URBAN RAINFALL INTERCEPTION OF EVERGREEN AND DECIDUOUS TREES FOR THE SOUTHEASTERN UNITED STATES

by

RYAN WESLEY BEAN

MARK ELLIOTT, COMMITTEE CHAIR
ROBERT E. PITT, COMMITTEE CO-CHAIR
LEIGH TERRY
DEREK J. WILLIAMSON
SHIRLEY CLARK

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ABSTRACT

Rainfall interception by tree canopies continues to gain interest amongst stormwater management professionals for green infrastructure. Field observations examined variances in interception processes for numerous species for the southeastern U.S. Knowledge gaps for urban rainfall interception specific to the southeastern U.S. describe the need for standard throughfall collection methods, a general lack of information for common species, and a weak understanding of differences in evergreen and deciduous trees.

Parallel experiments at six sites were compared for evergreen and deciduous trees during 235 total rains for the first hypothesis. Paired T-tests revealed that mean throughfall for evergreens was significantly less (greater interception) ($P<0.001$) than for deciduous trees. Full factorial analysis including rain depth, windspeed, and leafless period, indicated that all factors were significant in affecting interception. One-way ANOVA tests comparing the four sites found no statistical difference in the deciduous ($P=0.11$) or evergreen ($P=0.28$) species, allowed combining the data for subsequent hypothesis testing. Lognormal linear regressions of throughfall vs. rainfall provide insight into expected throughfall for both tree types and for each species. It is like that the heavy bark and porous properties for evergreen play a significant role in rainfall interception.

Throughfall for four street trees of different sizes across 33 rainfall events was observed for the second hypothesis. No significant differences in throughfall rates were observed for individual trees; however, grouping the trees by size revealed significant differences in canopy throughfall. A 2^3 factorial analysis including rain depth, tree size, and average windspeed showed that rain depth×windspeed interaction followed by the combined interaction of all factors also revealed significant interactions.

Hypothesis three studied throughfall at four different distances beneath a single oak (*Quercus phellos*) using tipping bucket rain gauges across 38 rain events totaling 27.8 inches. Paired T-tests showed highly significant differences in throughfall at each location. A 22 factorial analysis compared rain depth and wind direction, identifying significant rain depth differences. Lognormal linear regressions showed strong differences; throughfall was marginally lower near the tree trunk with increased throughfall observed nearing the edge of canopy, with interception decreasing at the edge of canopy due to the shade effect.

DEDICATION

Dedicated to my loving wife, E. Nicole Bean, Esq., for the unwavering support, steadfast confidence, and lofty standards within her scope of influence.

LIST OF ABBREVIATIONS AND SYMBOLS

%	percent
$<$	less than
$>$	greater than
C	measured canopy storage
C^{max}	maximum Storage
C^{min}	minimum Storage
DOCIORI	dependence of the canopy interception on the rainfall intensity
DOT	Department of Transportation
E^{pan}	pan evaporation
ET	evapotranspiration
GIS	geographic information system
GTR	General technical report
hr	hours
In	inches
LAI	leaf area index
LEED	Leadership in Energy and Environmental Design
m	meters
mm	millimeters

NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Association
PAI	plant area index
PAR	photosynthetically active radiation
P-M	Penman-Montieth equation
PSW	Pacific southwest
RAWS	regional automated weather stations
RI	Rainfall Interception
S	storage capacity
ThF	throughfall
USD	United States Dollar
USDA-FS	United States Department of Agriculture- Forest Service
VPD	vapor pressure deficit

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CHAPTER 1
INTRODUCTION

Rainfall interception is the process of capturing precipitation on the surfaces of the tree canopy where it is subjected to evaporation loss before reaching the ground. The intercepted rainfall is commonly measured as the difference between the gross open precipitation and net precipitation beneath the vegetated surface. Currently, research at many international locations is ongoing to define the impacts of trees in stormwater green infrastructure planning. Green infrastructure is defined by the U.S. Environmental Protection Agency as "plant or soil systems, permeable pavements or other substrates, stormwater harvest or reuse, or landscape to store, infiltrate, or evapotranspirate stormwater." Since many common trees used in green infrastructure can grow in different environments, their performance in rainfall interception should be well documented across spatial and temporal differences for accurate results. This research examined variance in interception processes for the southeastern United States. The field observations include numerous species common to the local environment with intent to aid in the development of the full picture and potential impacts of rainfall interception in green infrastructure planning.

Canopy rainfall interception is the water stored in tree canopies which is then evaporated from the tree leaf and branched surfaces. Interception loss can be measured indirectly by subtracting stemflow and throughfall from gross precipitation falling on a tree (Berland et al, 2017). The research on rainfall interception described in this dissertation collected rainfall under tree canopies at various sites in Alabama where trees cover is estimated to be 70.5% of the state

(USDA-FS, 2016) as shown on the U.S. Forest coverage map shown in Figure 1. Much of the rainfall in the southeastern U.S. is likely intercepted by tree canopies in natural settings because forests are the dominant land surface cover. This research focuses on potential rain interception under the spatial and temporal conditions in the southeastern U.S., specifically in urban areas as it affects stormwater flows. The southeast gets an "average of around 50 inches of precipitation each year, in most years this includes some frozen precipitation throughout the region, with the exception of most of Florida and southern Georgia." (North Carolina Climate Office, 2019). And as shown in Figure 1.1, a large swath for the southeastern United States is covered in mixed (evergreen and deciduous) canopies. This is a considerable amount of rainfall over dense canopies and an urban-focused (tree-scale) study of rainfall interception in this environment will aid development in the green infrastructure knowledge and understanding.

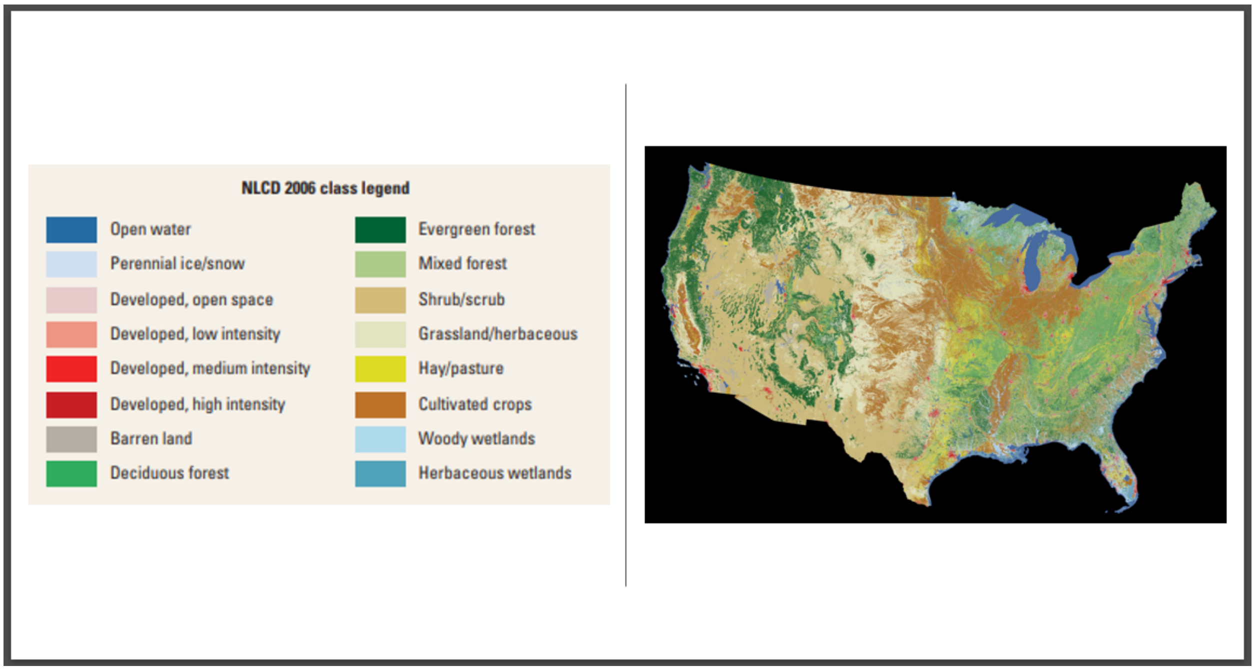

Figure 1.1 Map of the United States created using the National Land Cover Database layer (The National Land Cover Database (usgs.gov))

Whether the precipitation develops as a frontal, conventional, or a relief event, in the southeastern United States, it can be very intense, subject to long durations, and likely have short inter-event dry periods between events. These rain events combine with meteorological conditions to form saturated canopies in humid atmospheric conditions that could limit potential evaporation in the canopy; possibly compromising some of the expected benefits of rainfall interception. However, the use of rainfall interception should not be excluded in the southeastern U.S. merely for these less-than-ideal conditions. The beneficial uses of trees in landscape planning go far beyond the immediate reduction of rainfall by interception. There is also research interests considering the retention and detention capacities of strategically placed trees in an urban landscape, effectively slowing water down and changing the time of concentration for effluents. Runoff that would otherwise fall on imperious surfaces with a high runoff coefficient could be slightly reduced to the benefit of municipalities managing complex stormwater infrastructure. These advantages outline why urban trees or street trees are also promoted as more than natural shade and aesthetically pleasing features in landscape plans.

Rainfall interception by tree canopies continues to gain interest amongst stormwater management professionals. “It is possible that trees can effectively complement other green and gray infrastructure approaches to help meet stormwater control targets” (Berland et al., 2017). Urbanization continues to convert mixed timber forests common in the Southeast into planned communities or mixed-use developments, with curb and gutter road systems, sidewalks, roofs, and other impervious surfaces. Given adequate growing conditions, trees and the urban forest systems may be useful to stormwater managers and design engineers to help manage and mitigate the effects of stormwater runoff (Kuehler et al., 2017). The cohesion between industry construction practices and low impact development guidelines varies depending on the state, municipality, or local covenants that could enforce intelligent implementation of stormwater management techniques.

For example, in Alabama where the research is conducted, a low impact development (LID) guideline was published in 2013 by Dylewski and colleagues with several elements of green infrastructure. The document serves as a guide to aid planners in the state of Alabama in developing interdisciplinary practices as landscapes become more urbanized, with proportionately greater amounts of impervious surfaces. They discuss the challenges associated with implemented the "perceived barriers" to adding LID measures on a project, giving examples of local ordinances within the state promoting sustainable practices. The guide has methods to work through these issues to the benefit of environmentally friendly options. Their work also provides example works and calculations to provide a proof of concept for sustainable opportunity projects that can be incorporated into the site development. However, sustainable measures may add upfront cost to materials and practices that require a multi-year return on investment. The added cost can disadvantage the methods without the local ordinances, programmatic initiatives (e.g., LEED certification), or credit incentives aimed at countering the additional capital needed for the development. Through continued research to understand green infrastructure implementation that clearly defines actual benefits we may commercially adopt these practices. Understanding rainfall interception for common species in southeastern states is one area that must be clearly defined to support this line of effort. The data could be useful to designers developing landscape plans with elements of green infrastructure.

A study in Querétaro City, Mexico on the benefits of street trees in reducing runoff bound for municipal collection and processing a benefit of 0.18 USD per m3 (Gonzalez-Sosa et al., 2017). Their research looked at ways of reducing the runoff effects in urban areas and suggest that incorporating more trees into landscapes can substantially reduce effective precipitation falling on the ground through interception. These works must cost reduction and societal benefit to ensure their implementation over conventional practices. In Manchester, UK plots for open grass, asphalt pavement, and a planter box tree over asphalt were compared in standard watersheds. The simulation was conducting on two distinct slopes to expand the study parameters. Their combined results showed that even though the tree didn't outperform the grassed area, it far exceeded the runoff collected below the continuous asphalt surface (Armson et al., 2013).

Research on turf grass performance is much more complete. Runoff coefficients are well documented for turf areas and already incorporated into watershed calculations and models commonly used in design calculations. Furthermore, information and practices of evapotranspiration (ET) is better understood making their implementation into sustainable works easier to calculate and implement. Cleugh and colleagues state, "for every 10% increase in pervious cover, the annual ET increases by 62 mm y-1 from a base ET under urban consolidation of about 50% of that prior to urbanization." Upsetting this balance carelessly by not incorporating balanced ratios of grasses, trees, permeable surfaces, and other control measures could have impacts and consequences to the urban environment. A thorough understanding of rainfall interception for urban trees, as part of the complete water balance on a site, is key to further defining and adding to these potential benefits.

Trees have a measurable surface area to store water and larger storm events can quickly exhaust this storage. Alves and colleagues stated that "the interception of the species in the events of shorter duration, intensity, and precipitation are, on average, about 40% of the precipitation and, in the most intense and long-lasting rains, rainfall interception rate is about 3.6%. Hence, it is a well-known fact that rates and values obtained as interception parameters for the species are used by engineers and simulators against the need of an exact value and also due to the difficulty of studying the endless number of species that are used for urban afforestation in the cities" (Alves et al., 2018). We also must understand that trees vary between individuals of the same species by several factors that will be described further in this dissertation. These traits and conditions must be well defined to properly implement calculations and a basis of design to include tree plantings in stormwater design calculations. This research conducted at various sites in Alabama will improve understanding of how common species perform in the southeastern U.S. and fill in a small piece to a large puzzle of varying species performances against differing meteorological conditions.

A large portion of the precipitation storage on a tree is in the crown (limbs and leaves). Researchers commonly estimate the potential minimum storage in millimeters of depth with results typically ranging from less than 0.08 mm to well above 3mm, depending on the size of the tree (Smets et al., 2019, Baptista et al., 2018, Guevera-Escobar et al., 2007, Xiao et al., 2000; Teklehaimanot and Jarvis, 1991). These experiments include many different estimation methods to include the following: measured observations of trees (in-situ and ex-situ experiments); physical measurements of canopy size and densities; remote sensing methods; and extrapolations from analysis of leaf and branch structure. Literature describing storage is essentially a combination of retention (permanent water losses) and a small amount of detention (delayed releases of water) on a much smaller scale. Much like stormwater management practices in storing large amounts of surface water on site during construction and post construction in order to reduce or maintain the same calculated runoff as the preexisting conditions (Alabama DOT Permit Manual, 2014). The tree interception reservoir is emptied by evaporation, water flow down to the next layer along the stem surface, and surface and drip off the stem surface (Xiao et al, 2000). The retention being the water that stays on the tree until it evaporates. The detention (maximum storage) can be described as the dripping precipitation once the tree crown nears its natural rainfall holding capacity that is delayed temporarily reducing the peak runoff flow. Because the rainfall intensity and durations are generally larger in the southeast, understanding the benefits from rainfall interception locally would be useful in future site development guidelines. Each of the conditions described in the tree reservoir slow the flow of water onsite. The inclusion and consideration of these site conditions would aid designers in ensuring the stormwater infrastructure and drainage easements and are not compromised over time because of new effluents that were not part of the design calculations.

Transfer of this knowledge to the urban environment, where runoff is becoming an increasingly important issue, can be difficult as the conditions differ dramatically (Armson et al., 2013). Recent research recognizes and accounts for these issues, but little is known on how the findings can be extrapolated for seasonal and spatial differences, and across other tree species. The scale of interest likewise changes between a forest canopy and an urban landscape. At the forest-scale, gaps between trees and canopy density describe the sparseness of the canopy impacting rainfall interception. For many urban sites, the focus will likely be at the individual tree-scale. Urban trees are more likely spaced out to accommodate structure (buildings, roads, sidewalks, etc.). They will also likely be uniform in age and size, and of a few select species planted during site development. Because the trees are commonly added for pedestrian and aesthetics, only portions of the canopy may cover directly connected surfaces contributing to stormwater runoff. Accurate surveys of tree types and canopy coverage over connected surfaces inside the watershed area is necessary to account for the impacts these trees can have on runoff reduction. The consideration of tree canopies in urban planning derives the need for tabular planning standard designs and resources to properly account for water mass balance with respect to rainfall interception for a site. Much of the early literature on rainfall interception focuses on natural settings and dense populations of trees in closed canopies. It is still not clear how much of this information applies to typical urban areas with less dense plantings and varieties that may not be well researched by forest-scale research. In this dissertation, both natural forest canopies and single trees are studied to aid in the distinctions.

1.1 Literature Review

This chapter presents a literature review to evaluate the beneficial uses and role of planting and retaining trees in urban site developments, especially pertaining to stormwater management. The review also looks in depth at the natural conditions, physical science, and related research topics pertaining to rainfall interception by trees. Trees are ubiquitous, from landscaped plantings to forest remnants in developed zones, and hardy species growing in cleared areas without maintenance slowly regenerating forests. A tree’s ability to promote interception, infiltration, and flow reduction in green infrastructure is still being explored. Some cities are planned or developed with abundant tree cover and other cities reflect more hardscapes, but all may benefit from the inclusion of trees in landscape planning. Selecting the appropriate species and number of trees to incorporate into designs is however not well understood. Consultation with tree experts, such as urban foresters, is required to identify which species are most appropriate for the local site and climate conditions. Regarding species selection by hardiness and drought tolerance, information is already available for many areas (Gonzalez-Sosa et al., 2017). However, the quantitative tree functions in stormwater management are not as well known.

The ideal objective of stormwater management low impact development (LID) activities is to match the pre-development hydrologic cycle after development. Logically, including trees in these plans would require metric based calculations or estimates of rainfall intercepted by selected species to incorporate correct runoff estimates for the site. "While there is an agreement on the merits of protecting and restoring more natural flow regimes in urban and urbanizing catchments, stormwater managers need guidance on how to reach such an objective," as stated by Fletcher et al., 2014. Arguably, there are both positive and negative implications (though manageable) to the use of trees in urban areas. These must be carefully weighed to ensure the taxpayer costs are reasonable. All considerations must eventually be explored for utility to develop a comprehensive guide for their inclusion in landscape planning. For example, root infiltration can cause increased repairs to walking surfaces, curbs, sewer pipes (McPherson et al., 2002). In the fall, maintenance from the additional biomass associated with increased tree coverage may have impacts. Massive leaf falls may clog storm drainage inlets requiring extra maintenance, and limb maintenance required to maintain an appropriate tree canopy height can create large amounts of low-density biomass requiring labor intensive processing and disposal.

Some of the most obvious negative impacts are related to cost, whether through labor, maintenance, or sustainment. Post construction, newly planted trees require care and at times irrigation while root establishment take place in the topsoil. The following example gains to consider that are beneficial to quality of life: shading that prevents solar radiation from heating paved surfaces; pedestrian shade in high traffic areas; and more importantly reduction of energy usage in climate-controlled buildings (Akbari et al., 1992). Furthermore, many researchers have observed that trees reduce runoff to the benefit of municipalities and individuals (Sanders, 1986; Nowak and Dwyer, 2007; Armson et al., 2013). Other effects may reduce infiltration (reduced groundwater recharge and base flows in streams) and reduced runoff discharges to streams, due to increased interception, reducing costs in stormwater infrastructure. In 2002, Nowak and colleagues reported annual savings of $2.4 trillion or $630/tree for urban forests in the lower 48 United States. Some have overall quantified these savings as a positive impact to urban areas, citing that the savings ranging from $0.18/tree to $7/tree each year (Dwyer et al., 1992; Gonzalez-Sosa et al., 2017).

Contrarily, as the street trees age, there will likely be a noteworthy budget increase for maintenance of the trees and related structure that must be factored into the investment cost. A survey of aged urban forests and mature trees in Modesto, California determined that nearly 74% of the maintenance cost were related to the even aged, older street trees in various zones of the city, citing that “the issues such as sidewalk repair, root pruning, and trip-and-fall claims (were major contributors).

Figure 1.2 Cracked concrete sidewalk damaged from root growth elevating the slab 2 inches and causing trip hazards for pedestrian traffic

Because of the existing forest's even-aged structure and the reliance on benefits from Modesto ash, spending less on management at this time could jeopardize the future stream of net benefits" (McPherson et al., 2009). For these reasons, a thorough landscape plan is necessary to select appropriate species along streets, sidewalks, and in planter boxes. For example, a tree in a planter box with normally large growth potential may be limited on root depth and sprawl over time. As the roots continue to grow it naturally reduces the root to soil ratio; potentially stunting the trees growth. The confined three-dimensional space in the planter box further reduces available soil nutrients essential to the growth potential. And, over time as the roots expand with the space, it can displace and transport soil within the box as visible in Figure 3. The tree shown also shows signs of limb removal over time to accommodate pedestrian traffic, as well as displacement of the sidewalk by the roots causing major trip hazards that require costly repairs. These conditions can impact the health and growth potential of the tree, including the canopy structure impacting potential rainfall interception.

1.1.1 Tree Architecture & Canopy Structure

To form a better understanding of rainfall interception, one must understand there can be an extreme amount of variation between trees of different species. In 1998, Millet and colleagues state that the “most obvious distinctions exist in the tree’s crown. This is where limbs and branches begin forming from the bole of the tree at different heights and angles creating unique silhouettes in shape, size, and density. These variations also exist amongst trees of the same species.” These distinguishable traits are noteworthy with respect to storage potential and may be amplified when coupled with meteorological factors. Many researchers studying rainfall interception have cited canopy architecture as a contributing factor impacting storage by trees while explaining storage variation among (Xaio et al., 2000a&b; Murakami and Toba, 2013). Others below noted that the branch inclination also had important effects on the storage. While conducting rainfall interception experiments on 4 small trees in a laboratory, Li and colleagues looked at the water balance (including stem flow) to further understand how crown structure impacts rainfall storage. His experiments simulated rainfall ranging for normal intensity up to rates well beyond high intensity events (10-150 mm/hr in). Reporting that 40% of the interception dripped to the ground during the third phase reducing the maximum storage towards the minimum capacity that would remain after the event for evaporation (Li et al., 2016). They made observations on tree architecture differences for each species, and discovered critical findings related to the canopy architecture impacting the minimum and maximum storage capacity for each.

The term "tree architecture" (or “canopy architecture”) describes the “endogenous morphological processes undergone by trees, considering every aspect of their development, including their complete development sequence, from seed-sprout to senescence, no matter how complex their morphology may be” (Restrepo, 2018). Under natural conditions each sapling tree’s growth and development is unique as it strives to gain dominance in competing for sunlight. Collectively or individually, they create the “canopy structure” defined by the organization of upper tree limbs and foliar growth near the top of a tree. The way a tree develops is largely unpredictable. There are several theories proposed explaining the unique growth patterns between individual trees. A review by Millet and colleagues in 1998 of the succession mechanisms outlines four distinct tree growth patterns that hypothesize how trees individually or collectively affect the tree structural growth. Offering that environmental factor of the adjacent plants, random events and growth potential, interspecies competition, or natural selection all could impact the trees growth. These may all contribute to the growth morphology collectively or individually. The environmental factors and surroundings drastically affect the resulting growth pattern as compared to the various potential outcomes (Millet et al., 1998).

1.1.2 Leaf Area Indexing and Canopy Density

Common measurements of the fullness or density of the canopy architecture of tree or trees is estimated by leaf area indexing (LAI). Marshall and Waring (1986) defined LAI as the projected surface area of foliage per unit ground area. Calculations for LAI are either by direct measurements or indirect measurement techniques. Direct methods involve collection of leaf litter and destructive removal of leaves from trees throughout the seasons. One indirect method utilizes allometric models (basal diameter, height, diameter, etc.) to estimate LAI. Other advanced methods use photosynthetically active radiation (PAR) or terrestrial laser scanners to estimate the conditions through sensing equipment capable of digitizing the fractional differences in structure and ultimately measuring the three-dimensional density within the canopy by creating point clouds. The data is later post-processed to delineate the fractional coverage of the canopy over the known area. Regardless of the chosen method, the measurements are realized by perceiving the canopy in the zenith angle directly through the limbs and leaves and between the open air and the ground beneath the tree displaying the contrast of intercepted light. Many researchers interested in measuring or modeling rainfall interception are using LAI in defining the canopy condition metrics in their research. The practicality of measuring LAI to estimate storage potential for each tree or a population of trees within a given site may not be achievable due to cost or time the time of year when a survey of canopy (leaved or leafless) can take place. Instead known probability information for like species by age and condition may be useful in estimating the potential rainfall interception storage. Typical species selected for landscape plans in developments will grow similarly under the same environmental conditions and management and grooming regiments. These like canopies will likely have common interception potentials throughout their lifecycle. Measuring typical species at different growth stages should be explored to define the potential storage as these trees grow.

In a forest setting, a "closed canopy" is where the individual canopies meet and overlap (canopy closure) while competing for sunlight as they grow. The overlap and closure between trees are described as the canopy density and takes into consideration both the leaves and canopy structure. "Street trees" or "urban trees" will likely have different canopy characteristics, and expectedly much lower canopy density due a combination of the type and size selected for planting and the morphological impacts at the planting location as described in the previous section. They can be individual trees and co-dominant trees in select spaces. They can have tree architecture that is unique from the same species growing in a forest. They may also have canopy morphology able to extend further horizontally to reach more sunlight. Given that they are not constrained by some of the factors listed earlier in this text, these trees will develop fuller canopies without the obstructions and competition of surrounding trees. But individual street trees are commonly spaced further apart to make room for the numerous infrastructure requirements in an urban setting deriving the needed to view urban rainfall interception at the tree-scale. The master plans for a zone will impact how trees can be utilized to landscape the site plan. In Figure 4, a geographic information system (GIS) mapping project records the location and approximates the canopy coverage of street trees in the areas surrounding Union Station in the District of Columbia. It shows dense canopy coverage along the streets to the east, while the immediate areas around the tracks and building have little to no trees at all. Likewise, the western landscape, though denser than the central zone, has much lower canopy coverage due to the larger buildings, less streets, and space to line with vegetation. The distinctions between the zones show obvious challenges for including rainfall interception into sustainable features in all urban areas. It also shows that most of the tree exists along and streets with pavement and asphalt surfaces.

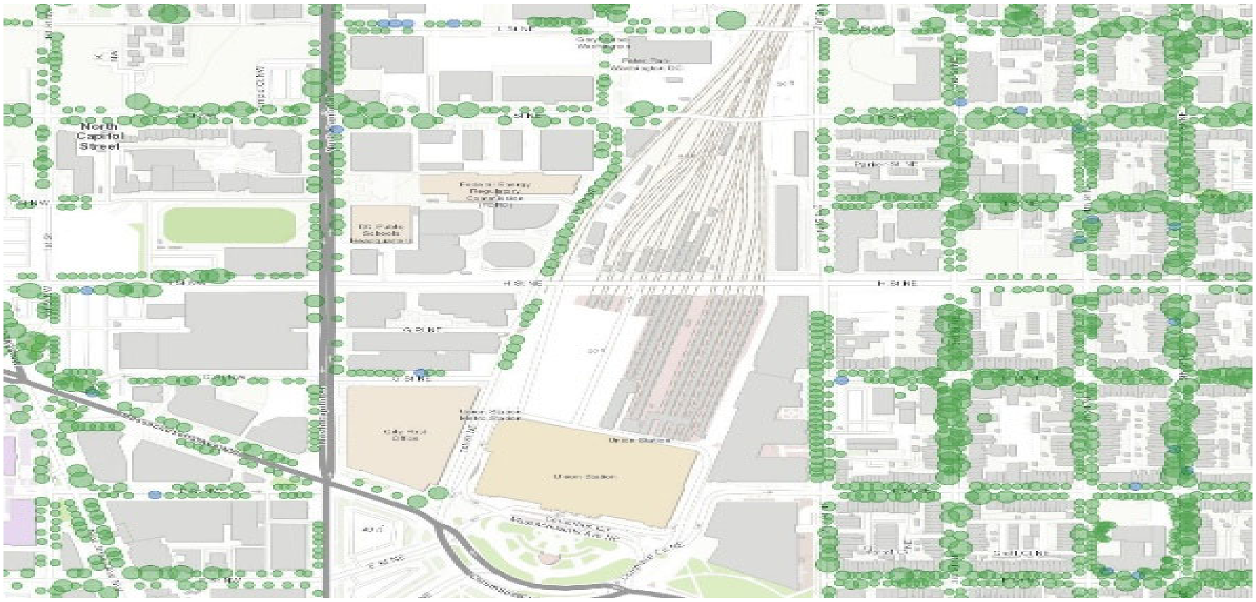

Figure 1.3 Survey of tree canopies near Union Station in the District of Columbia, U.S.A

In most cases, detailed summaries of the size, location, condition, much less as GIS database are available for street trees. But a general technical report (PSW-GTR-253) was published in 2016 by the USDA Forest Service specifically for the purpose of estimating these canopy conditions. The work is based on the observation, surveys and measurements of 14,487 urban trees of common species and conditions. The report also includes allometric equations for the species surveyed broken down by type and region. The guidelines and calculations in the report can be used to conduct site investigations in urban areas as a helpful resource to catalog this information, if needed. Common examples of these trees line the paths, sidewalks, and hardscape areas providing shade for pedestrians. These trees enhance the site functionally, provide shade to cool otherwise heat absorbent surfaces, and esthetically improve the area.

The growth potential of the trees depends on shading constraints such as adjacent buildings, limitations in the soil nutrient availability, or constraints in root development from compacted soil or pavements adjacent to the tree. Furthermore, “pruning practices, crown damage, and other stressors create variability in the growth of urban trees" (McPherson et al., 2016) that must be observed and cataloged to fully understand the distinctions of urban trees. Further, the individual tree architecture will impact the interception through branch inclination, fullness of canopy and number of branches in the path of rainfall. These conditions may collectively (or individually) create distinctive trends in throughfall, storage, and stem flow between species and even interspecies morphology.

Because the resulting LAI measurement yields a two-dimensional planar density ratio, it does not account for the vertical distance between branches in the canopy architecture. In 2019, Yang and colleagues surveyed four common urban planted street species near the Seoul National University in Seoul, Korea to further a three-dimensional understanding. They collected rainfall beneath the canopy of each tree for two months collecting six events with enough rainfall depth to analyze rainfall interception. For each species, they used a terrestrial laser scanner to measure each trees' canopy. From the data they were able to estimate morphology in the form of LAI, LAD, leaf angle, width and height of the crown. Of these variables LAI was the most important factor affecting interception. They were also able to the take the point cloud information for each tree and measure LAI vertically from the ground to the top of the crown and horizontally from the base of the tree detecting how it became denser closer to the bole and in the middle of the crown. They noted that the high interception rates observed during their experiment were affected by locating the tipping buckets under this leaf dense area of the canopy (Yang et al., 2019). Distance from the base of the tree could impact direct rainfall interception collection. Little such research is being conducted to measure the transect variation in direct collection of throughfall to gauge tree performance. Direct observations at multiple distances from the bole to the edge of the canopy may be helpful in determining variation in rainfall interception due to the variation in LAI throughout the canopy.

As researchers continue focus on the performance of street trees, they have exercised historical models and equations focused on a forest canopy. This is because for approximately 100 years much of the research focused on rain interception in natural forests. Regardless, this starting point helps to refine and expand these tools toward the focus in urban infrastructure. For example, a team conducting an in-situ experiment on two prevalent deciduous species common to Europe (Norway maple and small leaf lime) wanted to determine if the forest-scale models of Gash, Rutter, and WetSpa could be adapted to estimate urban tree rainfall interception. In 2000, Xiao and colleagues developed a three dimensional physically based stochastic model specifically for individual trees, but the European team lacked the resources to collect all the input data required for the model. They calculated LAI during the project and showed some distinction between the peak LAI and length of leaved time between the two species. Even though the maple had a higher LAI it dropped leaves sooner in the fall giving a seasonal advantage to the lime. The overall results during the measurement period showed that both species averaged 38% interception rate over the entire collection period (Smets et al., 2019). Because seasonal impacts affect performance, and rainfall is prevalent in all seasons, yearlong interception must be measured to ensure seasonal variation in southeastern species is estimated properly.

What is not well described in literature is the changes to canopy architecture (unevenly proportioned branch development) for assessing growth of urban trees using historical charts and calculations developed from forest conditions. (McPherson et al., 2016; Anderegg et al., 2015; Nowak, 1994; Peper and McPherson, 1998) In most cases, canopy growth is limited to where first space (if against a building), then direct or available sunlight exists. For example, when co-dominant trees compete for sunlight, each trees canopy is usually weighted away (extending branches and leaves) from the competitor to maximize sunlight exposure (Martin et al., 2012). Millet and colleagues describe these occurrences by a combination of interactions among species and a "natural right to succession as plants randomly grow in individual strategies of gigantism" (Millet et al., 1998). This causes the tree growth to stifle in the direction(s) where they compete for space. This same outcome would exist against a building or other structure depending on proximity and orientation to direct sunlight. The tree then develops with unbalanced growth, creating a static moment, and potentially making the tree susceptible to falling or losing large limbs on the side with more growth. The limits to growth could impact the fullness of the canopy and ultimately storage potential in the tree.

Unlike forest canopy trees, single or widely spaced plantings commonly develop lower branches along the tree. This is in addition to the upper crown structure that is needed maximize exposure to sunlight. Incidentally this increases leaved and branched surfaces at lower levels providing additional layers on the tree. This is differing from a forest canopy where branch architecture is predominantly dense up high close to the treetops and the bole and barren or very sparse as you get close to the surface. The benefit of these additional branch levels of the tree become additional surface storage on the tree, if they are not trimmed for maintenance, aesthetic desires, or utilitarian requirements on the site. This could also offset the lost surface in the tree trunk since the tree may not have to compete to grow taller. For rainfall interception, the algometric equations developed by McPherson and colleagues for the General Technical Report: Urban Tree Database and Algometric Equations could be correlated to the storage observations of the same specified species by region at different growth stages to recover a stable range of data. Collection at a large nursery, carrying numerous sizes of like species or a completed site that developed in phases and the landscape plan utilized the same species at each phase could yield preliminary results towards this goal.

1.1.3 Storage by Trees

Fundamental knowledge in understanding rainfall interception must include a thorough review of how rain is captured and stored on the foliar growth (leaves), branches, and bark surfaces. There are two common storage surfaces in the tree crown: the leaves and stems with the remaining storage held on the trunk of the tree. As precipitation passes through these surfaces some precipitation is intercepted at different layers in the crown depending on the surface density within the crown. And, as the crown drains, rainfall may again be intercepted at lower levels (Xiao et al., 2000a). There are several definitions that describe the maximum storage (and minimum storage) by trees which collectively define rainfall interception as a resource regarding stormwater management. The maximum storage (minimum), retention storage (detention), temporal storage (real) or dynamic storage (static) (Xiao et al., 2000a; Baptista et al., 2018; Guevera-Escobar et al., 2007; Kirnbauer et al., 2013; Kuehler et al., 2016) are all used interchangeably in recent literature, and for clarity maximum storage will be used throughout this research to describe precipitation collecting on the surfaces temporarily before draining to the surface. Likewise, minimum storage will be used to describe water remaining on trees' surface after the culminating rainfall. The minimum storage stays on the trees' surface and available for evaporation.

During a rain event over a canopy, the first phase of storage is the "wet up" or saturation phase as described by Rutter and Morton (1971). At the beginning of rainfall leaves on the outer crown begin to saturate. At leaf surface saturation droplets reconstitute and begin traveling along branches towards larger limbs like channelizing water collecting into larger more concentrated paths saturated portions of the canopy structure. Along the entire path, porous openings, dry or dead matter, epiphytes, and fibrous qualities on the surface of the tree architecture retain some of the water. The constitution of the tree canopy affects the combined storage potential. Lichens and mosses are more common on oak branches and trunks (than on evergreens) and can affect stemflow (André et al., 2008) by increasing storage on the trees surface. At the same time some rainfall, as spillage, or inefficiency in collection begin to fall to lower levels of the canopy where the process continues until saturation takes places within the entire canopy projection (mass of the canopy in direct contact with the rainfall). This saturation phase is where measured maximum storage begins. The flow that overcomes the resistance and attractive forces and drips is collected as throughfall. The short delay between open collected precipitation and throughfall describes the maximum storage of the canopy.

Maximum storage is impacted by the contact and differs by the tree's characteristics. Rain is held during the event for a brief period due to attractive forces that adhere the water droplets to the leafy and barked surfaces for enough time to slow down canopy drainage towards the ground ultimately delaying collection as runoff. The latter is the minimum storage and is described as the droplets remaining on the stated surfaces, either in place or traveling down the tree towards the bole, but not all the way to the ground. This is the measured storage that may eventually be return to the atmosphere instead of entering ground water as infiltration or stormwater runoff. Here the numerous spatial and temporal factors affect the probability of the intercepted rainfall. A more accurate representation of maximum storage must also separately account for the stemflow to partition the mass balance. Stemflow is the flow traveling through the entire length of the tree with enough energy to overcome the surface tension and attractive forces all the way down to the ground. For most deciduous trees storage area increases with new leaf sprout in Spring that eventually grow to peak potential in summer. Depending on rainfall leaves may remain healthy through most of the fall season. Eventually, senescence forms in the leafy canopy starting the deterioration process (generally in Fall through winter).

Figure 1.5 Full foliage & senescence (left) compared to new Spring growth after the leafless period

Abscission is the final step for releasing old leaves before the cycle repeats. The timeline for this is also species dependent. Some trees hold dry and decaying leaves throughout winter and complete abscission just before new buds form in Spring. Others release leaves early and have only a skeletal canopy throughout fall and winter as shown in Figure 1.6. Monitoring these transformations is important to compare the annual difference for deciduous trees against evergreens (e.g., pines) to compare minimum storage for rainfall interception.

Figure 1.6 Example for senescence, abscission, and new growth in oak street trees planted in Montgomery, Alabama (March 8, 2022)

Much of the moisture is unsteadily held on the canopy surface and any number of disruptions, or even vibrations by high winds may create enough kinetic energy to release some of the stored water. Time to evaporate this water is highly dependent on the buffering air storage capacity in order to be vaporized and truly intercepted. In humid environments the vapor pressure deficit is low, meaning the air's additional storage potential may not be capable accepting some or most of the rainfall stored on the surface or a near surface available state during the rain event or shortly afterwards. Since humidity and temperature are inversely related, the early evaporative cooling that can take place during the rain event could further reduce the vapor pressure deficit lessening the likelihood of evaporation. And, in these humid tropic and sub-tropic environments, the potential for follow-on rain events may further minimize the window of opportunity for evaporation on a saturated canopy. This is notably different from arid environments where much of the research is conducted in the United States. In drought conditions, evaporation is more likely, making the opportunity to capitalize on the detention storage from trees more productive for urban planners. The limited number of rainfall interception experiments conducted in the eastern and southeastern United States derives a need to survey typical species and conduct direct observations. The work would support knowledge gaps in the subject and further understanding for green infrastructure. Many researchers have looked at storage at each phase (wetting up, saturation, and drainage) to measure storage. This is an extremely difficult task to complete by in-situ experimentation.

A unique experiment conducted by Teklehaimanot and Jarvis (1991) developed a direct mass balance for small spruce trees by suspending the tree beneath a tripod structure; hanging the tree from a scale with a data logger in an effort to estimate boundary layer conductance and canopy storage for widely spaced trees. The tree was sprayed continuously until the weight remained constant for at least 50 seconds before allowing drying to begin. By collecting 1-min time series data of the gradual weight changes in the draining process, the drip phase is detected and delineated from the evaporative loss to determine the minimum and maximum storage. Meteorological conditions were collected to calculate evaporation from the wetted canopy and compared to the observed drying of the suspended tree. The method was repeated in different locations in the forest to replicate different spatial variability to adjacent trees (ranging 2-8 meters). The direct comparison of the observed and measured evaporation was used to examine two assumptions by Rutter (1971): when $C>S$, evaporation is equal to E^{Pan}; and when $C<S$ (partially wet canopy) the evaporation is $E^{Pan}(C/S)$. Both were validated in this study. Other findings support the extrapolation of the data for use on a large scale. Though they didn't display the data, they reported that their work displayed a linear relationship between storage and number of trees in a stand. They support this claim by relating their resulting interception per hectare to earlier work using different estimating methods with agreeable results. Most notable,

the data correlates the wet-bulb measurement and crown surface temperature throughout the experiment. The findings show that canopy surface temperature drops to wet-bulb temperature as the canopy saturates, and as it drains the maximum storage, the temperature quickly approaches the air temperature supporting the theory that evaporation begins shortly after the event. In the study all minimum storage evaporated between 40-120 minutes after rainfall ceased, proportionately depending on canopy density (2-8 meters).

A report in Querétaro City, Mexico looked at the benefits while contrasting two common street trees in reducing runoff bound for municipal collection by estimating the maximum and minimum storage. The paper considers isolated trees along streets and avenues to provide reduction modeled using Rutter interception method and producing dimensionless unit hydrographs to compare the peak flow. The research suggests a reduction of runoff into wastewater systems by 10-20% and delaying peak flows by 10-15 minutes; suggesting that a single tree crown could intercept an estimated 2.87-15.12 m^3 per tree each year. (Gonzalez-Sosa et al., 2017).

In 2016, Li et al conducted experiment of throughfall on four species of small individually growing trees in a laboratory setting. Artificial rainfall and a scale were used to saturate the trees to determine the minimum and maximum storage for each species. Each saturation experiment lasted 30 minutes allowing ample time to saturate the small trees. The process was repeated after ample drying time at three more rainfall intensities (increasing each time). Their results depict marginal increases in the C^{max} for each species. Likewise, the added intensity had modest impacts in increasing the C^{min} for most of the selected species. The rainfall depth retained as C^{min} and C^{max} (0.09-0.13 & 0.13-0.38mm) (per m2) corresponds to other work conducted in this review. By far, in a summary comparison of tree types, the coniferous "needle species", reported the highest C^{min} and C^{max} compared the broadleaf species in the review.

In direct comparison to trees, a 2019 report by Smets and colleagues suggests researching and potentially implementing small plants and grasses, shrubs, and other woody plants in lieu of the trees to reduce runoff. They look at three native plants and one typical grass blended turf in the study. They developed standard procedures to saturate the soil, weigh, and then saturate the plant to measure the minimum and maximum storage for each species. The results show that plants, much like the trees above in Figure 5, all performed differently based on the morphology and architecture of their canopies. And, that their storage is highly dependent of the same density and available surface area for storage. Using box plots and multiple linear regression to display and predict performance, they showed that the research is repeatable and a worthwhile alternative to trees, where better suited. And, that the research should be furthered citing economic advantages from the maintenance and upkeep prospective. There work also considered the overall biomass of the species, a metric that should be considered for congruity with other competing issues in urban reuse and renewable energy initiatives that also have interest in the plantings included in the urban environment.

In 2016, Xiao and McPherson surveyed, collected, and measured surface storage capacity for 20 common species in in Davis, California to further understand street trees. The species accounted for 77% of the canopy coverage within the study area. The sample population included broadleaf deciduous, broadleaf evergreen, and coniferous species. Their sample cuttings were preserved immediately to combat wilting and immediately subjected to a series of simulated rainfalls under weights and measures to estimate the amount of static storage capacity each species could hold. Amongst the species were several common to the southeastern U.S., including the Bradford pear (studied in this experimental plan). Each sample was later segmented as necessary and photographed against and background of know dimensions to accurately calculate the surface areas following a method developed by the USDA forest service (Peper and McPherson, 2003) and ArcGIS software tools. They used information from the Urban Tree Database and Allometric Equations GTR (USDA, 2016) to estimate growth for each of these species and canopy area for the other parameters required to model the samples storage potential. Only the leaves and stems collected in the cutting samples were analyzed, omitting the larger tree structure of the limbs and bole. Their report also defined surface minimum storage potential for all species between 0.59 and 1.81 mm for all 20 species. This range limits catchments potential benefits to smaller storms. The results provide valuable insight into the common species to be considered in green infrastructure planning. The data and methods add to the baseline considerations for other regions to further understanding of maximum and minimum storage of the species. Finding correlations in the minimum storage for these species with like specimen in the southeastern U.S. covered in this research would be useful in closing knowledge gaps for this subject.

Relative to storage of the tree below the canopy, the surface of the stem, branch and bole structure of the tree are important factors for minimum storage. The greater these surface storage areas, the more stored water there is available for evaporation. Larger species can be selected to add more minimum storage if urban spaces can accommodate the canopy structure, as well the root and soil requirements to sustain tree health. The USDA-Forest Service published the Urban Tree Database and Allometric Equations Report (PSW-GTR-253) with detailed planning factors to assist in selecting the appropriate trees at a given location. Amongst different tree the variation in depth valleys in barked surfaces also plays a major factor in increasing potential storage. In

2018, a study of honeylocust trees in New York, NY, US examined the sub-millimeter surface morphology of the barked and foliar surfaces throughout the seasonal phases of the deciduous species. The findings showed a slight decrease in storage capacity during senescence, but overall agreeance that micro reliefs in the surfaces promote storage capacity on the barked and foliar surfaces (Campellone, 2018).

In 2016, Li and colleagues conducted in-situ experiments on four small trees to study rainfall and tree structure characteristics. For one area of interest, they hoped to successfully examine collection, amalgamation, and eventual discharge of raindrops draining through the canopy, expecting sufficient volume for negative runoff impacts on the surface below. However, their observations found values much lower than expected. They attributed the reduced throughfall drip to uneven surfaces of the broadleaf species with curled margins, clear veins, and pits that likely inhibited the movement of small water droplets (Li et al., 2016).

Leaf water uptake and storage are important characteristics in understanding the storage component of rainfall interception. The wettability (storage capacity) or hydrophobicity (water repellency) of leaves influences canopy storage. Selecting the right trees with strong foliar wettability characteristics, high LAI, and good canopy architecture in a landscape plan can improve onsite storage. Analyzation at the leaf scale shows how leaf inclination and water droplets impact water retained by the leaf. The force of the rainfall changes the leaf inclination towards its maximum. As the water impacts the leaf some splatters away (“ejecta”), some drips away, leaving only a portion of the drop. This new leaf mass changes the leaf inclination, and as water evaporates the steady state changes the leaf inclination towards the original angle (Holder et al., 2020). The variance in these angles combine with wettability characteristics to define the leaf scale for minimum storage. The attraction is likely overcome by rainfall depth, intense rainfall, or large droplet size with enough inertia to break the water bond with the leaf. Related research in Colorado determined that the leaf hydrophobicity and water droplet retention of the adaxial ("top") leaf surface were important in influencing canopy storage capacity during the first few minutes of a rainfall event. As the rainfall duration increased, the leaf hydrophobicity and water droplet retention of the abaxial ("bottom") leaf surfaces became important (C.D. Holder, 2013). More research is needed in this area to quantify and relate these findings to relate and classify common species used in urban infrastructure.

With wettability, water uptake by leaved surfaces is another characteristic that should be considered by urban infrastructure planners. The two ways by which water can enter the plant as foliar uptake are from direct contact via precipitation or by condensation from fog onto the surface. The water is absorbed and held in the leaved cavities until the atmospheric conditions again promote evapotranspiration (Schreel and Steppe, 2019). Much of the research related to foliar uptake by leaves considers dry climates or drought conditions and the potential for trees to sustain themselves in dry stressing environments. But these characteristics are useful for landscape planners selecting species typical in green infrastructure to improve onsite retention and reuse of rainfall. A team of researchers at the University of California at Berkley studied 10 plant species and 6 trees common in the redwood forests to further understanding of water uptake by leaves in Redwood forests. The ex-situ experiment looked at foliar uptake capacity and fog exposure response in a greenhouse. Their work added to previous work in the field and showed that well hydrated leaves further increased water content increased between 2-11% depending on the species supporting foliar uptake. Two of the species in the experiment showed negligible response to foliar uptake supporting the idea that individual species performance is varied and must be carefully selected. The hydrophobicity or water retention capacity of each leaved species is an important characteristic when considering rainfall interception storage (Limm et al., 2009). Similar experiments defining hardy species with high foliar uptake will likewise broaden understanding and selection of preferred species. And with continued work, these characteristics should be categorized and added to other defining characteristics by species. This work continues to improve understanding of how water interacts with the trees' surfaces and defines storage in rainfall interception.

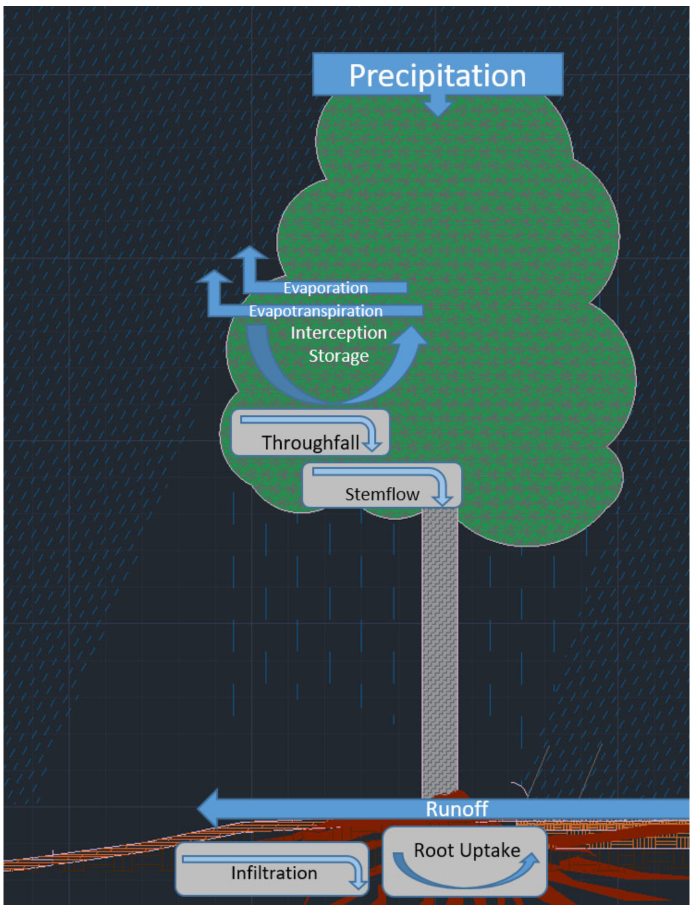

Figure 1.4-Illustration of hydrologic process for rainfall partitioning

1.1.4 Rainfall Partitioning

Throughfall, interception loss, and stemflow are the three components of (rainfall) partitioning by vegetation canopies (Yang et al, 2019), as shown in Figure 6 depicting the complete hydrologic process. A thorough understanding of these components and how they interact with canopy structure is necessary to include trees and other plantings in green infrastructure. The throughfall is the total precipitation collected beneath the canopy of the tree. The droplets can pass through the canopy without contacting the structure of the tree or drip from the tree canopy. As described in 1979 by J. H. C. Gash, the measured throughfall generally begins shortly after the storm event begins (“wetting up”) because much of the moisture collects on the leaves and must drip down the numerous branches before falling to the ground. The exception in delay being throughfall beneath a deciduous that has lost all it leaves and has very little canopy cover to delay precipitation. Likewise, the throughfall generally continues for a short time after the storm ends as the maximum storage naturally drains through the tree’s canopy structure. The direct collection methods measure the precipitation beneath the canopy to a collecting device or gauge near the tree in an open area. The droplets remaining on the leaves and bark surfaces, either in place or traveling down the tree towards the bole (main tree trunk), but not all the way to the ground define the kept interception loss. This is the measured minimum storage that may eventually be returned the atmosphere instead of entering groundwater via infiltration or stormwater runoff. The interception is the measured difference of the precipitation falling under the tree (throughfall) compared to the uninhibited rainfall outside the canopy. Numerous spatial and temporal factors affect the potential minimum storage. The moisture is precariously held on the canopy leaf and branch surfaces, and each single leaf behaves like a tipping bucket with residual storage (minimum storage) left in the bucket (Xiao et al, 2000b). Any number of disruptions, or even vibrations from the wind or wildlife can release some of the stored water.

Researchers are using a variety of direct methods to collect rainfall beneath trees to estimate rainfall interception. The common experimental equipment used ranges from simple plastic collectors to tube and funnel rain gauges that need to be examined after each event to tipping buckets with data logging capabilities. These methods require less set up, equipment calibration, and material resources to conduct than more complex collection methods. However, with concerns of transect variability in rainfall distributions at different positions under the canopy, researchers have selected another technique using troughs extending from the base of the tree to the edge of canopy to collect an even distribution. Many recent research endeavors have used the trough-type collection methods (Cuartas et al., 2007; Asadian and Weiler, 2009; Holwerda et al.; 2010; Salemi et al., 2013; Livesley et al., 2014). The troughs flow into a rain collector (usually a tipping bucket rain gauge) equipped with a data logger to record the accumulated flow. However, these methods require calibration for the new surface area that is larger and still require maintenance to manage clogging for an increased level of flow through the funnel. In 2000, Xiao and colleagues constructed a sloped wood framed surface beneath two trees; using a method to capture all the throughfall (and stemflow). The study area included two trees, as the cost of materials and labor to construct the catchment area is much more intensive. The method also requires calibration of data logging equipment as stated for the trough method. Because of the number of sites and the ultimate focus of understand how single streets trees perform, the research uses individual tipping bucket rain gauges to collect throughfall beneath the canopy and estimate rainfall interception.

The last component is stemflow. It is precipitation traveling from the canopy and branch structure to the main trunk and then directly to the ground, where the tree acts like an upright watershed, collecting rainfall at the farthest reaches (outer edges) of the canopy. As these leaves on the outer perimeter of the canopy saturate, droplets reconstitute and begin traveling along branches towards larger limbs channelizing water and collecting into larger more concentrated paths as stemflow. Along the entire path porous openings, dry or dead matter, fibrous qualities of the tree architecture, and even epiphytes or other organisms living on the tree retain some of the water. At the same time, some the rainfall, some as spillage, or inefficiency in collection, begin to fall to lower levels of the canopy where the process continues until saturation takes place within the entire canopy. The water that flows through the entire length of the tree with enough energy to overcome the surface tension and attractive forces all the way down to the ground is measured as stemflow. Stemflow is generally the smallest portion of the rainfall affected by a tree. There are exceptions where multi-leader trees, with high angled branch architecture, and smooth bark generate exceptionally high stemflow. Little information is available reporting or considering stemflow as a significant portion of runoff from a site. More likely, the stemflow infiltrates directly into the ground near the major roots of the tree aiding the hydrologic processes in uptake for evapotranspiration.

Work in Melbourne, Australia on eucalyptus trees over a 5-month period to study interception and stemflow. The work considers stemflow impacts in arid environments where water recharge is crucial in maintaining healthy water tables. The concept is equally relevant in urban spaces where heat islands and limited irrigation may impact street trees. Their method used troughs and helical catchment troughs to collect both canopy drainage and stemflow from the tested trees. Their results showed that the denser canopy of the Eucalyptus Nicholii had a superior interception rate than the blue gum eucalyptus reviewed in the research. They also observed a notable impact of bark on stemflow production. The deeply fissured and absorbent bark can eliminate measurable stemflow. Eucalyptus Nicholii had a much lower stemflow, producing no stemflow till nearly 4mm of fall. On the contrary, the smoother blue gum species produced stemflow within the first 1mm of rainfall (Livesley et al., 2014). Some areas and soils with better porosity may infiltrate stemflow on site, while others would benefit from the absorbent bark and branch surface where the runoff potential is higher due to excessive shade and lack of groundcover.

In 2017, Kaushal and colleagues looked at rainfall partitioning for three typical management techniques (coppicing, pollarding, and lopping) for removing excess branches on a common street tree (Morus alba). The aim of their work was to determine if the practices affected the stemflow production drastically by removing the limbs of like specimens using each of the methods. This practice could affect the management techniques of urban grown species used in green infrastructure projects if the results are significant for species common or preferred in landscape plans. For the experiment their results showed that lopping produced 10% stemflow (and the lowest interception rate). Stemflow for the coppicing (4.5%) and pollarding (5.8%) techniques performed better producing slightly lower but still higher than most literature. It is likely related to the small size of the trees, having and extremely low storage potential.

In 2018, Cayuela et al. studied several specimens of two distinct tree species: downy oak and scots pine. Their study focused on comparing the abiotic and biotic characteristics affecting stemflow for intra- and inter-storm events. Their findings correlated with other studies in many ways. Most notably the fact that smaller trees tend to funnel more water producing higher stemflow than a like larger specimen, because of the available storage in the larger tree canopies. They also noted that like most observations the stemflow accounted an extremely low amount of the total rain for each event, ranging <1% to 20% depending on the species and related conditions. They used a linear mixed model with repeated measurements to compare stemflow and funneling ratios. The abiotic and biotic factors were introduced as covariate fixed effects. They used principal component analyses to compare abiotic and biotic factors. And a k means clustering analysis to classify events. They produce a series of lag time box plots to show how each species performed post rainfall in stemflow production. It showed that the oak tended to flow longer after rain and slightly more storage for this drainage. Whereas the pine was quicker to shed water as stemflow responding sooner. This showed the distinction in each species biotic traits.

A study site in British Columbia, Canada by Schooling and colleagues looked at the major trait differences in street trees as compared to canopy-based forest research is of interest and a necessity to better understand the differences in rainfall partitioning. They looked at several species of deciduous species, compiling an exploratory cluster analysis, assigning 34 independent traits for 37 trees across the area; including species surveyed in this study plan. Only two out of the 37 species showed notable stemflow supporting research suggesting that stemflow is commonly a small fraction of the total rainfall (Asadian & Weiler, 2009; Kermavnar & Vilhar, 2017). The characteristics of the two species reporting measurable stemflow were both smooth barked with canopy architecture (inclined branches, multi-leaders, etc.) that improved stemflow. The findings also showed that highest stemflow yields for small rainfall events were from small trees. "This counter-relationship between SF (Stemflow) and DBH (Diameter at breast height) for this relatively small rain depth class is likely a consequence of greater water storage afforded by trees with larger boles and thus greater surface areas," (Schooling & Carlyle-Moses, 2015). A larger tree would have more branches, more surface area, more leaf area and thus more storage potential. One finding in the article suggests that smooth-barked, multi-leader trees with many inclined branches draining continuously to the bole yield the highest stemflow. They also noted that fissures in the bark could increase flow once saturation occurs. For single leader trees, steeper branches promoted stemflow the most. The highest reported stemflow was by the European beech tree.

The findings above coincide with a 2014 study by Livesly and colleagues on rainfall interception by eucalyptus trees in Melbourne, Australia over a 5-month period. The paper also considers stemflow impacts in arid environments where water recharge is crucial in maintaining healthy water tables. Their method used troughs and helical catchment troughs to collect both canopy drainage and stemflow from the tested trees. Their results showed that the denser canopy of the Eucalyptus Nicholii had a superior interception rate than the blue gum eucalyptus reviewed in the research. They also observed an impact of bark on stemflow production. The deeply fissured and absorbent bark can eliminate measurable stemflow. The Eucalyptus Nicholii had a much lower stemflow; not producing rainfall till nearly 4mm of rainfall depth. On the contrary, the smoother blue gum species produced stemflow within the first 1mm of rainfall. The smooth bark type increases stemflow funnels water to the ground where it is captured in the soil near the tree's root system. Some common species in south exhibits these traits and may likewise produce high stemflows.

1.1.5 Infiltration and Runoff Beneath the Canopy

After reaching the surface, how the rain is retained at the point of impact is dependent on the soil characteristics (ground cover, soil texture and compaction) that all affect the infiltration potential. The soil infiltration characteristics may be improved by numerous biological (i.e., worms, roots, etc.) and mechanical improvements. Likewise, accumulating leaf litter maintained under the tree can increase the water storage potential. The cover material provides shade from radiation, containing soil moisture near the tree's roots, and aids evapotranspiration in the hydrologic cycle. Debate on the types of leaf litter or other cover may be dependent on the location and cheap available options. A study of leaf litter storage capacity showed that the pine needles were on average 2.1 times greater than for broad-leaf litter (Zhao et al, 2019). Conversely, an experiment of storage capacity of deciduous cork tree litter outperformed pinus species in a similar series of experiments. They attributed the relative advantages in storage to the shallow depressions in the deciduous leave allowing water to pool. This knowledge is useful if the goal is to maximize the stemflow and infiltration down the trunk funneling the water to the tree roots. The abundance of the water increases the soil moisture available for uptake and eventual evapotranspiration.

In a 2020 study on how tree architectural characteristics affect stemflow, Gonzalez-Ollauri and colleagues observed and measured stemflow and infiltration for three large sycamore trees. They also dug trenches around the tree root structure to study the sub-surface fate of stemflow infiltrating the soil. To enact a control, one of the tree's stemflow was collected and not allowed to infiltrate the soil. To understand how stemflow affected the soil moisture, funneling by root structure, and subsurface flow, moisture sensing equipment and tracer dyes were placed around the trees. Simultaneous collection for: directional path and distance measurement; soil moisture and pressure measurements; and collection of total stemflow was executed for each rain event. These quantitative findings were paired with thirteen measurable traits surveyed on each tree with the potential to affect stemflow production and compared in a statistical analysis using R software. In the trenches, the trace dyes were observed as deep as 300mm in the vicinity of roots depicting the double-funneling or otherwise canalization of flow along roots of the tree. This observation was also measured by an apparent reduction in the hydrostatic pressure of the soil following rain events. The pressure increases in the inter-event period as the soil's moisture drained and balanced naturally. No surface runoff was reported in this study. Other findings in the study showed that smaller canopy and trunk size increased stemflow. The statistical analysis showed that rainfall was the most influential trait producing stemflow, followed by the number of primary a secondary branch in the canopy structure.

In Germany a team of researchers compared the infiltration potential for two common and contrasting street trees (*R. pseudoacacia* and *Tilia cordata*). The research showed that the black locust's fine, dense root structure increased infiltration. They also found that the two species had differing water use capabilities. The tilia transpired three times the water with deeper root structure, outperforming the black locust. Suggesting that each species play a specific role in improving infiltration and stormwater management opportunities. "The cumulative soil infiltration at 3.5 m under the canopies of Tilia was higher compared to 1m of black locust, 1m and 3.5 m of Tilia as well as control site" (Rahman et al., 2019). The author notes that the fine root biomass is also prominent at this distance from the base of the tree. To his point this continues to promote infiltration. Any stemflow contributing to runoff is therefore likely reclaimed at this distance from the tree.

1.1.6 Meteorological Effects and Spatial Variability

Rainfall interception research routinely involves collecting data for one or more meteorological conditions (e.g., rainfall, wind speed, relative humidity, etc.). As technology continues to improve, more advanced resources are now available providing archived climate data. The data can be resourced by remote sensing with instruments that measure passive microwave sensors able to detect wind speed, atmospheric temperatures, soil moisture, rainfall, and atmospheric water vapor (Horning, 2008). There are many offsite weather stations maintained for the public in the U.S. and are often located near airports and populated areas where data is being stored and accessible for use. Post processing this data may be required to ensure quality inputs are included in the model equations. For example, one of the collection sites in the experimental plan is located near Montgomery, Al. Data is easily searched and viewable for a recent history of rainfall and temperature readings using the National Oceanic and Atmospheric Association (NOAA) website. For a more detailed investigation you can access data from regional automated weather stations (RAWS) which is collected and summarized in many useful formats by the Western Regional Climate Center. Getting accurate data as close as possible to the area of interest is an important goal and should always be considered in field research of this nature.

As addressed above, the importance of trees in rainfall interception is their ability to store water on the leaved and woody surfaces. The efficiency of this process in storing more water is based on the rate of evaporation. The rate of evaporation is a complex combination of effects of net radiation, temperature, humidity and wind-speed (Rutter and Morton, 1977). A basic understanding of these common factors affecting evaporation will aid in the knowledge of rainfall interception which can eventually lead to an understanding of the subject. Therefore, a simple review of common factors is identified in the literature review and is included below.

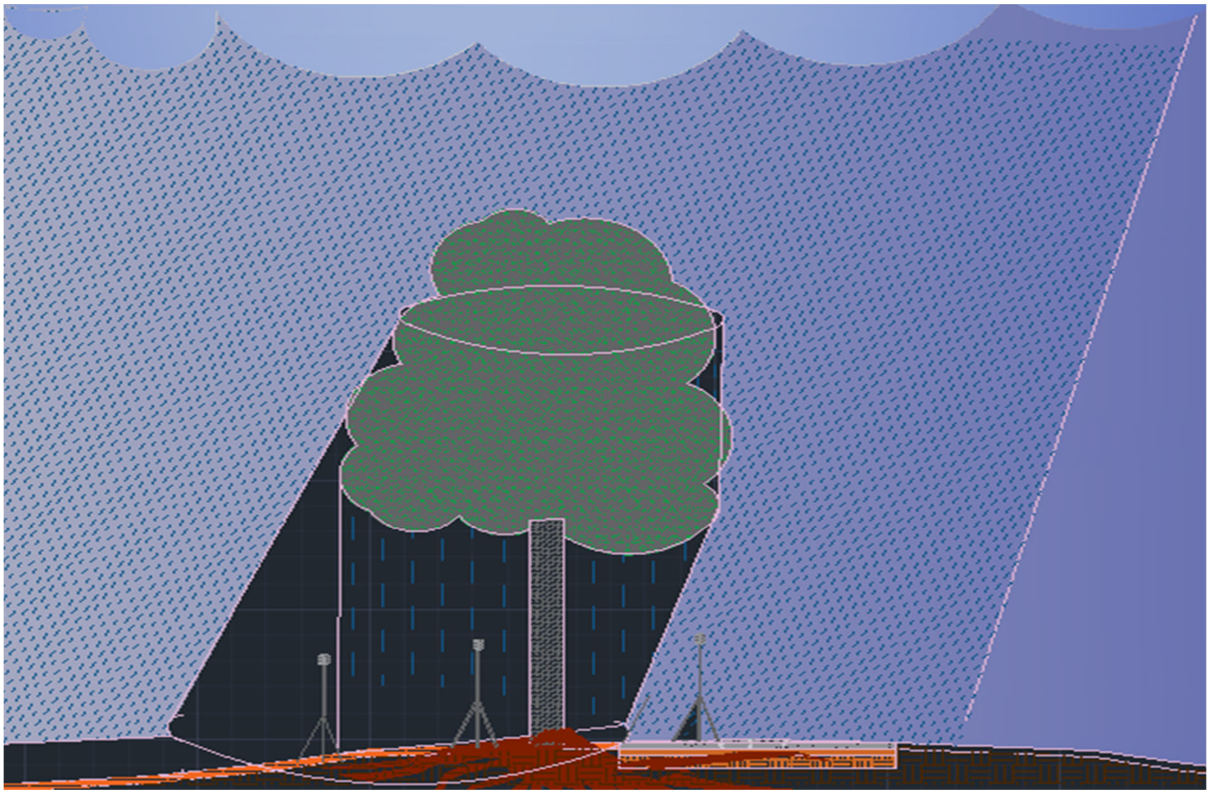

Figure 1.5-Illustration of rainfall shadow effect on a tree canopy

Wind speed has the potential to affect interception and storage by at least three mechanisms (1) increased evaporation, (2) blowing water droplets off the leaf reducing storage and (3) changing the angle of rain, causing a modification of the effective projection of the tree canopy. For the first mechanism, increased wind speed has the potential to increase evaporation for static water stored on the surfaces of tree canopy as it saturates (Van Stan et al., 2014). Increased evaporation is well documented through the related research topic of evapotranspiration. Windspeed is used to calculate aerodynamic resistance. Windspeed is also a key input in reference evapotranspiration, for a crop or this case leafy and wooded surfaces of interest. The aerodynamic resistance is simply heat transfer promoted by wind speed and is the visible evaporation of water droplets from these biological surfaces. For the purposes of green infrastructure planning, you would consider both evapotranspiration and rainfall interception to improve the mass balance for water on the site. The wind speed can increase the aerodynamic conductance for dominant trees and open street trees where the wind flux travels through the canopy. The rate of evaporation from a wet canopy is strongly influenced by the aerodynamic conductance (Pereira et al., 2009a). Therefore, the increased wind speed under the right conditions during a rain event can readily aid in evaporating the stored water and improving the efficiency of process.

When considering a single standing tree versus urban canopies, the different impacts of wind speed must be considered. For forest canopies, gusts of wind can shake off water stored on upwind trees while water on downwind trees can be retained, which makes inhomogeneous distribution of water on trees (Murakami and Toba, 2013). For a single tree, the windblown rain and turbulence in the air may overcome the attractive forces that normally hold a portion of the water to leaves or branch structure (Horton, 1919). This could drain the stored water to the ground and reduce the canopy storage efficiency. Furthermore, the sustained or gust wind could blow water off the trees surface. When the water initially clings to the surface in smaller quantities it is less likely, but as the rainfall continues to saturate the surfaces making larger drops or pools more vulnerable to loss as throughfall. And even when rainfall has not fully saturated surfaces, the water is still subject to gravitational flow through stem flow. Some characteristics of trees (e.g., slick bark, waxy leaved surfaces, etc.) can further limit these attractions. These losses would be considered inefficiency is most urban planned forests because trees are placed over impervious areas to protect them as a first contact buffer before the rain collides with the impermeable surfaces.

Windspeed can also modify the affective projection for the tree canopy. Likewise, the condition is more relevant with a single tree than with a canopy stand in a forest. The angle of incidence of rainfall affects the throughfall-runoff relationship, known as shadow effect (Véliz-

Chávez et al., 2014; Gonzalez-Sosa et al, 2017; Guevara-Escobar et al., 2007). Meaning that the wind speed could blow the rain at an angle (See figure 10) into the tree canopy instead of at the zenith angle (directly above the tree). This could affect the wetted storage and stemflow; depending on the tree architecture of the species involved (Xiao et al., 2000). The shape of the tree architecture (tall and cylindrical, short ellipsoid, etc.) for individual street trees could increase or decrease the wetted surface when windblown rainfall enters the canopy at an angle. Of course, rainfall depth and duration aid in thoroughly saturating the canopy, but for short (including high intensity) rainfall events, portions of the canopy could remain dry impacting storage potential. Guevara-Escobar and colleagues suggest the screen effect (or "shadow effect") is important and accounted for 18.7% of the interception losses by the tree canopy alone. On the downwind side of the crown, there is a marked reduction in measurable precipitation beyond the edge of the canopy. This thought process indicates that strategically placing trees to edge protect vulnerable areas of a landscape could reduce runoff in impervious zones of a watershed.

In 2018, Nytch and colleagues noted that the current literature doesn't cover enough variation in species across the world's urban areas. They were comparing two common species around San Juan, Puerto Rico. The work was intended to determine differences in interception for the species common in urban areas. They classified storms using the Federal Meteorological Handbook No. 1. Interception for both species remained equal at 22.7% for the deciduous and 16.9% for the evergreen species. Their results were statistically sorted using R software. The findings slight favoring one of the species during light to moderate storm events suggesting more storage potential for Albizia silk tree, a deciduous naturalized species in the region. Although, the species is dense with horizontal spanning limbs. Little significance was placed on the wind speed and gusts during the storms and how they impacted the projection and hydrophobicity of each species. With sustained winds reaching as high as 37 km/h, the propensity to shed water normally held in storage is likely, reducing the minimum storage. And the denser species may have been able to store more due to the protection the denser canopy provided downwind of the rainfall ("shadow effect").

Once the minimum storage is achieved on the leaves, limbs, and trunk evaporating the water faster increases the tree's efficiency with respect to rainfall interception. The water holding capacity of the air is a key factor to understand potential evaporation of water storage on the tree. Relative humidity and temperature changes are generally inversely related (but non-linear). As the temperature drops, the saturation vapor pressure drops in the air limiting air water storage potential. The best example is the dew point visible on early morning grass. As the temperature drops overnight, the relative humidity increases. This does not mean any more moisture is added to the air. Instead, the air's ability to store more water declines. As the air temperature continues to decline the available storage is eliminated, which is defined as the dew point creating condensation on nearby surfaces. As the air warms during the day, the water holding capacity of the air increases resulting in transpiration of moisture into the atmosphere. The vapor pressure deficit usually increases because the temperature increases ahead of the saturation vapor pressure.

The time of day, air temperature, and antecedent relative humidity are all factors that can impact rainfall interception. Early morning rain events under these conditions are likely to remain on surfaces longer minimizing potential interception on leaved surfaces. And, where higher wind speeds are involved, the reductions could be exacerbated by increased drip and throughfall from the canopy to the ground surface. Conversely, where the humidity is lower the wind speed and inter-event dry period can quickly dry water on surfaces increasing efficiency.

This concept is widely accepted from studies of evapotranspiration where the evaporation from leafy surfaces into the atmosphere is a key component.

During rain events, two modes of evaporation are considered in rainfall interception: evaporation from tree surfaces and evaporative cooling as the droplets pass through the warmer air. Rutter (1967) measured wet leaves that were up to 1° C cooler than the air above. In turn, the air above the wet canopy was itself on average 1° C cooler than at a reference climate station nearby, suggesting that the greater aerodynamic roughness of the forest led to greater evaporative cooling. Time to evaporate this water is highly dependent on buffering air storage capacity in order to be vaporized and truly intercepted. In humid environments, the vapor pressure deficit is low, meaning the air's additional storage potential may not be capable of accepting some or most of the rainfall stored on the surface or a near surface available state.

In a paper by Pereira and colleagues, tree surface temperature is explored to determine how it compares to the measured wet-bulb temperature during rainfall and when albedo is low. In the experiment temperature, wind speed, and net radiation are measured inside and beyond the canopy to examine the impacts to aerodynamic conductance during rainfall. Their work endeavored to simplify the meteorological requirements needed to estimate rainfall interception modeling at the tree scale. The observations included 353 storms where the canopy became saturated. In these events they observed that leaf surface temperature closely matched the wet-bulb temperature for events above 8mm h-1. They hypothesized, "that the closeness of the tree crowns surface temperature to wet-bulb temperature is strongly influenced by high values of aerodynamic conductance." Simplification for remotely sensed requirements could ease the difficulty in modeling and estimation of rainfall interception at the tree and forest-scale. Their work reported an evaporation estimate of 0.30 mm h-1 for when the canopy temperature is near the wet-bulb temperature. This figure is quite low, but the findings should be quantified and included in estimates derived by designers working on sustainable landscape plans. (Pereira et al., 2009a)

In a follow-on investigation Pereira and colleagues exercised their hypothesis of using the wet-bulb temperature in lieu of the well accepted Penman-Montieth (P-M) equation (1965) to estimate evaporation in several distinct canopies. During the analysis they determined that the wet bulb performed well in two of the forests (maritime pine stand and agroforestry plot), but overestimated interception in the remaining locations. This finding was related to canopy density, aerodynamic conductance, and ventilation distinctions in these plots. Whereas the two canopies that performed well were more sparse plantings with lower individual canopy densities. They were better ventilated with more uniform aerodynamic conductance at each level of the canopy thus evaporating more of the available water during the event. To the contrary, the remaining three had traits more characteristic of a closed canopy, and the model estimates needed to be adjusting to consider only the upper levels and exposed portions of the canopy to calibrate the observed rainfall interception rates. For these conditions and forest characteristics, the authors acknowledged that the wet-bulb method would not be better solution than the P-M method (Pereira et al., 2016). Though it is not viable for all forest stands the study may prove useful in urban applications where coverage is sparser and individual trees will likely be fully ventilated. In the previous 2009 study, the model showed promise because the method requires less meteorological data and assumes that the model for a single tree can be scaled up to represent the entire canopy. Both simplifications, can reduce the cost and time required to survey an urban watershed. And, if relatively uniform trees and tree species are used to landscape a zone, retroactive analysis of the site may become easier using this method to estimate rainfall interception.

In the Tsukuba Mountain Range of Japan an experiment was conducted to monitor meteorological changes during rain events to further understanding of the complexities of the environment. The authors conduct experiments on C. japonica forest stands and notes a distinction between the first and second half of a rain event. They determine that 95% of storage takes place on the first half of the event. Their work looks at time-series changes in the meteorological conditions surrounding the storm; noting a stark reduction in the vapor pressure deficit (VPD) (Iida et al., 2017). Their interest in finding out why water evaporates off the trees' canopy storage even though VPD falls off at the beginning of the storm and sustains throughout duration. Their observation could be due to low wind speeds. The boundary air may quickly evaporate the water up to the allowable storage. And, without substantial aerodynamic conductance to circulate the air and promote additional evaporation. If dryer from beyond the boundary layer of the canopy flows near the wetted surfaces the rainfall interception may be extended. The observations could be partially related to the collision of water droplets upon tree surfaces that subsequently fragment into smaller droplets. The smaller water droplets with greater surface are with each impact on the tree. These residual droplets on the storage surface are easily evaporated because droplets surface area to volume ratio is much larger creating the environment for evaporation.

Since trees have a finite storage capacity increased almost entirely by potential evaporation, event duration is the most obvious rain characteristic impacting rainfall interception. Examples of rain events where interception exceeds 50% of the event can be misleading without looking at the duration of the event, the estimated tree storage measure in depth, and the pre and post event weather conditions. For, example a mature and healthy tree in an arid climate has an estimated potential storage of 8mm and can maximize rainfall interception during a 13mm storm without considering additional evaporation from increased wind speed. In some regions this scenario is typical, but not reflective of all regions of the U.S. and certainly not reflective of all climates within urban areas where green infrastructure is most beneficial. In the southeastern states, a storm of this size and frequency is common. Forest-based research in the eastern U.S. has produced observations ranging between 15-25% (Bryant et al., 2005, Kirnbauer et al., 2013).

Combining optimal vapor pressure and temperature during a rain event can mitigate some of the total rain depth, but long duration rain events will eventually saturate tree canopies. Research in Melbourne, Australia determined that the denser canopy of E. nicholii was able to intercept most rainfall events that are <4 mm, whereas the thinner, sparser canopy of E. saligna intercepts <40% of even small rainfall events <2 mm (Livesly et al., 2014). One must also consider the inter-event for the record event. If the canopy is still holding latent moisture from a previous event the capacity may be diminished, increasing the impact of duration as is common for seasonal events in the southeastern U.S.

In 2018, Zabret and colleagues focused a birch (deciduous) and a pine species to determine their behaved differences in intercepting rainfall. The author conducts three years of data collection in Slovenia and uses local (3km distance) metrological data to correlate the findings using cluster analysis and regression tree branch comparisons. Determining that rainfall depth is the most significant factor in both. The pine tree far outperformed the birch tree. Intensity and rain drop size and speed were also contributing factors in their results. In this research, both coniferous and deciduous species are studied to determine their differences.

Rainfall intensity is another visibly contributing factor. As high intensity rains impact the storage surfaces, they can quickly exhaust the available storage depth. This still needs to consider the tree type, size, and condition to realize the effects. Nytch and colleagues found that the type of tree affected interception for small and medium intensity storms. Li et al (2016) states, “For small rainfall intensities (<30 mm h−1), no splash was observed when raindrops hit the branch and leaf surfaces because the relatively small median raindrop diameters and kinetic energy allowed the intercepted water to cumulate on the branches and leaves. While the opposite pattern occurred for larger intensities. Raindrop splash occurred when energetic raindrops struck and shook the crown. Therefore, the split droplets could have be temporarily intercepted but tended to fall off from leaf surfaces under the repeated agitation, which is likely why fluctuations in cumulative interception at rainfall intensity of 150 mm h−1 were observed.” The study reviewed rainfall intensities ranging from typical intensities for many to storms to some well beyond expectedly heavy storm events. Large rainfall depths can easily exceed storage for most trees and intense storms obviously increase the rate up to maximum storage, easily saturating smaller trees and new plantings on a site. Much of the rainfall interception studies focus on developed stands of trees and forest canopies. A closer look at small trees, typical in landscape architecture drawings and specifications, would be useful to understanding the realistic conditions affecting stormwater runoff on a site.

Other researchers have looked at raindrops size to study how it correlates to rainfall intensity with varying results. Blanchard and Spencer (1970) and Willis and Tattelman (1989) each observed that the drop size did not increase substantially for high intensity events. Instead finding the number of drops increased while the distribution of large drops (1 to 5 mm) stayed constant as part of the normal distribution. The increased intensity negatively impacts rainfall interception by producing more drops and larger drops increasing the kinetic energy (on the leaved surfaces). The impacting drops and splash evaporate as they continue to travel through the turbulent air and on the surfaces as they travel through the canopy (Murakami, 2006), suggesting the dependence of the canopy interception on the rainfall intensity (DOCIORI).

1.1.7 Modeling Rainfall Interception in Forest Canopies

The research history is extensive for rainfall interception in forest canopies. As far back as the late 19th century, multiyear data sets for comparing open ground and forest canopies were collected to measure rainfall interception (Horton, 1919). The reasons why research endeavored to model rainfall interception has changed overtime. Current interest includes (but limited to) green infrastructure planning. There are several empirical models developed for forest canopies that are now being applied by researchers to green infrastructure rainfall interception studies. Each of these require a great deal of sensed data to satisfy a predictive model.

Rainfall interception models were generally developed to predict interception for forest stands and further understanding watershed hydrologic conditions. These empirical and physically based models require input variables for several meteorological factors. Models generally fall into one of two types: Gash-type and Rutter-type models. The Rutter model was developed first in 1971 and is still widely used to this day. A review of relevant research on rainfall interception found that the most common method utilized in rainfall interception modeling is the Gash method. But, to this day the Rutter model is still the second most exercised in research worldwide (Muzylo et al., 2009).

The Rutter method uses a water balance approach to measure continuity of rainfall into the system, and calculates drainage and evaporation as the output. He later refined his model in 1975 to estimate wind speed for aerodynamic resistance and included a stemflow equation for larger storms. In a third volume, he focused on the model's sensitivity to climatological factors. From the work researchers thereafter set to build on this work applying the model to other stands and modifying the functions to improve efficiency (Calder et al., 1977; Gash and Morton, 1978). Changes in the meteorological conditions listed above in the previous section can impact model performance. Including evaporation, a key component, which is measured by consistent pan evaporation rates. In 1977, Rutter and Morton recognized this and published a follow-on report focused on sensitivity to rainfall intensity and evaporation rates. Regardless which model is selected for use on a site, the appropriate meteorological data must be sensed or collected on site or resourced from a location near the area of interest.

In 1979, Gash developed a simpler model that classified the storm in three phases: wetting up, saturated canopy, and post-storm canopy draining. Likewise, the Gash model was exercised in research worldwide. In 1995, Gash and colleagues published the revised version known commonly as the "Gash sparse" model. In this version, tree canopy evaporation is measured by the actual canopy coverage proportional to the total area at the surface ("gap fraction"). One strength in the revision is their acknowledgment that changes need not expand the number of variables and inputs needed for accurate modeling stating, "preferably requiring no more information than that which was used in the previous version to calculate the evaporation from a forest with a complete canopy." (Gash et al., 1995) This is an important understanding due to the relative difficulty in collecting data for accurate modeling. A less complicated and reliable model stands a better chance of being exercised in new areas. The reduced complexity adds an economy of performance through more trials in a given span of time. Whereas a more accurate model may be disregarded for requiring many more discrete inputs. It could also require more equipment or data that isn't readily available across the many regions and forest types needed to develop and calibrate model performance.

As discussed, a key component to a successful model is access to weather station data to estimate evaporation, regardless of the model type used. There are ample well-maintained Class A pan evaporation sites throughout the U.S. used to provide agricultural and climate data. Because of this, there is historical data available as monthly averages in published and online resources, as well as daily reported evaporation rates at numerous sites. These rates are commonly used to estimate evapotranspiration in crops to estimate the irrigation necessary for healthy growth. There is no single system of pan evaporation measurements for all locations in the U.S., but the data is reported regularly and archived. Readily available data is accessible online for most areas where green infrastructure would be considered. Despite a reasonable distance from an active weather station to the collection forest, there can be large micro-climate differences reported between the two locations. Therefore, sensing on site is preferred to accurately convey the conditions before, during and after rain events.

For example, in 2005 Bryant and colleagues surveyed and conducted a study on five distinct forest stands in southwestern Georgia, U.S. collecting 140 rain events. Though they collected numerous direct throughfall measurements beneath canopies, the weather station used to estimate daily evaporation was 7 kilometers away. The study area in their work is geographically like the sites and species studied in Alabama. The goal of the work was to collect throughfall data at each site, calibrate the model based on the findings and run comparisons for each of the sites using the Gash sparse. The five stands included: mature pines, planted pines, low land hardwoods, upland hardwoods, and mixed hardwood and pine forest. Because the study was conducted on a stand scale, no specific information is available for the direct canopy conditions above each of the gauges and collectors used in the work. The model results worked well for the coniferous species. They also showed that the models were most sensitive to actual canopy cover and storage; suggesting that the predictions for available storage at each tree has noteworthy variance within the canopy.

In 2009 study by Pereira and colleagues, two separate evergreen cork oaks were monitored for rainfall interception. One tree required monitoring net radiation to satisfy the Gash model and the other considered leaf surface temperature equal to wet-bulb temperature in lieu of the traditional method. The results maintained strong agreement with other studies, reporting and average 29% interception on an isolated tree and an estimated 6.2% interception by scaling up the results for all the canopy coverage in the sparse forest used during the study. Further, the cumulative differences in the modeled and measured interception were 28.93 mm, which is less than the calculated margin of error (44 mm). These results also validate the use of the wet-bulb temperature to estimate evaporation on the canopy surfaces, reducing the amount of input data in modeling rainfall interception. (Pereira et al., 2009b)

A 2017 report by Ghimire and colleagues also used the revised analytical model (Gash sparse) while collecting rainfall in forests distinguished by age. Their rainfall interception results proved typical, reporting rates around 20-26% with most of interception coming from smaller less intense rainfall with shorter duration. As with other sites, evaporation estimates were collected more than a kilometer from the forest. Even though this distance is much closer than what can be expected in an urban experiment the distance could cause errors in the estimates. One of their focuses was to determine if evaporation rates differed between the large-older and young-growing forests. To do this, they estimated wet-canopy evaporation by three methods.

They then used this information to calibrate results against the observed data; assuming the observations were a more accurate representation of rainfall interception within the canopy.

Ma and colleagues also used the revised Gash model to look at a deciduous and pine stands used in afforestation. Their goal is to advance research using the Gash model for semi-arid canopies. The intent is to provide a basis to calculate losses in semi-arid watersheds to estimate losses in runoff where water resources are limited. Their results were similar to other studies using the model, reporting between 1 mm and 4 mm (depending on species) of interception from a 25mm storm. Their research spanned one year to cover the leaved and leafless period and capture total annual storage. Their model results were agreeable to actual recorded observations for both sites. Coniferous trees outperformed the deciduous species in this experiment. He also notes that the thinned and open groves of the trees with larger basal areas observed less throughfall. He attributes this difference to thicker crown depth and denser leaf structure. Increasing interaction between raindrops resulting in greater retention. As one would expect, they noted a decrease in interception during the leafless period which was due to reduction in leaf canopy density (Ma et al., 2019).

Researchers continue to use the Gash, Rutter, and other models designed for forest canopies to close the gaps between natural forest conditions and developed urban sites. Research in developing areas of a Brazilian semi-deciduous rainforest looked at cleared lots where developments were planned and later reclaimed. For these regenerating forests a comparison of results for the Gash and Lui models determined that they either understated or overestimated the physically observed interception in a Brazilian semi-deciduous rainforest. Their work reported margins of error ranging from -17% to 11%, respectively (Junior et al., 2019). Within the limits in available remote sensing equipment, it should remain a focus to collect empirical field data for various common species and tree architectural variation characteristics to aid in developing easily attainable interception data for unique situations and for planning purposes.

Linhoss and Seigert (2020) compared five of the more common rainfall interception models during a 3-year study in a Maryland forest. They collected throughfall and stemflow at each site. Their interest reviewed the range, variability, and error in modeling individual events. This approach is unique since most study results group multiple storms and report less error across cumulative rainfall. They found the model was only able to predict medium interception events; with substantial errors for events below 1.2mm and above 6.9mm. The most important parameters in the findings were canopy and trunk storage and canopy cover. They also noted that the error in interception and stemflow modeling could partially contribute to variation in canopy cover, creating artificial spatial variation in measurements. Highlighting this error as a gap in the understanding defines an area that requires more focus. Another area where work is still needed is the partitioning of water between the stem storage and the total canopy storage. Because the surfaces are not always completely dry, as the models treat them.

Where all previous models discussed in this literature focused on modeling interception at the forest scale, a model proposed by Xiao and colleagues in 2000 conceptualized rainfall interception for a single tree. Their model requires three sets of input data totaling at least 14 inputs to produce a successful prediction. Their work studies an evergreen cork oak and Bradford pear on the campus of the University of California, Davis. The experiment used artificial rainfall (up to 9mm) in lieu of naturally occurring events. Their results show very high rates of interception as expected given the arid climate in this region of California. They noted that the previous models (Rutter, Gash, Calder, and Lui) focus on forest canopy and do not consider a single tree in a stand-alone condition. A single tree must also consider the effective crown dependent on the rainfall's direction due to windspeed. The model treats stemflow, drip, and storage separately. The model also breaks down rainfall drip towards the surface by layers to further delineate flow. Increased accuracy ideally would depend on the number of layers in the system, as much as the accuracy of the input data. The model considers tree architecture, health condition, as well as all the usual factors required by other models. The apparent viability of this model would depend on the availability of publicly resourced climate data and detailed surveys of the trees on the urban sites where this model may be exercised. The inherent challenges listed above give credence to the desire of researchers to continue using forest-scale models (Gash, Rutter, etc.) to further research in the field. Efforts to develop and expand modeling to explore beneficial uses of trees in urban landscapes for rainfall interception must reduce the number of variables for both the tree and the meteorological conditions to further understanding.

1.1.8 Rainfall Interception in Urban Landscapes

"While there is an agreement on the merits of protecting and restoring more natural flow regimes in urban and urbanizing catchments, stormwater managers need guidance on how to reach such an objective" (Fletcher et al., 2014). Of all land use changes affecting the hydrology in an area, urbanization is the most forceful. Urbanization is generally correlated with industries and commercial zones that further hydrologic changes within watershed areas. Basic tenets of green infrastructure intend on preserving and sustaining pervious attributes in these areas to retain potential runoff on site. By design, these goals support regulations set forth by the U.S. Environmental Protection Agency codified in 40 U.S.C. § 122.6 at the time of this review to govern stormwater in large and medium municipal separate storm sewers. Practices aimed at stormwater divergence as runoff infiltration or storage within the development are becoming more common endeavors as sustainability practices grow in the public sector. This is accomplished by leaving the new site runoff disconnected from the watershed using control measures. In Section 4106 of America's Water Infrastructure Act of 2018 the U.S. Congress appropriated $225 million for grants "to carry out projects to intercept, transport, control, treat, or reuse municipal combined sewer overflows, sanitary sewer overflows, or stormwater through the use of green infrastructure, water and energy efficiency improvements, and other environmentally innovative activities." This study considers the retention or minimum storage potential by trees in the landscape plan as part of green infrastructure projects. As stated in the previous sections, as an area is urbanized, the peak rate and volume of runoff increases measurably. These effects are caused by the following conditions: 1) a reduction in the opportunity for infiltration, evaporation, transpiration and depression storage [through excessive clearing of natural areas]; 2) an increase in impervious surfaces [in the form pavements and compacted soils]; 3) modification of the surface drainage pattern [including the replacement of surface streams with sub-surface channels] and associated development of stormwater management facilities (AL-SWCC, 2014).

In 2014, Fletcher and colleagues reviewed the problems that urban areas create for stream ecology; noting a lack of focus on protecting the urban streams as the receiving environment impacted by urbanization. The stream is modified by the development (buildings, roads, pavements, etc.) and related construction practices that modify the natural watershed increases total volume carried into the streams. These streams generally become wider and deeper to accommodate the increased, inconsistent flows and decreased ecological health in the post-development catchment-scale watershed boundaries. They also look at the practices of channelizing and straightening streams to make them more efficient which shorten the linear path and increase peak flows downstream. Streams may also be re-routed or piped to accommodate civil site plans. The authors identify that instead of bending and modifying flows to accommodate site development, planners should consider a “natural flow regime,” for the watershed as proposed by Poff and colleagues in 1997 as the basis of design. Defining the relevance of including trees for the purpose of rainfall interception is important to support the “natural flow regime” to give further credence to this approach. Potential mitigation projects to restore streams to pre-development conditions must incorporate holistic landscape plans, including green infrastructure, to ensure the controls are implemented across the entire source surfaces. As expected, it is likely easier to address these stormwater problems at the catchment area size prior to construction. This is because post-development modifications to streams and impervious surfaces in densely populated areas would likely increase cost to construction due to scheduling constraints and necessary project phasing required to accommodate the residents and local traffic.

In Alabama, stormwater runoff and erosion control are of constant concern in site development due to the large number of intense rains occurring each year. In most cases, inexpensive grass species are used for ground cover where new grades are suitable. Inclusion of more planted trees in an urban landscape may have benefits to consider in urban areas where grassed surfaces are not feasible. The advantages discussed in tree planting section of the AL-SWCC Handbook (2014) include runoff retention and detention, but there are many other benefits to consider, such as heat island reduction for example. Site improvements are feasible if the benefits out way the costs. Higher biomass waste management, grooming requirements, or elevated costs for included specific species and construction practices that do not conform to industry standards are example subjects that should be considered. Xiao and McPherson collected stemflow and measured nutrients and heavy metals against control samples from the nearby open collection site. The results suggested that trees had the ability to collect particulates trapped from the atmosphere, depositing them into the soil at the base of the tree. A comparison of pollarding, coppicing, and lopping mulberry trees (Morus alba L.) determined that there are noticeable differences in interception and stemflow between the methods (Kaushal et al., 2017). But no records of the biomass waste or intensive labor were surveyed in the study. Some pruning techniques can increase the height of trees by consistently removing lower branches stimulating growth up as it continues to sprout new grow higher in the canopy. Tree height has also been observed to marginally increase interception within the canopy (Murakami and Toba, 2013). These and similar management practices need further study to ascertain their impacts and benefits towards green infrastructure.

In general, adding more trees to urban landscapes would increase the canopy cover, thus increasing the storage potential to reduce discharge. Theoretical hydrographs under natural conditions have a much smaller peak flow at time of concentration and, with urbanization, the stormwater travels the same distance with shorter durations and higher flowrates. The aim is to introduce enough strategically placed trees in and around the hardscape surfaces to flatten and lengthen the flow period, reducing stress on municipal stormwater systems and receiving waters. This could reduce increased design capacity requirements in the future. In areas where planter boxes are required for the trees, you would also need to consider increasing infiltration from stemflow and throughfall during the storms. This was tested for plausibility in a two-year experiment in urban areas of central Mexico using two common species. In the urban study zone, they measured runoff of a typical watershed boundary with and without the trees to determine the potential benefits using dimensionless hydrographs. The results indicated a delay in peak runoff by 10 to15 minutes when trees were used in the scenario (Gonzalez-Sosa et al., 2017).

Successful implementation of tree plantings must include details describing placement, orientation, and proximity affecting the angle of incidence of the rainfall. Considering the canopy projection of the rainfall contacting the tree crown before hitting the ground surface is necessary to aid in this efficiency of this initiative. For example, if the prevailing winds and storms generally come from the northeast, trees placed on the east and north edges of impervious surfaces may reduce runoff during the peak runoff periods for a site. Proper tree placement could aid in runoff reduction goals for a watershed area.

The extensive use of artificial grass for athletic turfs, high traffic areas, and residential surfaces makes a valid argument for the use of artificial trees in lieu of green infrastructure where water conservation is a critical issue. A unique study in 2013 by Murakami and Toba study set small and average size artificial Christmas trees on a pan and collects rainfall to measure the interception outside in rain events. This provides an interesting perspective, because a comparison of artificial trees against living species can provide a valuable argument in locations where planting trees may be difficult to grow and/or maintain. Likewise, artificial trees and tree-like apparatus can be added to modern infrastructure (e.g., cellular towers) in places where cities planners control esthetic features of the environment. The research shows that comparable interception takes place on these surfaces when compared to living trees. Because the trees can be readily modified without destroying the integrity of the tree, they were able to thin and adjust height and planted density of the trees across various rain events to measure differences. Interception increased marginally when thinning the trees. Suggesting that turbulent mixing could be the explanation for the increase. The hypothesis would be that the turbulence and motility of the air increases the evaporation rate of the rainfall because less dense canopy structure doesn't dampen the wind speed traveling through the canopy (Murakami and Toba, 2013).

The number of research initiatives focused on developing rainfall interception to support green infrastructure is relatively small compared to the number of studies focused on large-scale forest canopies. The nearly century-long head start attributes to the distinction. Through continued research these practices can be substantiated and included in practical management plans.

Experiments and surveys in 2013 by Inkiläinen et al. for urban residential zones of Raleigh, North Carolina looked at how rainfall interception in these urban zones related to the canopy conditions of rural forests. Their hypothesis expected unique performance for these urban canopies due to the private maintenance regimes and aesthetic preferences. Because the trees in these zones grew and were maintained different than a rural forest, they expected unique tree architecture, with more layers and storage potential. During the experiments they collected events for 20 storms in the late summer and early fall for 16 residential yards using randomly placed collector buckets on each site. They noted a decrease in interception by 1mm for events where the interevent time was less than 24 hours. Their results also showed that rainfall interception ranged from 9.1-21.4%. The work provided agreeable results citing 4% decrease in storm-based throughfall between their work and similar forest-based data collected in Columbus, Georgia (Inkiläinen et al. 2013). In an annual or multi-year study these results could vary further and shed light on the distinctions between these differing canopy conditions.

A 2011 experiment in Oakland, California by Xiao and McPherson compared three common species: lemon, sweetgum, and a ginkgo tree. Intercepting 27%, 14.3%, and 25.5% respectively. The timeline of the experiment covered both leaved and leafless periods capturing a completed picture of rainfall partitioning of the compared species across 25 storms. The results of the experiment showed that the lemon tree far outperformed the other species during winter since it is an evergreen, and the other species were deciduous. Their work also collected stemflow for the species noting that the seasonal stemflow was affected by limbs angle and bark consistency. There was also an increase in stemflow in the deciduous trees in the fall without foliage. (Xiao and McPherson, 2011) The interception results in this experiment fell within the accepted range of similar research for singular, open-grown species. The winter performance for evergreen species needs further exploration in this due to the high rainfall averages in Alabama and the southeastern U.S.

The extensive use of artificial grass for athletic turfs, high traffic areas, and residential surfaces makes a valid argument for the use of artificial trees in lieu of green infrastructure where water conservation is a critical issue. A unique study in 2013 by Murakami and Toba study set small and average size artificial Christmas trees on a pan and collects rainfall to measure the interception outside in rain events. This provides an interesting perspective, because a comparison of artificial trees against living species can provide a valuable argument in locations where planted trees may be difficult to grow and/or maintain. Likewise, artificial trees and tree-like apparatus have been added to modern infrastructure (e.g., cellular towers) in places where cities planners control esthetic features of the environment (See Figure 13). Their experiment results show comparable interception takes place when compared to living trees. Because the artificial trees can be readily modified without destroying the integrity of the tree, they were able to thin, adjust canopy height, and planting density of the trees across various rain events to measure differences. They noted that interception increased marginally when their spread further apart. Suggesting that turbulent mixing could be the explanation for the increase.

The hypothesis would be that the turbulence and motility of the air increases the evaporation rate of the rainfall because less dense canopy structure does not dampen the wind speed traveling through the canopy (Murakami and Toba, 2013).

1.2 Knowledge Gaps

Much of the research in rainfall interception is focused on forest canopies dating back more than a century. A cursory review of this history is necessary to develop a fundamental understanding for how this research developed. Several approaches related to my own proposed work plan were reviewed for consideration. There were also ex-situ (i.e., laboratory based) experiments that yielded knowledge related to the subject but required equipment and time beyond the means of the experimental plan. Regardless, these topics were considered in the literature review to describe how the framework for this proposal developed. For example, I believe the distinction between minimum and maximum storage is a useful topic worthy of further research to benefit stormwater runoff reduction. But the work would involve different types of observations, potentially runoff collection at the site, and numerous lab-based approaches to precisely measure the changes in time-series water discharge from the trees. All of which were well beyond the operational capabilities of this study. Many researchers are also interested in modeling to predict performance, but the input parameters include accurate weather data sensed very close to the tree. This challenges the practicality needed to provide accurate predictions for the numerous species across different regions and urban areas. Still, these interests are acknowledged in the literature to help develop the plan of action. The next paragraph is a summary of the knowledge gaps that I identified relevant to the proposal and for consideration in the work plan.

From the literature review, there are major knowledge gaps in information and data pertaining to urban rainfall interception. As stated, before urban rainfall interception is only a small fraction of the knowledge related to forest-scale research. How does urban area tree interception differ from forest rainfall interception? The interceptions models and direct observations provide data, but researchers are challenged to retrofit the findings against urban trees. There are physical distinctions between urban grown and natural forest trees. The endogenous traits are visibly distinct in height and canopy shape. The canopy density if often visibly constrained in forest as they compete vertically and horizontally for sunlight. On the contrary, street trees are usually planted or develop further from other trees growing thicker and lower to the ground unless constrained by sunlight of tall infrastructure. Are soils different around and beneath urban trees? With large more dense canopies, does the root structure grow more improving soil porosity and infiltration? Since street trees are planted in or near heavy site-civil projects, they may be planted into heavily compacted soils, constraining root structure as they mature. Is the maintenance of understory and leaf removal mitigating the humus rhizome in the de-stratified soils after construction and reducing infiltration? Research is needed in this area to determine if they improve these soils. And, if the trees growth is limited because of the roots establish and spread slower.

More specifically, there is very little interception research in the southeastern United States; a region that is also densely forested and could potentially benefit from the study. Elsewhere are studies supporting the shade benefits from including trees in urban landscape plans, but the results show that they still require maintenance offsetting the cost savings to surfaces and building temperatures. With an abundance of trees and extreme diversity (i.e., deciduous, evergreen, native and exotic trees) many comparisons can be considered to begin assessing differences for commonly landscaped trees.

Equally insufficient are the distinctions between seasons, which are distinct in the South where deciduous and evergreen varieties are common in urban areas. Leaf senescence and abscission occur in late summer, fall and winter changing portions of urban canopies in this region. These distinctions are not well defined with respect to interception. Most previous research initiatives observe some storms within a single year, but multi-year, all season observance is necessary to understand and estimate potential rainfall interception. There are also some study comparisons of common species (somewhat relevant to this region), but they are either lacking in time, space, or both to provide basis for the extreme climate differences typical in southeastern climates.

There is also no definitive information from previous interception research comparing how trees of the same species differ by size. Key factors such as rainfall duration and intensity are obvious considerations for each of these gaps that must be explored in this region against typical varieties. In the literature review, some statistical comparisons were conducted towards these factors, but no results can be extrapolated for this region. Last, many researchers used rain gauges under canopy to measure forest and urban rainfall interception. But no working standards were found defining placement under the canopy. There was little discussion on measurement impacts from varying the placement under the canopy. No complete discussion was found addressing if the throughfall is reduced or increased by moving farther from or closer to the edge of the canopy. The findings listed above define the basis of the proposal and the work plan.

1.2 Hypotheses

The first hypothesis is that there are fundamental differences in interception characteristics between coniferous and deciduous trees for different seasons in the southeastern region. Because of substantial rainfall in the leafless period, the deciduous trees will have a significant increase in throughfall (rain passing through the canopy to the ground), furthering the comparative advantage of coniferous canopies for rainfall interception in urban settings. Direct throughfall measurements for both deciduous and coniferous species across all seasons were collected to test this hypothesis.

The second hypothesis is that direct observations can be made of different sized trees of the same variety (genus and species), and the resulting data will detect measurably distinct rainfall interception. The data will show that as the trees grow, their storage capacity (minimum retention) increases and increases predictably as they grow.

The third hypothesis of this dissertation research is that measured canopy throughfall is distinct and varying at furthering distances from the base of the tree to the edge of the canopy, and beyond, due to typical branch architecture that forms as tree grows in the zenith and towards available sunlight. It is assumed that there may be increased stemflow closer to the center of the canopy. Aligning multiple calibrated tipping buckets at evenly spaced distances from the bole of the tree (main tree trunk) to the edge of the canopy was used to test this concept.

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CHAPTER 2

METHODOLOGY

The purpose for this chapter is to clearly define the purpose for the dissertation research and the integral efforts performed over the study period. This chapter also serves to clarify the common themes and practices performed in each experimental chapter to include: site selection and setup, experimental design procedures, data collection and processing, and the statistical approach. Examples for each study site are used to illustrate these efforts and support understanding for these methods.

2.1 Site Selection

All research experiments are in the state of Alabama, United States. During preliminary discussion, sites were proposed in unique regions of the state furthering coverage and representing regions across the state. There are five major regions in the state (See Figure 14) and nine recording rain gauges were available. This provided the opportunity to cover experimental sites in three regions, as each basic site required three rain gauges. Two sites were selected in the northeastern portion ("Cumberland Plateau" and "Valley and Ridge" zones) of the state and one in the central part ("Coastal Plain") of the state. Selecting two sites in the northern regions of the state and one southern site covers elevation differences typical for many areas across the southeastern United States.

To satisfy the first hypothesis, parallel experiments were conducted to collect rainfall and throughfall comparing evergreen and deciduous trees for each season. An additional site was also selected in Montgomery, Alabama for the second and third hypotheses, tree size analysis and throughfall variation beneath canopies respectively. The second site compared four different sized willow oak street trees. The third site collect throughfall at four locations beneath a mature willow oak. In total four sites operated for the first hypothesis and one site each for the second and third hypotheses.

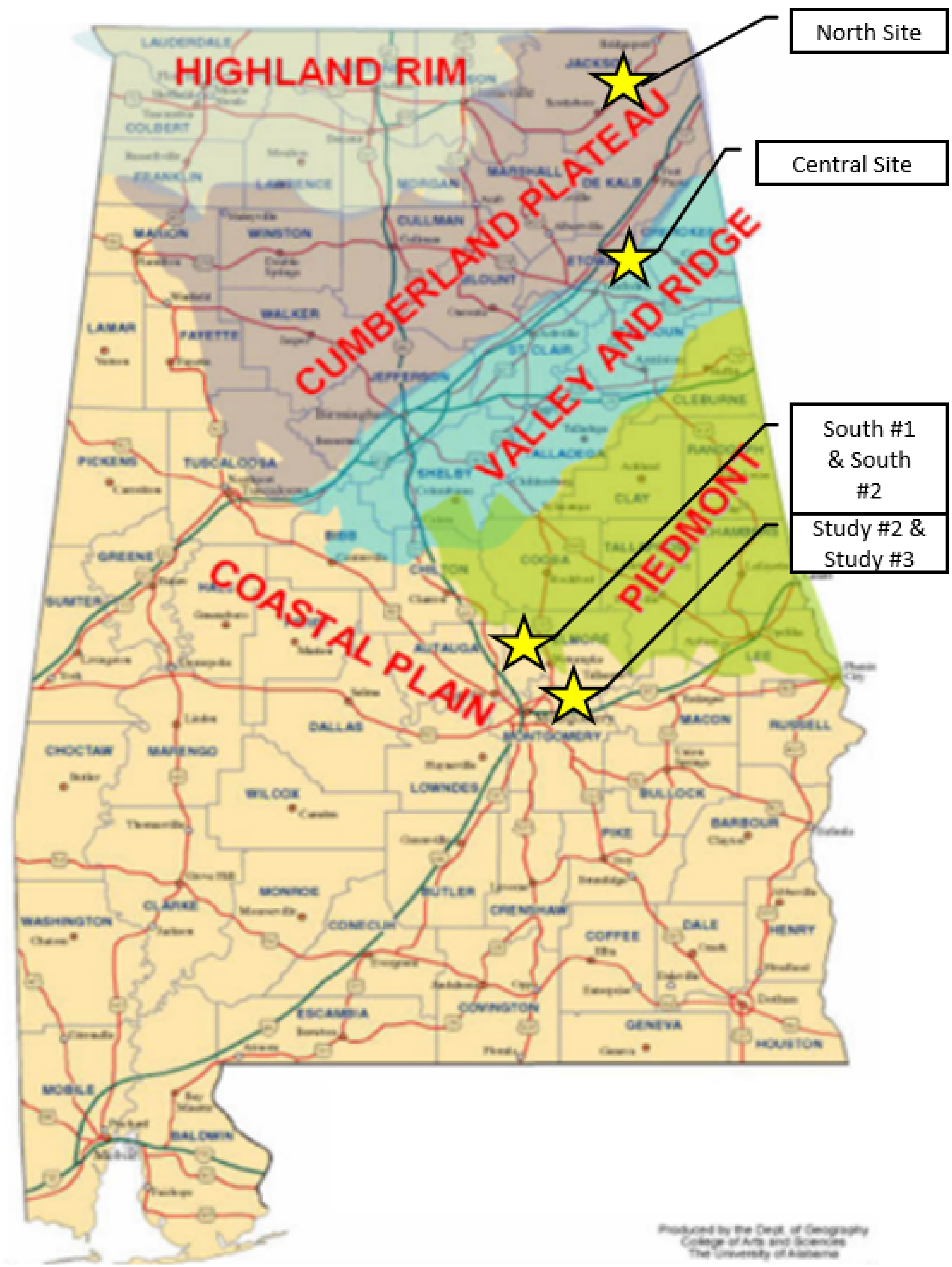


Figure 2.1 Illustration for regions in Alabama provided by the University of Alabama Dpt. Of Geography. Stars indicate approximate location for an experimental site.

A site near Ft. Payne, Wetumpka, and Centre were selected for the first study to compare evergreen and deciduous trees. A location in Montgomery was selected to study tree size and throughfall variability in street trees. Each of the sites provided ample space and a variety of trees for consideration. Since these are remotely maintained, cooperation and communication was necessary to ensure the equipment was secure and safeguarded in the environment. Periodic site checks and monitoring for clogs, damage, or disruptions were performed by landowners to support the data quality initiatives. This greatly enabled the remote research sites by limiting the number of site visits required by the principal investigator. Another consideration for a specific site selection was readily available weather data. The data needed to be open source and easily accessible for analysis to ensure successful observance-based experiments in the work plan. Historical long-term weather station data were available for weather stations within 20 miles of all three sites.

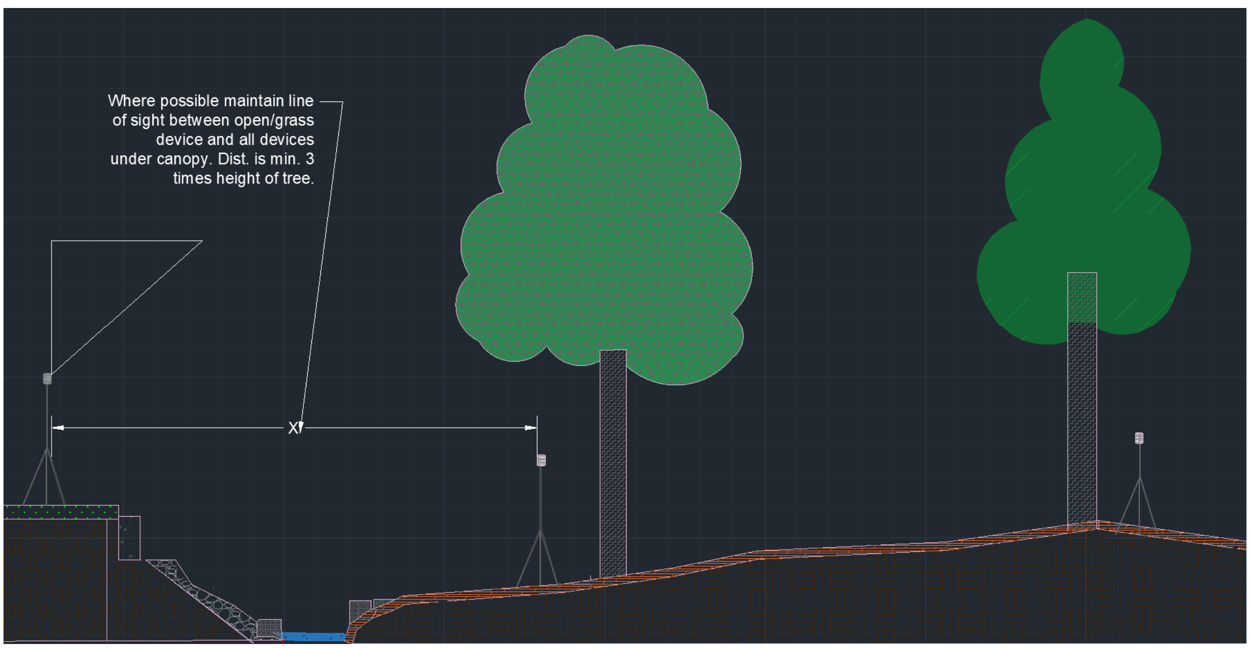


Figure 2.2 Illustration for typical experiment layout to compare evergreen and deciduous trees

2.2 Experimental Design

The premise for all experiments in this dissertation focuses on direct measurement observations of throughfall. The first three sites in the study used three rain gauges like the one shown in Figure 2.2. One rain gauge was under an evergreen tree, the second was under a deciduous tree, and the third was placed in the open field (unobstructed by the adjacent trees). Each tipping bucket rain gauge (HOBO Data Logging Rain Gauge RG3; Figure 2.3) collected precipitation to measure a response variable ("throughfall") for comparison to the control open area (grass) rain gauge.

Figure 2.3- HOBO data logging rain gauge RG3

For each study site, blocking factors are considered during tree selection to ensure the trees are similar in the following ways: measured size by diameter at breast height (DBH); canopy height and radius (estimated by field methods); leaf area density (visual inspection during summer); and good health to ensure that they each represent high storage potential for the selected species. Photographic records for each tree and the surrounding conditions were collected to support findings.

Measuring each tree by diameter at breast height (DBH) is a common forestry standard and was used at each experimental site to standardize tree measurements between the sites for comparisons beyond the site-scale. DBH is defined as the diameter of a tree outside the bark measured 4.5 feet (1.37 m) above the ground on the uphill side (where applicable) of the tree. The crown is defined as the branches and foliage at the top of the tree and was estimated by measuring the horizontal distance from the base of the tree to the edge of the canopy to estimate the radius of tree.

Each rain gauge was placed randomly beneath the canopy between the base of the tree bole and the edge of the canopy (Figure 2.2). To address repetition, the unit was not moved between storms. This ensured numerous throughfall samples were collected for the response variables and the controlled grass rain gauge. The goal was to collect throughfall for all seasons (summer, fall, winter, and spring) during leaved and leafless periods to measure seasonal impacts affecting the storage potential of each tree. The desired distance for the grass rain gauge was three times the height of the nearest tree, where possible to avoid disrupting the precipitation in the open area.

Each experiment was further classified as dominant, co-dominant, single, or forested. For the first year of collection, the work plan examined two sites with single trees each and one site with a uniform planted forest, to measure co-dominant trees. Collection for both classification types helped develop a baseline control for response variable distinctions between forested canopy and single trees. Likewise, these unique conditions were compared for statistically significant differences. Once enough rain events were collected at the co-dominant site, the rain gauges were repurposed to examine other research goals (hypothesis 2 and 3).

Each site was located near a continuously operated weather station and data was accessible via the Western Region Climate Center (See Appendix x.). All throughfall data and grass precipitation was logged in time series and post-process aligned with daily climate factors (namely average and peak windspeed, direction, etc.) for later use in the statistical analyses. The rain gauges used for all the experiments were HOBO Data Logging Rain Gauge RG3 (See Figure 2.4). Each device included a galvanized tripod, staking material, grounding wire, a data transfer shuttle, USB connection, and software. The device is a standard tipping bucket design. The internal data logger was set to collect temperature at 5-minute intervals and measure each tip for several months. Each tip measured 0.01 inches of precipitation.

Figure 2.4- HOBO Data Logging Rain Gauge RG3

2.3 Data Collection and Processing

The data collection process was quite simple. The rain gauges used (HOBO Data Logging Rain Gauge RG3) are battery powered and can store several months of rainfall data and temperature data (5-minute intervals) without reaching the storage capacity. The gauge is a typical tipping bucket and each tip corresponds to 0.01 inch of rainfall. The equipment and supplies necessary for field collection included: a laptop loaded with the HOBO software, a link cord to transfer the data, lightweight brushes and water to clean debris from the tipping bucket mechanisms, replacement batteries, and a small Philips-head screwdriver to open the weatherproof compartment (when required). It took less than 20 minutes to download data, clean and inspect the device, and launch the device for future rain events. Routine battery replacement after each data download was a best practice. Extreme cold temperatures were observed to decrease the battery life during the research.

Routine site visits between storms are part of best practices to ensure the observations were trustworthy. Before a storm, it was best to check each gauge by the following steps: inspecting the screen and funnel for clogging, checking the battery indicator light, and visually inspecting the tipping bucket (above and below) to ensure the “buckets” were clean and unobstructed. Without these visits, data may be inaccurate from clogs, obstructions, or other impacts (e.g., insects inside the gauge, falling limbs, small mammals climbing the stand, etc.) in the natural environment over time.

Figure 2.5- Clogging impacts water flow through the tipping bucket. Over time ponding will form in the funnel as the debris builds (left). Birds droppings commonly clog the screens leaving passed seeds in the funnel. (right)

Data failure risks were minimized through cooperation and communication with the landowners at each site to safeguard the devices and occasionally clear the screens. Because these gauges were under trees across multiples seasons, clogging was the most common problem. Numerous large storm events early in the collection period clogged devices by flushing small organic debris through the screen and collecting in the cone (Photo 13). This was common in the spring when small buds and reproductive structure from the trees fall off during events. Less common, but still noteworthy, were obstructions from stinging insects (e.g., paper wasps, spiders, etc.) that find refuge inside the dry section of the rain gauge. These insects have obstructed the tipping bucket mechanism on more than one occasion. Last, birds commonly perch on the devices (usually in the open field) depositing debris and unprocessed seeds through their excrement (Photo 14).

Figure 2.6 Compromising debris removed from funnel after a large rain

Raw data was downloaded in the field if the rain gauge was shown to be working properly. After a thorough inspection and any required maintenance, the rain gauge was launched again to continue logging data. If the rain gauge was non-responsive when linked to the laptop and basic troubleshooting was ineffective in initiating a link to the software, the rain gauge was removed and repaired before reinstalling the rain gauge in the field.

Once all data were recovered during a data download, it was viewed using HOBOware Version 3.7.21. The resulting observation data were easily viewed within minutes of the download (Figure 2.7). Multiple observations can be viewed at the same time using the software tools. The data was copied and overlayed in the same frame to quickly inspect the paired observations for the experimental site. The data imports with the proper scale and the differences in rain depth and throughfall were inspected before any processing.

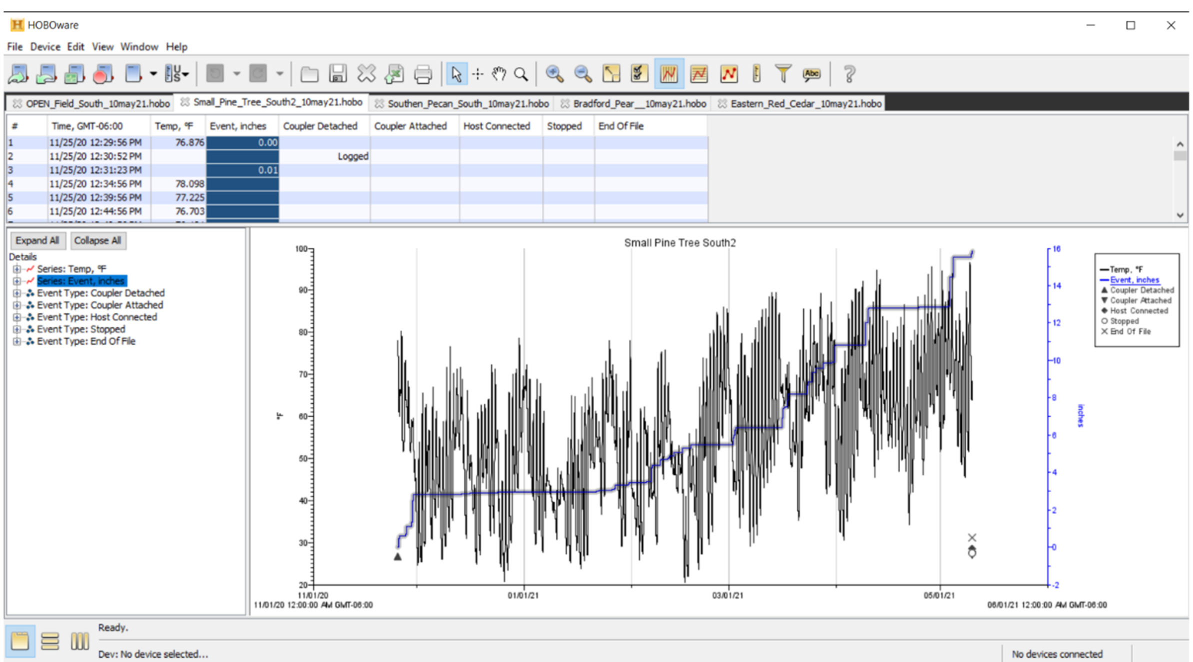


Figure 2.7 – HOBOware® software display for cumulative rainfall (in) and temperature (°F) data for six months under a pine tree

Figure 2.8 shows a typical data comparison from South #2 study site in Wetumpka, Alabama. This plot shows that the open area data stopped recording in August because of a power failure, while the three gauges collecting throughfall continued collecting data. The data were then easily exported as shown in Figure 2.8 to excel or other tabular formats where it can be summarized. All raw rain gauge data for this research was in time series measured in “tips” (equivalent to 0.01 in rain depth). Summarizing the data was the first step needed to compare the differences in the open field and throughfall beneath the canopy. The raw data was opened in Microsoft Excel and summarized. A sample for the raw import data is shown in Figure 2.9.

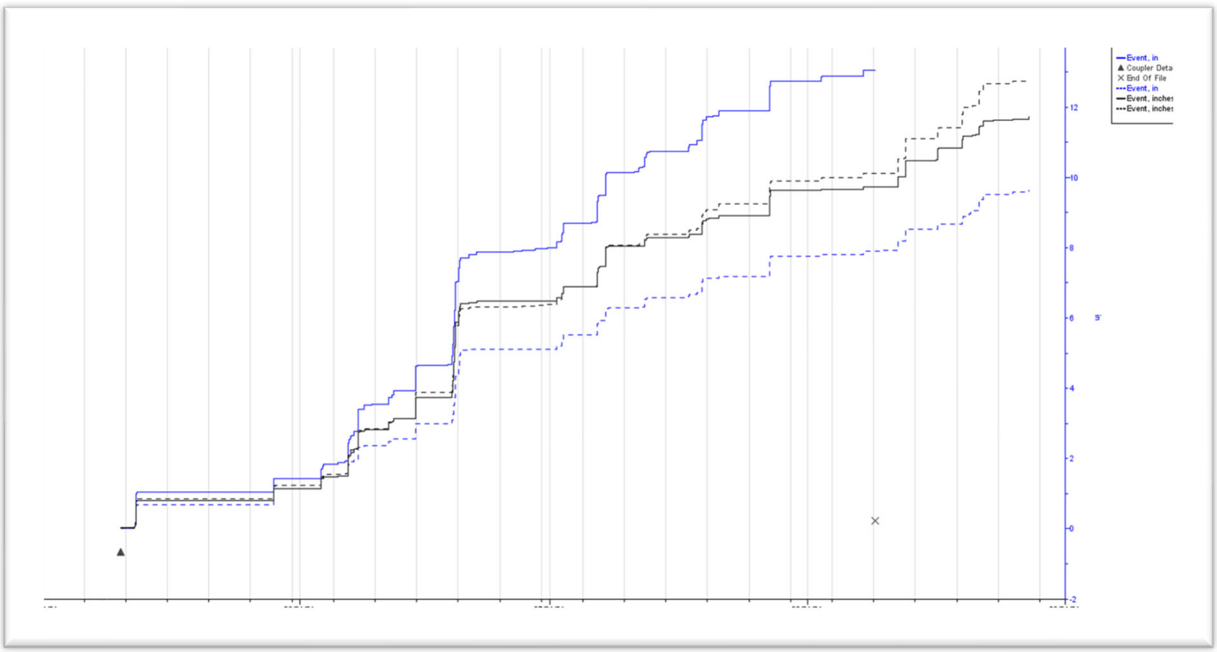


Figure 2.8- Overview for all records in the same time period using HOBOware® software

Plot Title: Bradford Pear_21oct19								
#	Date Time, GMT-06:00	Temp, °F (	Event, in (	Coupler D	Coupler A	Host Conn	Stopped (	End Of File (LGR S/N: 10775554)
1	12/5/2019 8:18	38.061	0					
2	12/5/2019 8:18			Logged				
3	12/5/2019 8:23	39.384						
4	12/5/2019 8:28	39.196						
5	12/5/2019 8:33	39.76						
6	12/5/2019 8:38	40.509						
7	12/5/2019 8:43	41.439						
8	12/5/2019 8:48	41.81						
9	12/5/2019 8:53	42.363						

Figure 2.9- Exported timeseries data using HOBOware® equipment and software

Filters are added to the exported data (fourth column, Figure 2.9) to only display time steps with tips. Logic and equations were applied to quickly distinguish storm events for inclusion in the summaries by subtracting the interevent time between each row. Table 2.1 is an example summary table. The example summary table is repeated for each rain gauge after each collection period. In this dissertation research, a six-hour dry interevent time was used to distinguish individual storm events. Once the storms were separated, the data were summarized to display event duration, inter-event time, rain depth, and rainfall intensity for each tree or open field location selected at each site. The processed data is then added to the total event site summary sheet for this location to be compared against the different tree types considered in this study.

Each site had multiple sample locations with paired continuous response and independent variables. The next effort was to align the data from each of the tables (evergreen, deciduous and grass) by row as described above, by rain event start time. This helps conceptualize the data (i.e., line by line) and perform quality control. Aligning data by rain event makes it easier to identify interruptions in collection from clogging and other errors. Questionable data by one or more gauges for a particular event was easier to recognize and compare after alignment.

start time	end time	duration (days)	duration (hrs)	intereve nt time (days)	intereve nt time (hrs)	start tips	end tips	rain depth (tips)	rain depth (inches)
E. Red Cedar									
	4/28/2020 8:27								
4/29/2020 8:27	4/29/2020 9:15	0.033669	0.808056	1.033669	1	1	3	3	0.03
4/29/2020 18:17	4/29/2020 21:20	0.126979	3.0475	0.503125	12.075	4	15	12	0.12
5/18/2020 21:29	5/18/2020 21:29	0	0	19.00681	456.1633	16	16	1	0.01
5/21/2020 20:09	5/21/2020 21:10	0.042072	1.009722	2.986215	71.66917	17	18	2	0.02
5/22/2020 12:24	5/22/2020 18:50	0.26787	6.428889	0.902975	21.67139	19	22	4	0.04
5/23/2020 22:08	5/24/2020 3:21	0.216875	5.205	1.354641	32.51139	23	35	13	0.13
5/24/2020 17:23	5/24/2020 17:52	0.020139	0.483333	0.604896	14.5175	36	38	3	0.03
5/25/2020 14:20	5/25/2020 14:20	0	0	0.852766	20.46639	39	39	1	0.01

Table 2.1 – Event summary sample location at each site

The events were aligned left to right (e.g., grass, pine, and oak) because data were typically recorded by the open field rain gauge first. This was due to canopy storage delaying throughfall until the canopy was saturated. However, in some cases rain was first detected under a tree canopy. This usually occurred in the winter during the leafless period, or sometimes during an event that moves in a direction where rainfall reaches the open field gauge last. Unusual observations and other results that did not fit the expected pattern were still be included in the statistical analysis. For example, several events in the preliminary data set included higher throughfall values than the at the open field location rain depth. If the open field observation was suspected to be in error and was excluded, the oak and pine data were still considered. If both the oak and pine recorded higher values, it was possible that results were still valid and can be included in a direct comparison (e.g., pine vs. oak) to analyze their differences.

2.4 Statistical Approach

The summarized data was aligned for comparisons during data processing and again underwent a thorough quality control process to remove any obvious errors in the observations and to check potential discrepancies against the original data sets prior to inclusion in the statistical analyses. All data summaries and tables were prepared using Microsoft Excel ®. Hypothesis tests and graphical representations for each site were prepared using Minitab®.

A single methodical approach was applied to each individual site to test data distribution normality. First the data was inspected visually on a scatterplot to look for trends, as well as congruency between the paired data and the independent variable.

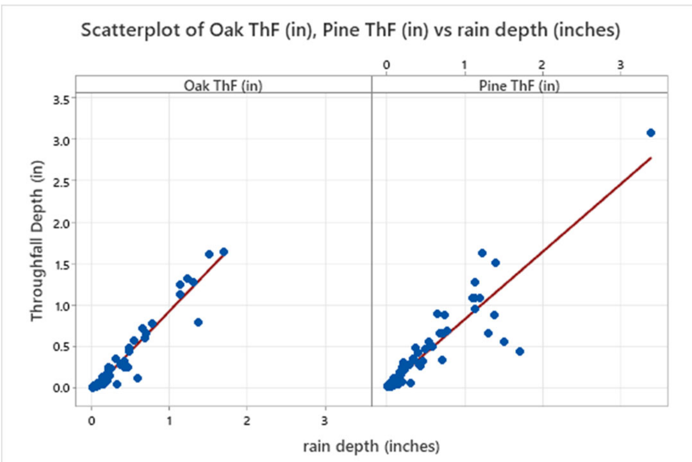


Figure 2.10 Example Central Site scatterplot for paired observations

The post-processed and summarized data for each of the four sites needed to be transformed in three ways: the difference reflecting tree interception storage (tree throughfall – open rain depth = storage), throughfall ratio (tree throughfall divided by open rain depth), and a log10 transformation of the throughfall and rain data. The lognormal transformation worked well to normalize the distribution for statistical analyses at each site. The lognormal transformed data shown In Figure 2.11 in the scatterplot appears more Gaussian.

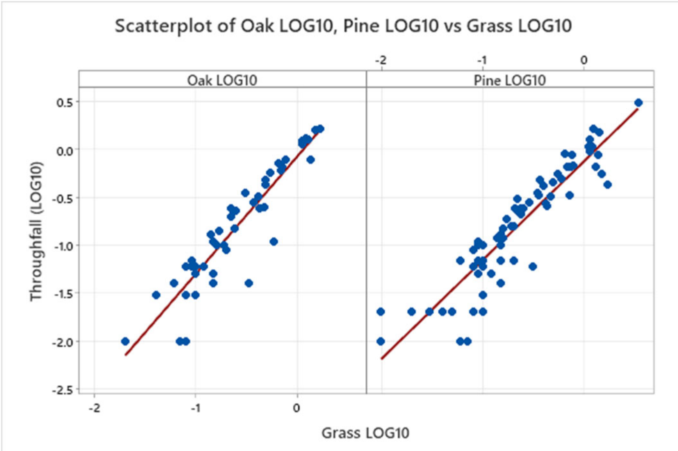


Figure 2.11 Example lognormal scatterplot for paired observations at the Central Site

Thereafter, individual value plots and scatterplots were used to conduct preliminary visual analyses of the data. The initial statistical approach included parametric tests (i.e., paired T-tests) to see if there were significant differences in the means for the evergreen and deciduous observations at each site. For each tree, a lognormal linear regression of throughfall vs. rainfall was performed to model the observed data. Minitab 4 in 1 residual plots were reviewed for goodness of fit, to observe any trends in the fitted value plots, and to identify any unusual observations as key indicators that may detract from the strength of the equations.

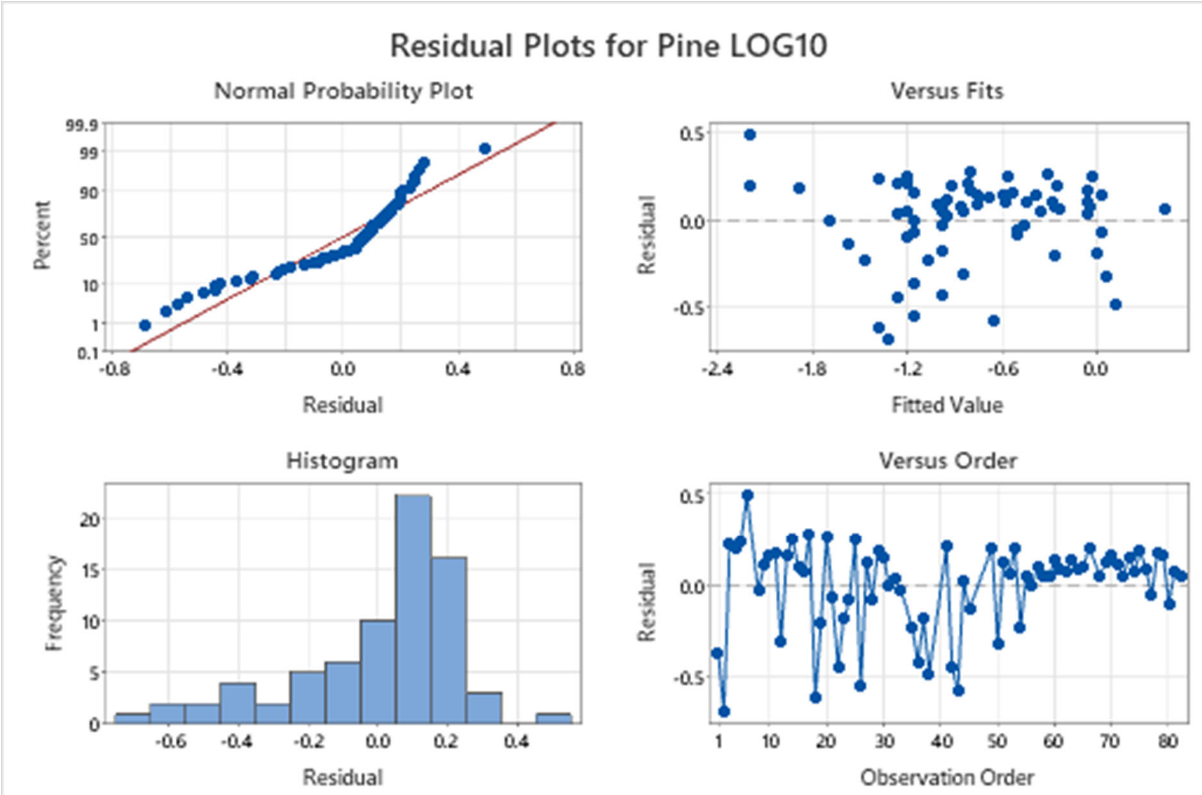


Figure 2.12 Example Minitab 4 in 1 residual plots for a lognormal linear regression

Each equation was summarized in a table for comparisons by tree type in each dissertation chapter. The lognormal equations were used to graph rain depth and throughfall to compare differences in tree types in support of the hypothesis for each chapter (See Figure 2.15).

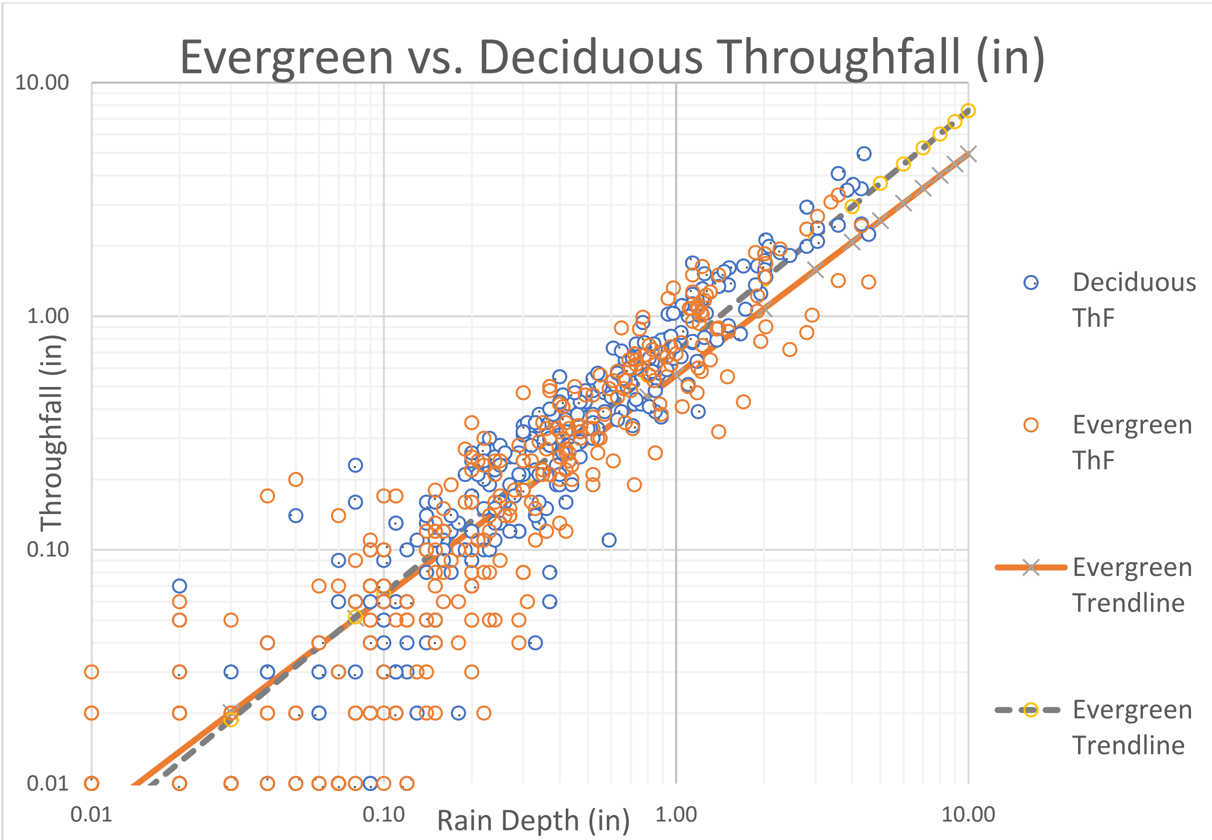


Figure 2.15 Evergreen and deciduous throughfall depth for trees in the southeastern U.S.

Full factorial (2^3) analysis were performed considering average daily windspeed, average rainfall intensity, rain depth, tree type, and leafless period as needed to support the hypothesis for each chapter. Table 2.2 is an example design of experiment to determine the significance of climatological factors for the site. Interaction plots were also produced for each factorial analysis to further identify the potential significant factors and their interactions.

Rain Depth	Intensity	Avg. WindSpeed	Rain Depth	Intensity	Avg. WindSpeed		Rain Depth x Intensity	Rain Depth x Windspeed	Intensity x Windspeed	RDxIxWS
small	light	windy	-	-	+		+	-	-	+
small	heavy	calm	-	+	-		-	+	-	+
large	light	calm	+	-	-		-	-	+	+
large	heavy	calm	+	+	-		+	-	-	-
large	heavy	windy	+	+	+		+	+	+	+
large	light	windy	+	-	+		-	-	+	+
small	heavy	windy	-	+	+		-	-	+	-
small	light	calm	-	-	-		+	+	+	-

Table 2.2 Design of experiment for climatological effects for the research site

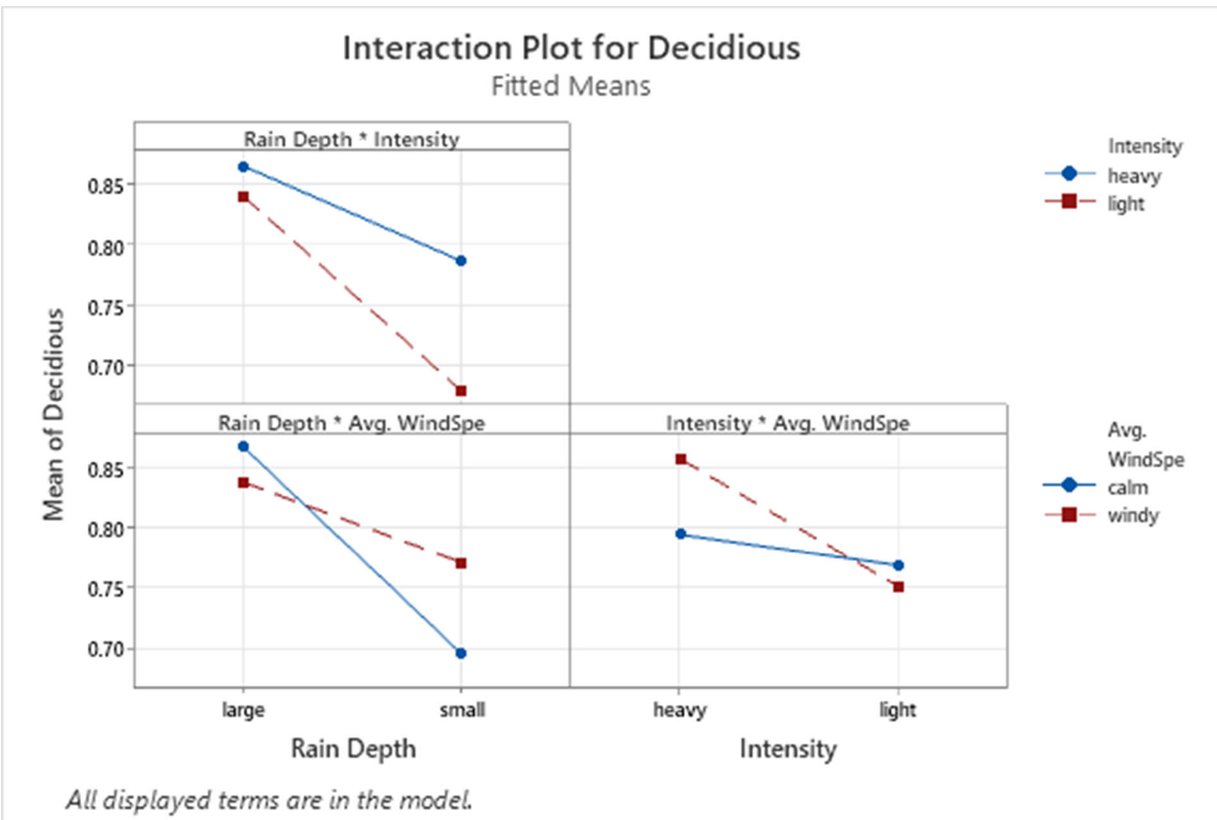


Figure 2.16 Interaction plots for climatological factors impacting throughfall

Significant categorical variables identified during the factorial analysis were displayed using boxplot graphs. Boxplots are highly useful in separating the range of data by multiple variables (e.g., storm size, leafless period, etc.) to graphically support analyses. Figure 2.17

shows multiple potentially significant differences between the groups of data for the transect tests.

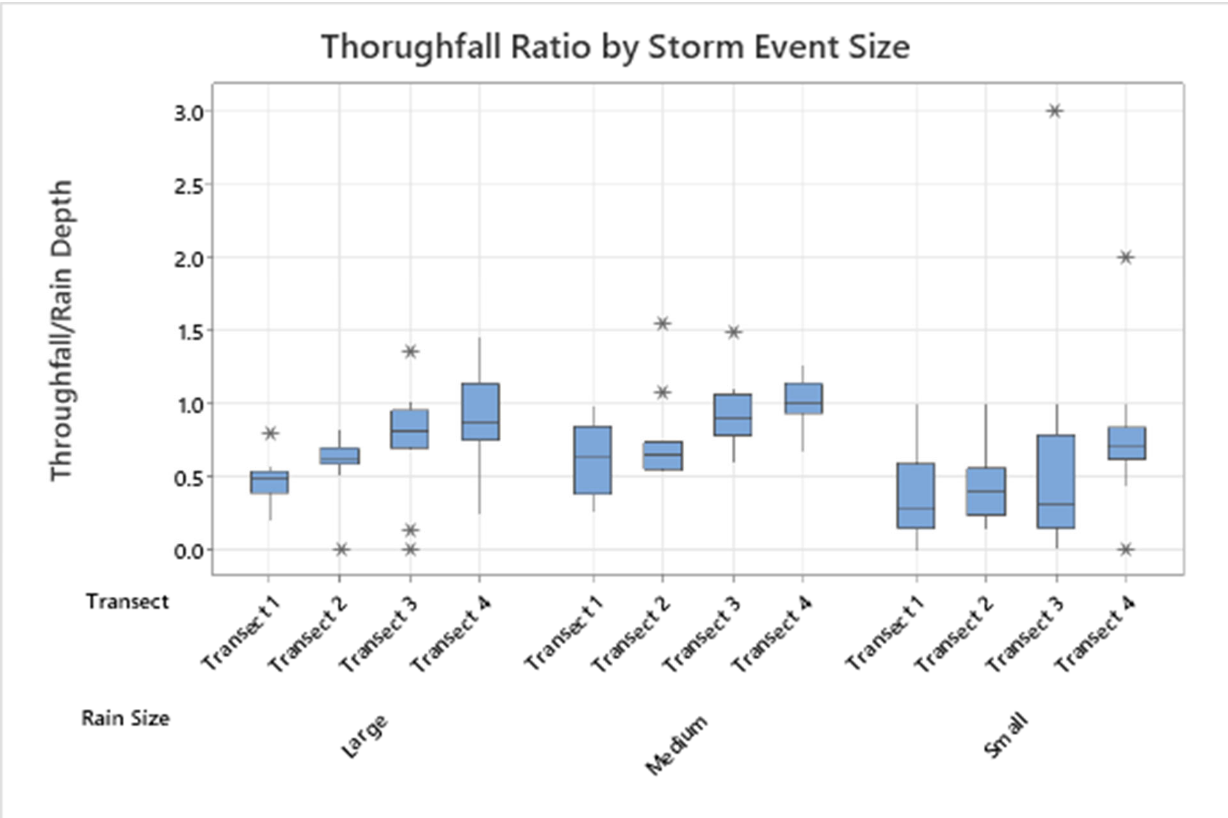


Figure 2.17 Boxplot for categorized storms for Study Site 3

CHAPTER 3

THROUGHFALL COMPARISONS FOR EVERGREEN AND DECIDUOUS TREES

3.1 Abstract

This study observed throughfall at four sites in Alabama located in the southeastern United States. Throughfall was compared for evergreen and deciduous trees during 235 total rains. Paired T-tests determined that the mean throughfall for the evergreen trees was significantly less (interception greater) ($P \leq 0.001$) than for the deciduous trees. While this finding may be counterintuitive, the difference is likely attributable to retention of rainfall on the bark and limbs of the evergreen species tested, rather than retention on the needles and cones. A 2^3 factorial analysis compared rain depth, windspeed, and leafless period, and found that all factors were significant. Additionally, one-way ANOVA tests comparing like trees between each of the four sites found no statistical differences in each of the deciduous ($P=0.11$) or evergreen ($P=0.28$) species, allowing the data to be combined to support the hypothesis. Lognormal linear regressions provided excellent results for both tree types and further described the expected differences in canopy throughfall for each individual tree considered and the combined equations for both evergreen and deciduous trees, for this region.

3.2 Introduction

The first hypothesis is that there are fundamental differences in interception characteristics between coniferous and deciduous trees for different seasons in the southeastern region. Because of substantial rainfall in the leafless period, the deciduous trees will have a significant increase in throughfall (rain passing through the canopy to the ground) furthering the efficiency of coniferous canopies for rainfall interception in urban settings. Direct throughfall measurements for both deciduous and coniferous species across all seasons will be collected to test this hypothesis.

Research in rainfall interception dates back more than a century beginning with simple observational data published by Horton in 1919. Since that time, numerous approaches have been considered, from stochastic methods to advanced modeling, all intending to better predict rainfall interception. In the latter portion of the history of this research field, more interest and focus has been directed towards tree interception information for use in stormwater green infrastructure to reduce runoff volumes associated with urban development. As environmental impacts become more important in society, we must endeavor to understand methods to create a balanced environment. Inclusion of street trees for green infrastructure without an understanding of the benefits is careless. Generally, speaking, it is likely most municipalities probably do not have a record of typical species in their confines, much less an understanding for which ones are more beneficial overall. In 2019, Nytch and colleagues noted major knowledge gaps for different species across the world. This is easy to comprehend if one considers the number of native growing and planted species in their nearest urban area. Only through meticulous and costly surveying could an entity begin to account for the number and type of species in a typical city in the southeastern United States.

The problem statement at large is still determining the roles trees and tree canopies have in urbanization. How and where do we place trees to maximize storage? What trees work best in different regions with unique rainfall patterns? What are the considerations that must be weighed when we gather enough information to begin developing design standards? And, at what point do the benefits of tree cover undermine other environmental controls with greater benefits?

Specifically in this chapter, we want to look closely into potential differences in throughfall response data for typical evergreen and deciduous species in the southeastern United States. This is a region of the United States with comparatively very little research when viewed as a part of the broader forest-scale study area and even less for experiments focused on the individual tree-scale. The region also has a vast natural tree coverage area compared to the rest of the United States. As urbanization expands outward into rural areas, new development could benefit from data and knowledge to quantify urban trees benefits included in green infrastructure stormwater management planning.

To satisfy the objectives stated in the hypothesis, direct observations of rain throughfall for several specimens of both evergreen and deciduous species were observed during a multi-year study. In 2011 Xiao and McPherson conducted a short experiment for three trees (deciduous and evergreen) in Oakland, California. However, research must be completed in various climates across the United States for a comprehensive understanding of the role of urban trees in stormwater management. A major objective of this research was to collect sufficient data for all seasons at multiple locations in Alabama to obtain sufficient data to clearly compare the quantitative and qualitive differences, as well as analyze the meteorological impacts on tree rainfall interception.

3.3 Materials and Methods

3.3.1 Site Description

This study (known as “Study 1”) is comprised of four experimental locations: one in Pisgah, Alabama; one in Centre, Alabama; and two in Wetumpka, Alabama. Alabama is a coastal state with various terrain features stretching North into the foothills of the Smoky Mountains range. Hereafter the first three of these sites are referred to as “North Site,” “Central

Site," and the "South #1 Site." The fourth site, which started later in this study was the second site operated in Wetumpka, Alabama, and is labeled "South 2" throughout the study.

Data collection began in the spring of 2016 in three Alabama locations: North site, Central Site, and South #1. This was a deliberate effort to begin observing paired data beneath similar-sized trees (one evergreen and one deciduous) at each of these locations. The goal was to collect continuous data for all seasons at each site. A total of 182 storm events were recorded at these three sites during the first collection year.

The North Alabama site, located in Pisgah, Alabama (34.729673 N, -85.759365 W) included a large mature southern red oak (21" DBH, diameter at breast height) and a mature loblolly pine (18" DBH) were selected based on their proximity and canopy similarities. The oak tree's canopy radius was approximately 20 feet and slightly larger than the approximately 16-foot radius for the pine. Each tree was dominant with numerous healthy low-level branches that would suggest that they both had good storage potential qualities during rainfall. The trees were approximately 200 feet apart and the open field gauge was placed between them in an open area to avoid collection issues during storm events. The elevation for this site was 1342 feet above sea level and the highest site considered in Study 1.

The Central Alabama site was in Centre, Alabama (34.095987N, -85.475541 W) and contained a white oak (12" DBH) and a loblolly pine (10" DBH) located in a planted forest area. The radius for the pine and the oak are both an estimated 10 feet. This was likely due to competition from adjacent trees competing for sunlight. Likewise, both trees were noticeably taller than the trees at the South #1 and South #2 locations. Each tree considered was co-dominant and next to trees of the same species. Both were selected for their qualities and proximity to each other and distance to the open area at the site entrance to collect quality rainfall measurements. The trees were approximately 300 feet apart and the open field range was centered between the trees near the east side of the canopy. This site was 745 feet above sea level.

South #1 Alabama site was in Wetumpka, Alabama (32.570004 N, -86.246036 W) and included a loblolly pine (12” DBH) and a willow oak (10” DBH). Both trees were dominant, growing singularly in an open field. The trees were 150 feet apart and the open field gauge was placed in between them. The site was 180 feet above sea level. The radius for the oak was approximately 8 feet, and the pine radius measured approximately 14 feet. Each of the trees at this site had very dense canopies compared to like species at the North and Central sites.

The South #2 Alabama site was also located in Wetumpka, Alabama (32.570004 N, -86.246036 W) and targeted two evergreen and two deciduous species each. Equipment from South #1 and the North site was repurposed for this study area. The evergreen trees selected for this site were a small loblolly pine (8” DBH) and a small eastern red cedar (7” DBH). The deciduous species selected at this site were a Bradford pear (14” DBH) and a native pecan (12” DBH). All four trees were dominant growing away from other trees in an open field. All four trees were less than 150 feet apart and the open field gauge was placed in between them to minimize errors in rainfall collection. The site was 180 feet above sea level. The radius for the pine was approximately eight (8) feet, and the cedar radius measured approximately six (6) feet. The radius for the pear is approximately six (6) feet, and the pecan radius measured approximately elven (11) feet.

3.3.2 Observation Period

The South #1 was the first site to begin operation. Since this is geographically the closest site to the researcher, it served as the test site for all equipment to ensure setup and operation in

February of 2016. The equipment started to collect data on February 27, 2016, with the first observed data on the 7th of March. Fifty-five (55) events were observed between March 2016 and August 2017. Unfortunately, nine months of data are missing in the middle of this data set due to a damaged hard drive that couldn't be recovered. Using RAWS station data, the estimated loss measured in rain depth is approximately thirty (30) inches. However, a reasonable amount of rain data in both the leaved and leafless period were recovered. A total of thirty-seven (37) inches of rainfall was observed during the remainder of the observation period.

The Central site began operation in June of 2016, observing eighty-two (82) rainfall events between June 2, 2016, and May 4, 2017. For this site, an additional 41 data events (totaling 11 inches of throughfall rain depth) were excluded due to a power failure and data loss for the open field gauge. Local weather data was available for comparison. However, a decision was made to exclude these throughfall events to ensure accuracy in the data. Overall, the site gauges successful collecting thirty-six (36) inches of rainfall for consideration in the experiment.

The North site began operation on March 1, 2016, with the first monitored storm event on the 7th of March. Thirty-eight (38) rainfall events were recorded at this site for a total of 17.6 inches of rainfall. A summary comparison for the nearest RAWS weather station (recorded 31.3. inches in the same period) determined that approximately half the rain events were collected successfully at this site. Clogging from debris flushed off the trees and bird droppings were common causes for gaps in data at each site, but these were most prevalent at the North site. Since this location was the most distant, supervision and maintenance problems severely impacted the number of successful observations. However, full data sets were collected during each season and, more importantly, the events were well distributed across the leaved and leafless period. This site was closed in February due to continued difficulties maintaining the equipment, the travel distance and time required to troubleshoot issues at the site. The equipment from the North Site was later consolidated with the equipment from South #1 and four new trees were selected meeting the same criteria.

A fourth study site was set up for further data collection to test this hypothesis. Data collection started in October of 2019. The equipment at this new location used equipment from South #1 and the North site. The equipment was cleaned a tested to ensure there were no calibration issues impacting future data. At this fourth new site ("South #2") an additional 119 rainfall events were observed between October 21, 2019, and August 12, 2021. Two evergreen and two deciduous trees were observed, increasing the amount of interception and throughfall data for the experiment. Summary tables for events at each study are included in the appendices for this dissertation, along with individual event summaries for all events included in the analyses.

3.3.3 Rain Event Observations for Evergreen and Deciduous Trees

To test this hypothesis, at least three rain gauges are needed for direct comparisons between responses for an evergreen and deciduous tree. An open field rain gauge collecting discrete continuous data very near the trees is also required to minimize variability in the rain depth at each collection point. It's also best to select contrasting trees near each other, and that are similar in size and age to ensure storage comparisons are represented without bias. Only one rain gauge is placed beneath the canopy of each tree. During the field installation the tree canopy was observed closely to ensure that placement is beneath an average representation of the canopy. The location is generally near the midpoint of the radius of the tree canopy, ensuring that the gauge isn't directly beneath main leaders or branches that could negatively skew throughfall. To inspect the chosen position, a camera was placed on top of the leveled rain gauge to take photos in the zenith directly above the gauge (See Figure 3.1). All throughfall response data and the independent data (precipitation) was logged in time series, post-processed, and aligned with daily climate factors (i.e., windspeed, direction, etc.) for later use in statistical analyses.

Figure 3.1 View in the zenith angle above tipping bucket rain gauge

3.3.4 Experiment Equipment

The rain gauges used during this Study 1 were HOBO Data Logging Rain Gauges RG3, as described in Chapter 2. At South #1, Central site, and North site, three devices (one open field, one evergreen, and one deciduous) were used through the entire observation period for each site. When all sites were active, a total nine gauges were operating simultaneously. At the South #2 site, five gauges were needed. Equipment from South #1 and the North site were cleaned, tested, and moved to South #2 to continue collection for four new trees (cedar, pine, pecan, Bradford pear) and one open field gauge. The internal data logger is set to the same logging parameters for all studies; to collect temperature at 5-minute intervals and measure 0.01 inches per tip of precipitation. To optimize successful data collection, routine inspections were needed to observe the screens and funnels to clear debris that can clog the funnel and alter the time-series volumetric measurements and ultimately the throughfall rates. This can impact the total measured throughfall, extend the event time under canopy, and misrepresent intensity. Many observations were rejected at every study site because of these conditions. From field experiences, best management practices included inspecting each gauge before an expected rain event and 24 hours after throughfall has ceased beneath a canopy. Otherwise, a clog may pond rainfall in the funnel or slowly drain in some cases.

3.4 Data Analysis

A single methodical approach was applied to each individual site to test data distribution normality. The post-processed and summarized data for each of the four sites needed to be transformed in three ways: the difference reflecting tree storage (tree throughfall – open rain depth = storage), throughfall ratio (tree throughfall divided by open rain depth), and a log10 transformation. The lognormal transformation worked well to normalize the distribution for statistical analysis at each site. Thereafter, individual value plots and scatterplots are used to conduct preliminary visual analysis on the data. Statistical comparisons were initially made for each site.

3.4.1 South #1 Analysis

During the seventeen (17) months where equipment was active at this site, fifty-two (52) observed rain events are evaluated for further analyses. The raw data for the experiment included one independent variable (rainfall depth, inches) and two dependent variables, the throughfall for one evergreen and one deciduous tree. All data is post-processed to align throughfall with the corresponding rain event. The data was plotted using statistical software (Minitab® and Microsoft Excel®) to view the distribution density for and test for normality. An example comparing observations with the lognormal transformations using a individual value plot is shown below (Figure 3.x). As described earlier, the data are transformed in three ways: LOG10, a throughfall ratio (throughfall/rain depth), rainfall interception storage (rain depth – throughfall). Each transformation was needed to perform the various parametric hypothesis tests and graphical analyses needed to test the hypothesis.

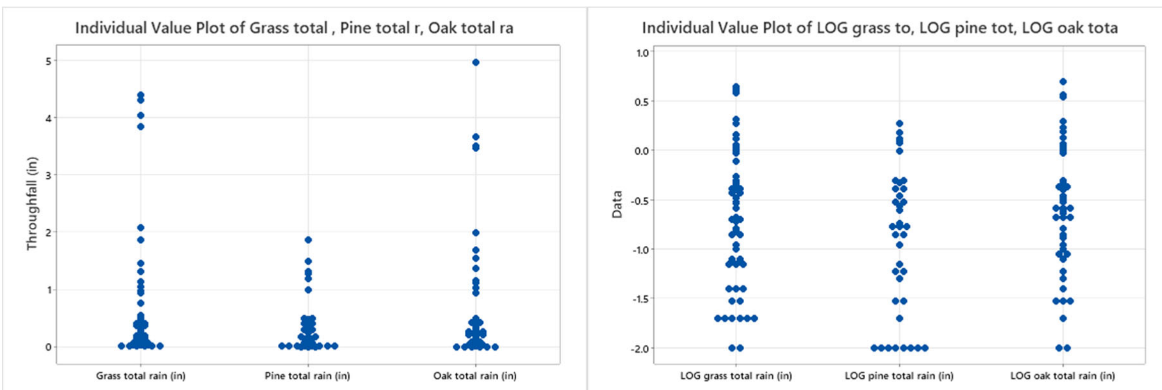


Figure 3.2 Individual plots for observations at South #1 (left) and lognormal transformations (right)

Paired T-tests were used to test the significance of the differences between throughfall means of the evergreen and deciduous trees as used for each site. For South #1, the T-test failed to reject the hypothesis (P=0.34). A review of the paired differences didn't reveal a large number of discrepancies, and it was concluded that it is plausible that that more observations may be required to support the hypothesis for this individual site. Lognormal linear regressions of rainfall vs. throughfall were performed next for each tree, with satisfactory (R^2=0.86) outcomes. The results for each site's individual regression coefficient results are listed in a summary table following the data analysis sections later in this chapter (See Table 3.1).

3.4.2 Central Site Analysis

The experiments for the Central site were very successful overall, despite some data loss near the end of the experiment. Eighty-two (82) observations of rainfall/throughfall pairs resulted in many comparisons amongst the three variables. The same procedures as described for South #1 above were repeated for this site. No issues were observed while reviewing each of the data distributions individually. The larger dataset at this site resulted in satisfactory lognormal data distributions. Paired T-tests were again not able to detect significant differences in the evergreen and deciduous trees (P=0.9) throughfall. A review of the distribution (listed below in Figure 3.3) best describes how similar the response distributions were in this case. It is possible, that the co-dominant characteristics impact the similarities at this site.

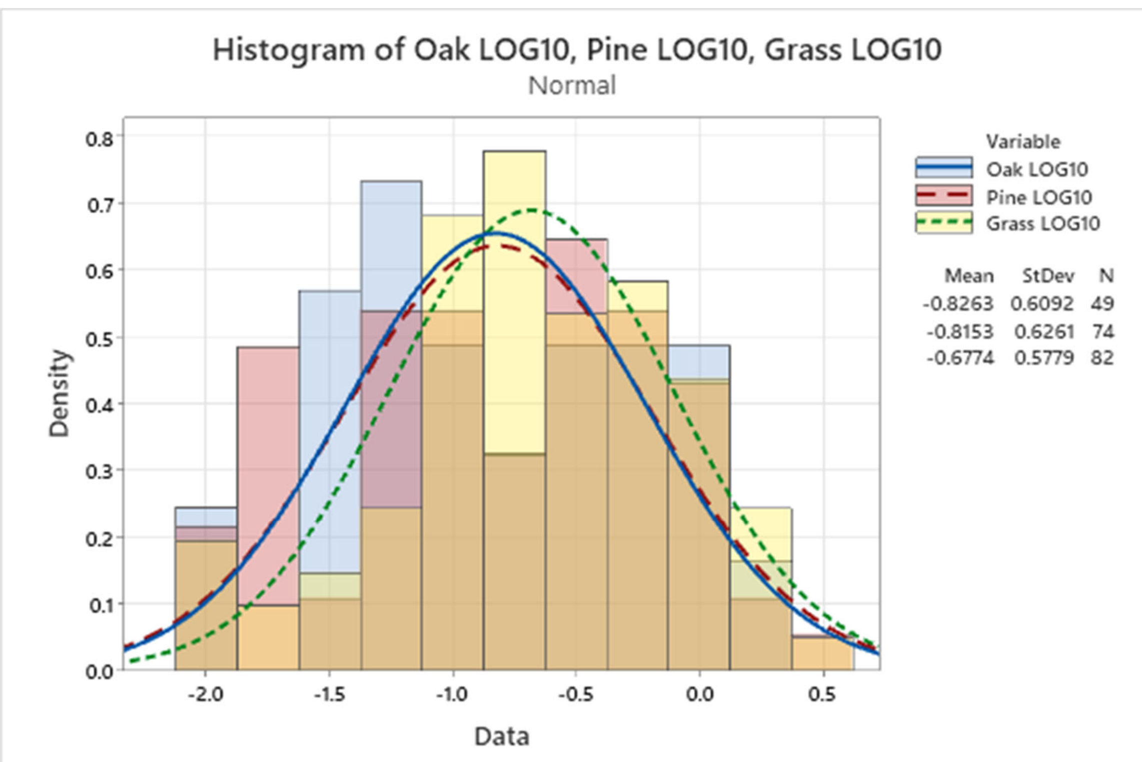


Figure 3.3 Histogram comparing Evergreen and Deciduous response data for the Observation period

The lognormal regressions of throughfall vs. rainfall provided very good results for both the pine (R^2=0.86) and the oak tree (R^2=0.95). With the larger number of data, several large residuals for both trees (Figure 3.4) were also seen. From a review of each data point with large residuals, several were found that may be explained as inaccurate measurements, as most appear to underestimate the throughfall when compared to the total rain depth and/or the adjacent response variable from the other tree.

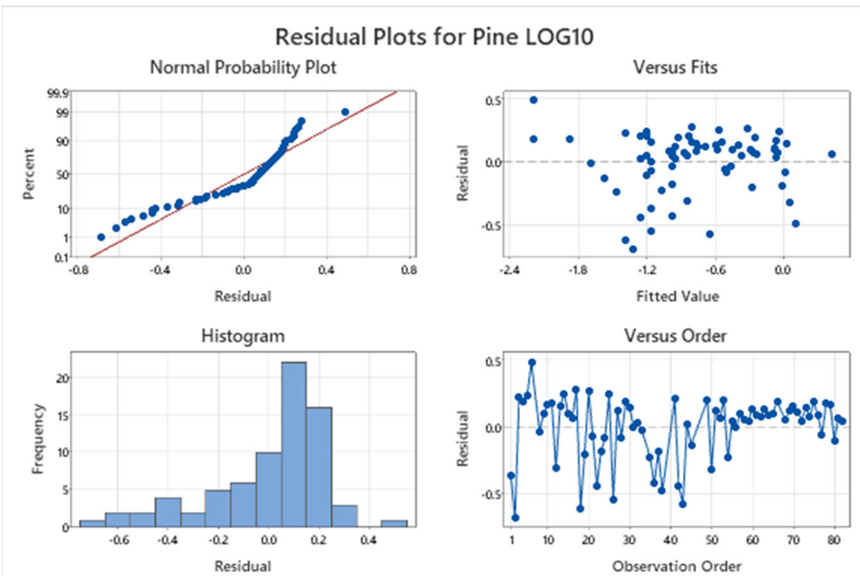


Figure 3.4 Residual plots for Central Site loblolly pine

A decision was made not to omit these observations because the number was not large enough to drastically impact the overall fit of the regression model. There is no method (post hoc) for the experiment parameters to determine if the large differences between evergreen and deciduous throughfall for these few events were inaccurate measurements or just uncommon but valid differences.

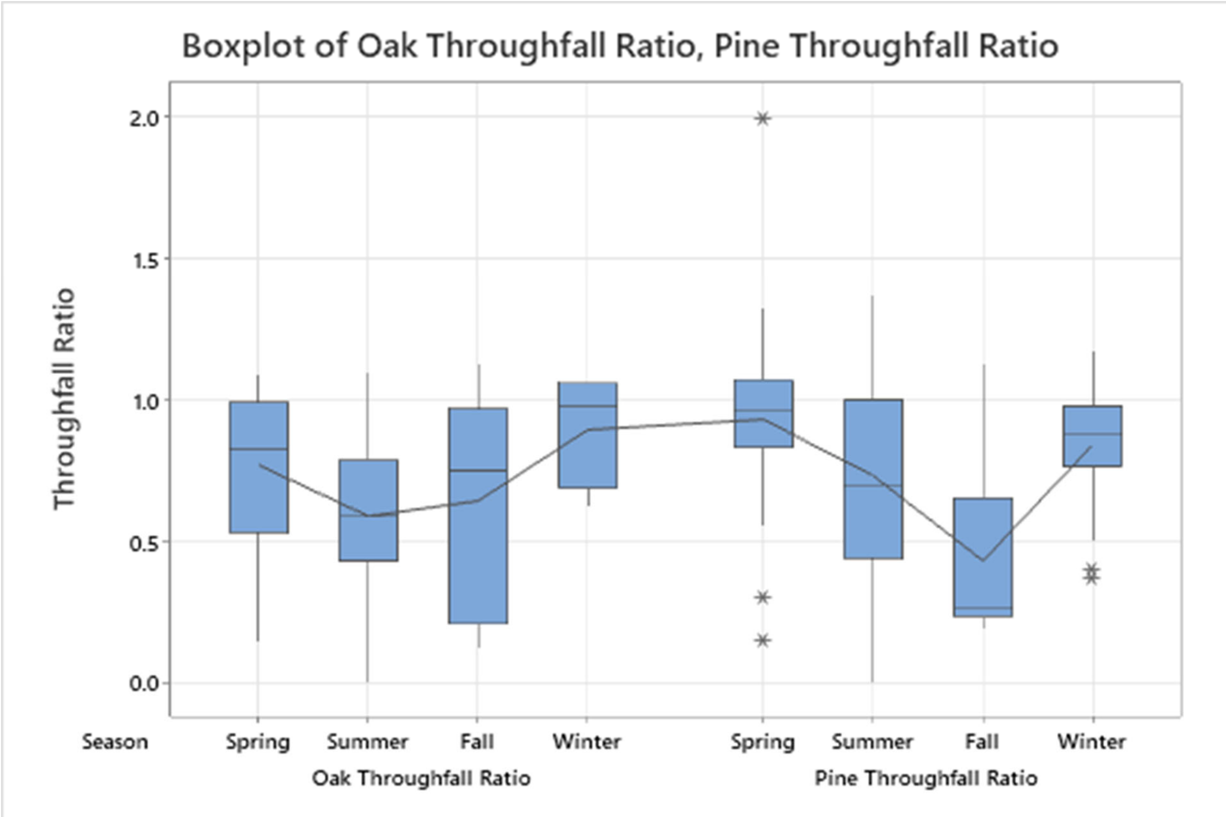


Figure 3.5 Boxplot for Central Site throughfall ratio by season

The observations for the site included all seasons and served to begin addressing the second part of the hypothesis: the seasonal impacts must be studied to incorporate the leafless period and how storage is impacted for deciduous species. In the above boxplot (Figure 3.5) with a mean connected line, you can see the subtle distinctions between spring and summer for the tree types. But none of the seasonal differences between trees appear to be significant for this site, corresponding to the results from the hypothesis tests. The most difference being the much lower Fall oak compared to the pine tree. Some of the variability may be explained by the relatively number of fall observations (9 in total) compared to the other three seasons at the Central Site.

3.4.3 North Site Analysis

Despite the relatively low number of observations for the North site, the paired data for the pine and oak results are comparable to the other sites covered in this chapter. The scatterplot below in Figure 3.6 displays the lognormal response of throughfall for each tree considered.

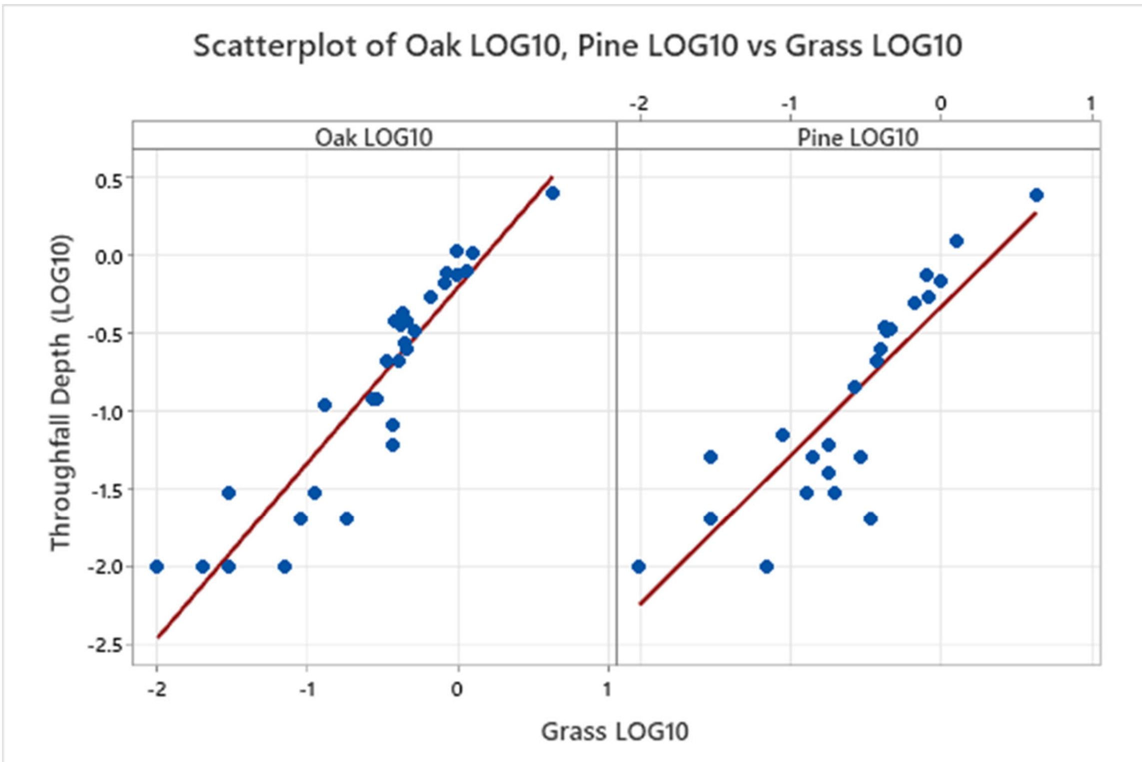


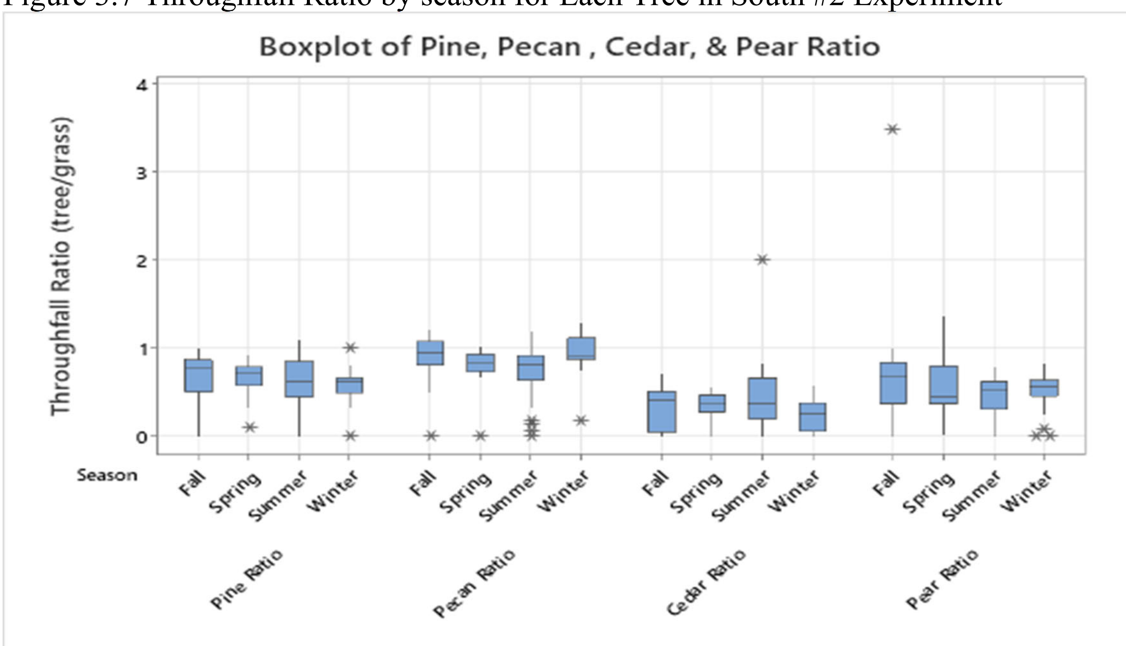
Figure 3.6 Scatterplot of Lognormal Throughfall for the North Site

Paired T-tests were used to compare the differences in means between evergreen and deciduous observations. For this site, the T-tests were again unable to reject the null hypothesis (H_0: μ_difference = 0.) with a P-value of 0.36, and the throughfall for each tree type were not found to be significantly different. More observations are needed to provide evidence for sufficient sensitivity to support or reject the null hypothesis. Regression analysis for the LOG10 transformation was conducted to predict the expected observations for each tree. Different from the hypothesis tests, the linear regression nicely constructed a regression equation for each response variable at the site with 87.7% R^2 and 77.4% R^2 for the oak and evergreen tree respectively.

3.4.4 South #2 Analysis

A native pecan, a loblolly pine, an eastern red cedar, and a Bradford pear (two evergreen and two deciduous trees) were observed simultaneously at this site. With 119 observations and twice the number of trees to consider, this site had a higher likelihood of identifying seasonal and tree type interactions. With more observations, a better representation for full seasonal response data enabled an analysis to be performed at the site-level to contrast the leaved and leafless periods. As for the previous sites, visual differences between species and seasons are seen, but paired tests are needed to quantify the significance of the differences. Full factorial analysis was also conducted at this site to develop the design of experiments to compare all locations to support hypothesis #1.

Figure 3.7 Throughfall Ratio by season for Each Tree in South #2 Experiment



Unlike the first three sites, paired T-tests produced favorable results (found significant differences in throughfall for different trees) for all six possible comparisons at South #2. For each of the six tests, the null hypothesis was rejected, with 5 results having P-values less than 0.001, and the pine vs. pear comparison had a P-value of 0.032. The larger number of observations and more direct comparisons between the individual trees aided in identifying significant differences by increasing the power to better predict the differences between each tree.

For this site, a full factorial (2^3) analysis was conducted that examined rain depth, average rainfall intensity, and average daily windspeed for each of the trees in South #2. Rain depth and windspeed were found to be significant factors affecting throughfall for each tree. A second full factorial (2^3) analysis was conducted examining rain depth, average windspeed, and leafless period. To help interpret these findings, interaction plots are shown below for the leafy season, windspeed, and rain depth interactions. Numerous interactions can be observed for most of the trees, however the cedar (Figure 3.11) displayed fewer interactions for any of the comparisons (generally parallel lines with no lines crossing). This is likely due to the high canopy density across all seasons, giving the relatively small tree a large, consistent minimum storage capacity. The photo below directly following a storm event shows a sizeable amount of water droplets held on the coniferous surfaces for the cedar.

Figure 3.8 Water droplets stored on surface of an eastern red cedar

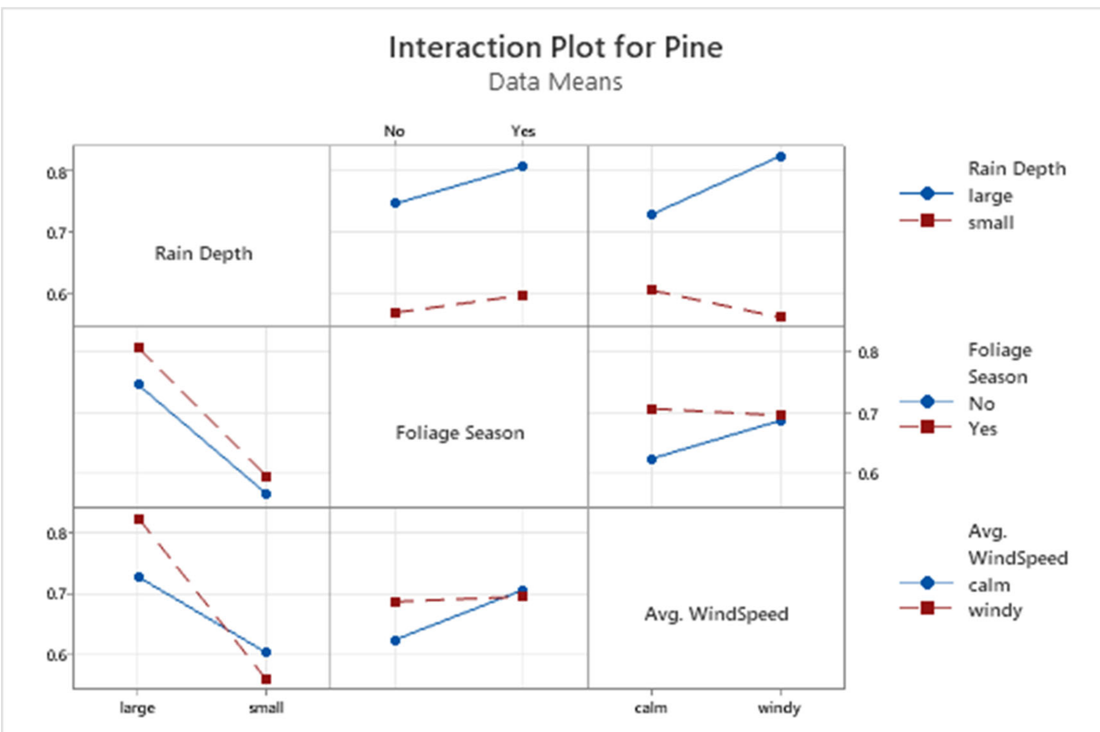


Figure 3.9 Interaction Plots for Loblolly Pine at South #2

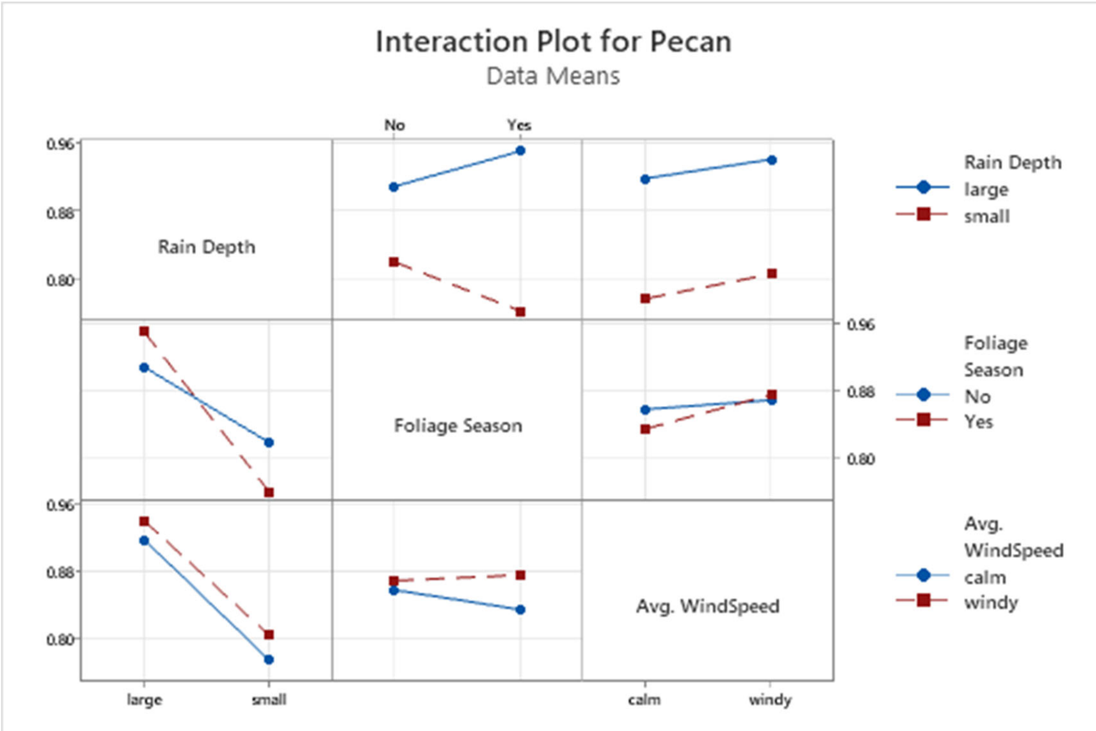


Figure 3.10 Interaction Plots for a Native Pecan at South #2

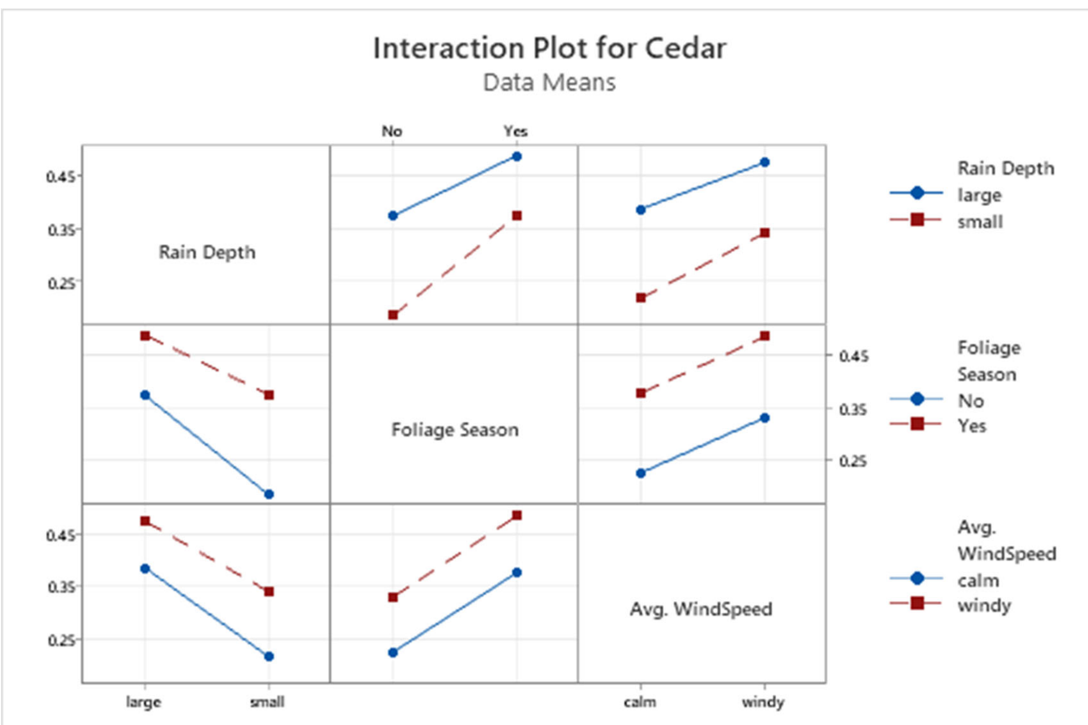


Figure 3.11 Interaction Plots for Eastern Red Cedar at South #2

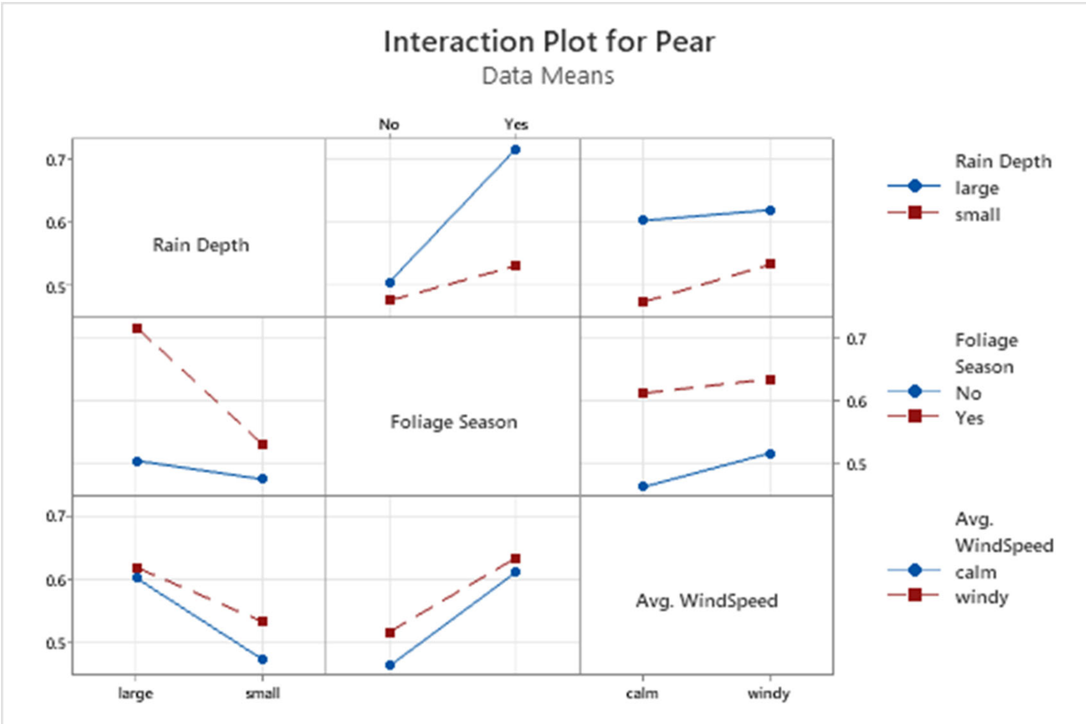


Figure 3.12 Interaction Plots for Bradford Pear at South #2

3.4.5 Combined Data Analysis for Hypothesis #1

Before any data from the sites could be combined, hypothesis tests were performed to compare like trees between each of the sites (i.e., Oak for North Site vs Oak for Central Site). To quickly tests for differences, the data were sorted into three columns for all four sites. One categorical data column for observation location (e.g., South #2, etc.), one column for deciduous response data and the other for paired evergreen tree observation (three columns total). A one-way ANOVA test was then used to compare lognormal differences between the means of all evergreen trees categorically by location. The ANOVA was repeated for the deciduous events categorically by location. In both tests, no statistical difference between the means could be identified. For the evergreen tree comparison, the P-value is 0.28 and for the deciduous test the P-value is 0.11. Meaning that in both cases the data at each site were not significantly different based on the number of observations available. Therefore, the data for each tree type were combined for all four sites. In figure 3.13, the summary output graph from each one-way

ANOVA’s individual value plot is shown below for lognormal evergreen and deciduous responses comparing each site. Hypothesis tests can then be used to compare evergreen and deciduous throughfall response data for all sites.

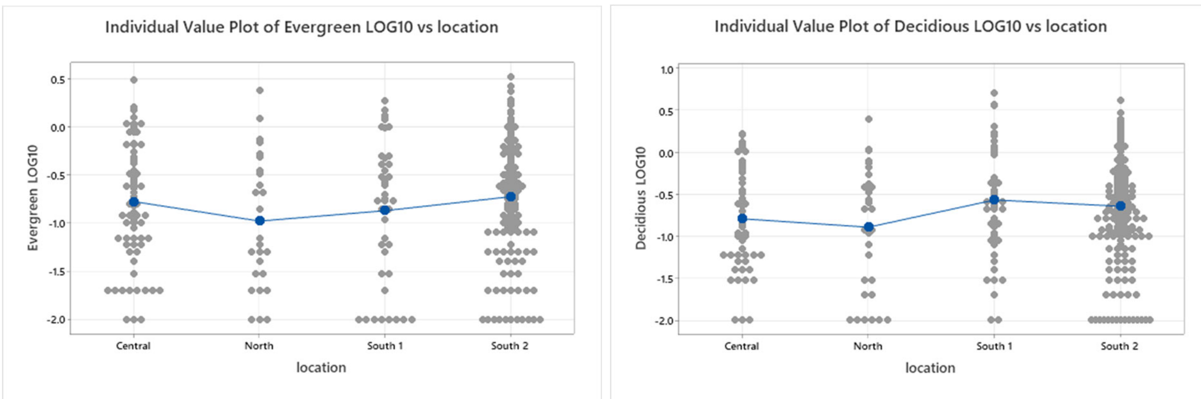


Figure 3.13 Individual Value Plot for LOG10 Evergreen (left) and LOG10 Deciduous (right) Hypothesis #1

Paired T-test were used to measure differences in the throughfall responses for each tree type. The data for all four sites were later sorted into a single series to include corresponding categorical data for each observation to compare all possible comparisons for evergreen vs. deciduous for each rainfall event in Study 1. The T-test performed on the data (Log10 transformed) produced favorable results ($P<0.001$) to reject the null hypothesis and conclude with 99+% confidence that the mean for evergreen throughfall was observed to be less than the mean for deciduous trees across all experiments.

Lognormal linear regressions for the combined data also produced favorable results, and the regression equations were added to a combined table to compare the hypothesis results against each tree considered in the study (see Table 3.1 below).

Table 3.1 Regression Coefficients for Throughfall by Dependent Variable							
Study	Tree	Intercept Term	P-Value	Slope	P-Value for Slope	R^2	Regression P-Value
Combined	Evergreen	-0.25	<0.001	0.95	<0.001	0.71	<0.001
Combined	Deciduous	-0.15	<0.001	1.03	<0.001	0.77	<0.001
North Site	Loblolly Pine	-0.33	0.002	0.96	<0.001	0.77	<0.001
North Site	Southern Red Oak	-0.21	0.004	1.13	<0.001	0.88	<0.001
Central	Loblolly pine	-0.12	0.007	1.03	<0.001	0.85	<0.001
Central	white oak	n/a	n/a	1.30	<0.001	0.95	<0.001
South #1	Loblolly pine	n/a	n/a	1.04	<0.001	0.86	<0.001
South #1	willow oak	n/a	n/a	1.01	<0.001	0.96	<0.001
South #2	Loblolly pine	-0.16	<0.001	1.16	<0.001	0.87	<0.001
South #2	Native Pecan	-0.058	0.035	1.11	<0.001	0.9	<0.001
South #2	E. Red Cedar	-0.47	<0.001	1.02	<0.001	0.69	<0.001
South #2	B. Pear	-0.24	<0.001	1.12	<0.001	0.83	<0.001

3.5 Results

The results for all four sites considered in this experimental provided useful data. But data analysis for any single site didn't provide sufficient evidence to support the stated hypothesis for this chapter by itself. A comparison for all evergreen and deciduous trees considered for all sites found no significant differences in the means (e.g north pine vs. south pine vs. central pine). This enabled combining the like data for each site categorically into three columns: combined evergreen; combined deciduous; and combined open field while maintaining time series information and other categorical variables. The observations (n=282) are treated as paired data, comparing two potentially distinct responses against the independent variable ("rainfall").

The comparisons are intended to satisfy key points for hypothesis #1. These tests were able to detect significant differences and reject null hypothesis that tests for no throughfall difference between the deciduous and evergreen species. Furthermore, it was found that the evergreen trees may yield a slightly higher storage potential across the different seasons annually (H_1: μ difference < 0).

The lognormal regressions performed for each tree type had satisfactory statistical results; overall regressions and slopes were all found to be significant. The combined evergreen and deciduous equations were used to develop expected throughfall vs. rainfall relationships for both species and the results provided additional evidence supporting the hypothesis. These results also estimated throughfall depths for both evergreen and deciduous for the southeastern United States as described below in Figure 3.14. These results are useful in planning for use of trees in landscape planning and stormwater green infrastructure projects.

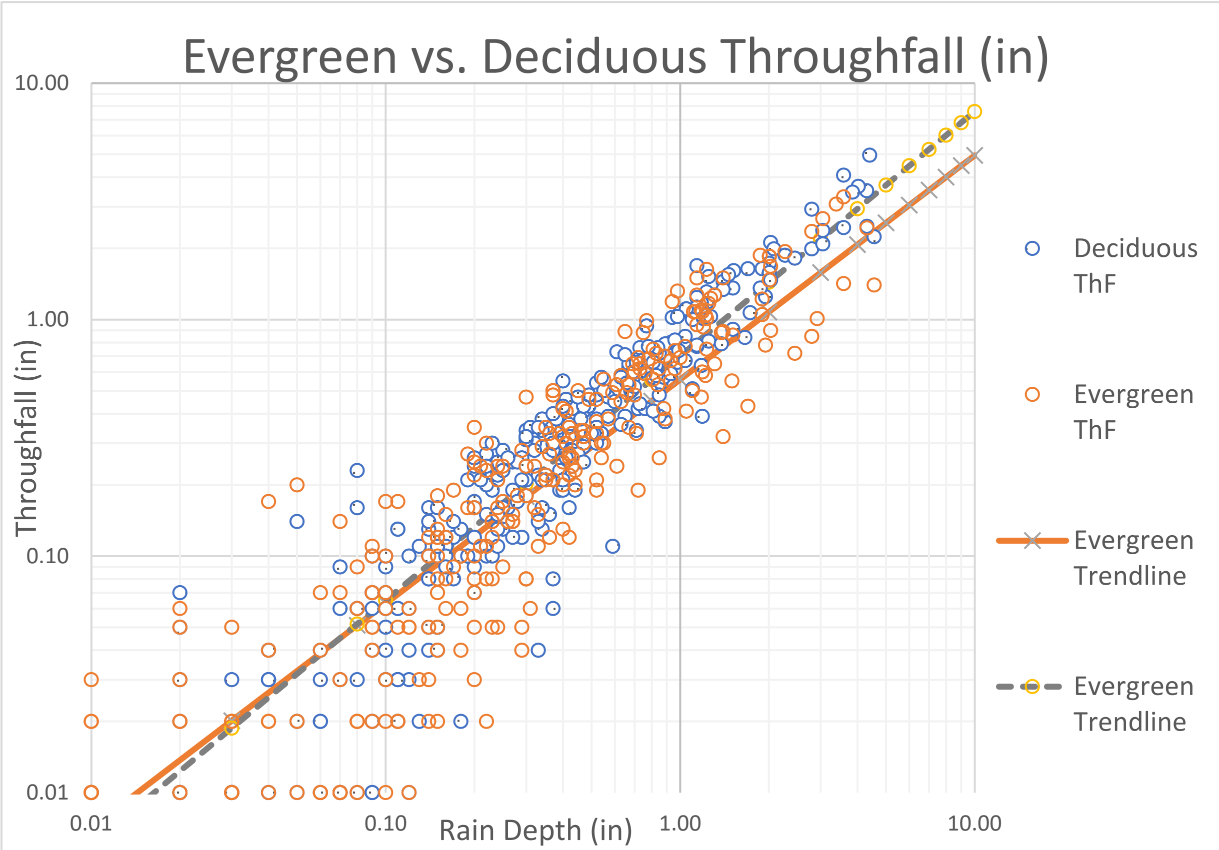


Figure 3.14 Projected Throughfall depth for evergreen and deciduous trees in southeastern U.S.

A full factorial analysis was conducted examining rain depth, average rainfall intensity, and average daily windspeed. All factors were found to be significant (Table 3.2) affecting throughfall based on the table of contrast results. Interaction plots were created to examine the interactions of these factors (listed earlier in this chapter). A second factorial analysis was performed incorporating rain depth, leaved or leafless season, and windspeed. Again, all three factors were found to be significant and interactions plots were created. A boxplot is shown below in Figure 3.16 describing the potentially significant differences between species and foliage (leaved and leafless period).

Table 3.2 Main Factors and Interactions for Study 1 for Weather Conditions

Factors and Interactions	Evergreen	Rank	Deciduous	Rank
Rain Depth	-0.36	6	0.48	5
Intensity	0.51	5	0.26	6
WindSpeed	1.22	1	1.829	2
RDxI	0.33	7	-0.165	7
RDxWS	-1.18	2	-1.834	1
IxWS	0.98	3	1.78	3
RDxIxWS	0.89	4	1.57	4

Table 3.3 Main Factors and Interactions for Study 1 for Leafless Period

Factors and Interactions	Evergreen	Rank	Deciduous	Rank
Rain Depth	-0.27	6	0.22	7
Leafy Season	0.87	4	0.48	5
WindSpeed	1.12	2	1.32	3
RDxLS	0.02	7	0.44	6
RDxWS	-1.19	1	-1.41	1
LSxWS	0.90	3	1.40	2
RDxLSxWS	0.86	5	1.11	4

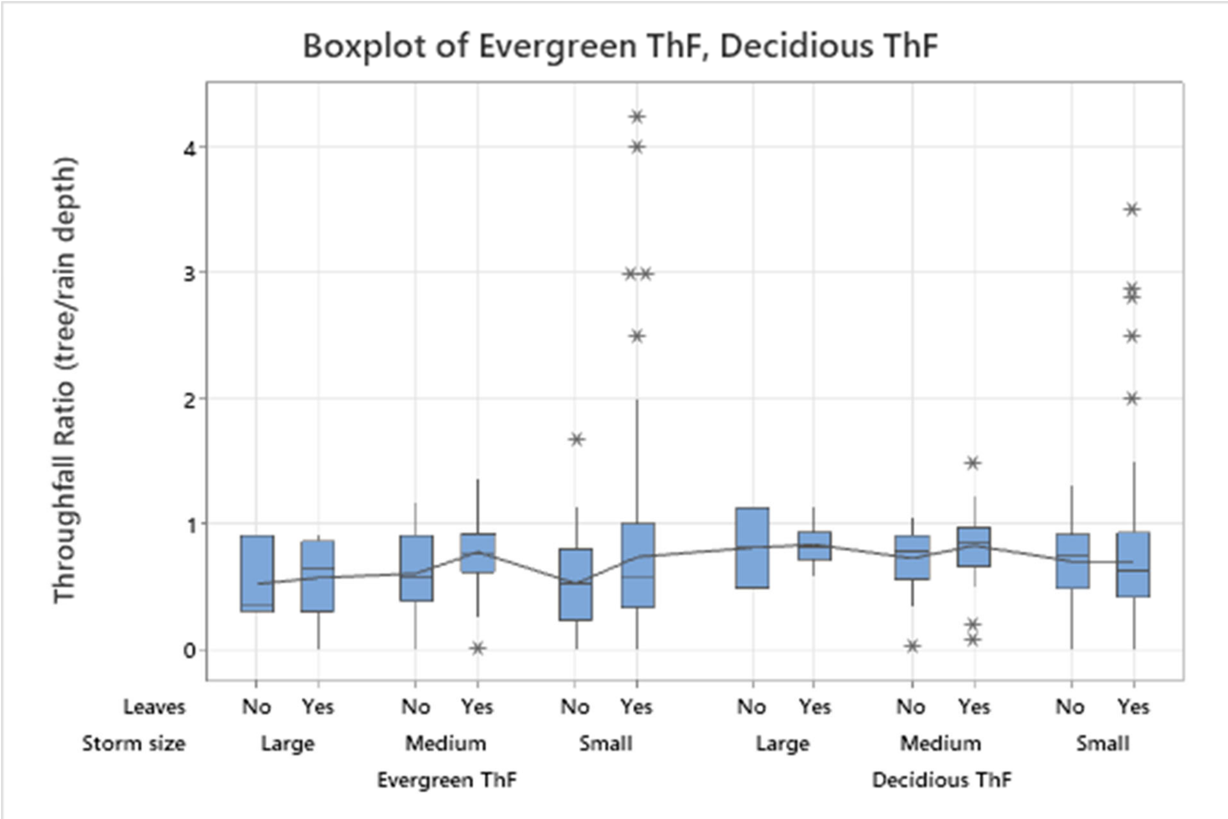


Figure 3.15 Storm Size and Foliage Impacts for Evergreen and Deciduous Trees

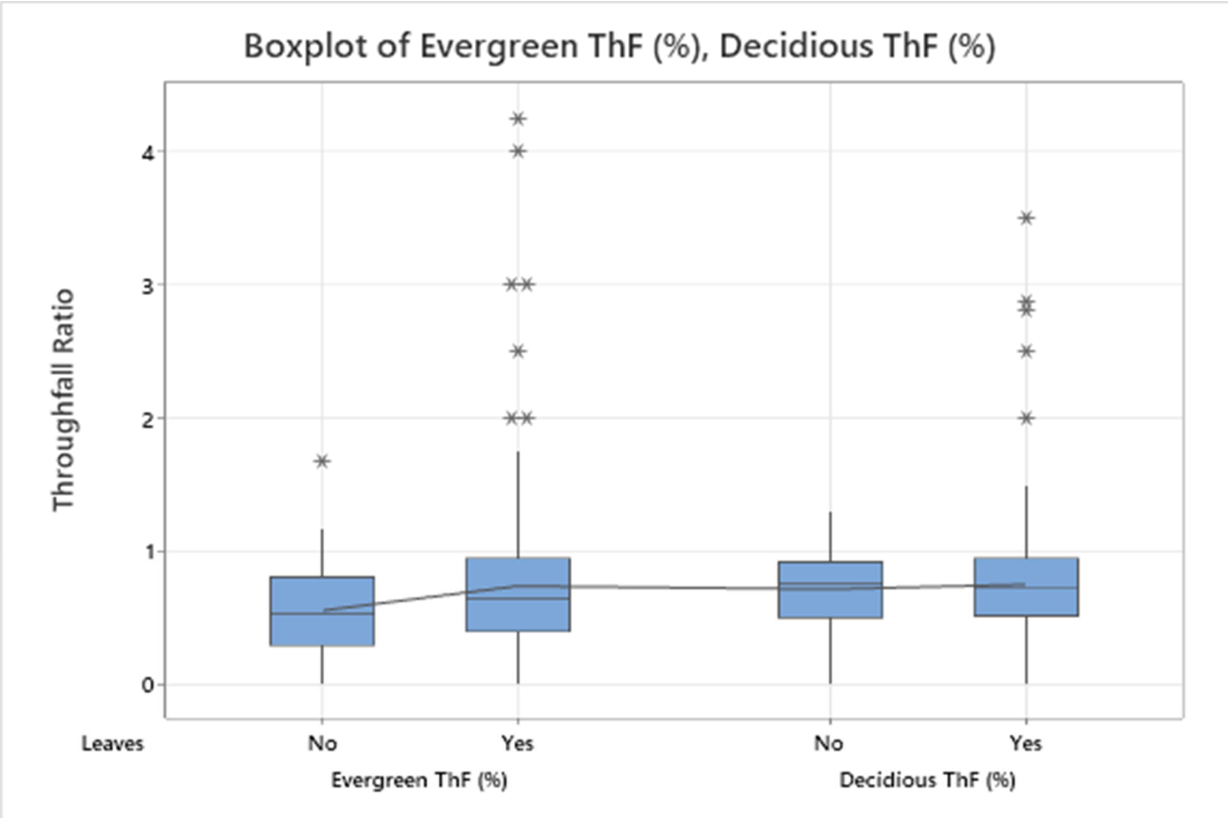


Figure 3.16 Boxplot comparing Evergreen and Deciduous trees in the leafless and leaved period

3.6 Conclusion

Overall, the data showed that the first hypothesis of this research is plausible based on the large amount of data collected, when the data were combined from each site. You can infer that there could be less throughfall under an evergreen tree as compared to a deciduous for a given year as shown in the Figure 3.16 above. Each of the site data collections individually did not result in sufficient data to identify significant differences in throughfall between the tree species. Later studies during this dissertation research investigated the effects of tree age/size, and the effects of locating gauges under different distances from the tree trunk to the canopy edge on throughfall. These data help define the expected storage potential for deciduous and evergreen species at different growth stages and the effects of throughfall near the edge of the tree canopies.

3.7 References

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Xiao, Q., & McPherson, G. G. (2011a). Rainfall interception of three trees in Oakland, California. *Urban Ecosystems*, *14*(4). https://doi.org/10.1007/s11252-011-0192-5

CHAPTER 4

THROUGHFALL COMPARISON OF FOUR DIFFERENT SIZED STREET TREES

4.1 Abstract

This study observed throughfall for four street trees in Montgomery, Alabama located in the southeastern United States. Throughfall differences were measured for 33 rains events during the experiment. Parametric and non-parametric tests were performed to compare differences in throughfall between individual trees, but no significant differences were produced. Grouping results for the two smaller trees and comparing the data to the grouped data for the two larger trees produced significant differences. Therefore, the data were combined to create two log normal linear regressions (one small and one large), in addition to the individual linear regressions for each tree. Lognormal linear regressions provided excellent results for each tree ($P \leq 0.001$) and further described the expected differences in canopy throughfall for categorically grouped results for willow oaks by size (small and large). A 2^3 factorial analysis for rain depth, tree size, and average windspeed was also performed, with strong results. Rain depth and tree size were both significant factors in the analysis. The rain depth x windspeed interaction followed by the combined interaction both produced very high interactions.

4.2 Introduction

The second hypothesis is that direct observations can me made of different sized trees of the same variety (genus and species), and the resulting data will detect measurably distinct rainfall interception. The data will show that as the trees grow, their storage capacity (minimum retention) increases and can be measured as they grow.

Tree architecture and canopy structure describe how trees grow, forming limbs and unique characteristics (Millet et al., 1998) creating surfaces for stored rainfall available for evaporation. storage. The literature review described relationships between the size, shape, and density of different trees and how they may relate to storage potential for rainfall interception. However, street trees or urban canopies are less dense with gaps or openings between each tree canopy, allowing each tree to grow outward with limbs lower (unless removed for shaping or maintenance) to the ground unless the tree is shaded by structure. Common examples for street trees are found in tree farms and nurseries (growing in better conditions) or developments (residential and commercial) where trees are part of the landscape plans. These planted species could grow similarly enough to have predictable minimum and maximum storage given they are not constrained by limited shade (e.g. from buildings, structure, etc.) impacting their shape and causing continued growth toward sunlight. Open street trees should be easier to calculate total interception to consider the stormwater runoff reduction needed to balance the site design criteria. Furthermore, understanding the potential storage over time as the tree grows could help define the timeline for a return-on-investment period to meet desired runoff reduction criteria. Relating expected growth as described by McPherson and colleagues in a General Technical Report: Urban Tree Database and Algometric Equations, could serve as a basis of design to include street trees in green infrastructure projects. This chapter introduces an approach, with observations, to study throughfall observations beneath several landscape planted willow oak trees of different ages and sizes to access the feasibility of this hypothesis.

The literature review showed that canopy storage is not well understood. Numerous approaches have been considered, including advanced modeling at the tree-scale and adaptations of forest-scale models. But models require extensive knowledge for canopy conditions and climatological factors that are not practical for designers. Instead, simple design standards for common species are needed to merge knowledge and understanding with standardized design standards for use in green infrastructure stormwater applications. Much of the research history is at the forest-scale, and the available urban-scale research is unable to satisfy this need. A combination of field assessments and common measuring techniques in urban areas were therefore used during this dissertation research using selected different aged trees of the same species to test this hypothesis. Recent research for street trees in urban areas have found that stormwater can be reused by as much as 20% (Gonzalez-Sosa et al., 2017) given proper implementation is considered. The goal for this chapter is to present baseline data needed to fill this knowledge gap for the southeastern United States. More is needed for direct observations at defined radial distances beneath different common trees by region to collect data and build comprehensive understandings for a wide range of conditions.

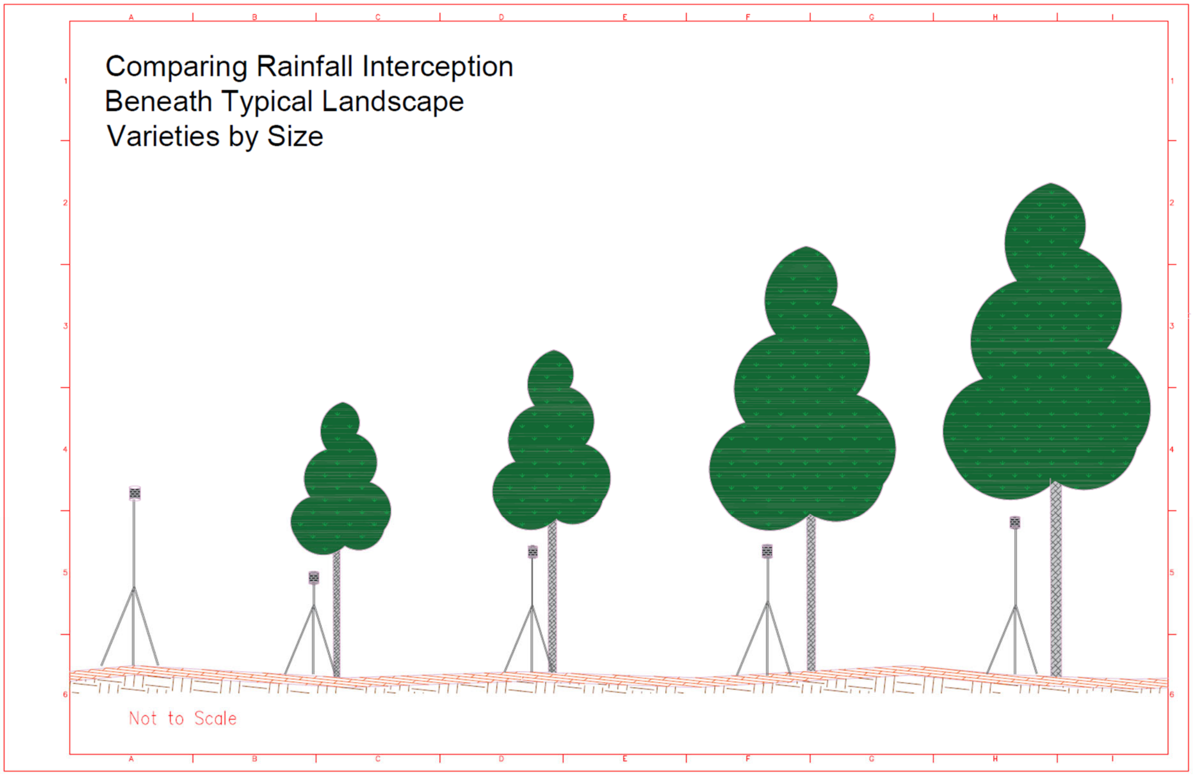

Figure 4.1 Illustration of experiment design concept for Study 2

4.3 Materials and Methods

4.3.1 Site Description

The site is in Montgomery, Alabama at the State Military Department. The site is in a mixed industrial and commercial zone of the city. All grounds on the 92-acre property are developed with multiple buildings and infrastructure, rigid, flexible, and pervious parking, green spaces, and other landscape features. Buildings were constructed between 1999 and 2010 and had a common landscape plan, providing an abundance of sample species. During each phase of construction of a multi-year building project, landscaping included trees of the same species (willow oak). During post-construction, additional younger trees were added to replace diseased and dead trees as part of the warranty period for construction. This provided a visible range of different aged and size trees of the same species for consideration in this research. The site is located near a major U.S. Air Force base with an active weather station linked to open access weather databases. Ambient weather conditions were recovered for each rain event observation period for use in the data analyses.

4.3.2 Observation Period

Data collection began in August of 2021 for Study 2 of this research task and concluded in January of 2022, with a total of 39 rain events observed. Study 2 was constrained by time and available equipment. Equipment for the experiment was unavailable until enough observations were collected for Study 1, which included multi-season and multi-year data. The earliest equipment mobilization was late summer 2021. A part of the experimental design procedure was to estimate the number of quality samples needed to fulfill the hypothesis. Assuming an allowable error of 0.2 and using the equation (Cochran 1963) listed below:

Number of samples = 4 x (standard deviation)^2/(allowable error)^2

Allowable error = 20%

Standard deviation = 0.563 (derived from the log10 rainfall observation in Study 1)

Calculated number of samples needed = 32

This experiment ran concurrently with Study 3 of this dissertation research in the same general area, which will be described in the next chapter. A review of historic data provided by the National Weather Service (https://www.weather.gov/wrh/Climate?wfo=bmx) daily climate normal patterns between 1991 and 2020 indicated 22 inches of expected rainfall during this timeframe, compared to the observed rainfall total of 20.4 inches.

Table 4.1 Rainfall Event Summaries for Study 2

Rain Event Summary	Interevent Time (days)	Rain Duration (hrs)	Total Rain Depth (in)	Average Intensity (in/hr)
number	39	39	39	33
total:		248.78	20.44	
min	0.27	0.00	0.01	0.01
max	15.03	39.68	2.34	0.44
avg	3.16	6.38	0.52	0.12
median	0.93	4.44	0.34	0.09
stdev	4.16	7.58	0.57	0.11
COV	1.32	1.19	1.1	0.90

4.3.3 Rain Event Observations for Tree Size Analysis

The initial goal was to collect continuous data during the leaf-on period for four distinct examples of a planted landscape species (i.e., smallest to largest). However, leaf senescence and abscission started occurring early than expected in December of 2021 after only receiving three rain events in November, totaling 1.25 inches of rain. Leaf abscission was noticeable by December 15, 2021, and most of the trees were bare by January 15, 2022. For this reason, the experiment was ended on January 3, 2022, before half of the leaf foliage was gone.

Figure 4.3 Selected Trees for Analysis

Multiple rain gauges were needed to work in unison for this experiment. Four distinct willow oaks were selected that fit a basic criterion: each of the four trees needed to be visually different in size, ranging from very small to large (see Figure 4.3) One rain gauge is placed beneath each tree approximately halfway between the trunk and the edge of the canopy. All rain gauges were located on the northern side of the tree to standardize meteorological factors for each rain event. Wind was also analyzed for each event. The rain gauges were not moved between storms. This ensures that numerous throughfall samples were collected for the response variables and the controlled grass rain gauge. The grass control rain gauge was located 300 feet North of the trees in an open area. All throughfall response data and the independent data (precipitation) was logged in time series and was post-processed and aligned with daily climate factors (i.e., windspeed, direction, etc.) for later use in the statistical analyses.

4.3.4 Experiment Equipment

The equipment used for this study was the same HOBO Data Logging Rain Gauges RG3 from Study 1. Four gauges were dedicated for Study 2. The fifth device ("grass") serves both Study 3 and Study 2 (a separate but related experiment). Since each of these devices were used previously in Study 1, they were cleaned and calibrated to ensure proper working order before being used in these studies. The internal data loggers were set to the same logging parameters as used during the previous study; to collect temperature at 5-minute intervals and measure 0.01 inches per tip of precipitation.

4.4 Data Analysis

Of the 39 observed rain events, 33 had observations beneath the trees and were used for multiple comparisons in the data analyses. The raw data for the experiment include one independent variable (rainfall depth, inches) and four dependent observations (one per tree). All data was post-processed to align throughfall with the corresponding rain event. The data was plotted using statistical software (Minitab® and Microsoft Excel®) to display and inspect the distribution density for normality. As with the data points in Study 1, the data was transformed in three ways: LOG10, a throughfall ratio (throughfall/rain depth), and rainfall interception storage (rain depth – throughfall). Each transformation was needed to perform the various parametric hypothesis tests and graphical analyses needed to test the research hypothesis for Study 2.

The statistical approach used during Study 1 was repeated during this study to test this hypothesis and included data transformations, parametric tests, regressions, and 2^3 factorial analyses. The statistical approach endeavored to determine significant differences in observations beneath each tree's canopy as a function of tree size. A scatterplot with trendline was first used to display the data. The graph revealed very little distinction between the four tree sizes. Further analysis was needed to determine any significant differences between each sample. As visible in Figure 4.3. the result differences are not easily distinguished. Paired T-tests were used first to measure all six combinations for the four observations with a null hypothesis of a difference for each comparison at the 95% confidence level.

Figure 4.3 A scatterplot for Study 2

A full factorial (2^3, considering rainfall depth, wind speed, and tree size) design to identify significant individual effects and joint interactions. The rainfall classification for the comparison used a +/- one inch break point between small and large rains. To study the wind interactions, mean daily windspeed using a break point of +/- 10 mph. Last, the four trees were reorganized to form two categories with the very small and small forming the "small (-)" group and the medium and large tree forming the "large (+)" group.

Last, lognormal linear regressions are used to define each observation since the distributions of the observations were not gaussian when displayed using individual plot diagrams. The equations were then used to create an expected throughfall ratio for typical storms to display the expected performance for different sized willow trees.

4.5 Results

Data transformations to obtain normalized distributions were used to indicate visible patterns between each gauge location and tree size. In this case, throughfall values marginally decreased as the tree size increased. Paired T-tests were performed for the six combinations of the four trees selected for the study. Of the six tests, only one (smallest vs. medium) produced a significant difference (P= 0.002). The null hypothesis was rejected for the comparisons between the very small (13-inch DBH) tree and the medium (27-inch DBH) tree, only. Again 32 samples were needed to have the precision desired to detect a 20% difference in throughfall at the 95% confidence level. It is likely that more observations are needed to better define the throughfall distributions for each tree, as several had fewer than 32 observations (estimated number of samples needed to detect a 20 percent difference). It is also possible that the 13-inch and 20-inch are very close in canopy storage. A Mood's median test was also performed using a non-parametric approach comparing the throughfall differences for of the tree sizes. This test also failed to reject the null hypothesis (P=0.162) based on the number of observations available.

A 2^3 factorial analysis for rain depth, tree size, and average windspeed was also performed, with strong results, to further explore the individual and interacting factors impacting the experimental results. Rain depth and tree size were both significant factors in the analysis. The rain depth x windspeed interaction followed by the combined interaction both produced very high interactions. These interactions will be used later to create boxplot diagrams to further interpret the interactions and look for potential significant differences in the classifications. Table 4.2 below provides the full list of the interactions and their ranks.

Table 4.2 Main Factors and Interactions for Study 3

Factors and Interactions	Calculated Effects	Rank
Rain Depth	0.8	4
Tree Size	-0.45	5
Average Daily Windspeed	0.16	7
Rain Depth x Tree Size	0.17	6
Rain Depth x Windspeed	-1.63	3
Tree x Windspeed	1.75	1
RDxTreexWS	1.75	2

The results revealed throughfall similarities between the smaller trees and the two larger trees. Therefore, these data were combined to create two log normal linear regressions (one small and one large), in addition to the individual linear regressions for each induvial tree. Each regression performed individual trees and the two for the grouped small and large tree categories produced significant results. All models produced high to very high p-values and r^2-values, and all six model summaries yielded significant correlations. A comparison chart for the combined small and large tree in Figure 4.3 shows the predicted differences in throughfall ratios.

Table 4.3 Lognormal Regression Coefficients for Throughfall by Dependent Variable						
Tree Observation	Intercept Term	P-Value	Slope	P-Value for Slope	R^2	Regression P-Value
Very Small	-0.0804	0.005	1.13	<0.001	0.95	<0.001
Small	n/a	n/a	1.34	<0.001	0.92	<0.001
Medium	-0.127	0.009	1.22	<0.001	0.86	<0.001
Large	n/a	n/a	1.44	<0.001	0.88	<0.001
Combined Small	-0.0808	0.007	1.19	<0.001	0.89	<0.001
Combine Large	-0.12	0.008	1.26	<0.001	0.83	<0.001

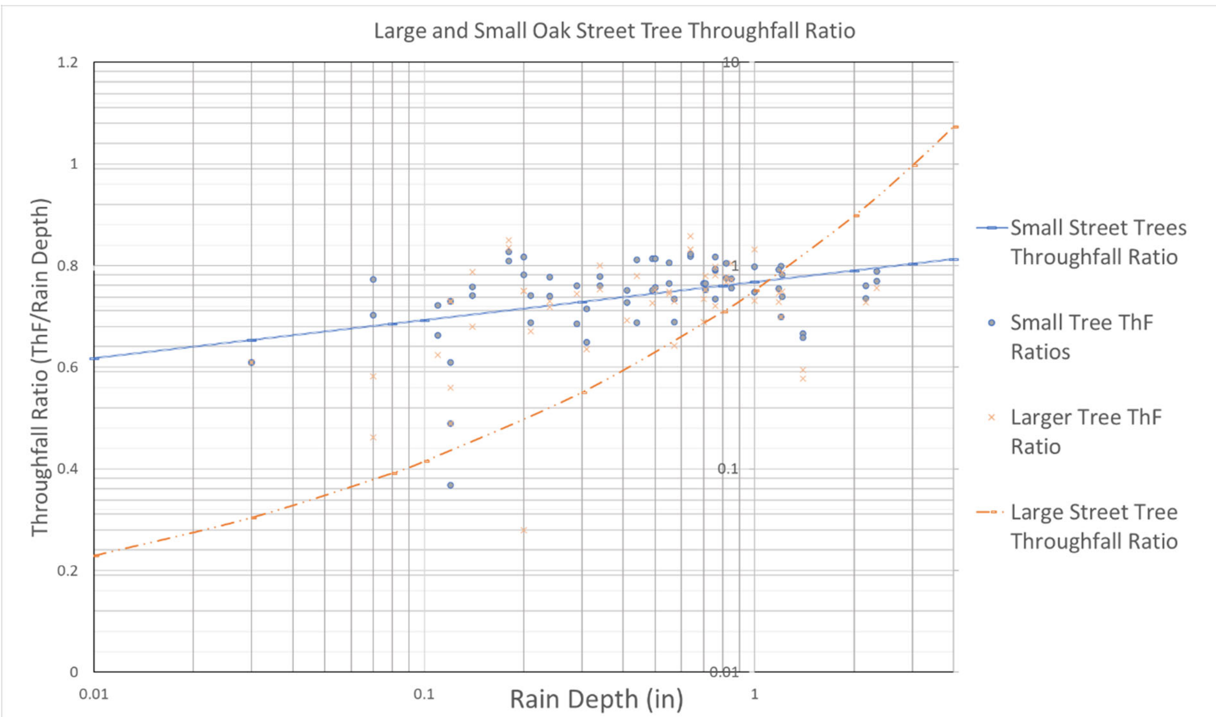

Figure 4.4 Projected throughfall ratio for large and small willow oak street trees

Since the above analyses indicated storm size being significant, the storms data were then reorganized to reflect three storm categories: less than 0.25 inches; 0.25-0.75 inches; and greater than 0.75 inches to further analyze the distinctions between storms by tree size and compare the composite differences between large and small storms. Of note, the large tree showed differences for small storms showed significantly less throughfall when compared to both large and medium sized storms. The boxplot graph below in Figure 4.5 displays how throughfall is much lower for small storms where the trees storage is likely retaining much of the rainfall. Likewise, the small trees displayed less noticeable differences in throughfall for the small storms when compared to medium and large storms. You may infer from the distinctions that the storage for these smaller trees is measurably smaller.

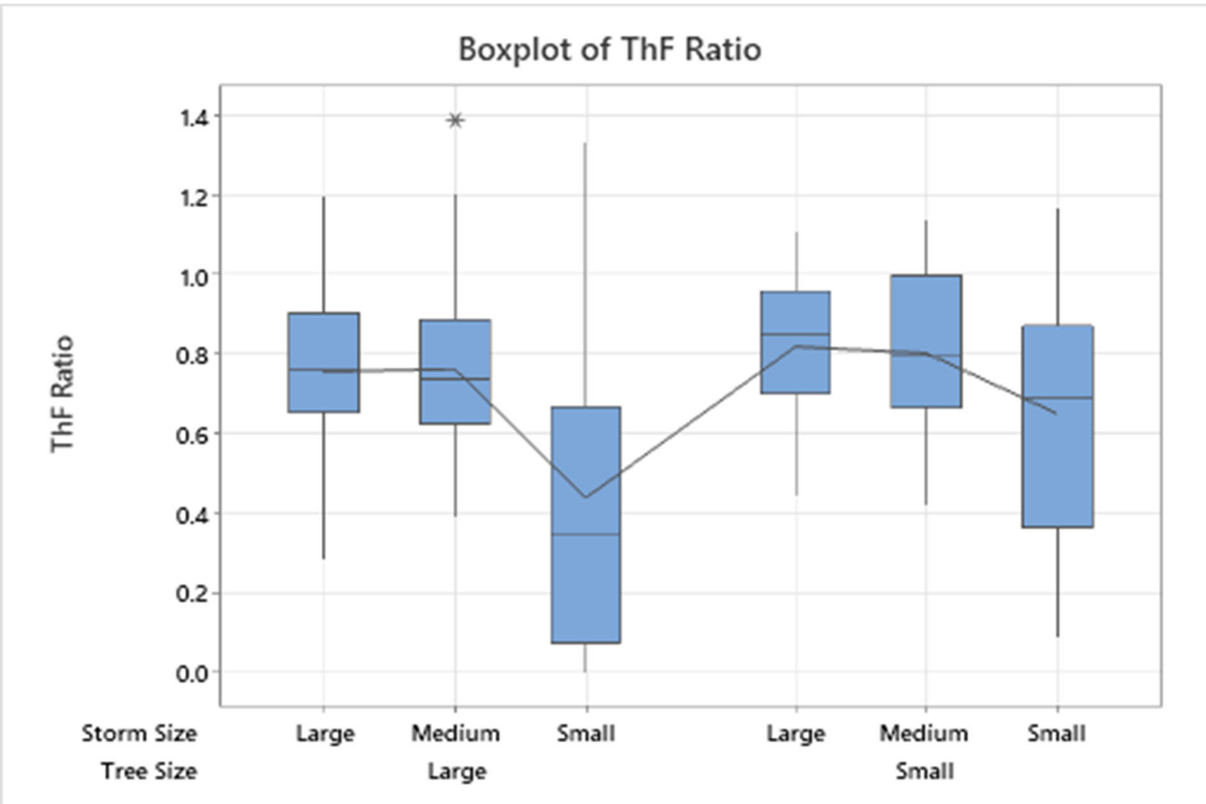

Figure 4.5 Boxplot comparing small willow oaks to large willow oaks by storm category

4.6 Conclusion

Overall, the data showed that the hypothesis is plausible, but clearly there are several considerations that may improve these results. First, the study was very short, only covering the latter portion of the leaf-on season and the beginning period for leaf senescence and abscission. This transition period may affect storage. Capturing only a portion of these growth and seasonal periods could impact differences in the data. Simply extending the observation period to cover full seasons would also increase the number of observations, normalizing the data further. It is also possible that smaller trees funnel more water towards their center as stemflow, impacting interception beneath the middle of the canopy. This would help explain the fractional differences between small and large trees of a common species. As the trees grow sprawling limbs, increased travel distances occur for stemflow which would modify the branch inclination and increasing the throughfall in larger older trees.

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CHAPTER 5

THROUGHFALL MEASURED BY TRANSECT VARIATION BENEATH A WILLOW OAK

5.1 Abstract

This portion of the dissertation research observed throughfall beneath different locations of a single mature willow oak (*Quercus phellos*) in Montgomery, Alabama. The experiment used four tipping bucket rain gauges to detect differences in throughfall beneath the canopy and measure the shading at the edge of canopy under different meteorological conditions. Throughfall observations (n= 152) were collected for thirty-eight rain events between August 28, 2021, and February 2, 2022, totaling 27.8 inches of rainfall. Paired T-tests determined highly significant differences in throughfall between the four positions under the canopy. A 2^2 factorial analysis compared rain depth and wind direction, noting significant rain depth differences. Lognormal linear regressions with excellent results showed strong differences in the observed throughfall beneath the canopy and edge of canopy. The results showed that the throughfall was marginally lower near the tree trunk with increased throughfall observed nearing the edge of canopy. As the rain depth increased, the interception continued to decrease at the edge of canopy due to the shade effect.

5.2 Introduction

The third hypothesis of this dissertation research is that measured the variation of canopy throughfall is distinct and varying at furthering distances from the base of the tree to the edge of the canopy, and beyond, due to typical branch architecture that forms as tree grows in the zenith and towards available sunlight. It is assumed that there may be increased stemflow closer to the center of the canopy. Aligning multiple calibrated tipping buckets at evenly spaced distances from the bole of the tree (main tree trunk) to the edge of the canopy can test this concept.

The interests in rainfall interception have changed with time, with initial interests in forest-scale processes, and now with increasing interests in tree-scale processes, including a desire to better understand street trees or sparse canopy coverage typical in urban areas (Armson et al., 2013). Tree and canopy architecture describe unique tree formations that can impact storage potential, which equates to distinct throughfall for each tree (Xaio et al., 2000a&b; Murakami and Toba, 2013). Hypothetically, like species grow similarly enough to have similar storage potential. Common species still have many unique growth characteristics that impact minimum and maximum storage. It's noted that branch inclination and leaf hydrophobicity minimize stored water on leaved and limb surfaces (Holder et al., 2020). This dissertation chapter introduces an approach to study throughfall considering these contributing factors.

The literature review noted that there are numerous methods used by researchers to collect direct observations of throughfall. Most methods collect throughfall randomly beneath the canopy, like the methods used in the study hypotheses in earlier chapters. Throughfall collection beneath the canopy is generally selected on location after a visual inspection of the tree canopy. For most experiments using tipping bucket, placement of the rain gauge is usually randomly beneath the canopy. Some more complex experiments use gutter channels, tarps or panels to collect from a large area or a slice of the canopy. Each method has benefits and challenges, but a single standard method is useful to further understanding in this field of study. Regardless, the method should be simplistic and easily reproduced to maximize useful data collection for common trees.

From the literature review, canopy throughfall variation is not well understood. From the onset of rainfall, the tree begins to distribute water based on the tree's canopy architecture and various climatological factors that may contribute to the storm event. Many researchers identified that weather conditions change the angle of incident rainfall, identifying the impacts contributing to throughfall-runoff relationships (Véliz-Chávez et al., 2014; Gonzalez-Sosa et al, 2017; Guevara-Escobar et al., 2007). These conditions may disproportionately distribute throughfall (e.g., higher throughfall close to center and lower levels near the edge of canopy). Defining the combined throughfall for a tree is important when data collection estimates rainfall interception at the tree scale. This is a known problem and can be easily solved by ingenuity. Researchers have developed complex experiments to collect all throughfall or a distributed section of the canopy, but the experimental methods to date are not able to measure the gradient in the transected portion of the canopy because they rely on a single device or a combination of sensing equipment to calculate the volumetric differences.

Understanding throughfall variation beneath the canopy can help standardize placement beneath the tree to measure an average throughfall for different species. If a known standard location can estimate the average for the canopy, simple collection methods can be applied for more trees advancing collection for different species. Another supporting interest considered if the differences were large enough to impact runoff. Is water shifted towards the trunk improving stemflow? Or does the water shed outward along the edge of canopy like an umbrella? Are the differences large or insignificant? If the throughfall can be defined for typical species considered in permanent landscape plans, placement can be specified to ensure coverage specified to increase storage capacity. Likewise, planter box dimensions could be maximized to protect the root growth and promote infiltration with a better understanding of throughfall beneath the tree canopy. The goal for this chapter is to collect baseline data relating to this knowledge gap. If the hypothesized conclusion is plausible, more work may be needed for direct observations at defined radial distances beneath the different trees to further understanding.

5.3 Materials and Methods

5.3.1 Site Description

The site for these measurements was in Montgomery, Alabama at the State Military Department. The site is in a mixed industrial and commercial zone of the city. All grounds on the 92-acre property are developed with multiple buildings and infrastructure, rigid, flexible, and pervious parking, green spaces and other landscape features. Buildings constructed between 1999 and 2010 had a common landscape plan providing an abundance of sample species. The site is located near a major U.S. Air Force base with an active weather station linked to open access weather databases. Ambient weather conditions were obtained for each rain event during the observation period to include in the data analyses.

The tree selected for this experiment is a mature, well developed willow oak (*Quercus phellos*) in the same general location as Study 2 to minimize travel time, supervision needs, and maintenance concerns during a much shorter observation period. Each of these factors can contribute to the accuracy of observations by inspecting all equipment before and after rain events. The tree is 50 feet from the northwestern corner of a two-story building on the site. The tree is estimated to be 35 feet tall, with a 47 inch diameter at breast height (DBH). The radius of the canopy is approximately 22 feet. The branch architecture is low hanging and the tree shows signs of pruning to remove lower branches and leaders on the bole. The species selected does not have a leafless period in this hardiness zone, even though it is the same variety as the trees from Study 2 that lost most leaves by late-December. Some leaf senescence and partial abscission was visible on February 15, 2022 approximately two weeks after the equipment was removed. But most of the canopy was still green through the full winter period.

5.3.2 Observation Period

Data collection began in August of 2021 for Study 3 and concluded in February of 2022, with 44 rain events observed. Study 3 was constrained by time and available equipment. Equipment for the experiment was unavailable until enough observations were collected for main Study 1, which collected multi-season and multi-year data in a related experiment. Earliest equipment availability for these tests was late summer 2021. A part of the experimental design procedure was to estimate the number of samples needed to test the hypothesis. Assuming an allowable error of 0.2 and using the equation (Cochran 1963) listed below:

Number of samples = 4 x (standard deviation)2/(allowable error)2

Allowable error = 20%

Standard deviation = 0.563 (derived from the log10 rainfall observation in Study 1)

Calculated number of samples needed = 32

This experiment ran concurrently with Study 2 in the same general area, targeting a much larger, mature tree of the same species as Study 2. A review of historic data provided by the National Weather Service (https://www.weather.gov/wrh/Climate?wfo=bmx) daily climate normal patterns between 1991 and 2020 indicated an average of 25.6 inches of expected rainfall during the study timeframe. Rainfall during this study period exceeded the expected average by 2.3 inches.

Table 5.1 Rainfall Event Summaries for Study 3

Rain Event Summary	interevent Time (days)	Rain Duration (hr)	Total Rain Depth (in)	Average Intensity (in/hr)
number	43	37	44	37
total:		289.1	27.9	
min	0.3	1.0	0.01	0.01
max	14.3	39.7	2.3	0.4
avg	3.2	7.8	0.5	0.1
median	1.1	6.3	0.4	0.1
stdev	3.9	7.7	0.6	0.1
COV	1.2	1.0	1.0	0.9

5.3.3 Rain Event Observations for Transect Variation

Multiple rain gauges needed to work in unison for this experiment. Three gauges were placed beneath the canopy on standard sawhorses. A fourth device is placed on the same sawhorse beyond the edge of the canopy (Figure 5.1) ensuring all devices are on the same horizontal plane. The devices are positioned facing North of the tree to standardize edge effects from high winds. Wind direction will be analyzed for correlation to each event. The units were not moved between storms. This ensures numerous throughfall samples were collected for the response variables and the controlled grass unit. The experimental tree specimen was a single mature willow oak. The experimental units are 50 feet west of the building edge. No significant shading from the building is expected due to the height of the tree and distance from the building. The grass control rain gauge was located 100 feet west of the tree in an open area. All throughfall response data and the independent data (precipitation) was logged in time series and was post-processed and aligned with daily climate factors (i.e., windspeed, direction, etc.) for later use in statistical analyses.

Figure 5.1 Study 2 Experimental Site for Measuring Throughfall Variation

5.3.4 Experiment Equipment

The equipment used for this study were the same HOBO Data Logging Rain Gauges RG3 from Study 1. Four gauges were dedicated for Study 3. The fifth gauge ("grass") served both Study 3 and Study 2 (a separate but related experiment). Since each of these gauges were used previously in Study 1, they were cleaned and calibrated to ensure proper working order before being used during this study. The internal data loggers were set to the same logging parameters as the previous study; to collect temperature at 5-minute intervals and measure 0.01 inches per tip of precipitation.

5.4 Data Analysis

Of the 44 observed rain events, 38 rain events recorded measurable throughfall for consideration beneath the canopy. The raw data for the experiments include one independent variable (rainfall depth, inches) and four dependent variables capturing throughfall at known distances (6 ft. apart) between the bole of the tree and the outer edge of the canopy. The last gauge was positioned approximately one foot beyond the edge of canopy. Hereafter, each observation is known as Transect 1, 2, 3, & 4, with Transect 1 being closest to the tree trunk and Transect 4 as the outermost gauge beyond the canopy edge. All data was post-processed to align throughfall with the corresponding rain event. The data was plotted using statistical software (Minitab® and Microsoft Excel®) to view the distribution density for normality. As with the data points in Study 1 and Study 2, the data was transformed in three ways: LOG10, a throughfall ratio (throughfall/rain depth), and rainfall interception storage (rain depth – throughfall). Each transformation was needed to perform the various parametric hypothesis tests and graphical analyses needed to support the hypothesis.

The statistical approach was used to identify any significant differences in the four observation locations beneath the tree's canopy. A boxplot graph of the throughfall data showed a marginal increase in throughfall as you move closer to the edge of canopy. Paired T-tests were used to measure each combination for the four observations with a null hypothesis of a difference for each comparison at the 95% confidence level.

A full factorial (22, rainfall depth, wind direction) design to study the potential for shade effects and their joint interactions for this experiment was also performed. The rainfall classification for the comparison used a one-inch break point between small and large rains. To study the wind interactions daily directions in degrees were collected for each event day. Categorization for wind direction was a two-part process in this case. First the wind was divided into four categories for general wind direction for North, South, East and West using the degrees as listed below in Table 5.2. Next these generalized cardinal directions were considered as either flowing parallel to, or perpendicular to, the transect line for the gauges with a goal to reveal significant contrasts between the two categories.

Table 5.2 Wind Direction Categories for Factorial Analysis

Wind Direction	Degrees	Parallel (+) Cross wind (-)
East	46-135	EW "-"
West	226-315	EW "-"
North	316-45	NS "+"
South	136-225	NS "+"

Last, a lognormal linear regression was used to define each observation since the distributions for the observations were not gaussian when displayed using an individual plot diagram. The equations were then used to create an expected throughfall ratio for typical storms to display the expected performance for the mature willow oak.

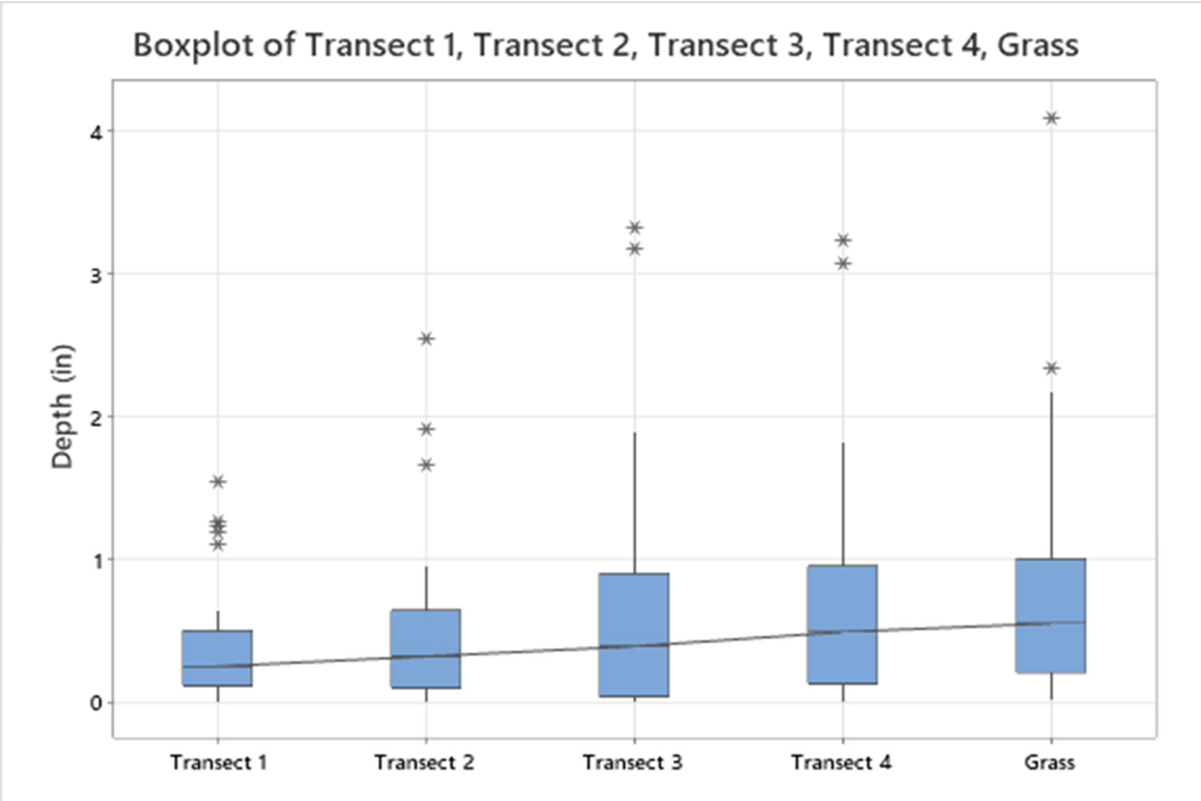

Figure 5.2 Boxplot of Throughfall Ratio for each observation at Study 3

5.5 Results

Data transformations normalized distributions and helped construct visible patterns between each gauge location. In this case, throughfall observations increased slightly from the inside at Transect 1 (nearest the trunk) to the outer edge of the canopy at Transect 4. Table 5.3 provides paired T-tests for the six combinations indicated significant differences except for the comparison for Transect 2 versus Transect 3 (P= 0.059). Overall, there is enough confidence for these observations to reject the null hypothesis. The experiment collected enough information to produce significant lognormal regressions of throughfall vs. rainfall for each transect location in the study. A fifth equation is included for the combined observations from the four interrelated samples. All five model summaries yielded satisfactory correlations (Table 5.4).

Table 5.3 Paired T-Test for all observations (Log 10)

Comparison	N	P-Value	SE Mean	95% Upper Boundary
Transect 1 vs. Transect 2	32	<0.001	0.034	-0.073
Transect 1 vs. Transect 3	30	<0.001	0.050	-0.104
Transect 1 vs. Transect 4	34	<0.001	0.043	-0.211
Transect 3 vs. Transect 4	32	0.016	0.049	-0.026
Transect 2 vs. Transect 4	31	<0.001	0.029	-0.158
Transect 2 vs. Transect 3	29	0.059	0.037	0.003

Table 5.4 Lognormal Regression Coefficients for Throughfall by Dependent Variable

Transect Observation	Intercept Term	P-Value	Slope	P-Value for Slope	R^2	Regression P-Value
Transect 1	-0.34	<0.001	1.03	<0.001	0.84	<0.001
Transect 2	-0.22	<0.001	1.10	<0.001	0.91	<0.001
Transect 3	-0.16	0.013	1.03	<0.001	0.81	<0.001
Transect 4	-0.09	0.01	0.94	<0.001	0.92	<0.001
Mature Willow Oak	-0.1912	<0.001	1.04	<0.001	0.84	<0.001

A 2^2 factorial analysis examined rain depth and wind direction to identify the shading effect beneath the canopy. Each of the factors were determined to be only marginally significant. The contrasts for Transect 4 were distinct from the other three observations, with the most significant factor being rain depth differences with no significance given for wind direction or their interaction. Interaction plots provided one noteworthy observation relevant to the hypothesis. The three gauges (transect 1-3) beneath canopy displayed the highest potential for interactions or rain depth and wind direction.

Table 5.5 Table of Contrast for Factorial Analysis

Position	Rain Depth	Wind Direction	Rain Depth X Wind Direction
Transect 1	0.11	0.14	0.31
Transect 2	-0.29	0.22	0.16
Transect 3	0.09	0.16	0.10
Transect 4	0.55	-0.02	0.00

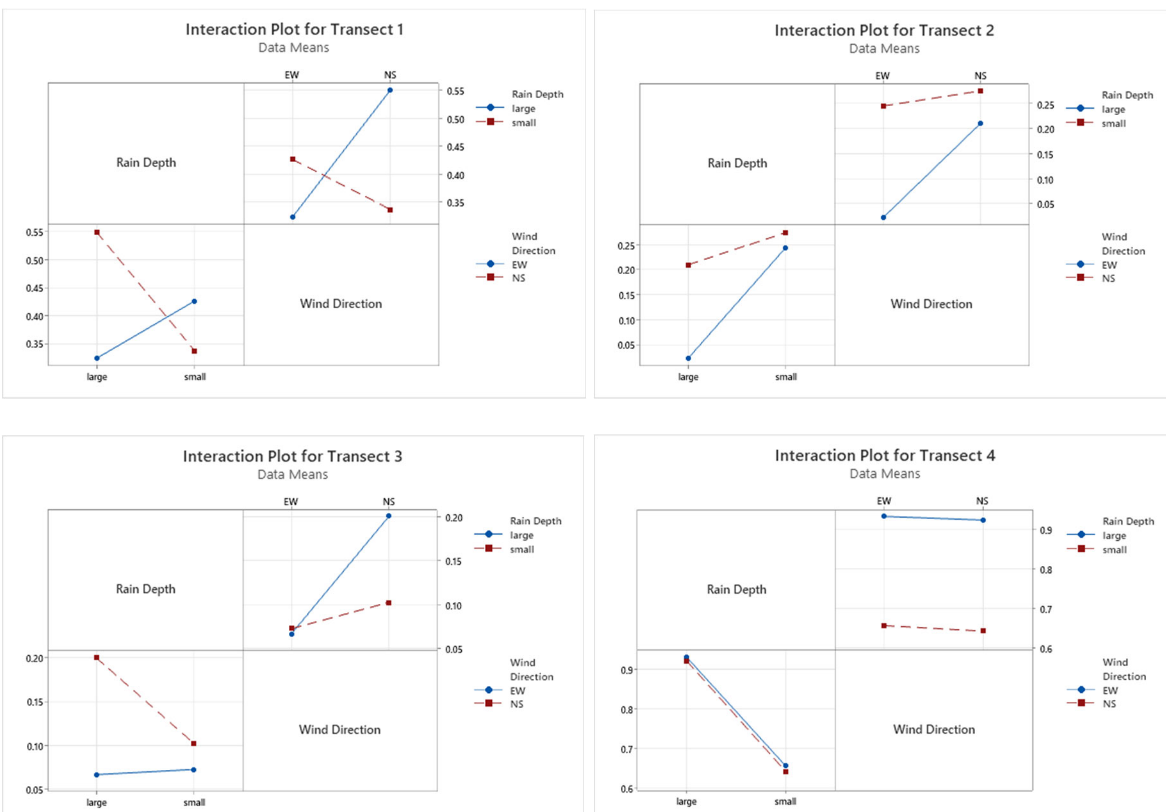

Figure 5.3 Interaction Plots for Study 3

Data were resorted into three categories: Small, 0.01 to less than 0.25 inches; Medium, 0.25 to less 0.75 inches; and Large, greater than 0.75 inches because rain depths were a significant factor. The box plots shown in Figure 5.5 compare the throughfall ratio for transect observations beneath the tree clearly show the distinctions between each rain category.

Figure 5.4 Photos of Canopy for Mature Willow Oak for Transect 1 through 4 (from left to right)

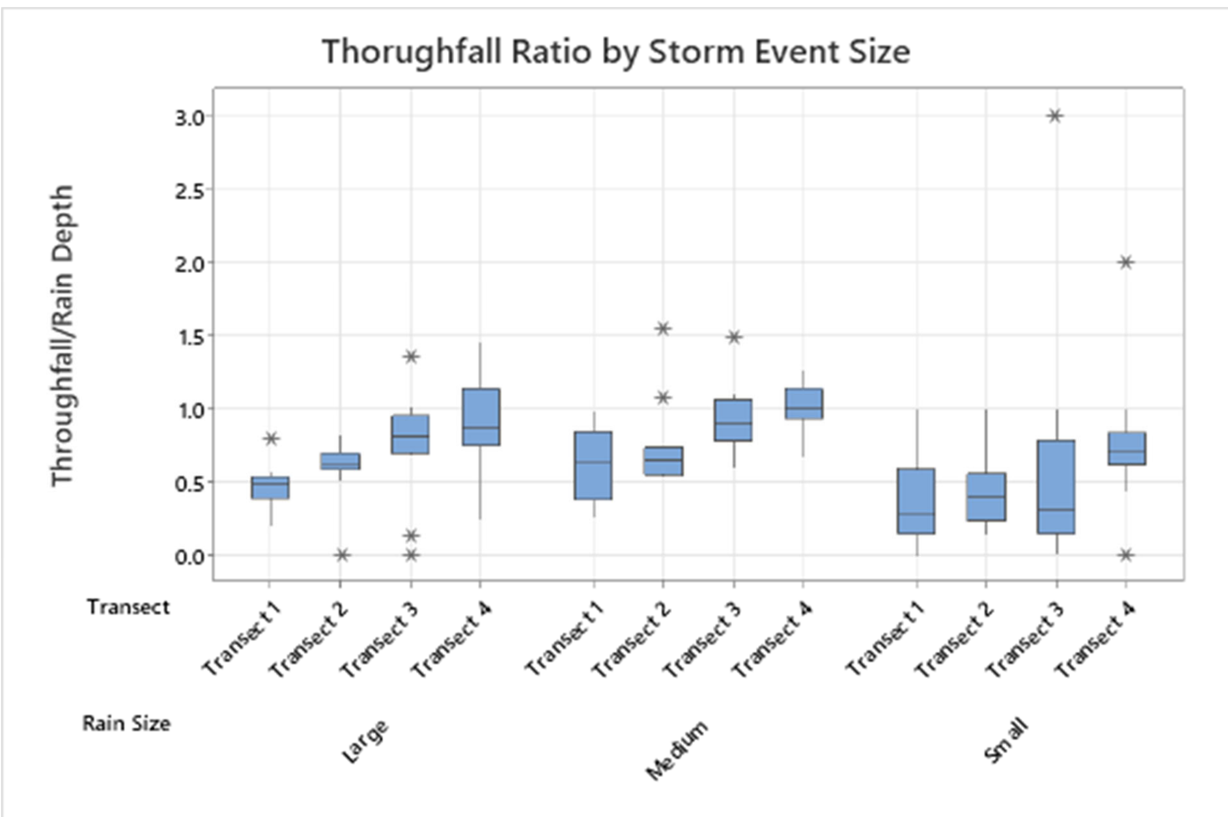

Figure 5.5 Boxplot for Categorical Rain Sizes (<0.25,0.25-0.75, & >0.75 inches)

The regression equations were developed to predict throughfall responses for each of the locations. The results listed below in Figure 5.6 are for Transect 1 through 3 which are beneath the canopy and Transect 4 located at the edge of canopy for rain depths ranging from 0.01 to 4 inches. The largest rain observed was 2.3 inches, so the 4-inch plotted location is a slight extrapolation. As expected, the results under the canopy are all similar. The edge effect for Transect 4 shows that with small rains the ratio is near one, but as the depth gets larger the ratio decreases rapidly, defining the shade effect near the edge of the canopy.

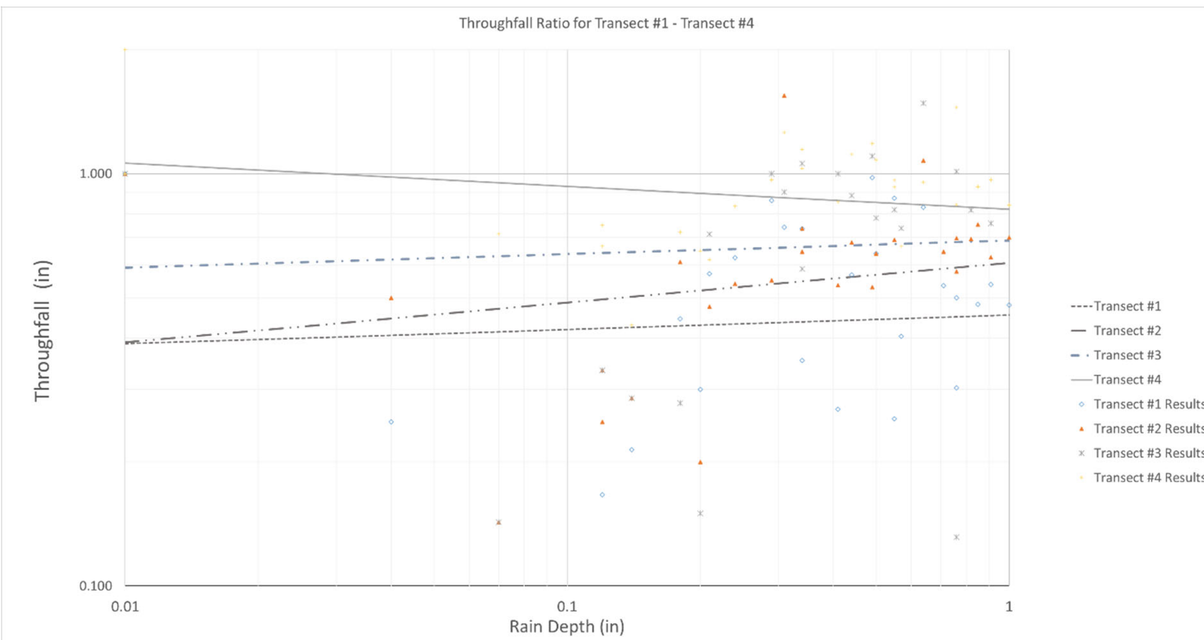

Figure 5.6 Projected Throughfall Ratio by Transect Variation Beneath Canopy

5.6 Conclusion

The literature for rainfall interception is focused mostly on forest-scale research topics, with a growing interest in urban tree studies. There are still major gaps in knowledge for how common landscape trees perform and how they are implemented in site planning. The results for this experiment showed significant differences in transect variations for throughfall beneath a mature willow oak canopy. Also, the edge effects of throughfall for this tree was detected slightly beyond the canopy. Edge effects may be a consideration during planning. It is likely that these results could be applicable for other deciduous oaks and like species with size and structure, but the results are likely to vary for other tree species that have significantly different structural characteristics. Additional research is needed to expand these findings to other distinct and common species worthy of consideration.

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CHAPTER 6

CONCLUSIONS AND FUTURE WORK

The literature review for this dissertation concluded that most rainfall interception research is focused on forest canopies, with fewer studies on urban trees that are typically less densely spaced. Recent interest in stormwater green infrastructure has increased the interest in urban tree rainfall interception. This knowledge gap is the framework of this dissertation research. A series of experiments were designed to collect throughfall information for common tree species in the southeastern United States. This dissertation recommends that more measurements of throughfall be performed for each geographical area of interest, considering the local rain conditions and common urban tree species. This knowledge for common landscape tree species will further knowledge development needed for design standards in stormwater green infrastructure planning. The following summarize the findings for each experimental chapter and how each effort contributes data and knowledge toward the research objectives and hypotheses.

In the southeastern United States, very little research has been conducted addressing urban tree rainfall interception. Because the southeast is densely covered in mixed (evergreen and deciduous) forests, a hypothesis was developed to test the differences in throughfall for both tree types for all seasons in less dense urban settings considering the leafless and full foliage for deciduous trees.

The first hypothesis is that there are fundamental differences in interception characteristics between coniferous and deciduous trees for different seasons in the southeastern region. Because of substantial rainfall in the leafless period, the deciduous trees will have a significant increase in throughfall (rain passing through the canopy to the ground), furthering the comparative advantage of coniferous canopies for rainfall interception in urban settings. Direct throughfall measurements for both deciduous and coniferous species across all seasons were collected to test this hypothesis.

The experiments for the first hypothesis included four parallel experimental sites collecting paired in three of the five unique topographic regions of Alabama. Through statistical tests to compare differences in the trees at each site (i.e., oak north vs. oak south) we can conclude that the data for each site could combined to compare deciduous vs. evergreen trees (categorically) for all four study sites for hypothesis #1. From the experimental results, one can infer the evergreen trees have measurably smaller throughfall amounts (greater interception) annually and therefore outperform deciduous trees in rainfall interception for the southeast. From the literature review, we can hypothesize that the heavy bark characteristics create a large porous (low density) surface to store water during each season. Further work studying water uptake by evergreen trees should be considered in future work. For hypothesis #1 we can comfortably reject the null hypothesis. The experimental results of this dissertation fulfill only a small fraction of the knowledge needed to fully understand typical landscape trees for stormwater green infrastructure planning for all areas and typical trees. Additional work is therefore needed for other common street trees using direct observation methods and procedures, such as described in this dissertation research.

During civil site development, a landscape plan is commonly included to supplement construction site stormwater control measures needed to stabilize the area after construction. Landscape plans commonly include small trees that can take decades to mature. In that time, each tree's canopy storage increases as the tree grows. Currently, there are no standard tables to estimate the future storage for these trees. This knowledge gap is a tenet for the second hypothesis in this dissertation research.

The second hypothesis is that direct observations can be made of different sized trees of the same variety (genus and species), and the resulting data will detect measurably distinct rainfall interception. The data will show that as the trees grow, their storage capacity (minimum retention) increases and increases predictably as they grow.

Graphically defining tree storage for common trees would support designers developing landscape plans for green infrastructure projects and measurably define the benefits over time for intercepting rain and reducing stormwater discharges. The second experiment ("Study 2") endeavored to predict the differences in storage capacity for different sized deciduous street trees (willow oak, *Quercus phellos*). The data showed that the hypothesis is plausible, but the experiment should be expanded to cover all seasons measuring the entire foliage period and leafless conditions.

In the design of experiment, it was estimated that for a 95% confidence level, 32 samples were needed to have the precision to detect a 20% or higher difference in throughfall. For this study, the large 36-inch oak only collected 20 useful throughfall responses and smaller 20-inch only collected 31 useful samples impacting the results for the Paired t-tests. This limited the power for the results. For the comparison between the 13-inch and 20-inch trees there was no significant difference even though the sample size was 33. But the comparison between the 13-inch and the 27-inch tree with a sample size of 32 yielded a statistically significant finding of lesser throughfall for the 27-inch tree. It is possible that the storage between the two smaller trees are very close in magnitude. Like the first hypothesis, the data were combined to create two categorical sets, smaller trees and larger trees. And again, the differences were tested using the same methods. This time the results were satisfactory, showing significantly lower throughfall for the larger willow oaks than for the smaller trees in the sample set. These results suggest we could again reject the null hypothesis with the recommendation that future work collect more samples to avoid the challenges in this experiment. But, for these reasons hypothesis #2 is only very plausible, and I cannot reject the null hypothesis without further observations.

The third hypothesis of this dissertation research is that measured canopy throughfall is distinct and varying at furthering distances from the base of the tree to the edge of the canopy, and beyond, due to typical branch architecture that forms as tree grows in the zenith and towards available sunlight. It is assumed that there may be increased stemflow closer to the center of the canopy. Aligning multiple calibrated tipping buckets at evenly spaced distances from the bole of the tree (main tree trunk) to the edge of the canopy was used to test this concept.

The last experiment for this dissertation research considered the differences in throughfall beneath the canopy to better understand rainfall interception observation. An experiment was designed to measure paired observations at different distances under a single canopy to test this hypothesis.

The study collected 38 samples during the study period which is more than the 32 samples estimated during the design of experiment process. Paired T-tests were used for multiple comparisons for each throughfall observations beneath the canopy with favorable results. These results show that throughfall increases as you move farther away from the base of the tree. A fourth rain gauge was placed just beyond the edge of the canopy to measure the "shadow effect." The throughfall at the edge of canopy closely resembles the rain depth over the grass for small rains. And as storms get larger, measurable interception at the edge of the canopy occurs because of the shadow effect. The significant differences found in this study support rejecting the null hypothesis in support of hypothesis #3.

Overall, the experiments and results of this dissertation further the understanding of rainfall interception and throughfall amounts for common deciduous and evergreen trees for the southeastern United States. Future work should consider the challenges and accomplishments for each study conducted during this research. A thorough review of common landscape trees (native and exotic species) is recommended to serve as a baseline to expand data collection. Further work should also define storage for the various trees considered to make it easier to properly consider trees in green infrastructure projects.

APPENDIX A

Rain Event & Throughfall Summaries for South # 1

Event #	Season	Beginning time	Duration (hrs)	Interevent time (days)	Rain depth (inches)	Avg Intensity (in/hr)	Oak ThF (in)	Pine ThF (in)
1	Winter	3/7/16 1:07 PM	0.09	2.0	0.41	4.66	0.46	0.41
2	Winter	3/12/16 8:17 PM	4.99	5.3	0.26	5.21	0.26	0.14
3	Winter	3/17/16 7:24 PM	2.07	4.8	0.16	0.08	0.09	0.06
4	Winter	3/18/16 5:34 AM	17.62	0.3	0.55	0.03	0.50	0.3
5	Spring	3/24/16 12:28 PM	3.95	5.6	0.37	0.09	0.30	0.01
6	Spring	3/26/16 7:42 AM	0.54	1.6	0.02		0.00	0.01
7	Spring	3/27/16 3:41 AM	0.22	0.8	0.04	0.18	0.03	0.01
8	Spring	3/31/16 8:04 AM	36.09	4.2	4.40	0.12	4.96	
9	Spring	4/6/16 9:12 PM	0.54	5.0	0.47	0.87	0.43	
10	Spring	4/13/16 4:09 PM	14.59	6.8	1.46	0.10	1.55	
11	Spring	4/15/16 4:19 PM	1.23	1.4	0.29	0.24	0.21	
12	Spring	4/16/16 3:12 AM	2.36	0.4	0.40	0.17	0.43	
13	Spring	4/22/16 4:09 AM	4.67	5.9	0.50	0.11	0.33	
14	Spring	4/27/16 5:19 PM	0.74	5.4	0.14	0.19	0.08	
15	Spring	4/28/16 6:41 AM	11.38	0.5	0.03		0.00	0.01
16	Spring	5/2/16 5:30 PM	2.66	4.0	1.05	0.39	1.11	0.41
17	Spring	5/3/16 8:30 AM	0.31	0.5	0.03	0.10	0.00	0.01

Event #	Season	Beginning time	Duration (hrs)	Interevent time (days)	Rain depth (inches)	Avg Intensity (in/hr)	Oak ThF (in)	Pine ThF (in)
18	Spring	3/13/17 7:53 PM	4.89	2.0	0.20	0.04	0.24	0.25
19	Spring	3/25/17 6:26 PM	10.97	11.7	0.77	0.07	0.94	0.99
20	Spring	3/30/17 5:33 PM	2.11	4.5	0.20	0.09	0.26	0.35
21	Spring	4/3/17 7:56 AM	4.79	3.5	0.94	0.20	1.02	1.19
22	Spring	4/5/17 4:32 AM	0.30	1.7	0.37	1.23	0.40	0.5
23	Spring	4/5/17 8:04 PM	0.03	0.6	0.02	0.61	0.05	0
24	Spring	4/23/17 7:37 AM	3.31	17.5	0.04	0.01	0.04	0.17
25	Spring	4/27/17 8:14 AM	0.28	3.9	0.07	0.25	0.09	0.07
26	Spring	4/30/17 4:52 PM	12.39	3.3	1.87	0.15	1.36	1.87
27	Spring	5/4/17 2:30 AM	3.69	2.9	0.08	0.02	0.16	0.02
28	Spring	5/4/17 4:00 PM	3.05	0.4	0.21	0.07	0.21	0.11
29	Spring	5/13/17 3:29 AM	1.28	8.4	0.02	0.02	0.02	0.03
30	Spring	5/20/17 2:58 PM	15.29	7.4	4.30	0.28	3.51	
31	Spring	5/31/17 6:39 AM	2.09	10.0	0.10	0.05	0.10	0.17
32	Spring	6/1/17 6:08 PM	1.14	1.4	0.07	0.06	0.06	0.14
33	Spring	6/4/17 6:22 PM	6.56	3.0	4.03	0.59	3.66	
34	Spring	6/7/17 3:54 PM	0.35	2.6	0.07	0.20	0.03	0.01
35	Spring	6/13/17 2:46 PM	0.08	5.9	0.04	0.49	0.01	0.00
36	Spring	6/15/17 5:15 PM	8.24	2.1	0.41	0.05	0.26	0.30
37	Spring	6/18/17 5:14 AM	4.72	2.2	2.08	0.44	1.99	
38	Summer	6/20/17 8:54 AM	3.86	2.0	0.33	0.09	0.35	
39	Summer	6/21/17 4:03 AM	65.37	0.6	3.85	0.06	3.46	

Event #	Season	Beginning time	Duration (hrs)	Interevent time (days)	Rain depth (inches)	Avg Intensity (in/hr)	Oak ThF (in)	Pine ThF (in)
40	Summer	6/24/17 8:40 AM	0.56	0.5	0.08	0.14	0.23	0.01
41	Summer	6/29/17 2:43 PM	19.93	5.2	0.98	0.05	1.03	1.32
42	Summer	7/2/17 12:11 AM	19.74	1.6	0.11	0.01	0.13	0.17
43	Summer	7/3/17 8:09 AM	n/a	0.5	0.01		0.00	0.03
44	Summer	7/8/17 3:22 PM	0.17	5.3	0.15	0.88	0.11	0.18
45	Summer	7/16/17 4:11 AM	2.87	7.5	0.45	0.16	0.47	0.5
46	Summer	7/21/17 2:41 PM	0.16	5.3	0.14	0.86	0.14	
47	Summer	7/24/17 8:34 PM	1.75	3.2	0.19	0.11	0.21	0.27
48	Summer	7/25/17 8:16 AM	n/a	0.4	0.02		0.01	0.05
49	Summer	8/7/17 12:09 PM	0.05	13.2	0.05	0.96	0.14	0.2
50	Summer	8/8/17 12:49 PM	6.09	1.0	0.30	0.05	0.32	0.47
51	Summer	8/9/17 1:28 PM	24.00	0.8	0.01		0.00	0.01
52	Summer	8/10/17 4:43 PM	7.17	0.1	1.14	0.16	1.69	1.5
53	Summer	8/14/17 2:05 PM	0.03	3.6	0.02	0.75	0.03	0.06
54	Summer	8/15/17 5:52 PM	2.17	1.2	1.31	0.60	1.16	1.27

Rain Event & Throughfall Summaries for the Central Site

Event #	Season	Beginning time	Duration (hrs)	Interevent time (days)	Rain depth (inches)	Avg Int (in/hr)	Oak ThF (in)	Pine ThF (in)
1	Spring	6/2/2016 14:25	0.42	1.0	0.10	0.24	0.03	0.03
2	Spring	6/4/2016 13:03	0.07	1.9	0.07	0.97	0.01	0.01
3	Spring	6/4/2016 22:15	0.90	0.4	0.06	0.07	0.04	0.07
4	Spring	6/5/2016 7:11	6.58	0.6	0.17	0.03	0.14	0.19
5	Spring	6/5/2016 20:03	2.61	0.4	1.23	0.47	1.31	1.63
6	Spring	6/6/2016 5:09	n/a	0.3	0.01	n/a	0.00	0.02
7	Spring	6/6/2016 16:03	0.09	0.5	0.05	0.53		
8	Spring	6/14/2016 19:12	0.30	8.1	0.47	1.54	0.25	0.32
9	Spring	6/15/2016 20:17	3.26	1.2	0.49	0.15	0.43	0.46
10	Spring	6/17/2016 13:40	0.32	1.6	0.22	0.69	0.24	0.23
11	Summer	6/25/2016 21:39	0.79	8.4	0.02	0.03		0.02
12	Summer	6/26/2016 10:06	1.82	0.6	0.20	0.11	0.09	0.07
13	Summer	6/27/2016 17:19	2.44	1.3	0.10	0.04	0.03	0.10
14	Summer	7/5/2016 8:56	3.79	7.7	0.37	0.10	0.28	0.48
15	Summer	7/6/2016 9:27	1.61	0.9	0.69	0.43	0.60	0.65
16	Summer	7/9/2016 12:02	1.22	3.1	0.19	0.16	0.10	0.16
17	Summer	7/10/2016 21:16	3.50	1.5	0.22	0.06	0.20	0.30
18	Summer	7/11/2016 20:55	0.06	0.8	0.06	1.06		0.01
19	Summer	7/17/2016 14:08	1.31	5.8	0.71	0.54	0.66	0.33
20	Summer	7/21/2016 21:54	1.94	4.3	0.65	0.34	0.71	0.89

Event #	Season	Beginning time	Duration (hrs)	Interevent time (days)	Rain depth (inches)	Avg Int (in/hr)	Oak ThF (in)	Pine ThF (in)
21	Summer	7/25/2016 14:04	10.91	4.1	0.10	0.01	0.06	0.06
22	Summer	7/28/2016 15:07	48.28	4.6	0.08	0.00	0.01	0.02
23	Summer	8/2/2016 11:50	0.32	1.9	0.15	0.47	0.05	0.07
24	Summer	8/4/2016 19:03	0.67	2.3	0.43	0.64	0.24	0.26
25	Summer	8/7/2016 18:58	2.46	3.1	0.09	0.04	0.06	0.11
26	Summer	8/10/2016 17:10	4.13	1.7	0.10	0.02	0.05	0.02
27	Summer	8/15/2016 16:38	0.49	4.8	0.25	0.51	0.23	0.24
28	Summer	8/16/2016 17:56	8.81	1.4	1.38	0.16	0.79	0.88
29	Summer	8/18/2016 15:06	n/a	1.5	0.01		0.00	0.01
30	Summer	8/19/2016 13:39	4.62	1.1	0.24	0.05	0.15	0.24
31	Summer	8/20/2016 0:08	19.79	1.1	0.10	0.01	0.06	0.07
32	Summer	8/21/2016 12:24	0.05	0.7	0.08	1.69	0.03	0.06
33	Summer	8/31/2016 21:56	0.23	10.4	0.15	0.66	0.11	0.10
34	Summer	9/1/2016 6:42	n/a	0.4	0.01		0.00	0.00
35	Summer	9/18/2016 11:46	2.52	17.3	0.12	0.05	0.06	0.05
36	Fall	9/26/2016 15:24	1.44	8.1	0.15	0.10	0.04	0.04
37	Fall	11/28/2016 21:54	9.54	63.6	1.31	0.14	1.27	0.65
38	Fall	11/30/2016 11:19	107.28	5.6	1.70	0.02	1.64	0.43
39	Fall	12/5/2016 12:34	7.80	0.9	0.59	0.08	0.11	
40	Fall	12/6/2016 2:49	7.72	0.6	0.33	0.04	0.04	
41	Fall	12/12/2016 9:14	1.26	6.0	0.08	0.06	0.06	0.09
42	Fall	12/13/2016 7:56	10.37	1.3	0.08	0.01	0.06	0.02

Event #	Season	Beginning time	Duration (hrs)	Interevent time (days)	Rain depth (inches)	Avg Int (in/hr)	Oak ThF (in)	Pine ThF (in)
43	Fall	12/18/2016 6:49	9.33	1.2	0.31	0.03	0.35	0.06
44	Winter	12/29/2016 1:34	2.76	10.5	0.16	0.06	0.10	0.12
45	Winter	12/31/2016 12:09	0.82	2.4	0.04	0.05	0.03	0.02
46	Winter	12/31/2016 20:33	11.94	0.8	0.49	0.04	0.48	
47	Winter	1/1/2017 16:19	10.40	0.8	0.54	0.05	0.57	
48	Winter	1/2/2017 12:47	8.96	0.8	1.52	0.17	1.61	
49	Winter	1/6/2017 13:07	24.39	4.7	0.09	0.00		0.10
50	Winter	1/19/2017 18:53	39.90	3.1	1.50	0.04		0.55
51	Winter	1/22/2017 1:13	1.04	0.6	0.16	0.15		0.15
52	Winter	1/22/2017 13:40	10.58	0.9	3.39	0.32		3.08
53	Winter	1/25/2017 20:56	2.01	2.9	0.21	0.10		0.24
54	Winter	2/2/2017 14:08	6.18	7.9	0.05	0.01		0.02
55	Winter	2/5/2017 3:04	1.96	2.4	0.09	0.05		0.07
56	Winter	2/6/2017 8:08	3.76	1.3	0.03	0.01		0.02
57	Winter	2/7/2017 11:33	6.01	1.2	0.36	0.06		0.33
58	Winter	2/8/2017 20:45	1.01	1.2	0.15	0.15		0.12
59	Winter	2/12/2017 17:26	0.13	3.8	0.20	1.52		0.16
60	Winter	2/15/2017 1:27	3.90	2.5	0.55	0.14		0.56
61	Winter	2/18/2017 6:16	4.05	3.2	0.24	0.06		0.21
62	Winter	2/21/2017 10:29	19.33	3.8	0.73	0.04		0.65
63	Winter	2/27/2017 9:25	2.18	5.2	0.35	0.16		0.35
64	Winter	3/1/2017 16:40	0.69	2.2	0.15	0.22		0.13

Event #	Season	Beginning time	Duration (hrs)	Interevent time (days)	Rain depth (inches)	Avg Int (in/hr)	Oak ThF (in)	Pine ThF (in)
65	Winter	3/7/2017 9:50	13.30	6.2	1.13	0.08		1.08
66	Winter	3/9/2017 23:56	3.71	2.2	0.75	0.20		0.88
67	Winter	3/11/2017 23:32	0.40	1.4	0.03	0.07		
68	Winter	3/12/2017 0:05	2.96	0.1	0.15	0.05		0.12
69	Spring	3/21/2017 18:23	0.48	3.5	0.29	0.60		0.28
70	Spring	3/25/2017 20:06	4.73	4.0	0.40	0.08		0.42
71	Spring	3/27/2017 18:27	7.27	2.0	1.11	0.15		1.08
72	Spring	3/30/2017 17:43	5.35	2.9	0.59	0.11		0.49
73	Spring	4/3/2017 5:09	6.31	3.5	1.40	0.22		1.50
74	Spring	4/5/2017 5:24	12.99	2.3	1.19	0.09		1.08
75	Spring	4/17/2017 19:56	n/a	12.1	0.01			0.01
76	Spring	4/18/2017 18:03	2.65	0.5	0.14	0.05	0.13	0.12
77	Spring	4/19/2017 15:35	1.84	0.9	0.42	0.23	0.32	0.27
78	Spring	4/20/2017 16:17	1.33	1.0	0.02	0.02	0.01	0.02
79	Spring	4/22/2017 19:30	16.54	2.8	1.14	0.07	1.24	1.27
80	Spring	4/27/2017 3:16	4.51	2.9	0.09	0.02	0.07	0.05
81	Spring	4/30/2017 16:41	17.44	3.4	0.78	0.04	0.77	0.68
82	Spring	5/4/2017 12:58	6.42	3.39	1.14	0.18	1.13	0.95

Rain Event & Throughfall Summaries for the North Site

Event #	Season	Beginning time	Duration (hrs)	Interevent time (days)	Rain depth (inches)	Avg Int (in/hr)	Oak ThF (in)	Pine ThF (in)
1	Spring	3/7/2016 13:00	0.04	4.0	0.38	9.77	0.38	
2	Spring	3/14/2016 8:22	3.88	0.9	0.46	0.12	0.25	
3	Spring	3/24/2016 11:24	10.03	14.1	0.99	0.10	0.74	
4	Spring	3/27/2016 12:44	1.78	2.7	0.13	0.07	0.11	
5	Spring	3/31/2016 7:27	18.21	4.5	1.14	0.06	0.78	
6	Spring	4/6/2016 18:26	2.76	5.8	0.45	0.16	0.27	
7	Spring	4/11/2016 12:27	12.22	5.1	0.51	0.04	0.33	
8	Summer	8/6/2016 11:24	0.00	0.9	0.01			0.01
9	Summer	8/18/2016 14:54	2.35	1.6	0.13	0.06		0.03
10	Summer	8/19/2016 12:57	13.53	1.4	0.20	0.01		0.03
11	Summer	8/20/2016 15:19	5.56	0.8	0.18	0.03		0.04
12	Summer	8/21/2016 5:08	5.00	0.6	0.14	0.03		0.05
13	Summer	8/26/2016 16:24	4.48	5.4	0.07	0.02	0.01	0.01
14	Summer	8/28/2016 16:03	0.70	1.8	0.18	0.26	0.02	0.06
15	Summer	8/31/2016 15:06	0.91	3.0	0.37	0.41	0.06	0.21
16	Summer	9/10/2016 21:30	2.83	10.3	0.37	0.13	0.08	0.21
17	Summer	9/18/2016 12:12	1.33	7.5	0.29	0.22	0.12	0.05
18	Fall	9/26/2016 12:26	1.36	8.0	0.34	0.25	0.21	0.02
19	Fall	10/20/2016 17:36	6.56	24.4	0.40	0.06	0.21	0.25
20	Fall	11/19/2016 4:23	1.32	29.2	0.11	0.08	0.03	0.00

Event #	Season	Beginning time	Duration (hrs)	Interevent time (days)	Rain depth (inches)	Avg Int (in/hr)	Oak ThF (in)	Pine ThF (in)
23	Fall	11/28/2016 20:47	40.42	6.6	4.31	0.11	2.48	2.44
23	Fall	12/3/2016 16:39	30.22	4.4	0.84	0.03	0.76	0.53
24	Fall	12/5/2016 12:15	21.17	1.4	1.00	0.05	1.07	0.69
25	Fall	12/12/2016 3:54	27.74	6.6	0.27	0.01	0.12	0.14
26	Fall	12/13/2016 16:22	0.00	0.4	0.01		0.01	0.01
27	Fall	12/17/2016 4:49	10.90	4.0	0.03	0.00	0.01	0.02
28	Fall	12/18/2016 1:42	10.73	0.9	1.27	0.12	1.03	1.23
29	Winter	12/27/2016 7:54	4.07	9.0	0.42	0.10	0.36	0.35
30	Winter	12/28/2016 23:45	2.60	1.6	0.81	0.31	0.66	0.75
31	Winter	12/31/2016 19:33	11.98	3.2	0.46	0.04	0.38	0.34
32	Winter	1/1/2017 17:12	4.74	0.6	0.43	0.09	0.42	0.33
33	Winter	1/2/2017 6:45	14.50	1.0	0.66	0.05	0.54	0.49
34	Winter	1/3/2017 7:33	0.71	0.5	0.02	0.03	0.01	0.00
35	Winter	1/4/2017 2:18	1.68	0.8	0.03	0.02	0.01	0.02
36	Winter	1/11/2017 6:16	1.83	0.4	0.03	0.02	0.03	0.00
37	Winter	1/12/2017 15:46	3.08	1.4	0.03	0.01	0.01	0.05
38	Winter	1/13/2017 8:23	8.66	0.9	0.09	0.010	0.020	0.070

Rain Event & Throughfall Summaries for the South Site #2

Event	Season	Start	Duration (hrs)	Inter-event days	Rain Depth (in)	Average Intensity (in/hr)	Pine ThF (in)	Pecan ThF (in)	Cedar ThF (in)	Pear ThF (in)
1	Fall	10/21/2019 13:05	n/a	6.61	0.02	n/a				0.07
2	Fall	10/22/2019 2:13	2.47	0.55	0.19	0.08				0.1
3	Fall	10/26/2019 14:45	3.11	1.27	0.6	0.19				0.45
4	Fall	10/30/2019 1:53	11.91	3.33	0.13	0.01				0.02
5	Fall	10/31/2019 9:06	4.13	0.80	0.73	0.18				0.6
6	Fall	11/7/2019 18:50	8.07	7.23	0.3	0.04				0.18
7	Fall	11/12/2019 1:02	5.28	3.92	0.98	0.19				0.66
8	Fall	11/14/2019 17:06	26.28	2.45	1.14	0.04				0.77
9	Fall	11/16/2019 8:01	n/a	0.53	0.01					0.01
10	Fall	11/23/2019 9:00	3.56	7.04	0.68	0.19				0.5
11	Fall	11/27/2019 6:27	3.81	3.75	0.15	0.04				0.05
12	Winter	12/1/2019 2:42	3.34	3.69	0.26	0.08				0.16
13	Winter	12/9/2019 22:32	1.00	3.00	1.73	0.02				1.07
14	Winter	12/12/2019 10:13	77.34	3.00	0.86	0.01				0.54
15	Winter	12/17/2019 5:39	7.16	1.59	0.85	0.12				0.48
16	Winter	12/18/2019 1:48	13.37	0.54	0.65	0.05				0.39
17	Winter	12/19/2019 23:14	0.25	1.34	1.66	0.42				0.84
18	Winter	12/23/2019 11:51	20.27	3.52	0.71	0.04				0.34
19	Winter	12/30/2019 12:20	5.98	6.18	0.39	0.07			0.03	0.19
20	Winter	12/31/2019 8:08	12.91	0.58	1.95	0.15			0.78	1.25
21	Winter	1/1/2020 10:15	32.37	0.55	2.92	0.09			1.01	
22	Winter	1/28/2020 13:45	1.69	7.05	0.52	0.31			0.19	0.35
23	Winter	2/5/2020 20:53	1.86	0.49	0.52	0.28			0.21	0.32
24	Winter	2/10/2020 3:26	1.54	3.66	0.88	0.57			0.42	0.57

Event	Season	Start	Duration (hrs)	Inter-event days	Rain Depth (in)	Average Intensity (in/hr)	Pine ThF (in)	Pecan ThF (in)	Cedar ThF (in)	Pear ThF (in)
25	Winter	2/16/2020 11:56	23.33	5.60	4.56	0.20			1.4	2.24
26	Winter	2/20/2020 10:20	13.10	2.96	0.72	0.05			0.19	0
27	Summer	6/22/2020 9:28	8.51	11.42	0.11	0.01	0.02	0.02	0.02	0.06
28	Summer	6/23/2020 18:50	11.00	1.49	0.54	0.05	0.3	0.5	0.26	0.33
29	Summer	6/24/2020 13:48	14.80	0.95	0.93	0.06	0.67	0.8	0.55	0.59
30	Summer	6/25/2020 22:25	1.38	0.80	0.27	0.20	0.15	0.25	0.14	0.19
31	Summer	7/1/2020 6:57	3.78	5.46	0.2	0.05	0.1	0.17	0.05	0.07
32	Summer	7/1/2020 22:10	0.39	0.49	0.06	0.15	0.01	0.02	0	0.02
33	Summer	7/7/2020 10:57	4.05	0.68	0.4	0.10	0.2	0.31	0.13	0.19
34	Summer	7/8/2020 12:35	12.84	1.43	0.22	0.02	0.11	0.11	0.08	0.1
35	Summer	7/12/2020 15:30	1.83	3.66	0.61	0.33	0.53	0.73	0.24	0
36	Summer	7/15/2020 15:51	1.58	3.00	0.35	0.22	0.22	0.29	0.21	0.22
37	Summer	7/23/2020 17:29	0.25	8.01	0.25	1.01	0.17	0.23	0.09	0.13
38	Summer	7/25/2020 18:21	4.00	2.19	0.47	0.12	0.32	0.44	0.34	0.29
39	Summer	7/26/2020 15:03	4.00	0.86	0.36	0.09	0.27	0.35	0.12	0.15
40	Summer	7/28/2020 18:36	2.74	2.10	2.01	0.73	1.85	1.73	1.47	1.58
41	Summer	7/29/2020 3:50	0.00	0.27	0.01		0	0.01	0.02	0
42	Summer	8/19/2020 20:20	4.46	7.13	2.8	0.63	0.85	2.93	2.36	1.99
43	Summer	8/20/2020 14:25	13.23	1.12	0.29	0.02	0.01	0.26	0.04	0.12
44	Summer	8/21/2020 22:25	3.63	0.93	2.27	0.63	1.94	1.87	**	**
45	Summer	8/25/2020 1:35	84.42	6.50	0.34	0.01	0.29	0.34	**	0.13
46	Summer	8/28/2020 14:00	3.28	0.14	0.7	0.21	0.6	0.58	0.48	0.52
47	Fall	9/10/2020 11:58	0.12	1.84	0.09	0.77	0.04	0.1	0	0.01
48	Fall	9/11/2020 14:31	8.11	1.44	0.23	0.03	0.14	0.22	0.08	0.1
49	Fall	9/12/2020 19:57	0.38	0.90	0.02	0.05	0	0.01	0.01	0.01
50	Fall	9/16/2020 2:39	20.17	1.28	3.59	0.18	3.3	4.08	1.42	2.45

Event	Season	Start	Duration (hrs)	Inter-event days	Rain Depth (in)	Average Intensity (in/hr)	Pine ThF (in)	Pecan ThF (in)	Cedar ThF (in)	Pear ThF (in)
51	Fall	9/17/2020 14:23	0.00	0.65	0.01		0.01	0.01	0	0
52	Fall	9/27/2020 9:04	0.56	3.06	0.52	0.93	0.46	0.54	0.37	0.48
53	Fall	9/28/2020 18:24	1.81	1.44	0.32	0.18	0.24	0.3	0.16	0.28
54	Fall	9/29/2020 9:29	1.08	0.60	0.04	0.04	0	0	0	0
55	Fall	10/9/2020 5:46	14.30	10.08	1.22	0.09	1.04	1.12	0.58	1.03
56	Fall	10/10/2020 9:03	5.91	0.79	1.23	0.21	1.01	1.18	0.75	1.04
57	Fall	10/10/2020 23:07	19.75	1.16	0.33	0.02	0.15	0.22	0.11	0.14
58	Fall	10/24/2020 8:50	4.35	1.52	0.96	0.22	0.74	0.81	0.62	0.82
59	Fall	10/25/2020 2:36	7.26	0.86	0.14	0.02	0.1	0.16	0.03	0.05
60	Fall	10/27/2020 20:36	5.16	2.66	0.09	0.02	0.05	0.07	0	0
61	Fall	10/28/2020 21:08	4.77	1.01	1.25	0.26	1.17	1.52	**	0.81
62	Fall	11/27/2020 18:50	7.17	0.32	0.67	0.09	0.53	0.63	0.35	0.53
63	Fall	11/29/2020 8:52	13.71	1.86	2.03	0.15	1.68	2.12	0.9	1.47
64	Winter	12/12/2020 17:51	4.75	6.18	0.25	0.05	**	0.28	**	0.16
65	Winter	12/13/2020 19:02	0.50	0.87	0.04	0.08	0.04	0.03	0	0.01
66	Winter	12/16/2020 3:49	7.87	2.36	0.22	0.03	**	0.27	0.02	0.15
67	Winter	12/19/2020 22:11	10.90	3.89	0.1	0.01	**	0.09	0	0.04
68	Winter	12/23/2020 20:14	15.11	4.09	1.51	0.10	**	1.36	0.86	0.91
69	Winter	12/31/2020 21:01	11.45	7.88	1.19	0.10	**	1.1	0.6	0.39
70	Winter	1/7/2021 9:55	18.70	6.84	0.34	0.02	0	0.38	0	0.16
71	Winter	1/11/2021 6:05	11.64	3.55	0.24	0.02	**	0.25	0.01	0.11
72	Winter	1/21/2021 7:55	26.03	10.68	1.1	0.04	**	1	0.5	0.51
73	Winter	1/26/2021 4:32	3.32	2.30	0.12	0.04	0.06	0.1	0.01	0.01
74	Winter	1/26/2021 22:51	9.42	1.02	0.42	0.04	0.26	0.4	0.12	0.16
75	Winter	1/31/2021 1:48	6.22	3.99	0.23	0.04	0.12	0.3	0.05	0.19
76	Winter	2/5/2021 0:34	3.63	4.84	0.15	0.04	0.05	0.12	0.02	0.1

Event	Season	Start	Duration (hrs)	Inter-event days	Rain Depth (in)	Average Intensity (in/hr)	Pine ThF (in)	Pecan ThF (in)	Cedar ThF (in)	Pear ThF (in)
77	Winter	2/10/2021 22:05	4.28	1.78	0.06	0.01	0.04	0.01	0	0.03
78	Winter	2/11/2021 9:13	9.96	0.70	0.24	0.02	0.16	0.22	0.05	0.13
79	Winter	2/12/2021 23:49	9.76	1.28	0.3	0.03	0.18	0.34	0.08	0.24
80	Winter	2/15/2021 12:20	4.12	2.29	0.3	0.07	0.24	0.31	0.08	0.21
81	Winter	2/17/2021 20:11	7.64	2.47	0.28	0.04	0.18	0.25	0	0.17
82	Spring	3/2/2021 4:29	19.56	1.74	1.4	0.07	0.89	1.45	0.32	1.34
83	Spring	3/16/2021 6:30	15.22	13.90	1.18	0.08	1.1	1.18	0.47	0.64
84	Spring	3/17/2021 6:00	5.68	0.58	0.03	0.01	0.01	0	0.01	0.01
85	Spring	3/17/2021 21:31	5.79	0.65	0.89	0.15	0.7	0.79	0.38	0.37
86	Spring	3/23/2021 14:08	5.99	5.70	0.85	0.14	0.62	0.72	0.26	0.39
87	Spring	3/24/2021 23:08	6.32	1.39	0.67	0.11	0.53	0.65	0	0.01
88	Spring	3/25/2021 21:12	8.75	1.02	0.44	0.05	0.23	0.29	0.2	0.19
89	Spring	3/28/2021 9:10	1.23	1.88	0.42	0.34	0.27	0.34	0.22	**
90	Spring	3/30/2021 18:13	2.41	2.43	0.1	0.04	0.01	0.07	**	**
91	Spring	3/31/2021 11:55	5.12	0.85	1.2	0.23	0.93	1.01	**	**
92	Spring	4/9/2021 8:43	6.66	1.40	1.9	0.29	1.22	1.64	1.05	**
93	Spring	4/24/2021 0:21	18.96	10.26	2.45	0.13	**	1.82	0.72	**
94	Spring	5/12/2021 1:29	7.47	0.04	1.04	0.14	0.77	0.85	**	0.67
95	Spring	5/28/2021 18:56	4.94	16.62	0.4	0.08	0.32	0.37	**	0.55
96	Summer	6/3/2021 11:05	7.14	5.76	0.39	0.05	0.33	0.3	**	0.23
97	Summer	6/5/2021 13:23	0.35	1.42	0.05	0.14	0.01	0.02	**	0.01
98	Summer	6/6/2021 17:39	9.54	0.69	0.72	0.08	0.69	0.68	**	0.42
99	Summer	6/7/2021 11:43	0.35	0.37	0.76	0.38	0.59	0.05	**	0.42
100	Summer	6/8/2021 15:31	2.22	0.72	0.12	0.05	0.05	0.04	0	0.03
101	Summer	6/11/2021 14:04	0.27	0.81	0.2	0.74	0.22	0.16	**	0.12
102	Summer	6/12/2021 1:02	4.39	0.63	0.17	0.04	0.09	0.12	0	0.08

Event	Season	Start	Duration (hrs)	Inter-event days	Rain Depth (in)	Average Intensity (in/hr)	Pine ThF (in)	Pecan ThF (in)	Cedar ThF (in)	Pear ThF (in)
103	Summer	6/14/2021 20:23	6.36	2.89	0.73	0.11	0.62	0.76	**	0.44
104	Summer	6/19/2021 5:29	25.53	1.57	3.05	0.12	2.67	2.38	**	2.09
105	Summer	6/21/2021 6:05	1.24	1.01	0.09	0.07	0.02	0.04	**	0.01
106	Summer	6/22/2021 4:31	0.87	0.92	0.07	0.08	0.03	0.01	**	0.01
107	Summer	7/1/2021 15:52	5.07	1.16	0.18	0.04	0.1	0.13	**	0.1
108	Summer	7/2/2021 8:10	8.61	0.83	0.52	0.06	0.33	0.38	**	0.3
109	Summer	7/6/2021 0:44	0.30	3.34	0.81	0.07	0.56	0.57	**	0.41
110	Summer	7/7/2021 17:25	2.54	0.74	0.63	0.25	0.58	0.58	**	0.36
111	Summer	7/12/2021 6:23	10.58	0.89	0.43	0.04	0.24	0.28	**	0.27
112	Summer	7/17/2021 17:22	1.64	4.73	0.2	0.12	0.08	0.12	**	0.1
113	Summer	7/19/2021 7:53	2.86	0.67	0.57	0.20	0.38	0.47	**	0.39
114	Summer	7/19/2021 20:43	0.56	0.44	0.11	0.20	0.05	0.06	**	0.03
115	Summer	7/20/2021 15:01	0.00	0.74	0.01		0.01	0	**	0
116	Summer	7/21/2021 8:45	0.41	0.76	0.15	0.36	0.08	0.16	**	0.05
117	Summer	7/27/2021 11:51	2.73	4.02	0.83	0.30	0.72	0.64	**	0.58
118	Summer	8/2/2021 15:42	1.81	6.12	0.14	0.08	0.02	0.1	**	0.04
119	Summer	8/7/2021 16:55	121.44	4.48	0.16	0.00	0.08	0.12	**	0.11
120	Summer	8/11/2021 20:27	2.66	2.26	0.47	0.18	0.3	0.41	**	0
121	Summer	8/12/2021 14:53	6.13	0.91	0.63	0.10	0.45	0.57	**	0

APPENDIX B

Study 2: Rain Event & Throughfall Summaries for the Tree Size Analysis (Hyp. #2)

Event	Start	Duration (hrs)	Intereven t days	Grass (in)	Average Intensity (in/hr)	Small 13 inch (DBH)	Small 20 inch (DBH)	Mediu m 27 inch (DBH)	Large 36 inch (DBH)
1	8/28/2021 13:11	2.4	6.55	0.12	0.05	0.04	0.02	0.02	0.08
2	8/29/2021 13:54	1.0	0.93	0.21	0.21	0.15	0.11	0.10	0.00
3	8/30/2021 12:50	20.7	0.91	1.40	0.07	0.65	0.62	0.43	0.39
4	8/31/2021 3:29	2.1	0.46	0.70	0.33	0.57	0.57	0.48	0.37
5	8/31/2021 16:00	9.3	0.27	0.11	0.01	0.07	0.05	0.04	0.00
6	9/1/2021 16:37	1.5	0.64	0.64	0.44	0.71	0.73	0.89	0.77
7	9/6/2021 15:20	6.5	4.89	0.12	0.02	0.08	0.01	0.03	0.00
8	9/8/2021 12:31	1.6	1.61	0.31	0.19	0.19	0.13	0.12	
9	9/14/2021 6:13	4.4	5.67	0.44	0.10	0.47	0.23	0.39	
10	9/14/2021 21:02	39.7	0.43	1.20	0.03	1.19	0.67	0.67	
11	9/16/2021 19:24	1.1	0.28	0.29	0.26	0.23	0.15	0.21	
12	9/17/2021 17:50	2.1	0.89	0.49	0.24	0.53	0.37	0.32	
13	9/18/2021 13:14	6.3	0.27	2.34	0.37	2.19	1.96	1.81	
14	9/19/2021 9:13	13.9	0.57	0.76	0.05	0.72	0.52	0.48	
15	10/4/2021 11:29	18.7	13.81	1.21	0.06	0.85	1.09	0.90	1.12
16	10/5/2021 18:01	12.6	0.49	0.57	0.05	0.30	0.39	0.23	0.38

Event	Start	Duration (hrs)	Interevent days	Grass (in)	Average Intensity (in/hr)	Small 13 inch (DBH)	Small 20 inch (DBH)	Medium 27 inch (DBH)	Large 36 inch (DBH)
17	10/21/2021 7:15	2.7	15.03	0.85	0.32	0.73	0.66	0.87	0.72
18	10/22/2021 1:33	5.2	0.65	0.55	0.11	0.45	0.57	0.41	0.40
19	10/27/2021 23:20	8.5	5.69	1.00	0.12	0.74	0.99	1.20	0.67
20	11/11/2021 15:46	3.8	14.33	0.76	0.20	0.73	0.84	0.68	0.75
21	11/22/2021 2:34	2.7	9.81	0.34	0.12	0.27	0.30	0.26	0.34
22	11/25/2021 22:26	2.5	3.71	0.14	0.05	0.11	0.10	0.13	0.07
23	12/6/2021 13:30	8.3	7.99	1.18	0.14	0.91	1.13	0.86	0.78
24	12/7/2021 21:26	11.1	0.99	0.50	0.05	0.39	0.54	0.38	
25	12/9/2021 20:32	8.8	1.50	0.41	0.05	0.27	0.31	0.22	
26	12/10/2021 15:30	6.7	0.42	0.07	0.01	0.04	0.06	0.02	0.01
27	12/11/2021 14:00	9.1	0.66	0.20	0.02	0.18	0.22	0.15	0.01
28	12/17/2021 23:20	0.8	0.31	0.03	0.04	0.01	0.01	0.00	0.01
29	12/18/2021 9:41	13.3	0.40	2.17	0.16	1.50	1.73	1.43	
30	12/29/2021 5:26	8.0	7.74	0.82	0.10	0.71	0.84	0.68	0.72
31	12/30/2021 14:54	1.1	1.06	0.24	0.22	0.17	0.21	0.16	0.15
32	1/2/2022 5:55	8.0	2.14	0.71	0.09	0.54	0.58	0.54	0.63
33	1/2/2022 20:31	4.4	0.27	0.18	0.04	0.19	0.21	0.24	0.22

APPENDIX C

Study 3: Rain Event & Throughfall Summaries for the Transect Variation (Hyp. #3)

Event	Start Time	Duration (hrs)	Interevent Days	Grass	Average Intensity (in/hr)	Transect 1	Transect 2	Transect 3	Transect 4
1	8/28/2021 13:11	2.4	6.55	0.12	0.05	0.02	0.03	0.04	0.08
2	8/29/2021 13:54	1.0	0.93	0.21	0.21	0.12	0.10	0.15	0.13
3	8/30/2021 12:50	20.7	0.91	1.40	0.07	1.10	0.95	1.26	1.02
4	9/1/2021 16:37	1.5	0.64	0.64	0.44	0.53	0.69	0.95	0.61
5	9/6/2021 15:20	6.5	4.89	0.12	0.02	0.01	0.04	0.04	0.09
6	9/8/2021 12:31	1.6	1.61	0.31	0.19	0.23	0.48	0.28	0.39
7	9/14/2021 6:13	4.4	5.67	0.44	0.10	0.25	0.30	0.39	0.49
8	9/14/2021 21:02	39.7	0.43	1.20	0.03	0.24	0.60	1.20	1.57
9	9/16/2021 19:24	1.1	0.28	0.29	0.26	0.25	0.16	0.29	0.28
10	9/17/2021 17:50	2.1	0.89	0.49	0.24	0.48	0.26	0.54	0.58
11	9/18/2021 5:27	1.3	0.40	0.04	0.03	0.01	0.02	0.00	0.00
12	9/18/2021 13:14	6.3	0.27	2.34	0.37	1.26	1.91	3.18	3.24
13	9/19/2021 9:13	13.9	0.57	0.76	0.05	0.23	0.53	0.77	1.10
14	10/4/2021 11:29	18.7	13.81	1.21	0.06	0.59		0.82	0.29
15	10/5/2021 18:01	12.6	0.49	0.57	0.05	0.23		0.42	0.38
16	10/21/2021 7:15	2.7	0.00	0.85	0.32	0.41	0.64	0.00	0.79

Event	Start Time	Duration (hrs)	Interevent Days	Grass	Average Intensity (in/hr)	Transect 1	Transect 2	Transect 3	Transect 4
17	10/22/2021 1:33	5.2	0.65	0.55	0.11	0.48			0.51
18	10/27/2021 23:20	8.5	5.69	1.00	0.12	0.48	0.70		0.84
19	11/11/2021 15:46	3.8	14.33	0.76	0.20	0.38	0.44	0.10	0.64
20	11/22/2021 2:34	2.7	9.81	0.34	0.12	0.12	0.25	0.36	0.39
21	11/25/2021 22:26	2.5	3.71	0.14	0.05	0.03	0.04	0.04	0.06
22	12/6/2021 13:30	8.3	7.99	1.18	0.14	0.51	0.71	0.90	1.02
23	12/7/2021 21:26	11.1	0.99	0.50	0.05	0.32	0.32	0.39	0.54
24	12/9/2021 20:32	8.8	1.50	0.41	0.05	0.11	0.22	0.41	0.35
25	12/10/2021 15:30	6.7	0.42	0.07	0.01	0.00	0.01	0.01	0.05
26	12/11/2021 14:00	9.1	0.66	0.20	0.02	0.06	0.04	0.03	0.13
27	12/17/2021 15:51	n/a	5.70	0.01		0.01	0.01	0.01	0.02
28	12/18/2021 9:41	13.3	0.40	2.17	0.16	1.23	0.00	1.56	1.62
29	12/19/2021 6:44	n/a	0.32	0.01				0.03	0.01
30	12/29/2021 5:26	8.0	7.74	0.82	0.10		0.57	0.67	
31	12/30/2021 14:54	1.1	1.06	0.24	0.22	0.15	0.13		0.20
32	1/2/2022 5:55	8.0	2.14	0.71	0.09	0.38	0.46		
33	1/2/2022 20:31	4.4	0.27	0.18	0.04	0.08	0.11	0.05	0.13
34	1/6/2022 14:31	1.0	3.57	0.34	0.35	0.25	0.22	0.20	0.35
35	1/9/2022 15:05	4.7	3.18	0.91	0.20	0.49	0.57	0.69	0.88
36	1/15/2022 14:36	21.6	6.69	1.60	0.07	0.65	0.94	1.34	1.39
37	1/20/2022 0:14	12.5	4.02	0.55	0.04	0.14	0.38	0.45	0.53

38	2/2/2022 16:01	44.0	2.20	4.10	0.09	1.54	2.55	3.33	3.08