Assessing Rainwater Harvesting Potential for Urban Multi-Family Housing Developments in Auburn, AL using a sUAS

by

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A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Sciences in Geography

Auburn, Alabama
May 5, 2018

Keywords: sUAS, rainwater harvesting,
stormwater, runoff, NSWC

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Abstract

Many cities today are facing growing pressure to develop in a sustainable manner, and green infrastructure is quickly becoming a popular strategy for addressing this. Through the incorporation of decentralized solutions for ecological problems associated with rapid urbanization, such as flooding and erosion, there is opportunity to mitigate the associated negative impacts while also reducing strain on current infrastructure systems. Additionally, since modern technology is providing researchers with cost-effective approaches to acquiring their data, then there is a lot of opportunity for these problems to be assessed effectively and in a timely manner. This study focuses on these concepts by using a small unmanned aircraft system (sUAS) to obtain aerial images of four multi-family housing developments in the city of Auburn, Alabama. With these images obtained from the sUAS, output maps are generated which can then be used to determine land-cover characteristics for the four study locations. The land-cover characteristics are then used as input values for the Environmental Protection Agency's *National Stormwater Calculator* tool. This tool is used to quantify the rooftop-based rainwater harvesting potential for each of the sites and determine the reduction impacts on stormwater runoff. The results of the stormwater calculator scenarios showed that if rainwater harvesting and collection were implemented, then the reduction in annual runoff is projected to be 1,148,305.48gal at the *Garden District*, 907,070,06gal at *Eagles South*, 1,220,869.59gal at *Tiger Lodge*, and 897,235.84gal at *Eagles West*.

Acknowledgments

The completion of this thesis is the culmination of many long hours of work, late-night coffee breaks, and constant support from my mentors, family, and friends. Completing this work has been a stout academic challenge and test of my determination during my academic career. I have learned things not only about my research topic, but also about myself and my professional interests along the way.

I would like to first thank my major professor, Dr. Chandana Mitra. Having worked with her for over 3 years now, I could not imagine where my career ambitions would be without her input. She has provided constant positive support during the pursuit of both my Undergraduate degree and my Graduate degree, providing me with professional wisdom that I will continue to use for the rest of my life. I look forward to our future collaborative work together and continuing to learn from her after I move on from my time at Auburn.

I also want to thank my committee members, Dr. Philip Chaney and Dr. Sweta Byahut, and the rest of my support network, including my fellow graduate student colleagues, faculty in the Department of Geosciences, my parents, and my loving wife, Lauren. I also want to thank Dr. Mark Hagood for piquing my interest in sUAS and supporting my ideas. Lastly, I want to thank my grandparents, Ann & James Ledbetter, for being so supportive of my education and taking personal interest in my career goals.

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List of Abbreviations

sUAS	Small Unmanned Aircraft System(s)
RHC	Rainwater Harvesting and Collection
NSWC	National Stormwater Calculator
LID	Low Impact Development
EPA	Environmental Protection Agency
SWMM	Stormwater Management Model
P4P	Phantom 4 Professional
GPS	Global Positioning System
GIS	Geographic Information System
RS	Remote Sensing
GSD	Ground Sampling Distance
DSM	Digital Surface Model
LULC	Land-Use/Land-Cover
GCPs	Ground Control Points

1. Introduction

Over the past several decades, the concept of sustainability and its gradual integration into city policy and planning has been an area of both contention and innovation. As city officials look to the future and try to best inform their policies, it is necessary to recognize the influence that concepts related to sustainable growth and development are playing. Early in its conceptual genesis, the notion of sustainability was often misunderstood to be purely a focus on maintaining the quality of the environment. However, now it is widely understood that sustainability not only incorporates concerns related to the environment, but it also pertains to the other aspects of vital importance to policy-making within a city, such as culture, society, economy, and politics (de Jong et al 2015). Currently, many cities across the US are placing growing emphasis on adopting sustainable approaches to city development issues, especially regarding the development of long-term plans and strategies that the city is interested in achieving (Gleick 2000, Salkin 2009). Sometimes these sustainable approaches can yield more cost-effective solutions to problems that would otherwise be handled with more traditional (i.e. costlier) methods. In more contemporary planning initiatives, many local governments are encouraging the adoption of such approaches through the usage of various incentives, requirements, and laws (Bayulken et al. 2015).

Of the various sustainable approaches that can be studied for city development and growth management, this study involves assessing the potential for rooftop-based rainwater harvesting applications for urban multi-family housing developments in Auburn, Alabama. With Alabama having on average 55 inches of precipitation per year, it represents a prime setting for this type of sustainable stormwater approach (NOAA US Climate Atlas). The pros and cons of rainwater harvesting & collection have been well documented in contemporary literature (Jones & Hunt 2010, Domènech & Saurí 2011, Angrill et al. 2017, Abdulla & Al-Shareef 2009). However, there is still a need for applied research on the subject and its feasibility within specific localities. Additionally, this study is electing to incorporate the use of a small unmanned aircraft system (sUAS) to acquire the aerial data necessary for quantifying the rainwater harvesting and collection (RHC) potential, as opposed to relying on conventional satellite or airborne data that is commonly obtained using expensive Light Detection and Ranging (LiDAR) equipment. sUAS are quickly becoming mainstream research tools that can provide extremely cost-effective data when the necessary aerial data might not already be available (Kršák et al. 2016). This study represents an ideal opportunity to assess the pros and cons of incorporating a relatively inexpensive sUAS (~$1500) and compare its results to the data produced by more conventional methods employed when acquiring aerial imagery.

The city of Auburn, Alabama has been a strong regional example for the incorporation of sustainability within its city development strategies, which is increasingly becoming a symptom of regional leadership and innovation (Cidell 2015). The city has even explicitly noted in their comprehensive plan the need for the gradual adoption of rainwater harvesting practices in both public and private buildings, with emphasis on residential development (Auburn CompPlan 2030). To better understand how the city could further implement RHC in residential zones, the outcomes of it needs to be studied within a neighborhood-scale context. Recognizing this as an area of interest for the city and the opportunities presented, there are three research objectives which this study will aim to meet:

1. Develop methodology for using sUAS-derived orthomosaic imagery in determining accurate land-use/land-cover classifications for four multi-family housing developments in Auburn, AL.
2. Delineate the total area of the building rooftops and other site classes using *ArcMap* and derive the land-use/land-cover compositions.
3. Quantify the reduction of rainwater surface runoff produced at each site if rainwater harvesting is implemented using the web-based *EPA National Stormwater Calculator*.

2. Literature Review:

2.1. Stormwater Management & Low Impact Development

Traditionally, stormwater management systems have heavily relied on engineering approaches to address stormwater concerns. These systems were designed to quickly and effectively move stormwater runoff from it origination point to the desired destination point off-site (Shuttleworth et al. 2017, Ahiablame et al. 2012). The original (and still current) goal for most urban stormwater management systems is to prevent urban flooding in areas that have experienced significant development. Often putting concern for the local environment to the side, these systems were considered to be the most effective means for handling stormwater. Paired with that mindset was the general perception that new sources of water needed to be found to meet an increasing demand. Over the 20th century a transition in water resource concern took place, putting more emphasis on the quality and effective reuse of current water sources as opposed to finding new sources (Boers & Ben-Asher 1982, Gleick 2000). With growing public awareness of the benefits of maintaining a natural hydrologic cycle vs a typical post-development cycle, there has been a push for management systems that are both effective and low impact to the environment (Zhou 2014). Looking at the dilemmas presented by urban stormwater runoff, and the growing concern for water resource usage and efficiency, Low Impact Development (LID) stands out as an intriguing concept for addressing these problems.

LID practices are a way for developers to reduce development costs by reducing reliance on conventional stormwater management systems (HUD 2003). Oftentimes LID systems can reduce the need for traditional conveyance systems, like paved gutters, curbs, and piping structures by "…treating water at its source instead of at the end of the pipe" (HUD 2003). LID systems utilize methods that try to maximize the ecological (and economic) benefits of natural processes like infiltration, evaporation, transpiration and on-site storage of stormwater (EPA 2007). Typical systems employed as LID approaches are generally focused on sustainable drainage, such as pervious pavement, infiltrations systems, and storm water collectors. However, there are other types of systems employed in LID that place emphasis on improvement of water quality in addition to addressing drainage; such as vegetated rooftops and rain gardens (Shuttleworth et al. 2017). The overall goal of LID development is to recreate the natural hydrologic cycle that existed in the pre-development phase of a location. This is important because in some watersheds up to 55% of rainfall runs off an urban surface, with only 15% infiltrating the ground. This is in comparison to natural landscapes which have approximately 10% of rainfall running off and up to 45% of the rainfall infiltrating the ground (ADEM 2014). For this reason, LID approaches are effective methods for minimizing the difference in infiltration and runoff by recreating natural features.

When discussing LID practices, it is necessary to detail some of the various types of approaches taken to garner the desired effects at sites. The US EPA separates LID practices into several categories consisting of: Conservation Designs, Infiltration Practices, Runoff Storage Practices, Runoff Conveyance Practices, Filtration Practices, and Low Impact Landscaping (EPA 2007). Although many of the practices tend to overlap into one or more of the related categories, they are each seen as promising routes to pursue for sustainable stormwater management approaches. Within the southeast region of the United States there are many promising examples of LID systems in place that illustrate many, if not all, of the mentioned LID practices (Jones & Hunt 2010, Sharon 2015, Alabama Cooperative Extension System 2016).

2.2. Rainwater Harvesting & Collection

RHC is widely understood to be a viable LID approach when the primary concern is management of the volume of stormwater in a location (Palla & Barbara 2017, Petrucci et al. 2012, Shuttleworth et al. 2017). Falling in line with the LID principle of trying to keep water at its site of origination, RHC is a physical approach to keeping the rainfall on-site and usable. There are many diverse types of RHC setups which can be as simple as connecting a 55-gallon barrel to a residential downspout, to as complex as conveying, collecting, filtering, and storing rooftop runoff from a large commercial building (Georgia Rainwater Harvesting Guidelines 2009, HUD 2003). Although the specifics vary between RHC systems, they all share common core similarities in their functions. RHC operates on the fundamental assumption that unless the rainfall in a catchment area is collected and stored, then a portion will infiltrate into pervious ground, another portion will evapotranspire, and the rest will runoff (presumably into a drainage system in an urban environment). Instead of letting a significant amount of the water runoff and be unused, RHC aims to capture that potential loss and put it toward the on-site water demands (Boers & Ben-Asher 1982). To facilitate the collection of rainfall, RHC systems are comprised of several key components.

RHC systems are generally composed of equipment that catch, convey, clean, store, and distribute rainfall on-site (Alabama Cooperative Extension 2016). Although the components can vary in both material and design, they all come together to form a cohesive system to manage stormwater. Oftentimes these designs are heavily dependent on the type of land development that has occurred at the site and what types of infrastructure are already in place. Some of the factors that are worth noting when assessing a site for RHC usage are: the presence of gutters, downspouts, storm drains, soil characteristics, existing plumbing, and elevational characteristics (Georgia Rainwater Harvesting Guidelines 2009). Each of these factors can play a significant role in determining the real-world feasibility of a system's implementation. For example, when considering the catchment component of a rooftop-based system, the researcher needs to factor in the roofing material and how it can impact the water quality; if the desired system is for potable water use, then certain roofing materials should not be used in the catchment area (Angrill et al. 2017, Hua-Peng et al. 2015). Another key factor to consider is the means of conveyance. If the desired conveyance system is a set of gutters, but the building does not already have a gutter system, then that could be a significant additional cost for the entire system. When costs are arguably the driving factor behind a system's potential implementation at a site, it is worth recognizing the value of systems that are already in place but that can be retrofitted for RHC (Pelak & Porporato 2016).

The uses and designs of RHC systems heavily depend on the problem being addressed by the system's implementation. Although RHC is overall a simplistic concept, it can serve to aid in a variety of problems. Historically RHC has predominately been used as a means for acquiring drinking water in regions where water resources were scarce

(Akpinar Ferrand & Cecunjanin 2014, Abdulla & Al-Shareef 2009). This statement is especially relevant when considering areas characterized by arid, semi-arid, and dry-wet seasonality which are known to affect water availability (Boers & Ben-Asher 1982). Now in recent decades with the emergence of centralized water resources in many places, RHC for consumptive use is seen as somewhat abandoned in necessity (Akpinar Ferrand & Cecunjanin 2014). Urban residents' water needs are largely met through centralized systems now, so there is a perceived lack of need for RHC. However, this is not necessarily the case for some regions that are facing rapidly growing populations and in-contrast shrinking water resources (Lee et al. 2015, Angrill et al. 2011). For these regions, the viability of RHC is being kept on the table for discussion.

Additionally, more contemporary research is illustrating the viability of RHC as a method for not only the benefit of collecting water, but more for mitigating stormwater runoff during storm events (ADEM 2014, EPA 2007, Palla & Barbara 2017, Petrucci et al. 2012). It is widely understood that urban stormwater runoff has the potential to cause negative impacts to urban streams and waterways (Bledsoe 2002, Paul & Meyer 2001, Daebel & Gujer 2005). These negative impacts are generally characterized by erosion, diminished water quality, increased water flow velocity, and an overall altered hydrologic cycle (Hogan et al. 2014). Incorporating a capture and storage system at the point where rainfall would otherwise land on the ground prevents the initial volume of rainfall (contingent on storage capacity) from becoming either runoff or infiltrating (if the ground is pervious). Using RHC as a decentralized method for buffering initial stormflow, while also reducing reliance on external water sources, has the potential to be both an eco-friendlier solution while also being less expensive (Jones & Hunt 2010). By capturing the initial stormwater runoff produced on rooftops during a storm event, there is an opportunity to prevent some of the dramatic initial flows that can cause heightened rates of erosion.

2.3. NSWC – National Stormwater Calculator

As more stormwater professionals are recognizing the numerous benefits of LID in stormwater management, there is a growing emphasis on including the practices in hydrologic modeling efforts (Elliott & Trowsdale 2007, Harris & Adams 2006). There are many variations of stormwater models available, each with unique inputs and outputs. One model that stands out in-particular for modeling stormwater runoff characteristics is the *Storm Water Management Model* (SWMM), produced by the US EPA. Arguably one of the most prominent models available, SWMM is a stormwater runoff model used for simulating both single and long-term rainfall events (Huber & Roesner 2013). It can quantify runoff volumes and rates, while also characterizing the water quality (EPA 2016). Making use of several of SWMM's core functions, the *National Stormwater Calculator* (NSWC) by the EPA acts as a simplified version of SWMM. NSWC is designed to estimate the amount of rainfall runoff from specific sites. This tool uses inputs based on local soil conditions, land-use/land-cover (LULC), and historic precipitation values (EPA 2014). Making use of several national databases for data inputs, the user only needs to supply site LULC information and select the types of low impact controls that are going to be incorporated in the calculations. The tool even considers evaporation rates which are supplied by local weather stations. Of the LID controls that can be implemented by the user within the NSWC, rainwater harvesting is one of them. The outputs of NSWC encourage multiple scenarios to be modeled so the effects of LID implementation can be compared across various assumptions and inputs.

2.4. Small Unmanned Aircraft Systems (sUAS)

The incorporation of small Unmanned Aircraft Systems (sUAS) in contemporary remote sensing research is increasingly being recognized as a viable, cost-effective method for acquiring aerial imagery (Remondino et al. 2011, Hardy et al. 2017). An important distinction worth noting is that with sUAS there are a variety of terms used, often interchangeably. These terms vary from geographic location and discipline, but the most common tend to be: small Unmanned Aircraft System (sUAS), Unmanned Aerial Vehicle (UAV), Drone, Remotely Piloted Vehicle (RPV), Remotely Operated Aircraft (ROA), Unmanned Vehicle System (UVS), and Remotely Piloted Aircraft System (RPAS) (Nex & Remondino 2014). These terms essentially mean the same thing, but sometimes there are slight differences. The key difference to be aware of is between sUAS and UAV; UAV is only the actual unmanned aircraft, whereas sUAS designates the aircraft and the ground station/receiver (i.e. the entire system). For simplicity and clarity, this study will mainly use the term sUAS when discussing the entire system and UAV when discussing only the aircraft itself.

Utilizing a sUAS in research has several distinct advantages over conventional aircraft methods including, but not limited to, the low cost of sUAS, their flexibility in data acquisition, improved spatial resolution, and improved temporal resolution (Agüera-Vega et al. 2017). These advantages all lend to sUAS's ability to fill the gap in aerial data acquisition methods that exists due to the excessive costs associated with conventional methods, like satellites and manned aircraft. Additionally, UAV platforms nowadays are sophisticated enough to conduct flights with little to no manual input from the remote pilot in command (RPIC). Their semi-autonomous and autonomous modes allow the researcher to conduct rigorous flight plans that can easily capture large swaths of area with a high amount of image overlap. While much of this depends on the particular sUAS being used, the standardization of autonomous flight modes is becoming increasingly mainstream in both consumer and enterprise UAVs. However, before looking further into the capabilities of contemporary sUASs, a solid understanding of the legal framework that they are governed under is necessary.

Within the United States, sUAS are regulated by the U.S. Federal Aviation Administration (FAA). The FAA defines Unmanned Aircraft System as, "…an unmanned aircraft and associated elements (including communication links and the components that control the unmanned aircraft) that are required for the pilot in command to operate safely and efficiently in the national airspace system." (Title 14 CFR Part 107). Currently, the rate of technological development of sUAS is arguably outpacing the rate of development of the regulations that govern them. This problem has significantly increased in recent years with the release of more consumer-oriented UAVs that can perform functions that many previously thought impossible (like autonomous flight, or long flight distances). In response to the dramatic increase in public & private interest on the subject, the FAA released a set of regulations in June 2016 that specifically addressed sUAS and using them in commercial pursuits. These rules and guidelines fall under Part 107 of Title 14 of the Code of Federal Regulations. Within the part 107 framework, a list of limitations and allowances is provided to the anticipated operator. Most of the regulations address the "common sense" aspect of using a sUAS in commercial pursuits, like not flying over large crowds of people or flying at night. However, the regulations can still put operators in a strange circumstance where their desired flight mission cannot be legally conducted, given the part 107 framework. Therefore, the FAA does provide a waiver system which can allow the operator to apply for a waiver to conduct his/her desired flight mission (provided that the waiver is approved). The only negative aspect of the waiver process is that the FAA recommends for the operator to submit his/her application at least 90 days before the anticipated flight mission. Fortunately, the waiver option was not needed to conduct the flights for this project. To assist in preventing any liability and to make sure public safety was addressed, the property managers' approvals for all four sites were acquired prior to conducting the sUAS flights. The managers were made aware of the proposed flight plans, their purpose, logistics, and any associated risks. Additionally, the managers notified staff and residents of the proposed flights and what to expect during.

3. Study Location:

3.1. Auburn, Alabama

The location of this study is Auburn, Alabama. Experiencing approximately 50”- 60” of precipitation annually, Auburn is situated in a relatively wet part of the U.S (NOAA U.S. Climate Atlas). See Figure 1 for Google Earth images of the geographic context of Auburn, Al. Although the city of Auburn only boasts a population of approximately 53,380 (US Census 2010) compared to Huntsville, Birmingham, and Montgomery with almost 4x as many residents each, it stands to be one of the regional leaders for innovation in sustainable development within Alabama. Additionally, Auburn is on track to continue urbanizing quickly, fueled by a rapidly growing student population. In a 2015 housing market study of Auburn it was estimated that 60.7% of apartments within Auburn’s effective market area were student occupied (Danter Company 2015). The study concluded that there was potential for growth in the Auburn multi-family housing market, largely due to the anticipated growth in the student population. Understanding that there will continue to be a need for housing, student housing especially, then reducing the anticipated developments’ impacts through LID controls could prove to be very beneficial in the long run.

Indicative of the city’s growing interest in sustainable development initiatives, Auburn had a downtown master plan prepared from 2013-2014 to establish a clear vision of downtown Auburn within the framework of the city’s comprehensive plan, CompPlan 2030

(Urban Collage et al. 2014). Amongst the various characteristics detailed in the plan, it was noted that 43.3% of the urban core land parcels were for residential use and only 4% of the land area was devoted to parks and open spaces. Since many of the residential land-uses in downtown consist of apartment-style housing, then implementing RHC might aid in reducing initial stormwater runoff in these highly-developed areas. The city has also been active in collaborating with Auburn University to address some of its sustainable development goals. Examples of this can be seen in the more recent partnership between the City of Auburn and Auburn University on urban sustainability in 2014 (City of Auburn 2014). This partnership, assisted by Portland State University, focused on following a one-year grant-assisted program, the “Urban Sustainability Accelerator Program”, which worked to implement aspects of the city’s downtown master plan and several other related projects. The willingness for proactive sustainable development within Auburn’s governance lends to its ability to be a suitable location for not only RHC studies, but other sustainability assessments as well.

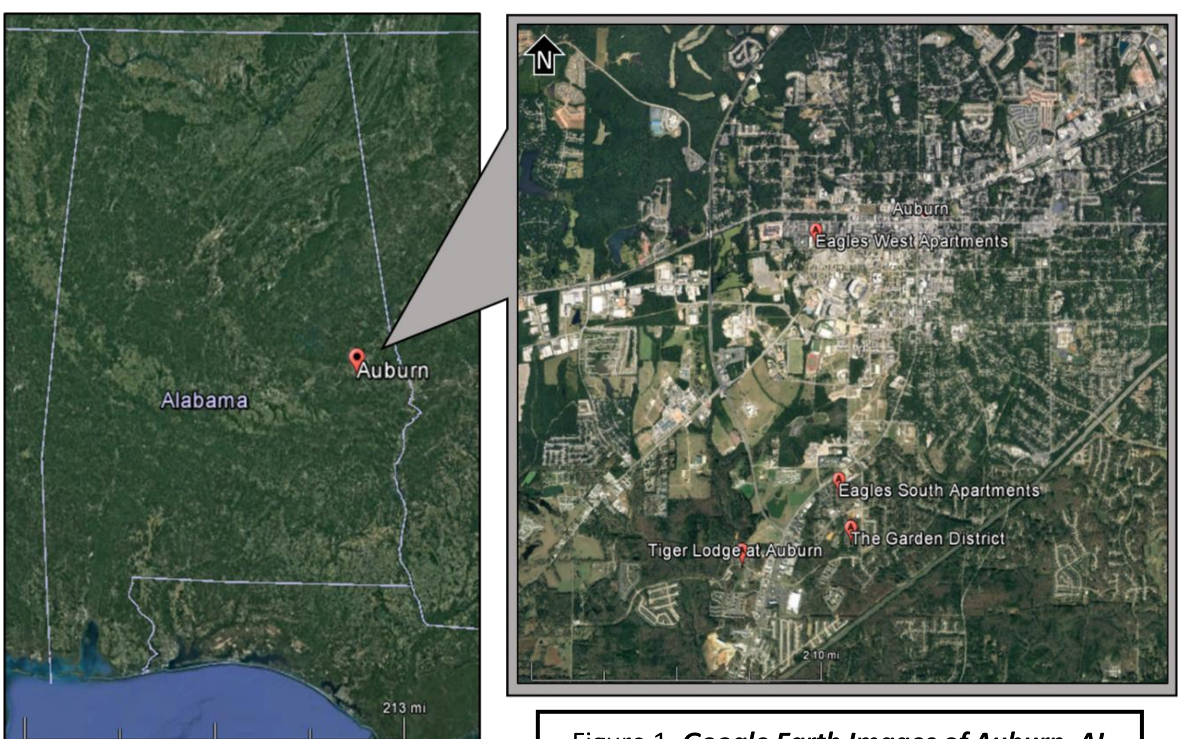


Figure 1. ***Google Earth Images of Auburn, AL***

3.2. Study Sites

Within Auburn, there are many suitable potential sites for analysis. As mentioned previously, the general development trend in Auburn follows the influence of the university and its student population. With that being stated, the proposed sites for analysis are apartment-styled housing developments that are primarily student occupied. Since it is estimated that the city of Auburn will need to continue to build new apartment complexes (Danter Company 2015), reducing each newly proposed development's contribution to stormwater runoff could prove beneficial in the long run. By studying a specific type of housing development any potential results of significance from the analysis could be used to inform city policy and regulation regarding that type. For this study, it would mean the results generated pertain only to student-oriented apartment complexes in Auburn and would be used to inform the policy related to that type of housing development. Also, with the methods used in this study, obtaining permissions for site analysis is necessary. By targeting apartment-styled housing developments, the researchers only need to coordinate with typically one property manager or owner, versus individual home owners (which would be the case for single-family housing developments). The apartment sites selected for study are: The Garden District Apartments, Eagles South Apartments, The Tiger Lodge Apartments, and Eagles West Apartments. See Figure 2 below for Google Earth images of the sites and their geographic context. These four sites represent four student-oriented housing developments, each with slightly varied design and layout. Due to the sites' varied design and layout, they will be useful in assessing the sUAS data generation methods and comparing the flight plan designs required by each. The four sites also act as case studies for potential RHC implementation, so their dissimilarities should prove useful in illustrating the varied results that could arise, given the application of a single policy change (i.e. Retrofit of RHC infrastructure on all student-housing in Auburn).

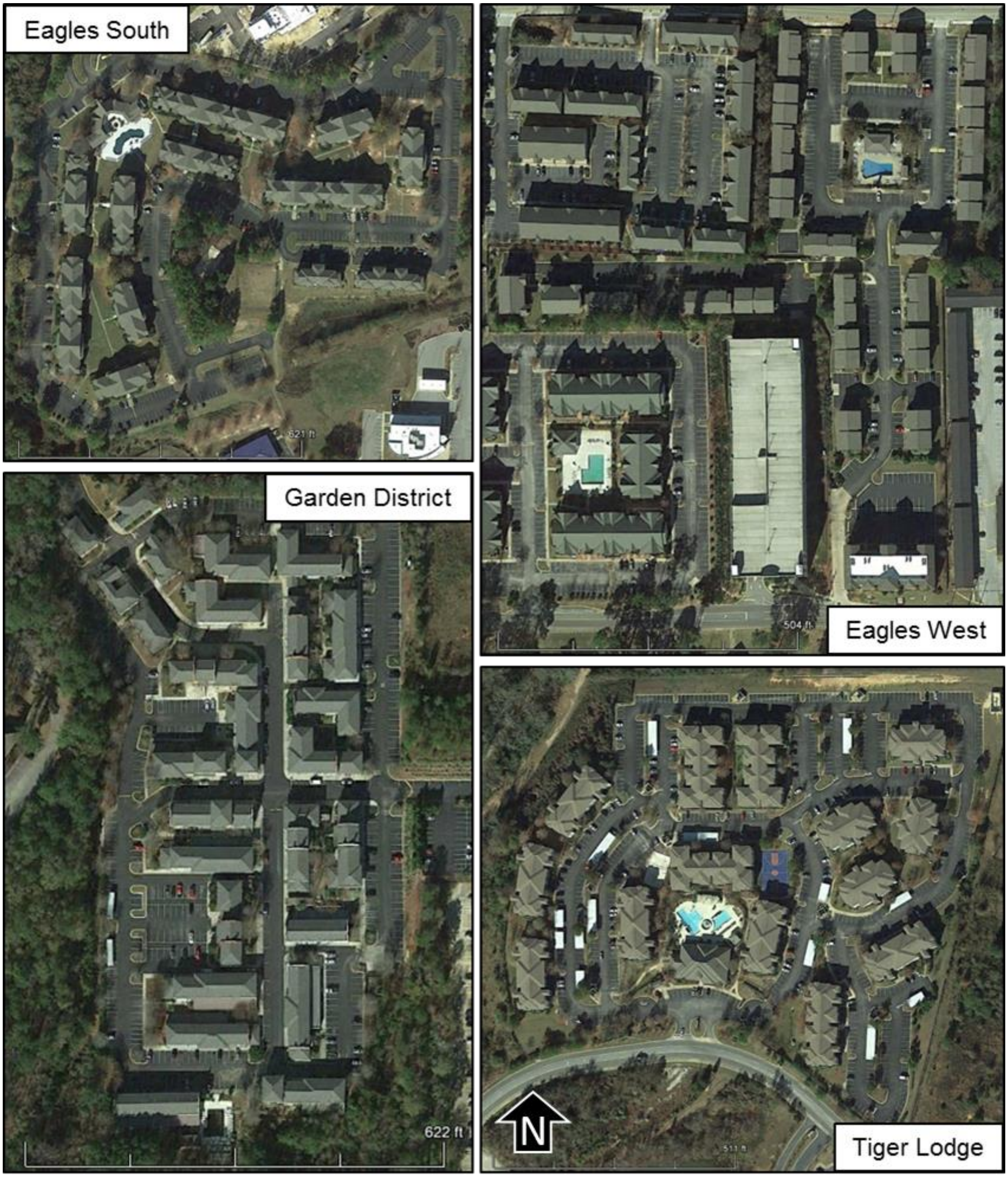


Figure 2. ***Google Earth Images of Study Sites***

4. Data & Equipment:

4.1. Data Requirement:

To accurately represent the RHC potential for a site, it is necessary to find out the LULC and dimensions of everything in the site. The apartment buildings and their surrounding land-uses need to be characterized and classified so quantitative values can be derived regarding their surface areas. This is all commonly accomplished in contemporary research through the collection, organization, and classification of high-resolution aerial imagery (Akbari et al. 2003), along with the assessment of 3D surface models. For this study, the RHC analyses will be dependent on classified orthomosaic imagery that is generated from the images captured by the sUAS. In addition to aerial imagery data, climate data, soil data, topography, and evaporation data will be needed in the NSWC phase of analysis. The climate and soil data are accessed through NSWC's interface and is provided by the U.S. Department of Agriculture's Natural Resources Conservation Service and the National Weather Service's National Climatic Data Center. Using a combination of inputs obtained from LULC data derived from imagery and local climate data, an accurate representation of the stormwater runoff characteristics of each site can be generated.

4.2. sUAS – DJI Phantom 4 Pro:

Instead of utilizing more conventional aerial imagery acquisition methods, such as satellite imagery or airborne LiDAR, this study will utilize a sUAS. The use of a sUAS will yield much higher resolution imagery of the proposed sites than the conventional methods, and it represents a growing trend in contemporary research of using sUAS as research tools in both urban and rural studies (Lisein et al. 2013, Hugenholtz et al. 2013). For Lee County, the best quality aerial data available (conventionally acquired via airplane) comes from a joint project lead by the City of Auburn, City of Opelika, Lee County, and Auburn University. This aerial imagery is 4-band orthorectified imagery with 6inch (15.24cm) spatial resolution and costed $476,103 for the 2017 acquisition (the most current available). In stark contrast, the sUAS that will be used in this study costs approximately $1500 and can yield map results with spatial resolutions under 1cm. The sUAS that will be used in this study is DJI's Phantom 4 Professional quadcopter (https://wwwdji.com/phantom-4-pro). The Phantom 4 Pro (P4P) boasts several technological advantages over its predecessors which makes it advantageous in research data collection: a 20-megapixel 1inch camera sensor, mechanical shutter, 5 direction infrared obstacle sensing, 30-minute flight time (in ideal conditions), and a 4.3 mile range from the receiver. With a 20MP camera, the P4P can take extremely high-resolution pictures (less than 1cm resolution) which is ideal for orthomosaic creation. The 30-minute flight time (per battery) and 4.3mile range allow the P4P to conduct flight missions over large swathes of area without requiring constant ground station repositioning. Additionally, the 5-direction infrared obstacle sensing technology provides another layer of liability protection since the P4P can avoid potential obstacles that could otherwise cause unexpected collisions. Lastly, the mechanical shutter on the camera proves to be invaluable with map-making since sUAS are in-motion when collecting the imagery, therefore the mechanical shutter prevents a blurring effect that is common in previous models with rolling shutter cameras. These technological advantages surprisingly come together at an average retail price of $1500 which makes this particular sUAS an attractive tool for researchers with minimal funds. However, this price can increase significantly depending on the accessories that are required depending on the research project's scope (such as extra batteries, propellers, etc.).

5. Methods Part I: sUAS Data Generation

5.1. sUAS Orthomosaic

To create the orthomosaic for each of the four sites, the P4P will be used to obtain nadir images which will then be processed into single image maps. For each study site, there will be approximately 750-1250 images captured at 45 meters above-ground-level. The specific number of images required for each site will depend on the site's overall area and parcel dimensions. Since the P4P geotags the images upon capture, every image will have geographic information which can be used to determine its absolute location. Once all the images have been captured for each of the sites, then they will be compiled and processed in a GIS/Remote Sensing (RS) platform.

After conducting the sUAS flights, the images obtained during each flight will be compiled and processed. For each site, there will be approximately 750-1250 images taken at 45m altitude, depending on the site's overall size. Fortunately, these images all have geographic data tied to them from the sUAS's GPS system. Due to this, all the images can be compiled in a GIS/RS platform to be orthorectified. The GIS/RS platforms used in this part of the analysis are *Pix4D Mapper* and *ArcMap*. *Pix4D Mapper* allows the user to upload all the imagery taken by the sUAS, and it will automatically overlap and merge all the imagery into a collection of useful outputs. *Pix4D* also offers the user the ability to incorporate GPS ground control points to verify the accuracy of the measurements produced in the final outputs. These outputs consist of a 2D orthomosaic map, a 3D textured model/mesh, and a digital surface model. The 2D map is the primary output of interest for the later analyses, but the 3D model aids in detailing the stormwater characteristics of each site.

5.1.1. Flight Plan Parameters

A unique flight plan is required for each of the four study sites. Since the image acquisition process is highly variable depending on the site's dimensions and layout, then the flight plans need to be customized to match each sites' characteristics. To create a flight plan, the user needs to select a preferred smart-phone/tablet application that is used to create sUAS flight plans. For this study, *Maps Made Easy* by Map Pilot was used (https://www.mapsmadeeasy.com/). *Maps Made Easy* was selected due to it providing a simple user interface that was designed for 2D orthomosaic outputs in mind and it is available at no cost. Other applications are available, however, there is great variation in quality, abilities, and pricing; the application selected for use will depend on the specific user's project goals.

When creating the flight plan in *Maps Made Easy*, the user is required to select the flight parameters for their specific flight. The parameters of concern for this study are: Altitude Above Ground Level (AGL), Image Overlap % (Frontal and Side), Maximum Speed, Battery Limits, and Camera Settings. The Altitude AGL is arguably the most important parameter because it has the greatest impact on the final images' quality and resolution. Altitude AGL also impacts the length of time that the flight requires to be finished. Generally, if a higher altitude is flown, then the flight is shorter in length, but the images have coarser resolution. If a lower altitude is flown, then the opposite is true.

Image Overlap is another important parameter that can greatly impact the quality of the project results. For *Pix4D Mapper* to be able to accurately orthorectify the images and create high quality outputs, the input images need to overlap with one another. The amount overlap will once again vary by project, but it is recommended by the developers of *Pix4D* to use at least an overlap of 75% frontal, and 60% side (See Figure 3 for overlap diagram). These percentages are the minimum recommended, so generally a higher amount of overlap will be used if the project allows for it. Higher image overlap has been shown to yield higher quality data outputs, however, there is a point of diminishing returns with the benefits obtained from the extra overlap (Torres-Sánchez et al. 2018).

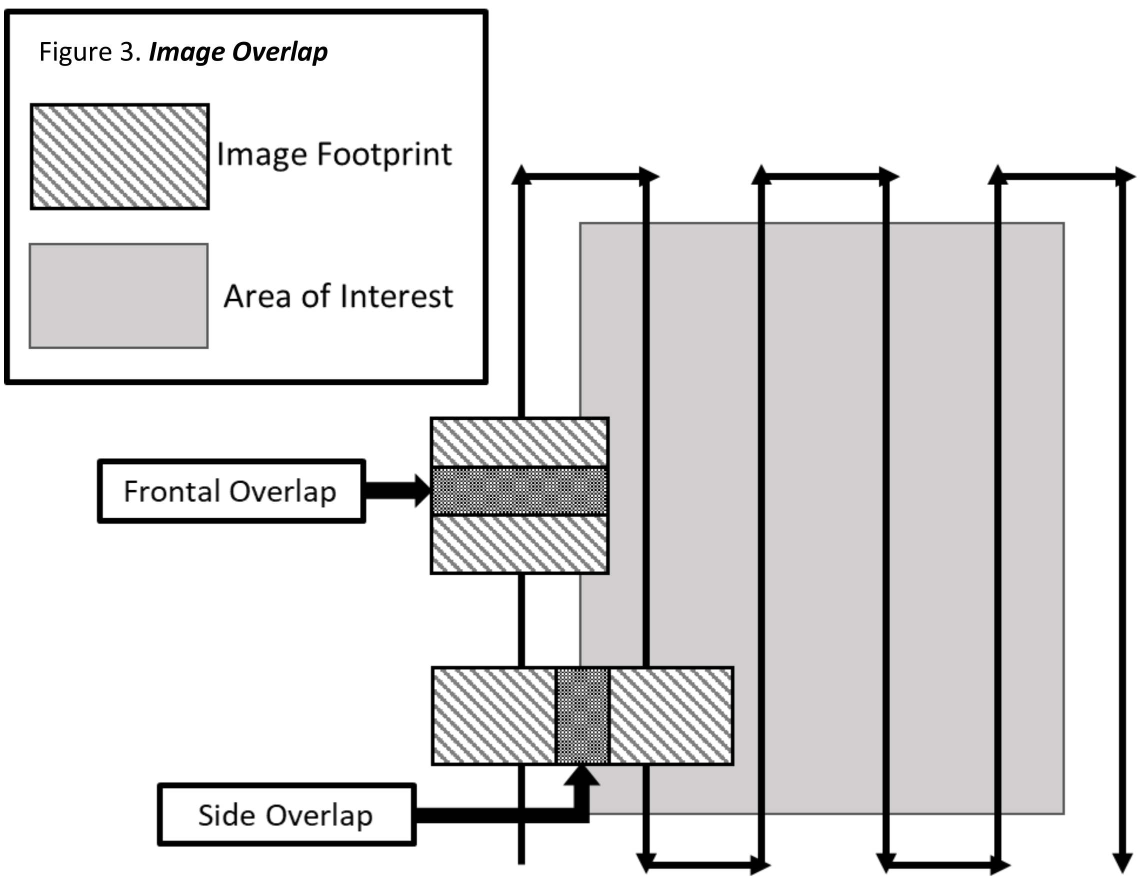


Figure 3. ***Image Overlap***

Related to image overlap, the maximum speed allowed is another parameter set by the user. To capture images with a higher amount of overlap, the speed of the UAV will generally need to be slower. Since the P4P has a mechanical shutter, speed should not negatively impact the quality of the images (i.e. blurring) but it can create problems for accurate overlapping of the images if it is moving too fast. For this reason, *Maps Made Easy* recommends default max speeds that pair with the image overlap settings. The last two flight parameters of concern, Battery Limits and Camera Settings, are more simplistic than the others and just require the sUAS operator to be aware of them during flight. *Maps Made Easy* allows for the user to manually set a battery limit to prevent draining the battery too soon to land and causing an operational hazard. The Camera Settings just require the user to select the white balance and if the conditions are more sunny or cloudy. Table #1 below lists the specific parameters of importance for each of the four flights at the study locations, as well as the number of images taken in total.

Sites:	Altitude AGL	Image Overlap	Camera Settings	Images Taken	Flight Time in Air
Garden District (4a)	45m	85% Frontal 80% Side	"Cloudy"	754	45min
Eagles South (3b)	45m	85% Frontal 80% Side	"Cloudy"	987	49min
Eagles West (3c)	45m	85% Frontal 80% Side	"Sunny"	453	25min
Tiger Lodge (3d)	45m	85% Frontal 80% Side	"Sunny"	1121	56min

Table 1. ***Flight Specifications.*** The flight altitudes, amount of image overlap, camera settings for white balance, number of images taken, and total flight time in the air are listed.

5.1.2. Image Acquisition

Once all the flight plan parameters have been decided on, then the flight plan's design layout needs to be created. Much like in a GIS platform, polygonal shapes are used to create a gridded flight pattern over the study sites. *Maps Made Easy* automatically creates the grid pattern within the polygon drawn by the user so the area coverage is optimal. The grid pattern will reflect the parameters selected by the user, especially regarding altitude and image overlap. With the flight design created and everything finalized, the flight plan can then be uploaded to the UAV. See Figures 4a-4d for the flight designs for each study location; white lines indicate the path of the UAV, orange dots are boundary marks, and the purple dots are the ground station locations.

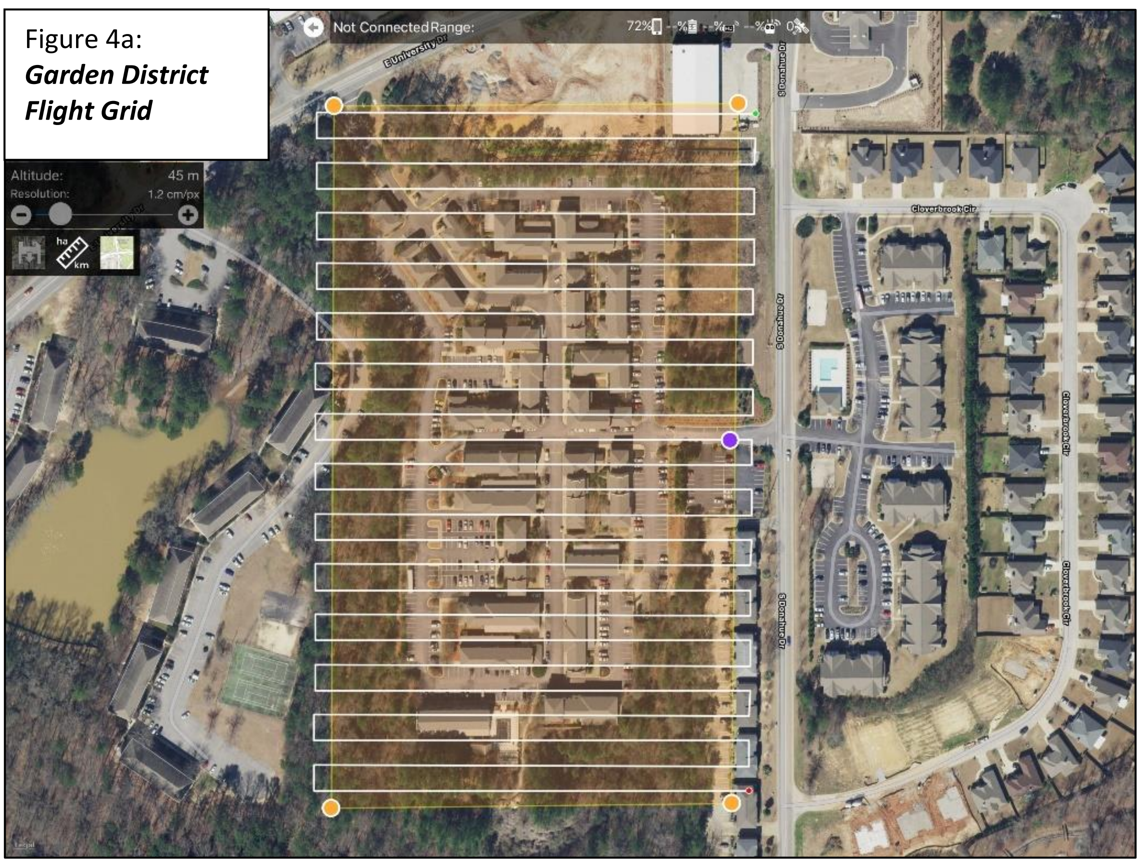


Figure 4a: ***Garden District Flight Grid***

Figure 4b:
Eagles South Flight Grid

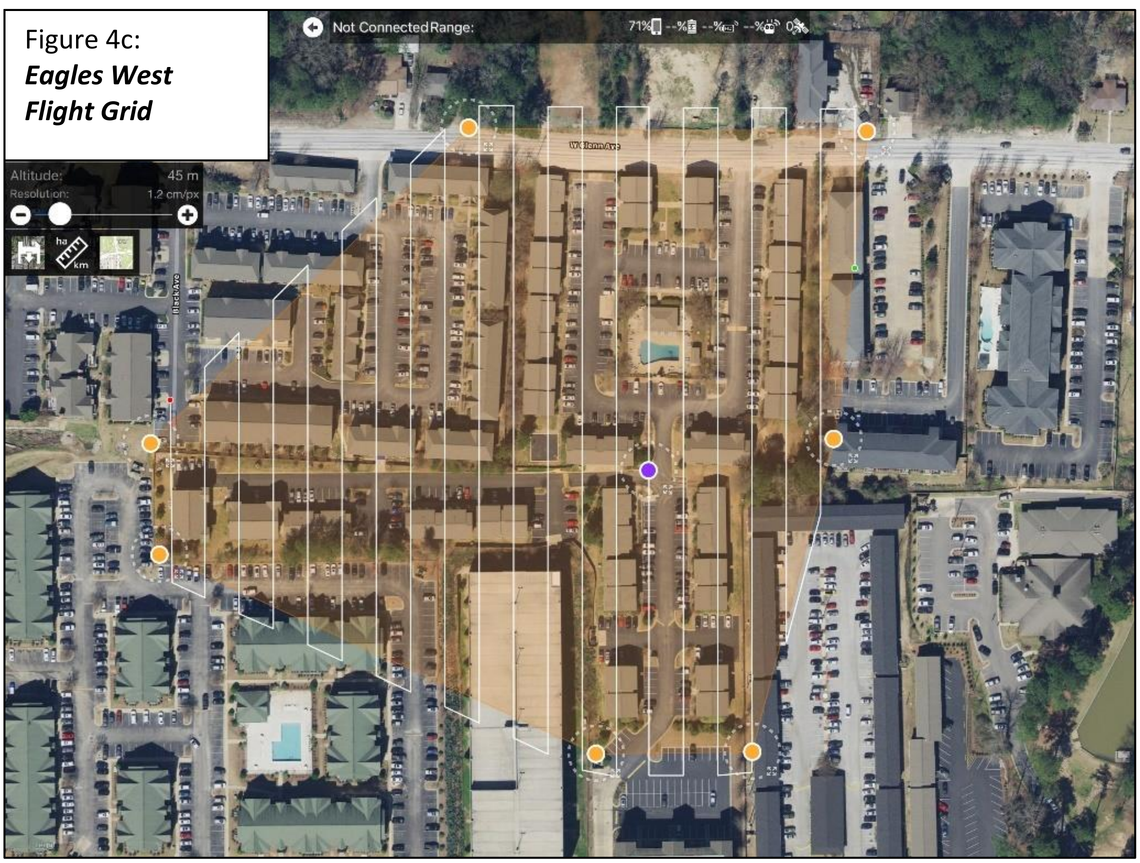


Figure 4c:
Eagles West Flight Grid

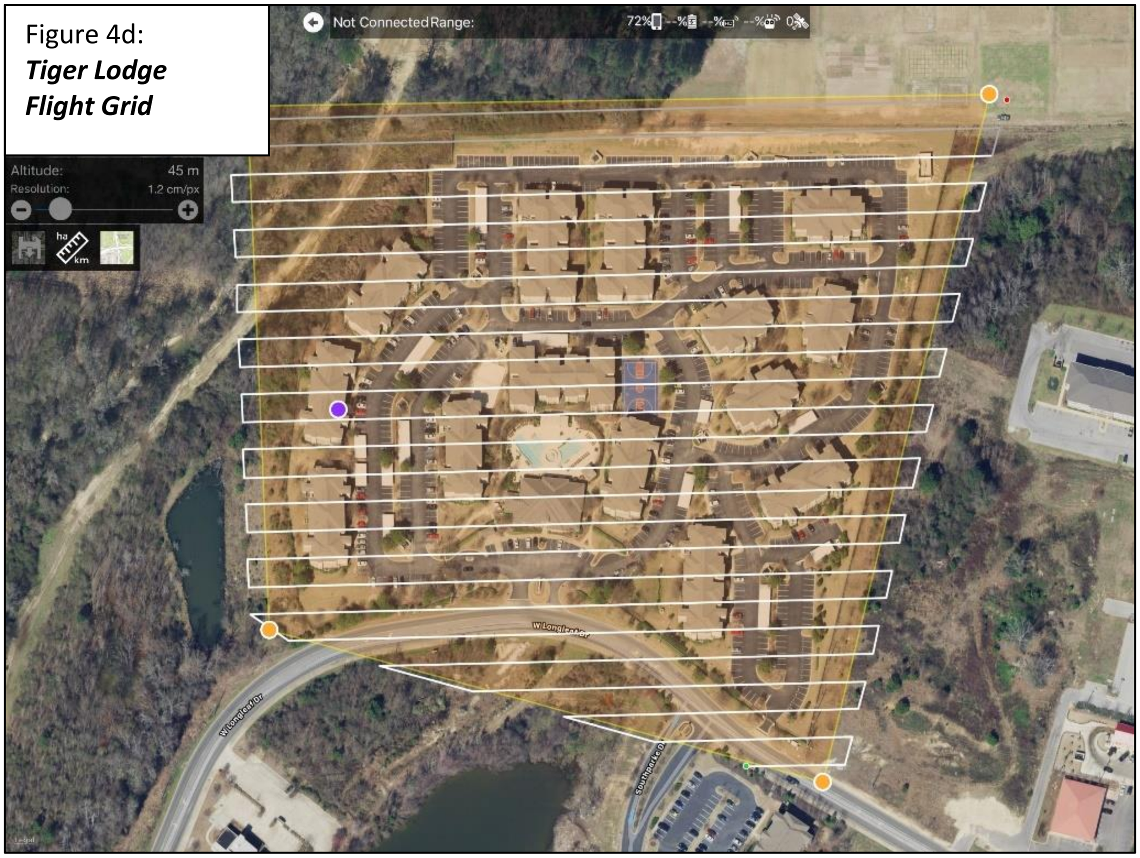


Figure 4d:
Tiger Lodge Flight Grid

5.1.3. Pix4D Processing: “Initial Processing” – Stage 1

After the flights are flown, then the images taken are collected from the sUAS and organized for processing in the photogrammetry software *Pix4D Mapper*. In *Pix4D Mapper*, processing is broken into three separate phases that are sequentially dependent: “Initial Processing”, “Point Cloud and Mesh”, and “DSM, Orthomosaic, and Index”. These three processing stages each contain their own unique options and parameters that are determined by the user before each stage is started. To determine which settings might be optimal for this project, it is necessary to understand how the three stages work and what processes occur during them.

During the Initial Processing stage, the uploaded sUAS images are used to create a "keypoint" cloud. In *Pix4D*, keypoints are unique textures detected in multiple images that are used to create 3D georeferenced points (Pix4D 2018). The keypoint cloud serves as the basis for all the following data processing steps, so it is crucial that it is high quality and has a lot of matches. Oftentimes, when attempting processing and the keypoint cloud turns out poorly, then the issue resides in a lack of image overlap. Optimal areas for keypoint generation tend to be heterogeneously textured, non-reflective, static, and simple in their geometry. In contrast, problematic areas for keypoint generation tend to be homogenously textured, highly reflective, dynamic, and contain complex geometry (Pix4D 2018). Examples of this would include areas with large bodies of water (which tend to be homogenous and reflective), dense tree canopies, or large agricultural fields. Fortunately, the sites for this study are considered urban in their built form, so they meet all the criteria for being optimal mapping locations. Since the basis of the keypoint cloud generation depends on finding matching textures between multiple images (Stretcha 2014), then there are more opportunities for matches when the amount of image overlap is higher.

Due to the smaller size of the four study sites, it is feasible to allow for longer processing time if the trade-off is higher quality results. For this reason, Geometrically Verified Matching (GVM) is incorporated in the Initial Processing stage. GVM is a processing option which allows for slower but more robust keypoint matches by enabling the software to consider the relative camera positions to get rid of geometrically unrealistic matches (Pix4D 2018). Without the option enabled, *Pix4D* would only use the images' content to determine keypoint matches. Another option that is enabled is the Rematch option, which allows the software to rematch and add more matches after the first part of the Initial Processing stage has completed; this setting by default is disabled for projects with more than 500 images. Lastly, the user can manually create keypoints to provide redundancy and to verify that the matching process is accurate. It is worth noting that the manually created keypoints are weighted to affect the results more than the automatically generated points. For all four study locations, 10 manual keypoints were created at distributed locations throughout each site since approximately 10 is the recommended amount by the *Pix4D* user manual for projects of this scale. Figure 5a illustrates a manual keypoint being created, and Figure 5b depicts the keypoint cloud (with manual keypoints) generated for the *Garden District* site.

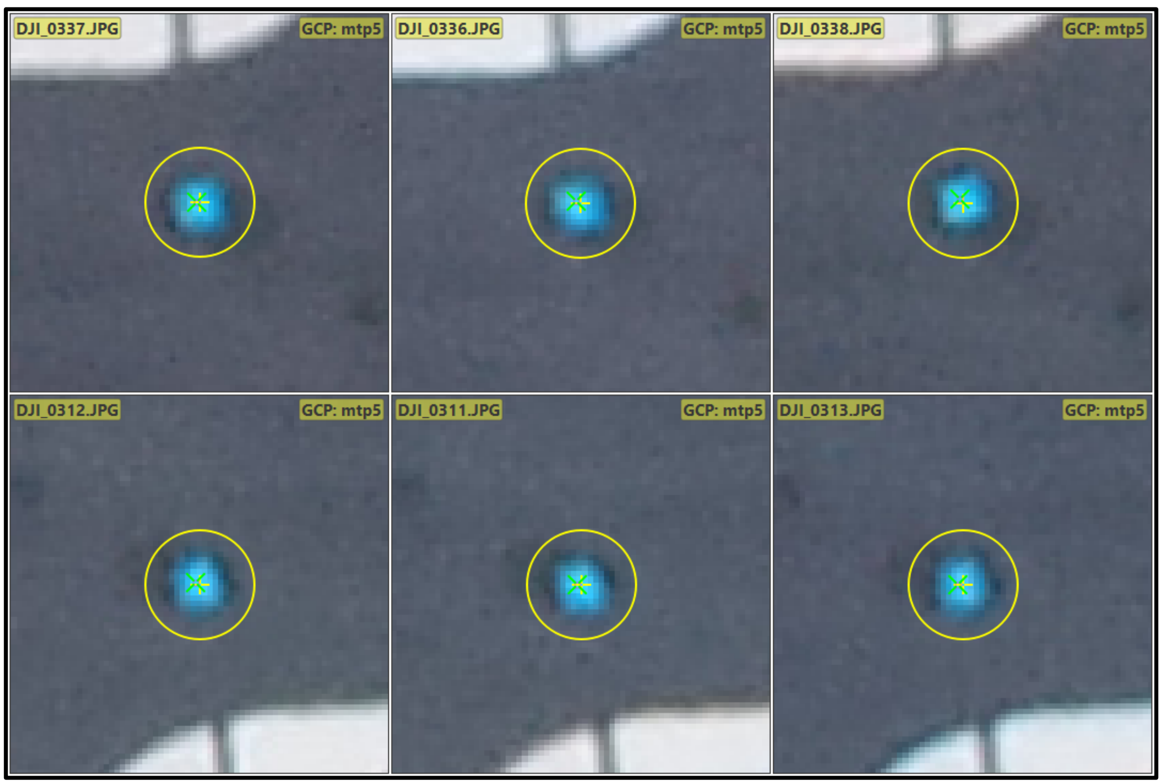


Figure 5a. ***Manual Keypoint Creation***. The user can manually designate common keypoints between multiple images. These are commonly created on small, permanent features such as road paint, building corners, or sewer covers.

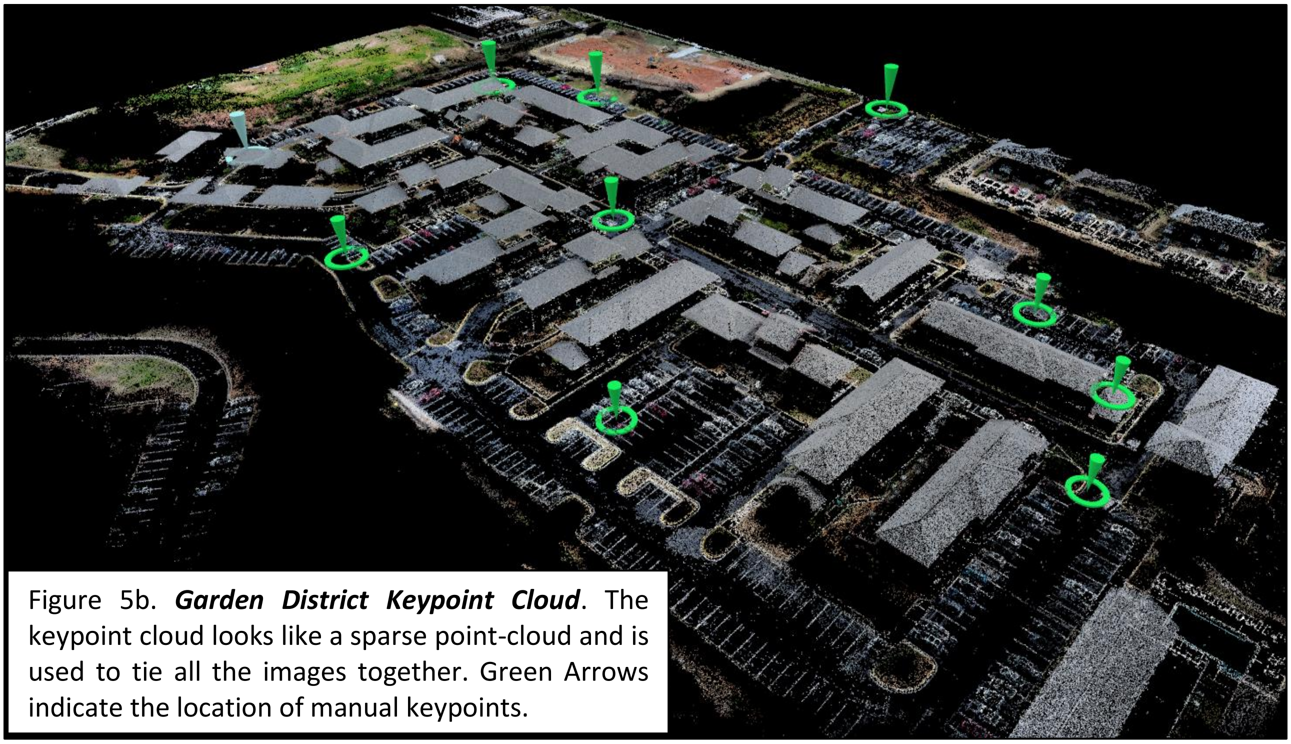


Figure 5b. ***Garden District Keypoint Cloud***. The keypoint cloud looks like a sparse point-cloud and is used to tie all the images together. Green Arrows indicate the location of manual keypoints.

After running the Initial Processing stage, the user can assess the resulting keypoint cloud for accuracy and determine if the data is ready to move onto the next stage, “Point Cloud and Mesh”; this accuracy check can be accomplished by looking at the quality report that is generated by *Pix4D* at the end of the Initial Processing Stage. The quality report provides information on several quality indicators, such as camera calibration (Figure 6), image geolocation, and the number of keypoint matches. Arguably the most useful quality indicator is the Uncertainty Ellipses map for the 2D keypoint matches; this figure depicts the computed image positions with links between matched images. The resulting map figure provides the user with an idea of what areas of the study site might be less reliable due to less keypoint matches being present. See Figure 7 for the Uncertainty Ellipses map for the *Garden District*.

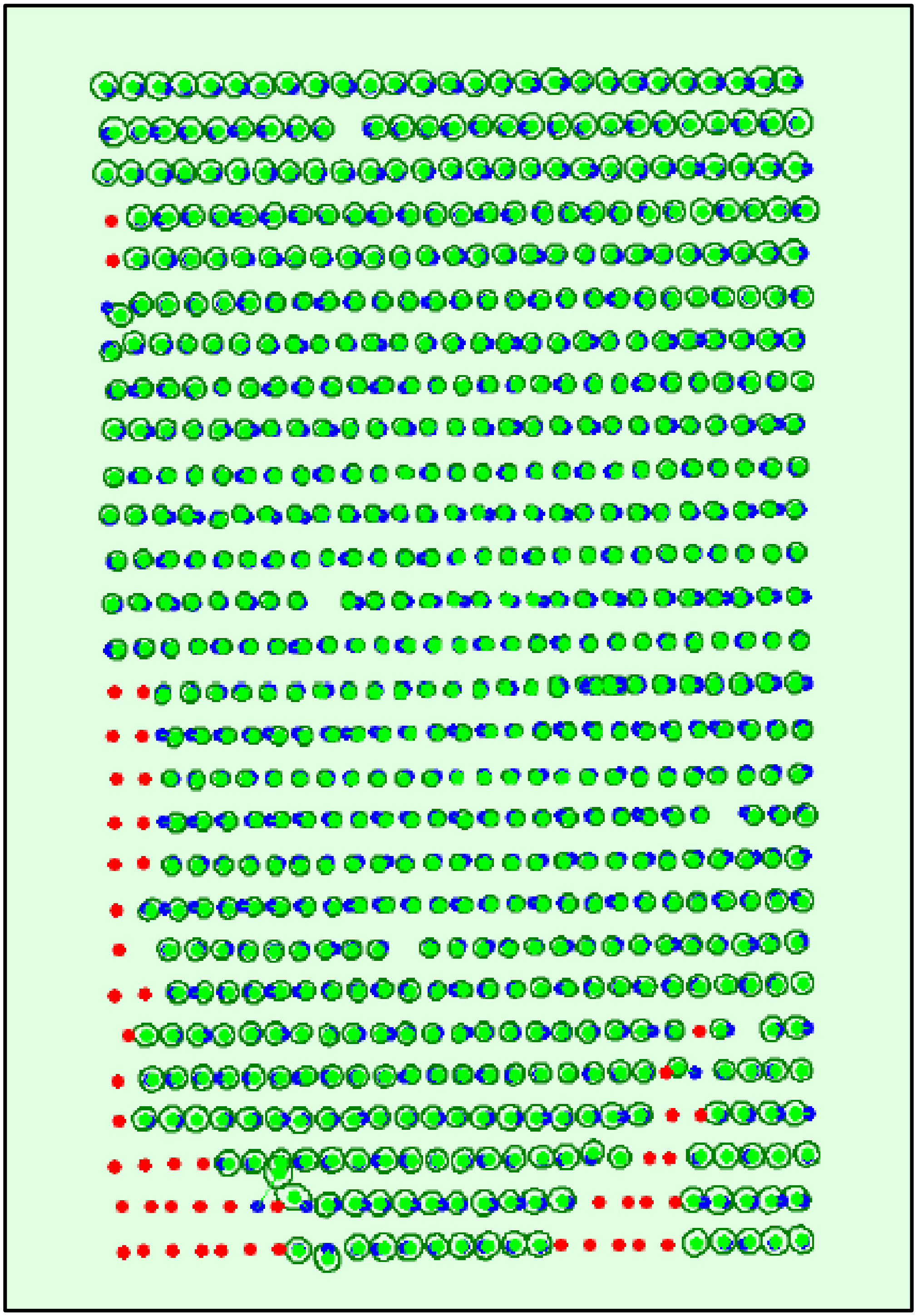


Figure 6. ***Image Calibration for Garden District*.** Image above shows the initial (blue) and computed (green) locations of the images. The red dots indicate uncalibrated images that were not used for the keypoint generation. Uncalibrated images generally result from a lack of image overlap, or the textures in those images were not optimal for matching.

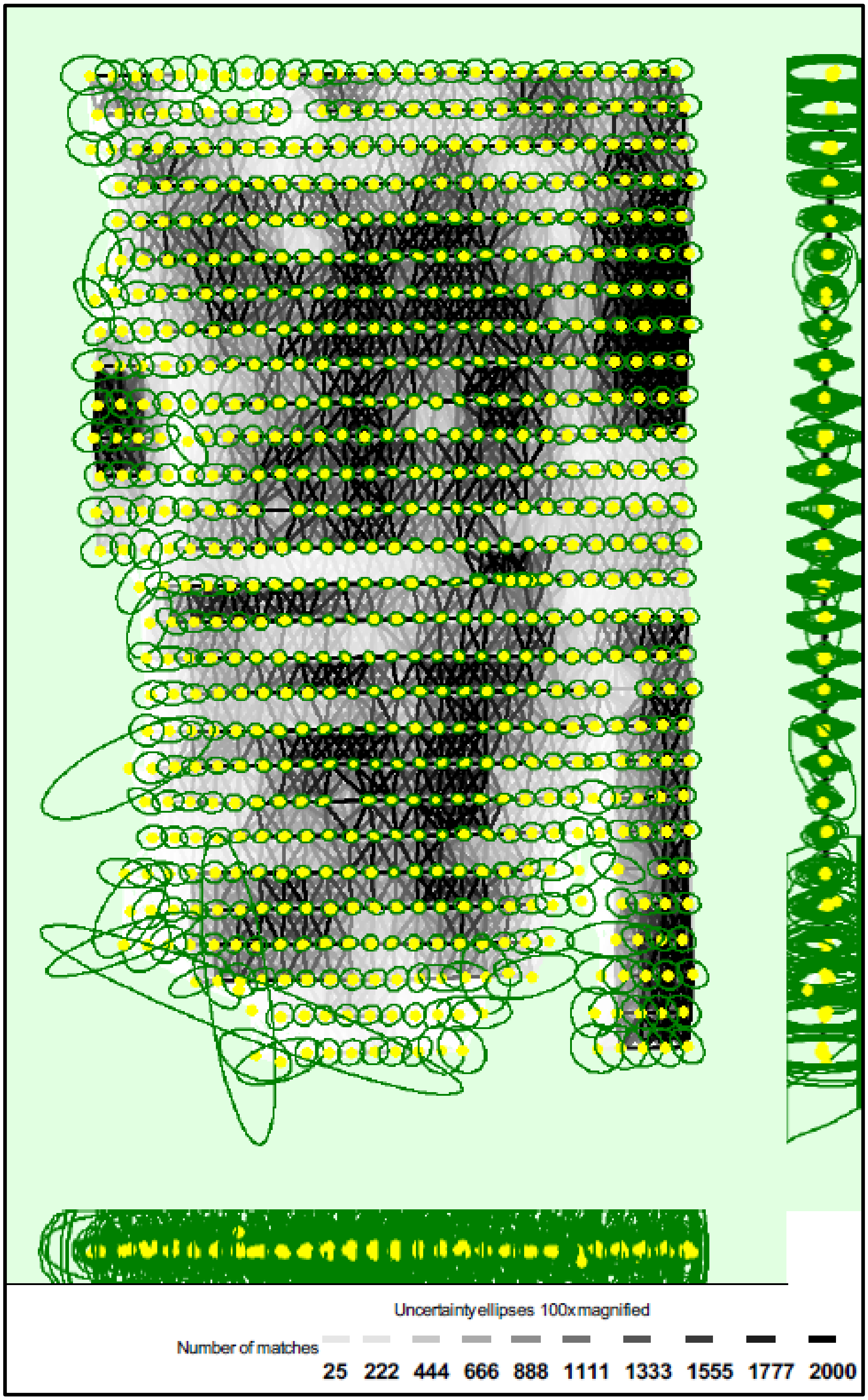


Figure 7. ***Uncertainty Ellipses for Garden District*.** Image on left shows the number of keypoint matches (links) between images. Dark links indicate more matches, brighter links indicate less matches. Areas with less matches are assumed to be less reliable in their measurement accuracy.

5.1.4. Pix4D Processing: “Point Cloud and Mesh” – Stage 2

During the Point Cloud and Mesh stage of processing, *Pix4D* will use the keypoint cloud and input images to generate a 3D densified point cloud and the 3D textured mesh outputs. The 3D densified point cloud is the primary mid-stage data product of interest since it will act as the input data for the third processing stage, which creates the 2D orthomosaic output. Just like with the options for the Initial Processing stage, there are several settings that need to be incorporated in the Point Cloud and Mesh stage that might differ from the defaults. One important setting is the minimum number of matches between images required for a 3D point to be created at any given location. For this project 3 minimum matches were required, based upon the *Pix4D* manual's recommendation for projects this size. Generally, if a higher number of minimum matches is required, then the resulting point cloud will only consist of points that were more commonly matched across images; there will tend to be less overall points, but those points would be assumed to be more accurately positioned. Another setting worth noting is the Matching Window Size, which determines the size of the grid used to match the densified points in the original images. The two options provided by *Pix4D* are window sizes of 7x7 pixels or 9x9 pixels. Generally, 7x7 pixels is selected for faster processing times and is suggested when used with larger projects that primarily consist of nadir images. 9x9 pixels tends to have a longer processing time but determines a more accurate position for the densified points in the original images (Pix4D 2018). For this study, a matching window of 7x7 was used since all the images taken were from a nadir orientation. Once all the settings have been selected, then the second stage of processing is initialized to create the point cloud data.

With the second stage of processing completed, then the point cloud results can be visually assessed for accuracy and quality. In some instances, *Pix4D* will generate incorrectly placed points around features, which can cause distortions in the final outputs, like the orthomosaic maps. These incorrect points need to be removed to improve the data before moving into stage 3 of processing. Fortunately, there is a tool within *Pix4D* that allows the user to manually edit the point cloud data and delete selected points. This tool, referred to as the Edit Densified Point Cloud tool, lets the user select groups of points via drawing a polygon shape over a group of points and then remove them from the point cloud (Pix4D 2018). All four study sites' point cloud data were manually edited to remove erroneous points using the Edit Densified Point Cloud tool. See Figure 8 for a comparison of before/after images during this process for a group of points.

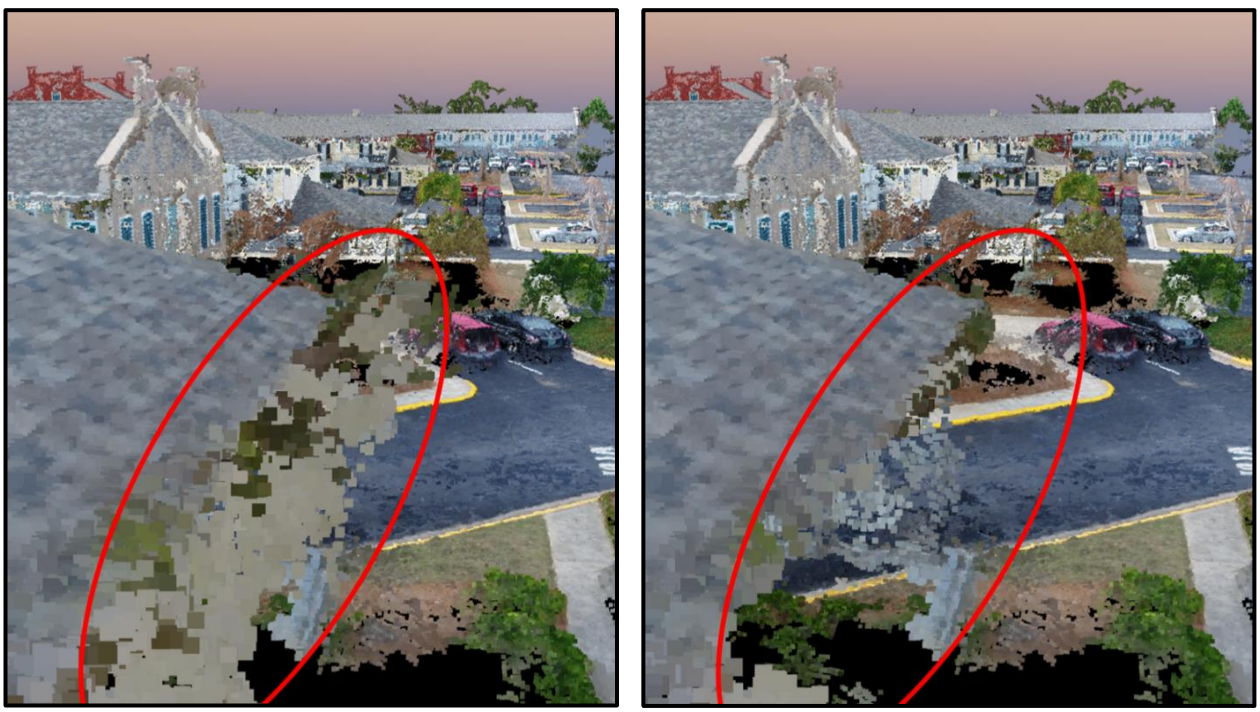


Figure 8. ***Before & After Image - Edit Densified Point Cloud*****.** Image on left shows points along the edge of a roof in the *Garden District* that are incorrectly located. Image on right shows what it looks like after the points have been removed using the Edit Densified Point Cloud tool.

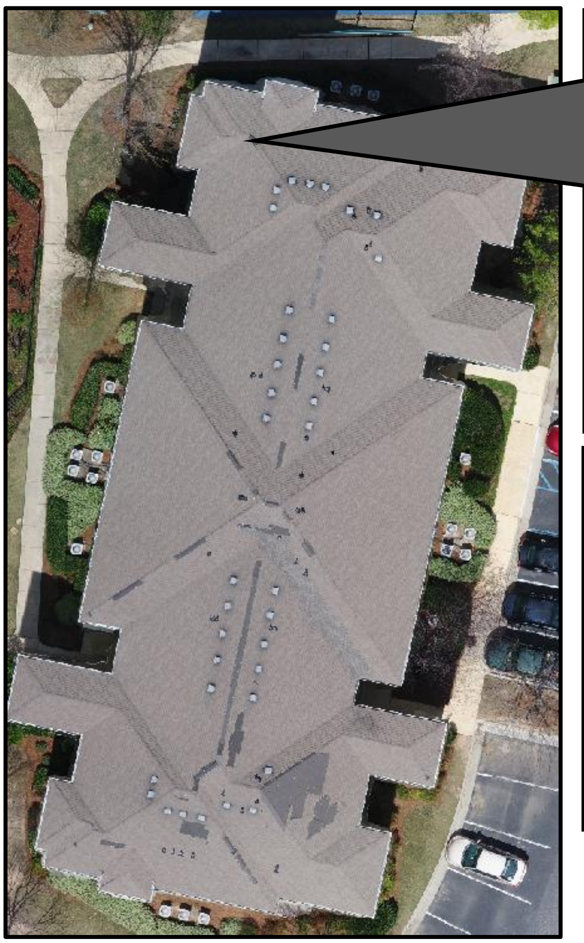
5.1.5. Pix4D Processing: “DSM, Orthomosaic, and Index” – Stage 3

With the point cloud data corrected and erroneous points removed, the last stage of processing can take place. The DSM, Orthomosaic and Index stage is the final phase of processing which focuses on generating elevational models (both Surface Models and Terrain Models), Orthomosaic maps, Contour maps, and Reflectance Index maps. For this project, we are only interested in the Orthomosaic outputs, however, the Digital Surface model is also required. *Pix4D* utilizes orthorectification, a method that removes the perspective distortion from the sUAS images by using the Digital Surface Model (Pix4D 2018). Therefore, the accuracy of the final orthomosaic output is completely dependent on the quality of the original 3D data generated in the first two stages of processing. Since orthorectification is used, then distances can be preserved and the orthomosaic outputs can be used for measurements (Pix4D 2018). *Pix4D* allows the user to set a Ground Sampling Distance (GSD) for the DSM and Orthomosaic, which for this project is 1.5cm. The GSD is determined by the altitude that the images were taken from and the quality of the camera used to take the images. Once the GSD has been set then the third stage can be initialized to create the final outputs.

5.1.6. Orthomosaic Results & Assessment

Once the third stage of processing has finished, then the final orthomosaic outputs should be generated. Now that all *Pix4D* processing is over then we can visually assess the quality of the output maps for any error artifacts. To achieve the best results of the manual digitization and the rainwater harvesting calculations that will take place in later steps, it is imperative that the building rooftop edges are free of artifacts and distortion effects in the orthomosaic maps. Often, features of significant difference in elevation in

Pix4D orthomosaic outputs can have mapping distortions along the edges of the feature; this would include features such as building rooftops, fences, statues, lamp posts, etc. Sometimes these distortions are of no concern if they do not affect the features' geometries. However, if they do affect the geometry of the feature then they need to be corrected. This correction can normally be handled by using the Edit Densified Point Cloud tool, like previously mentioned, and then re-running the third stage of processing. An example of these distortions can be seen in Figure 9 below.



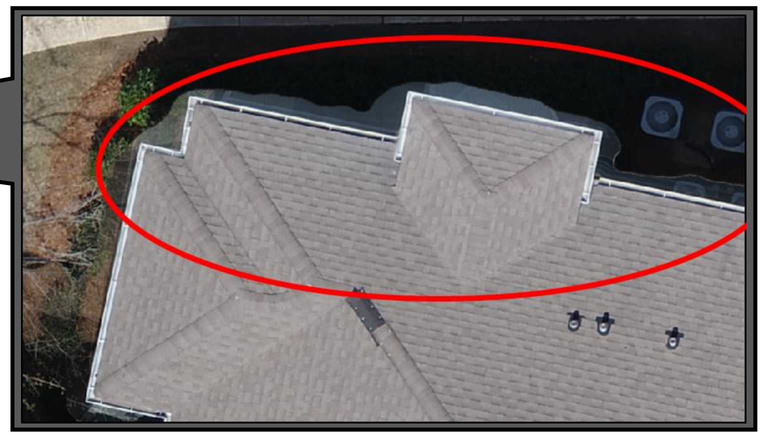


Figure 9. ***Orthomosaic Distortions on Tiger Lodge building.*** Image on left shows a view from the final orthomosaic of a building at the Tiger Lodge apartments. When zoomed in (above), there are some distortions near the roof's edge. This distortion does not affect the geometry of the roof's edge but does misrepresent what is on the ground adjacent to the building. This type of distortion has no effect on the geometric measurements of the rooftops, which is this study's primary measurement of interest.

The results of the Orthomosaic generation for each of the four sites can be seen on the following pages; see figures 10a-10d.

Figure 10a. ***Garden District Orthomosaic Map.*** Image above is the final orthomosaic output map for the *Garden District* site at 1.5cm resolution.

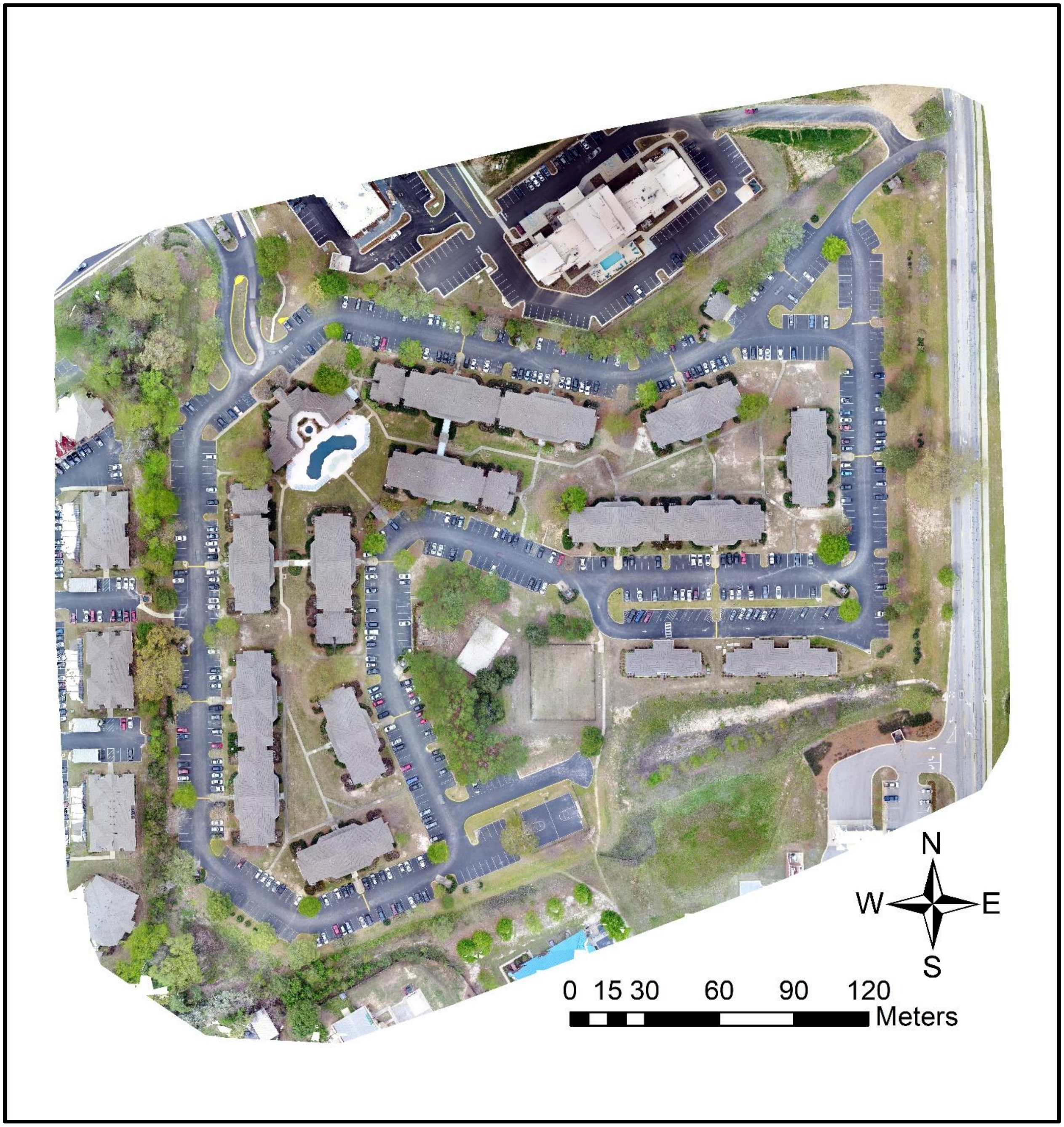


Figure 10b. ***Eagles South Orthomosaic Map.*** Image above is the final orthomosaic output map for the *Eagles South* site at 1.5cm resolution.

Figure 10c. ***Eagles West Orthomosaic Map.*** Image above is the final orthomosaic output map for the *Eagles West* site at 1.5cm resolution.

Figure 10d. ***Tiger Lodge Orthomosaic Map.*** Image above is the final orthomosaic output map for the *Tiger Lodge* site at 1.5cm resolution.

5.2. Image Classification of Orthomosaics

The orthomosaic map outputs for each of the four sites were successfully created using the sUAS imagery and provided little error in the orthorectification. Prior to the manual digitization, to validate that the output maps were created accurately and maintained proper geometry of shapes, they were compared to aerial imagery of the sites within the *Google Earth Pro* platform, as well as the previously mentioned 6'' aerial imagery available for Lee County. Since *Pix4D* can export the orthomosaics as *Google Earth* files (.kml), then they can be opened within *Google Earth* and overlaid on top of the default satellite imagery. The orthomosaic outputs were overlaid on top of the 6" imagery and visually inspected in *ArcMap*. A visual comparison to both sets of imagery can be conducted to verify that the features within the images line up when superimposed on each other.

With the orthomosaics finished for each of the four study sites, then the image classification step can begin. During this step of the project, the orthomosaic maps need to be classified into several classes that we will need for the rainwater harvesting calculations later. For now, the classes will be Pervious, Rooftops, and Impervious (excluding rooftops). Even though there are various image classification methods that would be well suited for this project, manual classification will be the simplest and provide the least amount of error. If project scale does not create a time-constraint, then manual classification methods tend to be more effective and efficient if the user is familiar with the area being digitized (Abburu & Golla 2015). Since the sites are relatively small, then the time spent manually digitizing is assumed to be less than what would be required in error correction for an unsupervised automated method. The GIS workflow for the manual classification method can be seen below in Figure 11.

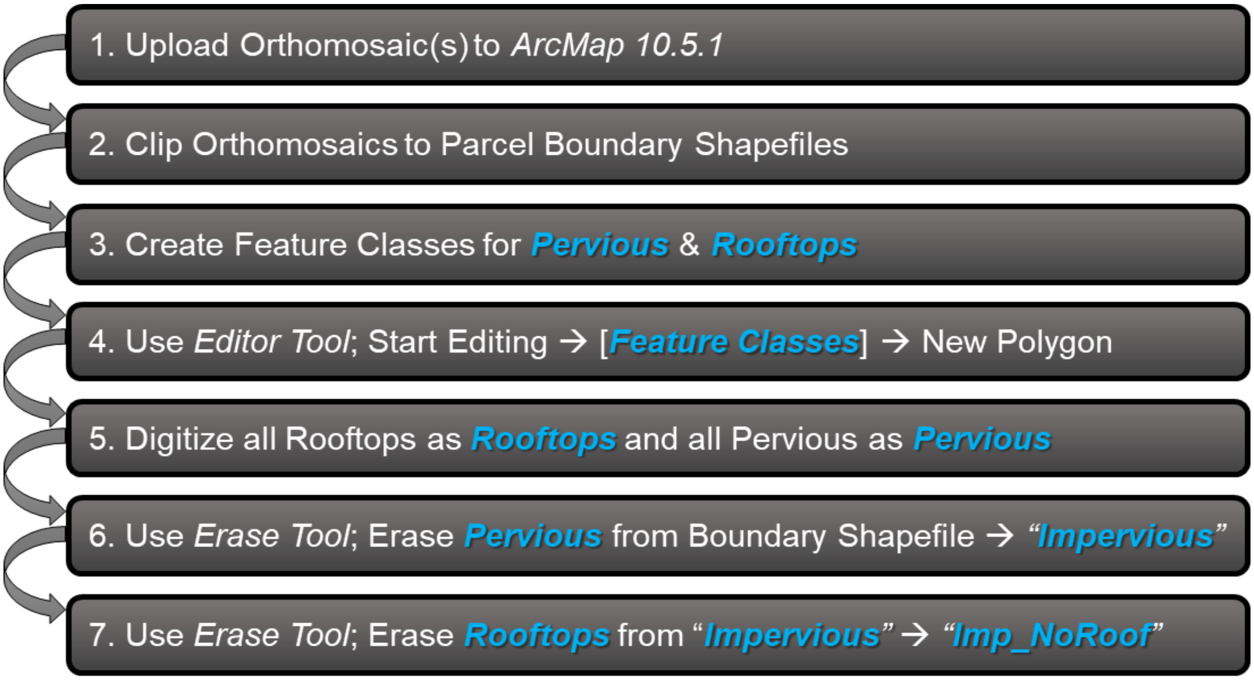


Figure 11. ***Manual Digitization Workflow.*** Diagram above lists the steps taken to digitize the images.

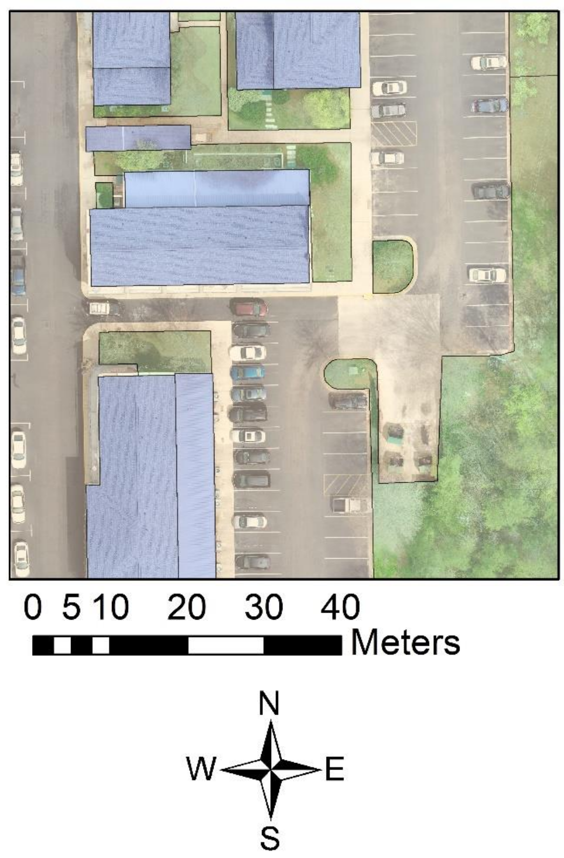
The process of manually digitizing each of the four sites is simple and only requires time and patience, for the most part. First the orthomosaics and any other necessary data are uploaded to *ArcMap 10.5.1*; this includes the city-provided parcel shapefiles which designate property boundaries for all land parcels in Auburn, AL. The parcel shapefiles will serve as our boundary indicators, since we want to present our results in relation to the parcel of land that the multi-family housing is located in. Since it is difficult to determine how much of the land surrounding the buildings needs to be considered with the LULC classifications and RHC calculations, this study will use the property boundaries to stay consistent between sites. Therefore, all resulting calculations will be specific to the land parcel that the multi-family housing is in. After all necessary data is added to *ArcMap*, then the orthomosaics for each study site will be clipped to the respective parcel boundary shapefiles. Since some of the orthomosaics include land outside of the parcel boundaries, then Clip is necessary to get rid of extra land that is not of interest (i.e. not within the property boundaries). After clipping the orthomosaics, the feature classes for “Pervious” and “Rooftops” need to be created for each site. By using the Editor tool, both feature classes for each site can be populated by creating new polygons over the appropriate LULC on the maps. Once finished, then we should have completely mapped classes for all the rooftops and pervious areas on all four maps. To classify all the remaining impervious areas (since all pervious has now been manually digitized), the Erase tool will be used to delete all areas classified as “Pervious” and “Rooftops” from the entire parcel boundary polygon. The result of this should be all the land that was not digitized into either of the two classes, “Pervious” or “Rooftops”, is now digitized as a single “Impervious” class. Then with one last step, the Erase tool can be used again to erase all “Rooftop” classified areas from the new “Impervious” layer, resulting in an impervious layer excluding rooftops. With those steps finished, we now have all four sites classified into “Rooftops”, “Pervious”, and “Impervious”.

6. Results Part I: Orthomosaics & Site Classifications

The results of the manual digitization of the four sites can be seen in Figures 12a-12d on the following pages. All four of the sites were able to be successfully digitized and the resulting LULC compositions were able to be computed using the Calculate Geometry tool in relation to the attribute tables of the land-use classes for each site. The Calculate Geometry tool allowed for the areal measurements of all polygons within a given class, to be measured in square meters (listed below figure descriptions). The computed area measurements for each of the classes are listed with the related figure below.

Figure 12a. ***Garden District Land-Use Classification.*** Image on the bottom-right shows a closer view of the classified features. Image on the left shows the full view of the classified parcel.

Land-Use Composition:
Rooftops: 11805.40m² (**15.84**%)
Pervious: 37483.08m² (**50.32**%)
Impervious: 25199.07m² (**33.83**%)
Total: 74487.55m²



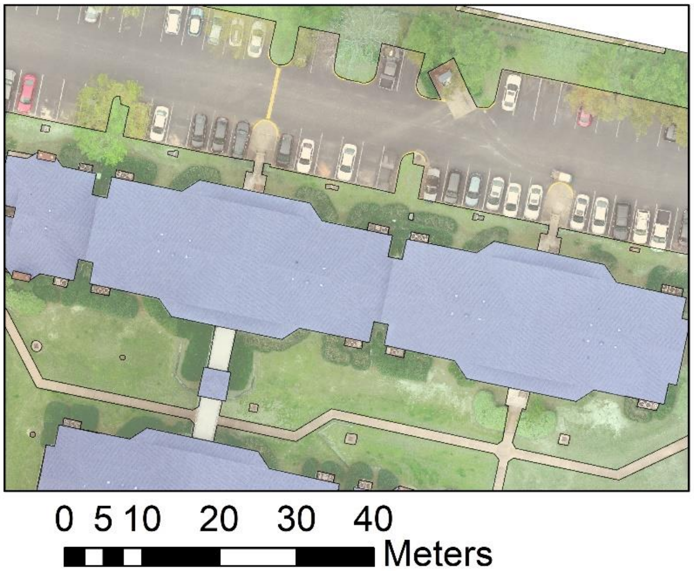
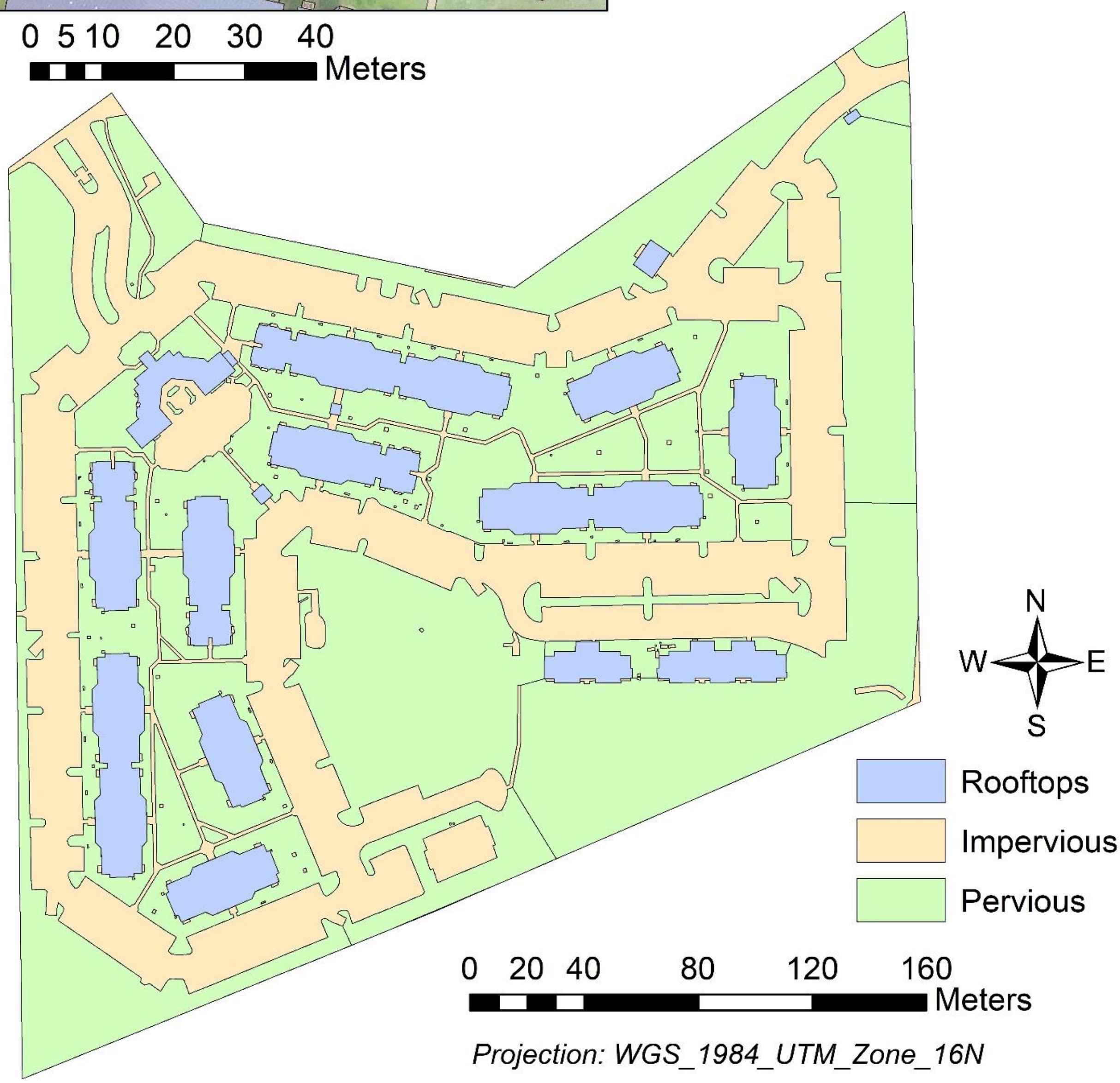


Figure 12b. ***Eagles South Land-Use Classification.*** Image on the left shows a closer view of the classified features. Image below shows the full view of the classified parcel.

Land-Use Composition:
Rooftops: 10,159.31m² (**12.93**%)
Pervious: 42,475.71 m² (**54.06**%)
Impervious: 25,930.68 m² (**33.01**%)
Total: 78,565.7m²



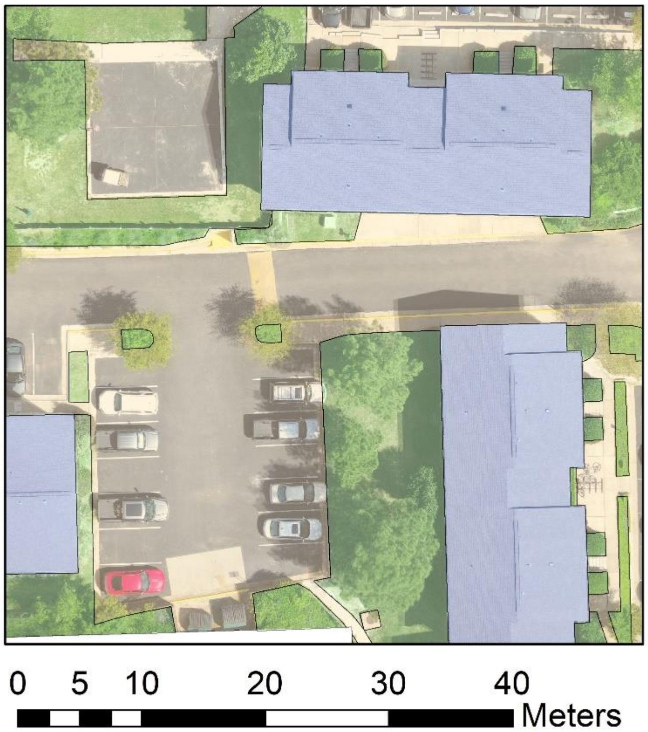
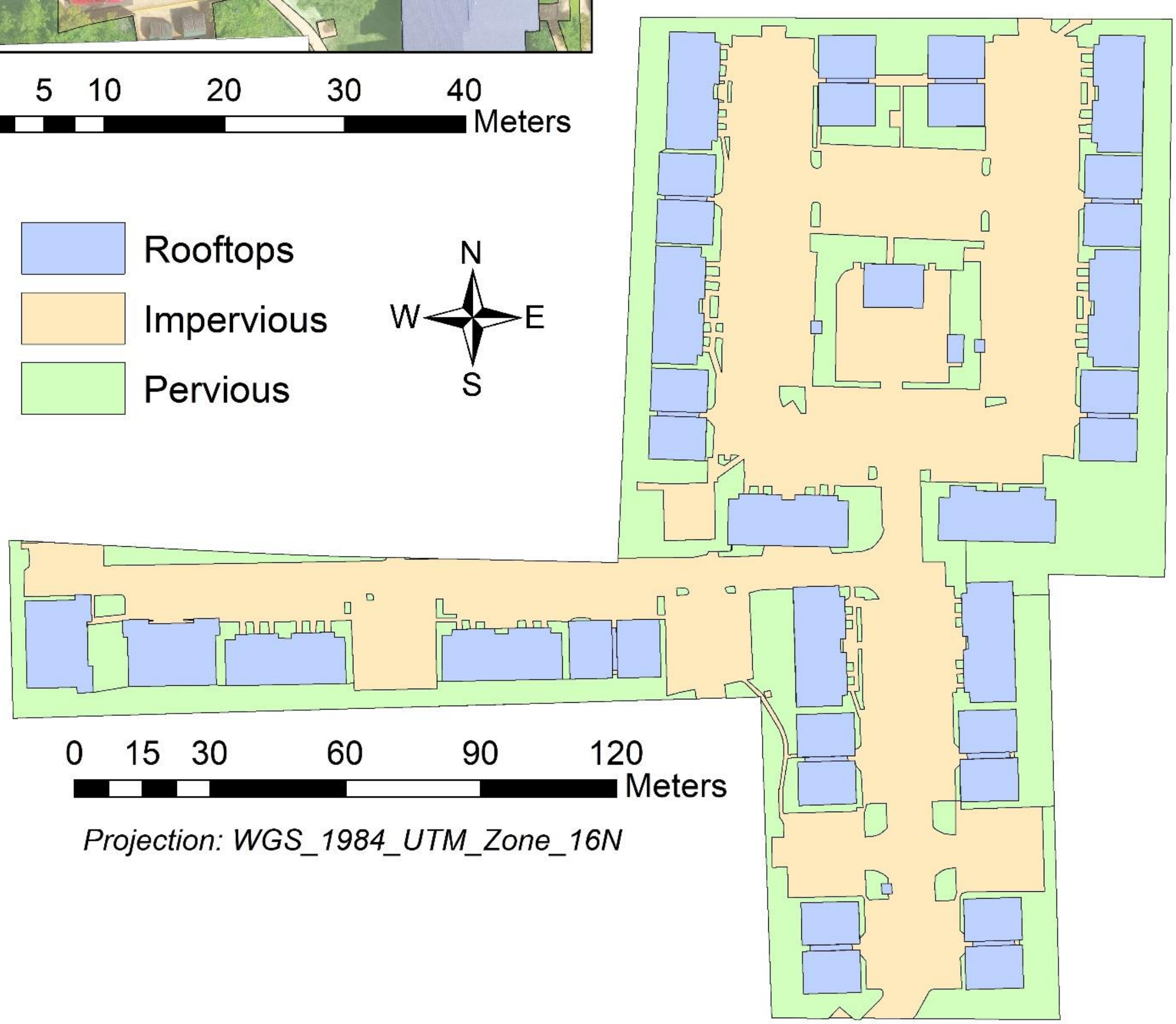


Figure 12c. ***Eagles West Land-Use Classification.*** Image on the left shows a closer view of the classified features. Image below shows the full view of the classified parcel.

Land-Use Composition:
Rooftops: 6407.41m² (**24.12**%)
Pervious: 7820.92m² (**29.43**%)
Impervious: 12341.84m² (**46.45**%)
Total: 26570.17m²



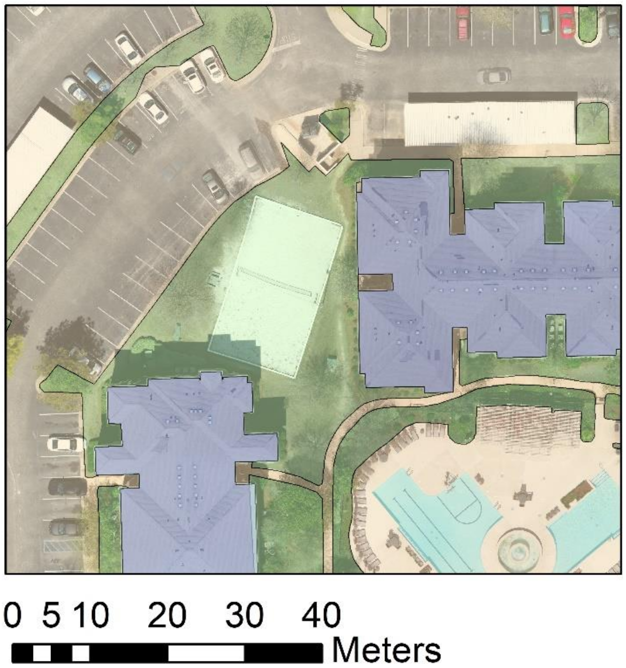
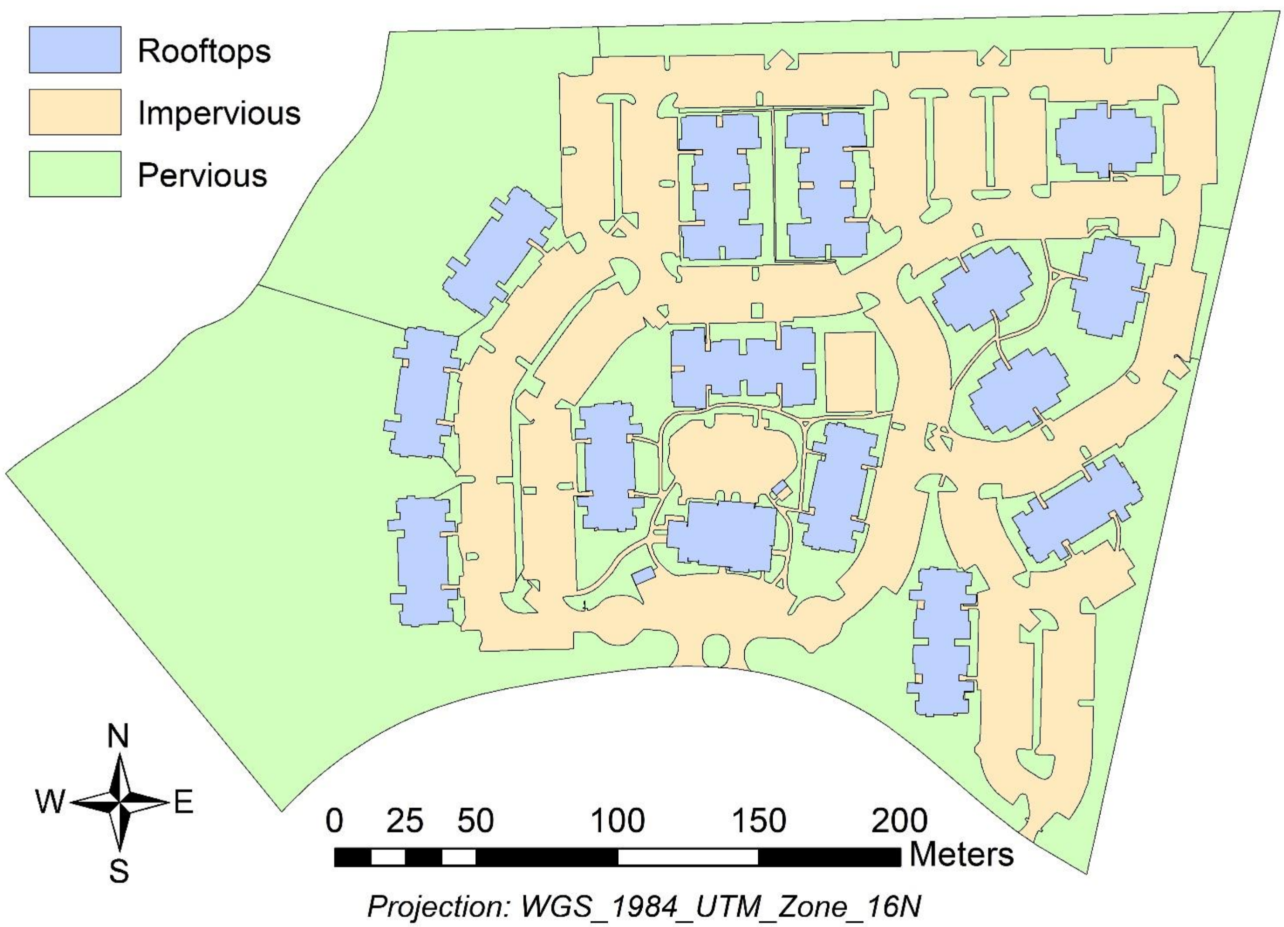


Figure 12d. ***Tiger Lodge Land-Use Classification.*** Image on the left shows a closer view of the classified features. Image below shows the full view of the classified parcel.

Land-Use Composition:
Rooftops: 13,083.12m² (**14.59**%)
Pervious: 46,532.91m² (**51.89**%)
Impervious: 30,060.20m² (**33.52**%)
Total: 89,676.23m²



7. <u>Methods Part II: Rainwater Harvesting Calculations</u>

7.1. National Stormwater Calculator

Now that each of the sites have been mapped and digitized to derive the LULC compositions, it is now time to move onto the second part of this project which is calculating the rainwater harvesting potential. With each of the sites fully digitized and characterized, the basic site measurement inputs necessary for the EPA's *National Stormwater Calculator* (NSWC) tool are ready. NSWC relies on data derived from several national databases, including soil data from the U.S. Department of Agriculture's Natural Resources Conservation Service and precipitation data from the National Weather Service's National Climatic Data Center. The user is required to supply the LULC data for each site of interest, as well as the characteristics of any Low-Impact Development (LID) method of interest (being rainwater harvesting in this study). These classes are entered as percentages of the composition of the site. Using the site classifications from the previous step, the LULC inputs can be used to run the calculator.

There is one caveat that needs to be addressed. The NSWC utilizes the following classes: Forest, Desert, Lawn, Meadow, Impervious, and other optional LID classes. The classes that we created for the four sites are only Impervious, Rooftops, and Pervious. The Impervious and Rooftops classes are fine to use as they are, however, the Pervious class needs to be adjusted. Since the purpose of this study is to ultimately quantify the runoff reduction with RHC implemented, then we are not concerned with the runoff differences between the pervious land-covers required for the NSWC. Therefore, since the only classes that are present in our pervious areas are Lawn and Forest, then all four sites will be assumed to be 50% Forest and 50% Lawn within their respective Pervious classes. This allows for the NSWC runoff outputs to not show differences between the pervious classes, but rather to only show the differences with & without RHC implementation.

To assess the potential for RHC in these sites, the calculator will be used to quantify stormwater runoff without rooftop RHC and the results will be compared to the stormwater runoff with rooftop RHC implemented. See Figure 13 below for a methods workflow diagram of the inputs and outputs associated with the NSWC tool.

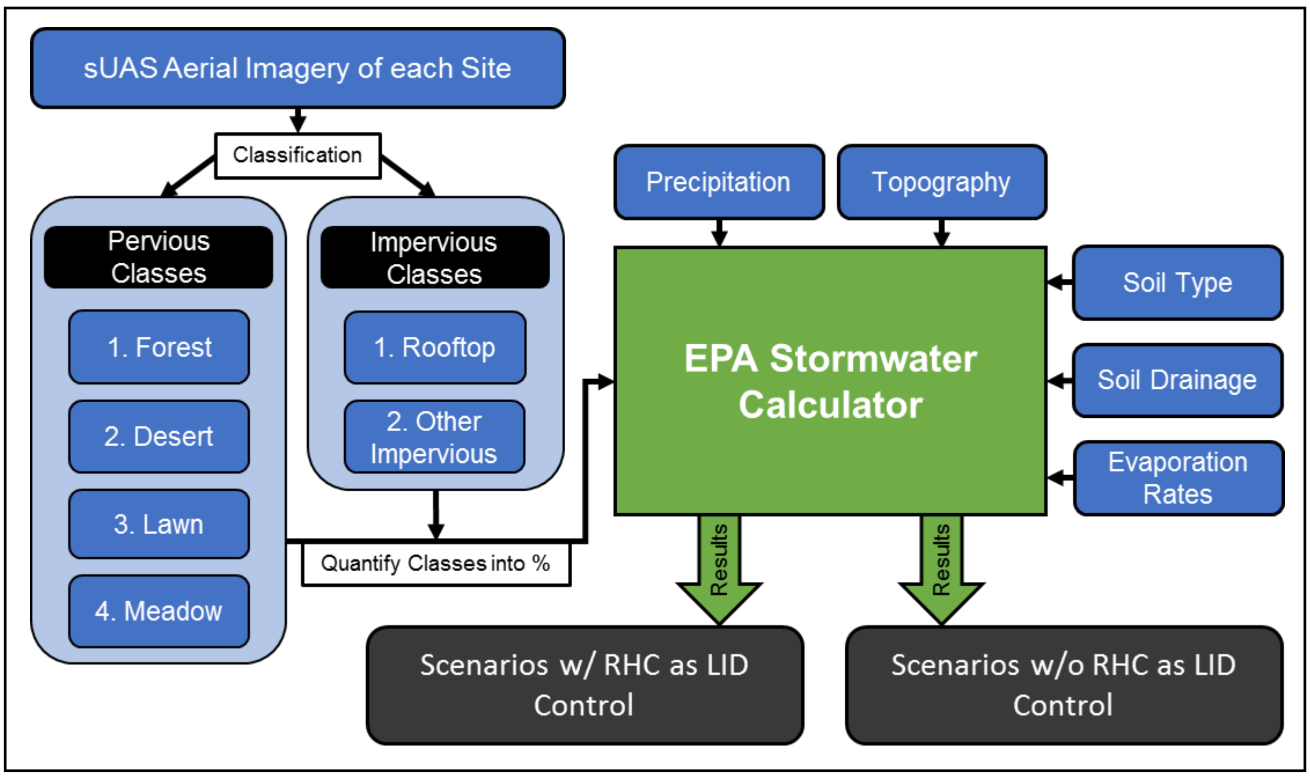


Figure 13. ***Methods Workflow.*** This figure illustrates the general workflow utilized to create RHC scenarios with the EPA's Stormwater Calculator (NSWC).

In September 2017, the EPA released an updated version of the NSWC that is now more user friendly and can be accessed via their website (https://swcweb.epa.gov/stormwatercalculator). The updated version (1.2.1) allows users to generate their scenarios and measurements directly in their web browser, without the need for downloading and installing the software first. This new iteration lends to the tool's simplicity and allows for less-experienced users to take advantage of its abilities. The mobile version will be used for this study to generate the RHC scenarios.

When creating the stormwater runoff scenarios in the NSWC, there are several parameters that need to be paid attention to. Since this study is primarily interested in the rainwater runoff reduction resulting from RHC implementation, then some assumptions need to be made for all four of the sites. The first assumption is that all the sites' pervious areas are exactly 50% lawn and 50% forest in composition. We do not want the NSWC scenario results to detect differences in runoff resulting from different pervious compositions within each site, but rather to detect the runoff differences resulting from RHC implementation. Therefore, this study is assuming that the pervious land composition for all the sites are the same. Another assumption that needs to be noted is that the potential location and structure design for rainwater harvesting storage tanks at each site (i.e. cisterns) are not considered in the scenarios. All the sites' NSWC scenarios will be generated with scenarios that do not rely on rainwater storage designs or sizes; a base storage value used in the NSWC for storage is 500-gallon cisterns with 500 gal/day use rate every 1,000sqft. The rainwater storage size inputs for the NSWC are set at the values mentioned above since those values do not impact the amount of rainfall reduction at the sites and the barrels are assumed to not overflow their capacity. For each of the four sites, two NSWC scenarios will be generated that show the runoff conditions with RHC implementation and without RHC implementation. These 8 scenarios will be modeled over a 10-year interval of precipitation data for Auburn, AL with a 0.1in. event threshold constituting a “wet day”; the event threshold designates the minimum amount of rainfall per day that is sufficient enough to be considered a rainfall event.

Once the 8 scenarios have been generated, then the resulting stormwater runoff predictions can be used to determine the total volume of rainwater that would constitute the runoff reduction at each specific site. Since the NSWC presents the runoff results in rainfall inches, then the difference in runoff reduction (i.e. the amount assumed to be captured by the rooftops and stored) can be used to derive the volume of rainwater that would be captured and not turn into runoff, in relation to the sites’ areal dimensions. The formula used to calculate the total amount of potential rainwater collection is extremely simple and uses the surface area measurement for the site, the amount of rainfall, and a conversion factor of .62gallon per 1inch rainfall per 1 sqft. Since 1inch of rainfall over 1 sqft. is equal to .62gallons of volume, then we can use that to figure out the total volume of runoff based on the two other variables. This formula is very simplistic and does not account for several factors that would affect the final volume estimates, so the results should be interpreted as simple approximations that provide a general indicator of the sites’ RHC impacts. The formula is:

[Rainfall (in.)] X [Surface Area (sqft.)] X [.62] = [Volume of Rainwater (gal)].

Using the *ArcMap* shapefiles for each of the four sites’ parcel boundaries, the total area for each can be calculated and used as the surface area input in the formula. Then the total reduction in rainfall runoff for each will be used as the rainfall amount inputs.

After inputting the values, the runoff reduction for each site can be presented in total volume amounts.

8. Results Part II: RHC Calculations

8.1. Garden District

The results for the Garden District RHC calculations can be seen below in Table 2a. The LULC composition used for the NSWC is 15.84% Rooftops, 33.83% Impervious, and 50.32% Pervious. The soil type condition was set as Sandy Loam (Moderately Low drainage). The runoff from pervious areas in the site was set at .5inch/hour. The surface slope was set at 5%.

Categories:	With RH Implementation	Without RH Implementation
Average Annual Rainfall (in.)	53.77	53.77
Average Annual Runoff (in.)	22.04	24.35
Days per Year with Rainfall	74.86	74.96
Days per Year with Runoff	52.37	55.27
Land Cover – Forest (%)	25.16	25.16
Land Cover – Lawn (%)	25.16	25.16
Land Cover – Impervious (%)	49.68	49.68
LID Control – Rain Harvesting (%)	15.84	0

Table 2a. ***Garden District NSWC Results.*** This table contains the NSWC results generated for the two scenarios modeled for the *Garden District* site.

An annual runoff reduction of **2.31in** can be achieved with RHC implemented at the site, given the parameters and assumptions used with the NSWC. Also, the number of days per years with runoff is reduced by **2.9 days**. Using the water volume formula,

[2.31in] x [801777.32sqft] x [.62gal], the total annual runoff reduction for the *Garden District* is **1,148,305.48gal**.

8.2. Eagles South

The results for the Eagles South RHC calculations can be seen below in Table 2b. The LULC composition used for the NSWC is 12.93% Rooftops, 33.01% Impervious, and 51.89% Pervious. The soil type condition was set as Sandy Loam (Moderately Low drainage). The runoff from pervious areas in the site was set at .5inch/hour. The surface slope was set at 5%.

Categories:	With RH Implementation	Without RH Implementation
Average Annual Rainfall (in.)	53.78	53.78
Average Annual Runoff (in.)	20.72	22.45
Days per Year with Rainfall	78.46	74.96
Days per Year with Runoff	51.27	53.87
Land Cover – Forest (%)	27.03	27.03
Land Cover – Lawn (%)	27.03	27.03
Land Cover – Impervious (%)	45.94	45.94
LID Control – Rain Harvesting (%)	12.93	0

Table 2b. ***Eagles South NSWC Results.*** This table contains the NSWC results generated for the two scenarios modeled for the Eagles South site.

An annual runoff reduction of **1.73in** can be achieved with RHC implemented at the site, given the parameters and assumptions used with the NSWC. Also, the number of days per years with runoff is reduced by **2.6 days**. Using the water volume formula,

[1.73in] x [845674.12sqft] x [.62gal], the total annual runoff reduction for *Eagles South* is **907,070.06gal**.

8.3. Tiger Lodge

The results for the Tiger Lodge RHC calculations can be seen below in Table 2c. The LULC composition used for the NSWC is 14.59% Rooftops, 33.52% Impervious, and 54.06% Pervious. The soil type condition was set as Sandy Loam (Moderately Low drainage). The runoff from pervious areas in the site was set at .5inch/hour. The surface slope was set at 5%.

Categories:	With RH Implementation	Without RH Implementation
Average Annual Rainfall (in.)	53.76	53.76
Average Annual Runoff (in.)	21.34	23.38
Days per Year with Rainfall	74.86	74.96
Days per Year with Runoff	51.37	54.57
Land Cover – Forest (%)	26.94	26.94
Land Cover – Lawn (%)	26.94	26.94
Land Cover – Impervious (%)	46.12	46.12
LID Control – Rain Harvesting (%)	14.59	0

Table 2c. ***Tiger Lodge NSWC Results.*** This table contains the NSWC results generated for the two scenarios modeled for the Tiger Lodge site.

An annual runoff reduction of **2.04in** can be achieved with RHC implemented at the site, given the parameters and assumptions used with the NSWC. Also, the number of days per years with runoff is reduced by **3.2 days**. Using the water volume formula,

[2.04in] x [965266.91sqft] x [.62gal], the total annual runoff reduction for the *Tiger Lodge* is **1,220,869.59gal**.

8.4. Eagles West

The results for the Eagles West RHC calculations can be seen below in Table 2d. The LULC composition used for the NSWC is 24.12% Rooftops, 46.45% Impervious, and 29.43% Pervious. The soil type condition was set as Sandy Loam (Moderately Low drainage). The runoff from pervious areas in the site was set at .5inch/hour. The surface slope was set at 5%.

Categories:	With RH Implementation	Without RH Implementation
Average Annual Rainfall (in.)	53.74	53.74
Average Annual Runoff (in.)	29.70	34.76
Days per Year with Rainfall	78.46	74.96
Days per Year with Runoff	57.37	61.27
Land Cover – Forest (%)	14.72	14.72
Land Cover – Lawn (%)	14.72	14.72
Land Cover – Impervious (%)	70.56	70.56
LID Control – Rain Harvesting (%)	24.12	0

Table 2d. ***Eagles West NSWC Results.*** This table contains the NSWC results generated for the two scenarios modeled for the Eagles West site.

An annual runoff reduction of **5.06in** can be achieved with RHC implemented at the site, given the parameters and assumptions used with the NSWC. Also, the number of days per years with runoff is reduced by **3.9 days**. Using the water volume formula,

[5.06in] x [285998.93sqft] x [.62gal], the total annual runoff reduction for *Eagles West* is **897,235.84gal**.

9. Discussion of Results:

9.1. Part I: Orthomosaics & Site Classifications

Research objective #1 was met after generating the results for Part I of this study. The orthomosaic generation and site classifications were critical in determining the RHC calculations in Part II. Due to the high resolution of the orthomosaic maps (1.5cm), the manual digitization steps were much more precise and allowed for obvious error to be corrected. An example of this can be seen in all the sites where there are portions of buildings and other impervious surfaces that were obscured by an overhanging tree or other vegetation; see the zoom-in portions of figures 12a-12d. The 3D data also allowed for specific areas to be more closely inspected when it was difficult to determine an area's LULC class from the orthomosaic map's nadir view. Since the digitization was manual, then these issues could be addressed and not misclassified. For all four sites, the quality reports produced by *Pix4D Mapper* indicated that the required inputs were sufficient to create reliable map outputs. This is especially true after the error correction methods were used and the outputs were re-generated. Within each site, the least reliable areas for measurements (but still reliable enough for this study) tended to be features on the maps that consisted of homogenous textures, such as parking lots and large grassy fields. Fortunately, the areas of primary interest (building rooftops) are also the areas that received the highest density of keypoint matches; see figure 7 again for an illustration of this.

In terms of measurement reliability, the orthomosaic maps used were assessed for accuracy both by *Pix4D* in the quality report outputs, as well as visually by overlaying them on top of airborne LiDAR imagery provided by Lee County. The quality reports for all four sites stated that the map outputs were reliable (using uncertainty measurements), aside from one minor portion of the *Garden District* site. In the *Garden District*, a small south-western grouping of images could not be properly calibrated, so they were left out of the processing steps. This is considered a negligible error since the area that could not be mapped is a completely forested area, so the manual classification was able to address the lack of image data at that location and still classify the area correctly.

The LULC classifications for all four of the sites yielded some interesting results, especially in relation to how much surface area of each parcel was composed of rooftops. Surprisingly, three of the sites (GD, TL, ES) all had relatively similar compositions of LULC: approximately ~12-15% rooftop, ~33% pervious, and ~50-54% impervious. *Eagles West* was the only site to significantly differ, demonstrating a much higher ratio of impervious and rooftops to pervious land-use. The difference between this site and the other three can be largely attributed to the fact that *Eagles West* is cloistered in a very urban location, surrounded by other dense multi-family housing. Even though *Eagles West* is smaller than all the other sites, it maintains a relatively high ratio of impervious surfaces that lends to its ability to generate more runoff per unit of area than the others.

9.2. Part II: RHC Calculations

The results of the RHC calculations demonstrated that there is a significant amount of rainwater that can be captured and prevented from becoming runoff at all four of the sites. For this reason, research objectives #2 and #3 were considered to have been met.

Even though the sites' LULC compositions and total parcel sizes vary, each site demonstrated a noticeable impact when RHC was implemented in the scenarios. Given the assumptions made, the four sites were able to reduce their parcel-specific runoff between ~900,000 gallons to ~1.2million gallons annually. Table 3 below presents the rainwater runoff reduction values for each site in comparison to one another.

Categories:	Garden District	Eagles South	Tiger Lodge	Eagles West
Total Volume of Annual Rainwater Runoff Reduction (gal.)	1,148,305.48	907,070.06	1,220,869.59	897,235.84
Annual Rainwater Reduction (in.)	2.31	1.73	2.04	5.06
Total Surface Area of Parcel (sqft.)	801,777.32	845,674.12	965,266.91	285,998.93

Table 3. ***Annual Runoff Reduction Results.*** This table contains the site-specific runoff reduction values in comparison to one another.

When looking at the final RHC volumes presented, it is necessary to keep in mind the assumptions mentioned that were used when calculating the RHC amounts. When running the NSWC, the RHC settings were set to account for the theoretical storage tanks emptying each day completely due to on-site water use. Since water demand can vary greatly among localities and residence style, it is difficult to accurately project how much of the potential rainwater would be collected and used by residents on-site. In future work, this could be accounted for by obtaining the water use statistics from the property owners of the housing developments and use those consumption numbers as a reference point in the calculations. Therefore, a more accurate storage container size could be proposed, given the characteristics of that specific site.

Another significant result from this study that needs to be discussed is the impact of the LULC composition in relation to the parcel's size. For example, *Eagles West* is only 29.63% of the size of the *Tiger Lodge*, however, *Eagles West* generated 73.49% of the amount of rainfall runoff that was generated at the *Tiger Lodge*. Even though *Eagles West* is much smaller in total area, its higher ratio of impervious surfaces and rooftops caused it to generate 3.02in more than the *Tiger Lodge* in annual rainwater runoff. This relationship between LULC composition and land size presents an opportunity for future studies, since knowing the relationship might be useful in city development planning. By establishing this relationship further, then there might be more opportunity for understanding the interplay between the surface conditions and the amount of runoff generated.

9.3. Limitations and Assumptions

The results generated by the NSWC illustrate significant impacts if RHC were implemented at each of the four sites, however, all these results' significance rely on several key assumptions and limitations that need to be addressed. For this study, there were assumptions made in both Part I (sUAS Data Generation) and Part II (Rainwater Harvesting Calculation) that impact the results, however, do not detract from the results' significance.

In Part I, it was deemed unnecessary to implement Ground Control Points (GCPs) to improve the geographic coordinate location information of the four sites. Since the measurements of interest in this study (i.e. rooftops, sidewalks, etc.) are small, then the impact of geographic coordinates have less impact on the quality of the final measurement results (Pix4D 2018). *Pix4D* can process sUAS imagery with or without image geotag information. Since the software processes the imagery based on image content, instead of solely relying on image orientation and location, then the impacts of not implementing GCPs at the four sites is negligible. Also, the use of Manual Keypoints (discussed in section 5.1.3) assisted in improving the accurate matching of points between images during processing. Another assumption made during Part I is that the manual digitization is completely representative of the parcel's LULC characteristics. Since this method of digitization was chosen, then there is a minor opportunity for user-induced error through mistakenly digitized LULCs. To address this, this study utilized the same person to digitize all four sites, to prevent variation between digitizations if multiple users were involved in digitizing. This study does acknowledge that there is potential for unaddressed error if the manual digitization was crudely performed by the user, however, the final classifications were visually inspected for error and considered free of any major misclassifications that might significantly alter the LULC classifications

In Part II, there were two major assumptions made. Since the NSWC uses relatively coarse supplementary data (such as the precipitation trends, soil conditions, and topographical conditions) in the calculations, then the resulting scenario measurements need to be recognized as demonstrative of the sites' conditions, but not a 100% perfect representation. For instance, the rainfall data used is collected at one single gauge location in the city of Auburn, however, rainfall patterns vary within the city, so it is expected that some of the sites might experience more rain or less rain than others during any given year. The second major assumption made was that the storage capacity and expected water usage for each site had no impact on the end results. All scenarios were created with the assumption that any rainwater collected would be immediately stored and then completely used; there would be no storage capacity overflows. If the sites were equipped with storage containers that were improperly sized (and residents failed to use all the collected water), then the benefits of RHC would be lost as the containers would overflow and contribute to runoff. For this reason, if RHC were implemented, then the storage capacity would need to be properly estimated to prevent being undersized and not fulfilling its purpose. Similarly, one limitation worth noting is that the runoff characteristics of any of the four sites cannot be assumed to accurately represent the characteristics of other urban properties in Auburn. Due to the significant variation in LULC conditions across parcels of land in Auburn, then the results for each site are unique to themselves and not suitable for acting as representations of others.

10. Significance of Research:

10.1. Stormwater Management & City Development

This study's results are significant to stormwater management professional and others concerned with city development and the use of LID controls. Since the EPA has a persistent interest in stormwater management practices and the implementation of Best Management Practices (BMPs), then it is no surprise that the NSWC tool is quite robust in its capabilities. This study demonstrated only one niche use of the tool, however, there are many more scenarios that can be created for a variety of purposes. Many of the steps taken in this project can be replicated but for a different LID control scenario, or a different geographical location. There are plenty of variables that can differ, however, the base process of determining LULC characteristics and inputting them into the NSWC to generate stormwater scenarios remains the same. Therefore, the real significance of this study rests in the fact that it is representative of what is possible with the NSWC. Urban planners, water resource managers, stormwater analysts, and many other professionals involved in development that is impacted by stormwater can make use of this tool, using very similar steps to those taken in this project.

This project has presented the possibility for future work to be conducted in Auburn using the NSWC on a much broader scale too. With the tool's simplicity, it would be rather time and cost effective for future studies to be conducted for other land parcels in the area. For instance, if there are flood-prone areas within Auburn, then this tool might be of use to officials concerned with mitigating the impacts of stormwater in those areas. By allowing the user to model several LID options, then multiple scenarios can be run to compare different approaches to solving a stormwater related problem. If more research is conducted on the subject in Auburn and similar cities, then there is also a potential for updating relevant documents (such as the CompPlan 2030) that pertain to stormwater management strategies using case-study evidence as support. By incrementally improving the regulations and strategies used to manage stormwater runoff, cities will be better prepared to develop in a more sustainable manner while addressing these critical issues.

10.2. sUAS use as Research & Outreach Tool

The assessment of using a consumer-grade sUAS as a research tool to acquire aerial imagery in an effective manner was another significant outcome. This study was originally intended to make use of conventional satellite imagery, or airborne imagery, however, the researchers were presented with the opportunity to use a sUAS to collect the necessary data. In terms of operational efficiency, the sUAS was simple to operate for data collection and took relatively little time to conduct the flights; operating the sUAS on the flight days was the easiest part of data collection. However, in terms of risk management and addressing liability, using an sUAS in this research project was a challenging task due to regulatory compliance requirements. Due to the current laws and regulations, operating an sUAS in urban settings is at times complicated and requires certain considerations (such as obtaining property owner or manager permissions). Ultimately, after addressing the necessary regulations, the sUAS proved to be an extremely efficient research tool and presents a myriad of opportunities for future research projects that necessitate high-resolution aerial imagery. Based on the results of this study and the growing body of literature on the subject, there are promising opportunities for the continued integration of sUAS in professional disciplines that at times utilize aerial data. Practitioners in urban planning, public safety, public works, and many other related disciplines stand to benefit from adopting some of the sUAS methods used in this study due to the broad applicability of the concepts.

Another significant result that came out of the use of a sUAS in this research project is that a series of outreach videos were created under the guidance and support of AmericaView, a nationwide consortium for remote sensing education, research, and geospatial applications. Sponsored by the United States Geological Survey (USGS), AmericaView supported a series of sUAS projects during Fall 2018 that also involved the creation of instructional videos related to the sUAS operations involved with the respective projects. Due to this support, a series of public outreach videos were created that demonstrate most of the methods and techniques used in this project (https://www.youtube.com/watch?v=RLSROJUDjfg&list=PLEHyYp32cIJGUJOnex6hsvgo-KuE_kRpK). These videos are designed to provide instructional assistance to public sUAS users and demonstrate the variety of uses for sUAS. Recognizing a lack of public awareness and knowledge on the topic, AmericaView has begun to actively educate the public about sUAS and their safe operations. As the commercial sUAS market continues to grow, a knowledgeable public will lend to the safe integration of sUAS in the U.S. National Airspace System.

11. Conclusion

The three main objectives of this study were to: 1. develop methodology for using sUAS-derived orthomosaic imagery in determining accurate LULC classifications for four multi-family housing developments in Auburn, AL., 2. delineate the total area of the building rooftops and other site classes using *ArcMap* and derive the LULC classifications, and 3. quantify the reduction of rainwater surface runoff produced at each site if rainwater harvesting is implemented using the web-based *EPA National Stormwater Calculator.* These three objectives are considered to have been addressed and met with meaningful results. Although there were several assumptions and limitations that affected the end results, none were considered impactful enough to take away from the results' significance.

The results of Part I (sUAS Data Generation) showed the feasibility of using a consumer-grade sUAS in aerial data collection and the process of turning these collected images into robust orthomosaic outputs. The process of acquiring the images took relatively little time and effort, however, the process of adhering to all regulatory requirements was more challenging. All four sites were successfully mapped and worked well in demonstrating the quality of orthomosaic that can be generated, assuming certain input parameters. When contemplating using a sUAS for research purposes, users need to also take the impact of regulatory barriers into account when designing their project. Even though a project might be operationally feasible, it might not be possible due to certain regulatory challenges that cannot be met given the conditions. Additionally, many municipalities are adopting “no drone” laws that prevent the operation of sUAS in certain areas of the city, or in the city at all. Fortunately, this was not an issue for Auburn, AL as the city does not currently have any prohibitive sUAS regulations that would impact this study.

The results of Part II demonstrated that the EPA’s NSWC works well for detailed stormwater studies, especially those pertaining to runoff quantity. Values for the reduction in runoff were able to be determined for each of the four sites within the tool, and using an additional simple water volume calculation, the actual total volumes of “captured” rainwater were able to be calculated. The values derived for each of the sites were determined to be approximately ~900,000gallons to ~1,200,000gallons of water annually. This amount of water is significant, however, there is a further step that could be taken in a continuation of this study. Like previously mentioned, if the water use statistics were known for each of the four sites, then they could have been compared to each site’s anticipated amount to be collected. This would provide a suitable illustration of how the RHC implementation would affect the actual water use on the site. Also, this study lacked the ability to provide fieldwork validation of the calculated annual runoff reduction values due to the four sites not currently having RHC systems in place. In future work, the methods used in this study could be applied to a site that has a system already in place, and then use the system as a validation for the calculated results from the NSWC.

By studying the impacts of RHC implementation, in addition to other LID controls, there is a lot of opportunity for city developers and planners to make informed decisions regarding the inclusion of sustainability in their development goals. With easy to use software readily available, such as the EPA's NSWC tool, stormwater professionals and other related practitioners are better equipped to handle the analyses they might need to conduct for their work. When coupled with easy to use aerial data collection equipment (i.e. sUAS), then a wide range of analytical applications are possible and the overall efficiency of a site's stormwater analysis can be greatly improved.

12. References:

Abdulla, Fayez A., and A. W. Al-Shareef. 2009. “Roof Rainwater Harvesting Systems for Household Water Supply in Jordan.” *Desalination* 243 (1): 195–207. doi:10.1016/j.desal.2008.05.013.

Abburu, Sunitha, and Suresh Babu Golla. 2015. “Satellite Image Classification Methods and Techniques: A Review.” *International Journal of Computer Applications* 119 (8): 20–25. https://doi.org/10.5120/21088-3779.

ADEM. 2014. “Low Impact Development Handbook for the State of Alabama.” *Alabama Department of Environmental Management*.

Agüera-Vega, Francisco, Fernando Carvajal-Ramírez, and Patricio Martínez-Carricondo. 2017. “Accuracy of Digital Surface Models and Orthophotos Derived from Unmanned Aerial Vehicle Photogrammetry.” *Journal of Surveying Engineering* 143 (2): 1–10. doi:10.1061/(ASCE)SU.1943-5428.0000206.

Ahiablame, Laurent M., Bernard A. Engel, and Indrajeet Chaubey. 2012. “Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research.” *Water, Air, & Soil Pollution* 223 (7): 4253–73. doi:10.1007/s11270-012-1189-2.

Akbari, Hashem, L. Shea Rose, and Haider Taha. 2003. “Analyzing the Land Cover of an Urban Environment Using High-Resolution Orthophotos.” *Landscape and Urban Planning* 63 (1): 1–14. doi:10.1016/S0169-2046(02)00165-2.

Akpinar Ferrand, Ezgi, and Fatima Cecunjanin. 2014. “Potential of Rainwater Harvesting in a Thirsty World: A Survey of Ancient and Traditional Rainwater Harvesting Applications.” *Geography Compass* 8 (6): 395–413. doi:10.1111/gec3.12135.

Alabama Cooperative Extension System. 2016. “Planning for Stormwater – Developing a low impact solution.” *Alabama Cooperative Extension (Alabama A&M University and Auburn University)*.

Angrill, Sara, Anna Petit-Boix, Tito Morales-Pinzón, Alejandro Josa, Joan Rieradevall, and Xavier Gabarrell. 2017. “Urban Rainwater Runoff Quantity and Quality – A Potential Endogenous Resource in Cities?” *Journal of Environmental Management* 189 (March): 14–21. doi:10.1016/j.jenvman.2016.12.027.

Bayulken, Bogachan, and Donald Huisingh. 2015. “A Literature Review of Historical Trends and Emerging Theoretical Approaches for Developing Sustainable Cities (Part 1).” *Journal of Cleaner Production*, Special Issue: Toward a Regenerative Sustainability Paradigm for the Built Environment: from vision to reality, 109 (December): 11–24. doi:10.1016/j.jclepro.2014.12.100.

Bledsoe, Brian P. 2002. “Stream Erosion Potential and Stormwater Management Strategies.” *Journal of Water Resources Planning & Management* 128 (6): 451.

Boers, Th. M., and J. Ben-Asher. 1982. “A Review of Rainwater Harvesting.” *Agricultural Water Management* 5 (2): 145–58. doi:10.1016/0378-3774(82)90003-8.

Cidell, Julie. 2015. “Performing Leadership: Municipal Green Building Policies and the City as Role Model.” *Environment and Planning C: Government and Policy* 33 (3): 566–79. doi:10.1068/c12181.

City of Auburn. 2011. “CompPlan 2030: The Comprehensive Plan for the City of Auburn.” *City of Auburn Planning Commission*. Auburn, Alabama.

City of Auburn. 2014. “City of Auburn and Auburn University Partner on Urban Sustainability” http://www.auburnalabama.org/PressRelease.aspx?PRID=1194

Danter Company. 2015. “A Student Housing Analysis in the City of Auburn, Alabama.” http://www.auburnalabama.org/planningDocs/Documents/Danter%20MF%20Study%202015.pdf

Daebel, H., and W. Gujer. 2005. “Uncertainty in Predicting Riverbed Erosion Caused by Urban Stormwater Discharge.” *Water Science & Technology* 52 (5): 77–85.

de Jong, Martin de, Simon Joss, Daan Schraven, Changjie Zhan, and Margot Weijnen. 2015. “Sustainable–smart–resilient–low Carbon–eco–knowledge Cities; Making Sense of a Multitude of Concepts Promoting Sustainable Urbanization.” *Journal of Cleaner Production*, Special Issue: Toward a Regenerative Sustainability Paradigm for the Built Environment: from vision to reality, 109 (December): 25–38. doi:10.1016/j.jclepro.2015.02.004.

Domènech, Laia, and David Saurí. 2011. “A Comparative Appraisal of the Use of Rainwater Harvesting in Single and Multi-Family Buildings of the Metropolitan Area of Barcelona (Spain): Social Experience, Drinking Water Savings and Economic Costs.” *Journal of Cleaner Production* 19 (6–7): 598–608. doi:10.1016/j.jclepro.2010.11.010.

E-CFR*: Title 14: Aeronautics and Space*. n.d. *Electronic Code of Federal Regulations*. Vol. Title 14: Aeronautics and Space. https://www.ecfr.gov/cgi-bin/text-idx?SID=e331c2fe611df1717386d29eee38b000&mc=true&node=pt14.2.107&rgn=div5.

Elliott, A. H., and S. A. Trowsdale. 2007. “A Review of Models for Low Impact Urban Stormwater Drainage.” *Environmental Modelling & Software*, Special section: Advanced Technology for Environmental Modelling, 22 (3): 394–405. doi:10.1016/j.envsoft.2005.12.005.

EPA. “National Stormwater Calculator” Epa.gov. https://swcweb.epa.gov/stormwatercalculator (accessed February 18th, 2018)

EPA. 2007. “Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices.” *United States Environmental Protection Agency*.

EPA. 2013. “Our Built and Natural Environments: A Technical Review of the Interactions Among Land Use, Transportation, and Environmental Quality.” *United States Environmental Protection Agency.*

EPA. 2014. “National Stormwater Calculator User’s Guide – Version 1.1” *Office of Research and Development, U.S. Environmental Protection Agency*.

EPA. 2016. “Storm Water Management Model Reference Manual Volume 1 – Hydrology.” *United States Environmental Protection Agency*.

Georgia DCA. 2009. “Georgia Rainwater Harvesting Guidelines.” *Georgia Department of Community Affairs*.

Gleick, Peter H. 2000. “A Look at Twenty-First Century Water Resources Development.” *Water International* 25 (1): 127–38. doi:10.1080/02508060008686804.

Hardy, Andy, Makame Makame, Dónall Cross, Silas Majambere, and Mwinyi Msellem. 2017. “Using Low-Cost Drones to Map Malaria Vector Habitats.” *Parasites & Vectors* 10 (January): 1–13. doi:10.1186/s13071-017-1973-3.

Harper, M.K. and Turner, B.G. 2015. “Estimated Use of Water in Alabama in 2010.” *Alabama Department of Economic and Community Affairs (The Office of Water Resources)*.

Harris, J. A., and B. J. Adams. 2006. “Probabilistic Assessment of Urban Runoff Erosion Potential.” *Canadian Journal of Civil Engineering* 33 (3): 307–18. doi:10.1139/L05-114.

Hogan, Dianna M., S. Taylor Jarnagin, J.v. Loperfido, and Keith Ness. 2014. “Mitigating the Effects of Landscape Development on Streams in Urbanizing Watersheds.” *Journal of the American Water Resources Association* 50 (1): 163–78. doi:10.1111/jawr.12123.

Hua-Peng Qin, Qiao-Ling Tang, Li-Yu Wang, and Guangtao Fu. 2015. “The Impact of Atmospheric Wet Deposition on Roof Runoff Quality in an Urbanized Area.” *Hydrology Research* 46 (6): 880–92. doi:10.2166/nh.2015.209.

HUD. 2003. “The Practice of Low Impact Development.” *United States Department of Housing and Urban Development*.

Hugenholtz, Chris H., Ken Whitehead, Owen W. Brown, Thomas E. Barchyn, Brian J. Moorman, Adam LeClair, Kevin Riddell, and Tayler Hamilton. 2013. “Geomorphological Mapping with a Small Unmanned Aircraft System (sUAS): Feature Detection and Accuracy Assessment of a Photogrammetrically-Derived Digital Terrain Model.” *Geomorphology* 194 (July): 16–24. doi:10.1016/j.geomorph.2013.03.023.

Jones, Matthew P., and William F. Hunt. 2010. “Performance of Rainwater Harvesting Systems in the Southeastern United States.” *Resources, Conservation and Recycling* 54 (10): 623–29. doi:10.1016/j.resconrec.2009.11.002.

Kršák, B., P. Blišťan, A. Pauliková, P. Puškárová, Ľ. Kovanič, J. Palková, and V. Zelizňaková. 2016. “Use of Low-Cost UAV Photogrammetry to Analyze the Accuracy of a Digital Elevation Model in a Case Study.” *Measurement* 91 (September): 276–87. doi:10.1016/j.measurement.2016.05.028.

Lee, Khai Ern, Mazlin Mokhtar, Marlia Mohd Hanafiah, Azhar Abdul Halim, and Jamaludin Badusah. 2016. “Rainwater Harvesting as an Alternative Water Resource in Malaysia: Potential, Policies and Development.” *Journal of Cleaner Production* 126 (July): 218–22. doi:10.1016/j.jclepro.2016.03.060.

Lisein, Jonathan, Marc Pierrot-Deseilligny, Stéphanie Bonnet, and Philippe Lejeune. 2013. “A Photogrammetric Workflow for the Creation of a Forest Canopy Height Model from Small Unmanned Aerial System Imagery.” *Forests* 4 (4): 922–44. doi:10.3390/f4040922.

Murphy, Sharon. 2015. “Assessing the Effectiveness of Extensive Green Roofs at Improving Environmental Conditions in Atlanta, Georgia.” *Thesis*, Georgia State University. http://scholarworks.gsu.edu/geosciences_theses/87

Nex, Francesco, and Fabio Remondino. 2014. “UAV for 3D Mapping Applications: A Review.” *Applied Geomatics* 6 (1): 1–15. https://doi.org/10.1007/s12518-013-0120-x.

NOAA. “U.S. Climate Atlas” *National Oceanic and Atmospheric Administration*. https://www.ncdc.noaa.gov/climateatlas/

Palla, A., I. Gnecco, and P. La Barbera. 2017. “The Impact of Domestic Rainwater Harvesting Systems in Storm Water Runoff Mitigation at the Urban Block Scale.” *Journal of Environmental Management* 191 (April): 297–305. doi:10.1016/j.jenvman.2017.01.025.

Paul, M. J., and J. L. Meyer. 2001. “Streams in the Urban Landscape.” *Annual Review of Ecology and Systematics* 32: 333–65. doi:10.1146/annurev.ecolsys.32.081501.114040.

Pelak, Norman, and Amilcare Porporato. 2016. “Sizing a Rainwater Harvesting Cistern by Minimizing Costs.” *Journal of Hydrology* 541, Part B (October): 1340–47. doi:10.1016/j.jhydrol.2016.08.036.

Petrucci, Guido, José-Frédéric Deroubaix, Bernard de Gouvello, Jean-Claude Deutsch, Philippe Bompard, and Bruno Tassin. 2012. “Rainwater Harvesting to Control Stormwater Runoff in Suburban Areas. An Experimental Case-Study.” *Urban Water Journal* 9 (1): 45–55. doi:10.1080/1573062X.2011.633610.

Pix4D. 2018. “Pix4D User Manual”. https://support.pix4d.com/hc/en-us/sections/200591059-Manual (accessed February 20th, 2018)

Remondino, F., L. Barazzetti, F. Nex, M. Scaioni, and D. Sarazzi. 2011. "UAV PHOTOGRAMMETRY FOR MAPPING AND 3D MODELING – CURRENT STATUS AND FUTURE PERSPECTIVES." *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XXXVIII-1/C22 (September): 25–31.

Salkin. 2009. "Sustainability and Land Use Planning: Greening State and Local Land Use Plans and Regulations to Address Climate Change Challenges and Preserve Resources For Future Generations." *Wm & Mary Envtl L & Pol'y Rev* 34: 51.

Shuttleworth, Andrew B., Ernest O. Nnadi, Fredrick U. Mbanaso, Stephen J. Coupe, Joris G. W. F. Voeten, and Alan P. Newman. 2017. "Applications of SuDS Techniques in Harvesting Stormwater for Landscape Irrigation Purposes: Issues and Considerations." doi:10.5772/67041.

Stretcha, Christoph. 2014. "Pix4D – Error Estimation" (White Paper)

Stretcha, Christoph. 2014. "The Ray Cloud – A Vision beyond the Point Cloud". Paper presented at *The XXV FIG International Congress: Engaging the Challenges, Enhancing the Relevance, Malaysia, 16-21 June, 2014*.

Torres-Sánchez, Jorge, Francisca López-Granados, Irene Borra-Serrano, and José Manuel Peña. 2018. "Assessing UAV-Collected Image Overlap Influence on Computation Time and Digital Surface Model Accuracy in Olive Orchards." *Precision Agriculture* 19 (1): 115–33. https://doi.org/10.1007/s11119-017-9502-0.

Urban Collage, Foresite Group, Inc, and Market + Main. 2014. "Auburn Downtown Master Plan". http://www.auburnalabama.org/planningDocs/ADMP_FinalReport_LowResolution.pdf

United States Census Bureau. 2010. "Profile of General Population and Housing Characteristics". https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=CF

Wayne Huber and Larry Roesner, 2013. "The History and Evolution of the EPA SWMM" in "Fifty Years Of Watershed Modeling - Past, Present And Future", A.S. Donigian, AQUA TERRA Consultants; Richard Field, US EPA (retired); Michael Baker Jr., Inc. Eds, ECI Symposium Series. http://dc.engconfintl.org/watershed/29

Zhou, Qianqian. 2014. “A Review of Sustainable Urban Drainage Systems Considering the Climate Change and Urbanization Impacts.” *Water* 6 (4): 976–92. doi:10.3390/w6040976.