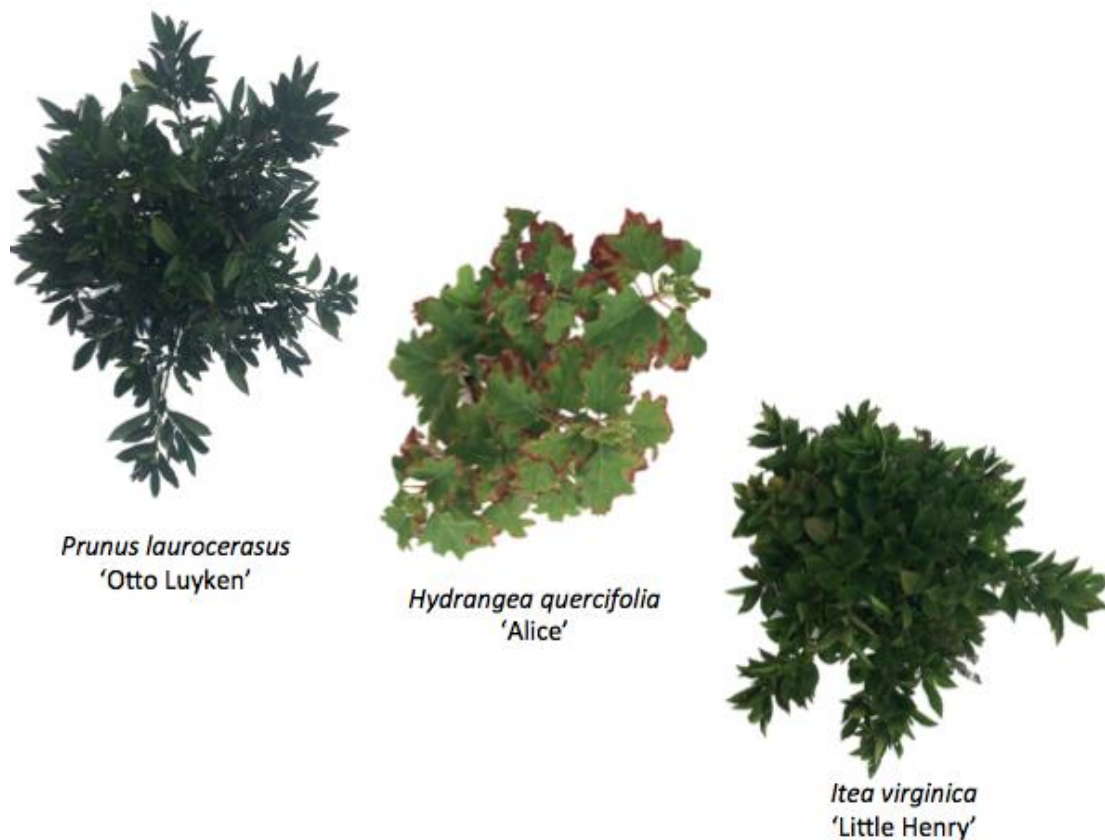


Figure 4- Species Studied

P. laurocerasus 'Otto Luyken' is a compact cultivar. It can grow to be one meter tall and, if not pruned, spread two meters wide. Leaves are oblong and flowers grow in racemes that bloom in April and May. Small drupes then grow and ripen in the late summer. *H. quercifolia* 'Alice' can grow up to two meters tall and equally as wide. Leaves can grow up to 15 centimeters long and have large lobes. Flowers grow in panicles that bloom around June. Bark of these stems peels off in sheets. *I. virginica* 'Little Henry' is native to Missouri, with Little Henry being the dwarf cultivar. These usually grow between one half meter tall, with a circular spread three quarters of a meter. Cylindrical flowers bloom in the summer and grow to be seven to ten centimeters long, and oval leaves range from two to ten centimeters. Leaves do not fall until early winter. These species were chosen because they are found on planting plans for green infrastructure in Philadelphia. All three of these species are found in stormwater management practices on Drexel University's campus.

Design Setup

To collect stemflow, collars were created on select branches of each individual, seen below in Figure 5. Branches were chosen to provide a variety of angles, circumferences, and aerial projected area sizes. A total of 12 branches were collared during this study. There were six collars on *P. laurocerasus*, five collars on *H. quercifolia*, and six collars on *I. virginica*. This allowed differences in stemflow amounts expected as each of these variables changes to be determined. Collars were not constructed on every branch of each individual and therefore this study does

not represent stemflow of the plant as a whole, rather the stemflow in individual branches.



Figure 5- Collar Design

The collar was created with heavy-duty aluminum foil and reinforced with 18 gauge aluminum wire. Vinyl tubing with a 0.6 centimeter outer diameter was secured to each stem using construction adhesive. Each tube was notched in a “V” shape so that it was flush against the branch when attached. The metal collar was constructed around the tube to fit each branch. The outside of the collar was then wrapped in a spiral of aluminum wire and sealed inside and out with construction adhesive. The vinyl tube was fed into a plastic soda bottle through a hole that was drilled in the cap. The sealant was also used to waterproof the opening in the cap. The only variation in setup is a 0.95 centimeter diameter vinyl tubing extender

attached the 0.6 centimeter tubing to accommodate the larger pot size of the *H. quercifolia* specimens. Bottles were kept upright around the pot using mildew resistant rope that was tied around the pot and bottles as seen in Figure 6.



Figure 6- Stemflow Collection System and HOBO Weather Station

Data Collection

For the purpose of this study, an inter-event rain period was defined as 12 hours. After each rain event, the weight of each bottle in grams was recorded. Two bottle sets were used, meaning dry bottles could be reattached to the plants after each event. The dry tare weight of each bottle was recorded and subtracted from the total weight to determine the weight of just stemflow after each event.

Bulk precipitation amount was available from several different sources. Options for rainfall data were a USGS gauge 850 meters away along the Schuylkill River, two tipping buckets in a weather station on site, a tipping bucket rain gauge on a Drexel University roof, or on-site containers that collected rainwater and were manually weighed and emptied. After analyzing the pros and cons of each option, the manually emptied containers were selected as the preferred rainfall measurement. The on-site tipping buckets, seen in Figure 7, were selected as the secondary rainfall record if data was missing from the primary source.

The weather station on site also provided wind direction, gust speed, wind speed, temperature, relative humidity, and time series event data. This data was available for the majority of the data collection time period. Any storms that there was precipitation data available but not supplemental data were included in averages, but excluded from further analysis.

CHAPTER 3: DATA ANALYSIS

The aerial projected area of each branch was needed convert from weight collected to depth of stemflow. This area can be defined as the area in square centimeters of the plant that rain would fall on, or the area looking straight down the y-direction at the plant. To determine the aerial projected area, photos were taken of the top view of each plant. This represents the area that precipitation would fall on during a rainfall event. Photos were taken of both the whole individual, as well as each specific collared branch. To minimize the amount of noise in the background of the photo, white paper was arranged to cover the pot and ground of the plant. For images showing the area of one collared branch, white cloth was used to cover the sections of the plant leading into the collar of interest. When taking photos, a reference square of 5 centimeters was held flat and at the same height as the widest part of the plant in each photo for use when processing the image.

Areas were determined using ImageJ software. Using the reference square held in the photograph, a scale of the image was set. This allows each pixel to be assigned an area. Next, the background of the photo was removed using the “Threshold Colour” feature and manual deletion of sections. Once the background of the photo was removed, the photo type was changed from 24 bit to 8 bit and the “adjust” “threshold” was used to color fill in the total area in red. Finally the “analyze” feature was used to output both the area as an excel file and a mask of the plant. The mask shows, in black and white, the pixels that were included in the area calculation. This was checked to ensure that no background noise was included in the area

calculation. A second validation was ensuring that the area of the reference square was reported accurately. The image below in Figure 7 shows a raw image and the mask of the image after processing.



Figure 7- ImageJ Area Analysis

Throughout the growing season, the aerial area of each plant was monitored. The minimum area and the maximum area observed throughout the season were compared to the area volumes taken on July 27th, or base value, to create a range for each species. *P. laurocerasus*, *H. quercifolia*, and *I. virginica* were found to be +/- 9, 16, and 30 percent of the base value, respectively.

Once the area for each branch was determined stemflow could be converted from grams to millimeters using Equation 1. The same calculation was used for the collected rainfall. Since a funnel led into the collection jug, the area of the funnel was used to convert from grams to millimeters rainfall. Percent stemflow, defined by the amount of incident rainfall that became stemflow, was then calculated as seen in Equation 2.

Equation 1- Weight to Depth Equation

$$Depth(mm) = \frac{10 * Weight(g)}{Area(cm^2)}$$

Equation 2- Percent Stemflow Equation

$$\% Stemflow = \frac{Depth Stemflow (mm)}{Depth Precipitation (mm)} * 100$$

Data about each precipitation event and the collared branches themselves was also compiled. Precipitation and stemflow depths were calculated using the area and weight of collected water, using the equation below. Evaporation from the bottles was found to be small, and unnecessary to account for in the period of time

between the rainfall event and the collection of sampling bottles. The amount of water remaining in the funnel and tubes was negligible as well, and therefore not included in calculations.

Circumference of each collared branch was determined by wrapping string around the branch directly above the collar. If the top of the collar had two branches entering the collar, the measurement from the larger branch was used. Branch angle was also determined for each collared branch. Photos taken parallel to the ground at collar height were processed in ImageJ to calculate the angle of each branch. The average leaf attachment for each species was also determined by taking the average attachment angle of five leaves from each species. The final characteristic about the collared branches collected was the cardinal direction each funnel faced. These were defined as N, S, E, W, NE, NW, SE and SW. The total time it was actively raining during each event was determined using data from the weather station. Intensity was determined by dividing the total depth by the length of each event. Gust speed, wind speed, wind direction, temperature, and relative humidity were provided by the weather station.

These additional characteristics were used in linear regression modeling to determine if stemflow could be predicted using known information about the individual and the event. Using SPSS, a stepwise linear regression model was created to determine which variables were statistically significant when predicting stemflow. The linear regression model includes the most statistically significant variable on the first iteration, then keeps adding one more variable until the model is no longer made more accurate with further additions. The final iteration includes

variables that are statistically significant when predicting the dependent variable.

The datasets examined were *P. laurocerasus*, *H. quercifolia*, *I. virginica*, and a fourth that included data from all species. Stemflow was defined as the dependent variable while the date of event, time of event, collar direction, gust speed, wind speed, wind direction, temperature, relative humidity, length of event, event intensity, event volume, branch angle, branch circumference, and aerial branch area were defined as the independent variables.

Table 1- Model Options

Option	Dependent Variable	Independent Variables
Model 1	LN % SF	LN
Model 2	LN % SF	Raw
Model 3	% SF	LN
Model 4	% SF	Raw
Model 5	Volume SF	LN
Model 6	Volume SF	Raw
Model 7	LN Volume SF	LN
Model 8	LN Volume SF	Raw

Eight model options, seen above in Table 1, were created by varying whether stemflow was expressed as a percent or as a volume, if the natural log of stemflow

was taken before analysis, and if the natural log of the independent variables was taken before analysis or not. All eight models used an alpha value of 0.1 to give a 90 percent confidence interval. The most appropriate model was chosen for each data set based on the R^2 value, the fit of the observed vs expected line, and the homoscedasticity scatter plot. The better the fit of the model, the more the variation in stemflow could be explained by the independent variables. Once a model type was selected for each dataset, the independent variables that were included in the final iteration of the model run represent the variables that are statistically significant when estimating stemflow.

CHAPTER 4: RESULTS

There were 25 rain events with data collected from June 6th, 2015 to October 10th, 2015, as seen on Figure 8. The minimum rain event depth during this time period was 0.75 mm and the maximum rain event depth was 60.16 mm. The average storm depth was 19.25 mm and the median depth was 14.05 mm.

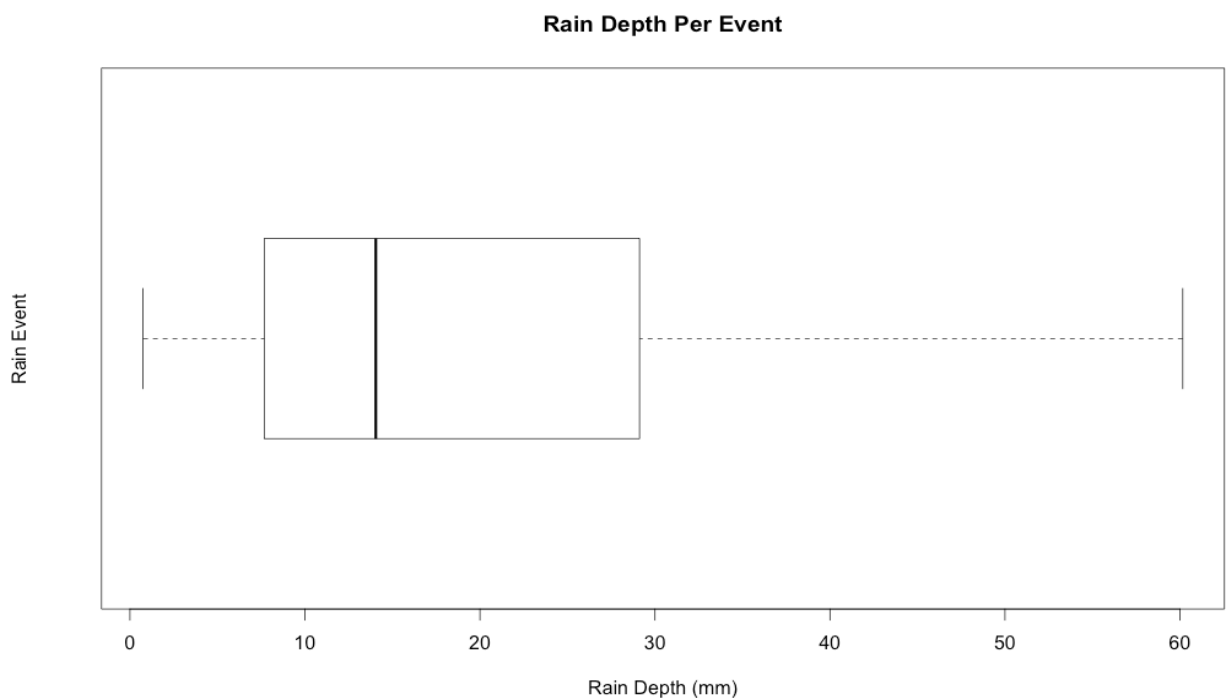


Figure 8- Rain Events Throughout Sampling Period

Stemflow was first examined as a percent per branch in each rain event, seen in Figure 9. Over the 25 rain events studied, the average of the six *P. laurocerasus* branches had an average stemflow of 11.4 %. The maximum percent stemflow found of one branch in one storm was found to be 54.0 %. *H. quercifolia* had an

average stemflow of 7.0 % and a maximum value of 57.6 %. *I. virginica* had an average of 4.4 % stemflow and a maximum of 27.7 %.

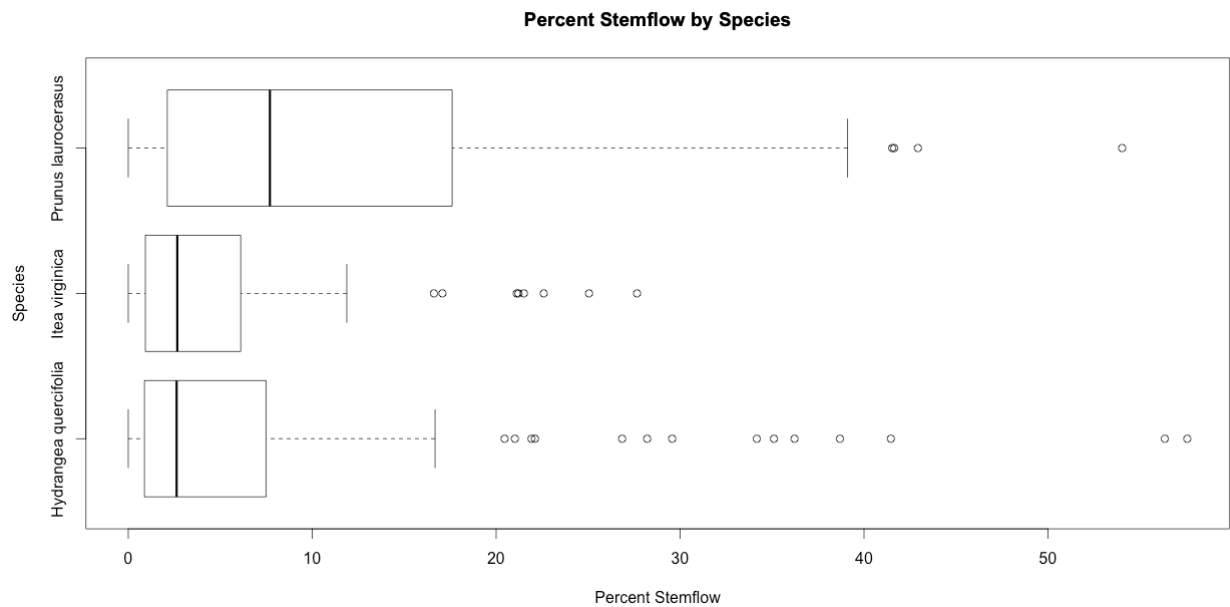


Figure 9- Percent Stemflow in Individual Branches in Each Event

These average values across the sampling period were compared with other species with published stemflow percent data. Figure 10 shows that all three species in this study fall within the published range of 2.2 to 26.4 percent stemflow.

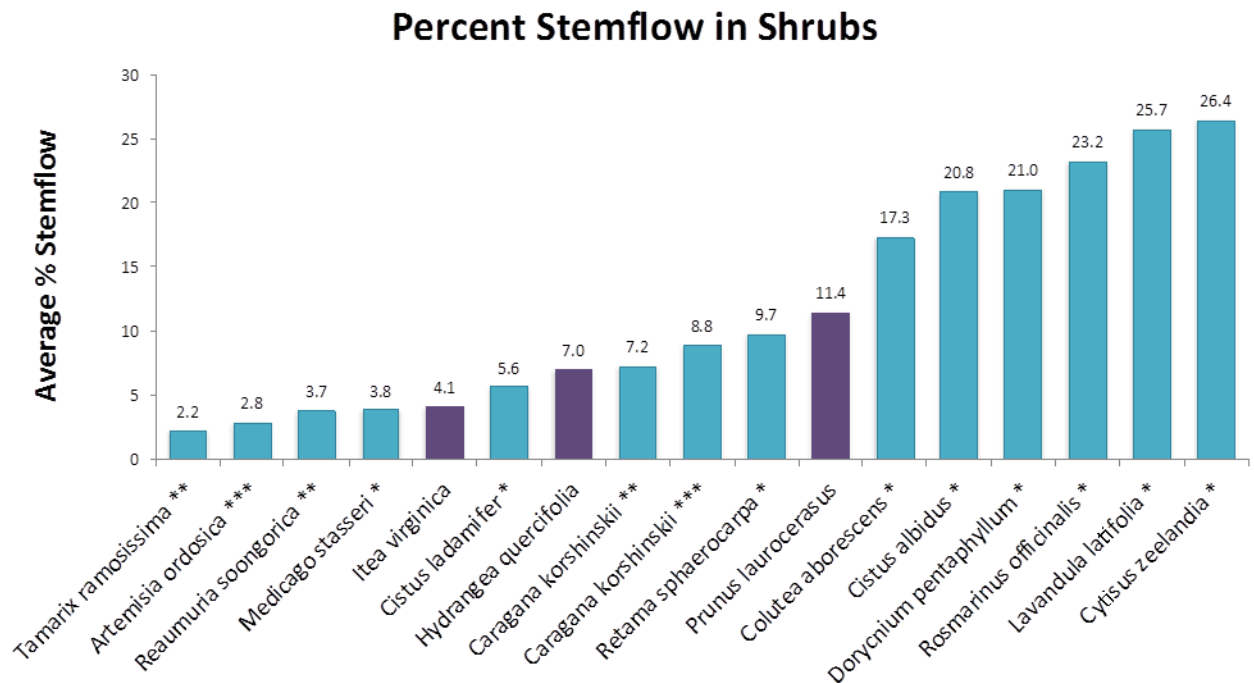


Figure 10- Determined Percent Stemflow Compared to Other Species, Sources: Li et al, 2008; Zhang et al, 2013; and Garcia-Estringana et al, 2010

To demonstrate the range in percent stemflow due to growth in the individual throughout the season, error bars are shown in Figure 11. The range in averages for *P. laurocerasus* was between 10.39 and 12.55 % stemflow. *H. quercifolia* ranged from 5.88 % to 8.34 % stemflow, and *I. virginica* fell between 3.07 % and 6.27 % stemflow.

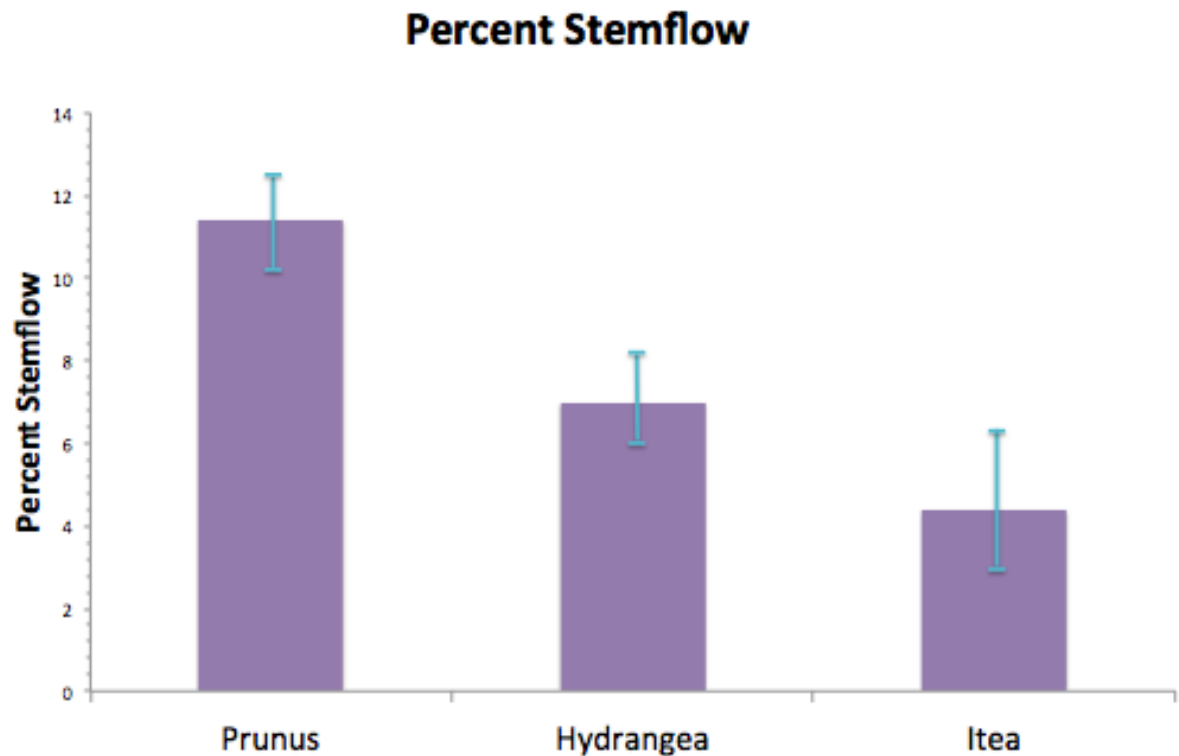


Figure 11- Range in Percent Stemflow Across Growing Season

Event depth versus the average percent stemflow found for each species was graphed to show trends for the three species. A best-fit line was added for each species, to determine if there is a relationship between event depth and percent stemflow. In Figures 12, 13, and 14 the slope and R^2 values can be seen for each of the three species. For the *P. laurocerasus*, the R^2 value was 0.032, the *H. quercifolia* the R^2 value was 0.217 and, for the *I. virginica* the R^2 value was 0.001.

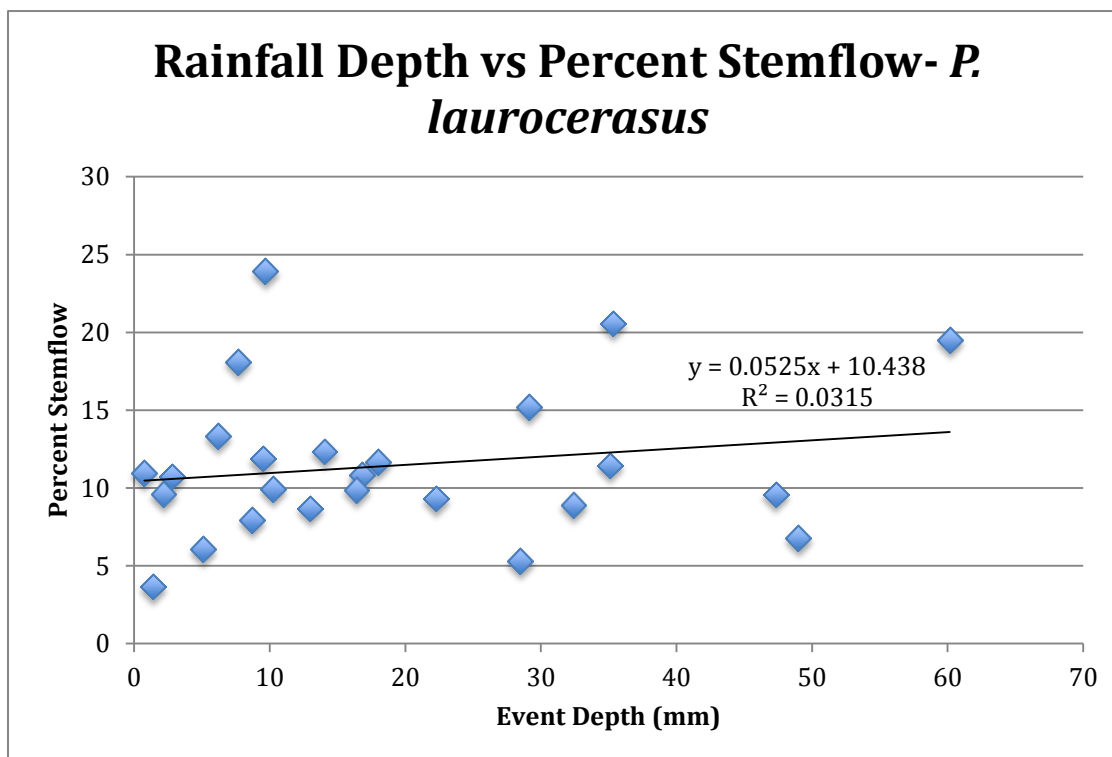


Figure 12- Event Depth vs Percent Stemflow for *P. laurocerasus*

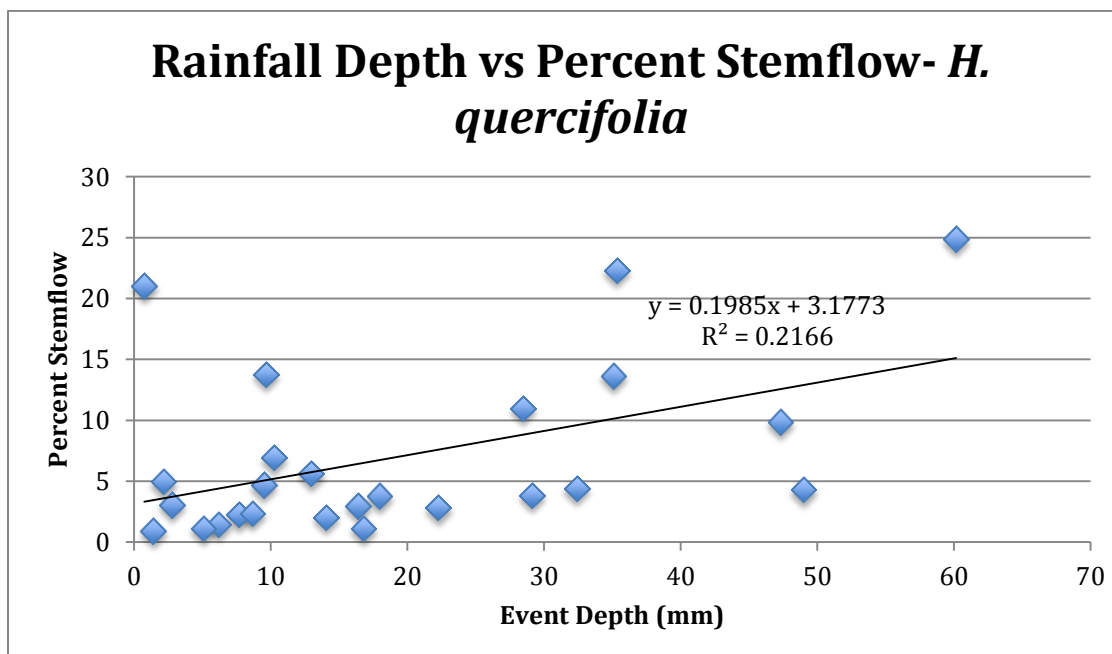


Figure 13- Event Depth vs Percent Stemflow for *H. quercifolia*

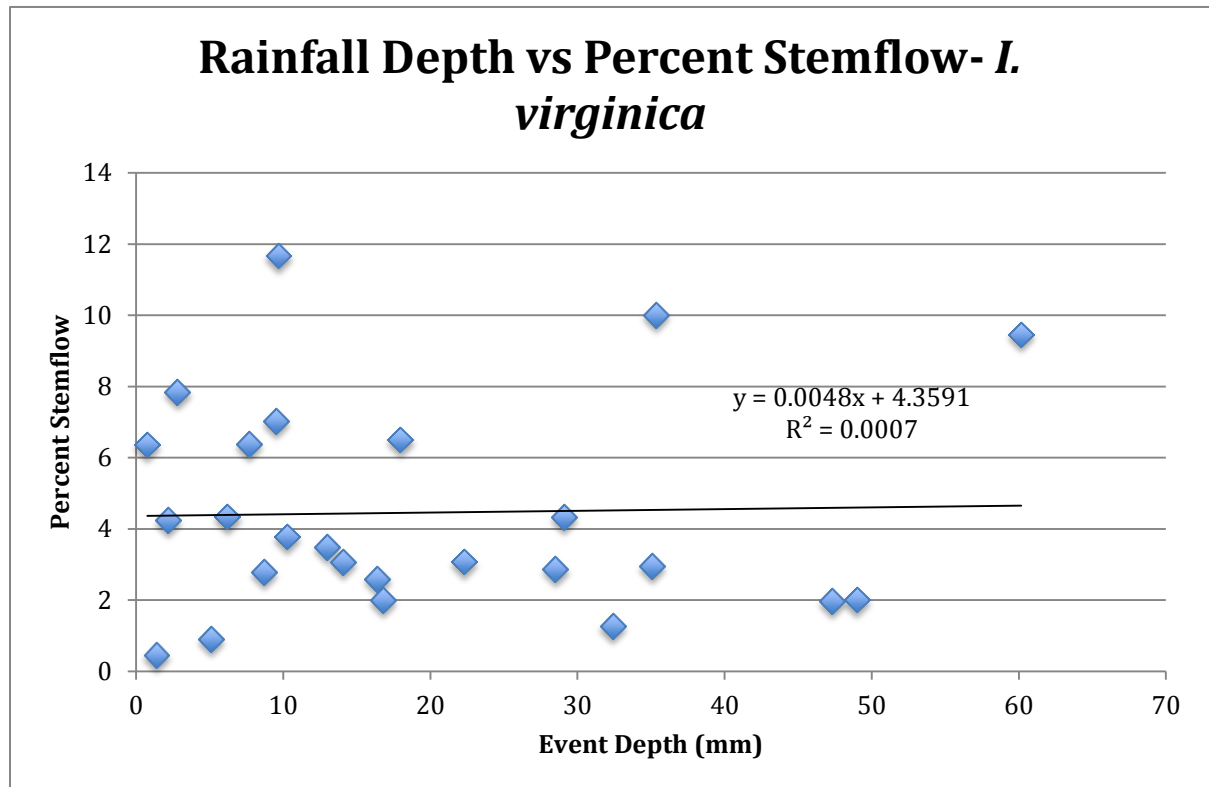


Figure 14- Event Depth vs Percent Stemflow for *I. virginica*

Rain events were then separated into events less than 14.05 mm, the median for the sampling period, and events greater than 14.05 mm. This represents small and large events for this particular sampling season. These are shown in Figures 15, 16, and 17 with blue data points representing small rainfall events and red data points representing large rainfall events. For small events, R^2 values were 0.100, 0.031, and 0.0045 for *P. laurocerasus*, *H. quercifolia*, and *I. virginica* respectively. Large events showed R^2 values of 0.087, 0.432, and 0.086 for *P. laurocerasus*, *H. quercifolia*, and *I. virginica*.

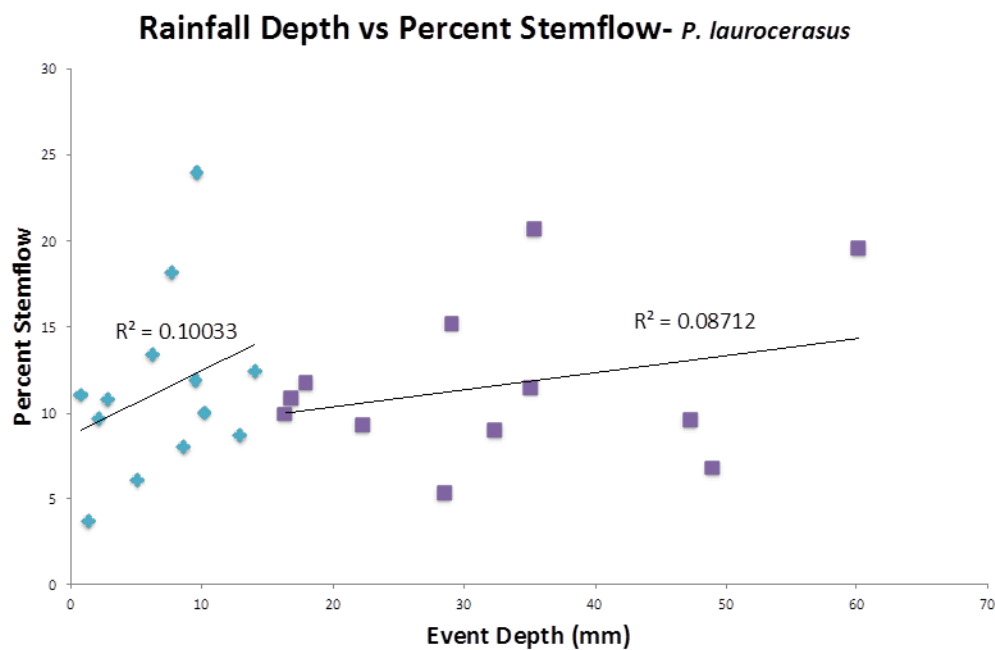


Figure 15- Small and Large Events for *P. laurocerasus*

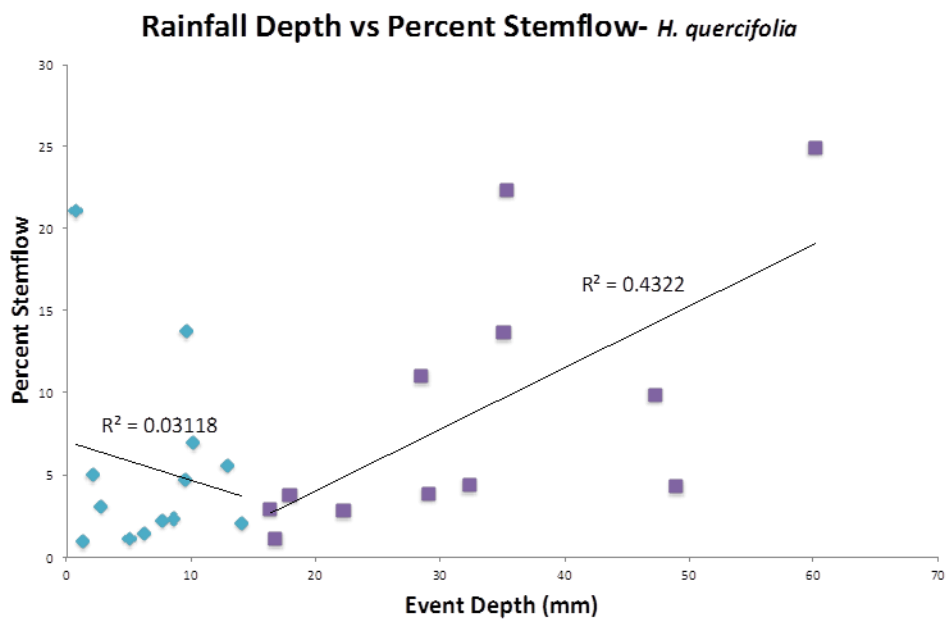


Figure 16- Small and Large Events for *H. quercifolia*

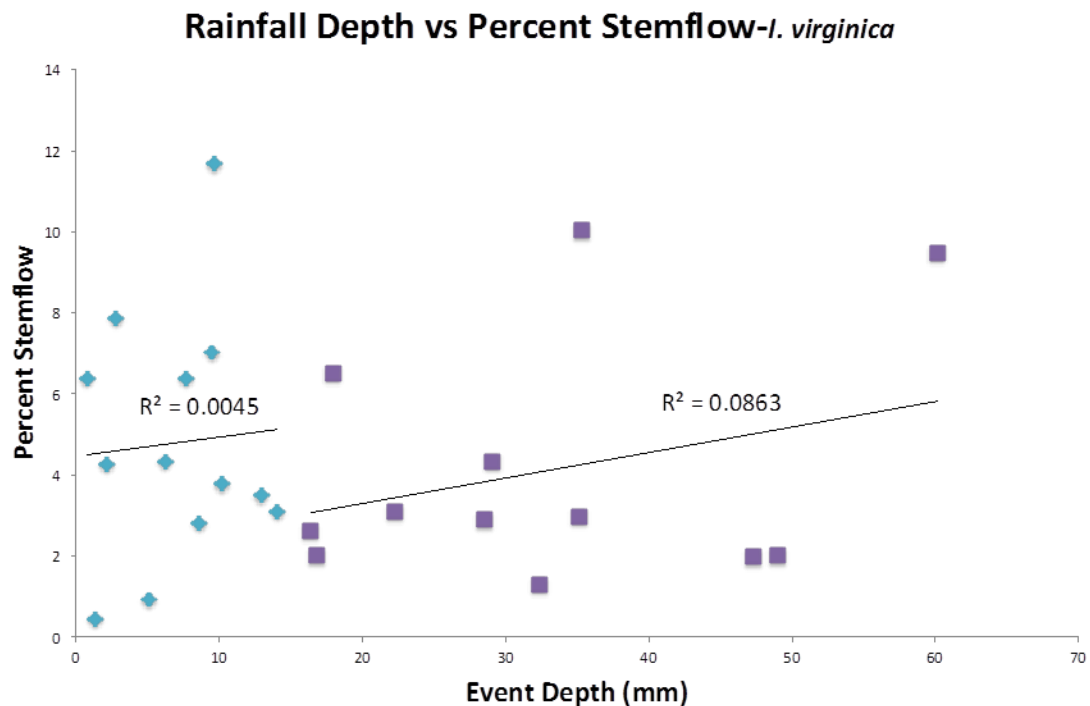


Figure 17- Small and Large Events for *I. virginica*

Linear regression in SPSS was used to determine which independent variables were statistically significant when predicting stemflow. For all four data sets, the dependent variable used in the model that gave the best fit was the natural log of stemflow volume. The datasets for *P. laurocerasus*, *H. quercifolia*, and all data had best results when the independent variables were normal, while the *I. virginica* data set was best when the natural log was taken of independent variables. Fit of each model against the expected line is shown below in Figures 18, 19, 20, and 21 for the four respective data sets.

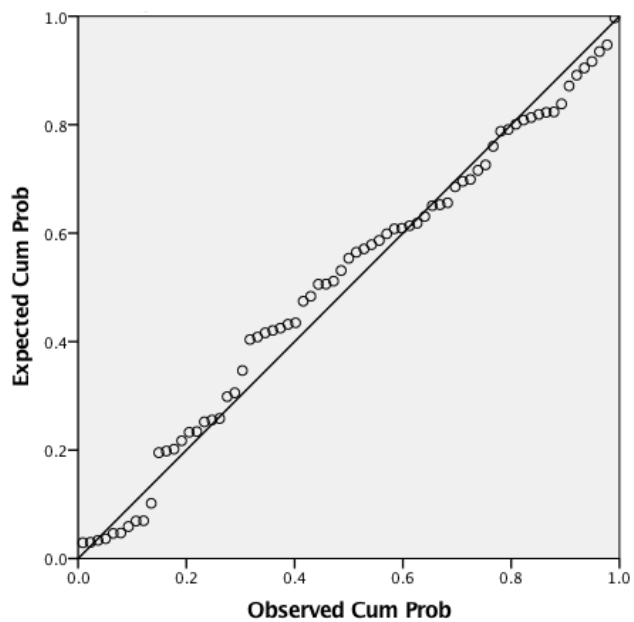


Figure 18- Fit of *P. laurocerasus* SPSS Model

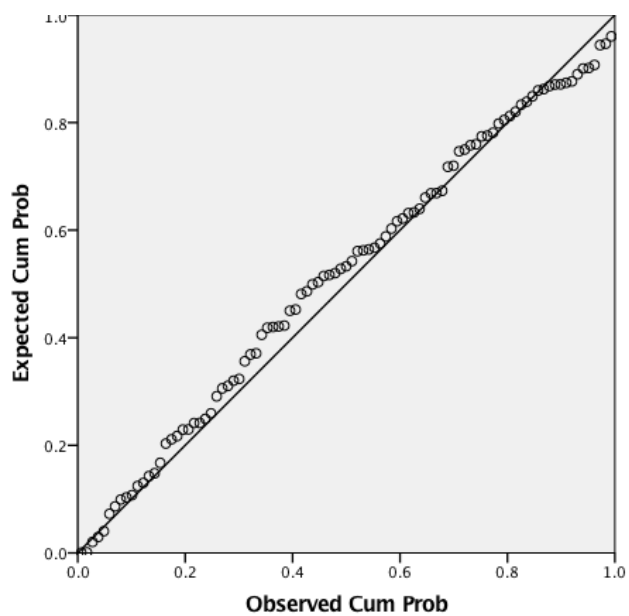


Figure 19- Fit of *H. quercifolia* SPSS Model

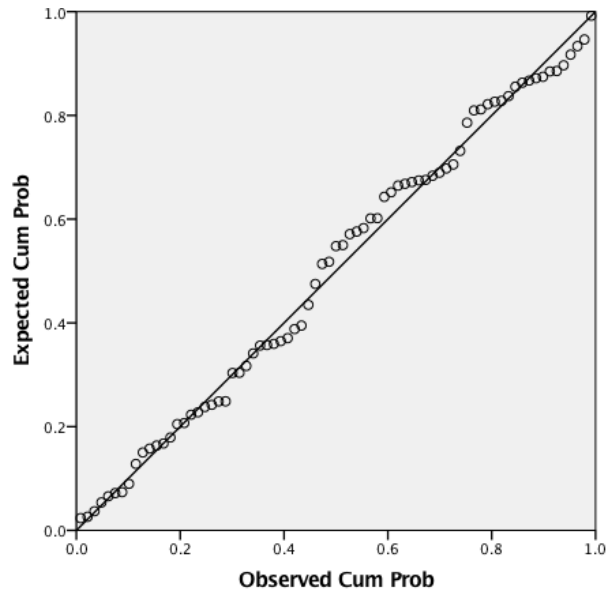


Figure 20- Fit of *I. virginica* SPSS Model

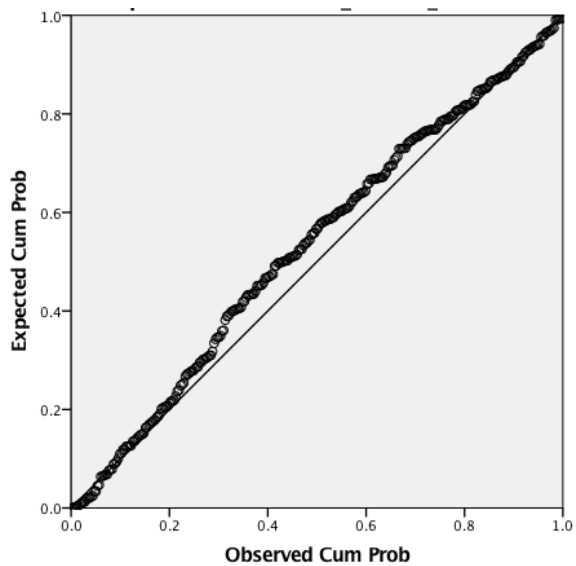


Figure 21- Fit of All Data SPSS Model

In Table 2, it is shown that the *P. laurocerasus* dataset had an R^2 value of 0.777.

This model included branch circumference, gust speed, collar direction, relative

humidity, temperature, branch angle, and aerial branch area as the statistically significant variables. *H. quercifolia*'s R^2 value was 0.551, seen in Table 3, and included branch circumference, gust speed, relative humidity, aerial branch area, total volume, and date. In Table 4, for *I. virginica*, the maximum R^2 value was found to be 0.785. This model included the natural log of gust speed, wind speed, total volume, branch area, wind direction, event intensity, collar direction and date. The final data set is shown in Table 5 and included data from all three species. This model had an R^2 value of 0.569 and included branch circumference, gust speed, species, relative humidity, aerial branch area, and date.

Table 2- *P. laurocerasus* Significant Variables

Variable	Coefficient
R^2	0.777
Branch Circumference	1.30
Gust Speed	0.34
Collar Direction	0.31
Relative Humidity	0.26
Temperature	-0.09
Branch Angle	-0.06
Projected Branch Area	0.02

Table 3- *H. quercifolia* Significant Variables

Variable	Coefficient
R²	0.551
Branch Circumference	0.98
Gust Speed	0.43
Relative Humidity	0.16
Projected Branch Area	0.03
Total Volume	0.01
Date	1.80E-07

Table 4- *I. virginica* Significant Variables

Variable	Coefficient
R²	0.785
LN Gust Speed	-2.63
LN Wind Speed	2.11
LN Total Volume	1.70
LN Projected Branch Area	-1.52
LN Wind Direction	0.77
LN Event Intensity	-0.44
Collar Direction	0.19
Date	2.32E-07

Table 5- All Data Significant Variables

Variable	Coefficient
R²	0.569
Branch Circumference	0.88
Gust Speed	0.52
Species	0.37
Relative Humidity	0.23
Projected Branch Area	0.01
Date	2.24E-07

CHAPTER 5: DISCUSSION

Stemflow values determined in this study are comparable with values found for other shrub species (Li et al, 2008; Zhang et al, 2013; and Garcia-Estringana et al, 2010). Previous studies found stemflow values ranging from 2.2 to 26.4 percent. This study found values that stemflow averaged 11.42, 7.00 and 4.39 percent for *P. laurocerasus*, *H. quercifolia*, and *I. virginica* respectively. A conclusive link between rainfall event and stemflow was not found, with the highest R^2 being 0.43 in *H. quercifolia* during large events. Significant factors when predicting stemflow amounts were, however identified through SPSS models.

Based on these models, there are significant differences in stemflow between these three species of shrubs. This information can be utilized in applications such as stormwater management design. A larger percent stemflow would indicate to a designer that a certain species would be able to direct larger amounts of water into the ground. Stormwater management practices want the most water possible to infiltrate, so species with higher percent stemflow should be chosen for green infrastructure installments. When choosing species for a green infrastructure project, it is important to make sure that plants can handle large amounts of water and pollution and that they are able to help direct as much water as possible into the ground. Choosing species with higher stemflow can help the green infrastructure sites infiltrate the most stormwater into the ground. This reduces the amount of runoff experienced during a rainfall event, which is the goal of green infrastructure. Understanding more about water budgets, and differences in water budgets between species will help designers make more informed decisions.

Each model did not result in the same variables being significant when predicting stemflow. Future studies should examine the differences between species that could be causing these discrepancies in significant variables. Throughout the study, the individuals were kept in pots instead of planted in the ground. This could change normal interactions the plants may have if they were planted in the ground, as they would be in any green infrastructure application. It is possible that being planted at ground level would influence the humidity around the plant, or how much wind the plant is subjected to. These factors would influence the amount stemflow expected. Future studies should focus on individuals in different environments to examine differences this could cause in stemflow. Plants in a heavily shaded environment may have different rainfall partitioning than plants in direct sunlight during a majority of the day. Another example could be plants in a wind tunnel created by urban buildings versus plants on the leeward side of a hill. Comparisons in stemflow could be examined between individuals in pots, well-spaced individuals planted in the ground, and individuals surrounded by other plants.

Another factor that could be greatly affecting stemflow between the species is several stresses the plants endured during the growing season. The leaves of the *I. virginica* individuals sustained a great number of insect damage. This may have decreased the amount of stemflow this species would normally have seen by allowing the precipitation to flow through these holes instead of being directed to the stem. Similarly, *H. quercifolia* suffered from sunscald, or plant sunburn. This

caused the edges of the leaves to become brown, brittle, and curled. This, too, would change the interactions between rainfall and the leaves.

R^2 values relating the amount of stemflow observed to the amount of stemflow predicted based on independent variables examined varried from 0.55 to .78 between species. This means that between 55 % and 78 % of variation in stemflow is explained by the examined factors. Between 45 % and 22 % of stemflow variation is still unexplained. Other factors should be examined to try to close this gap.

CHAPTER 6: CONCLUSION

This study determined that stemflow averages between 3 % and 12 % for the three species studied. It was found that there is a significant difference in stemflow between species and that between 55 % and 79 % of stemflow can be explained by the examined independent variables. Knowing that different species of shrubs have significantly different amounts of stemflow can help in the design of green infrastructure. If shrubs with higher stemflow amounts are chosen, this will allow designers to account for the fact that more water will be funneled directly to the ground. This can impact the efficiency of infiltration in a green infrastructure installation. Designs can be improved with less uncertainty about the hydrology of the chosen species.

Future studies should look for additional variables that may impact stemflow and isolate variables to help determine the impact of each variable on stemflow. Some possible factors that should be examined is the leaf area index of each individual, and age of the individual. It is also generally accepted that some plants may have microclimates surrounding them. Certain species may naturally be surrounded with slightly higher humidity or temperature, which would impact the amount of stemflow being collected. Future studies on microclimates of different species could help explain these differences.

Future studies should concentrate on isolating the studied independent variables to see the impacts of each one individually. New independent variables should be looked at to explain the remaining uncertainty in stemflow amounts. When choosing species to study, it would be beneficial to examine species that have

published percent stemflow values as a form of method validation. Additionally, studying species that are native and can tolerate conditions present in green infrastructure can provide the most benefit.

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