

Quantifying Tree Canopy Contributions to Stormwater Runoff Reductions in Urban Watersheds of the Southeastern United States

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ABSTRACT

Urban stormwater is a major contributor to surface water degradation in the United States, prompting cities to invest in ways to naturally capture, store, and slowly release runoff through “Green Infrastructure” (GI). One often overlooked potential contributors to stormwater management are urban trees, an integral part of a given city’s GI. Interception is of particular interest and describes a tree’s ability to capture and store rainfall, reducing the volume of stormwater that can degrade urban streams during storm events. While rainfall interception for full canopy, forested environments is well studied, limited research is available that characterizes the interception of open-grown trees, which are commonly found in urban areas. Nine trees from three common, urban, native species planted in three Knoxville-area parks were studied to quantify interception. Continuous measurements of were made using several automatic rain gauges positioned underneath tree canopies. When compared to gross precipitation, the measurements quantify interception, throughfall (rainfall that passes through the canopy) and stemflow (rainfall that travels down the trunk) of each tree. Data was collected from January 2018 to May 2019 to account for seasonal variations in canopy cover and precipitation patterns. Annually, red maples (*Acer rubrum*), white pines (*Pinus strobus*), and willow oaks (*Quercus phellos*) intercepted 24.4%, 52.4%, and 33.2% of gross throughfall, respectively. Further results demonstrate the effect of event duration, rainfall intensity, and seasonal variations on the interception potential of each species. Overall, these observations are a step toward allowing the storage capacity of urban trees to be properly credited as part of urban watershed restoration efforts.

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CHAPTER ONE

INTRODUCTION AND BACKGROUND

Introduction

Urban tree canopies increase the livability of cities by providing environmental and psycho-social benefits to the urban habitat. From an environmental standpoint, the urban canopy provides shade on hot summer days, reduces the effects of the urban heat island by releasing water vapor during the process of evapotranspiration and shading heat-reflecting surfaces, and reduces the potential for nuisance flooding and other runoff-related issues by intercepting and storing a percentage of rainfall from storm events (Xiao et al. 2000, Kuehler et al. 2017, Xiao and McPherson 2016, Zabret and Sraj 2018, Smets et al. 2019, Wang and Wang 2020). As well as retaining precipitation, urban trees increase quality-of-life for city inhabitants. Wolf (2003) showed that urban trees both increase the perceived quality-of-life of the inhabitants of urban centers and increase the price evaluation of consumers which may aid in driving economic activity for local businesses. Because excessive runoff is correlated to increased cost of infrastructure maintenance, soil erosion, and contaminant flushing which degrade the quality of urban aquatic environments, the National Academy of Engineering urges cities around the world to develop green infrastructure practices, such as the restoration of the urban tree canopy, to address the consequences of increased runoff volume and intensity while increasing the livability of urban centers (National Academy of Engineering 2008). For these reasons, greening efforts in major cities can be seen across the United States. In Nashville, Tennessee, stormwater management has shifted to a focus on green infrastructure and specifically to the co-benefits of the urban canopy in hopes of also weatherizing the city. Other efforts, such as those of Chesapeake Bay, aim to provide nutrient removal through tree root uptake and canopy retention (Prescott 2002) to preserve and restore the surrounding aquatic environment, and as a result, dozens of tree canopy restoration projects have been launched throughout the Northeastern United States. To properly credit urban trees for restoration efforts, a holistic understanding of the interception potential of urban tree species is imperative. Such crediting is used by watershed planners for prioritizing implementation of stormwater control measures (SCMs).

Urban runoff

As urban centers develop, there is a shift in cycles governing pollutant fate and water balances because of anthropogenic influences. These influences come in the form of physical changes to the environment such as concrete infrastructure that increases impervious surface, the addition of pollutants that are found in manmade materials such as oil, rubber, and metals, and the compaction of soils that decreases the natural permeability of the land. The combination of these physical additions to the environment creates a heterogeneous landscape with a highly complex water cycle that is rapidly evolving alongside further development and climate change (Kerkez et al. 2016, Kuehler et al. 2017, Wirion et al. 2017, Wałęga et al. 2019). Impacts of these changes to the natural system include increased rates and volumes of runoff that degrade the quality of urban streams, cause nuisance flooding, and decrease the lifespan of urban infrastructure (Inkiläinen et al. 2013, Kerkez et al. 2016, Epps and Hathaway 2018). To combat the effect of urban development on stormwater runoff, green infrastructure (GI) is becoming an increasingly popular way to restore natural function to the urban environment. While flood management is the main design goal of stormwater management, the use of green infrastructure produces additional benefits such as adding economic value to cities, sequestering atmospheric carbon, providing localized cooling to aid in mitigation of the urban heat island effect, and increasing air quality (Wolf 2003, Alves et al. 2019, Marando et al. 2019). Many forms of green infrastructure exist, and urban trees are often overlooked as a component of the green infrastructure system.

Urban tree canopies

Urban trees provide all the previously discussed benefits and co-benefits of green infrastructure. Trees are capable of significantly decreasing local temperatures in urban areas by providing shade and evaporative cooling, promoting infiltration by increasing the permeability of compacted urban soils through root development, and intercepting rainfall by allowing a portion of gross precipitation to be captured on leaf and branch surfaces where it is returned to the atmosphere through evaporation (Lin et al. 2016, Kuehler et al. 2017, Caplan et al. 2019). All of these benefits are worthy of further research, but studies quantifying rainfall interception of open-grown trees are scarce in literature.

Li et al. (1997), Xiao et al. (2000a), Guevara-Escobar et al. (2007), Staelens et al. (2008), Asadian and Weiler (2009), Asadian (2010), Livesley et al. (2014), Nytch et al. (2019), Smets et

al. (2019), Zabret and Sraj (2019), and others have quantified the interception losses of individuals, finding a range of 6 - 44% of gross precipitation for various deciduous tree species and 44.7 – 60.9% of gross precipitation for conifers. Fewer studies have quantified the impact of the urban forest on overall watershed hydrologic function. In one of the few such studies, Xiao and McPherson (2002) modelled annual rainfall interception of the urban trees in Santa Monica, California, determining that 1.6% of annual precipitation was captured by urban trees which was estimated to save \$110,890 of stormwater management and flood control measures. According to the same study, the savings were \$3.60 per year for 29,299 trees with only 570 mm of rainfall occurring over the simulated year. In Eastern Tennessee, where precipitation is between 40 and 50 inches per year (1,016 – 1,270 mm per year) and vegetation is more abundant, the annual flood control savings are likely to be even higher.

The lack of urban runoff reduction studies performed at the watershed or city scale is in part because of a lack of model verification such as that performed by Smets et al. (2019), and partly due to a lack of empirical data to verify said models against. Interception is highly variable by tree species, foliage density, and regional climate characteristics (Xiao and McPherson 2016, Zabret and Sraj 2018). As such, it is important to contribute to and expand the empirical dataset for trees native to various hydrologic regions as well as trees commonly used for urban landscapes in order to accurately model catchment-scale runoff reductions.

Static vs. Dynamic Storage

A thorough review of previous research on the topic reveals two main approaches to describe interception loss of trees: static storage and dynamic storage (Xiao and McPherson 2016, Smets et al. 2019, Keim et al. 2006). Static storage, otherwise known as minimum storage, saturation storage, canopy storage, or surface storage capacity, is described as the depth of water that must be stored on a tree canopy's surface before precipitation will flow to the ground as throughfall. The most simplistic application of this modeling technique is to assume that any rainfall past this depth will fall to the ground, but such a simple modeling technique does not account for important dynamics that occur during the interception process. Dynamic storage, also known as detention storage or maximum storage, is the amount of water that can be stored on the surface of the canopy temporarily and will either flow to the ground as throughfall, flow down the trunk of the tree as stemflow, or evaporate into the atmosphere after a storm event until the total

storage returns to the static storage capacity (Xiao and McPherson 2016, Keim et al. 2006). Studies that focus on canopy storage capacity and dynamic storage such as those performed by Xiao et al. 2000 and Keim et al. (2006) reveal complex interactions between rainfall characteristics (intensity, depth, and rainfall incidence angle) and tree characteristics (age, species, canopy health, and branch architecture) that influence rainfall interception. Until recently, the majority of the research on rainfall interception has focused on forested areas with widespread canopy cover which is difficult to apply to urban hydrology where most trees are grown in the open with less competition from other tree canopies, influenced by the urban heat island effect, and grown in compacted soils (Asadian and Weiler 2009, Asadian 2010, Kuehler et al. 2017, Smets et al. 2019).

Rainfall interception of open grown trees

Holistically, the rainfall interception process occurs both during and after rainfall events and is controlled by the storage capacity of the tree and the environmental conditions that promote evaporation. As rainfall begins, the canopy captures and stores water. The upper-most layer of leaves of the canopy begin to store water until an individual leaf's storage capacity is reached. Once excess water is added, flow from the leaf will begin which will either travel down the stem and become stored on the branch, fall off the leaf and deposit on another leaf, or fall through a gap in the rest of the canopy directly to the ground. Precipitation obstructed by the canopy that reaches the ground is called throughfall, while precipitation that falls directly through a gap in the canopy and isn't obstructed by any vegetative surfaces is called free throughfall. As the process of canopy wetting and throughfall occur, and after precipitation stops entirely, water is evaporated into the atmosphere as a function of the local temperature.

Many rainfall interception studies find a linear correlation relating interception loss to rainfall (Xiao et al. 2000a, Guevara-Escobar 2007, Staelens et al. 2008, Asadian 2010, Wang et al. 2013, Smets et al. 2019), while others have observed exponential and power functions exhibiting asymptotic behavior (Wang et al. 2013, Livesley et al. 2014). Gash (1979) refined the model created by Rutter et al. (1971) and developed one of the most widely used rainfall interception models today by creating a simplified version that maintains the linearity associated with most models while also describing the process based interception functions within the regression coefficients. While developed for forest stands, the equations describing the Gash interception model are applicable conceptually to the rainfall interception process experienced by open-grown

trees. The Gash model will not be derived here, but a brief explanation of the theory, important equations, and terms will follow. A linear relationship between interception and rainfall is in the form of the equation:

$$I = \mathbf{a}P_G + \mathbf{b}$$

Where I = Interception loss, P_G = Gross precipitation, and $\mathbf{a}$ and $\mathbf{b}$ are the coefficients that describe the slope and intercept of the equation. After derivation of the Gash model $\mathbf{a}$ is described as the mean evaporation rate after the canopy is saturated divided by the mean rainfall rate after the canopy is saturated.

$$\mathbf{a} = \frac{\bar{E}}{\bar{R}}$$

and $\mathbf{b}$ becomes a complicated term described by the storage coefficient, evaporation before canopy saturation, and the proportions of interception that are described by free throughfall and stemflow.

$$\mathbf{b} = \left(S + \int_0^{\hat{t}} E \, dt \right) \left[1 - \left(\frac{\bar{E}}{\bar{R}} \right) (1 - p - p_t)^{-1} \right]$$

Where S is the canopy storage capacity, $\hat{t}$ is the time required for the canopy to reach saturation, E is the evaporation rate before full canopy saturation is reached, p is the proportion of gross precipitation that flows through the canopy by stemflow, and p_t is the proportion of gross precipitation that is accounted for by free throughfall. This study and other studies have described the intercept coefficient as approximating the canopy storage capacity (Guevara-Escobar et al. 2007, Staelens et al. 2008, Wang et al. 2013).

Interception loss is highly variable and difficult to experimentally observe (Asadian 2010, Kuehler 2017, Zabret and Sraj 2019). Several techniques have been used to capture throughfall and stemflow, but like other environmental data, field studies on interception are associated with a large amount of uncertainty. Studies that use tipping bucket rain gauges often rely on 1 or 2 troughs positioned perpendicular to the stem to represent the entire canopy. This may lead to over or underestimation of collected throughfall due to funneling of water as it travels through the

canopy, a process controlled by canopy architecture and wind direction (Asadian 2010, Livesley et al 2014,). Zabret and Sraj (2018) showed in a study of a pine (*Pinus nigra*) and birch (*Betula pendula*) that not only does interception potential of trees vary by species and canopy metrics describing individuals, but the relative influence of meteorological variables is dependent on season as well as the climate characteristics of the region.

Knowledge Gaps and Objectives

The majority of studies on open-grown tree species in the urban environment apply a volume balance of a single individual with no replication, analyze few events and miss seasonal effects on interception, or apply a long-term volume balance that disregards individual events and is less useful for watershed planning and quantifying small-scale stormwater management utilizing trees as green infrastructure. In this study, three individuals from three tree species, red maple (*Acer rubrum*), white pine (*Pinus strobus*), and willow oak (*Quercus phellos*), were studied to accurately quantify their seasonal and annual interception loss potential for use in urban planning as a green infrastructure. Triplication was chosen to increase the power of generalizing the dataset to other open-grown trees of the same species and to account for possible variations within a species based on physical differences of the individuals. Instead of a long-term volume balance, tipping bucket rain gauges were used as part of a unique throughfall collection system that improves on previous techniques to increase resistance to axial and radial variability in throughfall volumes, decrease the time-scale at which data is able to be viewed which better informs urban design, and to aid in ease of data collection, allowing for a standard maintenance routine. Data was collected continuously from January 2018 to May 2019 to account for seasonal fluctuations in interception and throughfall. Stemflow was also monitored beginning in June 2018, differentiating the study from other large-scale interception studies that only collect throughfall and may miss a vital portion of the water balance. The goals of the study were threefold: (1) to contribute to a growing set of empirical data using a unique data collection system to inform planning decisions surrounding the urban canopy, (2) to quantify the interception potential of three open-grown trees in an urban setting in a region under-represented in literature, and (3) to determine the seasonally-variable influence of meteorological variables and tree canopy metrics on water retention of trees in the southeastern United States.

CHAPTER TWO

MATERIALS AND METHODS

Study area

Three Knoxville parks were chosen as locations for the study because of the species of interest they contain, accessibility within the park, and proximity to the University of Tennessee, Knoxville. Willow oak (*Quercus phellos*, Caswell Park), red maple (*Acer rubrum*, Adair Park), and white pine (*Pinus strobus*, Victor Ashe Park) were selected for the study because they are native to East Tennessee and the surrounding region and because their interception rates have yet to be quantified. Three trees were chosen in each park to allow replication and account for natural variations within the species, resulting in nine trees studied over a fourteen-month time-period. Only open-grown trees were chosen for the study to avoid overhead obstruction by overlapping tree canopies, allowing isolation of measurements to an individual specimen.

Tree characterization

Each tree varied in leaf area index (LAI), diameter at breast height (DBH), canopy area, canopy diameter, leaf area, leaf biomass, height, and branch architecture. Further, LAI was variable based on season (in particular for red maple and willow oak), so changes in these characteristics were expected over the course of the study. As such, measurements of LAI, DBH, and canopy width and height were taken every 6 months throughout the study and averaged for analysis (Table 2.1).

The diameter of the canopy was measured using a surveyor's tape in two directions perpendicular to each other from dripline (the farthest reach of the canopy) to dripline. The two measurements were input into i-Tree hydro to determine canopy cover (discussed below), and verified by averaging the two measurements and assuming the canopy to be circular (O'Brien et al. 1995, Xiao and McPherson 2011). Measurement of the diameter at breast-height—a commonly used metric of the maturation of a tree within a species—was performed using a standard DBH tape. A notable difficulty in obtaining a DBH measurement occurred with tree 2 in Victor Ashe park. At breast height, the tree grew as a double stem. The DBH for this tree was simply measured for both stems, and an average value was recorded. Tree height measurements were taken using a

Table 2.1: Study period averages of tree characteristics

Study Period Averages	Red Maple			White Pine			Willow Oak		
Tree Number	Tree 1	Tree 2	Tree 3	Tree 1	Tree 2	Tree 3	Tree 1	Tree 2	Tree 3
Canopy Diameter (m)	9.75	9.60	7.22	7.92	8.23	6.77	5.27	6.49	8.20
Tree Height (m)	9.54	12.5	12.5	6.81	9.14	8.38	7.98	8.53	10.16
Canopy Area (m ²)	74.77	72.48	40.89	49.46	53.24	35.88	21.97	33.26	52.95
DBH (cm)	24.2	22.4	18.1	25.6	35.1	25.0	20.0	23.2	26.6
Crown Missing (%)	15-20	20-25	20-25	1-5	5-10	10-15	0	1-5	0
LAI	4.4 (3.9 - 4.8)	5.1 (4.8 - 5.5)	6.9 (6.6 - 7.2)	5 (4.8 - 5.2)	6.2 (5.7 - 6.5)	5.7 (5.2 - 6.2)	4.5 (3.1 - 5.4)	4.4 (3.7 - 4.9)	5 (4.2 - 5.5)
Leaf Area (m ²)	328.95	369.11	282.59	245.69	327.41	203.81	99.31	148.15	264.89
Leaf Biomass (kg)	22.2	24.9	19.0	15.8	21.0	13.1	8.8	13.1	23.5

clinometer with a 66-foot baseline. When performing each tree survey, a percentage of leaf area missing from the crown was also estimated by two individuals in two directions and then averaged—a common technique for estimation of crown fullness (Schomaker 2007).

The results of each tree survey were input into i-Tree which utilizes the UFORE model to obtain Leaf Biomass—the estimated weight of the leaves comprising the canopy of each individual—in kilograms, Leaf Area in square meters, canopy cover in square meters, basal area in square meters, and Leaf Area Index (LAI). LAI is a measure of the density of leaves over the area projected by the tree canopy. It is measured as the area of the vertical projection of leaf surfaces divided by the area of the vertical projection of the canopy and is therefore unitless. The UFORE methods utilize regression equations for deciduous urban tree species and the same set of equations with a shading factor applied to the canopy projection for conifers (Nowak 2000).

The maturity and health of each tree is variable by park as well as within each species. The red maples were generally less healthy than the other two tree species; an estimated 15 to 25% of crown density was missing for each tree. The white pines had more variable crown health, missing 1 to 15% of leaf density, and of the three willow oaks, only tree 2 was estimated to miss a small portion of its crown density. Despite the portion of the canopy missing from the red maples and white pines, DBH was well correlated to both leaf biomass and leaf area as well as the vertically projected canopy area.

Monitoring methodology

Schedule 40 PVC troughs were placed under each tree and funneled into automatic rain gauges in a manner similar to Asadian and Weiler (2009). Davis automatic tipping-bucket rain gauges were chosen for their ability to record the depth of throughfall averaged over the vertically-projected surface area of each trough while providing information on the timing and intensity of the canopy-impeded throughfall. Water was funneled into the rain gauges with three 6-inch PVC pipes cut in half to form a trough. These troughs were laid at a 25-degree angle and extended from the dripline of the tree canopy to the opening of the rain gauge to quickly convey the throughfall into the mouth of the rain gauge while reducing water lost to splash that occurs at shallower angles (McJannet et al. 2007). The troughs and gauges were spaced evenly around the circumference of each tree canopy (each one representing a third) to account for radial and axial spatial variability in canopy density that affects throughfall spatially underneath the tree (Smets et al. 2019, Zabret

and Sraj 2018). Stemflow was collected using methods similar to Xiao and McPherson (2011). A length of 1-inch water conduit was cut in half down its length, wrapped around the stem approximately two full revolutions, and caulked with silicon to ensure a watertight seal. The conduit fed into a 1-inch PVC pipe which conveyed the stemflow into a tipping-bucket rain gauge placed in a plastic box to protect from exposure to throughfall. Crown area was used to convert the volume of rainfall measured by the stemflow rain gauges to a depth measurement as a part of the urban tree water balance equation (Xiao and McPherson 2011, Smets et al. 2019).

Finally, a rain gauge was also placed outside of the canopy to collect precipitation measurements and allow a water balance and assessment of storm characteristics (intensity, duration, etc.). The out-of-canopy rain gauge was placed level on a Unistrut and connected to a Hoboware event pendant that recorded precipitation depth in 1-minute intervals. The location was chosen away from any overhead obstructions and a manual rain gauge was placed directly next to the tipping bucket to allow calibration of the rainfall readings.

The throughfall and stemflow rain gauges were secured in place by two 2x4's that were nailed into the ground with landscaping nails. Wooden shims were placed in between the 2x4's and the rain gauges to ensure that the rain gauges remained level throughout the period of study. The throughfall and stemflow rain gauges were connected to a Hoboware U-21 microstation to record continuous measurements in 1-minute intervals throughout the year. A biweekly data collection and maintenance routine was performed to minimize rain gauge clogging and to avoid time drift of the sensors.

Rain gauge calibration

While tipping bucket rain gauges are subject to errors that are not associated with volume-capture approaches (Smets et al. 2019), the decision was made to use automatic rain gauges for the ease of data collection for a study of this scale. The Davis tipping-bucket rain gauges used in the study are rated to accurately record precipitation data up to a rainfall intensity of 102 millimeters per hour. The troughs, designed to convey water into the rain gauges, effectively increased the surface area contributing to the tipping bucket (i.e. beyond just the area of the bucket) by a ratio that ranged from 9.44 to 21.7 depending on the length of the trough. Therefore, at rainfall intensities between 4.7 and 10.8 millimeters per hour (depending on trough length), the 102 millimeter per hour range was exceeded for at least one throughfall gauge under one of the nine

trees. To account for errors in measurement that may have occurred due to exceeding this intensity threshold, and to calibrate the gauges to the known uncertainties added when using tipping buckets, a 7-point calibration was repeated three times for each throughfall gauge to obtain a linear correction factor to be applied throughout the dataset (Figure 2.1). During calibration, volumes ranging from 50 to 700 mL (the equivalent of 2.33 to 32.7 mm of gross precipitation) was continuously poured from the mouth of each trough directly into each throughfall gauge. Values from each of the three calibration runs were plotted for each gauge on each tree, and a linear regression was used to determine the correction factor to be applied to each rain gauge. Correction factors were applied by multiplying all throughfall values for a specific rain gauge by the inverse of the slope of the linear regressions plotted after calibration. The automatic rain gauges measuring gross precipitation were calibrated against manual rain gauges in the same location that were read intermittently throughout the study.

Outlier detection and removal

Throughout the study period, throughfall and gross precipitation values were impacted by physical phenomena such as vandalism, clogging due to the accumulation of leaves and needles at the mouth of the rain gauge, and freezing temperatures causing ice accumulation in the gauges. Additionally, the possibility of over-estimation of throughfall caused by the application of the linear correction factors to the dataset exists. To account for physical and calibration-related errors that could not be accounted for during the study, an outlier removal process was performed to clean the data. First, cumulative rainfall and cumulative throughfall averaged by tree were plotted against time for each storm and analyzed to observe any erroneous phenomena like clogging. A rain gauge was assumed to have clogged if its behavior deviated significantly from the other gauges, or if it exhibited obvious signs of clogging (i.e. a linear increase in rainfall depth with time that exists before or after the defined time boundaries of a particular storm event). If the rain gauge collecting gross precipitation was clogged, the data for that storm was removed. If it was a throughfall gauge that presented errors, the interception values were simply censored from the dataset and further statistical analysis. Rainfall and throughfall data from each gauge were plotted as a regression in JMP Pro for each of the nine trees in the study. A linear regression equation was

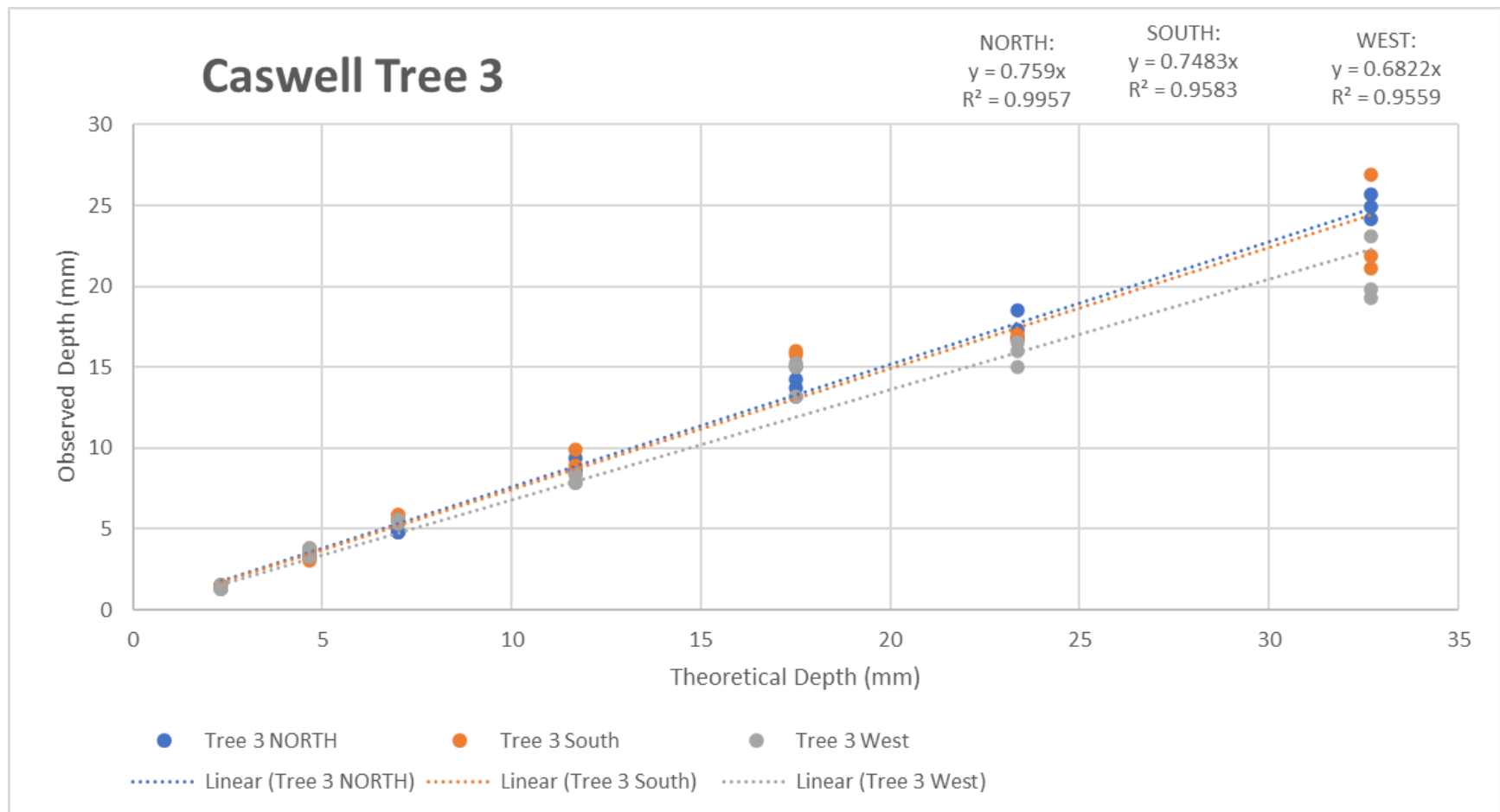


Figure 2.1: Example Calibration of Throughfall Gauges

produced, and a 95% prediction band was applied to the regression. It was assumed that values that fell outside the low or high boundaries of the prediction band were outliers, and data from that particular gauge was removed and the gauge was considered to not be properly functioning for that event. The data were then stratified by storm event, and events with two or more non-functioning rain gauges were removed from further analysis.

Rainfall partitioning

Interception loss was calculated as the amount of gross precipitation that cannot be accounted for directly by throughfall and stemflow measurements (Staelens et al. 2008, Xiao and McPherson 2011, Llorens and Domingo 2007). Interception loss was therefore calculated for each tree on a per-event basis as:

$$IL = P - (TH + SF)$$

Where IL is interception loss in mm, P is gross precipitation in mm, TH is average throughfall in mm, and SF is stemflow in mm. Stemflow collection did not begin until June of 2018, and was observed to be a negligible portion of the total water balance. Because of the relatively small contribution of stemflow to interception loss noted in other studies (Asadian and Weiler 2009, Llorens and Domingo 2007, Livesley et al 2014, Zabret et al. 2018, Smets et al. 2019), stemflow data for these events were censored from statistical analysis and ignored for rainfall partitioning.

Statistical analysis

All analyses on the cleaned data were performed in R version 4.0.0. Throughfall, interception, and stemflow data for each tree were tested for normality using the Shapiro-Wilk method. In all cases, the distributions deviated significantly from a normal distribution ($p < 0.0001$), so non-parametric tests were chosen for statistical analysis. The spearman rank correlation test was used to determine the magnitude and statistical significance of correlations, while Wilcoxon rank-sum tests were used to determine the significance of differences in sample means between groups. Because of the large sample size taken from each species, an effort was made to fit the plotted data to linear models to obtain storage capacity approximations. Analysis of the

residuals from the fitted models, verified by the Shapiro-Wilk test for normality, reveals a non-normal distribution, so the quality of the fitted trends must be considered with caution. Fitted trends follow patterns similar to several other studies that have fitted regressions without reported verification of the normality of the dataset (Staelens et al. 2008, Livesley et al. 2014, Zabret et al. 2018), and the regression equations herein are used with caution to infer relative differences between tree species.

CHAPTER THREE

RESULTS AND DISCUSSION

Summary of events

The events selected for analysis totaled 98 for the red maples and willow oaks and 97 for the white pines. Average rainfall amounts varied between parks due to the spatial variability of regional storm events as well as the outlier removal process. A summary of the data collected throughout the study period is presented below in Table 3.1. Per storm event, red maples experienced an average of 16.54 mm of rain, white pines experienced an average of 12.38 mm, and willow oaks experienced 14.91 mm on average. Rainfall intensity also varied between the parks with average peak 5-minute intensity being 21.50 mm/hr, 17.84 mm/hr, and 19.07 mm/hr for the red maples, white pines, and willow oaks, respectively. Despite these small differences, the data sets were considered analogous between all sites, allowing objective comparisons amongst the species. To define how performance varies with climate and seasonality, data collected throughout the study period was summarized, and then trends in the data were analyzed against various climatic parameters known to control per-event interception.

Interception, throughfall, and stemflow

Interception values for red maples (Mean = 3.310 mm, Median = 2.16 mm, SD = 4.120 mm) did not differ significantly from willow oaks (Mean = 2.88 mm, Median = 1.892 mm, SD = 3.857 mm) in the wilcoxon rank sum test ($p = 0.7245$). White pines had the highest interception losses (Mean = 4.568 mm, Median = 2.924 mm, SD = 4.625 mm) which deviated significantly from the red maples ($p < 0.001$) as well as the willow oaks ($p < 0.001$). On average, the white pines intercepted 52.4% of gross precipitation throughout the study period which compares well to other studies of open-grown conifers which have interception losses in the range of 44.7 – 60.9% (Asadian and Weiler 2009, Asadian 2010, Zabret and Sraj 2019). Since pines maintain their needles year-round, and the canopies of the pine trees studied were dense and healthy, it is reasonable that the highest interception rate was found for this species. Red maples and willow oaks intercepted 24.4% and 32.2% of gross precipitation, respectively, which also falls within the large range of open-grown broadleaf tree species of 6 - 44% (Guevara-Escobar et al. 2007, Smets

Table 3.1: Summary Statistics for Study Period

	Number of Events	Mean Gross Precipitation (mm)	Mean Peak 5-minute Intensity (mm/hr)	Mean Throughfall (mm)	Mean Stemflow (mm)	Mean Interception Loss (mm)
Red Maple	98	16.54 ± 16.76	21.50 ± 22.42	13.00 ± 14.20 75.56 ± 20.37%	0.0183 ± 0.0375 0.0757 ± 0.0889%	3.310 ± 4.120 24.36 ± 20.38%
White Pine	97	12.38 ± 12.32	17.84 ± 20.83	7.13 ± 9.55 47.36 ± 31.45%	0.0550 ± 0.1369 0.2739 ± 0.4817%	4.568 ± 4.625 52.43 ± 31.48%
Willow Oak	98	14.91 ± 18.67	19.07 ± 19.85	11.20 ± 14.78 67.53 ± 28.55%	0.0615 ± 0.1166 0.3030 ± 0.3511%	2.880 ± 3.857 32.21 ± 28.64%

et al. 2019, Zabret and Sraj 2019, Asadian 2010, Livesley et al. 2014, Xiao et al. 2000, Staelens et al. 2008, Li et al. 1997).

The lack of statistically different interception between the two deciduous species was notable. Despite having a lower average leaf area index and less sturdy leaf characteristics, the willow oaks had healthier crowns (See Table 2.1) which may explain the similarities in the two species interception losses. Not only did the canopy density of the two deciduous trees in this study vary, but the leaf structure and leaf-development period of each species is different which can affect a tree's interception performance (Keim et al. 2006, Xiao and McPherson 2016). The red maples monitored in this study were estimated to miss between 15% and 25% of the full crown while the willow oaks were generally completely full. Gaps in the canopy provide direct paths for precipitation to fall to the ground unobstructed as free throughfall (Smets et al. 2019, Nytch et al. 2019, Xiao et al. 2000), so despite the broader, rigid, textured leaves of the red maples having characteristics associated with a higher storage capacity (Xiao and McPherson 2016), the unhealthy canopy likely contributed to a larger gap fraction which may have resulted in the lower interception values, leading to the observed similarity in annual runoff-reduction potential of the two deciduous species.

Stemflow was generally a negligible portion of the tree canopy water balance which has previously been shown in literature (Xiao and McPherson 2011, Zabret et al. 2018, Smets et al. 2019). However, the average portion of gross precipitation attributed to stemflow for the white pine ($0.27 \pm 0.48\%$) and willow oak ($0.30 \pm 0.35\%$) were higher and more similar than that of the red maple ($0.08 \pm 0.09\%$). Significant differences in stemflow were only found between the maples and oaks ($p < 0.001$).

Variations within species

Figure 3.1 shows the boxplots of all interception loss data as a percentage of rainfall for each individual in each species. Highly significant deviations were not observed between the average interception losses for trees within each species except for white pine tree 2 and willow oak tree 1. While there was not a strongly significant difference between white pine tree 1 and white pine tree 3 ($p = 0.0530$), the interception losses of tree 2 were significantly higher than tree 1 ($p < 0.001$) and tree 3 ($p < 0.0001$). The canopy of willow oak tree 1 had a small vertical projection area, and a high average leaf area index (Table 2.1) which caused it to deviate from

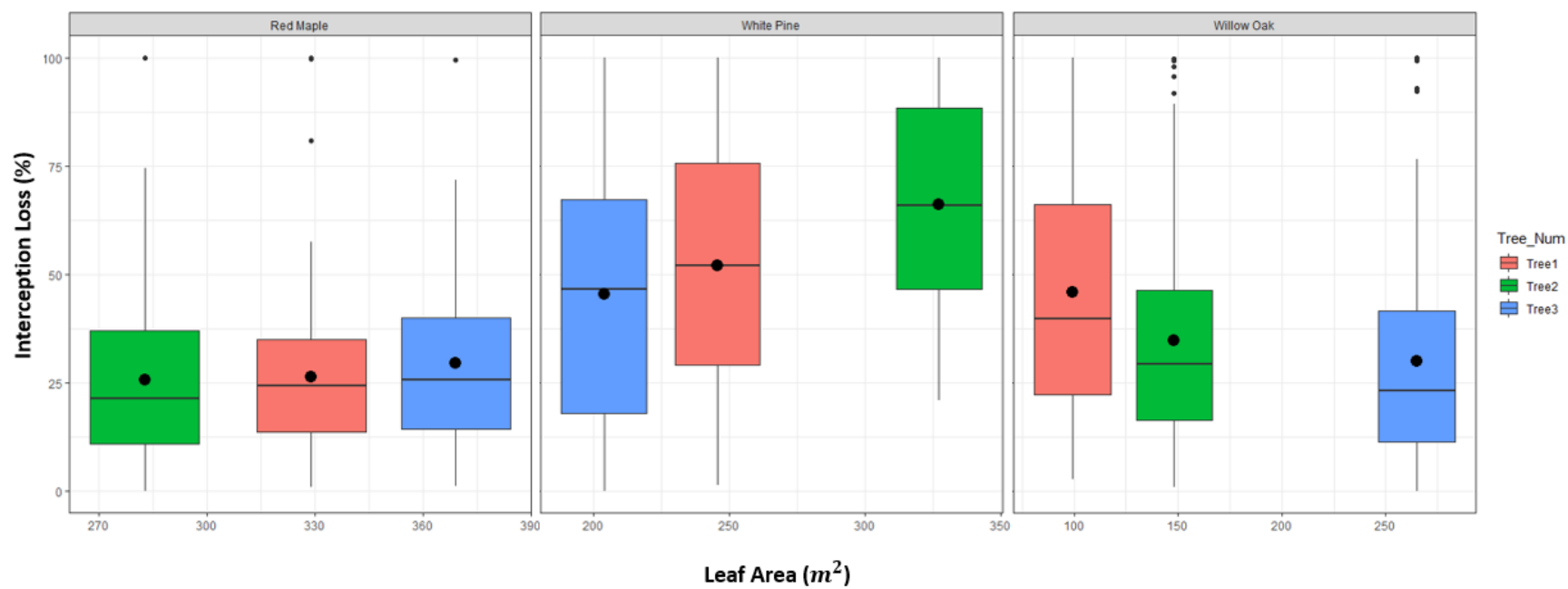


Figure 3.1: Interception loss versus leaf area (means represented by black dots)

trees 2 ($p = 0.0164$) and 3 ($p = 0.0531$) of the willow oaks, albeit at a higher significance level than the pines. No significant differences were found between the individuals of the red maple species. Leaf area has been identified in several studies as an explanatory factor for the interception loss potential of trees (Xiao et al. 2000, Livesley et al. 2014) while other studies have not found a statistical significance to the measure (Inkiläinen et al. 2013). Because only three canopy architecture measurements were made over the study period, it is difficult to determine the statistical significance of the measure, however, a noticeable trend was observable as leaf area increases within the different tree species. The pines and maples tend to increase in average interception losses as leaf area increases while the willow oaks seem to decrease with an increase in leaf area. Given the trends between leaf area and throughfall found in this study and throughout literature, as well as the significantly greater interception losses of white pine tree 2, it is reasonable to assume that leaf density plays a role in the interception loss potential of pines. Because of the significance level at which the other species differ with respect to interception loss, the validity of the trends in interception loss versus leaf area is difficult to determine and should be considered plausible but inconclusive. Because the majority of the trees within each species function similarly regardless of maturity and canopy density, throughfall, interception, and stemflow values will be considered comparable and representative of the species as a whole.

Trends in interception controlling variables

Responses to meteorological variables vary by tree species and due to seasonally variable canopy metrics (Zabret and Sraj 2018). To determine meteorological variability, throughfall and interception values were compared against event characteristics to determine what storm characteristics are most important for prediction of per-event interception loss values. Peak 5-minute rainfall intensity, gross precipitation depth, event duration, and antecedent moisture were chosen as the characteristics of each storm to be analyzed against throughfall and interception. Regression equations are cautiously observed in the data, and the Spearman's Rank-Order non-parametric test was performed to determine and verify the strength of correlation between each variable.

Rainfall depth

Interception loss and throughfall are best described here and in other studies by a linear regression against rainfall depth (Xiao et al. 2000, Staelens et al. 2008, Asadian 2010, Xiao and

McPherson 2011, Wang et al. 2013, Zabret et al. 2018, Smets et al. 2019, Wang and Wang 2020, Beidokhti and Moore 2021). Despite the understanding that there are some differences between trees within a species, all the data is considered here to be representative of the larger species itself. A moderate, significant linear relationship was observed between interception loss and rainfall depth for the three species in the study (Figure 3.2—red maple: $r^2 = 0.572$, $p < 0.0001$; white pine: $r^2 = 0.394$, $p < 0.0001$; willow oak: $r^2 = 0.473$, $p < 0.0001$). Similar correlation coefficients between interception loss and rainfall depth have been reported by other studies, and the Gash, Rutter, and WetSpa models produce results with similar trends for interception versus rainfall depth (Staelens et al. 2008, Wang et al. 2013, Smets et al. 2019). The correlations, particularly for the white pines, show spread in the data, and the correlation coefficients of the regression equations depict a greater variance than that of the two deciduous species. The lower strength of linear correlation in the white pines is likely due to the non-normality of the data at each park as well as the variability of the individuals in the pines (discussed above). In the non-parametric tests, moderate and significant correlations were observed between interception loss and rainfall (red maple: $\rho = 0.645$, $p < 0.0001$; white pine: $\rho = 0.535$, $p < 0.0001$; willow oak: $\rho = 0.501$, $p < 0.0001$). Event-specific climatic variables such as wind speed, wind direction, and temperature likely impact the quality of the regressions, but the equations agree overall with the trends found in throughfall which are much stronger (Figure 3.3—explained below).

Throughfall was plotted against gross precipitation for all trees by park (Figure 3.3). When compared to gross precipitation, throughfall tends to increase according to a significant and strong linear correlations (red maple: $r^2 = 0.96$, $p < 0.0001$; white pine: $r^2 = 0.86$, $p < 0.0001$; willow oak: $r^2 = 0.96$, $p < 0.0001$) which despite having non-normal residuals agree well with the non-parametric tests (red maple: $\rho = 0.975$, $p < 0.0001$; white pine: $\rho = 0.921$, $p < 0.0001$; willow oak: $\rho = 0.965$, $p < 0.0001$). Two observations can be drawn from the regression equations describing each species. The first is the canopy storage capacity of each species for the study period, which is described by the intercept coefficient of each equation (Wang et al. 2013, Staelens et al. 2008, Guevara-Escobar et al. 2007). While the exact amount of rainfall required to initiate throughfall will vary for each storm depending on the foliage status of an individual tree, the intercept coefficient for each of the regressions describe the depth of rainfall

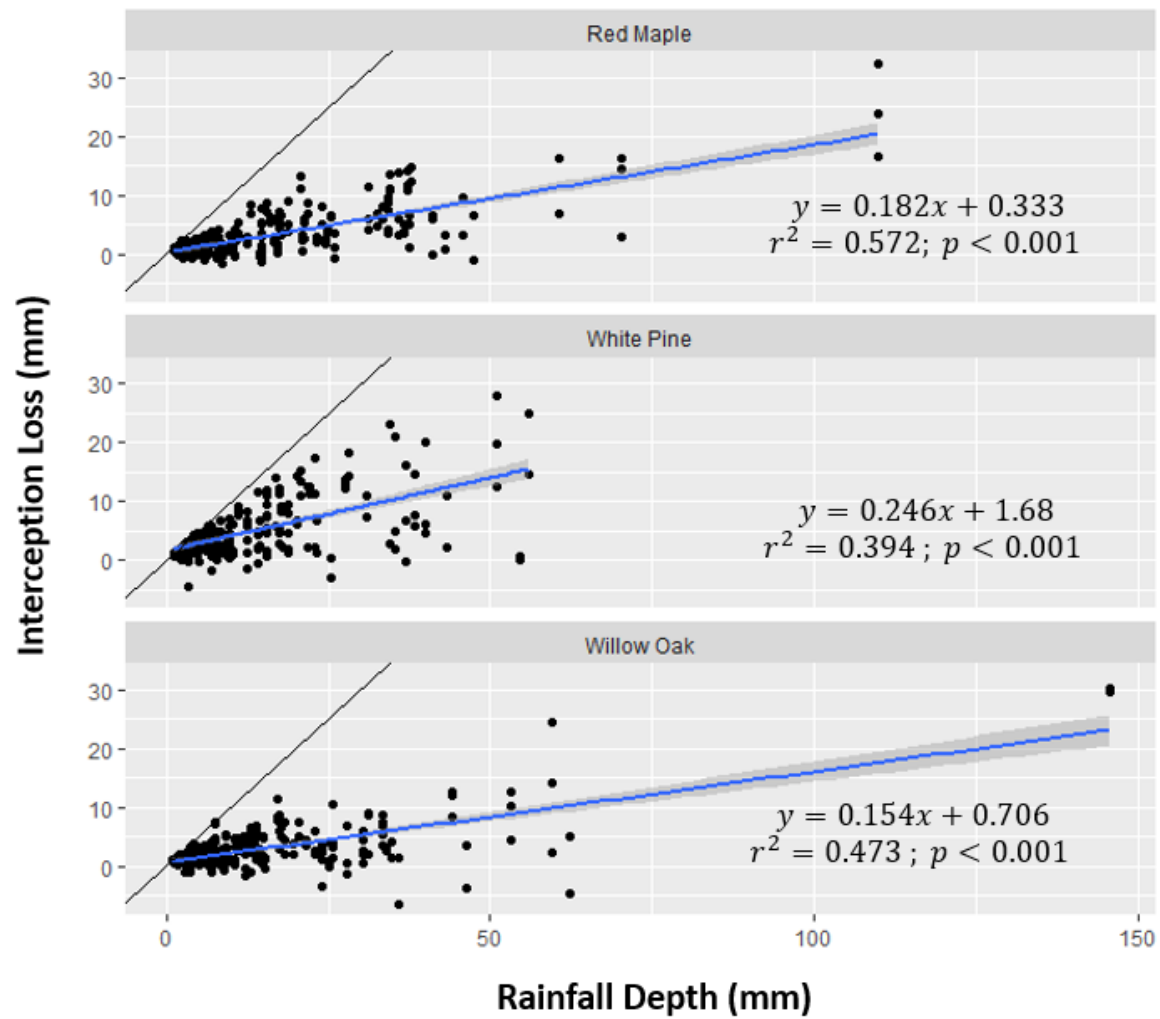


Figure 3.2: Interception versus rainfall depth

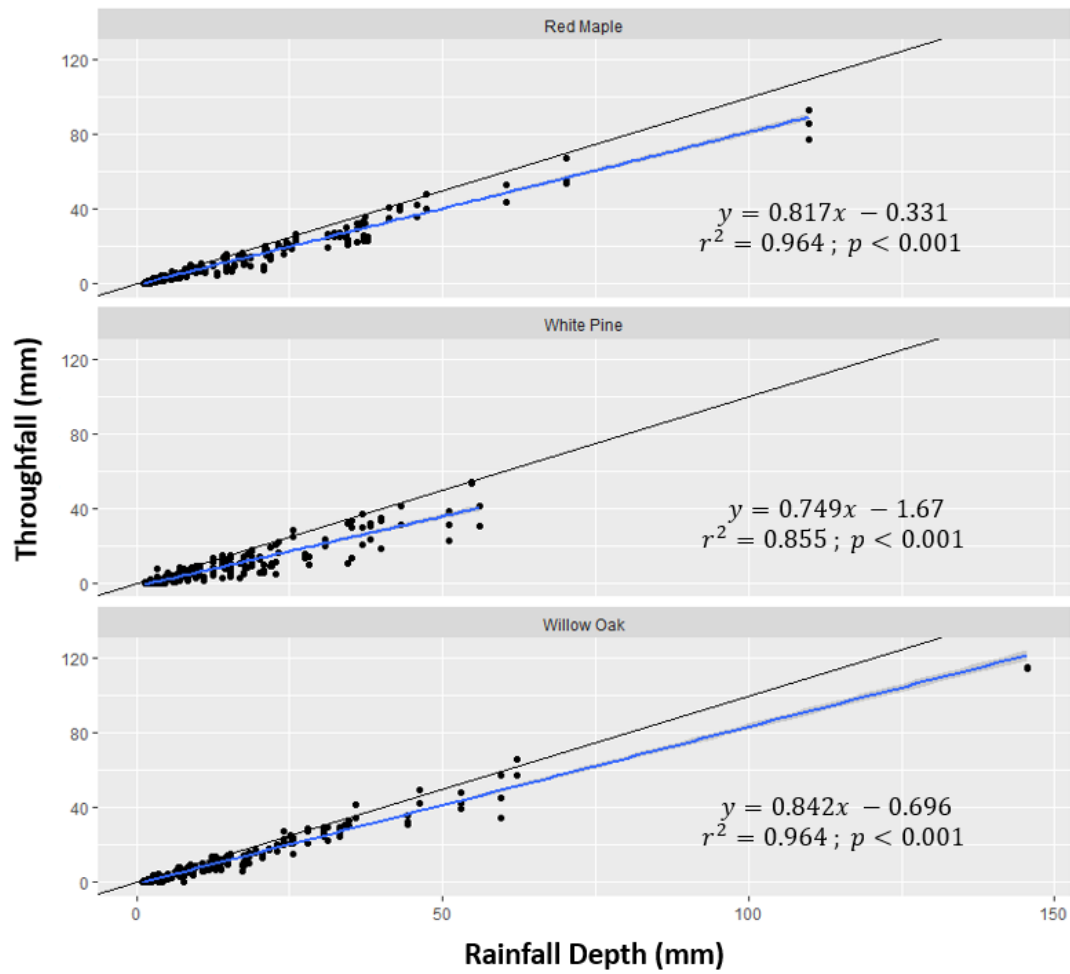


Figure 3.3: Throughfall versus rainfall depth

that causes the tree canopy to become saturated. As expected, the pines have the highest canopy storage capacity of 1.67 mm ($p < 0.0001$), while the two deciduous species have a lower storage capacity of 0.331 mm for the red maple and 0.696 mm for the willow oak. While the storage capacities of the red maples and willow oaks make sense in context of the trends, the intercept coefficient was less significant for the willow oaks ($p < 0.005$) and not statistically significant for the red maples ($p = 0.15$). The failure to determine a statistically significant storage capacity for red maples is likely due to the difficulty sampling at Adair park described above. The maples and oaks fall within the range of 0.22 – 1.17 mm for broadleaf deciduous tree species, and the storage capacity of the pines were within the expected range of 0.99 – 3.68 mm for conifers (Hutchings and Crowther 1988, Xiao and McPherson 2016, Wang and Wang 2020).

Some throughfall values fall above the line $y = x$ which means that throughfall was collected under the tree canopy in excess of rainfall collected by the gross precipitation gage. Negative interception values have been observed in other studies (Staelens et al. 2008, Livesley et al. 2014, Zabret and Sraj 2018, Nytch et al. 2019), and several possible explanations exist for throughfall values exceeding gross precipitation. First, as mentioned previously, the throughfall values were adjusted based on the calibration of the throughfall gauges at the end of the study period. While the calibration increased the accuracy of the data, it is possible that some throughfall values were over-estimated while implementing this procedure. It is also possible that paths of least-resistance are present in the tree canopy that promote flow to one part of the canopy dependent upon the specific wind conditions of a given storm event. Under such conditions, it is possible for a tree canopy to funnel water primarily to one rain gauge such that the spatial distribution of gross precipitation and throughfall are different. Another possible explanation for why throughfall values exceed gross precipitation may be present is that wind can change the angle of precipitation and rain that has not passed through the canopy may enter throughfall gauges unobstructed. Additionally, it is possible that short time periods between storm events could prevent complete drying of the tree canopy such that water from a previous storm contributes to throughfall of a future storm.

Intensity

For each storm event, rainfall rates were analyzed to determine the maximum depth of rainfall that occurred in a 5-minute period. Figure 3.4 shows all throughfall data collected

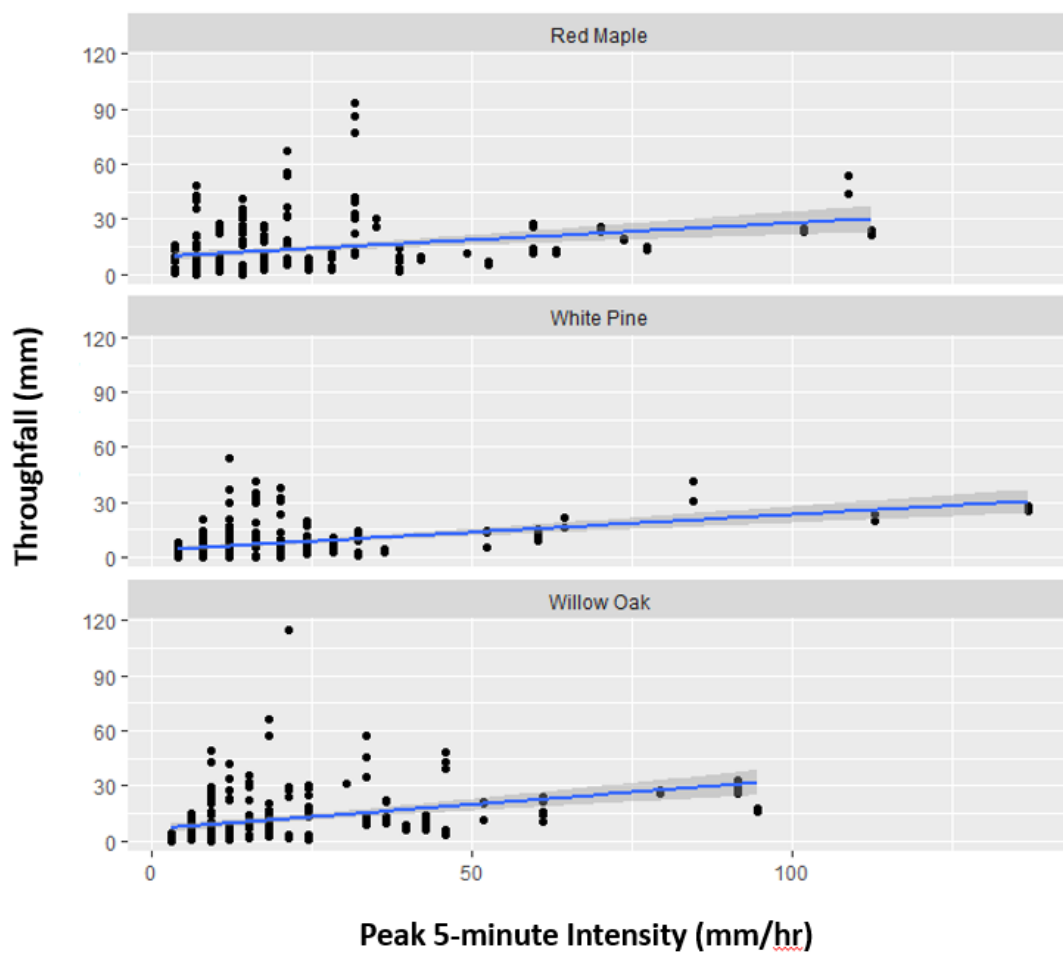


Figure 3.4: Throughfall versus peak 5-minute intensity

throughout the study period versus peak 5-minute rainfall intensity to determine potential relationships between intensity and throughfall. Moderate correlations were found over the study period between throughfall and peak 5-minute intensity using the spearman rank correlation test (red maple: $\rho = 0.406$, $p < 0.0001$; white pine: $\rho = 0.494$, $p < 0.0001$; willow oak: $\rho = 0.611$, $p < 0.0001$) which are best described by weak, yet significant, linear regressions (red maple: $r^2 = 0.0787$, $p < 0.0001$; white pine: $r^2 = 0.1606$, $p < 0.0001$; willow oak: $r^2 = 0.1202$, $p < 0.0001$). Rainfall intensity is known to greatly affect interception losses and dynamic storage during a rain event as seen herein (Kuehler et al. 2017, Xiao and McPherson 2016, Smets et al. 2019, Zabret et al. 2018, Keim et al. 2006). Zabret et al. (2018) determined that for a birch and pine, rainfall intensity was the most influential parameter during the leaf-off period which is not observed in this study (Figure 3.5). In the summer, when intensities are high, a linear regression of throughfall against peak 5-minute intensity is a moderate predictor of throughfall volume (red maple: $r^2 = 0.576$, $p < 0.0001$; white pine: $r^2 = 0.655$, $p < 0.0001$; willow oak: $r^2 = 0.524$, $p < 0.0001$), but in the winter, with long, low intensity storms, weak but significant linear relationships were only found for willow oaks ($r^2 = 0.289$, $p < 0.0001$) and for the maples ($r^2 = 0.072$, $p < 0.01$). As previously mentioned, the climate differences throughout the year are likely to impact the effect of parameters like intensity on throughfall values. During the summer, when intensity is a good predictor of throughfall (Figure 3.5), the willow oaks seem to have the lowest resistance to intensity with a slope of 0.306. The pines are comparatively resistant to intensity with a slope of 0.220, and the maples show a similar relative resistance to intensity with a slope of 0.261. The discrepancy in the magnitudes of the variance of the data (r^2) and the spearman correlation strength (ρ) are most likely due to the large deviation from normality present in the sampled data and may imply that the actual trend is non-linear. To be cautious, the strength of the linear regressions and their coefficients should be used cautiously to determine relative differences between species.

Duration

Each species' response to event duration was also described by a linear relationship to throughfall. (Figure 3.6) Weak and significant linear regressions describe the pines ($r^2 = 0.111$, $p < 0.0001$) and oaks ($r^2 = 0.185$, $p < 0.0001$), while the maples had a moderate and

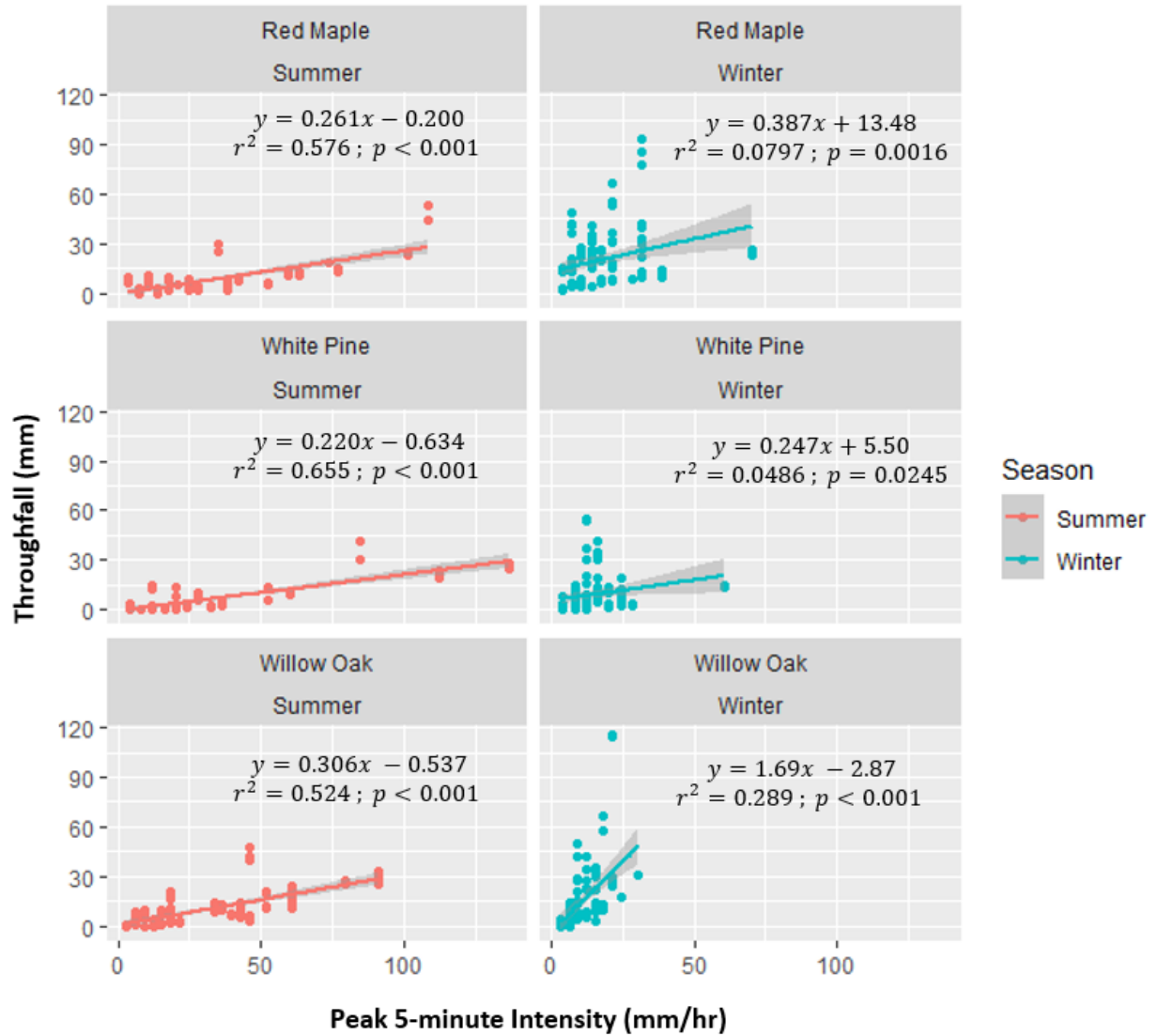


Figure 3.5: Summer and Winter intensity trends

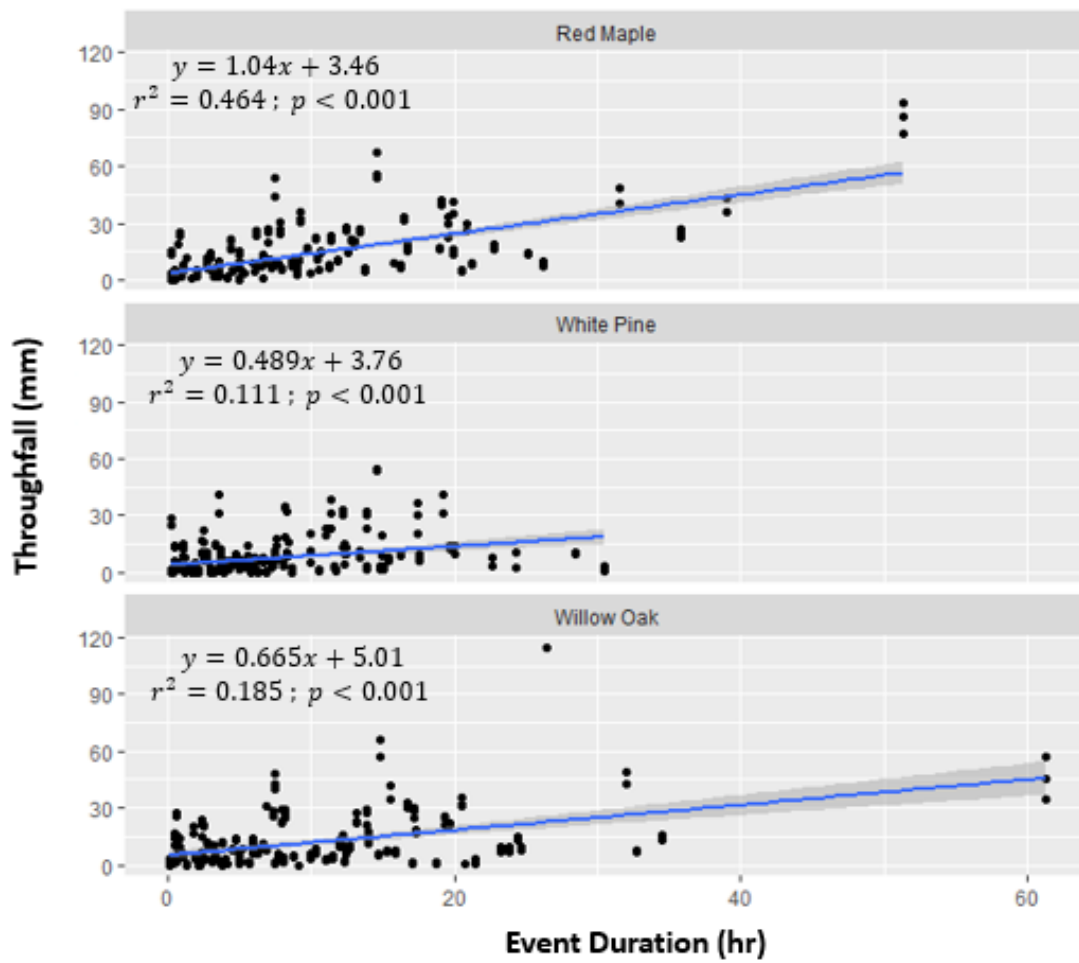


Figure 3.6: Throughfall versus event duration

significant correlation ($r^2 = 0.464$, $p < 0.0001$). Red maples show a more severe response to event duration than the other two species in the study with a slope coefficient of 1.04 compared to 0.489 and 0.665 for the white pines and willow oaks, respectively. As per the previously discussed issue with interpreting the correlation coefficients of the linear regressions, spearman correlations verify the relative influence of event duration on throughfall values for each species (red maple: $\rho = 0.652$, $p < 0.0001$; white pine: $\rho = 0.446$, $p < 0.0001$; willow oak: $\rho = 0.361$, $p < 0.0001$). Each of the red maples were missing a large portion of their canopy (Table 2.1), and it is likely that a large portion of the throughfall can be attributed to free throughfall (throughfall unimpeded by the canopy). If this is the case, then it follows logic that the influence of event duration would be much higher for the maples than the other two species since unobstructed rainfall will occur at a higher rate throughout an event. For the willow oaks, event duration was moderately and significantly correlated to throughfall in the winter ($\rho = 0.633$, $p < 0.001$), but weakly correlated in the summer ($\rho = 0.264$, $p = 0.0083$). If the amount of unobstructed throughfall controls a canopy's response to duration, then it follows that duration would show a greater correlation during the leaf-off period. The same trend was present for the maples where summer throughfall showed a weaker correlation to duration ($\rho = 0.422$, $p < 0.001$) than in the winter ($\rho = 0.583$, $p < 0.001$), but the difference is smaller in magnitude than the willow oaks that had comparatively denser canopies.

Antecedent moisture

Antecedent dry period is the gap in time between storm events that allows intercepted water stored on the surface of a tree's canopy to evaporate. Given that up to 46% of total interception loss of a tree occurs due to evaporation during the drying period between storms (Reid and Lewis 2009), antecedent dry period is a plausible controlling variable in the process of rainfall interception. However, several curves were fitted to throughfall versus antecedent dry period and little to no trend was observed, likely due to the complexity of this process. Likewise, in the spearman rank correlation test, no significant correlation was found between the antecedent dry period and throughfall for any species. It is likely that other controlling factors such as temperature, vapor pressure differential, and wind speed effect evaporation and water availability (i.e. the amount of moisture leftover on the tree canopy) after an event, thereby substantially influencing

these results. The other rainfall characteristics (i.e. storm intensity, duration, etc.) discussed herein can be more directly tied to the single-event performance of a tree in a given rainfall event.

Seasonal Trends in Interception Loss

As noted above, differences between species were apparent in the summary statistics which were attributed in part to seasonal changes in climate and leaf cover. To gain a better understanding of the seasonal differences between the tree species, boxplots and a summary table were made using data from all three trees at each park, parsed by season (Figure 3.7 and Table 3.2). The climate of East Tennessee varies throughout the year, and climactic variations as well as leaf cover were the two main factors considered for defining the seasons shown in the boxplots. Generally, the summer season of the region is described by short, intense spurts of precipitation, occurring from June to September, while the winter season has long, sizable storms from December through March that have a much lower average intensity than in the summer. In the autumn, the leaves of the deciduous species change color and fall from the canopy to the ground during the months of October and November. Spring is when deciduous trees begin to regrow their leaves in April and near full leaf development in late May. Seasonal data reveal two influential factors: (1) differences in interception for leaf-on/leaf-off, and (2) differences in interception due to shifts in rainfall patterns over the year.

White pines, in the urban setting, are desirable, sturdy trees with broad, dense crowns that cover the stem, ending near the base a few feet above the ground (Wendel and Smith 1990). Like other conifers, the white pines in this study showed consistent, high interception losses throughout the year. Despite the average intensity in the summer (10.2 mm/hr) being nearly quadruple that of the winter (2.84 mm/hr), the interception losses as a percentage of gross precipitation was only 7.8% greater in the summer (57.0%) than in the winter (49.2%). The autumn and spring losses remained fairly consistent and on average comprised 53.1% and 52.2% of gross precipitation, respectively. These results follow logically with the year-round leaf cover and healthy canopy of the white pines in this study and compare well to the findings of other studies (Asadian and Weiler 2009, Asadian 2010, Zabret and Sraj 2019).

The willow oaks in Caswell Park show more consistent interception losses than expected for deciduous trees during spring, summer, and autumn. The average interception loss is lower in the summer (38.5%) than in the autumn (54.2%) and spring (47.1%). The average intensity

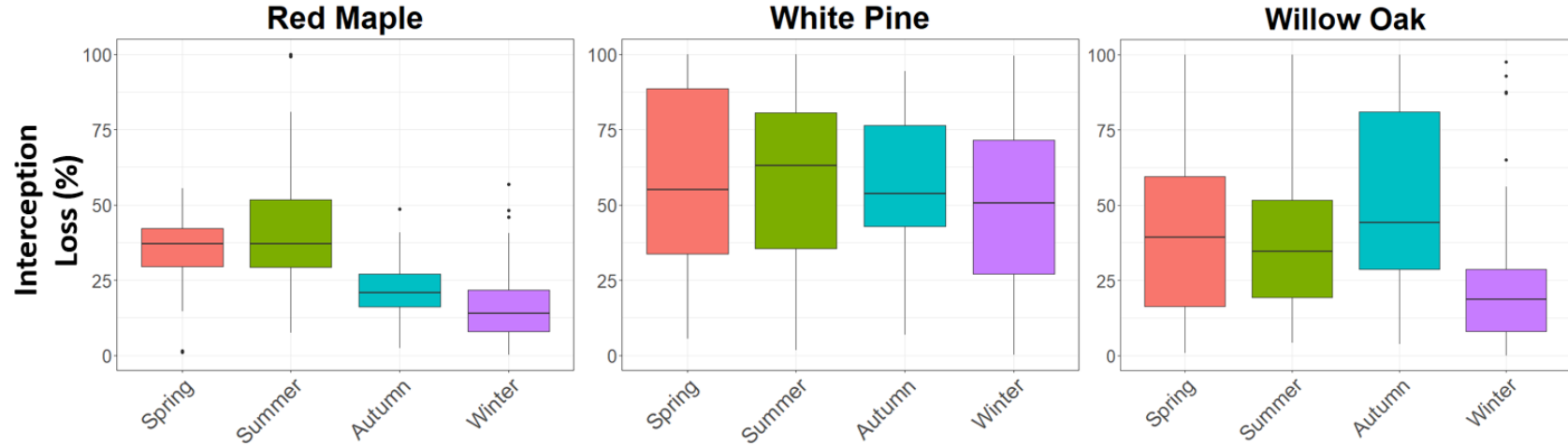


Figure 3.7: Seasonal fluctuations in interception loss

Table 3.2: Seasonal data summary

Seasonal Summary Data Averaged by Park

Statistic	Red Maple				White Pine				Willow Oak			
N	36	90	36	132	66	72	39	114	57	102	24	111
Average Interception (%)	32.3 ± 16.0	39.7 ± 22.1	20.5 ± 11.4	13.2 ± 13.8	52.2 ± 40.9	57.0 ± 27.9	53.1 ± 27.4	49.2 ± 28.9	40.5 ± 32.3	37.3 ± 24.5	54.2 ± 30.3	17.5 ± 23.3
Median Interception (%)	35.9	37.1	20.4	12.8	54.5	61.0	53.2	50.2	37.8	34.5	44.1	14.0
Average Rain (mm)	10.8 ± 10.8	12.6 ± 13.0	9.35 ± 7.25	22.8 ± 19.9	9.78 ± 12.5	11.6 ± 12.2	10.3 ± 7.13	15.1 ± 13.3	9.67 ± 9.07	13.6 ± 11.5	13.2 ± 19.0	19.1 ± 25.6
Average Intensity (mm/hr)	2.50 ± 2.80	10.3 ± 18.0	3.19 ± 4.20	2.07 ± 1.51	2.58 ± 2.75	10.2 ± 21.2	2.73 ± 3.33	2.84 ± 4.02	1.81 ± 3.27	9.39 ± 12.8	0.505 ± 0.366	2.78 ± 5.81
Average Duration (hr)	6.68 ± 5.44	4.90 ± 6.22	6.90 ± 6.44	13.4 ± 10.3	6.03 ± 6.46	5.10 ± 6.80	6.53 ± 5.16	9.06 ± 6.55	10.8 ± 8.71	5.36 ± 6.16	21.6 ± 17.7	10.4 ± 7.64
Season	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter

reaching the willow oaks in the autumn and spring were 0.505 and 1.81 mm/hr respectively, which was particularly low compared to the rest of the year. The dense, healthy canopies of the willow oaks (Table 2.1), combined with the low average intensity during these seasons, may explain the high interception percentages during the spring and autumn. Further, the autumn and spring canopy of the willow oaks are healthy as they are known to have long leaf-on periods which begin with budding between February and May and end with seeding as late as October (Schlaegel 1990). The lower interception percentage associated with willow oaks in the summer is explained by the high average rainfall intensity during the summer months (9.39 mm/hr), which follows logically from the previous discussion on willow oaks' weak resistance to precipitation intensity which may be influenced by leaf structure. Keim et al. (2006) found that canopy saturation occurs more rapidly during intense rain, while Xiao and McPherson (2016) determined that smooth, flexible leaves have the lowest storage capacity of the broadleaf types. Willow oak leaves are long, narrow, smooth, and flexible when compared to other deciduous tree species which may explain the tree's response to high intensity rainfall.

Red maples behaved like many other broad-leaved deciduous tree species studied (Llorens and Domingo 2007, Xiao and McPherson 2011, Livesley et al. 2014, Zabret and Sraj 2019). Red maples are known in East Tennessee to be one of the first trees that show color in the fall. Soon after that peak, they whither and fall to the ground. Leaf senescence occurs for red maples between late September and mid-October, and leaf mass development does not occur in scale until late May or June (Anderson and Ryser 2015, Xie et al. 2018). As leaf development begins in spring, red maples intercepted an average of 32.3% of rainfall. Peak canopy density occurred in the summer when, despite their low-density canopies, the red maples reached a peak of 39.7% of gross precipitation intercepted. Continuing the discussion on resistance to intensity, it is possible that the textured leaves and rigid stems of the red maple aid in reducing the effect of rainfall intensity on interception losses. The early senescence of red maples caused interception losses to rapidly decrease to 20.5% in autumn, eventually reaching a seasonal minimum in winter of 13.2% of gross precipitation.

CHAPTER FOUR

CONCLUSIONS AND FUTURE RESEARCH

Urban trees are an important part of the urban water balance and can effectively function as green infrastructure by reducing the portion of gross precipitation that contributes to urban runoff. The goal of this study was to identify meteorological and phenological variable effects on interception loss, and to quantify the annual interception potential of three open-grown, urban trees native to the eastern and southeastern United States at a scale that is scarcely present in literature. The methodology, while derivative of other studies that have quantified interception using tipping bucket rain gauges, is unique in the total capture area produced by the three troughs as well as the ability to account for axial and radial spatial variations in throughfall by including three troughs extending from trunk to dripline, each representing one third of the canopy. Few studies have monitored several trees within a single species and compared the interception loss potential amongst individuals. There were no highly significant differences present between the individuals in each species (except for one white pine and one willow oak—see discussion above), and the ability to average data triplicated in each species increased the robustness of the dataset and allowed grouping for the subsequent analyses. The conclusions drawn from this study are presented below:

- White pines had the highest overall annual interception losses as a percentage of gross precipitation, followed by willow oaks, and then red maples.
- The best overall predictor of interception loss, throughfall, and stemflow was gross precipitation depth. Precipitation depth showed a strong, significant correlation to throughfall for all species studied. Weak to moderate correlations were observed between rainfall depth and interception loss. Other influencing factors included duration, intensity, and seasonality.
- The impact of rainfall intensity was dependent on the time of year as well as the species. Red maples exhibited a significant linear correlation between throughfall and intensity in the summer, but no significant trend was observed for the winter. The same is true of the pines, but not the willow oaks which exhibited a significant, though weak, trend in the winter. Willow oaks had the most severe response to changes in intensity of the three

species in the study, where throughfall increased more per unit increase in peak 5-minute intensity than the other species.

- Duration had a less significant impact on throughfall than intensity or gross rainfall depth in this study. Red maples showed the strongest correlation to event duration of the three species studied. Weak, yet significant, linear correlations were observed for the pines and the oaks, while a moderate, significant, linear correlation was observed for the maples.
- No observable trend was noted using antecedent dry period as a predictor of throughfall, interception, or stemflow. While antecedent dry period determines the initial conditions of each canopy before a rainfall event, the process of interception is too complex to be predicted solely by how wet or dry the canopy is before a storm event. Further, other variables affect evaporation that were not considered herein.
- White pines had the most consistent interception potential annually due to evergreen species' consistent canopy density. Variations in interception losses throughout the year are attributed to seasonal meteorological variations. The response of white pines to meteorological variables also seemed to be relatively consistent throughout the study period.
- Willow oaks intercept rainfall more consistently than red maples on a seasonal basis which can be explained by their long leaf-on period as well as the density of the canopy. However, willow oaks showed decreased interception loss in the summer compared to the autumn and spring. This is attributed to the species' response to rainfall intensity which may be the effect of the flexibility and smoothness of willow oak leaves. Conversely, the density of willow oak canopies allows them to have a high canopy storage capacity during more mild events. During the spring, when the observed storms were long and less intense than the rest of the year, willow oaks exhibited very high interception losses.
- Red maples begin flowering early and lose their leaves early. There is a noticeable peak in interception losses by red maple canopies in the summertime when leaves are at their fullest, and a sharp drop in autumn and winter as the trees lose their leaves. Event duration controls throughfall volumes better than intensity for red maples, which were missing a large portion of their canopy. Assuming that the portion of missing canopy is strongly correlated to a canopy's gap fraction, the influence of event duration on throughfall can be

attributed to a higher proportion of free throughfall inherent to trees with large gap fractions.

- Leaf area predicted interception losses well only for the pine species, while the two deciduous species in the study did not vary significantly between individuals regardless of leaf area or other canopy architecture metrics. A noticeable trend was observed between total leaf area and annual interception loss for all species, but the only conclusive trends belong to the pines. Assuming that microvariations were not present in the meteorological conditions at Victor Ashe park, differences in canopy architecture are the only explanation for differences in interception loss potential within the species.

Considerations for future studies

During and after the study, it became apparent that several changes to the procedure, materials, and methods could have been implemented to increase the quality and quantity of data. Collecting accurate throughfall data with respect to timing and volume can be extremely difficult because of the amount of maintenance needed to upkeep rain gauges placed at the ground level. Several times throughout the study, ants, spiders, and even snakes, made a home of the throughfall gauges. In the case of ant colonies, the funnel opening leading to the tipping bucket was easily clogged, and the tipping bucket itself was sometimes obstructed from movement. Additionally, pollen, leaves, and needles were a constant maintenance concern for the prevention of throughfall gauge clogging. While a maintenance routine was performed to decrease errors associated with clogging, deposits of debris could occur mid-storm and cause gauge clogging (Figure A.2). To prevent errors due to maintenance, it would have been better to collect data and maintain the equipment on a weekly, rather than biweekly, schedule. The parks where the studied trees were located are heavily used by the Knoxville community, and, as mentioned above, vandalism was sometimes an issue for the gross precipitation and throughfall gauges. The ideal location for an interception study of open-grown trees would be in an isolated portion of a park that is inaccessible to the community.

Additional changes could be made to future studies that would aid in better understanding rainfall interception and providing data sets with even better quality:

- Other studies, mentioned previously, have proven the effects of wind direction and temperature on throughfall values which were not considered herein. Meteorological sensing is extremely important to explain funneling phenomena as well as to accurately quantify canopy storage values and determine gauge malfunctions due to clogging.
- Changes to materials would include the measurement method for crown architecture data. While there is no evidence that i-Tree's modeled tree architecture variables are not representative of the trees in the study, certain metrics such as branch angle and gap fraction are impossible to model without direct measurement through aerial photography or a canopy analyzer system. Without these values, it is impossible to estimate free throughfall proportions and therefore determine an exact value of canopy storage.
- Finally, the throughfall gauges used in the study had to be calibrated to the high volumes funneled to the gauges by the throughfall gauge troughs. To more accurately obtain throughfall intensity and depth, high intensity rain gauges should be used along with this method of throughfall collection.

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APPENDIX

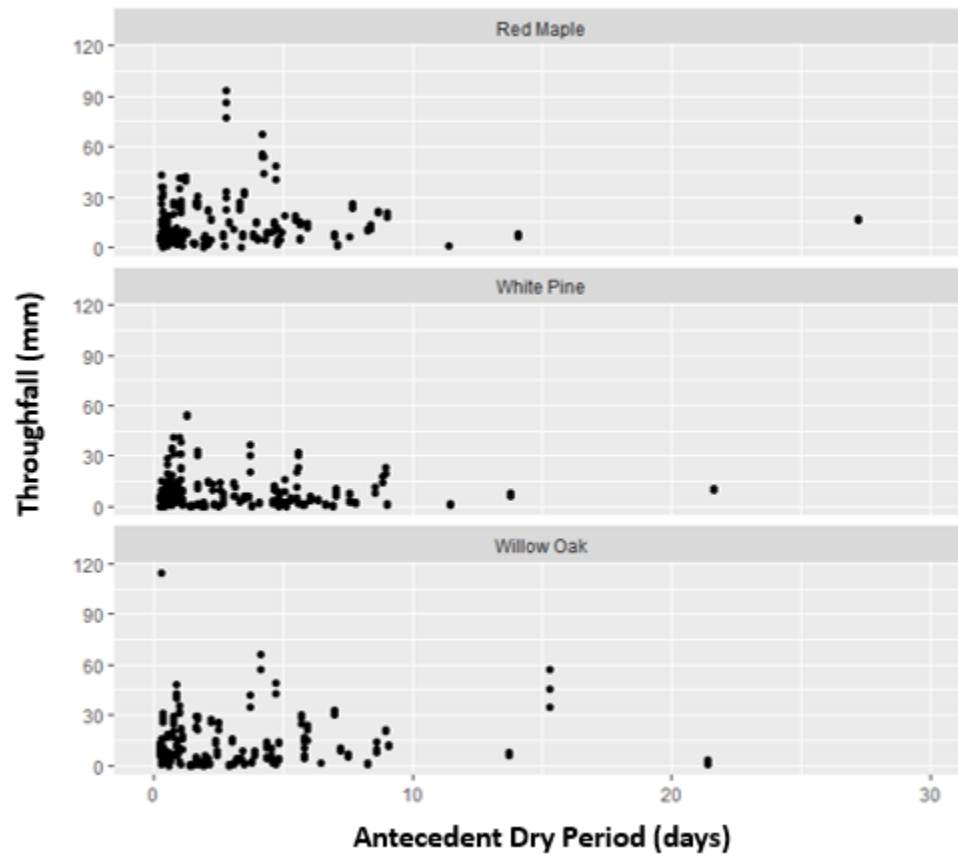


Figure A.1: Throughfall plotted against antecedent dry period for each species

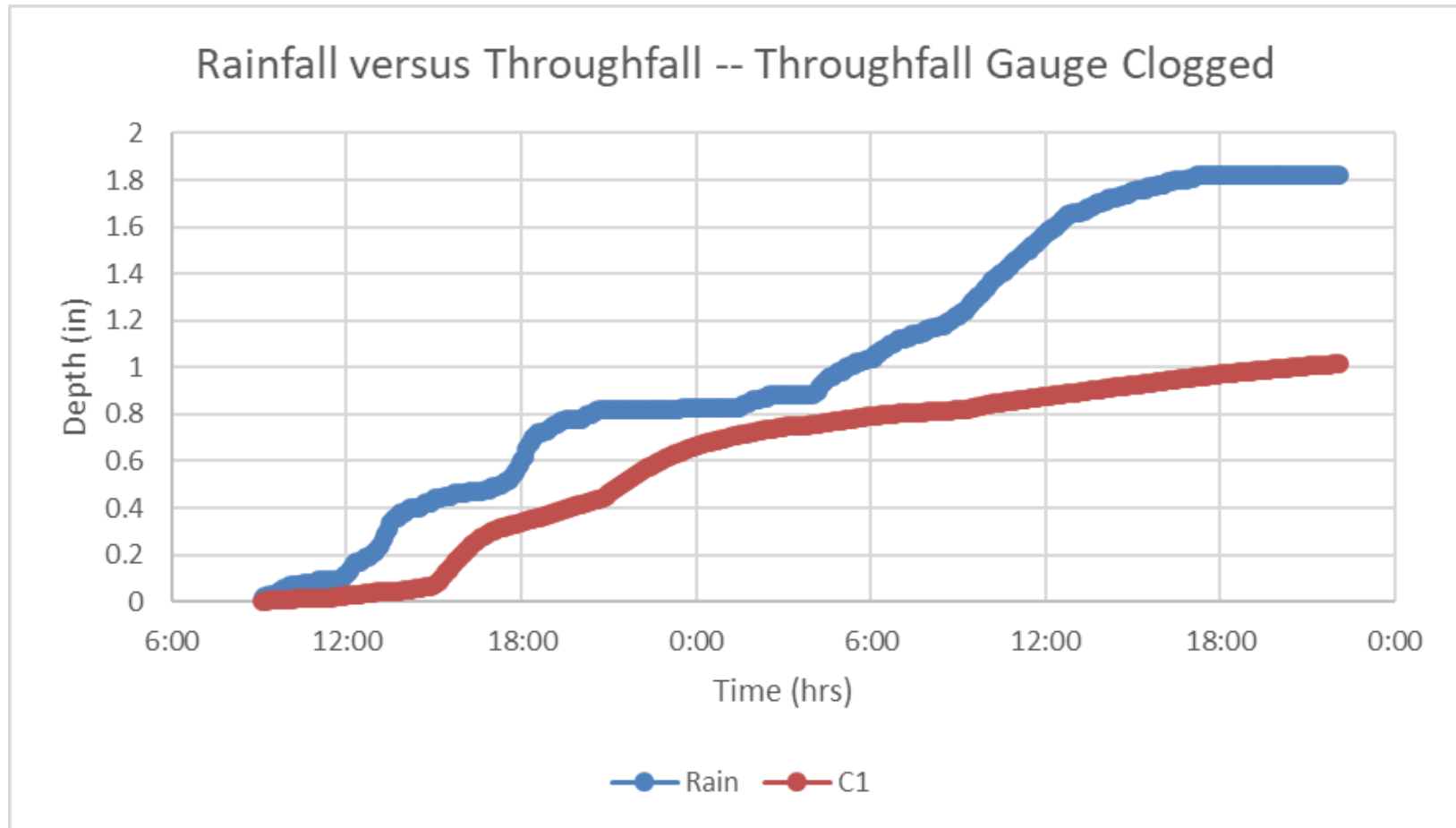


Figure A.2: Example of clogged throughfall gauge

VITA

Matthew Howard was born in Little Rock, Arkansas. At a young age, he moved to Maryville, Tennessee, where he spent his childhood. The climate and topography of Eastern Tennessee became home as Matthew found his passions in the natural environment surrounding him. He attended Maryville High School and earned the Rivalry Thursday Scholar-Athlete Award for his academic and extra-curricular efforts. After graduating high school, he moved to Knoxville to study at the University of Tennessee where he followed his interests studying water resources engineering. In May 2019, with honors, he graduated Summa Cum Laude with a Bachelor of Science in Civil Engineering and received the Chancellor's Citation for Extraordinary Academic Achievement. He continued his education as a graduate research assistant with Dr. Jon Hathaway as his adviser. He will graduate with a Master of Science in Environmental Engineering with a concentration in Water Resources in May 2021.