ABSTRACT

BERGESON, CHASE BENDER. Where Can the Water Go? A Characterization of Urban Infiltration Capacities Through Measurement, Modeling, and Community Observation (Under the direction of Dr. Katherine Martin).

Increasingly urbanized watersheds are creating new challenges for stormwater management, as some relevant aspects of urban hydrology and their perceived impacts by communities are not well understood. Infiltration models commonly used in rainfall-runoff predictions are often based on relatively undisturbed soils; however, highly disturbed and compacted urban soils may function almost as impervious surfaces, with very low infiltration rates. When soils become highly altered, soil maps and land cover data alone may not be sufficient to estimate infiltration rates across an urban watershed. As a result, models may frequently do a poor job estimating runoff volumes in urban areas. Additionally, urbanites may perceive issues of stormwater flow within a watershed that differ spatially from those predicted by models. Our research addresses these gaps in understanding using a sociohydrological approach that will help prioritize stormwater management within an urban watershed. In this study, we tested three common infiltration models, by comparing modeled infiltration rates to infiltration rates measured at 89 locations around the Walnut Creek watershed in Raleigh, NC. Based on these measurements we assessed which factors: land use, ground cover, time since development, and soil texture had the greatest impact on soil infiltration. We also asked residents of the watershed about where and how they experience flooding and about the practices that they use to maintain their own properties. Collected data was used to assess how social and hydrological data could be used jointly to improve our knowledge about urban hydrology.

We found that the commonly used, Horton, Green-Ampt, and Curve Number models typically underestimate soil infiltration rates in urban settings without inputs from field measurements. In this study, we propose an alternative model for predicting infiltration capacities based on a basin-wide random forest model. Results from field measurements show that urban forests and areas with forested ground covers have statistically significantly ($p<0.05$) higher infiltration capacities than other urban land. Additionally, urban residents perceive issues of flooding in their communities, often in publicly visible locations close to the areas that they frequent. Our results also indicate that although traditional infiltration models do a poor job in urban settings, urban soils in the Walnut Creek watershed are generally able to absorb the water from most precipitation events and may have high capability of infiltrating urban stormwater runoff. In the context of further reduction of stormwater runoff from impervious surfaces, the preservation of urban forests, especially adjacent to new development, could be important for maintaining and improving the ability of urban soils to absorb water. The prioritization of this and other stormwater control measures should be focused upstream of areas where residents find the most impacts from urban flooding and in areas with populations most vulnerable to flooding.

Where Does the Water Go? A Characterization of Urban Infiltration Capacities Through Measurement, Modeling, and Community Observation

by
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APPROVED BY:

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DEDICATION

This thesis is dedicated to the residents of the Walnut Creek watershed.

BIOGRAPHY

Growing up in Maryland on the shores of the Chesapeake Bay, I jumped in a canoe, went for a swim, or sat down with family and friends for a crab feast whenever I could. I was fortunate to grow up with my parents, siblings, cousins, and four loving grandparents nearby. In high school, my grandfather's tireless work for the local environment got me interested in environmental studies, but it was not until my freshman year of college when the passionate professor of a geoscience course convinced me to make protection of the environment, specifically water resource conservation and restoration the goal of my studies and career. In 2013, I graduated from The University of North Carolina at Chapel Hill with a BS in Environmental Science, a minor in Geology, and new family, friends, and experiences that will forever bond me to North Carolina. After graduating, I moved back to Maryland and undertook a year of service with the Chesapeake Conservation Corps. Through this program, I worked with a great team at the Anne Arundel Watershed Stewards Academy, trying to improve the health of the Chesapeake Bay through the training of community leaders in stormwater management and pollution-reducing behavior change campaigns. While there, I learned a lot about working with diverse groups, environmental education, and the issues that face the Bay. I wanted to get more hands-on research experience, so I worked for almost 5 years at the University of Colorado at Boulder in the CIRES Center for Limnology, where I conducted field and lab studies on many of Colorado's lakes and streams, before deciding to return to my studies, as well as friends and family back east and begin a Masters in Natural Resources at North Carolina State University. I hope my research will be useful to the field of urban hydrology generally and to residents of the Walnut Creek watershed specifically.

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Thank you especially to the greater Walnut Creek watershed community, including the residents of some of Raleigh’s oldest historically black communities. I acknowledge that my research took place on the ancestral lands of the Skaruhreh/ Tuscarora and Lumbee people who are still a vital part of North Carolina’s community today.

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1. INTRODUCTION

1.1 Background and Rationale

Urban areas in the southeastern United States are experiencing rapid increases in population growth and development (US Census Bureau, 2020), becoming home to hundreds of thousands more people each year. But with a large number of high precipitation events, the vulnerability of these populations to incidents of urban flooding and therefore property damage, personal injury, and water resource contamination is also increasing. A better understanding of the hydrologic functionality and predictability of urban soils, along with an understanding of the human perceptions of runoff effects could help managers to site more efficient stormwater control measures.

During rainfall events in urban areas, water runs off impervious surfaces, such as pavement and roofs, into storm drains, streams, or pervious areas. A high volume of stormwater from impervious surfaces can cause stream degradation at only 10-30% impervious cover. It can also cause pluvial or fluvial flooding and stream enlargement (Booth, 1990; Arnold and Gibbons, 1996; Paul and Meyer, 2001; Schueler, 1994; Phillips et al., 2019; Klonner et al., 2020), creating challenges for human health and safety. Just a 1% increase in urban area can reduce infiltration by 41% and double the amount of runoff (Ren et al., 2020). For these reasons, research on the urban hydrological effects of impervious areas has received much more attention than pervious areas (Law et al., 2009). However, the total amount of impervious surfaces may not be enough to explain the effects in water quality and quantity within a watershed. There are mixed results, on whether additional factors, such as land use and maintenance of vegetation significantly influence urban hydrology and urban soil properties. Some research has shown significant effects from these factors (Beck et al, 2016; Brabec, 2009; Sriwongsitanon and Taesombat, 2011; Tu et al., 2007; Viessman et al., 1970; Hamilton and Waddington, 1999; Pouyat et al., 2007; Law et al., 2009; Daniels and Kirkpatrick, 2006; Cook et al., 2012), while some has not (Wiesner et al., 2016; Hagan et al., 2012; Phillips et al., 2019; Ossola et al., 2015).

Green space or green infrastructure, and decreased impervious surface within watersheds, are seen as mitigative to stormwater runoff, as water is assumed to infiltrate into the soil (Alley and Veenhuis, 1983; Walsh et al., 2005; Silva and Silva, 2020). However, it is not clear that urban "green" spaces are as pervious as is often assumed in stormwater management planning. Altered soil properties (*i.e.*, compaction) lead to decreased infiltration capacities of green spaces, similar to those of impervious surfaces (Ziter and Turner, 2018; Rezaei et al., 2019) and green infrastructure that relies on these spaces for stormwater infiltration may lose effectiveness (Silva and Silva, 2020). The study of urban pervious areas could be key to siting stormwater control measures (SCMs) (Law et al., 2009).

Despite the fact that urban hydrologic soil function is often ignored in urban management, urban soils were first documented in 1847 (Lehmann and Stahr, 2007). Urban soils are frequently highly disturbed by human interactions such as heavy use, soil transport, construction, and urban debris and can comprise 60% or more of urban areas (Pouyat et al., 2007). In fact, the United States Department of Agriculture- Natural Resources Conservation Service (USDA-NRCS) classifies many urban soils in their own category of human-altered and human-transported (HAHT) soils (Galbraith, 2012), while the International Committee on Anthropogenic Soils (ICOMANTH), classify similarly human-impacted soils as Anthrosoils, Technosols, and Anthrosediments (Howard et al., 2017). Both Ajmone-Marsan et al. (2016) and Lehmann and Stahr (2007) suggest novel reclassification schemes for urban soils, as they are often too different from natural soils and change too rapidly to be captured by traditional soil mapping methods.

During development, removal of surface soil often exposes low conductivity subsurface soil (Schoeneberger et al., 1995). Soils become highly compacted and characterized by decreased pore space and thus, substantially decreased infiltration capacities (Craul, 1992; Gregory et al., 2006; Wang et al., 2017; Kelling and Peterson, 1975; Ma, 2008; Schwartz and Smith, 2016, Lim et al., 2006). These infiltration capacities are frequently highly variable across an area due to changes in soil structure, the influence of macropores, and poor soil management (Pitt et al., 2002; Wiesner et al., 2016; Pouyat et al., 2007; Andersen, 2020). In these areas, infiltration rates are inaccurately predicted by soil type alone (Kelling and Peterson, 1975; Hamilton and Waddington, 1999; Carmen et al., 2014; Schaake et al., 1996; Pitt et al., 2002). In fact, saturated hydraulic conductivity, which is often used as a proxy for infiltration capacity, of soils varies seasonally and follows more of a log normal distribution than a normal one (Moebius et al., 2007; Heitman, 2016; Díaz-Sanz et al., 2020; Phillips et al., 2019, Kelleher et al., 2020). Thus, traditional infiltration models, which are dependent primarily on soil texture for determination of saturated hydraulic conductivity, may inaccurately predict infiltration capacity over disturbed areas of a catchment (Schaake et al., 1996). Urban stormwater management must account for these human-impacted, urban soils (Lehmann and Stahr, 2007) by identifying how these areas differ from modeled expectations and how well they are able to function in the urban hydrologic cycle.

This thesis explored these topics within the Walnut Creek Watershed, near Raleigh, North Carolina. The central questions addressed are: (1) How can available data about soil type, land use, ground cover, and time since development be used to better predict infiltration capacities in an urban watershed? (2) How well do current infiltration models (Curve Number, Horton Infiltration Model, Green-Ampt Model), based on relatively undisturbed soils, predict infiltration capacities of disturbed, urban soils? (3) How do urban residents in the Walnut Creek watershed perceive infiltration within their own neighborhoods? (4) Where are priority areas for soil restoration or green infrastructure installation within the Walnut Creek watershed based on measured areas of low-infiltration and community observations of problem flooding areas? We took field measurements of infiltration data and compared this real-world data with infiltration models and a participatory map that was used to assess community knowledge and perceptions, and to map target areas for soil restoration to improve stormwater management.

1.2 Infiltration Modeling

The volume of runoff generated from a rainfall event and the spatial distribution of this runoff are important factors for cities in planning and stormwater management decisions. There are many different models for predicting runoff produced from rainfall events (Sitterson et al., 2017). Models that predict the infiltration component of rainfall-runoff models are of three main types: physical, empirical, and semi-empirical. While the models take different inputs, they are generally dependent on soil texture to determine soil's hydraulic properties and therefore how much water from a rainfall event will infiltrate (Sitterson et al., 2017; Wang et al., 2017; Liang et al., 1994, Salvadore et al., 2015). Estimates of soil infiltration rates are a key component to many rainfall-runoff models that are important for planning purposes. These models and the infiltration parameters they use are most often based on or adapted from relatively undisturbed soils or simplified physical models that do not account for soil compaction (Wang et al., 2017; Marsalek et al., 1975; Saadi et al., 2020; Schifman and Schuster, 2019).

In addition to land cover and soil types, several studies have suggested that runoff is affected by other factors, such as antecedent soil moisture (Merz et al., 2006). Demaria et al. (2017) and Pitt et al. (2002) found from Monte Carlo sensitivity analyses of variables used in Variable Infiltration Capacity models that the factors with the most impact on infiltration capacity are distribution of vegetation and climatic gradient, and soil type is a less important factor at a basin wide scale. Time since development or disturbance has also been found as an important factor for estimating infiltration, as bulk density decreases and soil organic matter increases with age (Díaz-Sanz et al., 2020; Scharenbroch et al., 2005). The imprecision in the spatial distribution of precipitation can make it difficult to accurately model infiltration on a basin-wide scale (Schaake et al., 1996; Michaud and Sorooshian, 1994), although urban land use and land cover changes have been shown to have a greater impact on runoff than rainfall patterns (Rezaei et al., 2019).

Past studies disagree on the impact of land and tree canopy cover on infiltration capacities. Many studies claim that land cover is an essential component to estimating soil infiltration rate, but Eigenbrod et al. (2010) assert that land cover-based proxies perform poorly for the estimation of many ecosystem services. Trees have been shown to increase infiltration capacities in urban areas (Armson et al., 2013; Bartens et al., 2008; Elliot et al., 2018; Firehock, 2018), but Kuehler et al. (2017) claim that there has been little analysis quantifying the overall benefit of urban trees for stormwater management, and Rahman et al. (2019) found that infiltration capacities are actually higher in open grass than grass below tree canopies in urban areas. Land use and land cover can also be closely tied to demographic and socioeconomic factors (Cook et al., 2012).

At the crux of the discussion of the estimation of runoff volumes is the use of total impervious area versus effective impervious area (Alley and Veenhuis, 1983; Walsh, 2005; Rezaei et al., 2019). Total impervious area is the total amount of impervious surface within a watershed, whereas effective impervious area is the amount of impervious area in a watershed that does not drain onto “green” surfaces, assumed to be pervious. Models often assume that a land cover is a binary of impervious or pervious (Guo & Urbonas, 2014). However, the infiltration capacity of some pervious areas may be closer to the infiltration capacities of impervious areas (Gregory et al., 2006), increasing the effective impervious area. Therefore, the rainfall-runoff models used in hydrologic models and stormwater management planning may underestimate runoff in urban areas (Wang et al., 2017; Schifman and Schuster, 2019). Studying how well urban greenspaces act as pervious surfaces could help improve the accuracy of rainfall-runoff models and assist in city planning and stormwater management.

Urban planners use rainfall-runoff modeling to quantify flooding in small urban catchments (Robbins and Pope, 1996). In the City of Raleigh, the SWMM and HEC-HMS models are commonly used (Wayne Miles, personal communication). Modelers frequently make assumptions such as uniform rainfall throughout the catchment, ignoring storage within the catchment, and avoidance of areas with regulated flow. These assumptions do not accurately represent the hydrological realities of a catchment and motivate the creation of more realistic models and management strategies, where local knowledge within the target area can be incorporated. We predicted that commonly used infiltration models would do a poor job of estimating infiltration rates in an urban setting and that adding information about urban sites, other than soil type would improve prediction of infiltration rates.

Several past studies (Table A1) measured soil infiltration capacities in a variety of land use and land cover contexts, but studies leveraged data from only one or two soil types or land use types, a limited number of samples, and usually only rural or moderately developed areas. Despite efforts to model infiltration rates based on digitally available data, field data has been shown to increase accuracy of estimates used for actual planning and management decisions (Andersen, 2020). Most previous research has failed to incorporate the relevant knowledge of the surrounding communities and relied entirely on their empirical or modelled data to assess infiltration capacities across a landscape. Some recent exceptions include work by Assumpção et al., 2018; Avellaneda et al., 2020; Gebremedhin et al., 2020; and Hassanzadeh et al., 2019, which show that community data can be incorporated into models. Additionally, Hasala et al. (2020) conducted a study on a subsection of the Walnut Creek watershed explored in this study to assess siting SCMs using both participatory mapping and hydrologic modeling.

1.3 Participatory Mapping

Efficient stormwater mitigation necessitates targeting areas with physical inefficiencies and a perceived impact on the health of communities. In areas where flooding occurs in limited amounts, but where people live and work, the negative effects may be much more serious than in relatively unpopulated areas that experience higher runoff.

Scientific research has been traditionally viewed as an elite endeavor that excludes most people. This can lead to many negative consequences, such as disconnection of populations from scientific research that directly affects them (Heaney et al., 2007) and negative feelings towards scientists and science in general (Safford et al., 2019). Increased community involvement is an essential tool needed to bridge the gap between scientists and nonscientists. Research gains substantial impact when people can become engaged with science and participate in making significant research advances (Shirk et al., 2012). Enhanced research impact is one of the benefits of incorporating participatory mapping into this project.

Participatory mapping, also sometimes called participatory geographic information systems (GIS)(PGIS) or public participation GIS (PPGIS), is a method for incorporating local, place-based knowledge into planning and management decisions. Maps are generated with the help of the local community which they are designed to serve (Corbett, 2009). The information provided by the map can support planning by local governments, non-government organizations (NGOs), and project managers to incorporate the will of the community in decision making about mitigation measures that should be developed for the largest positive impact (Jaligot et al., 2019; Fagerholm et al., 2012). De Groot et al. (2010) also note that these maps are a useful tool in Multi-Criteria Decision Analysis and other decision-making processes at a regional or smaller scale. In addition, participatory maps create awareness within a community about particular issues, stimulate community engagement, empower local communities, and can increase trust in government and researchers (Fagerholm et al., 2012; Klonner et al., 2020). Observations by the people who live within a community can fill gaps in scientific data, serve as a useful real-world comparison for modeled and sampled data, and improve intervention implementation and planning. Through participatory mapping, researchers can learn about stormwater runoff impacts in the community under study, likely sources of low soil infiltration capacities, and opportunities for stormwater mitigation.

Citizens can identify problem and priority areas of flooding and ponding within their communities. In this way, participatory mapping serves as a powerful complementary dataset to estimates of stormwater generated by rainfall-runoff models. Research shows that participatory data has potential to not only be complementary to modeled hydrologic data, but can in some cases be used in urban hydrologic modeling, especially in data scarce areas (Assumpção et al., 2018; Avellaneda et al., 2020; Gebremedhin et al., 2020; Hassanzadeh et al., 2019). The use of participatory methods to map the risk of communities to hazards including flooding as a complement to hydrologic modeling is even part of the United Nations International Strategy for Disaster Reduction's Sendai Framework (UNDRR, 2015).

Research on public perceptions of urban flooding in the hazard and risk management field have shown that people who have low trust in government resources available to help them in the case of flooding, will be more likely to have heightened perceptions of flood risk regardless of actual threat (Seebauer and Babcicky, 2020; Klonner et al., 2020). Therefore, it is possible that study participants' perceptions of flooding in their community could be influenced by their trust in the government resources available to them. Residents of low-income and marginalized communities that have received little help from the city in times of previous flood events, may have heightened awareness of their threat from flooding, regardless of threat level, compared to those in more affluent communities who receive ample government support.

Similar studies comparing citizen perceptions of flooding and modeled flooding and ponding in urban areas have been conducted by Klonner et al. (2020) and in a subsection of the Walnut Creek watershed by Hasala et al. (2020). Klonner et al. found that residents who own their homes identify larger areas of flood risk than pedestrians just passing through an area (2020). The indication that residents have higher awareness than outsiders of flooding issues is an important reason to survey the populations of certain communities to get a more accurate spatial understanding of on-the-ground flooding, rather than government officials who do not live in communities coming in to determine flooding issues on a case-by-case basis. We predict that residents within the watershed will be aware of and able to identify flooding hotspots in their communities, particularly in areas with high populations. These areas may also be the ones with lowest infiltration rates, due to high rates of development.

Traditional views of hydrologic and ecosystem planning focus on “natural” relatively undisturbed areas, but such research fails to recognize the importance of urban hydrology in an increasingly urbanized world (Grimm et al., 2008). The recognition of urban environments as an important frontier of research and understanding guides us in future management decisions and study of the world in which humans live. Additionally, as humans we are an integral part of the urban system. Our perceptions of our surroundings and our roles and priorities within them are important to measure and incorporate into decision-making processes. Urban areas can no longer be treated as hydrological anomalies, due to the essential role they play in the lives of a growing urban population and the major impacts that they can have on watersheds as a whole. Treating them as edge cases could lead to holes in our knowledge that could negatively impact urban populations. We must learn how to restore our urban hydrology for both humans and the environment. Such restoration efforts require a thorough understanding of the process of soil infiltration and the role it plays in the urban sociohydrological system (Haynes et al., 2013; Chen et al, 2014; Mohammadshirazi et al., 2016; Mohammadshirazi et al., 2017; Olson et al., 2013; Pitt et al., 1999; Ma, 2008; Moebius et al., 2007, Sax et al., 2017; Kees, 2008).

2. MATERIALS AND METHODS

2.1 Study Area

The Walnut Creek watershed is a 101.69 km^2 HUC 8 basin located in Wake County, North Carolina. It is a subbasin of the Upper Neuse watershed. The watershed extends across a large part of the city of Raleigh, and parts of the cities of Cary, and Garner. Raleigh has average annual temperatures ranging from 5.5°C in January to 26.2°C in July and gets an average annual rainfall of 1173 mm (National Climate Data Center, 2021).

Flooding in the Walnut Creek watershed (Figure 2.1) has been a significant issue for decades. The predominantly minority communities of Rochester Heights and Biltmore Hills have been subject to substantial pluvial and fluvial flooding events and research has been conducted in those communities to assess community perceptions of and hydrologic modeling of nuisance flooding for the placement of stormwater control measures (SCMs) (Hasala et al., 2020). Flooding problems also persist in the headwaters of the watershed near Cary and further southeast in the watershed. Stormwater management is a priority for The City of Raleigh and other groups within the watershed; planning for future management is a major goal. This is especially prescient given ever-increasing development within the watershed, including pending development of Raleigh's Downtown South complex and Cary's Carolina Yards. Urban stormwater control measures are often put in place in wealthier areas of a community, not necessarily areas of greatest need (Hasala et al., 2020). Many groups within the community, such as Partners for Environmental Justice, the Water Resources Research Institute, the Raleigh Stormwater Management Commission, and the Watershed Action Team are working on planning initiatives and community engagement surrounding these issues and the best ways to efficiently and equitably site SCMs in the watershed.

2.2 Data Collection

2.2.1 Site Selection

We used QGIS 3.8 (QGIS Development Team, 2018) random points feature to select sample sites stratified by land use categories within the Walnut Creek watershed. We chose an equal proportion of sampling points within low development, high development, and residential land use types at random within the watershed, for a total of 102 sampling locations. We chose this as a reasonable number of sites that could be sampled within the available time frame for this study.

Since the sampling locations occurred on both public and private lands, we obtained permission before sampling at any location. If we could not obtain permission for a certain site, we randomly chose another site of the same land use type to replace it, until the field season ended in September 2020. We obtained permission for low and high development sites through a combination of phone calls and email if the information was readily available (for example if the property was a business, church, or school). For 11 properties, we sent letters to landowners with contact information to request permission to sample the properties. For randomly chosen single-family residential properties, we knocked on residents' doors to explain the project and hand out a letter explaining the project and sampling procedure. We also provided researcher contact information and asked for permission to sample. If nobody was at home, we left a letter on the resident's door (Figure C3). We were granted permission to access 7 of the randomly chosen residential sites, which we sampled in the 2019 field season, before shutdowns related to the COVID-19 pandemic went into effect. During the 2020 field season, due to pandemic related precautions, door-to-door recruitment of randomly chosen residential properties was prohibited by the Institutional Review Board. After this point, we chose residential sites by volunteer opt-in and volunteers were taken from the participatory mapping survey, described below. We obtained an additional 31 residential samples from this group. We were also able to obtain permission to sample 24 random low development and 24 random high development sites.

2.2.2 Infiltration Measurements

We measured infiltration rates using a single-ring infiltrometer constructed out of a 12” length of 6”-diameter PVC pipe. The North Carolina State University Biological and Agricultural Engineering Research Shop beveled a PVC pipe on one end to allow for ease of ground penetration (Wheeler et al., 2002; Bartens et al., 2008) and we marked measurements every ⅛” depth inside and outside of the infiltrometer so that we could measure depth in ground and depth of ponding as seen in Figure 2.2.

We chose a single-ring infiltrometer for its ease of use in urban soils. Double-ring infiltrometers are standard for soil infiltration measurements, but are difficult to get into the ground in compacted soils or soils with large amounts of rocks, roots, or urban debris (Díaz-Sanz et al., 2020), causing increased incidence of leaks. They also require significantly more water to operate, which was not always practical to transport in the field. The single-ring infiltrometer is easy to transport and use which makes it ideal for field measurements. In tests comparing the single and double- ring infiltrometers, we did not find a large difference between measured infiltration rates (Figure 2.3a). The consistency we report between infiltrometer types mirrors the findings of Saltiel et al. (2018 unpublished), who found little difference between the 2 methods at multiple sites (see Figure 2.3b from their study). For these reasons, we used a modified version of the ASTM method D3385-18 (D18 Committee, 2018) and the USGS Field Method for Measurement of Infiltration (Johnson, 1963) with a single-ring infiltrometer.

At each site, we selected four infiltrometer locations within a 1 square meter plot, following the method of Pitt et al. (2008) and Schifman and Schuster (2019). Soil infiltration rates within an area can be highly variable due to macropores in the soil. In order to get a better estimate of soil infiltration rate within a certain area, we considered four replicates sufficient to analyze variation in infiltration capacity at a given sampling location.

We installed infiltrometers on flat ground to avoid the influence of slope on infiltration measurements. We gently pounded the infiltrometers into the ground with a rubber mallet to approximately 1” depth. In cases of thick root masses or extremely compacted soils, we first cut a narrow trench in the ground with a 10” pruning saw to a depth of about 1” for ease of infiltrometer penetration (Loague and Gander, 1990). We gently patted down the soil around the edges of the trench to resemble the undisturbed soil and prevent leakage.

In slower infiltrating soils, we used a refilled falling-head method (Diaz-Sanz et al., 2020) with measurements every 5 minutes for 90 minutes. With this method, we filled the infiltrometer to a depth of ~2 inches (approximately 1000mL) and recorded the drop in water level every 5 minutes, then refilled the infiltrometer to the original head. If water level did not drop far enough to be measured in 5 minutes, we made measurements at time intervals in which measurable changes in water level could be recorded. We calculated infiltration rate as the depth of water that infiltrated the ground per unit time for each replicate at each site in inches/hour. We measured infiltration capacity as the constant infiltration rate calculated for the final timespan. Infiltration rate usually became constant after 30 minutes to 1 hour, although literature reports vary from 10 minutes (Gregory et al., 2006) to 6 hours (Johnson, 1963). Using saturated infiltration rate reduces effects from differences in the antecedent soil moisture at the time measurements are taken. We used this method to take 243 measurements at 69 locations. We excluded an additional 37 measurements due to leaks noticed during sampling.

In fast infiltrating soils (>25 in./h), we used a falling head infiltration measurement (NRCS, 1994) for 5 repetitions. With this method, we poured a known volume of water into the infiltrometer. We recorded the time it took for all of the water to drain into the soil in seconds. We considered water fully drained, when no pooled water was visible on the surface. We used this method to take 70 measurements at 19 locations. We excluded an additional 6 measurements due to leaks noticed while sampling. Falling head tests are less accurate than constant head tests (Andersen, 2020), however infiltration rates in fast infiltrating soils were so high that inaccuracies in infiltration measurements are unlikely to make a difference in estimations of runoff from these sites. These sites will be able to fully infiltrate water from most storm events in this area, even very large ones.

Since infiltration rates varied over orders of magnitude across sites, we log-transformed infiltration rates to create an infiltration index for each measurement. Log transformed rates were divided by the maximum log-transformed infiltration rate to create an infiltration index that ranges from 0 (lowest infiltration rate) to 1 (highest infiltration rate). Transformations followed Equation 1 below.

$$Index = \frac{\log(infiltration\ capacity + 1)}{maximum\ (\log(infiltration\ capacity + 1))} \tag{1}$$

2.2.3 Soil Texture/ Hydrologic Soil Group

The Soil Survey Geographic Database (SSURGO) classifies 33 soil types within the Walnut Creek watershed. Mapped soils are mostly loamy and sandy. The most commonly mapped soil series in the watershed are Cecil-Urban complex, 2 to 10 percent slopes (10% of watershed) and Chewacla and Wehadkee soils, 0 to 2 percent slopes (9% of watershed). All other soil types cover 7% or less of the watershed area. However, 28% of the soils in the watershed are mapped as “Urban land,” with an additional 23% having an “Urban land” soil complex (SSURGO 2020). Therefore, the soil properties for over a quarter of the watershed are not available from the best available soil map and another quarter of soil properties may be unreliable.

Due to substantial development in the watershed, the soil data from these maps may not be accurate at any given location. During development, soil disturbance from digging and levelling may remove topsoil, exposing underlying layers of soil. Additionally, a new layer of topsoil may have been deposited on the surface during soil transport.

SSURGO’s classification of Urban land (Ur) for 28% of the Walnut Creek Watershed does not have associated soil properties, such as texture or hydrologic soil group. For samples with an Ur SSURGO soil classification (31% of total samples), we substituted soil properties from Wake County’s soil map (Wake County GIS, 1976). SSURGO data doesn’t change soil properties based on urban impacts to soils and urban soils tend to be dominated by human-impacted soils, leading to another source of error in the SSURGO dataset that impact model performance (Kelleher et al., 2020; Schifman and Schuster, 2019; Díaz-Sanz et al., 2020; Lim et al., 2006).

2.2.4 Land Use

Land use has been shown to greatly impact soil hydraulic properties (Horel et al., 2015; Holman-Dodds et al., 2003) and therefore we considered it an important measure for this study. Land use data used for site selection came from Wake County Property land class data from

December 2020. Wake County identifies 22 different land classes in the Walnut Creek watershed. Since some of these land classes occupy only a small proportion of the watershed, we regrouped them into low development, high development, and residential land uses (Pouyat et al., 2007) and determined a proportional number of sampling sites for each land use type. Low development land accounted for 22% of the watershed, high development accounted for 38%, and residential sites accounted for 36% of the watershed. We did not group other land uses making up about 4% of the watershed. See Table 2.1 for further information about how they were grouped.

We verified actual land use on the ground. In total we sampled, 38 residential samples, 24 low development (ex. forested, vacant lots, parks), and 24 high development sites (ex. industrial, commercial). We divided low development land uses into forested and unforested low development, from here on referred to as forested and low development respectively; residential land into low density residential (single-family homes) and high density residential (apartments, condos, and townhouses); high development land use groupings remained unchanged. Forested sites are those defined as having >50% tree canopy cover. Low development sites included parks, meadows, and undeveloped vacant lots that were not primarily forested. High development land uses included industrial and commercial land, school yards, and churches in urban areas.

2.2.5 Ground Cover/ Vegetation Cover

We determined ground cover classification on-site at each sampling location. We classified ground cover by the highest percentage ground cover within 1 square meter of the sampling location. We classified grass, moss, pine straw, leaf litter, mulch, or bare ground.

We measured vegetation cover by creating 1 and 100 square meter plots centered on the sampling location. We assessed vegetation within the plots ocularly (Godínez-Alvarez, 2009) using the UN Food and Agriculture Organization (FAO) land cover classification scheme (*Land Cover Classification System - Classification Concepts and User Manual*, n.d.) and estimating percent cover of herbaceous vegetation, shrubs, and trees to the nearest 5% (Kelleher et al., 2020).

2.2.6 Time Since Development

Studies have shown that hydraulic conductivity of soil tends to increase with time since development (Grimm et al., 2008, Ziter and Turner, 2018; Zimmerman et al., 2006). Thus, time since development could be an important factor in predicting likely infiltration capacities. We obtained data on the year of most recent construction on a parcel from Wake County Property Data from December 2020 for measurement of this parameter.

2.2.7 Soil Compaction

We estimated surface soil compaction in the field using a pocket penetrometer (Pitt, 2002) that reads compaction levels up to 5 tons/ft^2 (Kelleher et al., 2020). We also estimated surface compaction using the bulk density of the soil as a proxy for soil compaction. Bulk density is considered to be a good proxy for compaction by Carter et al. (1990) and Schumacher et al. (1990). We sampled bulk density with a bulk density sampler, which we pounded into the ground with a slide hammer to a depth of 4 inches. This depth allows an estimate of surface level soil compaction without much risk of cutting into any below ground pipes, cables, or power lines. In certain cases, where there was a risk of cutting utility lines, we called North Carolina 811 to have all lines marked by utilities before sampling. We recorded the number of blows that it took for the top of the sample chamber to become level with ground. We then removed the sample from the inner ring of the sampler to avoid the bias of compaction during sampling. The actual soil column sampled was 2.25 inches in height by 2.75 inches in diameter, with a volume of about 219 cm^3. The sample was stored in a Whirl-pak® bag until analysis. We then determined bulk density in the lab using the Canadian Society of Soil Science method 66.4.1 (Carter and Gregorich, 2008, p. 866), in which a known volume of soil is dried and weighed at 105°C for 24 hours. We calculated bulk density according to Equation 2. Compact soils were defined as those with bulk densities that affect plant growth as a proxy for restriction of water as seen in Table 2.2.

Bulk Density (D_b)(g/cm^3):

$$D_b = (W_d - W_t) \div (V) \tag{2}$$

Where,

W_d is the mass of the dry soil sample in a tin (g)
W_t is the mass of the tin (g)
V is the total volume of the sample (cm^3)

2.2.8 Antecedent Soil Moisture

An important factor in soil infiltration rate is the amount of moisture in the soil before a rain event (Pitt, 2002). If a soil is saturated prior to the rain event there will be less pore space for the rainfall to penetrate the soil, leading to overland flow. If the soil is very dry before a rain event, the soil may form a crust which will prevent initial rainfall from being absorbed by the soil, until the crust seal is broken. Alternatively, drying of soils can lead to cracks in the soils, macropores, in which water will flow preferentially.

Since antecedent soil moisture has a dramatic impact on infiltration rates, the soil's volumetric water content before infiltration measurements must be controlled. Since we sampled across many sampling dates, the previous soil moisture could be vastly different between sites.

The use of final infiltration rate after 90 minutes of wetting allowed us to obtain saturated infiltration rates, which controlled for samples taken on different dates or in different geographical locations with different antecedent soil moisture conditions.

We took initial and final volumetric water content readings with a Field Scout TDR100 Soil Moisture Meter. We used a modified version of the CoCoRaHS (Goble, n.d.) method to validate soil moisture data obtained in the field. We weighed the soil core after collection and then dried at 105*C for at least 24 hours and reweighed. We calculated the volumetric water content using Equation 3.

Volumetric Water Content (θ):

$$\theta = ((W_w - W_d) \div (W_d - W_t)) \times (D_b \div D_w) \quad (3)$$

Where,

W_d is the mass of the dry soil sample in a tin (g)
W_t is the mass of the tin (g)
W_w is the mass of the wet soil in the tin (g)
D_b is the bulk density of the soil (g/cm^3)
D_w is the density of water (~1) (g/cm^3)

2.2.9 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (K_{sat}) is the ability of soil to move water through its pore spaces. It is an important input into the Horton and Green-Ampt models and is determined primarily by soil texture. For the models used in this study, we estimated K_{sat} using the supplied tables in the SWMM technical manual (Rossman, 2016) for each respective model based on the soil textures estimated from SSURGO data. These values can be found in Appendix B.

2.3 Models

2.3.1 Infiltration Models

There is no universal methodology for modelling rainfall-runoff (Salvadore et al., 2005); in fact, there are hundreds of different models available. Decisions about which models to use are determined by the research questions, availability of data, and familiarity of the research with the model or model platform. As a representative sample of existing models, we chose to look at three of the most commonly used models for determining infiltration in rainfall-runoff models: the Horton Model, the Green-Ampt model, and the National Resources Conservation Service (NRCS) (formerly Soil Conservation Service) TR-55 Curve Number (here after referred to as Curve Number) method commonly used by engineers and hydrologists to predict runoff. For example, one of the models used by the City of Raleigh, the Stormwater Management Model (SWMM), gives the option of using the Green-Ampt, Horton, or Curve Number methods for runoff calculations (Rossman 2016). Beven et al. (2012), Wilcox et al. (1990), and Schaake et al. (1996) all argue that simple infiltration models that do not depend on too many variables do a better job of estimating catchment runoff and are more generally useful than more complicated models. All three of these models are relatively simple and do not make use of very many variables. Below, we detail each of the three models analyzed.

1. The Green-Ampt Model (1911):

The Green-Ampt model is a physically based model derived from the Richards equation (Beven, 2012, p.161) which is not intended to be field-calibrated. The Green-Ampt model aims to evaluate impacts of land use on the hydrologic cycle (Wilcox et al., 1990), and is used in WEPP, ANSWERS, SWMM, and CREAMS among other rainfall-runoff models (Chahinian et al., 2005; Silva and Silva, 2020). The model and its parameters are detailed in Equation 4 below.

For this study, we estimated parameters for the model using the supplied tables in the SWMM technical manual (Rossman, 2016) based on SSURGO or Wake County soil types. Tables used to estimate model parameters can be found in Table B1 and B2. We assumed rainfall rate used in model simulation to be 1 inch/hour. We ran the model in R (R Core Team, 2020) using a modified script from Moore (2020). The scripts used to run all models can be found on GitHub (https://github.com/chasebergeson/thesis_R).

$$f_t = \frac{K_s}{2}[1 + \frac{\psi_f(\theta_{ns} - \theta_a)}{F_t}] \tag{4}$$

Where,

f_t is the infiltration capacity at time t in volume/time
F_t is the cumulative infiltration until time t in volume
K_s is the saturated hydraulic conductivity in volume/time
θ_{ns} is the volumetric water content
θ_a is the antecedent soil moisture
ψ_f is the capillary pressure at the wetting front in volume

2. The Horton Model (Horton, 1939):

Horton’s infiltration model is an empirically based model which is derived from soil infiltration in forested and cultivated soils. The Horton Model assumes that infiltration rate decreases exponentially with time, due to extinction phenomena, until it reaches a constant non-zero rate (Horton, 1941). The model is used in MARINE and SWMM, among other rainfall-runoff models (Chahinian et al., 2005, Jumadar et al., 2008). The model and its inputs are detailed in Equation 5. For this study, we estimated parameters for the model using the supplied tables in the SWMM technical manual (Rossman, 2016) based on SSURGO or Wake County soil types. Tables used to estimate model parameters can be found in Table B3 and B4. We ran the model in R (R Core Team, 2020) and the code can be found on GitHub (https://github.com/chasebergeson/thesis_R).

$$f_t = f_c + (f_0 - f_c)e^{-kt} \tag{5}$$

Where,
f_t is the infiltration rate capacity at time t (in/h)
f_c is the final infiltration rate capacity (in/h)
f_0 is the initial infiltration rate capacity (in/h)
k is the infiltration rate capacity decay constant

3. The NRCS Curve Number Method (Soil Conservation Service, 1989):

The NRCS Curve Number method is an empirically based model, derived from experimental data. Inputs include hydrologic soil groups and land cover types. It is commonly used by engineers for estimating runoff. The model is used in SWAT and SWMM, L-THIA, among other rainfall-runoff models (Chahinian et al., 2005; Grove et al., 2001). The Curve Number method uses the soil type to categorize soil into hydrologic soil groups. After determining the hydrologic soil group, it is combined with land use type to choose a place along a curve which will predict the amount of runoff from a certain amount of precipitation as seen in Figure 2.4 (Soil Conservation Service, 1989). The Curve Number method is simple to use and does not require calibration, but this technique does not take into account rainfall duration or intensity (Wilcox et al., 1990). Soil bulk density is not directly incorporated into this model, but it has been suggested that changing the hydrologic soil group based on compaction could be a way to introduce its effects (Law et al., 2009; Lim et al., 2006). For this study, we estimated parameters for the model using the supplied tables in the TR-55 technical manual (*Urban Hydrology for Small Watersheds: TR-55 Curve Number Method*, n.d.) based on SSURGO or Wake County soil types and field survey vegetation cover and land use. Tables used to estimate model parameters can be found in Table B5, B6, and B7. We assumed rainfall rate used in model simulation to be 1 inch/hour. We ran the model in R (R Core Team, 2020) and the code can be found on GitHub (https://github.com/chasebergeson/thesis_R).

2.3.2 Random Forest Modeling

In addition to running some of the most commonly used infiltration models to test how well they did in our urban watershed, we also created a new model using digitally available datasets on soil, time since development, land class, and land cover to generate a random forest prediction of infiltration index at the 1m² scale.

For this model, we generated a new land cover classification using National Agriculture Imagery Program data (USDA Farm Service Agency, 2016) at the 1 m scale. Land cover types found in the watershed using this imagery were classified by Zhenzhen Zhang using the HERCULES method (Cadenasso et al., 2007). Classified land cover types included coarse vegetation (trees), fine vegetation (grass), impervious cover, bare ground, and water. A stratified random point sample of about 50 of each land type was selected (Congalton, 1991) for a total of 243 points. These points were used to generate 30 square meter polygons around the points. Pixels within these polygons, a total of 207958, with data in the red (R), green (G), blue (B), and near infrared (nIR) bands, were used as training data for a random forest model to predict land cover classes across the entire watershed. We manually analyzed generated polygons to make sure that they did not encapsulate any pixels of the wrong land cover class and we manually resized them if needed. We ran a random forest model using 70% of these pixels as calibration data and 30% as validation data. Using values from the R, G, B, and nIR bands the random forest model predicted land cover classes at each 1m² plot in the watershed. The resulting model had an out-of-box error rate of 3.06%.

We rasterized polygon data of time since development and land class from the Wake County Parcel data cited above, and soil texture from SSURGO data, to the same 1m² scale as the land cover data. We combined the four raster files using the stack function (Figure 2.5).

We extracted values for each of these four layers at each location where there was an infiltration measurement using the extract function. After optimizing input parameters for a new random forest model, we used 80% of the infiltration site data to train the model and 20% to validate it. We used 500 trees and all 4 variables to create the model. This model was used to predict infiltration indices across the watershed.

We processed spatial data for these models with R (R Core Team, 2020) packages rsample (Silge et al., 2021), randomForest (Liaw & Wiener, 2002), ranger (Wright & Ziegler, 2017), caret (Kuhn, 2020), and snow (Tierny et al., 2018). We ran spatial data manipulations with R packages raster (Hijmans, 2020), rgeos (Bivand & Rundel, 2020), sf (Pebesma, 2018), sp (Pebesma & Bivand, 2005; Bivand et al., 2013), rgdal (Bivand et al., 2021), classInt (Bivand, 2020), ggmap (Kahle &Wickham, 2013), tmap (Tennekes, 2018), leaflet (Cheng et al., 2021), and ggpubr (Kassambara, 2020).

2.4 Participatory Mapping

In order to align measured infiltration rates with observed instances of flooding and ponding in the watershed, it was necessary to survey the local population and have residents map their observations. The survey for this study was classified as exempt and approved by the North Carolina State University Institutional Review Board on June 26, 2020 (IRB Protocol: 20992).

2.4.1 Recruitment

The target audience for the survey was residents of the Walnut Creek watershed over the age of 18. We used convenience and snowball sampling to solicit participant involvement in the study through the online distribution of the survey. We distributed a flier advertising the survey (Figure C2) with a link to the survey. The flier was distributed to a list of NC State College of Natural Resources graduate students, faculty, and staff with the request that it be sent out to neighborhood listservs, Twitter, Facebook groups, NextDoor accounts, or similar in the watershed. We then pushed the survey out through watershed community groups, such as the Watershed Action Team (WAT) and the Water Resources Research Institute (WRRI). There was a third push in early September when we sent the survey out again through NC State channels. There were fewer responses with each recruitment push. All survey and recruitment materials were administered in English only. Both the language of materials and conduct of the survey exclusively online, likely excluded segments of the target population from being able to take the survey.

2.4.2 Survey

We designed a digital, online survey to allow residents to map up to 5 locations of observed flooding or ponding within the watershed. Residents received an online survey developed with the Qualtrics software (Qualtrics, Provo, UT). A copy of the survey can be found in Figure C3. The survey included a maximum of 38 questions and was designed to be about 10 minutes in length. Responses were collected from July 8, 2020 to October 8, 2020. Survey questions asked participants to identify which part of the watershed they were most familiar with by pinning a location on a map of the watershed. The map was divided into 9 subsections: Cary, Central Raleigh, East Raleigh, Garner, South Raleigh, Southeast Raleigh 1, Southeast Raleigh 2, West Central Raleigh, West Raleigh. Out of 111 participants, 45% were most familiar with West Raleigh and an additional 28% were most familiar with West Central Raleigh. There were no participants from Garner or Southeast Raleigh 2. A heatmap of most familiar places in the watershed can be seen in Figure 2.6.

Participants were also asked to identify a location on a Google map where they saw ponding or flooding and indicate how frequently flooding occurred (very infrequently, infrequently, somewhat frequently, frequently, very frequently). This data was gathered in Google Map in Google's WGS84 reference system. All location data used for this study was taken in this reference coordinate system. Map data is gathered by Volunteered Geographic Information (VGI). It has been noted that this type of data lacks measures of uncertainty, checks of its accuracy, and precision, and must be asserted as true without citation (Goodchild, 2007), however research by Haklay suggests that VGI can be fairly accurate (2010).

The map allowed participants to zoom in or out to the scale that best allowed them to orient themselves on the map. The watershed was also shown as a shaded region on the map for orientation. Participants could enter a location in the search bar to zoom to a particular spot or drag the red pin to the desired location (Figure 2.7). For those that could not see the map or that had technological issues with the point rendering, a follow-up question allowed respondents to add a detailed description of the location where they saw flooding. 3 participants responded with 5 descriptions of ponding/flooding instead of a map point due to technical difficulties with using the map. Points described were added to the map manually by researchers. Several participants included both a map point and a text description of flooding/ponding locations. In these instances, we verified that the marked point agreed with the described point. If not, it was assumed that participants wanted to note an additional point and the described point was added manually to the map. 111 participants noted 98 sites of flooding and ponding within the watershed (an additional 3 points were indicated outside of the watershed and were excluded from the study).

Participants were also asked whether they know about serious impacts of flooding in the past 5 years, including private property damage, public property damage, injury to a person, contaminated streams, or something else. They were asked about yard composition and maintenance with questions modeled off of a Utah Survey (Jackson-Smith & Flint, 2014). Additionally, we asked a series of basic demographic questions to assess the survey population.

Participants were also asked to volunteer for infiltration sampling on their residential property to find additional residential sampling locations during the pandemic. If they agreed to participate, they were asked for their address and contact information to ensure that their property was within the watershed and to follow-up. If they volunteered their property for sampling, they were sent a follow-up email with more details about the sampling process. A second email was sent with a suggested date and time range for sampling. In the event of rain, participants received a third email with another date and sampling time. If participants did not opt out at this point or any previous point, their property was sampled at the date and time scheduled and participants were notified by text or phone call to let them know when researchers arrived at the property to sample.

2.4.3 Mapping

Maps can take many forms depending on their intended purpose and the community who makes them. Some common forms are hand drawn maps, physical copies of scale maps, GIS based maps, and multi-media internet-based maps (Corbett, 2009), but all of these maps can be used as powerful visualization tools (de Groot et al., 2010). The most common method, and an integral part of the work presented here, includes a self-administered survey with a mapping component (Brown and Fagerholm, 2015). The selected map for this study was designed to be easy for community participants to use and also for decision-makers and researchers to analyze. In particular, we facilitated this survey using internet-based maps.

Both polygon and point data can be used in participatory mapping to indicate points of interest on a map. Point data is shown to put less cognitive burden on participants, while providing more difficulty for researchers in analysis of point data that may represent larger areas. Point data is also found to produce a more conservative estimate of spatial clustering than polygons and is better for self-administered surveys, such as the one used in this study. For these reasons, we used point data in this study. Additionally, the use of digital maps with adjustable scales can theoretically increase accuracy of point data (Goodchild, 2007), but as mentioned below can introduce uncertainty due to the variation in scales used by participants. (Brown and Pullar, 2012)

2.5 Data Analysis

We performed data analyses including data entry, calculations, data organization, and plotting mostly in R (R Core Team, 2020) using R Studio (R Studio Team, 2020) and the tidyR (Wickham, 2020), dplyr (Wickham et al., 2021), readxl (Wickham & Bryan, 2019), ggplot2

(Wickham, 2016), and plotly (Sievert, 2020) packages. Some data entry and data organization was done in Microsoft Excel 16.47 (2019).

2.5.1 Influential Factors

In order to determine the most influential factors contributing to soil infiltration rate, we used the non-parametric Kruskal-Wallis test and Dunn's test on the parameters of soil type, ground cover type, land use type, and time since development (<50 years, 50-100 years, >100 years. The Kruskal-Wallis test is a one-way analysis of variance test, in this case used to detect whether or not to reject the null hypothesis that infiltration measurements taken at sites with any of these given parameters have the same distribution as infiltration measurements taken at a site with a different parameter value. The alternative hypothesis is that there is a significant difference ($p<0.05$) between distributions of groups within a parameter. If we found a significant difference using the Kruskal-Wallis test, Dunn's test was run on that parameter. Dunn's test is the non-parametric version of the Tukey test, used to test the null hypothesis that there will be no difference in infiltration measurements between different groups for each parameter value. The alternative hypothesis is that there is a significant difference ($p<0.05$) between infiltration measurements of groups within a parameter.

2.5.2 Model Analysis

In order to test the accuracy of the models, we used the Nash-Sutcliffe model efficiency coefficient (NSE). NSE is a measure of model performance frequently used to evaluate rainfall-runoff models, by comparing the modeled parameter at any given time to the average of the parameter at all times. An NSE > 0.75 was considered good, between 0.75 and 0 was considered acceptable, <0 was considered poor (Wang et al., 2017). A NSE of 0, indicates that the modeled values do as well as using the mean value of infiltration measurements for a given site. An NSE of <0 can be interpreted as the predicted modeled values being less accurate than the mean value for a given site. NSE is usually used to evaluate the model efficiency of rainfall-runoff models in their entirety, instead of only the infiltration portion of the model. However, it is used by Wang et al. (2017) to evaluate individual infiltration models. We ran NSE calculations using the R hydroGOF (Zambrano-Bigiarini, 2020) package.

2.5.3 Survey Data

We also analyzed survey data using the Kruskal-Wallis and Dunn's tests to evaluate the relationship between survey response data on lawn maintenance and infiltration indices. General summaries of survey responses with and without paired infiltration measurements were also analyzed. We analyzed spatial analysis of where survey respondents were most familiar and where they observed flooding using QGIS and ArcMap.

2.5.4 Spatial Analysis

We performed spatial analyses for this project using ArcGIS 10.7.1 (ESRI, 2019), QGIS 3.14 and 3.8 (QGIS Development Team, 2018), Google Maps (Google, n.d.), and R 4.0.2 (R Core Team, 2020). We ran most spatial processing in QGIS or ArcMap. We used R for spatial processing of raster files related to random forest modeling. We used a Google Maps API centered on the Walnut Creek watershed as an inset in the administered survey. We chose priority areas for restoration as areas upstream of observations of flooding and with low infiltration indices.

3. RESULTS

3.1 Infiltration Measurements

We checked the normality of our data using QQ-plots and the Shapiro-Wilk normality test ($p < 0.01$) and found that our infiltration rate data was not normal, which is often the case with infiltration data (Phillips et al., 2019; Kelleher et al., 2020). Therefore, we applied the non-parametric Kruskal-Wallis test and Dunn's test (Díaz-Sanz et al., 2020) to test the significance of different factors on infiltration rate.

Measured infiltration capacities ranged from 0.00-388.49 in/h (0-9868 mm/h). We measured mean infiltration capacity of all sites as 19.22 in/h (488 mm/h) and median infiltration capacity was 7.50 in/h (191 mm/h). We found infiltration capacities above about 25 in/h (635 mm/h) at sites measured with the NRCS infiltration method, although it is likely that final infiltration capacity was not reached due to the large volume of water needed to reach an infiltration capacity. Infiltration capacities at these sites would take much more than 90 minutes to reach or are very high. In either case it would take very high volume, long duration storms to exceed the infiltration capacities at these sites, but we will refer to these final infiltration rates as infiltration capacities for the purposes of this discussion.

When we stratified by infiltration field method, the mean final infiltration capacity of sites sampled with the NRCS method (n= 17) was 70.3 in/h ± 54.4 in/h (1786 mm/h ± 1382 mm/h) and median final infiltration capacity of 42.8 in/h (1087 mm/h). Sites that we sampled with the constant method (n=68) had a mean final infiltration capacity of 6.93 in/h ± 5.87 in/h (176 mm/h ± 149 mm/h) and median final infiltration capacity of 5.98 in/h (152 mm/h). At forested sites, 40 measurements were taken with the NRCS method and 24 measurements with the constant head method.

3.1.1 Time Since Development

Year of development on sampled parcels ranged from 1896-2010, with most sites developed since the 1950s (Figure 3.1). Development on parcels for the whole watershed range from 1760-2021. We did not find a statistically significant relationship ($p<0.05$) between time since development of a site and infiltration rates with an age grouping of every 50 years or on time since development as a continuous variable, as seen in Figure 3.2.

3.1.2 Land Use

Within classification of land use, infiltration capacities in forested areas were statistically significantly different from all other land uses ($p<0.01$). No other land use classifications were statistically significantly different from one another. Mean infiltration capacities at these sites can be found in Table 3.1 and a comparison of infiltration capacities across land uses can be found in Figure 3.3.

3.1.3 Ground Cover/Vegetation Cover

There was a significant difference ($p<0.05$) in infiltration capacities between bare ground or ground covered in turf grass and ground covered with pine straw or leaf litter. Forested ground covers having significantly different infiltration capacities than highly managed ground covers (Figure 3.4).

There was a weak slightly positive correlation between tree cover at 100 m^2 and infiltration index ($R^2= 0.12$, $p<0.05$). There was no significant relationship between tree cover at 1 m^2 and infiltration index ($R^2= 0.03$, $p<0.05$). There was no significant relationship between % herbaceous cover at 100 m^2 and infiltration index ($R^2= 0.03$, $p=0.1$). There was no significant relationship between % herbaceous cover at 1 m^2 and infiltration index ($R^2= 0.06$, $p<0.05$) (Figure 3.5).

3.1.4 Soil Compaction

Measured soil bulk densities were generally low and ranged from 0.2-1.04 g/cm³. As expected, infiltration capacity has a negative correlation with soil bulk density and compaction level ($R^2 = 0.25$, $p<0.05$, slope=-0.6) (Figure 3.6).

3.1.5 Soil Texture

Soils at sampling sites were measured to be mostly sand or sandy loams as seen in Figure 3.7. Based on soil textures from soil maps, 60% of sites (51/85) had loamy sand, sandy loam, or sand soils (sandy) compared to measured rates in which 97% (73/75) of sites where soil texture was measured had sandy soils (Figure 3.8). Measured and mapped soil textures were the same for 18.7% of measured samples (14/75). Infiltration rates were not statistically significantly different ($p<0.01$) between soil textures (Figure 3.9).

3.1.6 Soil Moisture

There was a negative relationship ($R^2 = 0.337$, Slope= -0.01, $p<0.001$) between infiltration capacity and antecedent soil moisture (Figure 3.10). Forested sites had much lower antecedent soil moisture than other sites. This is likely due to the rapid infiltration rates in those soils that keeps soils from holding moisture for long periods. These sites were also less likely to reach saturation during infiltration measurements and may therefore be represented by artificially high infiltration capacities. Excluding forested sites there is weaker negative relationship ($R^2=0.119$, slope=-0.006, $p<0.01$). Laboratory measurements of % Volumetric water content versus antecedent soil moisture measured via TDR can be found in Figure 3.11

3.2 Models

When we assessed Horton, Green-Ampt, and Curve Number infiltration models using NSE, all models do poorly with NSE<0. All models tend to underestimate infiltration capacity. An example of model performance versus measured data can be seen in Figure 3.12 and 3.13. Modeled infiltration capacities were off by about an order of magnitude. Our model had an acceptable NSE of 0.54. Modeled infiltration indices across the watershed can be seen in Figure 3.14.

The random forest model based only on digitally available datasets explains 58% of variability within infiltration indices and 19% of infiltration capacities. We ran another random forest model using collected field data to see how well a random forest model based on field data could perform. Using field bulk density, vegetation, compaction, city, soil and air temperature data, the model was able to capture 68% of variability in infiltration index and 30% in infiltration capacities. Bulk density was found to be the most influential factor in this model.

3.3 Survey

72 survey participants completed the survey. Of participants that completed the entire survey, the average completion time was 36.1 ± 164.5 minutes. This included participants who completed the survey over multiple days. If those participants are excluded, the average completion time was 10.1 ± 13.2 minutes. 67 participants began, but did not complete the survey. Of these, 6 participants marked observations of flooding on the map and 2 responded with information about lawn maintenance. Although surveys were incomplete, these observations were included in the study. Participants marked 1.23 flooding observations on average. 4/14 points observed by people in Cary were outside of Cary. 1/2 points observed by people in

Central Raleigh were outside of Central Raleigh. 2/4 points observed by people in East Raleigh were outside of East Raleigh. 1/2 points observed by people in South Raleigh were outside of South Raleigh. 1/1 points observed by people in Southeast Raleigh were outside of Southeast Raleigh. 5/24 points observed by people in West Central Raleigh were outside of West Central Raleigh. 16/50 points observed by people in West Raleigh were outside of West Raleigh.

Participants were disproportionately wealthier, more highly educated, and whiter than the population of the watershed as a whole. This may impact survey results. Most respondents did not provide demographic information when they took the survey. Of respondents who did, most were between the ages of 25 and 65 with a fairly even distribution between 10-year age groups (25-34, 35-44, 45-54, 55-64). Of respondents who provided income information, most had household incomes over $100,00 per year. Of respondents who indicated their gender, there were 20 female respondents and 10 male respondents. All respondents, who indicated their highest level of education had at least a 4-year degree, with half having doctorates. Almost all respondents who indicate their race or ethnicity identify as White.

Results showed that there is no statistically significant difference ($p<0.05$) in infiltration capacities of yards mown with weed whackers versus push mowers. Lawns mown with weed whackers had higher infiltration rates than those mown with other methods, but these lawns likely also have less lawn grass than those mown with more traditional mowers (Figure 3.15). There is also no statistically significant difference ($p<0.05$) in infiltration capacities of lawns mown or watered at different frequencies (Figure 3.15 and 3.16).

29 respondents described their lawns as grass, 7 as mixed vegetation, 16 as having natural groundcover (ex. moss, clover, etc.), 2 did not have a lawn, and 1 had a wooded lawn. More specific vegetation types can be found in Table 3.2. There were no significant differences in

infiltration rates based on self-reported lawn types, results can be seen in Figure 3.17, but the range of infiltration indices of lawns with natural groundcovers is higher than that of lawns with grass.

32 respondents reported witnessing private property damage in the watershed caused by flooding, 19 witnessed seeing public property damage, 1 witnessed injury to a person, 26 witnessed stream contamination. Other damages reported included sedimentation, stormwater runoff pollutants, and near injury to people on Dana Dr.

3.4 Precipitation Infiltrated

Almost all sites had saturated infiltration capacities capable of infiltrating most rain events in Raleigh in the past 2 years (Figure 3.18). Precipitation events are likely to bring higher rainfall rates due to a warming climate in the future. Thus, the percentage of rain events that will be fully infiltrated across the watershed will likely decrease.

4. DISCUSSION

4.1 Use of available datasets to predict infiltration capacities in urban watersheds

We found that different land uses and land covers can all significantly affect infiltration rates. Estimates of these factors can be determined from digitally available datasets, such as satellite imagery used to estimate land cover, or county data on zoned land use. While these datasets provide only rough estimates of actual conditions in any location, they may be good enough to improve estimates over those predicted with traditional infiltration models. There are also similar impacts on infiltration rates by antecedent soil moisture and bulk density. When measurements of bulk density, antecedent moisture, and ground cover were added to the random forest model used in this study, we were able to explain 68% of variability in infiltration rates, as opposed to about 20% using only digitally available datasets. We found that the model was most sensitive to soil bulk density. If estimates of these additional properties are available via field measurement or another source, they may help improve models further.

We found that by combining our field data with available information on soils, land cover, land use, and time since development we were able to improve estimation of infiltration rates across the watershed. The Nash Sutcliffe efficiencies of common models were < 0 (poor), while that of our random forest model used to predict infiltration indices was about 0.51 (acceptable). With higher resolution, more up-to-date datasets, or inclusion of more datasets that affect infiltration rate, this model may be improved even further.

4.1.1 Soil Texture

Soils of measured sites in this study were mostly sandy. While North Carolina is known for its clayey, Cecil soils, SSURGO soil maps of this watershed show mostly sandy soils in the study area. It is also likely that in much of the developed landscape, soil added back to developed sites has high sand content, as is common practice in developed areas where turf grass will grow in order to mitigate compaction from construction activities, therefore increasing infiltration, and allowing for denser vegetation growth (Taylor and Blake, 1984).

Our direct measurement of soil texture in this study was based on a method that does not work well for sandy soils. For this reason, the exact textural class of soil samples may not be accurate, but we are confident in our determination of soils as sandy vs. clayey. In the future, we would conduct a field texture analysis, such as the ribbon method, to determine the approximate texture at each site and use lab methods as appropriate for the given textural class.

The SWMM manual has a caveat that default values provided for model parameters may not be appropriate for sandy soils due to their high infiltration rates. The manual notes that saturated hydraulic conductivity values in sandy soils, which can be used as approximations for infiltration capacities were found in one study to range between 7 and 18 in/h, much higher than the 0-0.45 in/h listed as default values for the SWMM Horton model (Carlisle et al., 1981; Rossman). Another problem with trying to use default parameter values noted by Rossman, is that literature values of the infiltration decay constant range from 0.67-120 in/h. Discrepancies between initial infiltration rate in this study and that of the SWMM model may be less important, since the SWMM model adjusts these values based on soil moisture accounting within the larger model. With the large variability in infiltration capacities and decays across the landscape, it is not surprising that default methods of these models work poorly, especially in sandy soils whose infiltration capacities are less well documented in the literature. Our study provides evidence that heeding these warnings is very important for accurate prediction of infiltration with any model.

4.1.2 Time Since Development

The year in which a structure was built on any given property in Wake County, NC is publicly available in the Wake County parcels layer as “YEAR_BUILT.” These years range from 1760-2021. Parcels on which there has been no constructions are given a year of 0, although this does not mean that the land has not been altered in some way, such as for agriculture or recreation. We did not find a significant difference in infiltration rates between parcels that had been developed a long time ago (>50years) and those that were developed more recently, but our random forest model did find that YEAR_BUILT was the most influential factor in determining infiltration rate at a site (Figure 4.1). This is likely because there is a significant difference between sites that have constructions on them and those that do not (i.e., the 0 values). Reports in the literature on the influence of time since a site was developed on infiltration rate are mixed. Some studies find that in places where construction happened a long time ago, soils have redeveloped some of their structure and therefore have higher infiltration rates, than those with new structures (Woltemade, 2010; Yang and Zhang, 2011; Diaz-Sanz et al., 2020) While, we did not find a significant impact of infiltration rate in this study, it may be due to the imprecise measurement of time since development used here.

4.1.3 Land Cover

We assessed land cover by classifying remotely sensed NAIP data at the 1m scale into coarse vegetation (trees/shrubs), fine vegetation (grass), impervious cover, water, and bare soil. Since these classifications were made using satellite imagery, they will not necessarily match the field observations of ground cover, which were made during infiltration measurements. Tree cover frequently blocks satellite views of grassy areas below. Additionally, the classification of land cover from satellite imagery is not as accurate as manual classification and, in some cases, may have trouble distinguishing between shadows and some land cover types. The satellite classified land cover was used in the random forest model and was less significant than soil texture or year of construction.

Ground cover as identified in field sampling was classified into more discrete categories, including turf grass, other grasses, forest litter, and bare ground. Percent vegetation of herbaceous, shrub, and trees was considered at the 1 m^2 and 100 m^2 plot. This more detailed assessment of ground cover as opposed to land cover, allowed us to find significant differences in infiltration rates that we may not have been able to see otherwise. Sites with forest litter (leaf litter and pine straw) were more likely to have higher infiltration rates than sites with bare ground or turf grass, even if covered by a tree canopy. This influence may be obscured by land cover estimation in the random forest model as there is no way to tell what the ground cover is under a tree canopy.

4.1.4 Land Use

Land use, labelled land_class in the random forest model, was determined from land classes outlined by Wake County parcel data. For the purposes of classifying land use when we took infiltration measurements, we were able to more precisely characterize the land use of a plot based on available field indicators or talking with residents or managers. Some vacant plots were completely forested while some were bare ground. Some “residential” plots were managed lawns, some were community athletic fields, and others were highly managed gardens, some agricultural land was actually forested. We were able to classify sites, such as athletic fields, from low development to low development with high human use or from low development (non-forested) to forest. These reclassifications of land uses were helpful in determining how actual use influences infiltration capacities at a site. Using these classifications, we were able to determine that forested sites had much faster infiltration rates than non-forested sites.

With less specific classifications of land use available from Wake County data without ground truthing at each site, it is difficult to differentiate the 22 Wake County land classes into useful land uses (low development, high development, residential). Based on the 89 locations sampled, we attempted to use the most common field assigned land use for a given land class as the assigned land use for plots with that land class in the model. That said, this is not a perfect method of classification and models may be improved if a better land use dataset is available.

4.2 Current infiltration models perform poorly.

The common infiltration models, used in many rainfall-runoff models all do very poorly in estimating infiltration rates within this watershed. When models are run with default values, as outlined for use with the SWMM manual, and based on information from the SSURGO soils database, models tended to underestimate soil infiltration rates within the watershed. Modelled infiltration rates did slightly or much worse than just taking the average of infiltration capacities across the watershed. One reason that models may do such a poor job in urban areas is that for much of the watershed, the SSURGO soil type was identified as “Urban.” For this soil type, there is no available data about the soil properties, which are necessary model inputs. Thus, model inputs were reliant on other sources of soil data, that were from ~50-year-old soil maps. Soil properties may have changed significantly since then.

We expected that models would perform poorly in this area, but we were surprised to find that rather than overestimating infiltration rates, the models actually underestimated rates. This may be partly related to inaccuracies in the soil maps, indicated above. In fact, many of the sampled sites had sandier soils than those mapped. However, the default values suggested for use as the initial infiltration rates and infiltration capacities were much lower than those found in this study, leading to lower estimates of infiltration rates at all times. Wang et al. (2017) also found consistent underestimation of infiltration for clayey soils, but found that models both underestimated and overestimated infiltration for sandy soils.

The decay constants recommended for use in the Green-Ampt and, to a lesser degree, Horton methods, actually approximated that of the actual, measured infiltration curve (Figure 3.12). The narrow range of initial infiltration rates and infiltration capacities provided as default values to the SWMM model will result in large errors for any infiltration rates that do not fit within those narrow estimates. The recommendations against using these default values are discussed above. Berndtsson (1987) found that the Horton model worked fairly well in an urbanized catchment when calibrated with field data. Using field or literature data, either as inputs to the model or to make adjustments to this range of input values could likely improve model performance, as is recommended in the SWMM manual.

Estimates from the Curve Number method tended to start much lower than other modeled infiltration rates and stay low. Infiltration capacity of this model tended to be lower than other models across the board, but was sometimes close to that predicted by the Horton model. Zariello (1998) also found underestimation of infiltration by the Curve Number method. For this watershed, the Curve Number method performed the worst of all models and Green-Ampt performed the best. If use of these models without field-based parameters is necessary, we would recommend using the Green-Ampt method.

4.3 Watershed residents notice flooding and its associated damages.

Our survey of where residents of the watershed experienced flooding or ponding showed that many people do observe and experience flooding within their communities. Observations of flooding were most often noted in public locations, such as street intersections, shopping centers, parks, and along greenway trails rather than on private properties. This is likely due in part to the more visible nature of these locations to the general public, as noted by Hasala et al. (2020). These sites are likely to be observed by more people and therefore more likely to be reported. Another reason for the abundance of observations in public locations versus private properties is that those areas tend to have a greater proportion of impervious surfaces and are more heavily used, leading to greater soil compaction and lower infiltration rates.

Beyond the survey, there were many residents of the watershed who were eager to tell us in the field about issues of flooding and ponding that they perceived on their own or their neighbors' properties. This data is not formally incorporated in this study. It is likely that there is flooding and ponding occurring on private properties; most sites indicated in Cary were on such properties. Preventing, flooding of private properties, especially as a result of runoff from public spaces should be a goal of stormwater management, but flooding and ponding in public locations is most likely to have the highest impact on the community population as a whole and should be easier to accomplish as projects on public property may be easier to get permission to take on and can be implemented on a larger scale. These public projects will also have potential for slowing and reducing stormwater flows to private properties that may cause flooding.

A majority of observed flooding and ponding locations were located in the headwaters of the watershed, with quite a few locations in Cary and from North Carolina State University's Campus to the west. This is likely due to the disproportionately high number of survey respondents who indicated that they were most familiar with these locations compared to downstream portions of the watershed in the southeast. However, it is interesting to note that these are also the most populous parts of the watershed and more highly developed than the downstream area of the watershed. Surprisingly, there were very few observations of flooding in the highly developed downtown area of the watershed, but the headwaters do have more impervious cover and less forested areas than the southeastern portion of the watershed.

Many of the flooding observations were within or adjacent to the Walnut Creek floodplain (Figure 4.2). Clearly, development within the floodplain is unsustainable and is likely to cause problems for humans and the environment. Most observations of flooding within the floodplain were in areas containing only greenways or parks. Unfortunately, development extends into the floodplain in some areas of the watershed. Notably in Cary, in a neighborhood of mostly mobile homes in Cary and in Raleigh, homes off of Dana Dr., parts of the Walnut Terrace neighborhood, parts of the Rochester Heights, the newly developed affordable housing community, Beacon Ridge Apartments, and parts of the neighborhood off of Dacian Rd. and Rose Ln. These developments within the floodplain are primarily home to low-income and racial-minority residents (Figure 4.3). The fact that Raleigh is currently developing a public housing project within the floodplain is unacceptable because vulnerable low socio-economic populations could once again be subject to flooding in their communities.

There is work being done to raise awareness about flooding and ponding issues within the communities in these floodplain developments and to fight for environmental justice for these communities. These communities, especially Rochester Heights, have been the subject of recent research about flooding within the watershed (Hasala, 2020) and have been in the news for the large flooding events that occur there (Shaffer, 2017). The Rochester Heights community has attempted to implement their own stormwater mitigation strategies, by installing rain gardens and other green infrastructure projects (Neusteter, 2018; Garcia-Cuerva, 2018). With increasing development of the watershed, such as the pending Downtown South (Parker, 2021) and Carolina Yards (Sanchez-Guerra, 2020) projects, the amount of runoff within the watershed will likely increase, exacerbating flooding within these communities. Additionally, the continued rapid population growth in Raleigh will lead to more development within the watershed, loss of valuable forested areas, and decreases in the functionality of soils.

Our survey did not find many observations of flooding within these most vulnerable floodplain communities, however, residents of these communities were not targeted to take the survey, due to concerns about overburdening the community after a similar survey that was conducted there in 2019 (Hasala). In addition, it was difficult to reach many residents due to pandemic restrictions and the disbanding of the Raleigh Community Action Committees in 2019 by the Raleigh City Council. However, Hasala et al. (2019) doucmented many resident observations of flooding within the Rochester Heights community (Figure 4.4).

Residents of the watershed not only witness locations of flooding and ponding within the watershed, but also the negative effects that come along with it. 41% of survey respondents indicated knowledge of private property damage that resulted from flooding in the past 5 years, 24% indicated knowledge of public property damage, 35% indicated knowledge of stream contamination, and 1 person knew of human injury that resulted from flooding in the watershed. Flooding is perceived as a damaging and dangerous force within the watershed.

Survey respondents were largely white, affluent, and well-educated in much higher proportions than the population of the watershed as a whole. Additionally, due to the snowball recruitment strategy of recruiting through University College of Natural Resources and Walnut

Creek Watershed Action Team (WAT) listservs and therefore also the neighborhoods and associated groups of people who work in these fields, there is most likely bias in results. People who work in this field may be more aware of flooding and other natural resource problems within the community, they may also be less directly affected by it. Additionally, people who work in Natural Resources or have interest in taking a flooding-related survey and/or having infiltration sampled on their properties may be more likely to be concerned about or manage their properties in such a way as to increase infiltration or heavily amend soils. Indeed, many survey respondents whose properties were sampled worked directly in the water resources field or had a close relationship with someone who does. Many properties also had extensive vegetable or native plant gardens. For these reasons, it is likely that residential infiltration rates for this area are likely overestimated compared to other properties in the area. Additionally, many samples were taken in the same neighborhoods as people volunteered in clusters. The overrepresentation of residential infiltration from certain neighborhoods over others, will also likely influence infiltration rates, possibly by decreasing the variability in measured infiltration rates across the watershed. More representative residential measurements from randomly selected properties throughout the watershed may have yielded different results. This is difficult, considering the challenges associated with sampling on private properties (Dyson et al., 2019), such as obtaining permission and scheduling. Although random selection was the initial intent for this study, the COVID-19 pandemic which prevented face-to-face contact with residents.

4.4 Priority restoration areas

Some of the areas with lowest infiltration are in the headwaters of the watershed. This, along with the majority of observed flooding locations in this area (Figure 4.5), points to those areas of the headwaters with the lowest infiltration rates being the best candidates for restoration projects aimed at increasing the infiltration capacities of soils, such as compost amendment, sand additions, deep tillage, or the planting of more trees. Areas of particularly low predicted infiltration are the Strother and Oakdale Park areas of Raleigh and the WakeMed Soccer Park in Cary. Both of these areas are upstream of where a lot of the observed flooding locations were indicated. The Avent Ferry Rd. corridor, near Gorman Street was one of the most common locations of observed flooding.

As previously mentioned, areas that did not reveal a large number of flooding observations in this study, but are developed within the floodplain are also likely places for stormwater mitigation of the surrounding area to be targeted. Areas with low predicted infiltration rates near Rochester Heights are the area near southeast of the intersection of Peterson St. and Garner Rd. and much of the area between South Wilmington St. and Garner Rd.

Increasing infiltration rates in the headwaters of the watershed will help in reducing stormwater runoff throughout the watershed. As infiltration rates are predicted to be low in this area and the area already experiences many instances of flooding, projects in this area would be most beneficial. It will also be important to target restoration in areas surrounding development within the floodplain, to help decrease the flood burden in those communities. Additional locations to target restoration should be any available pervious spaces in the vicinity of lots of impervious area, such as parks in downtown Raleigh, as these spaces will need to have the highest infiltration rates in order to reduce runoff from surrounding impervious areas.

4.5 Other Findings from Measurements

High infiltration capacities in this watershed may be explained by the high proportion of sandy soils, which have larger pore spaces and generally faster infiltration. While many infiltration capacities reported in the literature are lower than those we measured in this study (although still within the range of infiltration measurements captured here) (Kelling and Peterson, 1975; Kays, 1981; Gregory et al., 2006), the infiltration rates measured by this study generally agree with Pitt et al. (2004) who found mean infiltration rates in sandy, non-compact urban soils to be 15.0 in/h; with Felton and Lull (1963) who found infiltration rates in residential lawns to be 6 in/h and 34.8 in/h in wooded areas; with Rahman et al. who found infiltration rates in grassy areas up to 12 in/h; with Woltemade et al. (2010) found 0-60 in/h in residential lawns; with Yang and Zhang (2011) found urban infiltration rates ranging from 0 to 26.7 in/h; with Zimmerman et al. (2006) found infiltration rates in forests of 80 in/h; and with Berndtsson (1987) who found infiltration rates in an urban catchment, between 0 and 14.3 in/h. Research conducted in Durham, NC by Carmen et al. (2014) also found some surprisingly high infiltration rates in residential yards with clay loam soils. In their study, they found that regularly mown yards absorbing stormwater from roofs through disconnected downspouts were able to infiltrate 59-99% of roof runoff. Spence et al. (2012) also found little runoff from residential lawns, with <1% of precipitation leaving lawns as overland flow. Our findings support their conclusions that pervious spaces in this area have the potential to infiltrate high levels of runoff from impervious surfaces.

At high development sites, 88 measurements were taken with the constant head method and 8 measurements at 2 sites were taken with the NRCS method. These fast-infiltrating sites in high development areas were taken on a mulched site on NC State’s campus that appeared to be managed to prevent flooding of a building. The other site was in a church-yard next to a sidewalk and street, but was on the edge of a forest and had 95% tree cover in the square meter of the samples and 90% tree cover in the 100 square meter area. These two sites were excluded as outliers. All low development land without forest and high-density residential land was measured using the constant head method. 28 low density residential measurements were taken with the NRCS method and 104 with the constant head method.

Soil bulk densities within the watershed were also found to be generally low, with all measured soil bulk densities except one, found to be less than 1.60 g/cm^3, which is the bulk density commonly accepted to restrict root growth in sandy clay loam or sandier soils (*Soil Health- Bulk Density/Moisture/Aeration*, 2019). While the Walnut Creek watershed encompasses urban landscapes, most of the development in the watershed is developed, open space or developed, low intensity (Figure 4.6) (NLCD, 2016), which could lead to less soil disturbance than that found in more intensely developed watersheds. It is good news for the watershed that infiltration capacities throughout the landscape are high enough to fully infiltrate direct precipitation from most storms. However, it is unclear whether additional stormwater inputs to pervious areas in the form of runoff from impervious surfaces, will also be able to be fully infiltrated in most precipitation events. It is likely that in areas with high amounts of total impervious areas, even those that drain to pervious areas could cause overland flow that will lead to flooding. In order to avoid this problem, I recommend that when possible impervious surfaces should be drained to forested areas with significantly higher infiltration capacities.

Infiltration rates varied over an order of magnitude, with forested areas having much higher infiltration rates than more developed areas. This is consistent with research showing that trees can increase infiltration (Rahman et al., 2019; Yang and Zhang, 2011). Trees can develop macropores in the soil with their roots, allowing faster channels for water to flow. Trees also take-up water with their root system. Additionally, forest soils tend to be high in organic matter, which has large pore spaces through which water can be infiltrated. Even unforested sites, such as residential lots with trees near the measurement sites, tended to have faster infiltration rates than those without trees.

Although, higher than expected infiltration rates were found throughout the watershed, infiltration rates in forested areas, those with more natural land covers, such as leaf litter or pine straw had significantly higher infiltration rates relative to non-forested areas or those with turf grass. If stormwater runoff is of special concern in certain areas, one strategy for reducing runoff could be to plant more trees. It will also be important to protect forested areas within the watershed as a precipitation sink in a larger urbanized area.

5. CONCLUSIONS

While urban flooding continues to threaten many vulnerable urban populations, this study helps to shed some light on the urban hydrological system that may lead to the increased impact of flood prevention measures, such as SCMs. The most commonly used infiltration models for rainfall-runoff modeling do a poor job of representing the highly variable infiltration rates of urban soils, when standard parameters are used. This may result in overestimation of runoff in rainfall-runoff models that use infiltration estimations. Without the use of time and cost intensive field measurements to improve model performance, a different approach to estimating urban infiltration measurements may be necessary. In this study, we propose a new model, based on random forest prediction, for estimating infiltration rates based on digitally available data. This model is capable of more accurate infiltration measurements at a fine scale for an entire watershed.

The additional input of participatory data from the community for which models are run may assist in model validation and in prioritizing areas of special concern in regards to runoff. Using this data in combination with modeled data could help prioritize the placement of SCMs within a watershed in areas with low infiltration rates and high community observation of flooding.

This study shows promising results that our urban soils may actually have more hydrological functionality than expected. Capitalizing on the fast infiltration rates of some soils, especially those in our lightly managed urban green spaces and urban forests could be helpful in reducing the harmful impacts of runoff from neighboring impervious surfaces. Although precise predictions of infiltration rate at any given point remains a challenge, information about the relative infiltration capacity of various urban landscapes could prove useful in planning and zoning. With the relatively fast infiltration capabilities of urban forested areas and non-forested area with tree-cover and leaf litter or pine straw on the ground, managers may be able to capitalize on the abilities of these soils when planning urban development. The preservation of urban green spaces, especially forests throughout urban watersheds could be key to reducing urban flooding.

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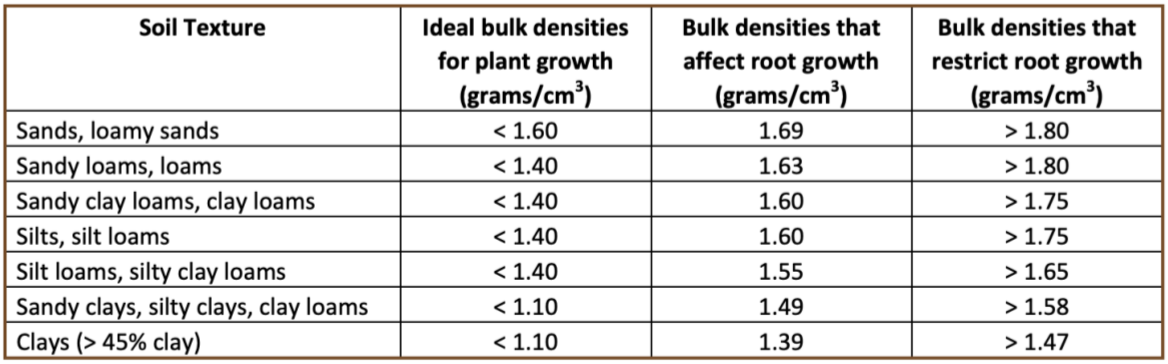
TABLES

Table 2.1 *Land use types in the Walnut Creek watershed* according to Wake County (July 2019) property data. Land classes in red were categorized as high development, green were categorized as low development, and yellow as residential for the purposes of choosing initial sampling sites.

Land use code	Land use description	Total area (km^2)	% of land use
AWI	Acre With Improvement, No House	0.67	1
AHS	Acres Greater Than 10 With House	0.86	1
COM	Commercial	6.96	7
IND	Industrial	3.16	3
XMT	EXEMPT	27.42	27
AGR	Agriculture	2.60	3
APT	Apartment	5.36	5
HIS	Historic	0.10	0
HOA	HOA	2.19	2
CEM	Cemetery	0.49	0
RET	Retirement Home	0.03	0
LEA	Leasehold Imps	0.00	0
MFG	Manufactured Home	0.07	0
CON	Condominium	0.00	0
COX	Condo Complex	0.98	1
PTX	Part Exempt	0.39	0
RHS	Residential Less Than 10 Acres	26.38	26
STA	State Assessed	1.56	2
MHP	Mobile Home Park	0.96	1
GOL	Golf Course	0.13	0
VAC	Vacant	13.13	13
WSS	Water/Sewer System	0.02	0
FOR	Forestry	5.21	5
HRT	Horticulture	0.67	1
OTHER	Unidentified	2.34	2
Total		101.69	100

Table 2.2 *Bulk density's effect on plant growth* based on soil texture. (*Soil Health- Bulk Density/Moisture/Aeration*, 2019)



Soil Texture	Ideal bulk densities for plant growth (grams/cm^3)	Bulk densities that affect root growth (grams/cm^3)	Bulk densities that restrict root growth (grams/cm^3)
Sands, loamy sands	< 1.60	1.69	> 1.80
Sandy loams, loams	< 1.40	1.63	> 1.80
Sandy clay loams, clay loams	< 1.40	1.60	> 1.75
Silts, silt loams	< 1.40	1.60	> 1.75
Silt loams, silty clay loams	< 1.40	1.55	> 1.65
Sandy clays, silty clays, clay loams	< 1.10	1.49	> 1.58
Clays (> 45% clay)	< 1.10	1.39	> 1.47

Table 3.1 *Mean infiltration rates for different land uses in the watershed*. Forested areas had significantly higher infiltration capacities than all other land use types. Infiltration rates for all land uses were highly variable.

	Forested	Low Development	High Development	High Density Residential	Low Density Residential
Mean ± Standard deviation of Infiltration Capacity in in/h (mm/h)	73.8±61.1 (1875±1552)	7.07±5.28 (178± 134)	8.38±7.49 (213±190)	5.13 ± 5.82 (130±148)	10.8±12.4 (274± 315)

Table 3.2 *Residential yard vegetation beyond lawns, as reported by survey respondents.* The most commonly reported vegetation were trees, shrubs, and flowers.

	small trees	bushes/ shrubs	large trees	flowers	vegetable garden	other	succulents
# of respondents who indicated a vegetation cover	49	48	47	42	23	7	4

FIGURES

Figure 2.1 *Flooding in the watershed.* Cars drive through a flooded portion of the road in the Walnut Creek watershed days after a hard rain.

Figure 2.2 *Single-ring infiltrometer marked with measurements at ⅛" intervals made from a beveled PVC pipe.*

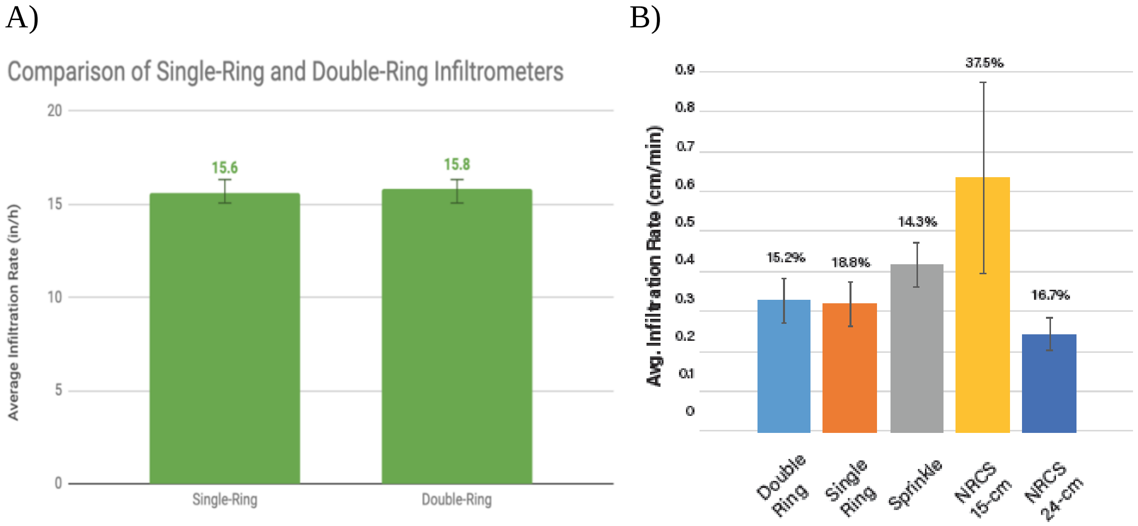


Figure 2.3a and 2.3b *A comparison of infiltration rates using different infiltrometer methods.* (A) Infiltration measurements taken in this study were similar with a single-ring and double-ring infiltrometer. Error bars shown are the standard deviation of infiltration rates taken with each type of infiltrometer. Labeled numbers are the average infiltration rates taken with each method. (B) Comparison of four different infiltration methods from Saltiel et al., 2018. The single and double ring infiltrometers are represented in orange and light blue. Measures infiltration rates were similar for both methods and within the range of variation for each.

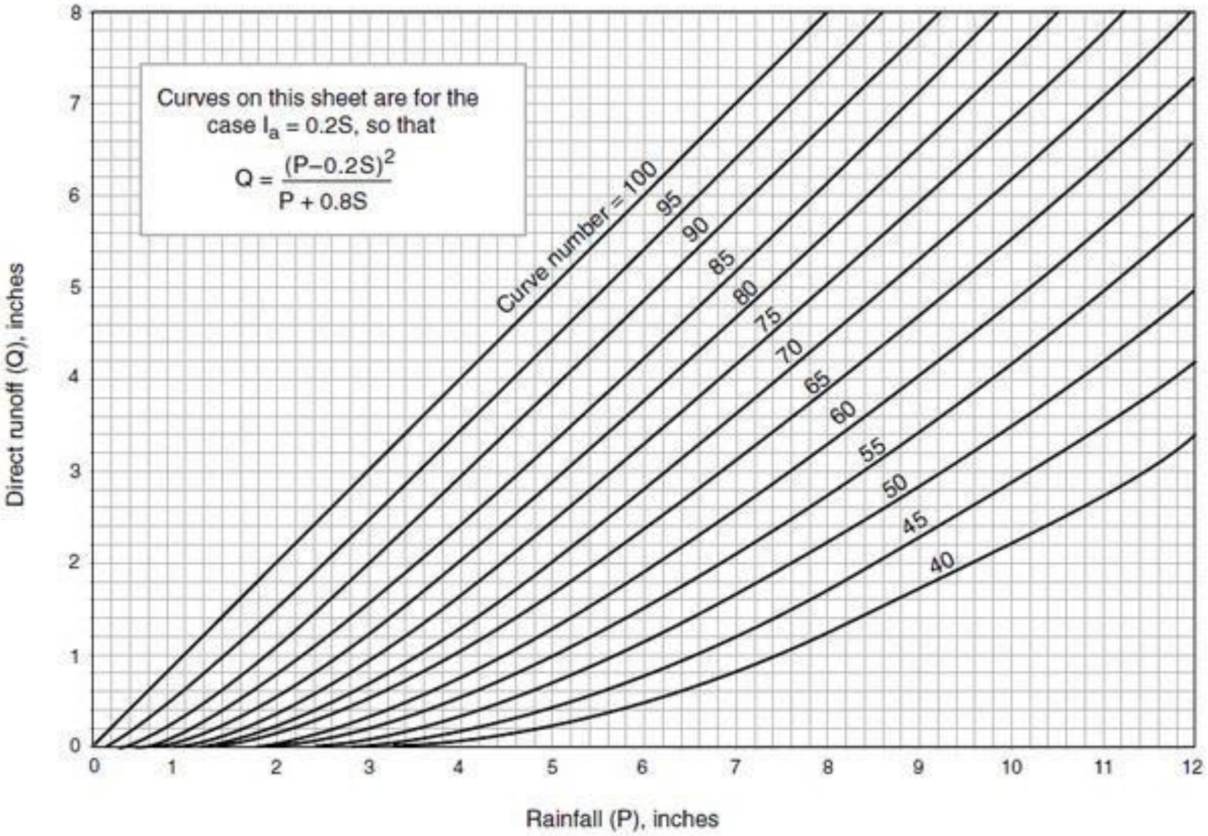


Figure 2.4 *Curve Numbers*. Rainfall-runoff curves used to determine runoff from precipitation with the Curve Number method. Higher curve numbers indicate less infiltration, for example impervious surfaces often have curve numbers in the upper 90s. Following the corresponding curve for any given curve number will give an estimate of runoff in inches for any given depth of rainfall. (Soil Conservation Service, 1986)

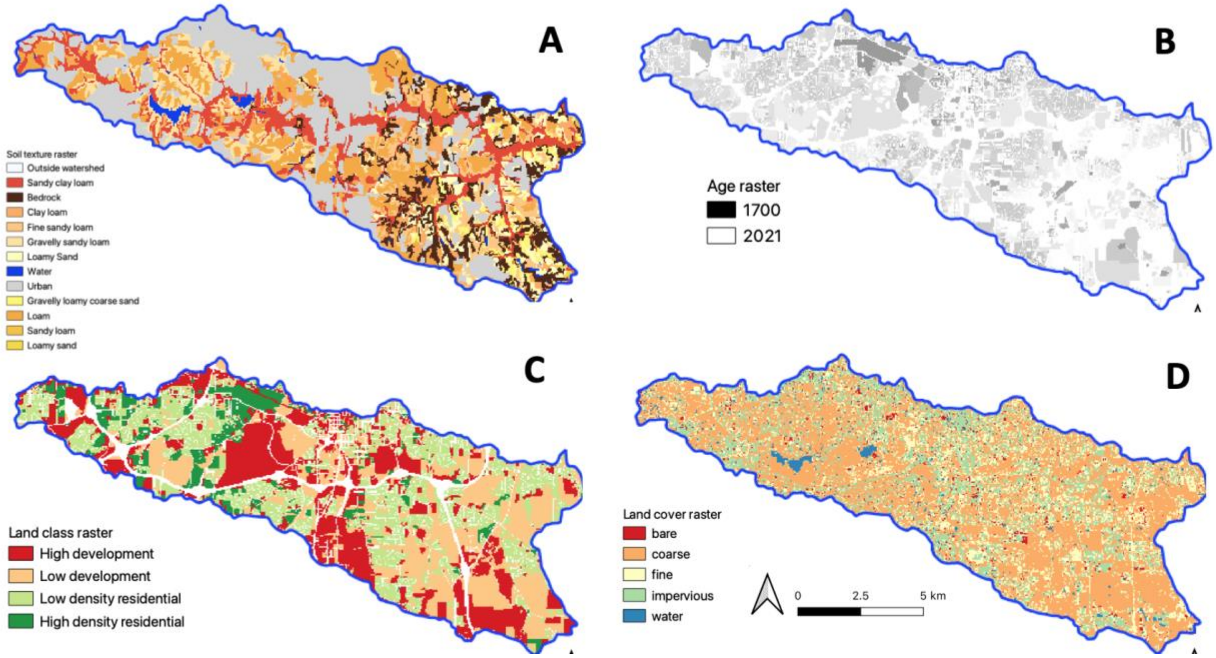


Figure 2.5 *Raster layers* of four different parameters within the watershed were combined to provide corresponding data for each sampling point and for prediction of infiltration indices across the watershed with the random forest model. In all layers, the dark blue color is the watershed boundary. (A) A raster layer of the SSURGO soil textures throughout the watershed. Gray areas are classified as "Urban land" and did not have an associates soil texture. (B) A raster layer of year of development throughout the watershed as determined from Wake County parcel data. Darker colored areas were developed longer ago than lighter areas. (C) A raster layer of land classes throughout the watershed as determined from Wake County parcel data. Wake County land classes were grouped and reclassified based on land uses used in this study. (D) A raster layer of land cover throughout the watershed developed from a random forest model based on NAIP data at the 1-m scale. Coarse areas are those covered in vegetation such as trees and shrubs, fine areas are those with fine vegetation, such as grass.

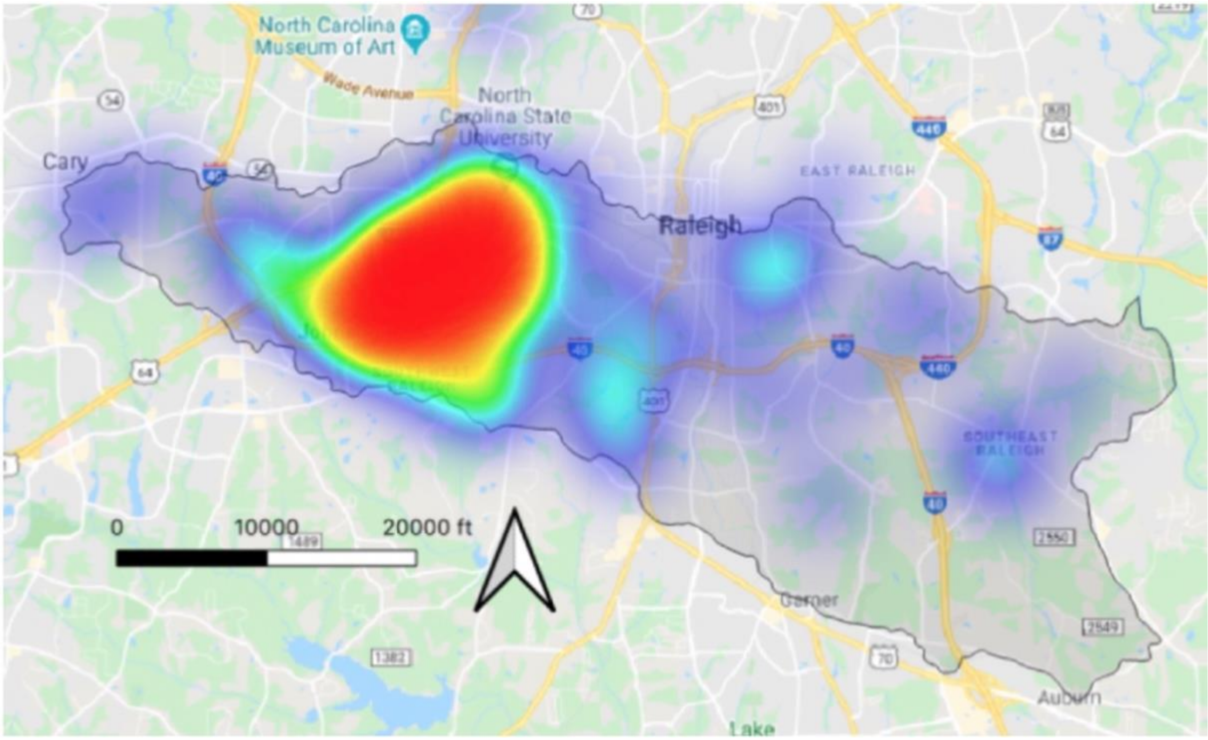
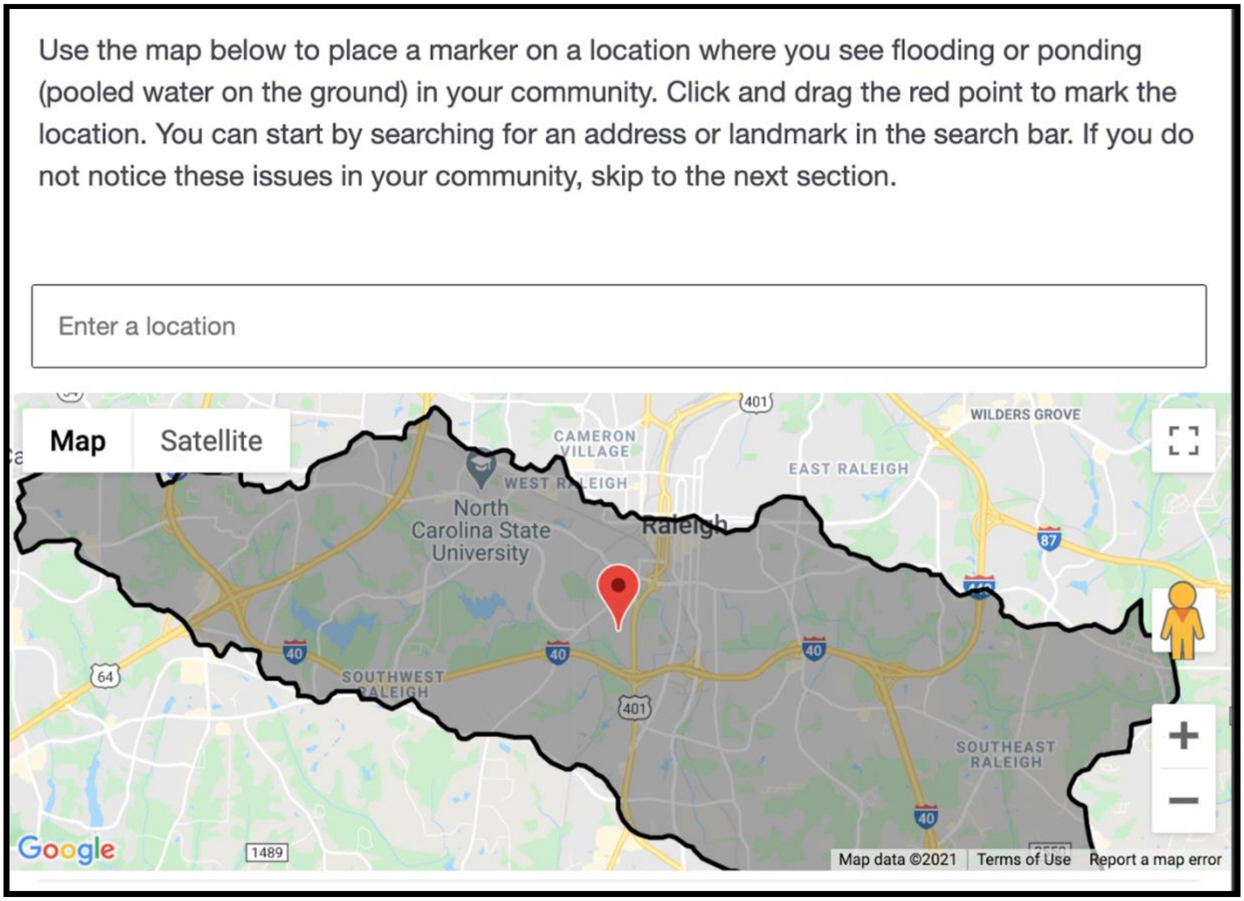


Figure 2.6 *Familiar locations heatmap.* A heatmap of locations in the watershed that survey respondents were most familiar with. Most respondents were most familiar with West and West Central Raleigh.



Use the map below to place a marker on a location where you see flooding or ponding (pooled water on the ground) in your community. Click and drag the red point to mark the location. You can start by searching for an address or landmark in the search bar. If you do not notice these issues in your community, skip to the next section.

Enter a location

Figure 2.7 *Survey map.* The map that participants saw when they took the survey. Participants were able to move the red pin manually on the map or enter an address in the location bar to move it automatically. Participants could also zoom in and out or use the satellite view of the map. Watershed boundaries are showing in black to help participants check to see if there point falls within the watershed, but participants were not required to place the pin within the watershed. Latitude and longitude data for each placed pin were available to the research team after they completed the question. Participants were not required to complete this question, but could complete it up to 5 times.

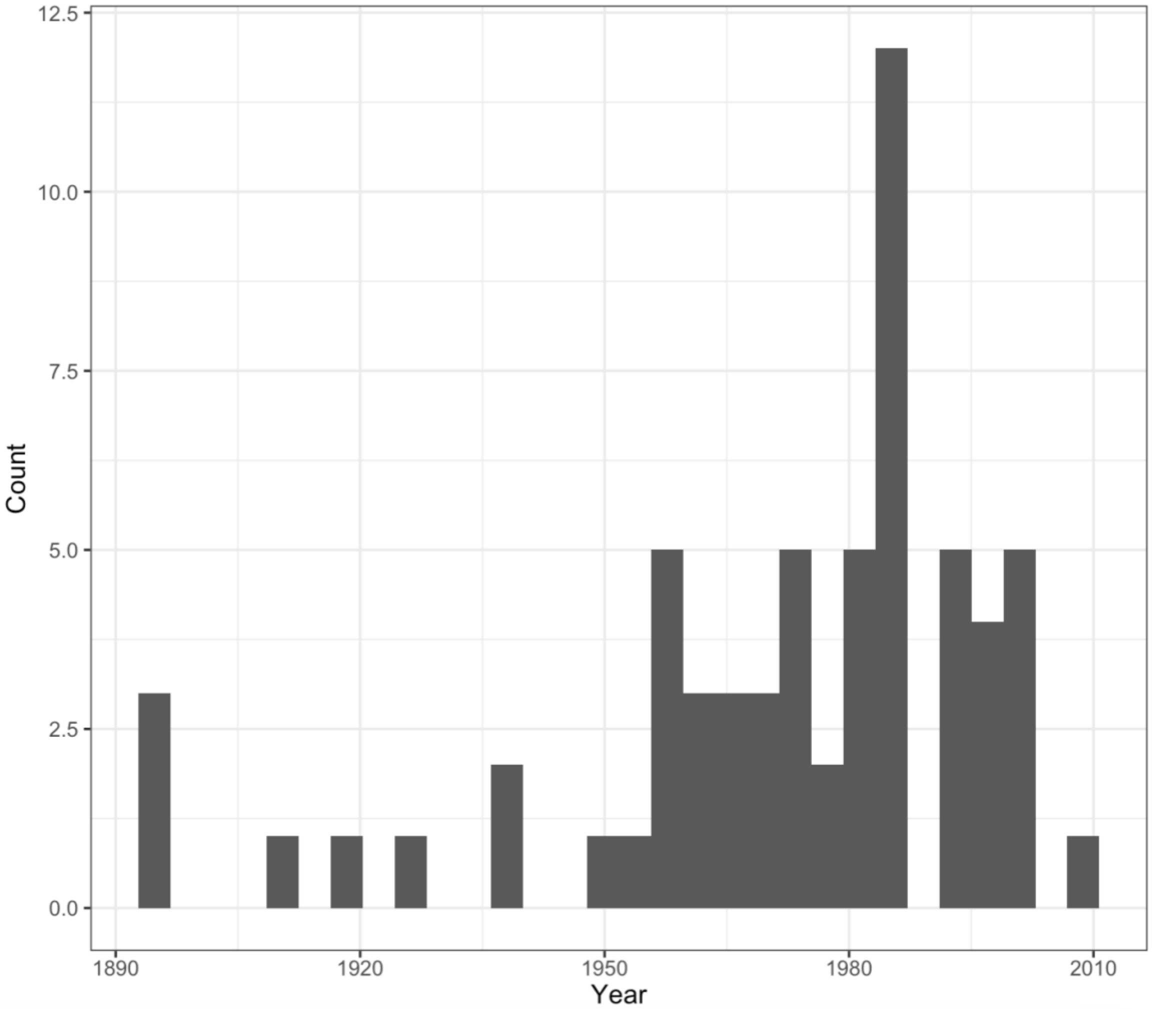


Figure 3.1 *Years of development.* The distribution of years of development of sampled sites ranges from about 1896-2010, with most sites developed since the 1950s. Development records in the watershed as a whole range from 1760-2021.

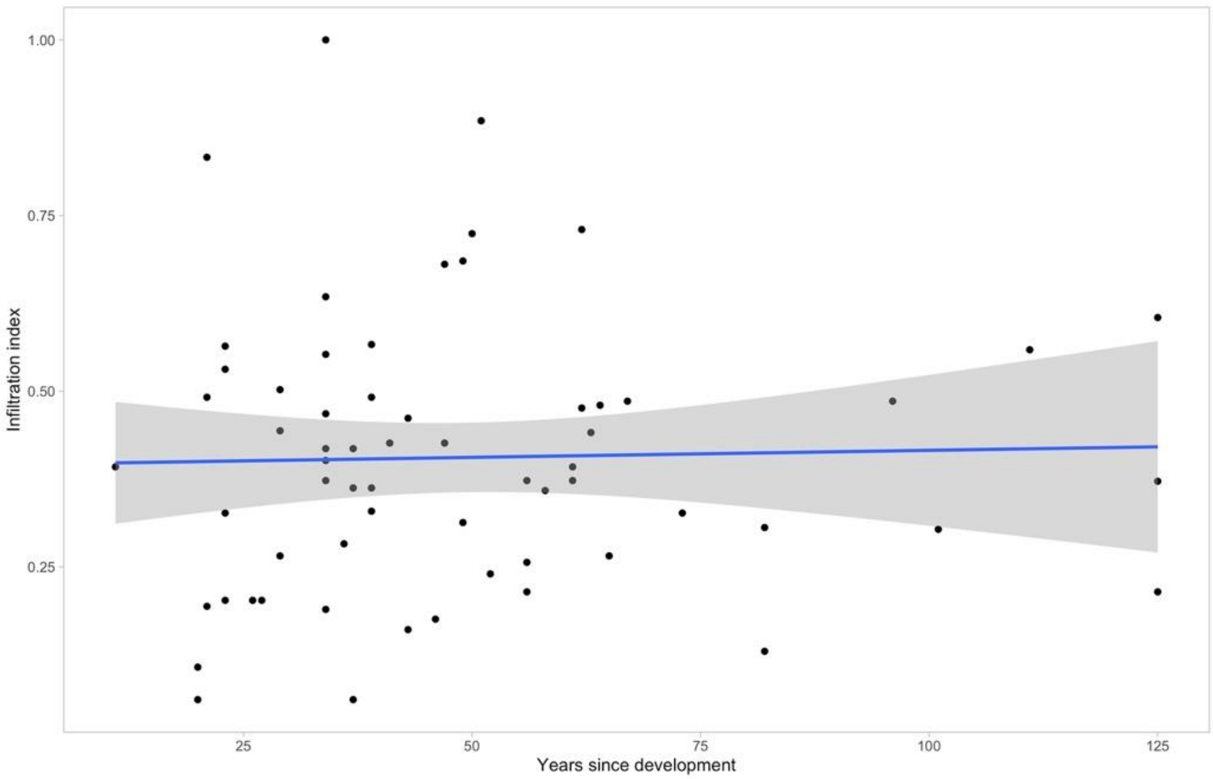


Figure 3.2 *Infiltration index vs. years since development.* No significant relationship was found between time since land development and infiltration index (R^2=-0.02, p=0.8).

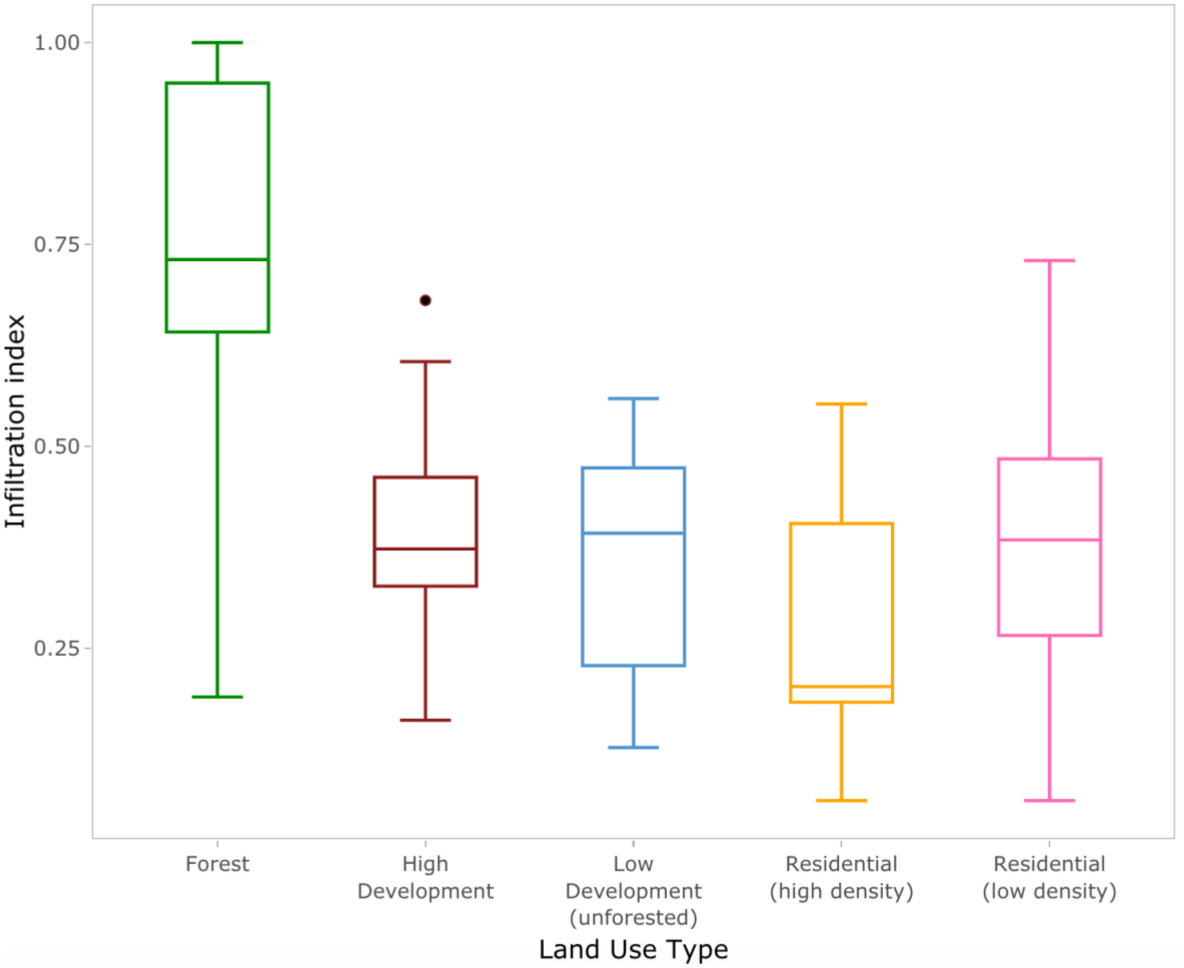


Figure 3.3 *Infiltration indices as a function of land use type*. Sites with forest land uses had significantly higher infiltration rates than other land uses, but also had the largest range in infiltration indices. Low density residential sites also had large variabilities in infiltration rate.

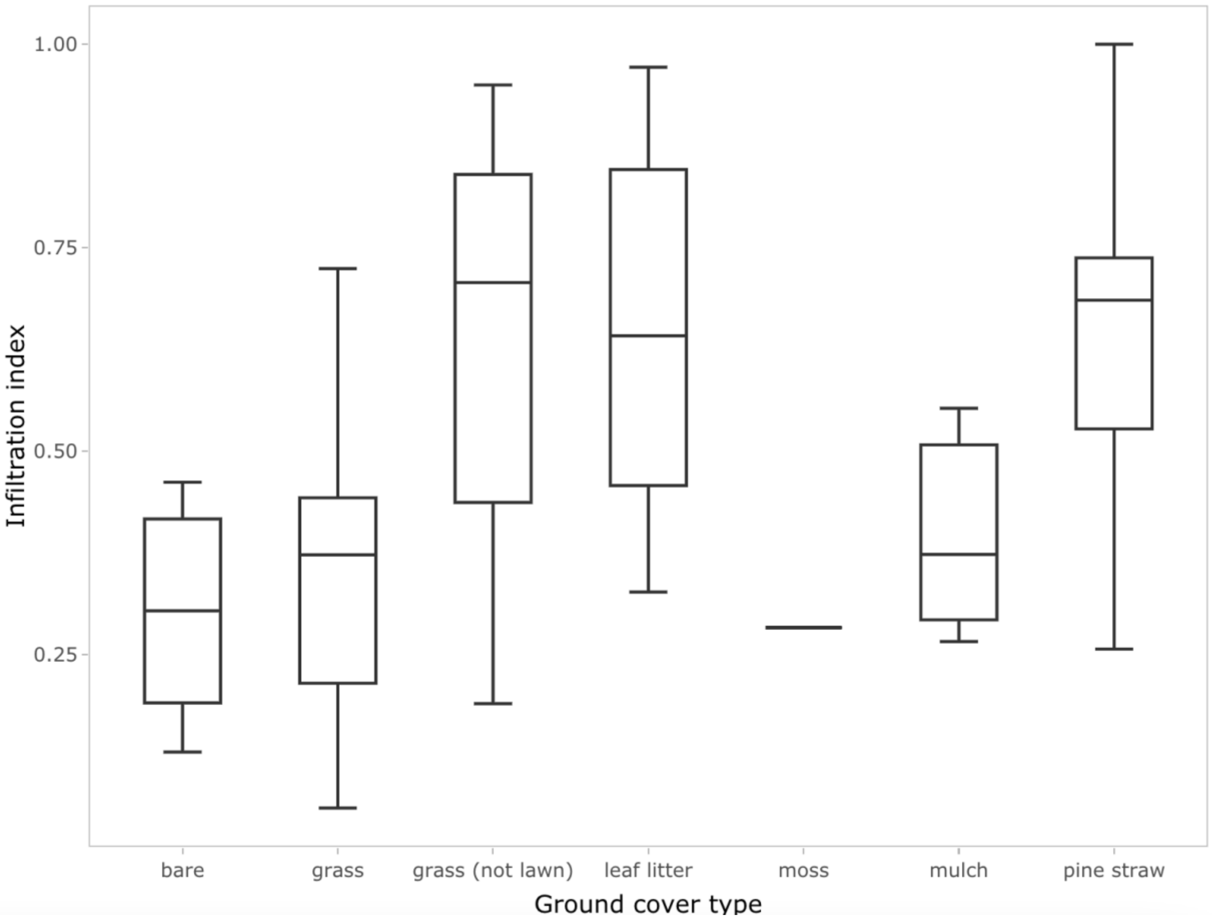


Figure 3.4 *Infiltration indices as a function of ground cover*. Natural forested ground covers had generally higher infiltration capacities than turf grass or bare ground.

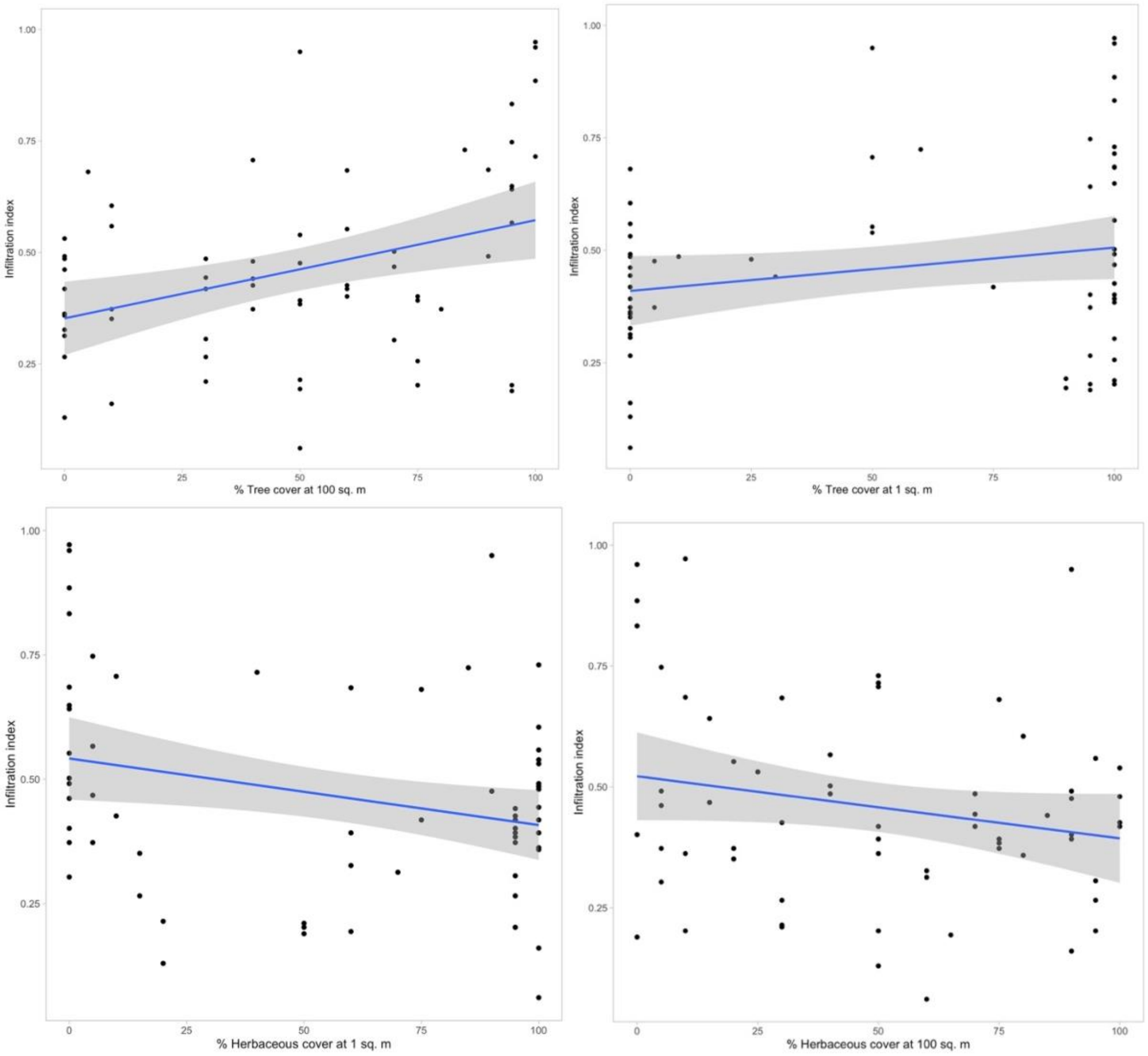


Figure 3.5 *Infiltration index vs. vegetation cover*. There is a weak slightly positive correlation between tree cover at 100 m^2 and infiltration index (R^2= 0.12, $p<0.05$). There is no strong relationship between tree cover at 1 m^2 and infiltration index (R^2= 0.03, $p<0.05$). There is no significant relationship between % herbaceous cover at 100 m^2 and infiltration index (R^2= 0.03, $p=0.1$). There is no strong relationship between % herbaceous cover at 1 m^2 and infiltration index (R^2= 0.06, $p<0.05$).

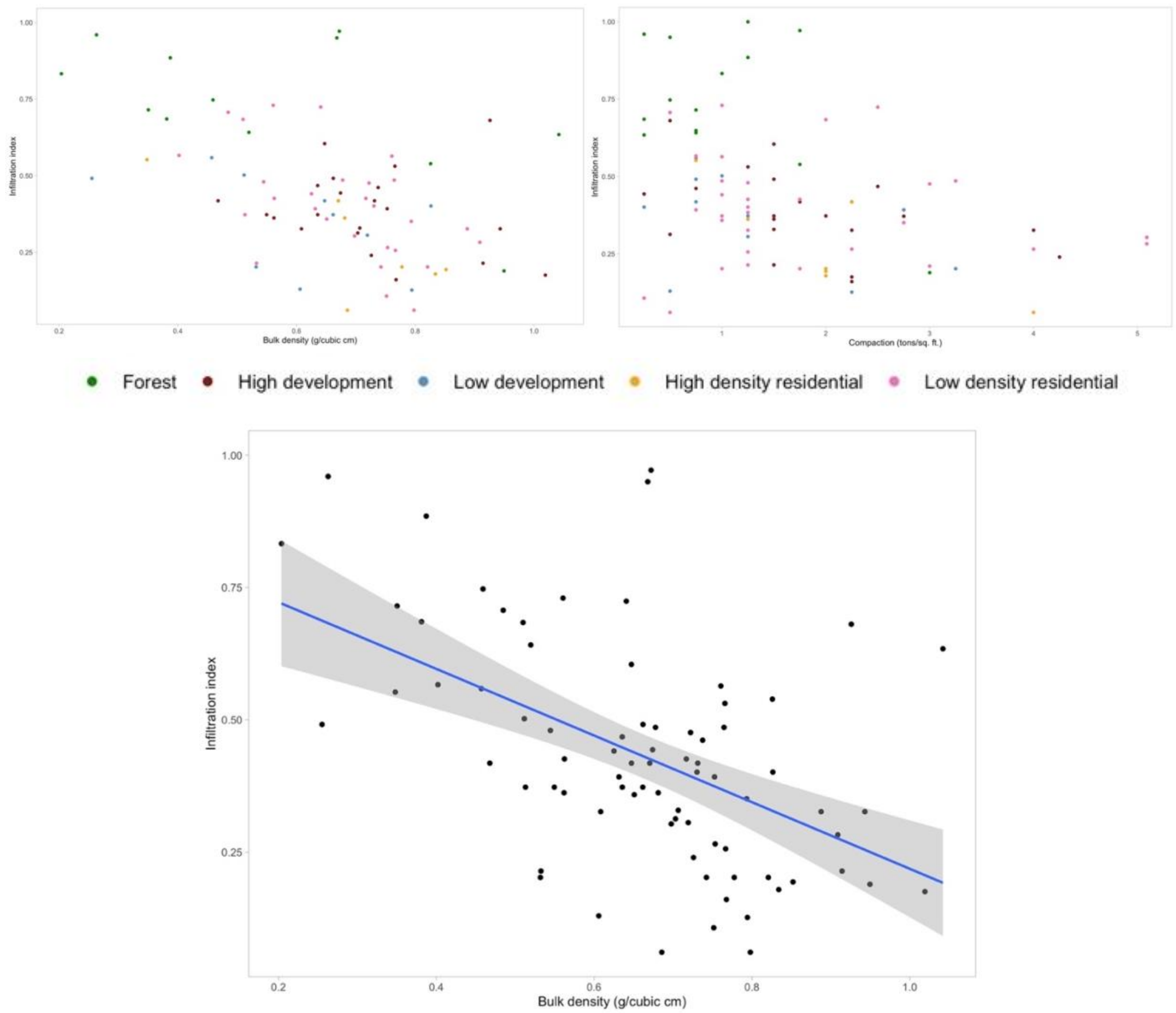


Figure 3.6 *Infiltration indices as a function of soil compaction*. (Top) Infiltration index compared to bulk density in grams/cubic cm and compaction level in tons/square foot. (Bottom) Infiltration index compared to soil bulk density are negatively correlated (R^2= 0.25, $p<0.05$, slope=-0.6). Soils with increasing bulk densities have decreasing infiltration capacities. In urban areas where soils are compacted, this could have big effects on the ability of green spaces to infiltrate stormwater.

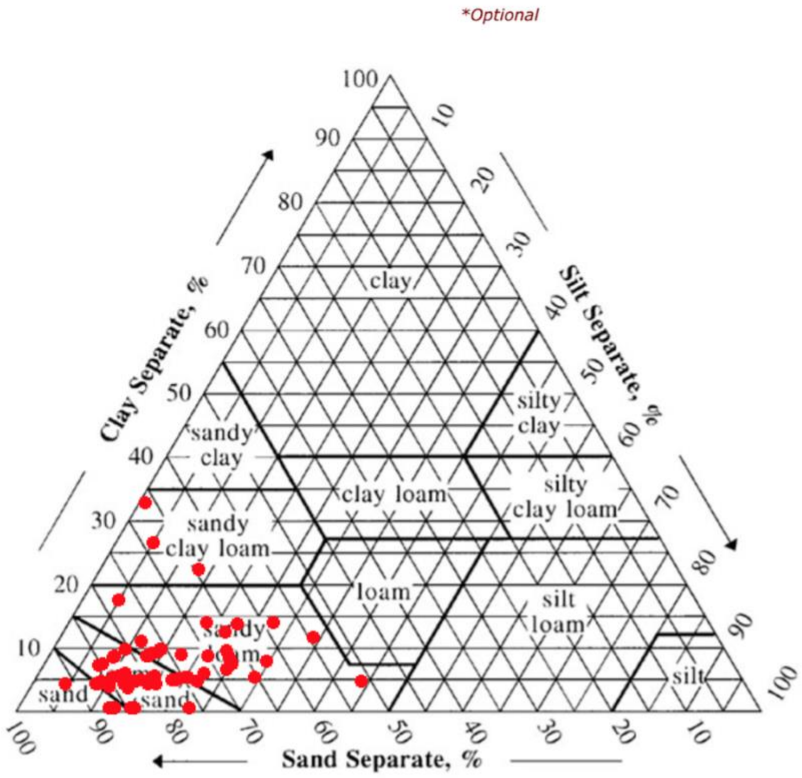


Figure 3.7 *Measured soil textures* were mostly sandy. Red dots display measured soil textures on this soil texture triangle generated with the NRCS Soil Texture Calculator (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167).

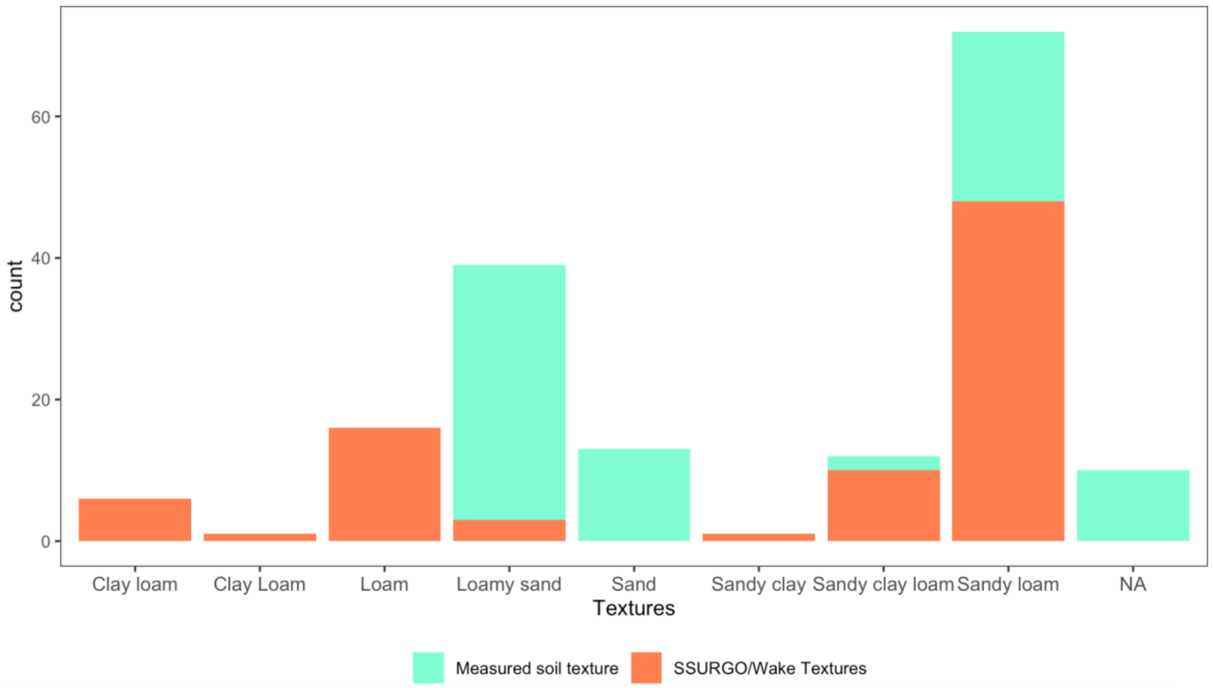


Figure 3.8 *Measures vs. mapped soil textures*. Measured and mapped soil textures for field sites were mostly sandy. Measured soils, labeled NA, were soils whose textures could not be determined accurately in the lab.

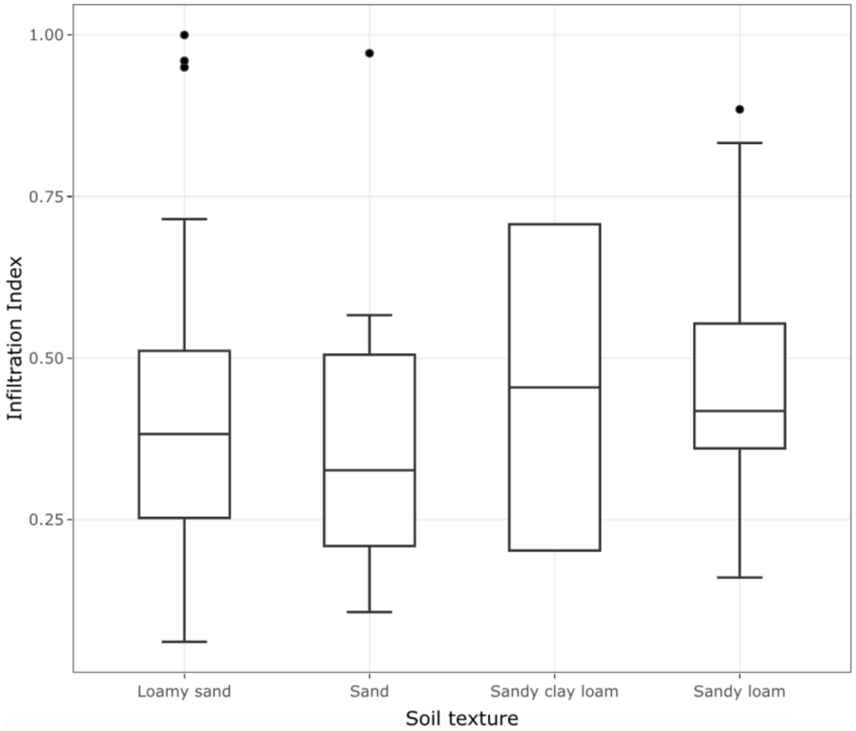


Figure 3.9 *Infiltration index vs. soils texture*. Soil infiltration index by measured soil texture. Soils were generally sandy.

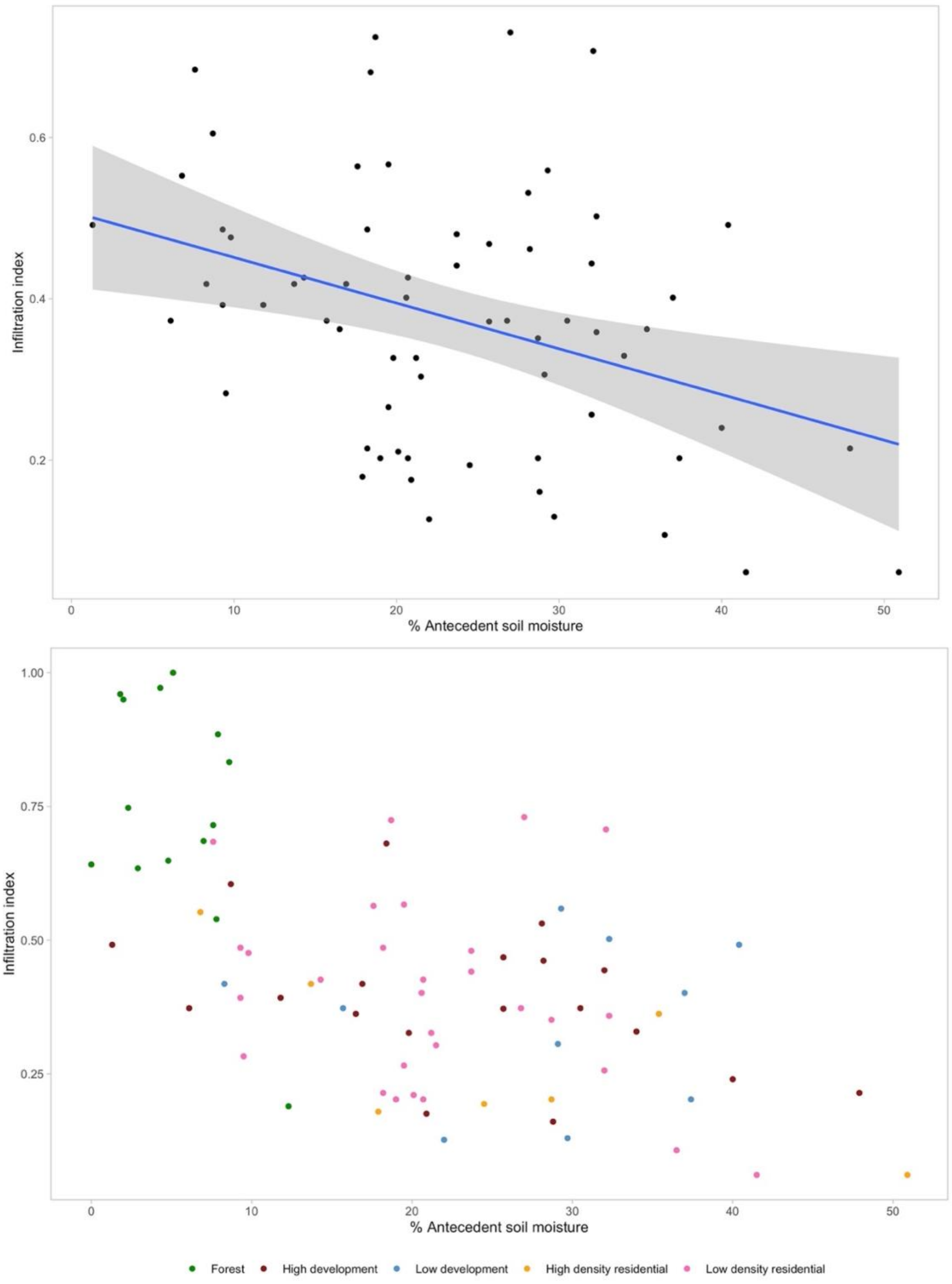


Figure 3.10 *Infiltration index vs. soils moisture.* There is a negative correlation (R^2= 0.337, Slope= -0.01, p<0.001) between infiltration rates and % antecedent soil moisture. Even after running infiltration measurements out for 90 minutes, sampling sites with higher initial soil moisture had lower infiltration capacities. However, when forested sites are removed, where infiltration capacity was most likely not reached, R^2= 0.119.

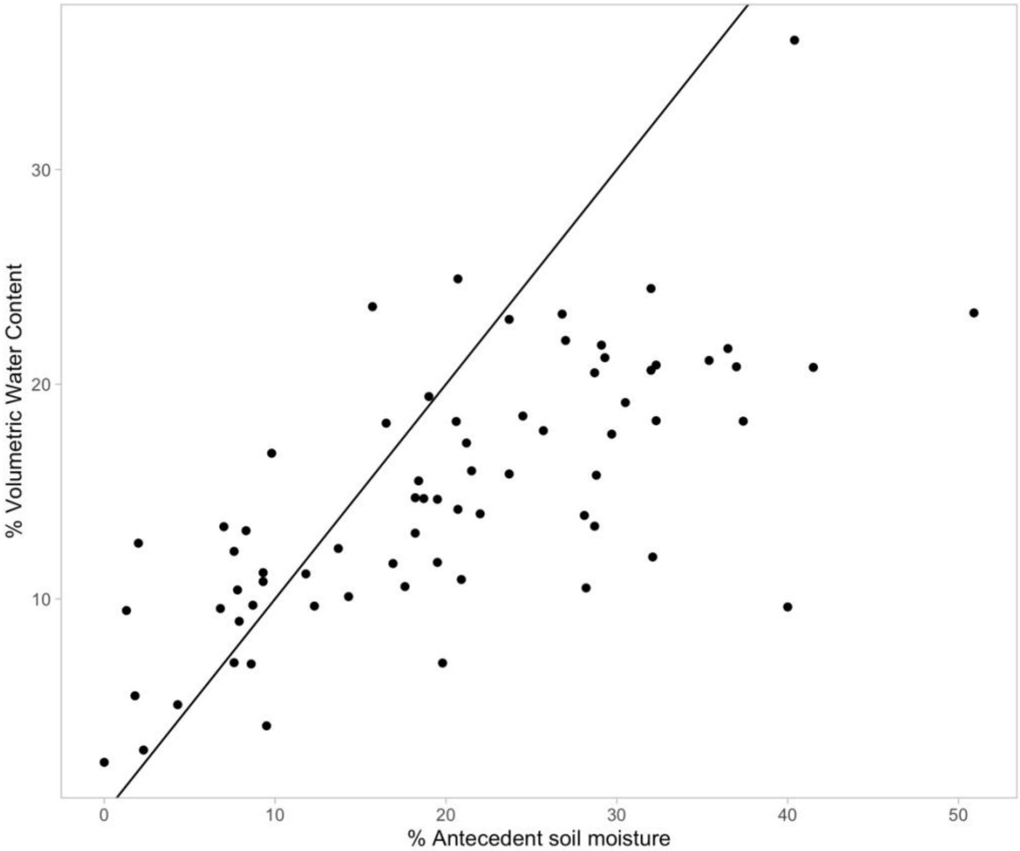


Figure 3.11 *Volumetric water content vs. antecedent soil moisture.* Volumetric water content measured in the lab varies with % antecedent soil moisture determined in the field, however there is not a 1:1 relationship between the 2 (y=x is shown on the figure above). At higher water content values, this may be due to loss of moisture in soil transport between field and lab and moisture residue left on sample bag.

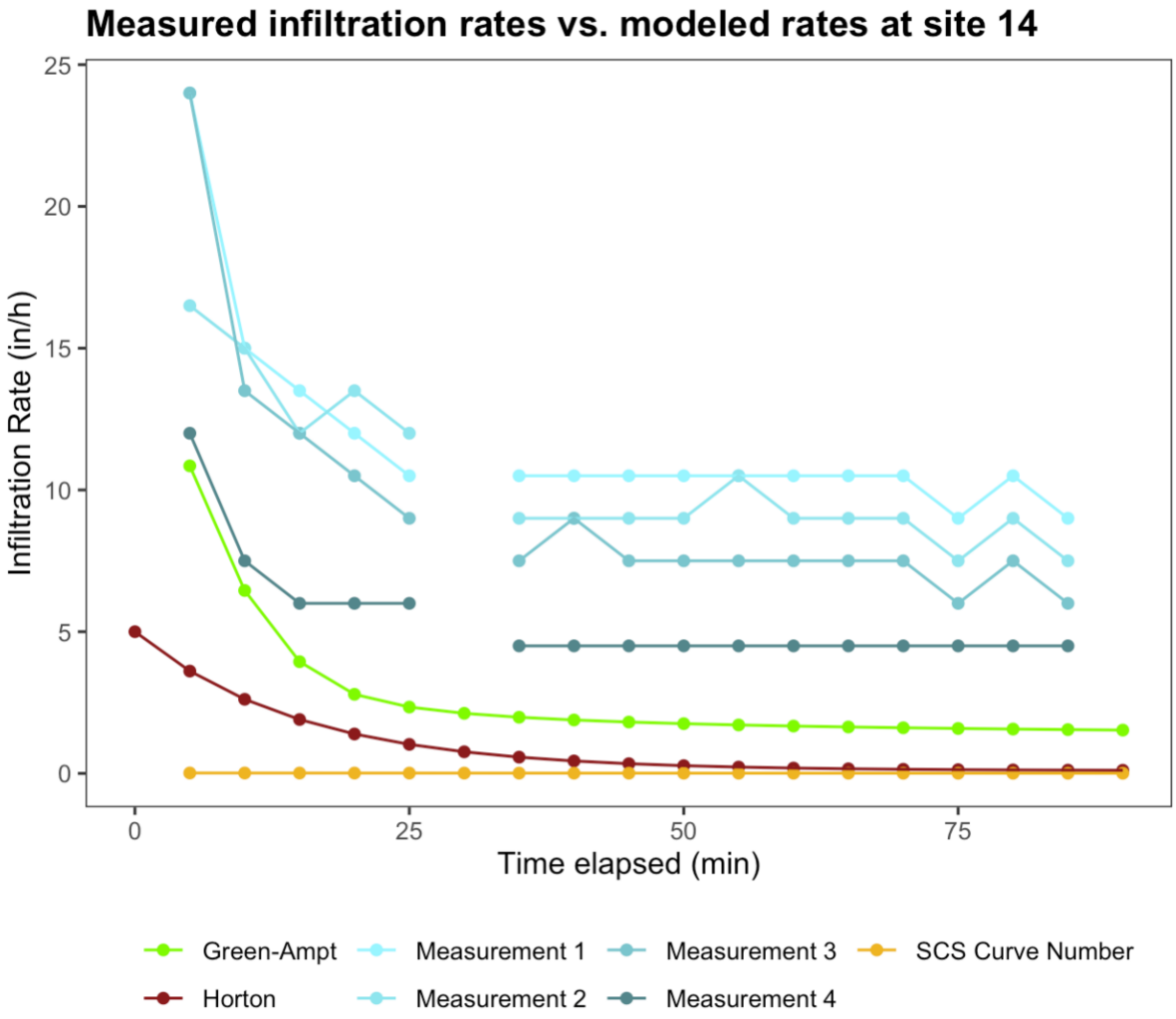


Figure 3.12 *Modeled infiltration rates.* An example of measured versus modeled infiltration curves at an urban site. All three models underestimate infiltration rates at this site. Infiltration rates are highly variable even at locations less than 1 meter apart.

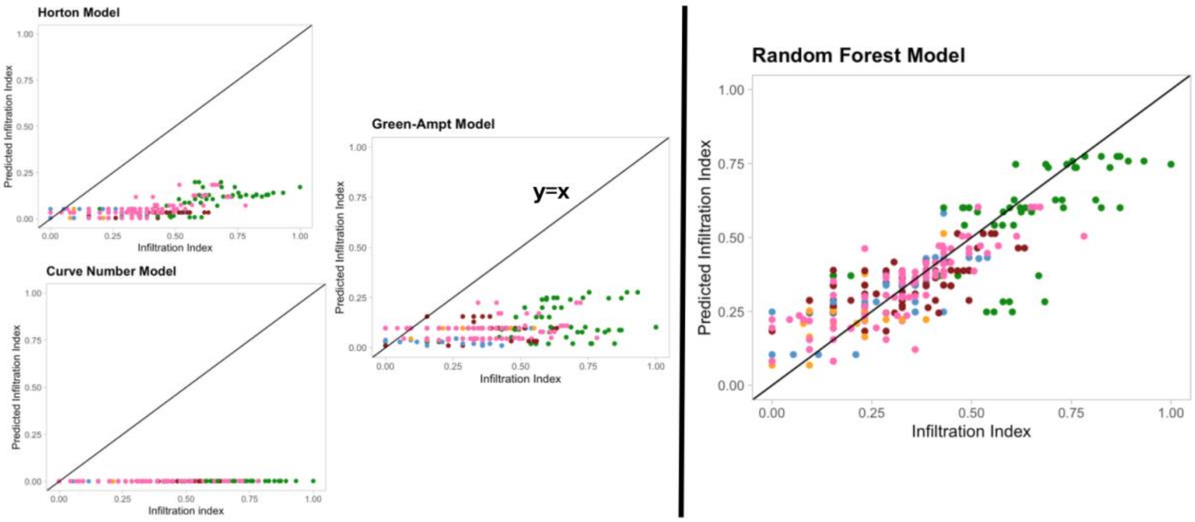


Figure 3.13 *Model comparison* Infiltration indices for commonly used models are overestimated in most cases. With the random forest model generated in this study, infiltration indices are estimated more closely, with $R^2= 0.7$. Measured infiltration indices are shown on the x-axis and modeled infiltration indices are shown on the y-axis. The y=x line is also shown on each graph.

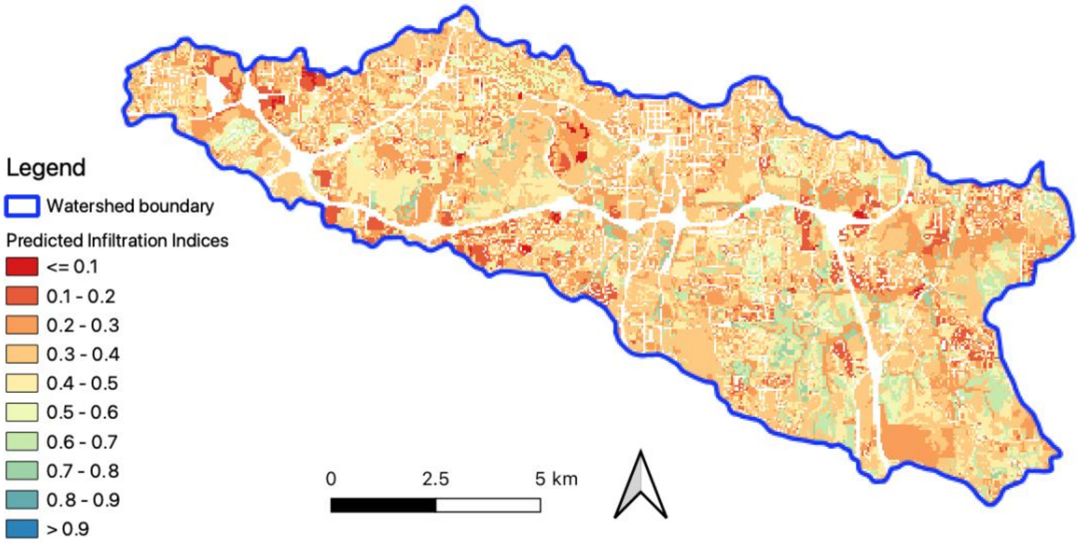


Figure 3.14 *Results of random forest model used to predict infiltration indices across the watershed*. Results are displayed at the 1m scale. White areas are impervious road corridors excluded from predictions. Red areas are predicted to have the lowest infiltration capacities, while yellow and green areas likely have higher infiltration capacities. The southeast area of the watershed appears to have higher infiltration capacities than the south and northwest parts of the watershed.

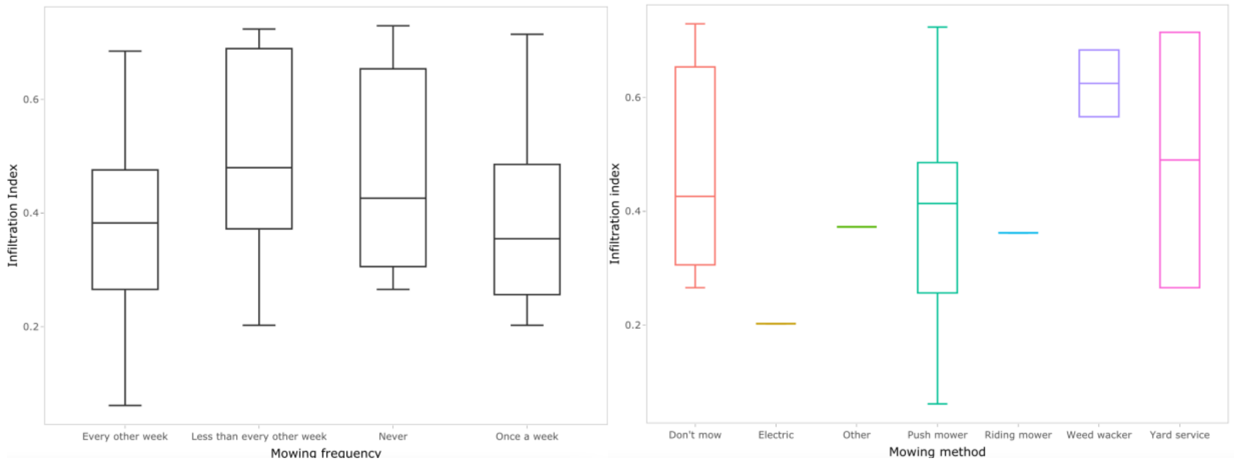


Figure 3.15 *Infiltration indices as a function of mowing*. (*Left*) Infiltration indices of residential yards mown at different frequencies as reported by residents. (*Right*) Infiltration indices of residential yards mown with different methods as reported by residents.

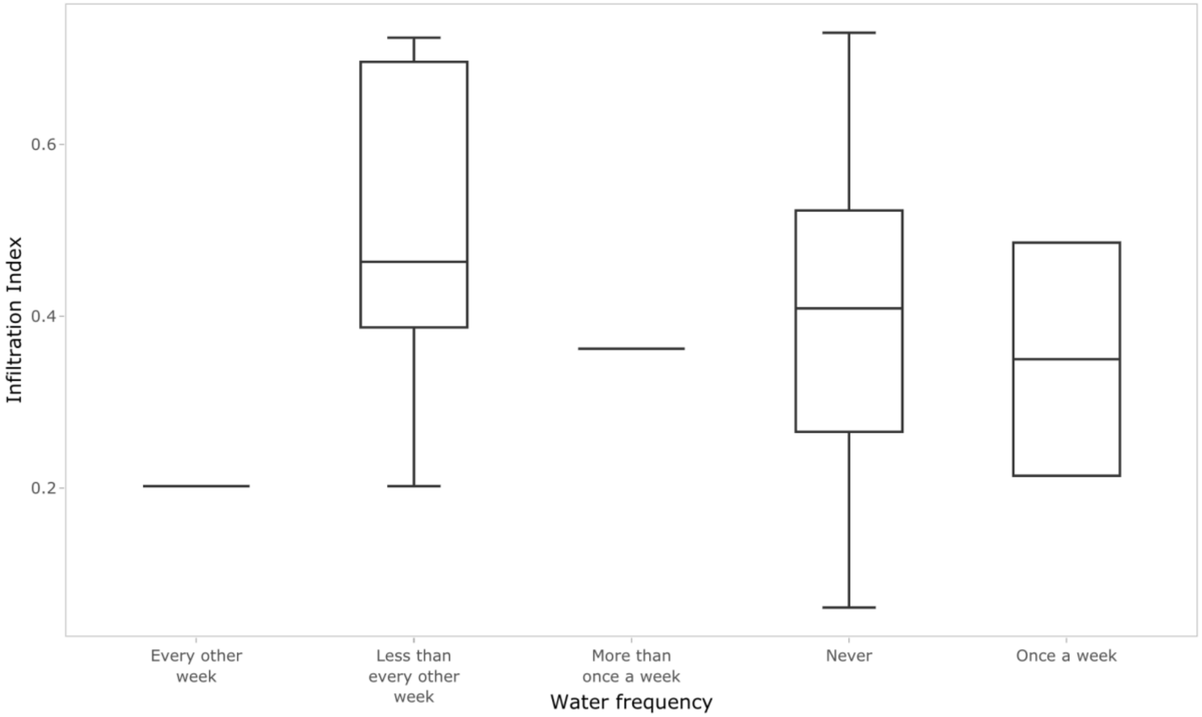


Figure 3.16 *Infiltration indices as a function of watering.* Infiltration index and watering frequency of yards. (Top) Infiltration indices for lawns watered at different frequencies. (Bottom) Infiltration indices of lawns watered for different lengths of time.

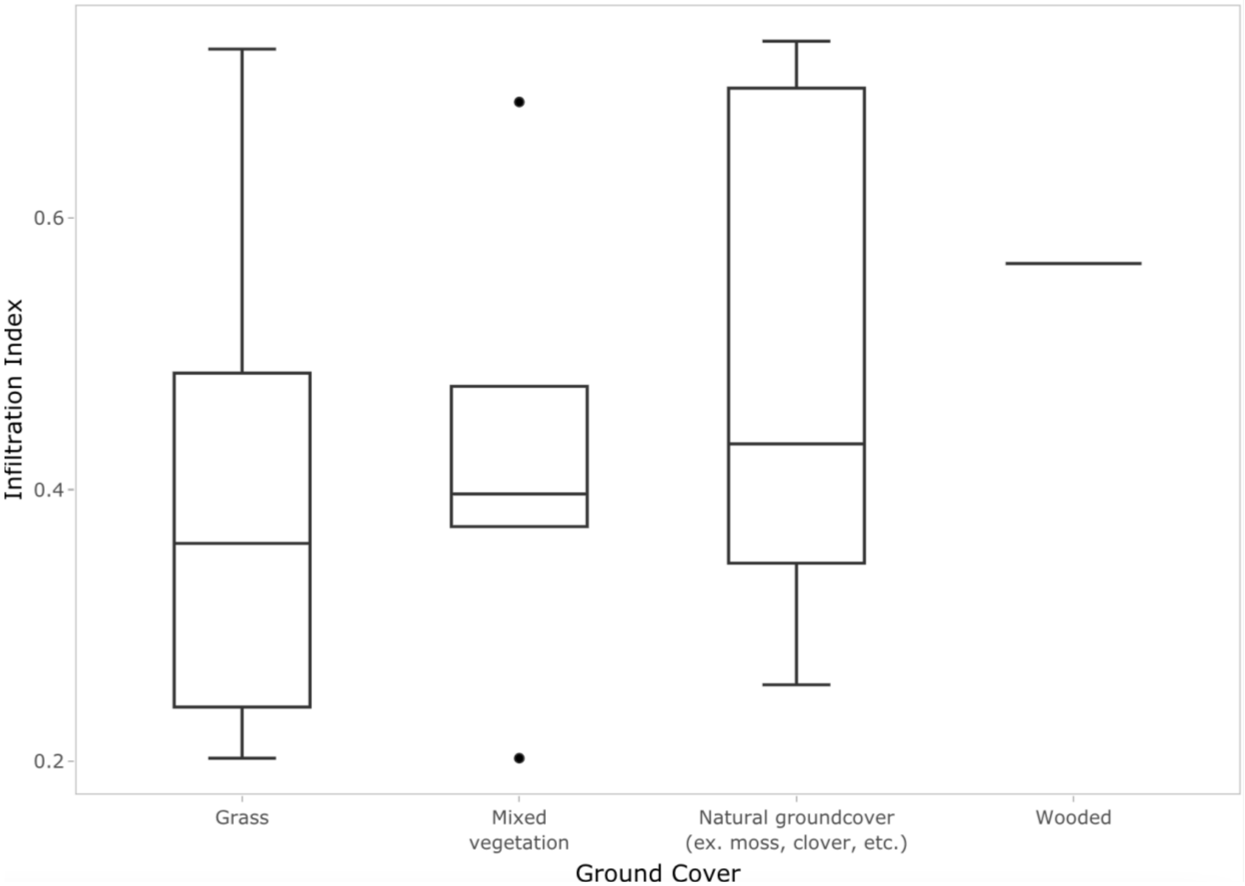


Figure 3.17 *Infiltration indices as a function of survey reported lawn cover*. Differences in infiltration indices based on self-reported residential vegetation covers. There were no significant differences in infiltration rates based on self-reported lawn types

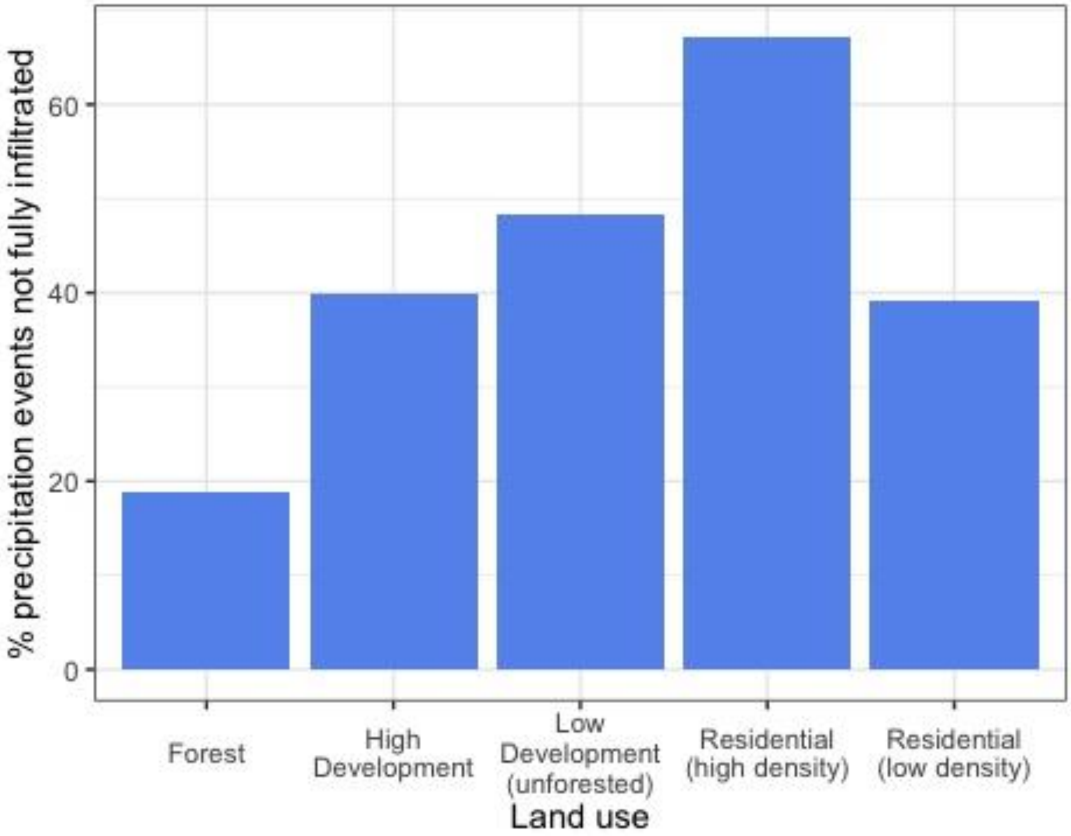


Figure 3.18 *% Precipitation that could be infiltrated by each land use.* Out of 3,661 total rain events (precipitation> 0 in per 15-minute interval) since rainfall records began (2018) at USGS gauge 354525078382645, there was a very small percentage of rain events that could not have been infiltrated at any of the measured sites. Less than 1% of rain events exceeded infiltration capacities at most sites. Relative to other sites, high density residential sites had capacity to infiltrate the lowest number of rain events.

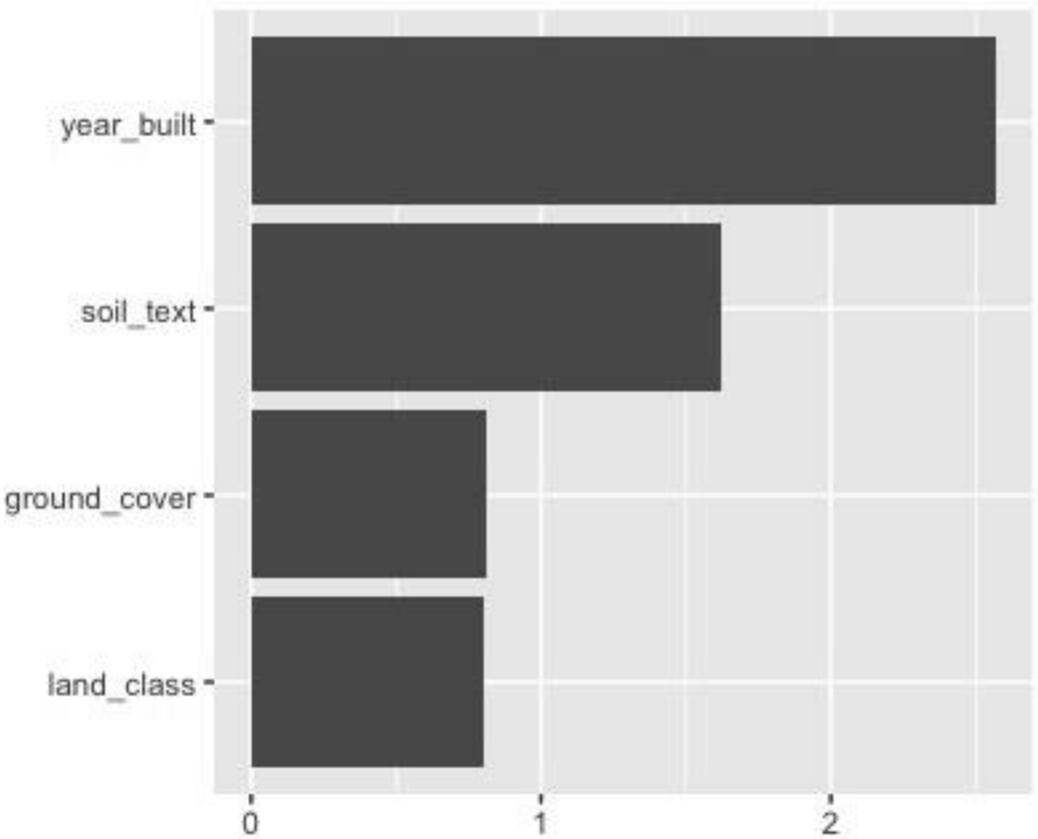


Figure 4.1 *Most influential factors on infiltration rate* as determined by the random forest model.

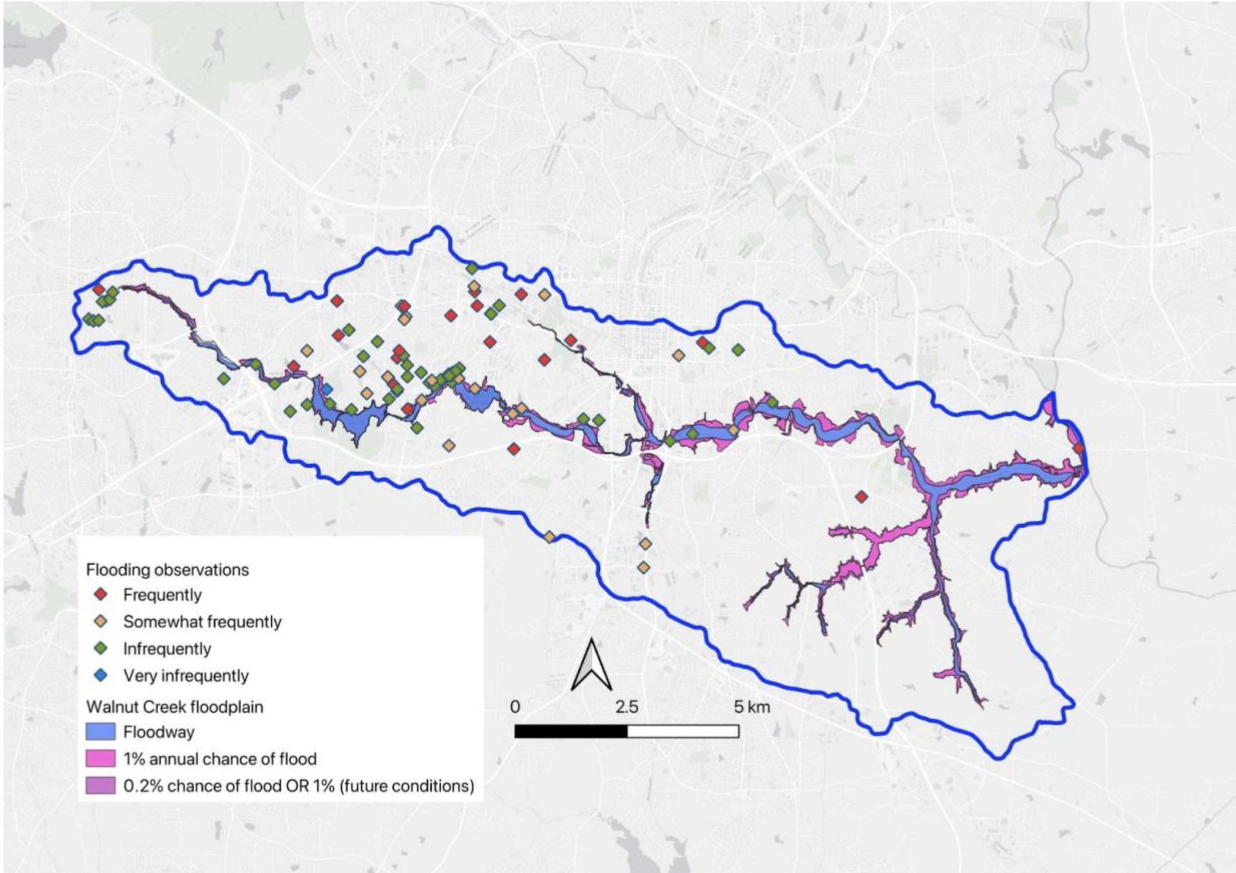


Figure 4.2 *Observations of flooding and ponding by community residents*, many of which are within the floodplain, especially those along Avent Ferry Rd.

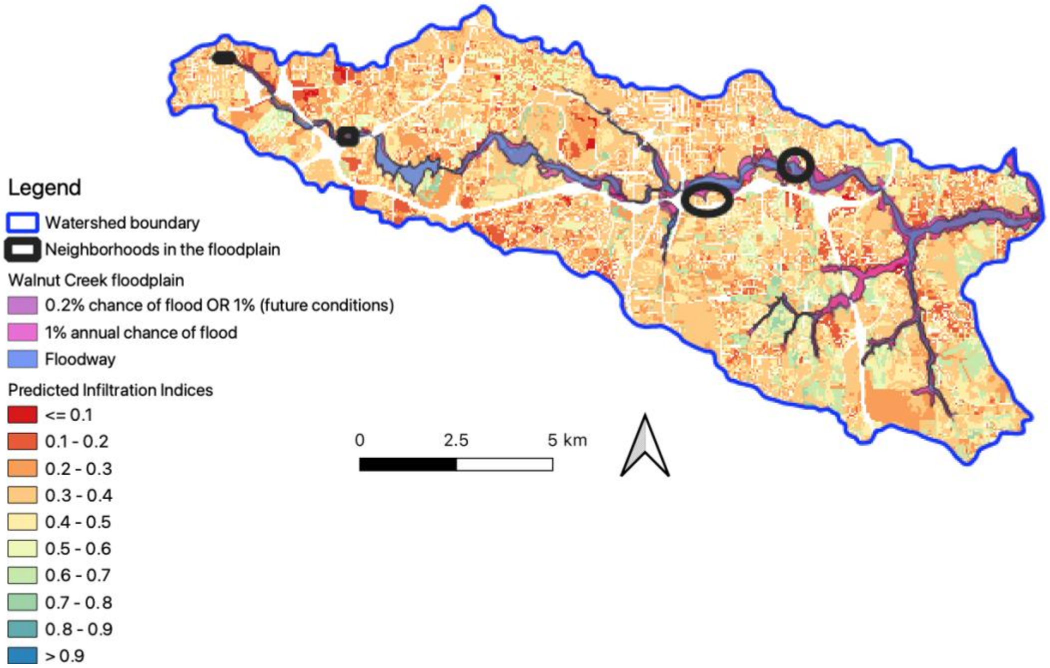


Figure 4.3 *Neighborhoods within the floodplain that may also experience frequent flooding.* These neighborhoods include many with majority black populations and low-income residents of the watershed.

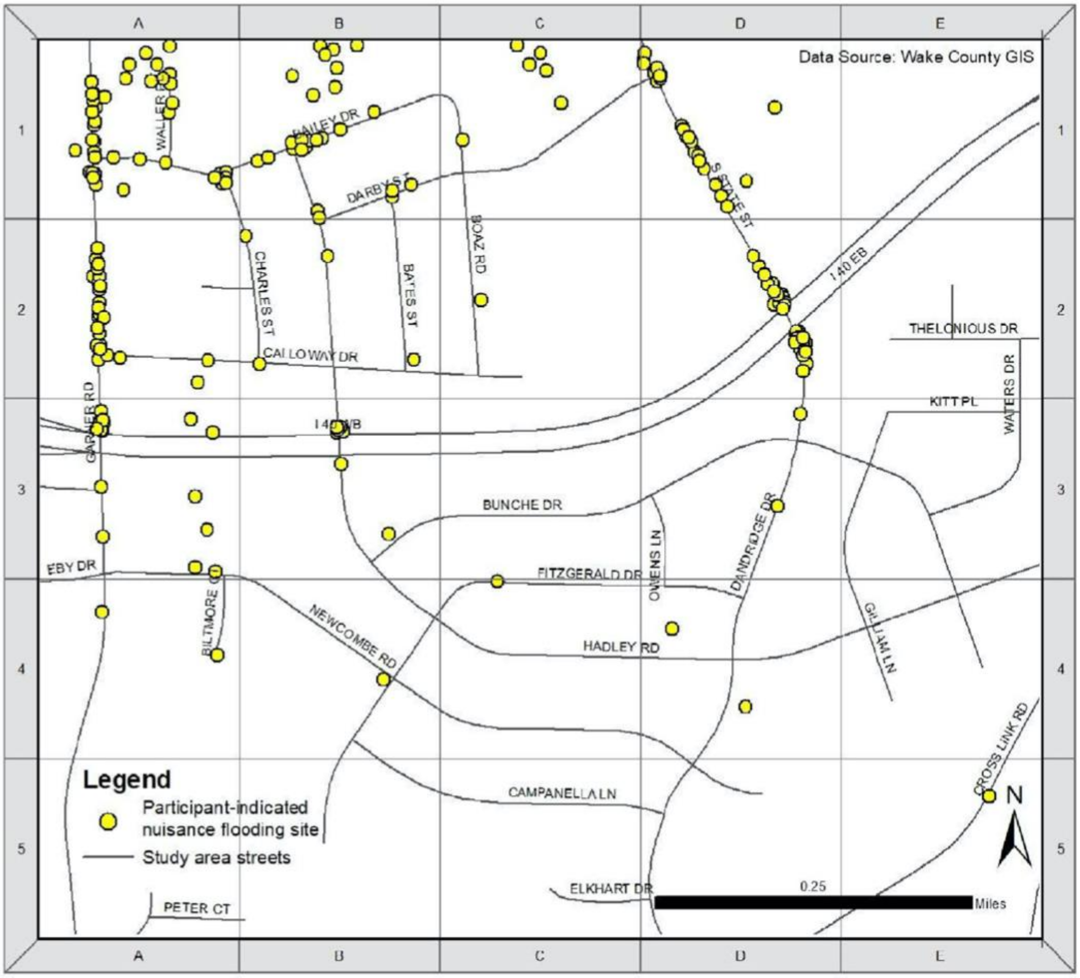


Figure 4.4 *Observations of flooding in the Rochester Heights neighborhood*. (From Hasala et al., 2020)

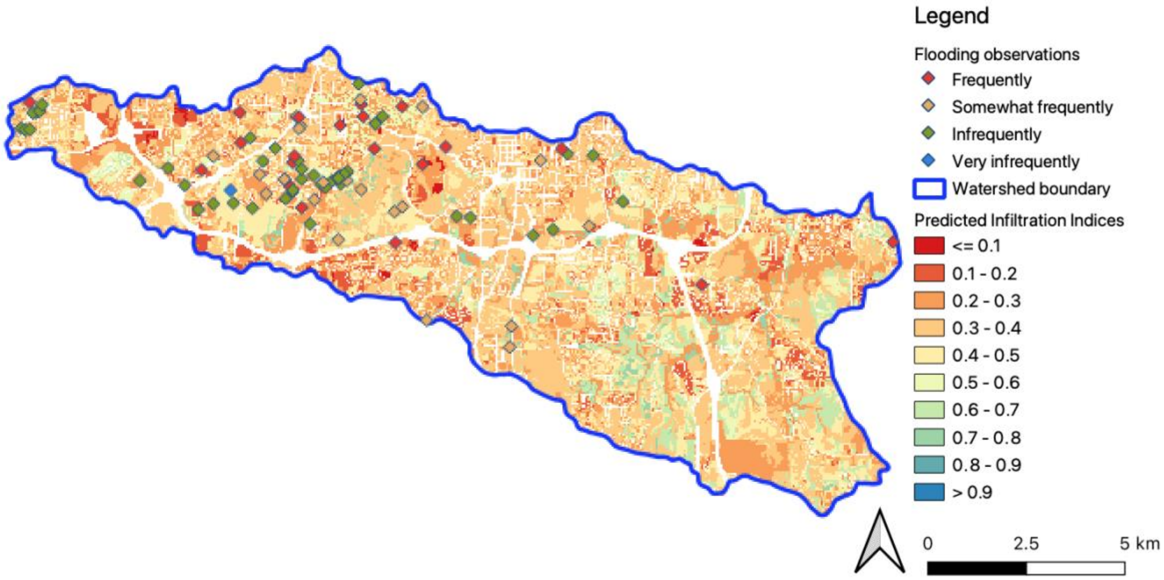


Figure 4.5 *Modeled infiltration indices across the watershed overlain with observations of flooding*. Most flooding observations are in the western part of the watershed.

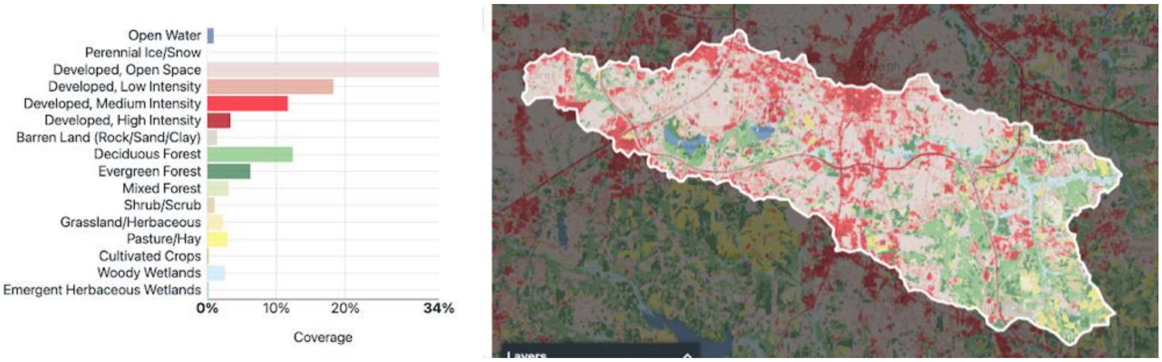


Figure 4.6 *Land cover in the Walnut Creek watershed*. As classified by the National Land Cover Database (NLCD), most development in the Walnut Creek watershed is Developed, Open Space or Developed, Low Intensity. The third most common land cover is Deciduous Forest. Figure adapted from: https://modelmywatershed.org/analyze

APPENDICES

APPENDIX A

Literature Review

Table A1. *A selection of previous infiltration studies*.

Citation	**Study Objectives**	**Infiltration method**	**Other methods/meas.**	**Results**	**Statistical Analysis**
Berndtsson, 1987	Looked at the application of Horton and Philip's infiltration equations as applied to infiltrometer measurements in a small semiarid catchment in a mostly rural area	Constant head double-ring infiltrometer took 52 measurements for 40-60 minutes		Found a difference in infiltration characteristics in different geomorphological zones Very high variability Horton model works better than Philip Philip overestimates low infiltration rates and underestimates high infiltration rates Vegetation increases infiltration rate compared to bare soil Infiltration rates do not follow a smooth decay	Statistically analyzed coefficients of equations- found them to be well approximated by an exponential function Least-square fitting
Bi et al., 2014	Investigated the effects of coal mining on soil physical properties with 3 different vegetation covers	Double-ring infiltrometer. Infiltration rate became stable after 60-90 minutes	Bulk density: knife ring method Used Kostiakov equation to calculate infiltration rate using both initial rate and rate decay	Vegetation influenced bulk density and bulk density had largest impact on soil infiltration rate after 1-year	Multiple linear regression analysis
Carmen et al., 2014	ability of lawns to absorb water from disconnected downspouts	double-ring infiltrometer	antecedent soil moisture: estimated from 72h rainfall record Soil texture: ribbon method Bulk Density: ASTM	59-99% volume reduction from disconnected downspouts	

Table A1 (continued).

Chahinian et al., 2005	Compared 4 infiltration models: Morel-Seytoux (which is modified from Green-Ampt), SCS CN, Philip's, Horton's at the field scale	Used in-situ rainfall simulators- unclear what type	Rainfall: tipping-bucket rainfall gauge Soil moisture: Time domain reflectometer at 0.2 m depth at 3 locations within field	Morel-Seytoux model worked best SCS CN worked worst Horton more consistent than Philip	Performed a sensitivity analysis using RMSE and chose 3 most influential variables for calibration of models, relied on predicting the rest from soil texture Morel-Seytoux calibrated with saturated hydraulic conductivity and capillary height Horton calibrated saturated hydraulic conductivity, infiltration rate of the plot under dry conditions, decay constant SCS CN method does not lend itself to calibration
Eldridge et al., 2000	Looked at removal of surface crusts and effects on infiltration rate in a desert	Used a disk permeameter for 30 minutes, sealed along the outside edge to prevent leakage, able to insert 7-10c m into the ground		Found big impacts from removal of crust	Used one- and two-way ANOVA
Elliot et al., 2018	Do trees decrease compaction and improve infiltration rates?	Double-ring infiltrometer		Size of trees don't matter, infiltration rate significantly improved if tree has a guard Found little influence from ground cover (mulch, vegetation)	ANOVA

Table A1 (continued).

Felton and Lull, 1963	Looked at how suburban development in PA impacts the ability of soils to absorb and store precipitation	Used double-ring infiltrometer and NRCS method		Created an index for infiltration rates based on land cover types and infiltration rates Suggested: mulching, cover cropping, planting trees, water spreading, sod, and terracing for better lawn management Woods had highest infiltration rates followed by fields, and finally lawns	
Gregory et al., 2006	Looked at compacted vs. non-compacted soils influence on infiltration rate	Double-ring infiltrometer- constant head for 40 minutes with measurements every 1 minute, found rates became constant after 10 minutes	Philip's infiltration equation Recommended used of cone index as a proxy for compaction	Found a 70-99% reduction in infiltration rate with soil compaction, effectively approaches infiltration rate of impervious surface Did not see significant difference among different durations of compaction, but there was a difference in weight of compaction equipment	ANOVA
Haynes et al., 2013	Looked at effects of different remediation techniques on soil infiltration in compacted soils	Cornell sprinkler infiltrometer	Bulk density: AMS 6.4 cm diameter soil-core sampler Particle size distribution: hydrometer method	Aeration makes soil worse, best results from compost addition and deep tillage	

Table A1 (continued).

Kays, 1979	Looked at relationship between soil morphology and infiltration rate in suburban Piedmont of NC	Single-ring infiltrometer, constant head for 180 minutes		Found soil texture to be less important for urban infiltration rates Runoff was not generated for most storm events Runoff occurred during high rates of rainfall or when surface sealing took place Excessively disturbed soils had substantially lower infiltration rates (1-5% of those for forested soils)	
Kays, 1981	Looks at effective imperviousness by counting infiltration rates less than 2cm/h as impervious and how to improve infiltration			Suggests using trees in most lawns to improve soil fertility Disturbed areas can increase flooding	
Kelling and Peterson, 1975	Looked at nutrient runoff from lawns in developed areas	Modified spray infiltrometer for 90 minutes		Compaction from development biggest influence on soil infiltration	
Loague and Gander, 1990	Looked at spatial variability of soil infiltration rates in a rangeland catchment	250 single-ring infiltrometer measurements Reached steady state infiltration within 60 minutes, driven 5 cm into ground, cut narrow slit		Found soil type is not very important for infiltration rate, but past conditions are very important Infiltration rates are highly variable and 2 measurements at the same location could differ 9-fold Vegetation type important	Did not recommend their geostatistical method for future studies

Table A1 (continued).

Pitt et al., 2008	Wanted to investigate the infiltration behavior of urban soils with a variety of soil types and levels of compaction.	Turf-Tec double-ring infiltrometer run in triplicate. Drop in water level recorded every 5 minutes for 2 hours.	Soil Texture: ASTM D 2488-93 Standard Practice for Description and Identification of Soils (Visual-Manual Procedure) and ASTM D 422-63 Standard Test Method for Particle Size Analysis Compaction: >300 psi with cone penetrometer Antecedent moisture: ASTM Method D 2974-87 (Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils) Bulk density: “Sand and balloon test”	For clayey soils antecedent moisture and compaction were important for determining steady state infiltration rate For sandy soils compaction had a bigger effect on infiltration rate.	
Rahman et al., 2019		Mini-disk infiltrometer		Grassy areas infiltrate better than grassy areas under trees Max infiltration occurred 3.5m from trunk	Two-sample t-test ANOVA Tukey’s HSD test Spearman’s rank correlation test
Woltemade, 2010	Looked at soil disturbance from excavation and compaction of infiltration rates in residential developments and compared results with TR-55 Curve Number	Used a double-ring infiltrometer on 108 sites		Suggested ways in which CN method could be adapted to deal with compacted soils Found soil texture to not play a big role Called for a richer dataset	ANOVA

Table A1 (continued).

Yang and Zhang, 2011	Looked at the impact of compaction on infiltration rate	Double-ring infiltrometer	Soil texture: pycnometer Looked at runoff coefficients	High variability in final soil infiltration rates Best infiltration in areas with grass and trees	Used average and standard deviation of combined urban functional zones, used simple Pearson correlation coefficients between infiltration rates and other soil properties Used one-way ANOVA for differences in final infiltration rate of different urban functional zones with degree of compaction
Zimmerman et al., 2006	Looked at legacy effects on infiltration rates of soils	Hood infiltrometer	Rainfall: tipping-bucket rain gauge	Found high impact of legacy effects Recovery time of Ksat longer that infiltration rate	ANOVA Transformed data to fit Gaussian behavior best re-expressed by 4th root log transformation

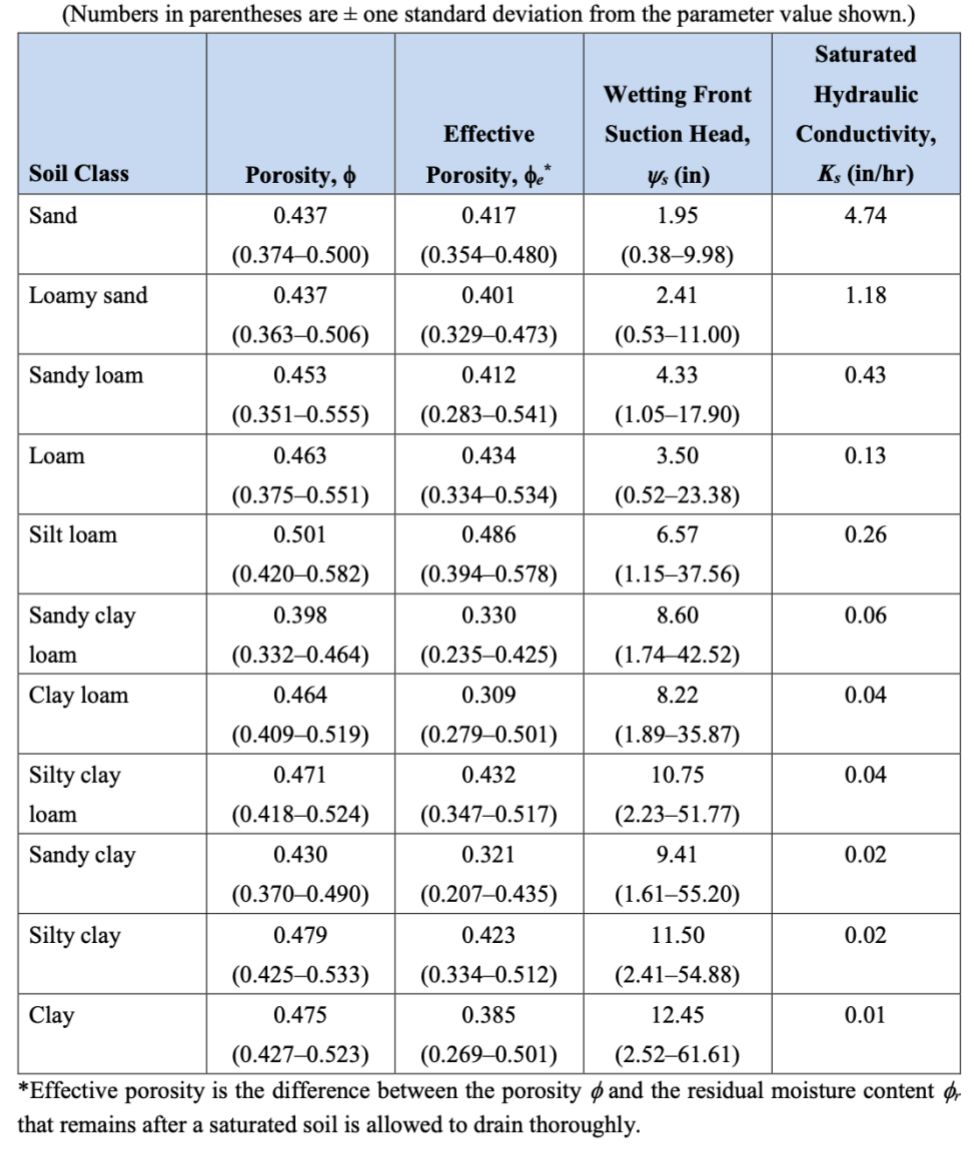
APPENDIX B

Model Data

This Appendix contains tables from SWMM model default suggestions (Rossman, 2016) used to determine parameters for models.

Green-Ampt

Table B1. *Mean values for wetting front suction head and saturated hydraulic conductivity for the Green-Ampt model* were taken for each site based on the SSURGO soil type. Values are from Rawls et al. (1983).

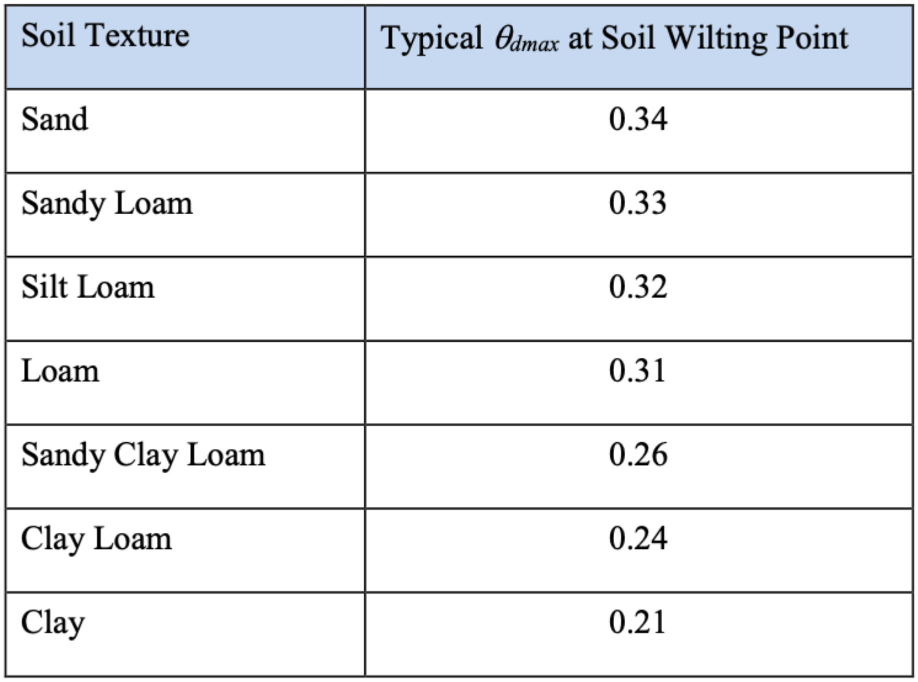


(Numbers in parentheses are ± one standard deviation from the parameter value shown.)

Soil Class	**Porosity, ϕ**	**Effective Porosity, ϕ_e***	**Wetting Front Suction Head, ψ_s (in)**	**Saturated Hydraulic Conductivity, K_s (in/hr)**
Sand	0.437 (0.374–0.500)	0.417 (0.354–0.480)	1.95 (0.38–9.98)	4.74
Loamy sand	0.437 (0.363–0.506)	0.401 (0.329–0.473)	2.41 (0.53–11.00)	1.18
Sandy loam	0.453 (0.351–0.555)	0.412 (0.283–0.541)	4.33 (1.05–17.90)	0.43
Loam	0.463 (0.375–0.551)	0.434 (0.334–0.534)	3.50 (0.52–23.38)	0.13
Silt loam	0.501 (0.420–0.582)	0.486 (0.394–0.578)	6.57 (1.15–37.56)	0.26
Sandy clay loam	0.398 (0.332–0.464)	0.330 (0.235–0.425)	8.60 (1.74–42.52)	0.06
Clay loam	0.464 (0.409–0.519)	0.309 (0.279–0.501)	8.22 (1.89–35.87)	0.04
Silty clay loam	0.471 (0.418–0.524)	0.432 (0.347–0.517)	10.75 (2.23–51.77)	0.04
Sandy clay	0.430 (0.370–0.490)	0.321 (0.207–0.435)	9.41 (1.61–55.20)	0.02
Silty clay	0.479 (0.425–0.533)	0.423 (0.334–0.512)	11.50 (2.41–54.88)	0.02
Clay	0.475 (0.427–0.523)	0.385 (0.269–0.501)	12.45 (2.52–61.61)	0.01

*Effective porosity is the difference between the porosity ϕ and the residual moisture content ϕ_r that remains after a saturated soil is allowed to drain thoroughly.

Table B2. *Theta dmax for the Green-Ampt model was selected from this table based on SSURGO soil types*.

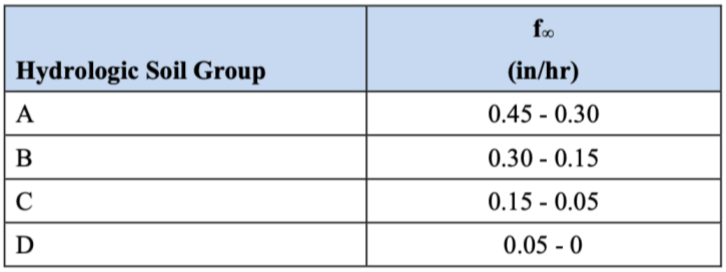


Soil Texture	Typical θ_{dmax} at Soil Wilting Point
Sand	0.34
Sandy Loam	0.33
Silt Loam	0.32
Loam	0.31
Sandy Clay Loam	0.26
Clay Loam	0.24
Clay	0.21

Horton Model

The decay constant was assumed to be 4 /hr.

Table B3. *f∞ for the Horton model*. This table was used to estimate f∞ for the Horton model. The middle value was taken for each Hydrologic Soil Group (A= 0.375, B=0.225, C=0.10, D=0.025). The data from the table comes from Musgrave (1955).



Hydrologic Soil Group	**f_∞ (in/hr)**
A	0.45 - 0.30
B	0.30 - 0.15
C	0.15 - 0.05
D	0.05 - 0

Table B4. *Initial infiltration rate for the Horton model*. This table was used to estimate initial infiltration rate for the Horton model. Soils were assumed to be partially dried out. Dense vegetation was considered herbaceous cover at the 1m plot of at least 50%.

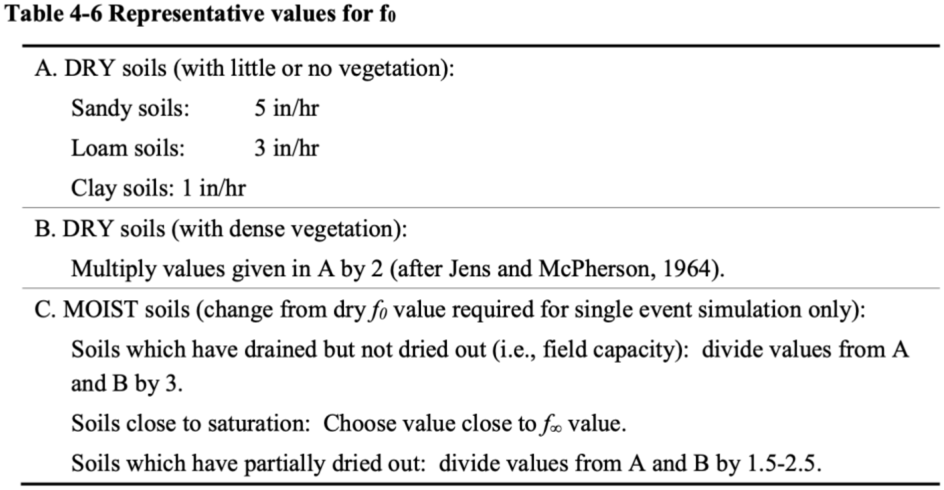


Table 4-6 Representative values for f_0

A. DRY soils (with little or no vegetation):

Sandy soils: 5 in/hr
Loam soils: 3 in/hr
Clay soils: 1 in/hr

B. DRY soils (with dense vegetation):

Multiply values given in A by 2 (after Jens and McPherson, 1964).

C. MOIST soils (change from dry f_0 value required for single event simulation only):

Soils which have drained but not dried out (i.e., field capacity): divide values from A and B by 3.

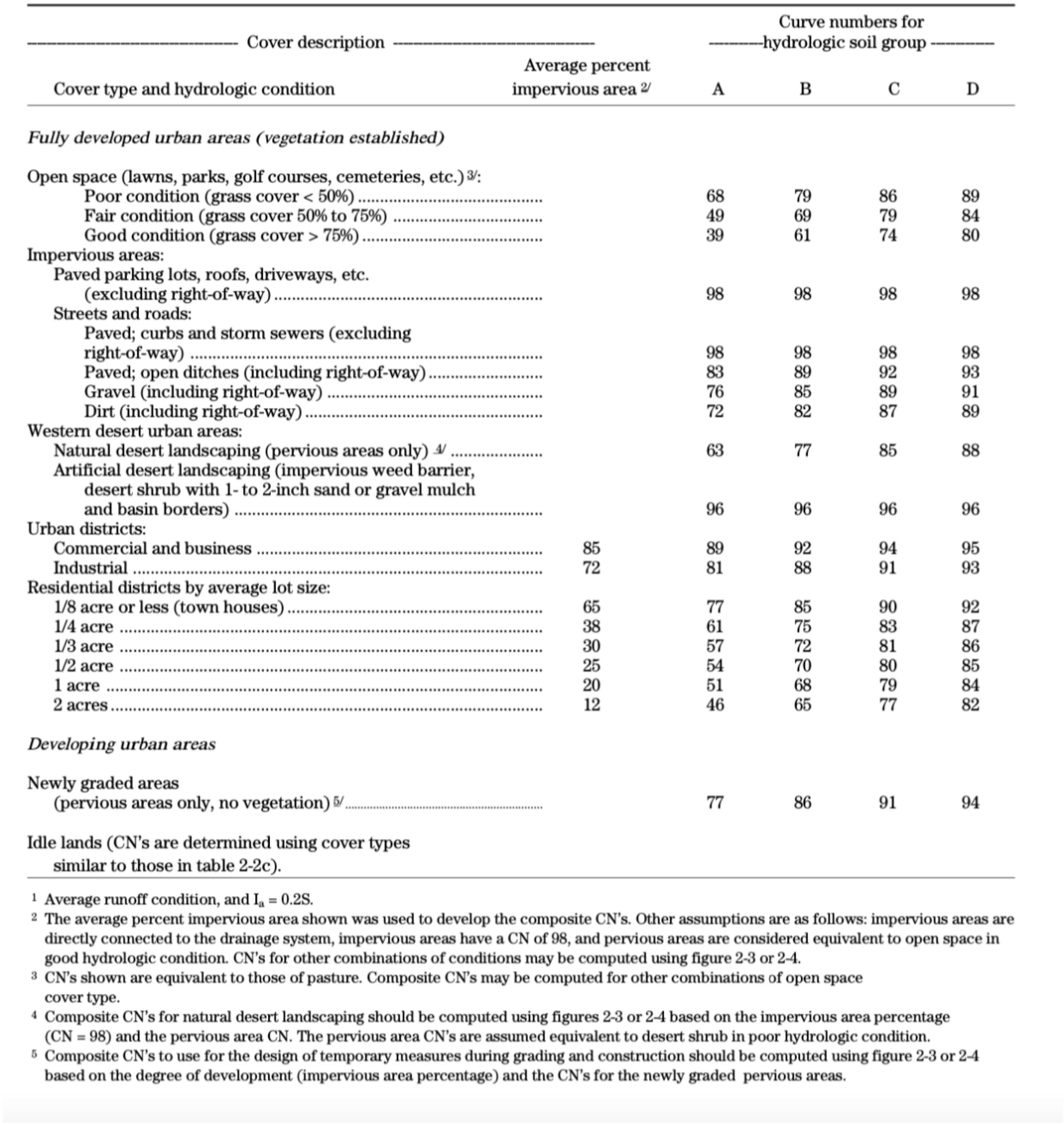
Soils close to saturation: Choose value close to f_∞ value.

Soils which have partially dried out: divide values from A and B by 1.5-2.5.

Curve Number

Curve Numbers were selected from the following tables (*Urban Hydrology for Small Watersheds: TR-55 Curve Number Method*, n.d.).

Table B5. *Runoff curve numbers for urban areas*.



Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) [5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

[1] Average runoff condition, and $I_a = 0.2S$.

[2] The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.

[3] CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.

[4] Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.

[5] Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

Table B6. *Runoff curve numbers for cultivates agricultural lands.*

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment [2]	Hydrologic condition [3]	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

[1] Average runoff condition, and I_a=0.2S

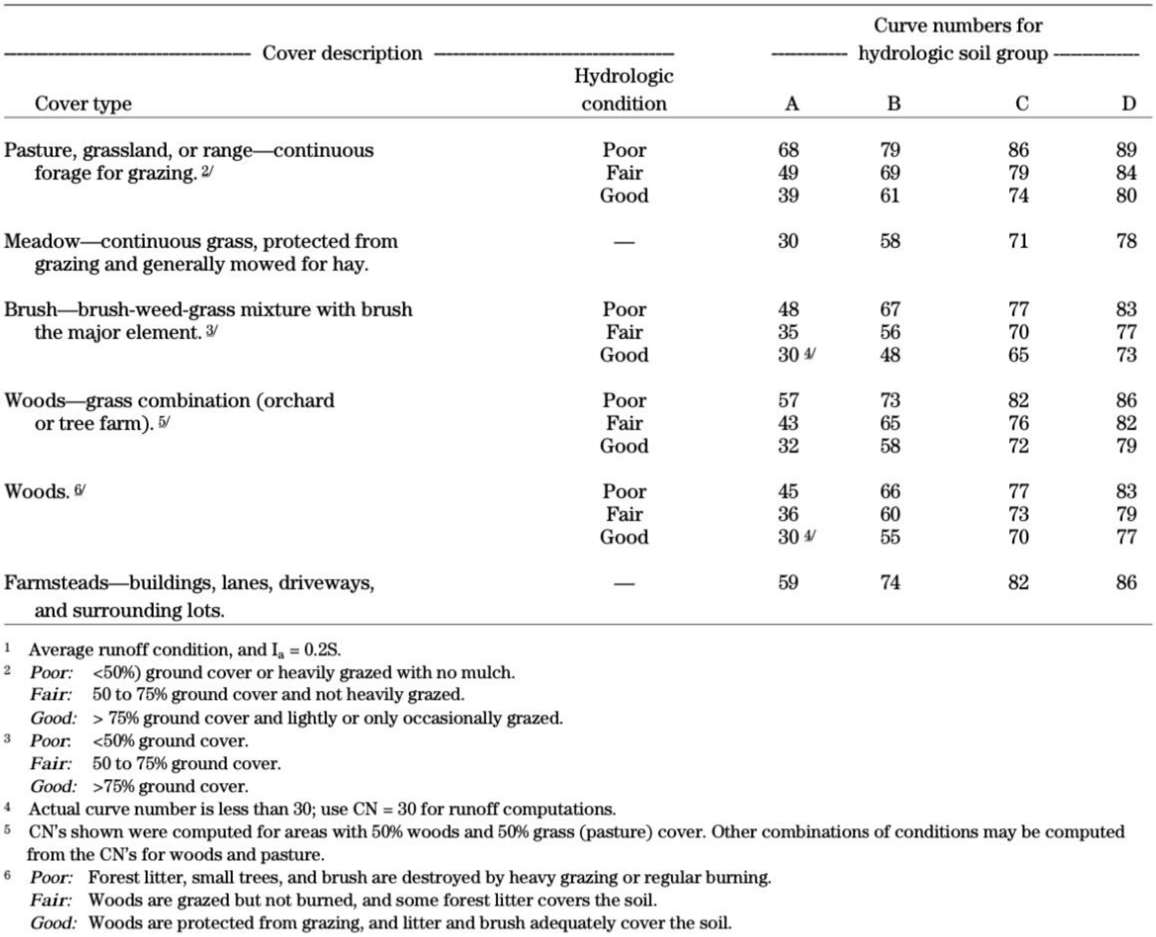
[2] Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

[3] Hydraulic condition is based on combination factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness.

Poor: Factors impair infiltration and tend to increase runoff.

Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Table B7. *Runoff curve numbers for other agricultural lands*.



Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition	A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. [2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. [3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 [4]	48	65	73
Woods—grass combination (orchard or tree farm). [5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. [6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 [4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

[1] Average runoff condition, and $I_a = 0.2S$.

[2] *Poor:* <50%) ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: > 75% ground cover and lightly or only occasionally grazed.

[3] *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.

[4] Actual curve number is less than 30; use CN = 30 for runoff computations.

[5] CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.

[6] *Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

APPENDIX C

Survey materials

Figure C1. *Survey*

Walnut Creek Watershed Urban Flooding Survey

Start of Block: Block 1: Consent

Q1 Are you 18 years of age or older?

○ **Yes (1)**

○ **No (2)**

Skip To: End of Survey If Are you 18 years of age or older? != Yes

Q2 Before starting this survey, please read the attached consent form and download for your records. If you no longer wish to participate in this study, please choose, "No, I do not consent" below.
Adult informed consent

○ **Yes, I consent. (1)**

○ **No, I do not consent. (2)**

Skip To: End of Survey If Before starting this survey, please read the attached consent form and download for your records.... != Yes, I consent.

End of Block: Block 1: Consent

Start of Block: Block 2: Heat Maps

Q63 The following questions will help us understand flooding patterns within your community. For the purposes of this survey, your community is defined as The Walnut Creek Watershed, outlined in the map below. If you are unsure if you live here, you may answer the survey anyway, although your answers may be excluded from the study.

Q3 Which area are you most familiar with? Please click on the area below.

End of Block: Block 2: Heat Maps

Start of Block: Block 3: Interactive Maps

Q13 Use the map below to place a marker on a location where you see flooding or ponding (pooled water on the ground) in your community. Click and drag the red point to mark the location. You can start by searching for an address or landmark in the search bar. If you do not notice these issues in your community, skip to the next section.

____

Q67 If you are unable to view the map above, but would still like to note a place where you see flooding or ponding in your community, you may include a description of the location here. Please be as specific as possible.

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Q14 How often do you see flooding or ponding at this location?

○ Very infrequently (maybe one time) (1)

○ Infrequently (every once in a while, during a hard rain) (2)

○ Somewhat frequently (at least once a month) (3)

○ Frequently (almost every time it rains) (4)

○ **Very frequently (always flooded, sometimes even when it has not just rained) (5)**

Q15 Is there another location where you see flooding or ponding?

○ **Yes (1)**

○ **No (2)**

Skip To: End of Block If Is there another location where you see flooding or ponding? = No
Skip To: End of Block If Is there another location where you see flooding or ponding? ! = Yes

Display This Question:
If Is there another location where you see flooding or ponding? = Yes

Q16 Use the map below to place a marker on a location where you see flooding or ponding (pooled water on the ground) in your community. Click and drag the red point to mark the location. You can start by searching for an address or landmark in the search bar. If you do not notice these issues in your community, skip to the next section.

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Q68 If you are unable to view the map above, but would still like to note a place where you see flooding or ponding in your community, you may include a description of the location here. Please be as specific as possible.

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Q17 How often do you see flooding or ponding at this location?

○ Very infrequently (maybe one time) (1)

○ Infrequently (every once in a while, during a hard rain) (2)

○ Somewhat frequently (at least once a month) (3)

○ Frequently (almost every time it rains) (4)

○ Very frequently (always flooded, sometimes even when it has not just rained) (5)

Q18 Is there another location where you see flooding or ponding?

○ Yes (1)

○ No (2)

Skip To: End of Block If Is there another location where you see flooding or ponding? = No

Display This Question:
If Is there another location where you see flooding or ponding? = Yes

Q19 Use the map below to place a marker on a location where you see flooding or ponding (pooled water on the ground) in your community. Click and drag the red point to mark the location. You can start by searching for an address or landmark in the search bar. If you do not notice these issues in your community, skip to the next section.

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Q66 If you are unable to view the map above, but would still like to note a place where you see flooding or ponding in your community, you may include a description of the location here. Please be as specific as possible.

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Q20 How often do you see flooding or ponding at this location?

○ Very infrequently (maybe one time) (1)

○ Infrequently (every once in a while, during a hard rain) (2)

○ Somewhat frequently (at least once a month) (3)

○ Frequently (almost every time it rains) (4)

○ Very frequently (always flooded, sometimes even when it has not just rained) (5)

Q21 Is there another location where you see flooding or ponding?

○ Yes (1)

○ No (2)

Skip To: End of Block If Is there another location where you see flooding or ponding? = No

Display This Question:
If Is there another location where you see flooding or ponding? = Yes

Q22 Use the map below to place a marker on a location where you see flooding or ponding (pooled water on the ground) in your community. Click and drag the red point to mark the location. You can start by searching for an address or landmark in the search bar. If you do not notice these issues in your community, skip to the next section.

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Q69 If you are unable to view the map above, but would still like to note a place where you see flooding or ponding in your community, you may include a description of the location here. Please be as specific as possible.

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Q23 How often do you see flooding or ponding at this location?

○ Very infrequently (maybe one time) (1)

○ Infrequently (every once in a while, during a hard rain) (2)

○ Somewhat frequently (at least once a month) (3)

○ Frequently (almost every time it rains) (4)

○ Very frequently (always flooded, sometimes even when it has not just rained) (5)

Q24 Is there another location where you see flooding or ponding?

○ Yes (1)

○ No (2)

Skip To: End of Block If Is there another location where you see flooding or ponding? = No

Display This Question:
If Is there another location where you see flooding or ponding? = Yes

Q25 Use the map below to place a marker on a location where you see flooding or ponding (pooled water on the ground) in your community. Click and drag the red point to mark the location. You can start by searching for an address or landmark in the search bar. If you do not notice these issues in your community, skip to the next section.

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Q70 If you are unable to view the map above, but would still like to note a place where you see flooding or ponding in your community, you may include a description of the location here. Please be as specific as possible.

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Q26 How often do you see flooding or ponding at this location?

○ Very infrequently (maybe one time) (1)

○ Infrequently (every once in a while, during a hard rain) (2)

○ Somewhat frequently (at least once a month) (3)

○ Frequently (almost every time it rains) (4)

○ Very frequently (always flooded, sometimes even when it has not just rained) (5)

End of Block: Block 3: Interactive Maps

Start of Block: Block 4: Survey Questions

Q27 Are you aware of any instance since 2015, where flooding and/or stormwater caused the following impacts in your community?

	Yes (1)	No (2)
Private property damage (1)	○	○
Public property damage (2)	○	○
Injury to a person (3)	○	○
Contaminated streams (4)	○	○
Other: (5)	○	○

Page Break

Q64, do you have a yard?

○ Yes (17)

○ No (18)

Skip To: End of Block If Do you have a yard? = No

Page Break

Q28 Which of the following best describes your lawn?

○ Grass (1)

○ No lawn (3)

○ No groundcover (4)

○ Natural groundcover (ex. moss, clover, etc.) (5)

○ Other: (6) ____

Page Break

Q29 What other types of vegetation do you have in your yard? [Choose all that apply.]

☐ Large trees (1)

☐ Small trees (2)

☐ Flowers (3)

☐ Vegetable garden (4)

☐ Succulents (5)

☐ Bushes/ shrubs (6)

☐ Other: (7) ____

Q30 In the summer, how often is your yard watered?

- ○ **Never (1)**
- ○ **Less than every other week (2)**
- ○ **Every other week (3)**
- ○ **Once a week (4)**
- ○ **More than once a week (5)**

Q31 In the summer, how many minutes on average is your yard watered?

- ○ **I don't water my yard. (4)**
- ○ **0-10 (5)**
- ○ **10-20 (6)**
- ○ **20-30 (7)**
- ○ **30-40 (8)**
- ○ **40+ (9)**

Q32 How often is your lawn mower in the summer?

- ○ **Never (1)**
- ○ **Less than every other week (2)**
- ○ **Every other week (3)**

○ **Once a week (4)**

○ **More than once a week (5)**

Q33 How is your lawn mower?

○ **Push mower (1)**

○ **Riding mower (2)**

○ **Other: (3) ____**

○ **N/A (4)**

Page Break

End of Block: Block 4: Survey Questions

Start of Block: Block 6: Volunteers

Q34 Would you be willing to participate further in this study, by having infiltration measured on your property in a way that limits risk to you and to researchers? You can find more details here: Letter to property owners

○ **Yes (1)**

○ **No (2)**

Skip To: End of Survey If Would you be willing to participate further in this study, by having infiltration measured on you... = No

Q35 Thank you for agreeing to let us sample on your property. You will receive more information soon via email. Please provide your contact information, so that we may contact you at that time. Your contact information will not be shared with anyone outside of the research team and will only be used for research purposes.

Q36 Where is your property and how can we contact you?

○ **Street Address (1) ____**

○ **Street Address Line 2 (2) ____**

○ **City (3) ____**

○ **State (4) ____**

○ **Postal Code (5) ____**

○ **Email Address (6) ____**

○ **Phone Number (7) ____**

○ **Are there any special instructions for accessing your property? (8)**

____

Q71 What is your preferred mode of contact to let you know that we are on your property to sample?

○ **Call (1)**

○ **Text (2)**

End of Block: Block 6: Volunteers

Start of Block: Block 5: Demographic Questions

Q37 These last questions will help us to know which perspectives we have and have not captured within the Walnut Creek watershed. Your answers will be treated as confidential and no information that identifies individual respondents will be released outside of the researchers. These questions are important, but you may leave them blank.

Q38 What is your age?

○ 18 - 24 (1)

○ 25 - 34 (2)

○ 35 - 44 (3)

○ 45 - 54 (4)

○ 55 - 64 (5)

○ 65 - 74 (6)

○ 75 - 84 (7)

○ 85 or older (8)

Q39 To which gender identity do you most identify?

○ Male (1)

○ Female (2)

○ Other (3)

○ Prefer not to answer (4)

Q40 What is the highest level of education you've completed?

○ Less than high school (1)

○ High school graduate (2)

○ Some college (3)

○ **2-year degree (4)**

○ **4-year degree (5)**

○ **Professional degree (6)**

○ **Doctorate (7)**

Q41 What would you estimate was your total household income last year?

○ **Less than $25,000 (1)**

○ **$25,000- $49,999 (2)**

○ **$50,000-$74,999 (3)**

○ **$75,000- $99,999 (4)**

○ **Over $100,000 (5)**

Q42 Which category best describes your race or ethnicity?

☐ **White (1)**

☐ **Black or African American (2)**

☐ **American Indian or Alaska Native (3)**

☐ **Asian (4)**

☐ **Native Hawaiian or Pacific Islander (5)**

☐ **Latino/a/x (6)**

☐ **Other: (7) ____**

Page Break

End of Block: Block 5: Demographic Questions

Figure C2. *Recruitment Post*

Hello neighbors! Do you live in the Walnut Creek Watershed, mapped below? If the answer is yes, please consider taking a quick survey to help map flooding in our community. The survey is part of an NC State graduate project and should only take 10-15 minutes of your time. If you have any questions or would like to know more, please contact Chase Bergeson at cbberges@ncsu.edu.

https://ncsu.qualtrics.com/jfe/form/SV_2ugsQLrVuwGIK3P

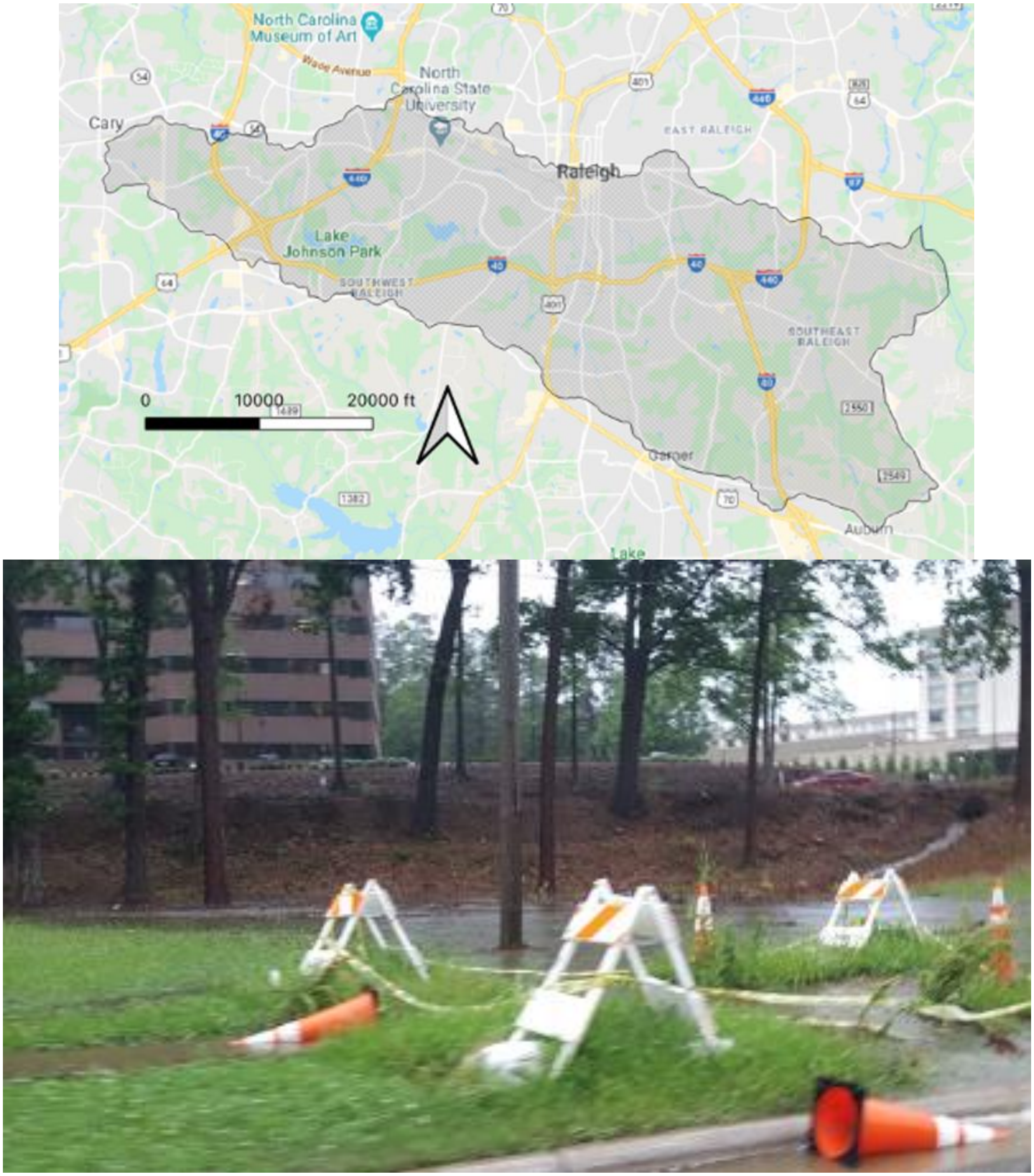

Figure C3. *Letter to homeowners*

To whom it may concern:

I am a graduate student at North Carolina State University studying Natural Resources in the Forestry and Environmental Resources Department. I am conducting a research project with the goal of characterizing urban soil infiltration rates around Wake County. Soil infiltration rate is a measurement of how quickly water can be absorbed by the ground. Infiltration rates can be affected by many factors, such as soil composition, soil compaction, antecedent soil moisture, land cover, temperature, and vegetation. In an effort to measure infiltration rates in many different locations, locations from around the Walnut Creek watershed were randomly chosen based on land use. Your property was selected for infiltration measurement.
In order to measure infiltration rates, we use a single ring infiltrometer. This is essentially a piece of 6” diameter PVC pipe. The length of pipe is inserted approximately 1-2 inches into the ground. A known volume of water is then poured into the ring, and the time it takes to be absorbed by the soil is measured. In order to get the PVC pipe into the ground, we may have to hammer the pipe in with a rubber mallet or use a saw to cut an ~1 cm ring for the pipe to be inserted. This may cause minimal damage to the ground. We will be performing the experiment at 4 spots at each location. The whole process takes about 2 hours. We will also be taking a small soil sample, which will involve excavating a 3” diameter hole to a depth of ~6” deep.

If you will allow us to sample on your property or would like more information, please send an email to cbberges@ncsu.edu or call (410)917-8224. You do not have to be present for us to sample, but if you would like to be there, please let us know what dates and times would work best for you.

Sincerely,
Chase Bergeson
MS Student- College of Natural Resources
North Carolina State University
2213 Jordan Hall
Raleigh, NC 27606