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Land Management Controls on Hydraulic Conductivity of an Urban Farm in Atlanta, GA

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LAND MANAGEMENT CONTROLS ON HYDRAULIC CONDUCTIVITY OF AN URBAN FARM IN ATLANTA, GA

By

HAYDEN HINTON

Under the Direction of Katie Price (PhD)

ABSTRACT

Increasing urbanization is often accompanied by problematic changes in watershed hydrology. Decreasing surface permeability can lead to increased overland flow volumes, which may spread surficial contaminants and increase the strain on municipal stormwater infrastructure. This study examines a mixed-use property in the Proctor Creek watershed in Atlanta, Georgia, to better understand how land-management practices influence soil overland flow potential. Field saturated hydraulic conductivity (K_{fs}) measurements were collected from soils 1) subjected to compaction, 2) in urban agricultural use, and 3) under common lawn maintenance. Mean values were 9.1E-7 cm/s, 2.2E-4 cm/s, and 9.0E-6 cm/s respectively. Measurements were collected in-situ with the use of the Aardvark constant-head permeameter. Statistical analyses indicated a substantial difference in K_{fs} based on land-management practices and that urban farming can increase soil K_{fs} and limit overland flow. Additional analysis revealed no significant difference in grain-size distributions suggesting land-management practices controlled K_{fs}, not soil texture.

INDEX WORDS: Saturated hydraulic conductivity, Urban farm, Hydrology, Overland flow, Constant head permeameter, Aardvark permeameter, Land management practices

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DEDICATION

This thesis is dedicated to my family who encouraged me to accomplish my goals in higher education and to my late grandfather Bernard Young who inspired me to pursue a career in physical science.

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I would like to acknowledge Dr. Nader S. Rad and the staff at Excel Geotechnical Testing in Roswell, Georgia, for not only conducting grain size analysis, but also for the valuable guidance provided throughout this process.

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1 INTRODUCTION

1.1 Field-Saturated Hydraulic Conductivity

Hydraulic conductivity is a parameter that describes how water moves through soil and is key for understanding a precipitation event's potential to produce overland flow. Overland flow can transport sediment and solutes across the surface of the soil (Easton et al., 2007). There is also the potential for excess overland flow to contribute to the erosion of drainage areas and stream channels (Chin 2006; Harden, 2006; Price et al., 2010). Understanding a particular soils readiness to achieve overland flow, by considering the field-saturated hydraulic conductivity, can lead to a better understanding of these concerns.

Field-saturated hydraulic conductivity (K_{fs}) describes how water moves through soil that has been brought to a near-saturation state (Nimmo et al., 2007). This implies the soil is initially unsaturated and is brought to a near-saturation state by the introduction of water to the vadose-zone by ponded water or large amounts of rainfall. As opposed to soils that are fully saturated, such as soils existing under the water table for an extended period of time, soils in the vadose zone have air trapped in the pores even in when brought to a near saturated state by the introduction of copious amounts of water to the surface or subsurface (Gallage et al., 2013). This small amount of trapped air leads to K_{fs} values being slightly lower than fully saturated-hydraulic conductivity values experimentally determined in a laboratory setting. The air trapped in the capillaries of the soil can block some water passages restricting the overall flow of water in soil (Reynolds and Elrick, 1987; Gallage et al., 2013).

K_{fs} is influenced by many soil properties that affect the overall infiltration characteristics of the soil (e.g., texture, compaction, and macroporosity) (Horton, 1945; Gregor, 2006; Nimmo et al., 2007; West et al., 2007; Emadi et al., 2008). These factors, along with K_{fs}, not only dictate how much water can infiltrate into the soil's surface, but also how water moves through the vadose zone. How quickly water drains through the vadose zone determines whether the infiltration rate will be exceeded by the precipitation rate during a storm event. This is known as infiltration excess overland flow or "Hortonian overland flow". If overland flow is produced because the soils become completely saturated and water can no longer infiltrate, saturation excess overland flow occurs (Horton, 1945; Martinez-Mena, et al., 1998).

1.2 Overland flow in Urban Environments

Understanding what causes overland flow is particularly important in urbanized areas. Where infiltration rates are decreased due to more impervious surfaces, overland flow can be exaggerated, and flood "flashiness" can be increased due to land management practices typically associated with urbanization (Price et al., 2010; Fletcher et al., 2013). An excess of overland flow and runoff can alter the natural flow regime of an area increasing the strain on municipal infrastructure and natural drainage networks by accelerating surface erosion (Chin, 2006). Overland flow also increases the mobility of surface contaminants and introduces them to streams and drainage pathways where they can eventually contaminate local water sources. Sources of contaminants are common in urban environments from roadways (Deocampo et al., 2012) and industrial sites presently or historically active (Suh et al., 2011; Bradham et al., 2014).

K_{fs}, along with many other hydrologic characteristics, can change depending on how the land is managed (Hamilton and Waddington, 1999; Gregor, 2006; Emadi et al., 2008). For this reason, K_{fs} values are compared based on land management practices for this study. For example, soils in the naturally forested region of the Southeastern United States typically have relatively low bulk densities and large macropore networks resulting in higher K_{fs} values than similar soils in deforested areas or soils that have undergone a drastic land management change such as the conversion to livestock pasture (Emadi et al., 2008; Price et al., 2010). These changes can be even more drastic in areas undergoing urbanization, where an increase in impervious surfaces such as streets, pavements and rooftops occurs. These surfaces effectively stop infiltration of surface waters and increase peak overland flows (Leopold, 1968; Fletcher et al., 2013).

Although not all land surfaces are typically paved in urban areas, any alteration to the soil may potentially change hydraulic properties. The most common of these pervious surfaces include, but are not limited to, home lawns, municipal parks, and other areas that include “low-impact development” practices. Some studies have shown that the most influential soil treatment that contributes to lower infiltration rates and K_{fs} values is soil compaction. Soil compaction most often occurs when soils are being prepared for development and are intentionally compacted for structural integrity, but soils are often unintentionally compacted when being converted to lawns (Hamilton and Waddington 1999; Gregor, 2006). The lower infiltration rates produced in these soils have been shown to increase overland flow (Price et al., 2010). It is important to mitigate these effects by utilizing land management practices that promote surface water infiltration and decrease overland flow to reduce the negative effects of extreme runoff prevalent in many urban areas. Vegetative surface that have been unintentionally compacted may not behave as the pervious surfaces they are assumed to be. More data on runoff potential of these “quasi-permeable” surfaces is needed for stricter modeling.

1.3 Urban Farming and Overland Flow

Urban farming is one such practice that can potentially increase the infiltration rate of surface soils, considering techniques used in preparing soils for planting crops. Various common agricultural practices increase or decrease infiltration rates. This leads to more or less overland flow depending on how the land is managed. Soils in forested areas that have been cleared for pastures or lawns have shown to decrease infiltration rates, while soils that were cleared and then tilled for crops show an increase in infiltration and decrease in runoff (Harden, 1991; Harden, 2006; Price et al., 2010). Soils undergoing urban farming are often tilled, which, by design, decreases bulk density at shallow depths. The introduction of a variety of plants potentially increases the density of the macropore network. Some studies even suggest that the tree branch mulch and chips used to cover the surface of many urban farms could decrease sediment transport and overland flow (Hueso-González et al., 2014). This study seeks to compare soils in an urban environment that were intentionally compacted (e.g. fill material), soils that were managed as common lawn soils, and soils that have been utilized for urban farming.

1.4 Common Permeameters

There are several ways to measure the hydraulic conductivity of soils in the unsaturated (vadose) zone. This is can be accomplished by use of infiltrometers in the field, or by the use of techniques in a laboratory setting (e.g., Reeve, 1957; Klute and Dirksen, 1986; Kumar et al., 2010). The objectives of this study includes collecting K_{fs} measurements in-situ, therefore, instrument comparisons will focus on equipment used to measure the K_{fs} in-situ. In-situ K_{fs} measurements have been shown to more accurately represent composite soil hydraulic characteristics (Price et. al., 2010).

Some of the most common devices used to measure K_{fs} in the field are in represented in three categories: down-hole constant-head well permeameters, pressure infiltrometers, and tension infiltrometers (Elrick and Reynolds, 1992a). While all methods and equipment generally produce similar data, the differences between them comes from the measurement duration, need for specialized equipment, labor requirements, and the measurement uncertainty in the K_{fs} values

(Nimmo et al., 2007; Theron et al., 2010). One of the first things to consider when choosing which method best suits the needs of a study is the depth of the target soil. Two of the mentioned types of infiltrometers (the pressure infiltrometer and the tension infiltrometer) are required to rest directly on the soil. This can be done by easily by resting the device directly on the land surface after clearing away debris, or more laboriously by digging an access pit and resting the device on the bottom (Elrick and Reynolds, 1992a). This is considerably more effort and may even require the use of heavy equipment depending on the targeted depth.

The pressure infiltrometer (e.g., Bouwer, 1966; Bagarello et al., 2009) consists of a mariotte bottle attached to a ring that is forced directly into the surface of the soil. Water drains from the mariotte bottle and infiltrates the surface of the soil (Reynolds and Elrick, 1990a). The flow rate of water into the soil is measured and used to calculate the K_{fs}. An air tube inserted into the mariotte bottle can be raised up or down causing varying degrees of water displacement providing a means to adjust the steady water pressure (Elrick and Reynolds, 1992b).

The tension infiltrometers (e.g., Ankeny et al., 1988; Perroux and White, 1988) works similarly in that they consist of a mariotte bottle resting on the surface of the soil (a ring forced into the surface of the soil may or may not be employed) (Reynolds and Elrick, 1990a). The difference is that while the pressure infiltrometer applies positive pressure to the water-soil interface forcing water into the soil, the tension infiltrometer allows the water to seep into the soil under negative pressure. This is achieved by placing a porous material between the water and the soil surface. Water seeps through the porous material and into the soil under a steady water potential which is controlled by a second mariotte bottle (Elrick and Reynolds, 1992a). This produces a wetting zone within the soil and does not saturate the soil like the pressure infiltrometers and down-hole constant head permeameters do.

The down-borehole constant head well permeameter (e.g., Bouwer, 1961; Reynolds et al., 1983, Hinnell et al., 2009) consists of a water supply retained in a mariotte bottle with one end inserted into a borehole augured into the target soil at the target depth (Elrick and Reynolds, 1992b). This can also be achieved by connecting a water reservoir via a tube for water passage to a device inserted into a borehole. In both cases, water is fed from the reservoir into the borehole and a constant depth of water is maintained in the borehole. Based on the volume of water ponded in the borehole and the infiltration rate, a K_{fs} value is calculated (Philip, 1985; Reynolds and Elrick, 1990a; Elrick and Reynolds, 1992a).

1.5 Statement of Purpose

It is understood that urbanization increases impervious surface area which increases overland flow volumes (Shaw, 1994; Rose and Peters, 2001). Given this, it is then important to understand how water moves through the remaining pervious surfaces to consider the best land management practices that promote surface infiltration and groundwater recharge in urbanized areas. This study compares the K_{fs} of urban soils under three land management practices: lawn, urban farming, and compacted fill on a single property. Additionally, grain size analysis was conducted on all three land management types along with observations of overland flow and drainage paths immediately following a storm. Understanding any significant difference in the rate at which water infiltrates into these types of soils will provide insight into how readily overland flow may occur during storm events in urban environments.

1.6 Study Area

1.6.1 Proctor Creek watershed

This study was conducted on a property located within the Proctor Creek watershed. The Proctor Creek watershed (PCW) is approximately 41 km^2 and occupies a large portion of the city of Atlanta on the west side between the Chattahoochee River and Downtown Atlanta. This is an urbanized watershed with approximately 34% impervious surface cover (City of Atlanta 2016). With PCW's headwaters in the downtown core of the city, urban runoff is a major contributor of streamflow in this watershed (Park Pride, 2010).

Several studies have shown the dissolved, suspended, and bedload fractions of Proctor Creek sediments exhibit trace metal concentrations that are above biotic tolerances and regulatory limits (McConnell, 1980; Horowitz et al., 2008; Peters, 2009). The public health problem in this area is compounded by pathogen contamination from wastewater treatment facilities, contaminated legacy industrial sites or "brown-fields", and a drastically altered flood regime due to excess urbanization in the watershed. The unremediated brownfields in the area, combined with an increase in flashiness for Proctor Creek, contribute to the spread of contaminants not only in the PCW, but also to other areas of Georgia, since Proctor Creek is a tributary of the Chattahoochee River (Peters, 2009). It is important to understand the potential for soils in urban areas to exhibit infiltration-excess overland flow so the problems associated with brownfields can be mitigated, and a more natural hydrological flow regime in the Proctor Creek watershed can be restored (Kaushal et al., 2014).

1.6.2 Good Shepherd urban farm land-use past and present

This study was conducted on a single property, occupying one city block approximately 1.5 hectares in area near downtown Atlanta, GA. Conducting this study on a single property had the benefit of avoiding potential K_{fs} variations based on large scale spatial factors. This allowed K_{fs} variations based only on land management practices to be more apparent. All testing was conducted between November 2015 and March 2016.

The property was purchased by its current management in 1990 from the City of Atlanta. It had been used as a landfill for construction material, such as removed soils and concrete from local construction sites. The property existed as a green open space until 2007 when the City of Atlanta removed several meters of material from the west and northwest sides of the property to install an updated sewer main. The vegetation was removed from most of the remainder of the property as well. From 2007 to 2009, natural vegetation regrew over the property. In 2009, the central area of the property was converted to an urban farm roughly half the size of the current state of the farmed area. The area of the property utilized for urban farming slowly grew to its current size from 2009 to present. Urban farming techniques employed here included the laying down of a mixture of fine sand and loose gravel initially. This was then covered by several layers of cardboard scraps and composted organic material. The areas that were not explicitly used to grow crops (e.g., foot paths) were covered in wood chips. In 2014, the west side of the property was filled in with soil from local construction sites to create a more level topography across the property. This fill material was compacted by heavy machinery. The current state of the property is the largest extent of the urban farming area to date. The lawn area of the property has gone through the least amount of alternation since the property was purchased in 1990 (English N., personal communication, June 15, 2016).

1.6.3 Geology and soils

The soil series on this property is entirely classified as Urban Land (Ub) (Soil Survey Staff, 2016a). Ub is also often referred to as unclassified city land (Ua) and occupies a large portion of Fulton County. Specific mapping of these soils is considered not feasible since they are so altered or obscured from decades of urban works, therefore no official soil description (OSD) is available (Soil Survey Staff, 2016b). For the purpose of this study, soils were categorized based on land-management practice. Three major categories were identified: compacted fill material, farm soils, and lawn soils. These three major soil categories were generally observed to occupy the west, center, and east portions of the property, respectively. A minor category was also identified as a sink area. The soils in the sink area, occupying the northwest corner of the property, were observed to be consistently either fully saturated, or submerged under water for the entire duration of the study period and were not tested.

Figure 1 shows a satellite image of the property from August 24th, 2015. The delineation of each land-use category was determined by soil observations and communication with property managers. Buildings and roads are excluded from these delineations. The area labeled "Fill" is the total extent of the fill material that was moved onto the property in 2014. The area labeled "Farm" is the total extent of the property that the urban farming techniques discussed above were utilized. The area labeled "Lawn" is the remainder of the property that was not subjected to any urban farming techniques, construction, or severe alteration since 2007. This area has only been managed under common lawn maintenance. The area labeled "Sink" is the total extent of the area which remained fully saturated or submerged under water. This area was generally 1 to 2 meters lower in elevation than the rest of the property.

Figure 1: Satellite image of the Good Shepard urban farm property with sampling locations labeled.

2 METHODS

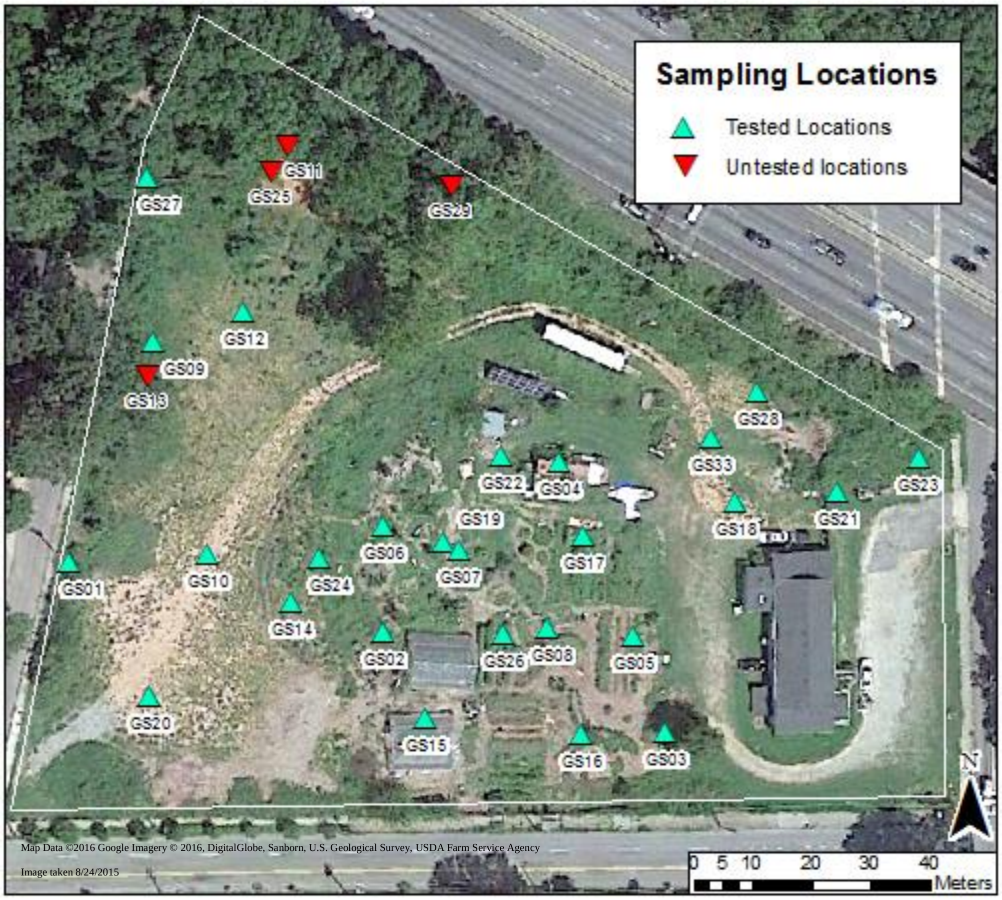

Figure 2: Satellite image of the Good Shepard urban farm property with sampling locations labeled. Each triangle symbol represents one locations. At each location there were three boreholes (sites) tested.

2.1 Sampling Point Determination

Thirty sampling points were generated across the Good Shepherd farm property (Figure 2). The first 7 sampling points were selected intentionally to ensure the various soil types present were initially represented as part of a pilot study. The remaining sample points were selected using a random point generator in ESRI's ArcGIS v. 10.1. Points that fell on roads, buildings, or were otherwise inaccessible, were discarded. Of the thirty total sampling points that remained: 7 fell on compacted fill material, 12 fell on farmed soils, 8 fell on lawn soils, and 3 fell in the saturated sink area in the northwest corner of the property (GS25, GS11, and GS29). This area was approximately 3-4 m lower in elevation than the rest of the property. The soil in the bottom of this area was consistently observed to either be saturated or submerged under water. Since the methods used in this study for testing K_{fs} assumed soils were not fully saturated when the test began, the sampling points in this area were not tested. Sampling point GS13 fell on the compacted fill material area. The other sampling points in this area were observed to require very long test durations and sampling point GS13 was not tested due to time limitations. The sampling points were located in the field using a Yuma 2 Trimble GPS tablet with an accuracy of ± 3 m.

2.2 Aardvark Permeameter

This study used the Aardvark permeameter developed by Soil Moisture Inc. to collect infiltration rate data from each sample location that is then converted to K_{fs} values. The Aardvark permeameter is a down-borehole constant head well permeameter that uses a down-hole float valve to maintain an adequate ponding of water. Constant head refers to the condition that the water in the well is ponded and keeps a constant depth as the test is conducted. Other popular down-borehole techniques developed include the use of an Amoozemeter (Amoozegar and Warrick, 1986) and the Guelph permeameter (Reynolds and Elrick, 1987). The Aardvark permeameter can be used to determine K_{fs} in the field reliably and quickly compared other methods and equipment (Theron et al., 2010).

This study used a constant-head down-borehole permeameter so that K_{fs} data could be collected 25 to 30 cm below the soil surface to avoid shallow variations in soil composite characteristics. The Aardvark permeameter was the selected brand due to the convenient use of the software with a connected PC tablet. This software allowed for a high level of control over each test. This provided consistency for all testing.

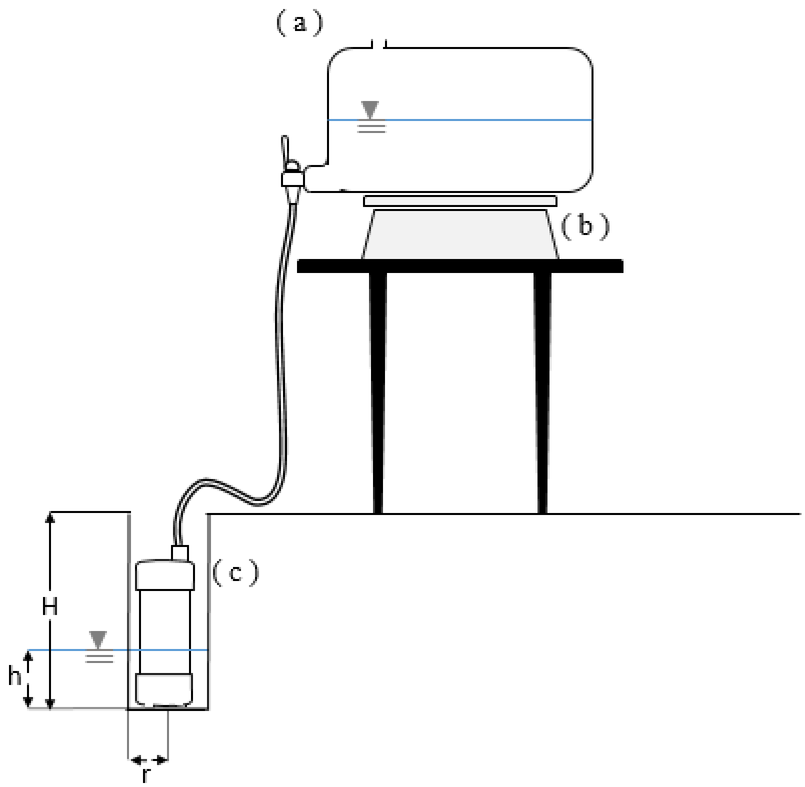

Figure 3: Simplified schematic diagram of the Aardvark permeameter test setup. (a) headwater reservoir (b) digital scale (c) Aardvark permeameter module (APM) (H) depth of borehole (h) depth of ponded water in the borehole (r) radius of the borehole.

Figure 3 shows a simplified schematic of the Aardvark permeameter. The basic components consist of a large water reservoir (a), a digital scale (b), and the Aardvark permeameter module (APM) (c). The flow of water from the reservoir to the APM via a ⅜ inch tubing, is controlled by a simple open/closed valve attached to the reservoir. The tube connects to the reservoir valve and APM via quick-connects. The APM is a floating bottle valve mechanism and is shown in Figure 4.

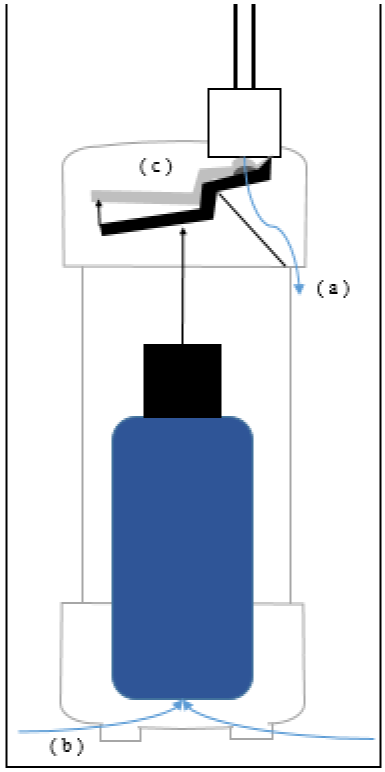

Figure 4: Aardvark permeameter module (APM)

Water flows from the reservoir, down the tube, into the borehole, and out of the APM through the opening near the top (a). As this flow fills the borehole with water, water re-enters the APM through the large holes in the bottom (b). As the water surface rises the float bottle in the APM rises. The float bottle lifts the small flow trigger (c) in the top of the APM and shuts off the flow of water into the borehole. This float bottle mechanism effectively keeps the water level in the borehole constant by only supplying enough water to keep the float bottle in contact with the flow trigger. As the water infiltrates into the surrounding soil and the water height decreases, the float bottle lowers and releases the flow trigger to allow more water into the borehole until the water height increases to the desired constant level. The constant height water level can be manipulated by suspending the APM at different depths. If the APM is resting directly on the soil in the borehole, the constant water level will be approximately 7 cm, which is the case for this study.

The reservoir rests on a digital scale that measures the water loss from the system with an accuracy of 0.2 ml. The digital scale was connected to a Trimble Yuma 2 GPS tablet were the infiltration rate was recorded. The infiltration rate could also be measured by hand without the use of the software by recording the readings from the scale at known time intervals. Data was collected by hand and by using the Simply Data ™ software, developed by the manufacturers of the Aardvark permeameter, Soil Moisture Inc.

2.3 Borehole Preparation

At each sampling location three wells were dug in a triangle arrangement, 1.0 m apart. Initially, the area was cleared of surface debris, and any surface roots or gravel were removed from the area. A loam soils hand auger with continuous edging was then used to dig the boreholes so the inside surface of each borehole was constantly being scraped as they were dug, to prevent clay smearing inside the borehole. The target depth for all boreholes was between 25 cm and 30 cm based on similar studies (West et al., 2007; Price et al., 2010). The loam soils auger produced a borehole with an approximate diameter of 11 cm. The auger was turned by hand so any disturbance along the side walls of the borehole could be observed and avoided. If a large root or gravel was obstructing the auger before the target depth was reached, the borehole would be abandoned and a new borehole would be dug. New boreholes would be no closer than 1 m to any other boreholes dug in that location if possible.

A sizing auger was then carefully inserted into the borehole. The sizing auger was equipped to scrape the bottom corners and surface of the borehole to give it a more uniform cylindrical shape. It was very important to ensure each borehole had an approximately similar shape, since the equations used to calculate the K_{fs} value were very sensitive to the dimensions of the boreholes (Elrick and Reynolds, 1992b; Jabro and Evans, 2006). The borehole was scraped with the sizing auger until the bottom surface appeared flat and rough in texture. The last step in preparing the boreholes was to insert a wire brush. Since clay smearing along the inside walls of the borehole could drastically affect the infiltration rate along the soil water interface (Bagarello, 1997; Rienzner, 2014), the wire brush was inserted to thoroughly scrape the walls, bottom, and corners of the wells before testing.

2.4 Field Saturated Hydraulic Conductivity Data Collection

Once the well was observed to meet the standardized dimensions for this study, a depth of 25 cm to 30 cm with a diameter of approximately 11 cm, the APM was inserted. All connections and valves were verified to be working properly, along with the scale and software. The scale was tared before the full water reservoir was placed on top. The water valve was opened and the software or technician recorded the values on the scale as water initially rapidly filled the borehole up to the target water level of 7 cm. It was necessary that the entire assembly be covered, since light wind activity could disturb the reservoir on the scale and produce errors in the readings. The wind effect on the system was mitigated by placing a large plastic barrel around the entire assembly. The barrel was placed over the assembly so that the open end of the barrel was resting on the soil surface. The table, scale, and reservoir were covered underneath the barrel while a USB cable ran out of the barrel and connected to the Simply Data™ software and a ⅜ inch tubing ran out of the barrel to the APM in the borehole. The rim of the barrel was propped open so the tube was undisturbed and not pinched. Holes were left in the walls of the barrel so the technician could still see the equipment inside. The technician needed to verify readings on the scale and monitor the equipment for any leaks, or other errors, while each test was conducted.

Another potential error source on scale readings was leaks in the assembly. If any small amount of water leaked from the reservoir, connectors, or tube, the software would record that water loss as infiltration into the borehole. Many precautions were taken to ensure any leaks did not go unnoticed. All connects were sealed thoroughly with silicone gel. The assembly was dried before testing so any moisture on the surface would be easily recognized. Dry paper was placed under the reservoir so that when the test was completed any wetness on the paper would indicate a leak. If a leak was found during or after a test was ran, the leak would be fixed, the data collected for that test would be discarded. The test would be repeated starting with digging a new borehole 1 m away from the initial point to ensure any water in the soil from the previous failed test would not affect the new measurements. This process was repeated until three successful measurements were obtained at each sampling location. Each borehole was represented by its own measurements and K_{fs} calculations.

2.5 Field-Saturated Hydraulic Conductivity Calculations

Two equations were considered for use in this study to calculate the K_{fs} values from the steady-state infiltration rate and borehole dimensions. Initially, the Glover solution was considered based on its use in a similar study (Price et al., 2010).

Equation [1]: $K_{fs} = CQ/(2\pi H^2)$

This solution was not applicable for this study for several reasons. The Glover solution (Zanger, 1953) (Equation [1]) has been found to only be reliable in calculating K_{fs} values when the ratio of the height of the ponded water in the borehole (h) to the radius of the borehole (r), is larger than 5 (Amoozegar, 1989; Jabro and Evens, 2006), $h/r > 5$. The reason for this is the

Glover solution does not take into account the gravity and capillary components of flow in soils that are initially unsaturated (Reynolds et al., 1983; Elrick and Reynolds, 1992b; Jabro and Evans, 2006). The Glover solution assumes the soil is initially saturated (i.e., soils below the water table). The Glover solution can still be applicable for soils that are initially unsaturated (i.e., above the water table and below full saturation) with h/r =10 when gravity only accounts for 1.5% of flow, as opposed to lower h/r ratios such as h/r = 0.5 when gravity accounts for 30% of flow (Elrick and Reynolds, 1992b). The height of the ponded water to the borehole radius determines the influence of hydrostatic pressure in the setup. If the well is very small and the ponded water is very deep (e.g., a 2-inch diameter with 2 feet of ponded water) then the h/r is going to be very high (e.g. 24). In this case, the Glover solution can still be used since the hydrostatic pressure influence is dominating the flow, making the influence of gravity and capillary flow negligible (Reynolds and Elrick, 1992b; Jabro and Evans, 2006). However, if the h/r ratio is very small (e.g., a 11 cm diameter with 7 cm of ponded water), such as this study with the use of the Aardvark permeameter, then the hydrostatic pressure component of flow has less of an influence and the gravity and capillary components of flow have much stronger influences. In this case the Glover solution no longer adequately describes the hydraulic conductivity of the soil surrounding the borehole and can result in frequent overestimations of K_{fs} values. This is especially true in unsaturated fine textured soils (Reynolds and Elrick, 1992b; Jabro and Evans, 2006).

2.5.1 The Reynolds and Elrick solution

The solution developed by Reynolds and Elrick (1989, 1990, 1992b) (Equation [2]) adequately describes the flow from a constant head down borehole permeability test in unsaturated soils (vadose zone) by considering the gravity and capillary components of flow (Jabro and Evans, 2006). This equation can be written as:

Equation [2]: $K_{fs} = Q(C/(2\pi h^2 + \pi C r^2 + 2\pi(h/\alpha))$

where K_{fs} (cm/s) is the field-saturated hydraulic conductivity, Q (cm^3/s) is the steady-state infiltration rate, C is a dimensional shape factor empirically determined, h (cm) is the height of the ponded water in the borehole, r (cm) is the radius of the borehole, and α (cm^{-1}) is the $K_{fs} / \Phi m$ ratio (Φm (cm^2/s) is the matric flux potential). The first sum term on the right of the equation ($2\pi h^2$) is similar to what is also represented in the Glover solution (Equation [1]) as the basic flow component or hydrostatic pressure component of flow (Zanger, 1953; Elrick and Reynolds, 1992b). The second term in Equation [2] ($\pi C r^2$) represents the gravity component of flow. The third term ($2\pi(h/\alpha)$) represents the capillary flow component. The third term is very important for this study and its consideration is the reason the Reynolds and Elrick solution was used for K_{fs} calculations. This is due to the unsaturated state of the soil before testing, the dimensions of the borehole created by the provided Aardvark permeameter equipment, and the target depth of the boreholes for this study.

The empirical determination of the *C* value estimates are reported in (Reynolds and Elrick, 1987) and defended in several studies (Reynolds and Elrick, 1983; Elrick and Reynolds, 1992a; Elrick and Reynolds, 1992b). The aforementioned studies suggest values for *C* based on experimentation. The *α* value also requires independent estimation, based on the same soil descriptions used for the *C* value (White and Sully, 1987; Elrick et al., 1989). Values for *C* and *α*, in this study; were chosen based on soil descriptions (Table 1). The last column in Table 1 indicates which soil type from Figure 1 was assigned to which *C* and *α* values.

Table 1: C and α values (Reynolds and Elrick, 1987). Land Management practice assigned refers to the designated soil type of each area shown in Figure 1.

Soil Type	Soil Descriptions	α	C	Land Management practice assigned
I	Compacted, Structure-less, clayey or silty materials such as landfill caps and liners, lacustrine or marine sediments, etc.	0.01	0.688	not used
II	Soils which are both fine textured (clayey or silty) and unstructured; may also include some fine sands.	0.04	0.709	compacted fill material
III	Most structured soils from clays through loams; also includes unstructured medium and fine sands. The category most frequently applicable for agricultural soils.	0.12	0.664	farm and lawn soils
IV	Coarse and gravely sands; may also include some highly structured soils with large and/or numerous cracks, macropors, etc	0.36	0.664	not used

2.5.2 The matric flux potential

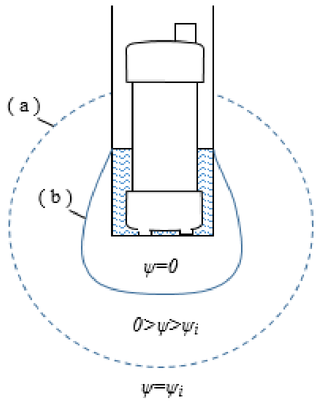

Figure 5: Simplified schematic diagram of (a) the wetting zone front and (b) the saturated bulb.

As the test was conducted, water infiltrated through the soil-water interface in the borehole and into the surrounding soil. Figure 5 shows a simplified diagram of the soil as the test is conducted. Initially, a wetting front is formed (a) and extends radially from the borehole as the negative tension from the capillary forces moves water through the soil. The matric flux potential (*Φm*) describes the capillary forces in a soil that allow the soil to take up water. These capillary forces are less than zero and move water through the "wetting zone", the unsaturated flow zone of the bulb created by the constant-head well permeameter. The upper limit of the soil water pressure head (ψ) is zero and exists within the field saturated bulb (b) where the soil is fully saturated and capillary forces no longer control flow. The lower limit of ψ is essentially the initial ψ (ψ_i) and exists outside the wetting zone in the dry unsaturated soil of the vadose zone. Therefore, the values for ψ between the field saturated zone front and the wetting zone front are between zero and ψ_i (Reynolds and Elrick, 1987; Elrick et al., 1989; Elrick and Reynolds, 1992a). The Φm is defined in Equation [3]:

Equation [3]: $\Phi m = \int_{\psi i}^{0} k(\psi) d\psi$

Where $\psi_i \leq \psi \leq 0$ and $k(\psi)$ is the hydraulic conductivity-pressure head relationship (Reynolds and Elrick, 1987). The Φm can also be more or less important based on soil type. For example, a very sandy soil will have a steep curve and high ψ_i resulting in a low Φm, but soils rich in clay content will have a shallow curve and low ψi and higher value for Φm. Resulting in a more meaningful impact of Φm for the K_{fs} in Equation [2] (Elrick et al., 1989). This describes the importance of using equations that consider capillary forces when determining K_{fs} in unsaturated soils that have high clay contents such as this study. It is unnecessary in saturated soils considering $\psi i \geq 0$.

2.5.3 Steady-state infiltration rate

The key parameter for calculating the saturated hydraulic conductivity in soils is the steady-state infiltration rate of water into the soil. Steady-state infiltration rate is often defined as the point at which the infiltration rate into the soil becomes constant. This can also be stated as the point at which changes in infiltration rate over time becomes negligible. The K_{fs} value can also be calculated for each measurement as a test is conducted, and when the change in K_{fs} value becomes negligible, steady-state condition has been met (Nimmo et al, 2007; West et al., 2007;

Amoozegar, 2014; Rienzner and Gandolfi, 2014). Following the general design of similar studies, infiltration rates were calculated over periods ranging from 1 to 5 minutes (Rienzner and Gandolfi, 2014). These readings were then used to calculate an infiltration rate and K_{fs} value for each time interval. Each test was conducted until one of two conditions was met: (a) steady-state condition was achieved, as indicated by a minimum of three consecutive infiltration rates of the same time interval exhibiting values within ± 10% change, or (b) an extended period of time had passed without achieving steady-state condition, as defined above, and the test was ended due to time limitations. For condition (a) the average of the K_{fs} values for the last three readings was used. For condition (b) the last reading obtained was used and represents an overestimation of the K_{fs} value. As a test approaches steady-state, the K_{fs} values decrease and slowly approach a constant value (Elrick et. Al., 1989); therefore, collecting a K_{fs} value before a test has reached steady-state will produce an overestimation.

2.6 Grain Size Analysis

Samples collected for grain size analysis were randomly selected in the field from the existing sampling points shown in Figure 1. A total of 9 samples were collected with 3 from each of the 3 soil types. The fill material samples were collected from locations GS01, GS10, and GS14. The farmed soil samples were collected from locations GS02, GS08, and GS17. The lawn soil samples were collected from locations GS03, GS23, and GS28. All grain size analysis was performed in a geotechnical laboratory in accordance with ASTM standards.

2.7 Statistical Methods

Basic descriptive statistics (mean and standard deviation) were calculated for the K_{fs} values for the soils in each land management category. The Kruskal-Wallis H test (KW-test), non-parametric one-way ANOVA on ranks, was used to evaluate differences in soil K_{fs} values as a function of land management practices and to test the variability among locations within a given land management practice. Results of the grain size analyses were also tested for significant differences across land management types. This was done by conducting 4 separate KW-tests for each grain size class: gravel, sand, silt, and clay. A KW-test was used instead of a parametric ANOVA test because the sample sizes were so small. All statistical analyses were performed using Microsoft Excel and R software.

3 RESULTS

3.1 Field-Saturated Hydraulic Conductivity Results

A total of 30 locations were selected for testing. Seven locations were selected a priori, and the remaining 23 were randomly identified. Of these 30 locations, four were discarded and not tested (locations GS11, GS13, GS25, and GS29) due to unsuitable conditions. Three boreholes or "sites" were tested at each location and assigned calculated K_{fs} values with the exception of site C of location GS30; the data for this site was corrupted and lost. A final total of 77 sites were assigned K_{fs} values. Among these 77 sites, 73 of these K_{fs} values were calculated based on steady-state condition (a) and 4 were calculated based on steady-state condition (b). These conditions are defined and described in section 2.4.3 of this study. Field measured K_{fs} values across the entire property ranged from 2.1E-8 cm/s to 1.3E-3 cm/s. The fill material soils exhibited the lowest K_{fs} values, between 2.1E-8 cm/s and 3.2E-6 cm/s. Farmed soils exhibited both the highest overall K_{fs} values and the greatest variability, between 1.8E-7 cm/s and 5.2E-3 cm/s. Lawn soils exhibited the least variability in K_{fs} values, between 3.3E-7 cm/s and 3.6E-5 cm/s.

Table 2 shows the K_{fs} values for each site at each location tested. The K_{fs} values calculated based on steady-state condition (b) are indicated with an asterisk. Following the design of similar studies (West et al., 2007; Price et al., 2010), the geometric mean of all three sites at each location is also listed on Table 2 and used in subsequent statistical analyses.

Table 2: Summary table

Location	Site	K_{fs} (cm/s)	Geometric Mean (cm/s)	Soil Type
GS01	A	1.6E-06	1.6E-06	Fill
	B	1.6E-06		
	C	1.6E-06		
GS02	A	5.2E-03	1.3E-03	Farm
	B	1.4E-03		
	C	3.0E-04		
GS03	A	1.5E-05	7.4E-06	Lawn
	B	9.0E-06		
	C	3.0E-06		
GS04	A	8.2E-06	3.2E-06	Lawn
	B	7.0E-06		
	C	5.6E-07		
GS05	A	3.7E-05	5.8E-05	Farm
	B	9.8E-05		
	C	5.4E-05		
GS06	A	2.0E-04	6.1E-05	Farm
	B	3.0E-06		
	C	3.9E-04		
GS07	A	9.0E-06	1.1E-05	Farm
	B	1.5E-05		
	C	9.0E-06		
GS08	A	6.0E-07	2.4E-06	Farm
	B	3.0E-06		
	C	7.5E-06		
GS09	A	3.9E-08 *	3.6E-07 *	Fill
	B	3.2E-07		
	C	4.0E-07		
GS10	A	3.2E-07	3.2E-07 *	Fill
	B	2.1E-08 *		
	C	3.2E-08 *		
GS11		Not Tested		Drainage
GS12	A	4.0E-07	1.2E-06	Fill
	B	1.2E-06		
	C	3.2E-06		
GS13		Not Tested		Fill
GS14	A	1.6E-06	8.2E-07	Fill
	B	1.1E-06		
	C	3.2E-07		
GS15	A	6.7E-06	2.0E-05	Farm
	B	9.5E-05		
	C	1.3E-05		

Location	Site	K_{fs} (cm/s)	Geometric Mean (cm/s)	Soil Type
GS16	A	5.0E-07	4.5E-07	Farm
	B	1.0E-06		
	C	1.8E-07		
GS17	A	3.0E-06	1.2E-05	Farm
	B	1.3E-05		
	C	4.4E-05		
GS18	A	1.0E-05	1.0E-05	Lawn
	B	6.0E-06		
	C	1.8E-05		
GS19	A	1.5E-05	4.5E-06	Farm
	B	2.0E-06		
	C	3.0E-06		
GS20	A	1.6E-06	7.7E-07	Fill
	B	7.0E-07		
	C	4.0E-07		
GS21	B	9.0E-06	6.9E-06	Lawn
	B	6.0E-06		
	C	6.0E-06		
GS22	A	1.5E-06	2.5E-06	Farm
	B	1.5E-06		
	C	6.7E-06		
GS23	A	7.5E-06	8.8E-06	Lawn
	B	6.0E-06		
	C	1.5E-05		
GS24	B	4.5E-06	4.3E-06	Farm
	A	6.0E-06		
	C	3.0E-06		
GS25		Not Tested		Drainage
GS26	A	1.0E-06	1.2E-06	Farm
	B	6.0E-07		
	C	3.0E-06		
GS27	A	5.2E-06	3.6E-06	Lawn
	B	3.0E-06		
	C	3.0E-06		
GS28	A	6.0E-06	1.6E-05	Lawn
	B	3.6E-05		
	C	1.8E-05		
GS29		Not Tested		Drainage
GS33	A	3.3E-07	1.6E-06	Lawn
	B	8.0E-06		
	C	lost		

* - *Kfs* values calculated based on steady-state condition (b) described in section *2.4.3 Steady-state infiltration rate.*

The K_{fs} data for all analysis results and figures are presented in the following groupings (hereafter referred to as "data sets"):

- Sites-A: K_{fs} values calculated based on steady-state conditions (a) and (b) for each site;
- Sites-B: K_{fs} values calculated based only on steady-state conditions (a) for each site;
- Locations-A: geometric mean of K_{fs} values calculated based on steady-state conditions (a) and (b) for all sites in each location; and
- Locations-B: geometric mean of K_{fs} values calculated based only on steady-state conditions (a) for all sites in each location.

It is important to note that each subsequent representation includes a smaller sample size than the previous. Table 3 and Table 4 summarize the mean and standard deviation of each data set

Table 3: Mean Kfs values for all data sets

Mean				
Data Set	Fill	Farm (cm/s x 10^{-5})	Lawn	All
sites-A	0.09	22.03	0.90	7.67
sites-B	0.11	22.66	0.90	7.89
Locations-A	0.08	12.24	0.72	4.35
Locations-B	0.11	13.35	0.72	4.73

Table 4: Standard deviations for all data sets.

Standard Deviation				
Data Set	Fill	Farm (cm/s x 10^{-5})	Lawn	All
sites-A	0.08	88.50	0.76	61.02
sites-B	0.08	89.71	0.76	62.64
Locations-A	0.06	36.87	0.46	25.18
Locations-B	0.04	38.46	0.46	26.75

3.1.1 Kruskal-Wallis H Test (ANOVA)

The results of a Kruskal-Wallis H Test (K-W test) analysis, summarized in Table 5, show a significant difference in K_{fs} values based on soil type. All data sets had p-values lower than the significance threshold of 0.01. A K-W test conducted on data set site-A provided a p-value of approximately 1.5E-6, which was the lowest p-value of all data sets. When the K_{fs} values for data set Sites-B was analyzed the p-value increased very slightly to approximately 1.7E-5. The site-A and Site-B data sets were significantly larger than data sets locations-A and locations-B which produced p-values of 0.004 and 0.009 respectively.

Table 5: Kruskal-Wallace H test results for all data sets

Kruskal-Wallace H Test				Sample Size			
Data Set	chi-squared	p value	*df*	Fill	Farm	Lawn	Total
sites-A	26.87	< 0.001	2	18	36	23	77
sites-B	21.99	< 0.001	2	15	35	23	73
Locations-A	11.26	0.004	2	6	12	8	26
Locations-B	9.44	0.009	2	4	11	8	23

3.1.2 Relative Frequency

Figure 6 shows histograms of K_{fs} ranges by relative frequency for each soil land-management category. The K_{fs} values from sites located in the farmed soil were spread across the K_{fs} ranges relatively evenly compared to the other soil categories. The lawn soils occupied the middle ranges while the K_{fs} values from sites located in the fill material category were in the lower K_{fs} ranges consistently. Figure 7 shows the box plots of K_{fs} values for all three soil categories.

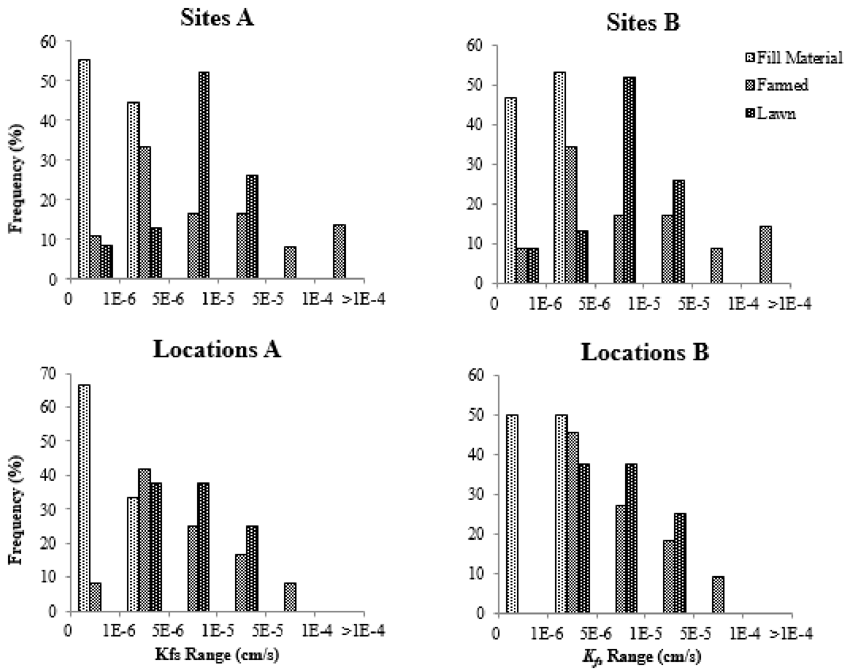

Figure 6: Relative Frequency Histograms

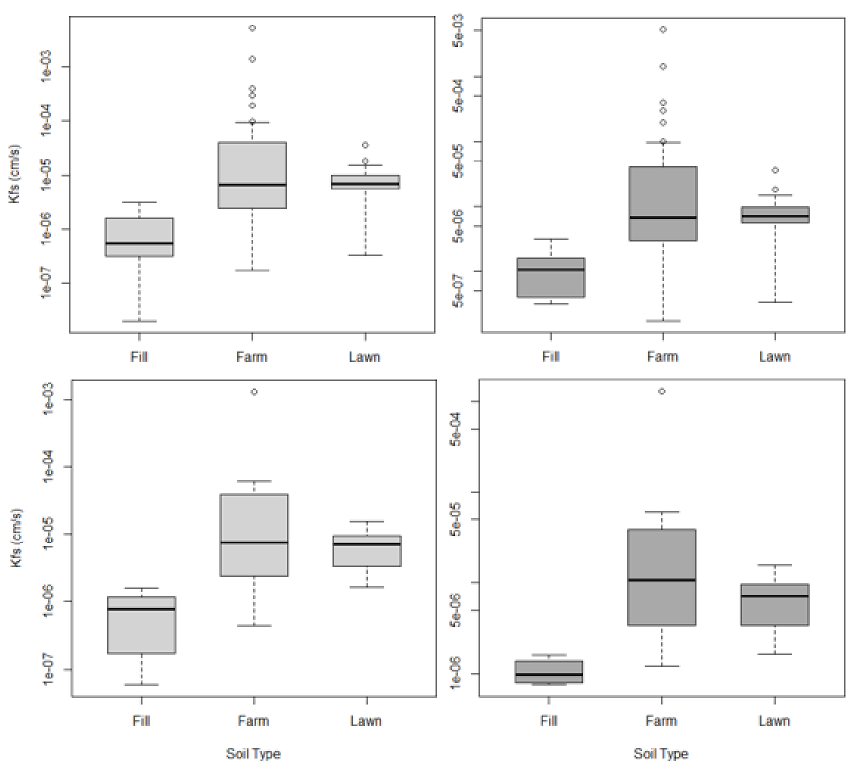

Figure 7: Boxplots of Kfs distribution

3.2 Grain Size Analysis

The compacted fill material soil type exhibited average gravel, sand, silt, and clay percentages of 1.3%, 50.4%, 17.9%, and 30.4%. The farmed soils average gravel, sand, silt, and clay percentages were 4.4%, 49.7%, 24.6%, and 21.4%. The lawn soils average percentages for gravel, sand, silt, and clay content were 3.8%, 47.6%, 21.9%, and 26.7%. Results of the K-W tests exhibit no significant difference between the three land management types based on grain size classes. These results are reported in Table 6.

Table 6: Kruskal-Wallace H test results for each grain size class

Kruskal-Wallace H Test				Sample Size			
Grain Size Class	chi-squared	p value	*df*	Fill	Farm	Lawn	Total
Gravel	4.32	0.12	2	3	3	3	9
Sand	0.62	0.73	2	3	3	3	9
Silt	2.49	0.29	2	3	3	3	9
Clay	2.76	0.25	2	3	3	3	9

4 DISCUSSION

The core data produced in this study is the result of a K-W test on all data sets. The goal of this variation on an analysis of variance was to statistically reveal if there is any significant difference in the K_{fs} values of soils based on the land management practices they were subjected to. The soils, and subsequent K_{fs} values, were broken up into three categories, based on how the soils have been treated over the past several (10+) years. The results of a K-W test revealed that even with a strict p-value threshold of 0.05, all data sets showed a significant difference. As one would expect, the smaller data sets, locations-A and locations-B, produced the largest p-values. Even still, these p-values were below the threshold of 0.01 at 0.004 and 0.009, respectively. It is for this reason the K_{fs} values in this study were organized in four different data sets, to show that even with the least ideal data size, statistical analysis revealed a significant difference in K_{fs} values based on land management practices. This point is even further justified with the larger, more ideal, data sets sites-A and sites-B. With the results of a K-W test for these data sets revealing p-values many orders of magnitude smaller than the threshold of 0.05, the significance is readily apparent. It was also important to test for significant differences in grain size distribution between the three land management soil types. The results of the ANOVA test performed on each separate grain size class based on soil types revealed no significant differences. This helps rule out the possibility that the significant differences in K_{fs} values was due to soil texture variations.

With variation in K_{fs} values between these three land-management practices clearly defined, the values themselves can be examined to reveal what impact these practices can have on a soils potential for overland flow. With large portions of urban areas being covered in impervious surfaces, it is important to understand how the remaining pervious surfaces can be utilized to decrease overland flow. The farmed soil produced an overall higher K_{fs} mean, this study potentially revealed that urban farming techniques employed here produced drastically higher K_{fs} values compared to soils subjected to common lawn practices and intentional compaction.

4.1 Sample Size

This study looked at two different sample sizes. The largest included 77 samples of K_{fs} values that each corresponded to one tested borehole. The smaller sample size included 26 K_{fs} values that represented the geometric mean of the three K_{fs} values acquired from each borehole at each location. The data was presented in this way to show that even if the sample size is large, as in data sets sites-A and sites-B, or small, as in data sets locations-A and locations-B, the results of the analysis of variance on K_{fs} based on land management practices shows a significant difference between K_{fs} values based on land-management practices.

4.2 Land Surface Variability

The calculated K_{fs} of the farmed soils demonstrated a very wide range of values. This reflects the inconsistency in how the soil was treated, even over small areas. For example, the vegetable bed areas of the urban farm have undergone extensive alteration. These soils may have had material removed several inches down and replaced with agricultural soils, sand, or organic material several times. Soils very near these beds that served as walking paths may have been subjected to far less alteration. Even though the farmed soil area shown in Figure 1 has been subject to urban farming techniques for seven years, there are unknown variations in the extent to which each unit area has been altered and to what degree. This is reflected in the wide range of K_{fs} values for the farmed soils. Some of the locations tested in this area had K_{fs} values many orders of magnitude larger than the other two soil types, while some of them exhibited K_{fs} values that were very similar or even lower than Kfs values from the other soil types.

Land-use variability can also affect the aggregate infiltration rates at the land parcel scale. At this particular property we have three soil types, defined by their alteration, that occupy large percentages of the property. The results of this study show that they each exhibit different infiltration rates. We can see that if this property had only one of these soil types that occupied the entire parcel of land, the parcel as a whole would have drastically different hydrological properties. For example, if the entire property had been subjected to the same treatment and alternation that the compacted fill soil had, the overall infiltration rate would be much lower and the likelihood that the entire property would exhibit overland flow would increase. This would increase all of the issues associated with exaggerated overland flow on the property. However, if the entire parcel was subjected to urban farming techniques, the mean infiltration rate of the parcel would increase. This could mean less overland flow could occur and the issues associate with large run-off volumes would potentially greatly decrease. Lastly, if the property was entire covered in soils subjected to common lawn practices, it would resemble one of the most common types of pervious land surfaces observed in urban environments, like those in the front and back yards of homes and park areas.

Table 7: Weighted mean K_{fs} values of whole parcel excluding the sink area. Also includes Kfs values under different conversion scenarios.

Soil Type	mean Kfs	Area	Precent Area	Weighted Mean of Parcel	Fill to Lawn	Farm to Lawn	50/50 farm/lawn	All Farm	All Lawn
(-)	(cm/s)	m^2	(%)	(cm/s)	(cm/s)	(cm/s)	(cm/s)	(cm/s)	(cm/s)
Fill	9.1E-07	4554.9	34.8						
Farm	2.2E-04	3265.8	25.0	2.0E-05	5.8E-05	3.2E-06	5.7E-05	2.2E-04	9.0E-06
Lawn	9.0E-06	5256.4	40.2						

Table 7 shows the K_{fs} that may exist for the property under different land conversion scenarios. The first part of the table shows the mean K_{fs} values, the area in m^2, and the percent area of each land management type. The total area of the property considered in all analysis on Table 7 excludes the area occupied by the sink area shown on Figure 1. The second section of Table 7 shows the different conversion scenarios. The “Weighted Mean of Parcel” column reports the mean K_{fs} of the property based on the mean of each land management type and the percentage of the total area in which they cover, under current management scheme. This indicates the mean K_{fs} of the entire property is 2.0E-05 cm/s. The “Fill to Lawn” column indicates what the mean K_{fs} of the property would likely be if all of the fill material was not present and the portion of the property it occupied was managed in the same way as the lawn soil. The “Farm to Lawn” column considers the same, but as if the farm soil was replaced by lawn soil. This reflects the mean K_{fs} value of the property of urban farming never took place. The values on this table indicate that the presence of the urban farm increases the mean K_{fs} value of the property by an order of magnitude compared to the property without the urban farm. If the compacted fill material was removed, and the entire property was converted to 50% farmed soil and 50% lawn soil, the mean K_{fs} value would not change as significantly, as indicated by the “50/50 farm/lawn” column of Table 7. The last two columns show the mean K_{fs} value of the property if the entire property was converted to either farm soil or lawn soil, the latter being a very common parcel type in urban areas.

The shrinking and swelling behavior of more clay rich soil can also pose interesting variations. When dry, the soils can crack on the surface. This may have the effect of drastically increasing the K_{fs} of a soil initially. As a storm event continues, clay swelling could lead to much lower K_{fs} values. This is, however, a minor concern on this property since Georgia soils in this area exhibit little to no swelling potential (King, 2016).

4.3 Impact of Urban Farming on K_{fs} and Overland Flow

The impact on overland flow mentioned here only refers to infiltration excess overland flow, or “Hortonian overland flow”. These K_{fs} indicate the rate at which water is capable of flowing down through the soil. Comparing these K_{fs} values to the precipitation rate of a storm event can lead to an understanding of a soils potential to produce Hortonian overland flow.

Overall, the impact of urban farming on overland flow is still significant even though K_{fs} values are not uniformly increased. This study shows that in many locations, the K_{fs} values of farmed soils are drastically increased compared to the compacted fill material soils and even the lawn soils. This indicates that in these areas, overland flow is potentially decreased and more water infiltrates into the soil surface during storm events. The ground cover, which can reduce effects of overland flow and associated sediment transport (Hueso-González et al., 2014), also varies across the soil types on this property and potentially impacts overland flow.

Overland flow can be directly observed in the field during or immediately following a storm event. Figure 8 shows an image of the surface of the compacted fill material after a storm event. Overland flow paths can be seen across the surface. These paths lead to the drainage area in the northwest corner of the property. Figure 9 shows an image of this drainage area submerged under several feet of water after this storm event. Figure 10 show a gully two meters across leading to this drainage area that most of the drainage paths across the compacted fill material lead to. Along these flow paths, sediment transport and surface erosion is readily seen.

Figure 8: Drainage paths on fill material

Figure 9: Sink area

Figure 10: Gully in sink area

Figures 11-13 show images of the farmed and lawn soils on the property after the same storm event. While ponded water can be seen in some places across these land covers, there did not appear to be any major drainage pathways eroding the surface of these soils. Compared to the compacted fill material, these soils are covered in vegetation. The lawn soils are covered in grass or gravel typical of urban lawns. The farmed soil exhibited a variety of ground covers. Most of the farmed area was covered wood chips, cardboard scraps, and composted organic material of various depths from 1 to 6 inches. The soil underlying these additives in some areas appeared very similar to the soil under the grass cover in the lawn areas, while some areas exhibited a mixture of gravel and sand.

Figure 11: Farm area

Figure 12: Farm area

Figure 13: Farm area

4.4 Steady-State Determination

It is important to note that the K_{fs} values obtained in this study are meant to be compared relative to one another. This study aims to determine whether a significant difference exists between the K_{fs} of different observed soil types. It is important that each test is conducted under the same method and standardization to limit the amount of factors that can contribute to K_{fs} variations. It is for this reason K_{fs} values calculated under steady-state condition (b) were used for analysis in data sets sites-A and locations-A. Although these K_{fs} values did not graphically or numerically reach true steady-state conditions the overestimates of their K_{fs} values still provides statistically significant lower values compared to other sites. These sites exhibited very low infiltration rates as soon as the test began. The slow infiltration rate was at the limit of detectability of the equipment used unless the reading time interval was drastically increased compared to the rest of the sites in this study. Major variations in study design such as this were avoided for consistency. The K_{fs} values for these very slow soils was calculated using the lowest infiltration rate determined based on the few readings acquired for these sites. These sites did not reach true steady-state conditions and therefore represent an overestimation of K_{fs}. Since the K_{fs} values calculated in this way exhibited some of the lowest values in the study, they still provided a good relative comparison.

4.5 Sensitivity of *C* and *α* Values

As mentioned in section 2 of this study, Equation [2] has two variables, *C* and *α*, whose values were chosen based on the soil descriptions in Table 1. *C* is a dimensionless shape factor that was empirically determined and *α* is the ratio of K_{fs} to matric flux potential (*Φm*). Table 1 shows that one set of *C* and *α* values were chosen for the compacted fill material K_{fs} calculations, while a different set was used for the farmed and lawn soil calculations. The lower *C* and *α* values reduced the K_{fs} values of the compacted fill material compared to the farmed and lawn soil. While the *C* and *α* values chosen for each soil type were justified by matching the soil descriptions in Table 1 to observations made in the field, it is important to explore how sensitive Equation [2] is to these values.

Taking the highest K_{fs} value for the farmed soil with the lowest K_{fs} for the compacted fill material and exchanging the *C* and *α* values used in their calculations can show if those values drastically change the results. The K_{fs} value calculations for the compacted fill material used *C* and *α* values II, 0.04 and 0.709, from Table 1. This produced a K_{fs} value of 3.2E-7 cm/s for location GS10 site A which was the lowest K_{fs} value measured for the compacted fill material under steady-state condition (a). If the same *C* and *α* values used for the farm and lawn soils, III, is used in calculations of the compacted fill materials K_{fs}, the value becomes 6.0E-7 cm/s. This value is still in the lower range of all K_{fs} values measured in this study. Likewise, if the highest

K_{fs} measurement from the farmed soil uses the lower *C* and *α* values initially used for the compacted fill material it drops from 5.2E-3 cm/s to 3.9 cm/s.

Since this study used a non-parametric one-way ANOVA test on ranks, altering these values to this small degree would not alter the rank of all the K_{fs} measurement drastically enough to change the significance of the K-W test.

4.6 Limitations

This study was primarily limited by time. Conducting K_{fs} test in the field can require a long period of time per test. Experiences in this study lead to the conclusion that soils with lower K_{fs} values generally take longer to reach steady-state condition than soils with higher K_{fs} values. It was for this reason soils in the fill material on this property were given overestimated K_{fs} values and one location was not tested. These could have been avoided if there was time to allow a test to run for several hours or even over an entire day. This was not possible in this study considering the property could only be accessed during certain hours and equipment could not be left on site unattended.

Maintaining consistency in soil conditions was also particularly difficult in this study. Since this study focused on field-saturated hydraulic conductivity, rather than saturated hydraulic conductivity, the soils tested were not fully saturated when the tests began. This caused unavoidable inconsistencies in the saturation level in the soils from one area to another and from one day to another. This could be an issue with some more clay rich soils. Depending on the level of saturation in clay rich soils, they could be at different points of shrinking and swelling. This could lead to variations an inconsistency in K_{fs} measurements.

4.7 Future Work

The data from this study could be expanded upon but running additional analysis on other possible sources of K_{fs} variations. For example, spatial interpolation of K_{fs} values would show if a significant difference in K_{fs} values exists based on the sites and locations proximities to one another. Comparing infiltration rates measured in this study with precipitation rate data from the same area will help further articulate the impact these land-management practices have on overland flow.

5 CONCLUSION

The growth of urban areas and subsequent increase in impervious land cover creates many challenges in water resource management and quality. Not only do impervious surfaces increase, but so do land management practices that increase the compaction of soils. This produces more stream "flashiness" and a higher potential for a soil to produce overland flow. As storm water flows over the surface and into streams it can alter the natural flow regime and introduce anthropogenic contaminants which reduce water quality (Hollis, 1975; Olson et al., 2013). This is particularly in issue in the Proctor Creek Watershed where the headwaters are located in downtown Atlanta, Georgia (Peters, 2009).

Studying the hydraulic properties of soils that make up the remaining pervious surfaces in urban areas can provide insight on how readily these soils will produce overland flow in during extended precipitation events. Comparing hydraulic properties between soils can provide an understanding of the impact difference land-management practices can have on urban soils. Soils in many urban areas are classified as Ub (urban land) and lack OSDs that can help in estimating hydraulic properties (Soil Survey Staff, 2016a,b). This is due to the highly altered nature of urban soils, underscoring the importance of studying them in situ.

Field-saturated hydraulic conductivity (K_{fs}) is one such property that is measured in-situ and provides insight on a soil's readiness to produce infiltration-excess overland flow. This study used the Aardvark Permeameter to measure the soil's K_{fs} on a single urban property. The results showed a significant difference between the K_{fs} values of soils under three different land-management practices: compacted fill material, common lawn practices, and urban farming techniques. The compacted fill material produced K_{fs} values lower than the other soil categories and showed more soil erosion and drainage across the surface immediately following a storm event. The land-cover across the lawn and farmed soils appeared to limit the apparent surface drainage paths and erosion while also producing higher K_{fs} values. The farmed soils had the widest range of K_{fs} and the widest range of surface alteration practices.

As previous surface area becomes smaller in developing urban areas, it is important to consider the impact and alteration increased overland flow volumes has on the natural flow regimes of a watershed. Urban Farming could contribute to restoring natural flow regimes given the substantially higher range and mean K_{fs} values measured in soils subjected to urban farming techniques in this study.

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