CRANFIELD UNIVERSITY

Raulatu Munidang Piwuna

Effect of Greenspaces on Soil Hydrology within Urban Ecosystems

School of Water, Energy and Environment
Land and Water Management with Integrated Studies

MPhil Thesis
Academic Year: 2012 – 2016

Supervisors: Dr T. Hess and Dr P. Burgess
September 2016

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Philosophy

ABSTRACT

Urban greenspaces provide a regulatory ecosystem service for some of the hydrological processes within urban ecosystems. However, soil hydrological properties can vary with variations in urban vegetation type having an impact on the hydrological balance. This study was carried out to determine the effect of urban vegetation type, species and its management within urban ecosystems to deliver a water regulatory service (with soil moisture content, water infiltration rate, hydraulic conductivity as indicators).

The research combines data from field and plot measurement. At the field scale, 78 fragments located in Bedford, Luton and Milton Keynes, UK, over a range of soil textures (clay, clay loam, sandy loam and silty clay loam) were investigated. The vegetation types were categorised as managed grass, managed herbaceous, shrubs, trees over managed grass, trees over unmanaged herbaceous, unmanaged herbaceous and woodland/trees. Infiltration rate was not different for the different vegetation types while unsaturated hydraulic conductivity was greater for the managed grass 308 ± 223 mm d^{-1} than the unmanaged herbaceous 88 ± 51 mm d^{-1} on sandy loam soil.

Experimental treatments at plot scale were investigated. A combination of floristic (3 levels: “no”, “some”, “many”) and structural (3 levels: “short”, “medium”, “tall”) manipulation on each plot and 1 non-manipulated plot, located in Cranfield, UK, on a clay soil. There was no difference in infiltration rate, hydraulic conductivity and soil moisture content related to species richness or plant height.

The results of the study show that urban vegetation type, increased species richness, and plant height do not negatively impact infiltration rate, and soil moisture content, while hydraulic conductivity is increased using the managed grass on a sandy loam soil. Therefore, the planting of mixed and species rich and different urban vegetation type is encouraged for its other values in the society.

Keywords:

Infiltration rate, Hydraulic conductivity, Soil moisture content, Urban vegetation type, Species richness, Ecosystem service

DEDICATION

This research project is dedicated in the loving memory of two great men in my life and that of my family:

Baba John Piwuna

and

Prof (Rev) D. N. Wambutda

They both believed education is an effective tool for both personal and general benefit of mankind.

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Everlasting Father, Jesus I give you all the glory.

REPORTS AND PRESENTATIONS

Raulatu Piwuna, Supervisors: Tim Hess and Paul Burgess: Initial results of a study on the effects of vegetation and its management on infiltration and hydraulic conductivity. Unpublished report to the Urban BESS, 15th December 2014.

Raulatu Piwuna, Supervisors: Tim Hess and Paul Burgess: Preliminary results of a study on the effects of vegetation and its management on infiltration and hydraulic conductivity. Unpublished report to the Urban BESS, 5th December 2015.

Raulatu Piwuna, Supervisors: Tim Hess and Paul Burgess: Effect of vegetation on infiltration rate and hydraulic conductivity within urban ecosystems. Presented to: Female Researchers Network Annual Lecture Event, 3rd June 2015, Cranfield University.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
BD	Bulk density
BESS	Biodiversity and Ecosystem Service Sustainability
BS	British standard
DEFRA	Department for Environment, Food and Rural Affairs
EA	Environment Agency
F3UES	Fragments, Functions, Flows and Urban Ecosystem Services
MA	Millennium Ecosystem Assessment
MFM	Many flowers medium
MFS	Many flowers short
MFT	Many flowers tall
MG	Managed grass
MH	Managed herbaceous
NERC	Natural Environment Research Council
NRCS	Natural Resources Conservation Service
NFM	No flowers medium
NFS	No flowers short
NFT	No flowers short
NM	Non manipulated
PD	Particle density
SFM	Some flowers medium
SFS	Some flowers short
SFT	Some flowers tall
S	Shrubs
SMC	Soil moisture content
SMG	Shrubs over managed grass
SMH	Shrub over managed herbaceous
SOM	Soil organic matter
SSEW	Soil survey of England and Wales
SUD	Sustainable urban drainage
SUH	Shrub over unmanaged herbaceous

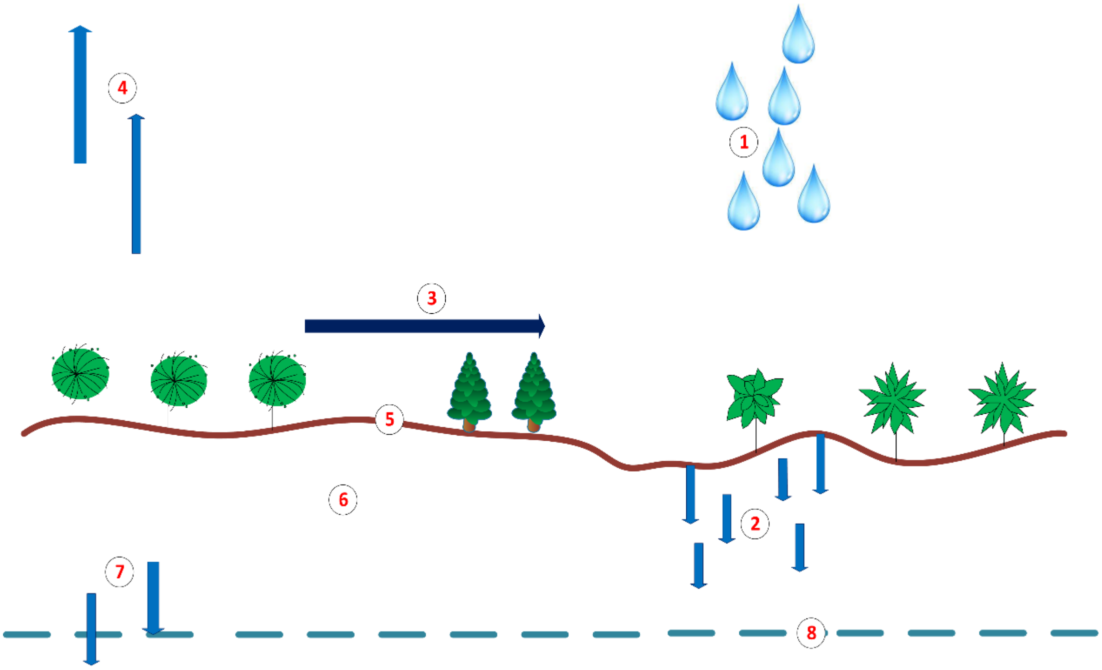
T/W	Trees/woodland
TMG	Trees over managed grass
TMH	Trees over managed herbaceous
TUH	Trees over unmanaged herbaceous
UH	Unmanaged herbaceous
USDA	United Sates Department of Agriculture

1. Introduction

The background and wider context of this research as well as the identified knowledge gap is presented. It includes research aims and objectives and concludes with an outline of the thesis structure.

The services provided by ecosystems are varied but all have direct or indirect contributions to human well-being (Costanza *et al*. 1997). The Millennium Ecosystem Assessment has provided an appraisal of the state of the global environment. It also classified ecosystem services as supporting, provisioning, regulating and cultural (MA, 2005). Urbanization associated with an increase of population can result in increased pressures on urban services and systems within urban ecosystems. Urban services and systems such as transport, housing densities, water supply, greenspaces and waste management. The construction of new transport routes and houses has increased sealed surfaces with tarmac and concrete reducing pervious exteriors. Therefore, the urban ecosystem is subject to alteration of the hydrological balance as natural vegetation is replaced with sealed and compacted surfaces (Shuster *et al*., 2005). The sealed and compacted surfaces leads to an alteration on hydrological processes. The alteration changes the percolation and recharge of groundwater and the amount of runoff generated with impacts on water quality status of surrounding water bodies and risk of flooding which leads to loss or damage of properties amongst other effects within the urban ecosystem. Thus, highlighting the need to use the permeable surfaces which includes the greenspaces to increase water infiltration leading to groundwater recharge and increased water storage thereby reducing the amount of surface runoff generated and to restore the natural functioning of hydrological processes. This is also necessary as existing designed sustainable urban drainage (SUD) infrastructure is not able to cope with the increased urban density and associated sealed surfaces under extreme weather events (Gill *et al*, 2004). Storm events being a major source of flash flooding in urban areas.

Water is an important component of the physical environment playing a vital role on human development. It sustains human and other biotic life, essential in food production, and can play important role in recreation. Many places are affected by either a surplus or deficit of water. The actual water available in a given location depends largely on the balance between precipitation and evaporation (Ward and Trimble, 2004). Water, unless the soil is saturated, compacted or sealed can always enter and infiltrate the soil except intensity of rainfall is higher than infiltration. The hydrological cycle at a field scale is balanced by processes as shown in Figure 1.1. The primary route of inflow is precipitation leading to interception, stemflow, overland flow, infiltration, moisture storage and outflow through evapotranspiration, and deep drainage/percolation into the groundwater/water table surface. The illustration shows all major components of the hydrological cycle. The role of soils include provision of an initial reservoir from which plants can extract water needed by the plant, some of which is lost through transpiration. Also, during raining seasons, an unsaturated soil can absorb water and hence reduce amount of runoff generated and the related risk of flooding and pollutants flushed with the runoff.



1 – Precipitation. 2 – Infiltration. 3 – Overland flow. 4 – Evapotranspiration. 5 – Soil surface. 6 – Moisture storage. 7 – Percolation/Drainage. 8 – Water table surface

Figure 1.1 The components of the hydrological cycle at field scale.

Vegetation and the water cycle as shown in Figure 1.1 are fundamentally linked (Hutjes *et al*., 1998; Kucharik *et al*., 2000; Arora, 2002) and therefore hydrological cycle is directly or indirectly modified by changes in vegetation (Liang *et al*., 2015). Vegetation plays an important role in the hydrological balance of a catchment (Kucharik *et al*., 2000).

The role of vegetation in regulating the flow of water is governed by factors such as soil type, topography, percentage vegetation cover and precipitation interactions.

Furthermore characteristic features of these factors are interlinked by landscape and plant habitat evolution. Runoff generation and evapotranspiration are also closely related to the distribution and composition of vegetation communities. This has been shown by the study carried out by Dunn and Mackay (1995). The differences in the amount of annual runoff are controlled not only by differences in precipitation amount, but also by the geographical distribution of deciduous and evergreen vegetation (Peel *et al*., 2004).The interaction between vegetation and land surface hydrology is important in relation to maintenance of the ecosystem, water resource planning and flooding risks.

As an example, there has been an increase in the occurrence of excess surface runoff leading to floods in the UK over the last few years (EA, 2016). In order to address the occurrence of flooding from surface water runoff within urban areas in the UK, the urban greenspaces has been recognized as having an important role to play with the flood risk management (EA, 2016 and DEFRA, 2005). The role of vegetation in the hydrological balance contributes to the modification of runoff and reduced flood risk. This has been shown by studies evaluating hydrological benefits and processes, focused on the use of models with maps of urban land covers (Pauleit and Duhme, 2000; Whitford *et al*., 2001). In order to address the effectiveness of the urban greenspaces in reduction of runoff, there have been several studies on the effects of vegetation on surface water runoff in urban areas (Meshgi *et al*., 2015; Armson *et al*., 2013; Verbeiren *et al*., 2013; Inkilainen *et al*., 2013; Bernatzky, 1983) and water infiltration and storage (Beard and Green, 1994; Roy *et al*., 2000). Most studies on the effect of vegetation on hydrological balance in urban ecosystems are based on a rainfall - runoff response on broad groupings of sealed and unsealed (vegetated) surfaces (Niehoff *et al*., 2002; Salvadore *et al*., 2015; Silva *et al*., 2016). However, in order to address the use of urban green vegetation to improve the hydrological balance thereby reducing runoff, increasing downward infiltration and storage of water, in-field measurements of soil hydrological properties must be understood. Therefore, further understanding on how the urban vegetation type and species richness can change the infiltration, soil water storage and runoff generation within the urban ecosystem is important to improving the urban hydrological balance. Studies in urban ecosystems investigating the variability of soil hydrological properties through empirical measurements are very few (Ossola *et al*., 2015). Urban vegetation type can have a very significant effect on water infiltration, soil moisture content and runoff generation.

Empirical data on water infiltration, soil moisture content and runoff generation are important for making of informed decisions on ecological management of storm water, as urban green spaces are often cited as potential areas for storm water stoppage (Dietz and Clausen, 2008). The understanding of the contribution of greenspaces for providing regulatory services within the urban ecosystem is limited. Furthermore, reconstruction of urban drainages to a larger system capable of rapidly redirecting the water would not only be costly, but would also establish the risk of flooding downstream and lessen the effectiveness of water treatment installations (White and Howe, 2002).

1.1 Wider context: Fragments, Functions and Flows (F3UES), Biodiversity Ecosystem Service Sustainability (BESS) Programme

The Urban BESS project (details of the project can be found on www.nerc-bess.net) research theme referred to as the Fragments, functions and flows – the scaling of biodiversity and ecosystem services in urban ecosystems, F3UES have established a project. The F3UES is a part of the bigger project – Biodiversity and Ecosystem Service Sustainability (BESS), funded by the UK Natural Environment Research Council. One of the F3UES objectives is to address three of the BESS research themes of functional relationships between biodiversity and ecosystem services; resilience of biodiversity-ecosystem service relationships to changing conditions; monitoring and evaluation of ecosystem services. An approach of the F3UES project involves documenting biodiversity – ecosystem service relationships aimed at determining relationships between biodiversity and ecosystem services; addressing BESS research themes of: Functional relationships; monitoring and evaluation.

These functional relationships are planned to focus on three ecosystem services: regulating, provisioning and cultural services aimed at changing service provision associated with diversity manipulation. Regulating services are the benefits obtained from the regulation of ecosystem processes. In this respect water regulation is one of the ecosystem services, to be addressed in the BESS project within urban landscapes, which is the basis of this MPhil research. The subsequent section will describe the link between the BESS project and this research project.

Figure 1.2 shows the relationship between the BESS project and this research study. Specifically, this research forms part of the F3UES with an investigation on water regulation services within the urban ecosystem using green spaces.

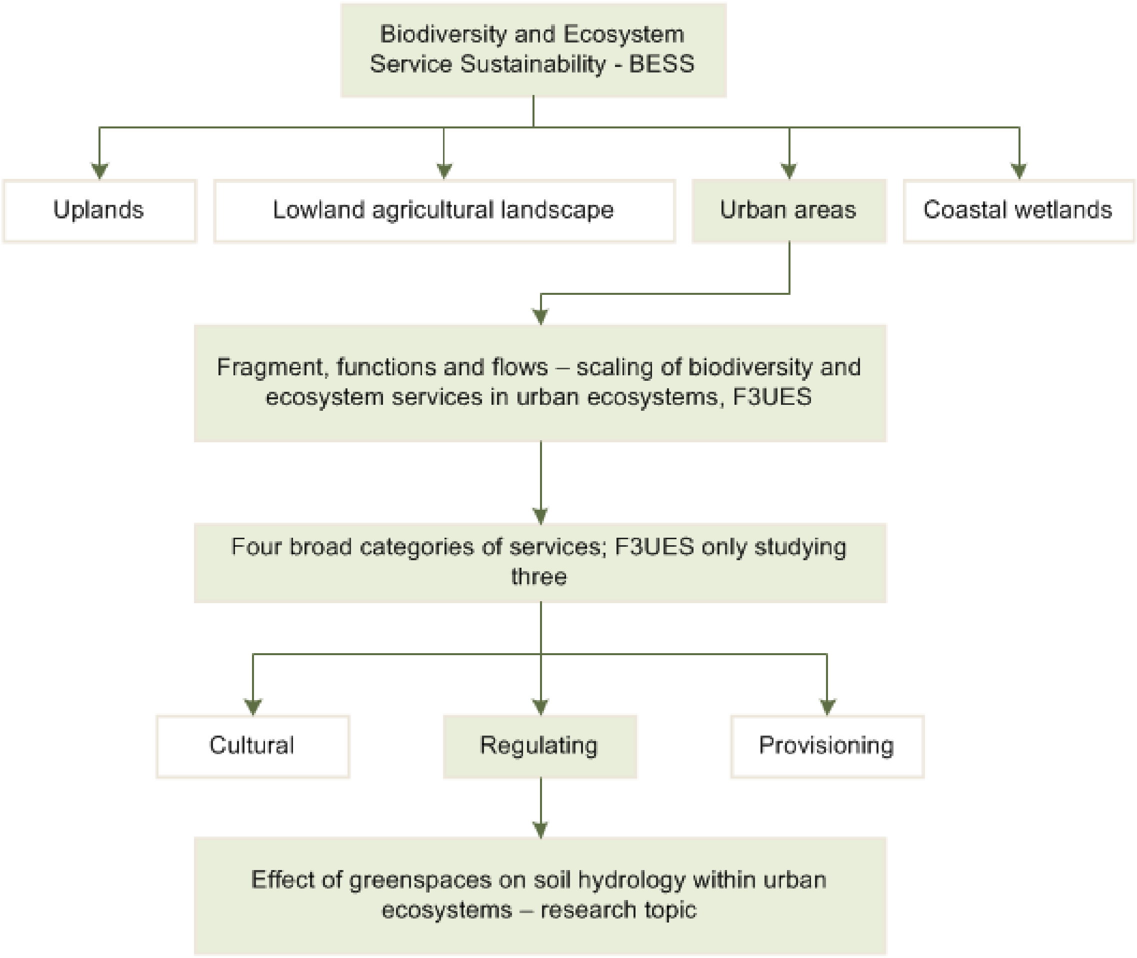


Figure 1 2 The research relation to the larger BESS project

The urban environment has a fragmented structure. The methodological approach to the project by the F3UES is at a landscape scale (referring to scale of approach) based on the recognition and utilization of the fragmented structure and its effects on flows of materials, organisms, environmental influences and people as a key to developing a practical understanding of the role of urban form on ecosystem service provision (BESS Urban Group, 2014).

Whilst the study is situated within the F3UES project, it has its own aims and objectives (Section 1.2) which will contribute to the project on biodiversity within the urban ecosystem. Furthermore, this research is both informed by and informs the wider

F3UES project. This is particularly notable in the methods and justification for the selection of towns in UK, and selection and design of manipulated vegetation for the project.

1.2 Research aim and objectives

1.2.1 Aim

The aim of this study is to determine the effect of urban vegetation type, species and its management within urban ecosystems to deliver a water regulatory service (with soil moisture content, water infiltration rate, hydraulic conductivity as indicators). Although water quality is an aspect of the ecosystem service it is not within the scope of this study. The wider aim will be to inform greenspace management practices, which will reduce excess surface runoff occurrence which sometimes leads to flooding and associated degradation of the environment.

1.2.2 Hypothesis

Null - Difference in urban vegetation type and its management does not have an effect on soil moisture content, water infiltration rate and runoff generation within urban ecosystems.

Alternative – Differences in urban vegetation type and its management has an effect on soil moisture content, water infiltration rate and runoff generation within urban ecosystems.

1.2.3 Objectives

In order to achieve the stated aim and test the hypothesis the following objectives have been developed for the urban ecosystem:

1. To assess the role of vegetation within urban ecosystems and why they are important in the context of the hydrological cycle (through literature search).

2. Characterise infiltration rates on designated fragments/sites in Bedford, Luton and Milton Keynes, UK.

3. To carry out measurements on an experimental site in order to determine the soil type, vegetation diversity and management.

4. To measure and evaluate on the experimental plots the effect of vegetation and its management on:

I. Topsoil moisture content,

II. Water infiltration rate,

III. Unsaturated hydraulic conductivity

5. To identify the vegetation diversity and its management patterns that improve the measured hydrological parameters leading to a reduction in runoff generated. Provide knowledge for the use of greenspace diversity and its management as a regulating urban ecosystem service.

1.3 Research Approach

The research approach adopted in this study is divided into two phases. Phase one is a combination of an initial critical review on existing knowledge relating urban ecosystems and hydrological balance and field scale fieldwork; while phase two comprised of plot scale fieldwork to achieve the research objectives. This approach results in a combination of techniques that provide insight into the mechanisms of soil hydrological properties within the urban ecosystem.

The review on existing knowledge highlighted the gap in knowledge for the study. This was followed by field scale measurements of fragments under categorised urban vegetation type for infiltration rate and hydraulic conductivity. Phase two of the study involved plot scale experimental measurements of manipulated urban vegetation species and physical processes (infiltration rate, hydraulic conductivity, and soil moisture content) operating in the field. The results from both field measurements (fragment and plots) provided empirical data of the soil hydrological properties. However, due to practical and financial constraints, there were limits on the number and scale of measurements that could be performed.

This study focuses on the effect of urban vegetation on soil hydrological related properties. The results of this study will contribute to reducing the existing gap on empirical data on the effectiveness of urban vegetation type and species diversity to improve the site hydrological balance.

1.4 Thesis structure

The thesis is structured into five chapters as shown in Figure 1.3. Chapter 1 provides an introduction to the study and background knowledge, including aim and objectives of the study. Chapter 2 focuses on reviewing the current literature on urban ecosystem, and urbanization, ecosystem services, soil hydraulic properties and urban vegetation that led to identifying the knowledge gap within the literature. Chapters 3 and 4 detail the first and second phases of the field work on infiltration rate, hydraulic conductivity and soil moisture content and include the methodology, results and principal conclusion(s) from this research. Chapter 5 is a synthesis of the findings from the study from Chapters 3 and 4 to provide conclusions about the effect of urban vegetation species on hydrological component and reports the main conclusions of the research including suggestion for further research.

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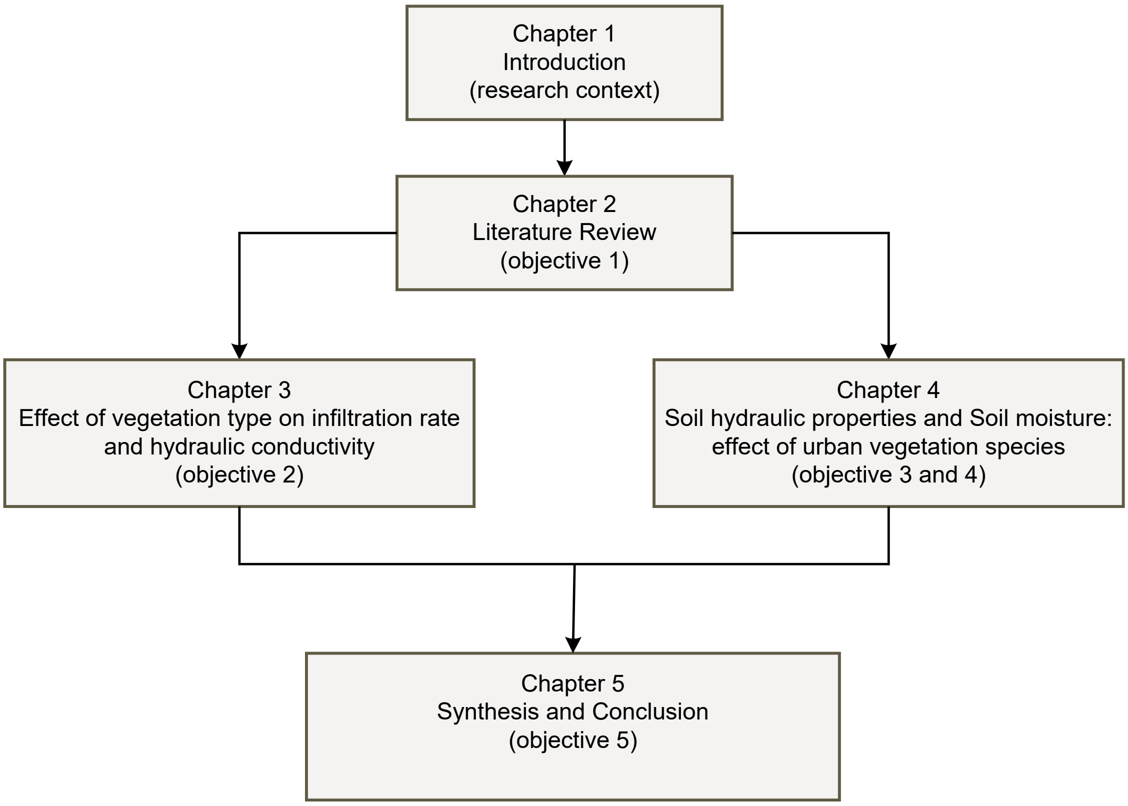

Figure 1.3 Thesis structure.

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2. Hydrological functions of urban green spaces: literature review

2.1 Introduction

This chapter addresses objective one, starting with definitions of key concepts that relate to the urban ecosystem namely urbanization, ecosystem services, and urban greenspaces. Subsequently, soil hydraulic and hydrological properties and vegetation effects are considered. It concludes with addressing the vegetation and how it impacts the hydrological cycle. The literature search aided in defining the research gap and hence the justification for this research.

2.2 Urbanization and Urban ecosystem

2.2.1 Urbanization

An urban area is commonly defined as the built environment and its external environs that are between the buildings (Swanwick *et al*., 2003). MacGregor-Fors (2011) and Pickett *et al*. (2001) define an urban area as being populated, provided with basic services like drainage, electricity and water supply where more than 1000 people per km^2 live and/or work, where a significant proportion of the land area (> 50%) is covered by predominantly sealed, impermeable, and hard surfaces. It is also defined by morphology and the distribution of urban land across the territory (EEA, 2006). The definitions mentioned above agree with the assertion by Seto *et al.* (2013) that there is no general agreement on a definition of what is urban. An urban area can be defined in other contexts such as the density of economic activity, form of governance structure used to delineate what is a town, city or city region. For this study, the definition by MacGregor-Fors (2011) and Pickett *et al.* (2011) was used for the fragment studies in Chapter 3.

The world's population is expected to increase from 6.8 billion in 2009 to 9.1 billion in 2050 (United Nations, 2009). According to Schell and Ulijaszek (1999) as cited in (Li *et al*., 2005), 65% of the world's population is expected to be urban by 2025, with an expected increase in the number of people living in urban areas to rise to almost 84 % by 2050 (United Nations, 2012). Human migration away from rural existence and by changing former rural areas into urban areas have been the main cause of growth in urban living (United Nations, 2006). Rural populations are progressively decreasing as a result of the urban population growing at an increasing rate (United Nation, 2006).

Urbanization is a multidimensional process that manifests itself through the rapidly changing human population and changing the land cover (Seto *et al*., 2013). Urbanization is changing the surface of the planet, having a strong environmental impact (Newman, 2006). It represents one of man's widespread and essential alterations of the natural environment. In order to meet the demands of the inhabitants of these new urban areas, housing densities have increased, including the construction of efficient transport routes, and the creation of industrial and commerce districts. The development associated with urbanization significantly alters the hydrology of an area. It includes a reduction in the amount of water infiltration into the soil and increases the rate at which the water travels over the surface, thus greatly increasing both surface water runoff and peak discharge rates following a rainfall event and or snowmelt (Leopold, 1968; Douglas, 1983; Asadian and Weiler, 2009). The decrease in vegetation cover and increases in impervious surfaces such as paved roads, sidewalks and concrete buildings increase the total amount of runoff, flooding, erosion and the cost of storm water management (Pauleit and Duhme, 2000; Zhang *et al.*, 2012).

2.2.2 Urban ecosystem

Bolund and Hunhammar (1999, p.294) defined the ecosystem "as a set of interacting species and their local, non-biological environment functioning together to sustain life". Bolund and Hunhammar (1999) give a simple definition of an urban ecosystem as all natural green and blue areas in a city, including street trees and ponds. They also identified the following seven different urban ecosystems: street trees, lawns/parks, urban forests, cultivated land, wetlands, lakes/sea and streams. Urban ecosystems are the natural ecosystems that have been made different by humans in various ways and in varying degrees. The urban ecosystem, a complex ecosystem is composed of natural, social and economic components (Ma and Wang, 1984; Tjallingii, 1995; Szumacher, 2011) furthermore, an urban ecosystem consists of residents and their environment in certain time and space scales. Zhang *et al.* (2006) assert that the urban ecosystem is the most complicated ecosystem, very easily interfered with by the changes of artificial and natural environmental conditions, making it pertinent to produce an eco-environment crisis.

2.2.3 Urban green space

The term green spaces are often used interchangeably with open spaces and presumed to be the same (Lee *et al*., 2010; Swanwick *et al*., 2003). Green spaces are urban areas consisting of predominantly unsealed, permeable, surfaces such as soil, grass, shrubs, trees, and water on privately or publicly owned land (Balram and Dragićević, 2005;James *et al*., 2009). de la Barerra *et al*. (2016) in their study considered greenspaces as public goods which allow unrestricted access to all citizens and represent miniature of nature for all residents including urban parks, squares, sidewalk and median strips. The urban green space size between buildings varies in size from small private back gardens to large public parks and forests. The general perception of the urban ecosystem is that of a built area, but the overall cover of vegetated areas can exceed that of buildings, asphalt, and other sealed surfaces. (Gill *et al*., 2004). The densely built-up inner urban areas and commercial and industrial areas can have vegetation cover that is below 5 % of the total surface area while low-density residential areas have a higher vegetated surface cover (Pauliet and Duhme, 2000; Akbari *et al*., 2003). Conservation or re-establishment of large areas of vegetation may be necessary in order to obtain equivalent benefits for biodiversity (Pert *et al*., 2010).

According to Davies *et al*. (2008), there is a need for an improved understanding of relationships between green space and urban form particularly in regions that are already heavily urbanized and expected to increase. Urban areas are characterised by a very high level of human intervention on natural processes. All hydrological sub-processes in urban areas must be considered in much smaller temporal and spatial scales than those in rural areas because cities are areas with a very high level of human interference with natural processes, hence the need for the data to be site specific. (Niemczynowicz, 1999). This entails that the work of present urban hydrologists must be closely integrated with land use policy, city and landscape planning, development control, building construction, economy, legislation, education and social acceptance issues and local community involvement.

Urban green spaces vary in composition (types and quantities of vegetation) providing several ecosystem services which have been studied extensively and documented (Gomez-baggethun *et al*., 2013). There have been extensive studies on the services provided by urban green space from health, social, economic, ecological and town planning aspects. The literature mostly focused on the potential of green spaces to improve well-being through stress reduction, opportunities for physical activity and mental well-being through concentration restoration. The urban green spaces also provide effective habitats for diverse animals and plants, living things which otherwise would be unable to continue to exist in urban areas (Jones and Leather, 2012; McKinney, 2008). Other benefits include provision of ecological balance considerations and information for landscape planners to make cities fit for the dwellers (Bolund and Hunhammar, 1999; Campbell, 1996; Byomkesh *et al*., 2012); Social well-being through social integration, engagement and participation (example Seaman *et al*., 2010; Barbosa *et al*., 2007); economic benefits and costs (example Swanwick *et al*., 2003). Urban green spaces contribute to the reduction both of rate and volume of surface water runoff, as well as providing flood water storage (Gill *et al*., 2004). Although there are a variety of positive effects, negative effects also exist including trees that are a source of pollen which may cause allergies and the emission of volatile organic compounds which lower individual health (Kuser, 2000; CURE and Tyndall Centre, 2003).

According to Pauleit *et al*. (2005), there is a lack of adequate information on the environmental effects of urbanization and dynamics of green space. The soil surface conditions play a major role in the use of urban green spaces within the ecosystem.

The aforementioned problems of urban ecosystems can be reduced by the greenspaces as highlighted above by the provision of ecosystem services.

2.2.4 Impact of urbanisation on urban ecosystem

There have been four major effects identified related to the massive changes in the environment that alter the ecology of the cities. First, urbanisation makes cities net producers of carbon dioxide and lower amounts of stored carbon; secondly, it affects climate with cities tending to be hotter than countryside creating what is known as the urban heat island; another effect is that cities are regarded as having lower biodiversity and finally, urbanisation affecting the hydrology: cities shedding more water as runoff into their streams and rivers from alteration of hydrological processes (Figure 2.1) (Oke, 1978; Douglas, 1983; Bridgeman *et al*., 1995; Whitford *et al*., 2001).

The growth of urban areas brings significant changes in major properties of the land surface and atmosphere affecting moisture, emissions, radiation and thermal mass (Oke *et al*., 1991; Roth, 2002). The impacts include habitat fragmentation and changes in both the quality and quantity of the stormwater runoff which result in changes to hydrological systems (Jacobson, 2011). According to Mao and Cherkauer (2009), they assert that human activity is one of the major driving forces leading to changes in land cover characteristics. They stress that the land cover change subsequently affects hydrologic processes. Furthermore, increasing urbanisation radically modifies the ecology of landscapes which includes an alteration of species composition, species diversity, and proportions of alien species (Tratalos *et al*., 2007; Hardy and Dennis, 1999; McKinney, 2008). In their study Tratalos *et al.* (2007) comparing the surface runoff in five cities found that areas with a high proportion of green space had lower runoff, this was also found in Xian, China where runoff coefficient was lowest in green space areas when comparing different land patterns (Li *et al*., 2010).

2.2.5 Effect of the urban ecosystem on the hydrological cycle

The hydrological characteristics of a catchment are affected by urbanisation .Generally, urbanisation results in (a) reduction in the amount of infiltration into the ground, (b) an increase in the speed of runoff, (c) increase in exposure to the hazard of flooding, and (d) increase in the amount of precipitation (Bridgeman *et al*., 1995). The presence of storm water, foul drainage systems, leakage from mains water supply in urban areas also has an effect on the water balance of a catchment (Mansell, 2003).

An increase in surface runoff within an urban ecosystem is an important issue because it can result in polluted lakes and streams from runoff that washes pollutants from a variety of sources including parking lots, construction sites and industrial storage yards; riverine siltation and flooding and sewer overflows where the capacity of drains is overwhelmed by the runoff. However, engineers have addressed the issue by typically upgrading to a larger system capable of rerouting the water or increasing the number of sewers and drainage channels (Douglas 1983; Sanders, 1986) which would not only be costly and disruptive on the land use but would also pose a risk of flooding downstream and reduced efficiency of water treatment installations (White and Howe, 2002). Therefore, endeavours have been on improving conventional and innovative storm water management practices to decrease the runoff volume associated with pervious and impervious land covers (Battiata *et al*., 2010). O'Sullivan *et al* .(2011) have found that increasingly sustainable drainage systems (SUDS) are being used to increase the level of drainage for an urban area while minimizing the pollution risk associated with these water drainage systems. The control on water pollution and movement done by the urban drainages is based around the use of permeable hard surfaces and the increased use of vegetation to reduce runoff.

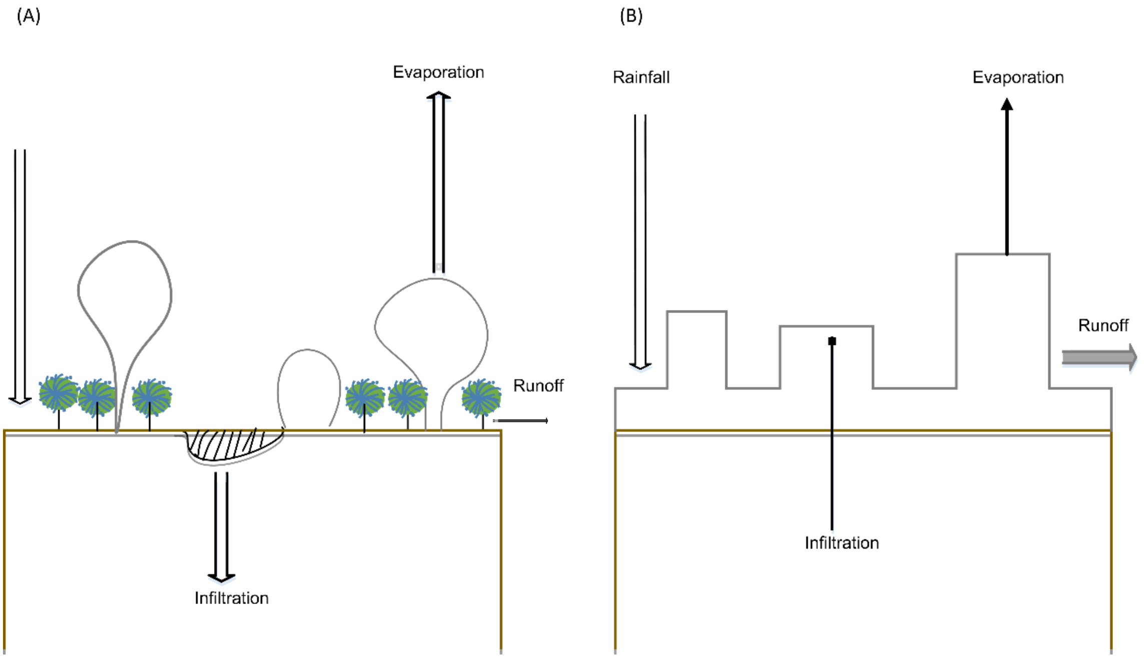

Figure 2.1 Effect of urbanisation on hydrology (A) representation of rural areas, (B) representation of urban areas (Whitford et al., 2001)

Home sites, parking spaces, buildings and road surfaces all decrease the surface area of soil on the Earth's surface. Deng *et al*. (2012) established that impervious surface area is an indicator of environment change and is regarded as an important parameter for hydrological cycle simulation, water management, and area pollution assessment. Their study showed that percentage change of impervious surface area had a deep relationship with the economic development of an area, and thereby urbanization. Another case study showed that annual potential evapotranspiration varies spatially for different types of land use and land cover in Shalamulun River watershed: results revealed that both potential evapotranspiration and runoff decreased with changes in land use and land cover thus having a significant impact on the hydrological cycle (Yang *et al*., 2012). Armson *et al*. (2013) reported that increasing area of paved surfaces results in a decrease in the permeability of soil and infiltration rates, and acceleration in surface runoff. However, Redfern *et al*. (2016) argue based on the result of their study that urban greenspaces and soils can be degraded in their water holding capacity and infiltration potential. They also found that aged urban road surfaces that have cracks and joints provide a preferential pathway for infiltration, increasing urban infiltration and reducing runoff, thus highlighting the fact that not all greenspaces improve urban hydrological balance and not all impervious surfaces are wholly impervious.

In summary, activities related to urbanisation substitute vegetated areas for the built environment thereby having environmental impacts on the functioning of the urban ecosystem.

2.3 Ecosystem Services

The dynamic reciprocal action between plants, microorganisms, animals and their non-living environment working as a well-balanced functional unit makes up an ecosystem (UNEP, 2013). The Millennium Ecosystem Assessment defines ecosystem services as 'the benefits people obtain from ecosystems' (Millennium Ecosystem Assessment (Program) and Millennium Ecosystem Assessment, 2005; p.53). However, this definition is not same as that of de Groot *et al*., 2002, Wallace 2007, Fisher and Turner 2008 and Boyd and Banzhaf 2007. They argue that service can be a component of the ecosystem (for example, water), a benefit (clean water), a function or a process (for example, nutrient cycling). The Millennium Ecosystem Assessment classified ecosystem services into four main groups:(a) supporting services – services necessary for the production of all other ecosystems such as soil formation, and nutrient cycling; (b) provisioning – products obtained from ecosystems such as water, timber and fibre; (c) regulating services – benefits obtained from regulation of ecosystem processes such as climate, floods, disease, wastes and water quality; and (d) cultural services – non-material benefits obtained from the system such as recreational, spiritual and aesthetic benefits. The ecosystem provides services for humans; these are the environmental benefits and natural functions provided by ecosystems for the benefit of human population from ecosystem functions (Costanza *et al*., 1997). Based on this definition there are seventeen groups of ecosystem services (Costanza *et al.*, 1997). Blue Sky Green Space (2011) and Costanza *et al*. (1997) have outlined important recreational and environmental services that green spaces perform which sustain biodiversity and human life. Most urban areas are designed to have amongst the built areas, natural open space and greenbelt areas with trees and plant life. These natural areas and parks have provided habitat for wildlife, preserved some beneficial ecological processes, and enhanced the quality of life for people living and working in these communities (http://www.eco-pros.com/biodiversity-urbanecosystems.htm). However, the increasing number of buildings have crowded out vegetation and trees (Santamouris *et al*., 2001; Whitford *et al*., 2001). Urban green space reduces temperature through shading and evapotranspiration, which in turn help to create a comfortable external environment for humans as well as potentially reducing energy usage in buildings and mitigating heat island effects (Bolund and

Hunhammar 1999; Tsilini *et al*., 2015). Vegetation filters pollutants from the air, thus reducing pollutants in the air, and trees store and sequester carbon as they grow (Mullaney *et al*., 2015). They provide habitats for plants and animals in the urban environment, and can serve as wildlife corridors to maintain local habitats and allow species to move to new climate spaces. The benefits of urban greenspace for the improvement of human health conditions for urban residents has been studied extensively (Clark *et al*., 2007; Abraham *et al*., 2010; van Herzele and de Vries, 2012; Thompson *et al*., 2012). A few studies have assessed hydrological changes from an ecosystem services perspective such as Tomich *et al*. (2004) and Aroson *et al*. (2007) as cited by Davies *et al*. (2008). They all agree that ecosystem services are altered by land-use or land cover change. The loss of ecosystem services has economic impacts affecting a wide range of stakeholders; and there are net positive benefits of reversing these impacts when executed appropriately (Le Maitre *et al*., 2007).

However, different habitats provide different types of ecosystem services, urban ecosystems are especially important in providing services with direct impact on human health and security such as urban cooling, noise reduction, and runoff mitigation. Table 2.1 provides a classification and description of important ecosystem services provided in urban areas based on the Millennium Ecosystem Assessment (MA, 2005).

From the listed urban ecosystem services and products/benefits, the focus of this study is on the regulatory service and one of the benefits (water regulation) lying within the "regulating services" category provided by urban green space.

Table.2.1.
Classification and benefits of urban ecosystem services based on the Millennium Ecosystem Assessment (MA).

Ecosystem services	Products/Benefits
Provisioning	Food, fresh water, wood, pulp, medicinal plants
Regulating	Climate regulation, water purification, water regulation, pollination, erosion control
Cultural	Tourism, Recreation, Spirituality
Supporting	Habitat for species, maintenance genetic diversity

2.3.1 Regulating services

Regulating services are the capacity of natural and semi-natural ecosystems to adjust to some degree essential ecological processes and life-support systems through biogeochemical cycles and other biospheric processes. An example of services derived from water regulation function out of others includes the maintenance of natural irrigation and drainage, and the buffering of extremes in the discharge of rivers and regulation of channel flow (de Groot *et al.*, 2002). In addition to maintaining ecosystem and biosphere health, these regulatory functions provide many services that are beneficial to humans such as clean air, water and soil, and biological control services. Furthermore, water regulation deals with the influence of natural systems on the regulation of hydrological flows on the earth's surface (Pert *et al.*, 2010). Maintaining the regulatory hydrological ecosystem services provides the greatest opportunity pertaining to the protection of biodiversity (Chan *et al.*, 2006). Hydrological services such as the provision of water quantity and quality often depend on the condition of the native vegetation within the catchment (Pattanayak and Wendland, 2007). However, according to Yang *et al.*, 2015 the regulatory service provided by urban green space in relation to water are afforded less attention. Studies including Bernatzky, (1983) and Shepherd, (2006) have shown that urban green space can reduce surface runoff efficiently.

The processes that determine the effect of urban vegetation considered for this study are infiltration rate, hydraulic conductivity and soil moisture content. The following section gives a brief description of these indicator properties and what they depend on, highlighting their effect on soil hydrology.

2.4 Soil hydraulic properties and soil moisture content

The movement of water through the soil matrix is dependent on soil conditions that affect the movement and retention, or not, of water. The properties are infiltration rate and hydraulic conductivity, henceforth referred to as indicators of hydrological regulation.

2.4.1 Infiltration rate

Infiltration is the process by which water on the ground surface enters into the soil. The actual measure of the rate at which water is entering into the soil at any given time from rainfall or irrigation event is the infiltration rate. It is an important process that divides rainfall between soil store and water available for the generation of runoff. Infiltration rate is similar to hydraulic conductivity to the extent that they both are a measure of the soil profile allowing water movement through it. The infiltration rate of water in the soil is determined by forces of gravity and pressure, forces that act on the water at the surface (Dingman, 2002). The nature of these forces is determined by the roughness and slope gradient of the soil surface, saturated conductivity of the soil surface, the rate at which water arrives at the soil surface, and antecedent soil moisture condition. According to Godwin and Dresser (2003), infiltration is affected by the amount, type of vegetation and surface cover, including moisture content of the soil and soil texture. Therefore, enhancing infiltration rates is essential to increase groundwater recharge, reduce runoff and risk of flooding and pollution of water bodies within the urban ecosystem.

2.4.2 Hydraulic conductivity

Hydraulic conductivity is the rate of water flow under a unit hydraulic gradient through a unit cross-sectional area of the soil. The soil hydraulic conductivity in saturated soils is determined by the soil texture and structure which determine the size of the channels. In unsaturated conditions, both the soil moisture and texture will determine the rate of movement. There is an increase in conductivity with increasing soil moisture to a maximum at saturation.

2.4.3 Soil moisture content

The soil moisture content can be expressed as the degree of saturation of the soil. There is a lower limit beyond which plants are no longer able to extract water from the soil. This is termed the wilting point. Another important soil moisture value is the residual soil moisture when all the gravitational water has drained, termed the field capacity (Gardiner, 1960).Soil moisture is defined as the amount of moisture in the root zone, that is, moisture available for evapotranspiration. Soil moisture content is modified by capillary action and gravity. The force of gravity moves the water down through the soil profile, while capillary action moves water through the soil due to the attraction between the water molecules and the walls of the channels through which it moves. The force of gravity is less than the capillary force and hence water can move up through the profile. The rate of capillary movement is controlled by the size of the pathways and hence is dependent on the soil texture. Generally, any precipitation that does not infiltrate into the soil becomes runoff, flowing into rivers and streams through quick flow processes. The smaller pathways that exist in finely-textured soils have a greater capacity to hold and retain water than coarser soils with larger pores. Soil moisture at the start of an infiltration event is an important factor in determining the response of the soil to the infiltration event (Seeger *et al.*, 2004). When the soil is near saturation at the start of the precipitation event, it is more likely that saturated conditions will develop and hence leads to ponding and the generation of runoff. Nevertheless, through the change in soil moisture content, vegetation affects the frequency at which the soil gets saturated which in turn controls the likelihood of runoff generation.

2.5 Hydrological effects of vegetation

Vegetation acts as a cover for the soil surface. Through the hydrological cycle, it influences the movement of water from the atmosphere to the earth's surface soil and underlying rock. Vegetation delivers water regulatory functions mainly through interception of rainfall by leaf canopy, water storage by soil capillaries and the downward infiltration of precipitation. Vegetation can be described in terms of two main components: above–ground such as leaves and stems and below-ground comprising the rooting system.

The relationship of vegetation to overland flow is generally understood, based on studies, that with increasing plant cover overland flow is reduced. This relationship is commonly used in representing the effect of vegetation within the hydrological cycle, thus, highlighting the role vegetation has in the amount of runoff generated on the area of interest (Puigdefábregas, 2005). The following processes describe vegetation features and how they affect the hydrological cycle:

1. Evapotranspiration

Evapotranspiration is the combined process of the removal of moisture from the earth's surface and surface waters by evaporation and transpiration from the vegetation cover. There is less evapotranspiration by plants when vegetation is reduced. The ability of vegetation to reduce soil moisture is also recognized. There are three main vegetational influences on evapotranspiration; albedo, stomatal control and root water uptake.

2. Interception

Interception impacts the amount and distribution, both temporally and spatially, of water reaching the soil surface. The leaves of plants, trees, in particular, have a better surface area than that of other smooth surfaces, such as grass, for rainfall interception associated with the urban environment. Rainfall is divided into two parts on contact with the canopy of the vegetation cover. These are direct through fall, (rain that reaches the ground after passing through gaps in the canopy) and intercepted fraction, (rain that strikes the vegetation cover). The holding and consequent evaporation of water droplets from the vegetation surface is termed interception. According to Woo *et al.* (1997), rainfall interception is the main reason for reduced runoff from vegetation. Furthermore, according to Domingo *et al* (1998) even though interception operates at the scale of individual plant species, it can be critical in estimations of the hydrological response of heterogeneous landscapes. The precipitation on reaching the vegetation is either:

I. Retained as interception storage - stored on leaves and stems and maybe evaporated back into the atmosphere. The leaf area, tree species, storm intensity, surface tension are some of the factors that determine the capacity of the interception storage (Aston, 1979).
II. Stem flow - reaches the ground by running down the trunk, stems, and branches
III. Leaf drainage – the volume of leaf drainage is equal to the volume of temporarily intercepted through fall less the volume of stem flow.

Therefore, a reduced vegetation cover results in less interception of rainfall by plants.

3. Infiltration

Vegetation increases the chance of rainwater infiltrating than an unvegetated soil surface (Styczen and Morgan, 1995; Wilcox *et al.*, 1998). Through an increase in the infiltration rate vegetation may decrease the amount of runoff generated during a storm and thereby increase the time taken for runoff to occur.

4. Surface roughness

Soil surfaces have varying degrees of surface roughness which influences the amount of surface depression storage, a fraction of the surface covered by water, the amount of rainfall excess required to start runoff and overland flow (Moore and Larson, 1979). Surface roughness is an important parameter controlling the speed of the generated runoff. It is also inversely related to both velocity and quantity of runoff. For a given amount of runoff, doubling the roughness increases the water depth (Styczen and Morgan, 1995). The level of roughness depends on the morphology of the plant and its density of growth.

The literature search for this study found that studies on ability of vegetation to improve soil hydraulic indicators and reduce runoff has been studied more in agricultural systems than any other ecosystem.

2.6 Effect of vegetation on hydrological balance by affecting hydraulic indicators.

The following referred research papers highlight the links between the hydraulic indicators and water regulation.

According to Ossola *et al.* (2015) from their study in Melbourne, Australia, where they grouped urban vegetation based on complexity as low-complexity parks, high –complexity parks and high–complexity remnants. Saturated hydraulic conductivity was an order of magnitude higher in two of the complex habitats than in the low-complexity park due to fewer soil macro pores present in the low-complexity parks. Their measure of soil water holding capacity showed that the low-complexity parks were significantly higher than the high complexity parks and remnants. The high complexity parks and remnants would be able to absorb most of the rainfall without generating runoff, while the low-complexity park would generate runoff after a modest precipitation event.

Li *et al.* (2008), according to their study on physical simulation of rainfall infiltration, conclude that the major means of changing underlying surface water infiltration is to plant vegetation which would regulate the rain water storage, decreasing urban surface runoff coefficient.

Yang and Zhang (2011) through their research on water infiltration in urban soils and its effect on the quantity and quality of runoff showed that based on their grouping of urban vegetation types into lawns, lawns with tree, trees with shrub and no vegetation, that final infiltration rate was significantly higher for the lawns with trees present. However, the average infiltration rate of the vegetation types was not significantly different due to the large variation in infiltration rate within the groups even though the no vegetation area had the lowest value. They also conclude from the study that a reduction in infiltration rate increases the runoff coefficient and the volume of surface runoff. As a result, the frequency of floods due to an excess runoff in urban areas with compacted soils is higher than in areas with non-compacted soils. Gregory *et al*. (2006) in their study measured infiltration rate and soil compaction before and after the conversion of natural forest, planted forest and pasture sites to residential area in urban North Central Florida, USA. They found in their study that average mean water infiltration rate was 77.3 cm h^{-1} before land use conversion decreasing to 17.8 cm h^{-1} after conversion, showing increased soil compaction caused a reduction in saturated hydraulic conductivity by 75 %.

Urban green spaces have positive effects on water infiltration, for example turf grass, based on literature review and analyses by Beard and Green (1994) and Roy *et al.* (2000) in their study, found that turf grasses preserve water by their ability to trap and hold runoff which results in storage in the soil, more water infiltrating and enhancing groundwater recharge. The result of their study showed saturated hydraulic conductivity was higher in the turf grass horizon than in other horizons which they suggest is linked to the macro pores created by the roots of the turf grass and worm burrowing action.

This section has reported some of the research into how a change in vegetation may have an effect on hydrological regulation by affecting the hydraulic indicators. Hydrological components of the balance can vary at smaller scales depending upon differences in vegetation type/ species. Although there has been some research in the urban area, it has not been extensive. Urban green spaces can alter infiltration rate, hydraulic conductivity, soil moisture content and consequently amount of runoff generated. Common urban vegetation type and species can potentially also have an effect on the hydraulic indicators contributing empirical evidence on the potential of urban green spaces and soil hydrology within the urban ecosystem. This study aims to contribute from empirical evidence the effect of urban vegetation type and species on key hydrological processes and the implications for urban habitat management.

According to Leopold (1968), the primary factor related to the quantity of runoff is infiltration characteristics and is related to land slope and soil type including type of vegetation cover. Studies on the effects of different types of vegetation on surface water runoff have been extensive. Kim *et al*., (2014) investigated the effects of vegetation canopy on surface runoff under different types of forest canopies. Their result showed that broad-leaf vegetation produced the largest amount of surface runoff (Sawtooth oak and Japanese larch > Chinese cork oak approximately equal of the difference between shrub > Korean pine). Mohammed and Adam (2010) who looked at the effect of forests planted with P. halepensis, natural vegetation dominated by S. spinosum, natural vegetation where S.spinosum was removed, cultivated land and deforestation on runoff generation found that forest and natural vegetation dominated by S. spinosum had the lowest runoff with averages of 2.02 and 1.08 mm respectively compared to other treatments. In addition run off increased (4.03 mm) for the deforestation compared to that of the forest site. Pan and Shangguan (2006) found that compared with bare soil grass plots had a 14- 25 % less runoff.

Urban green space which includes tree canopy, lawns and farmland positively influence urban hydrology through soil-water storage and enhanced infiltration into the root and soil zones as well as interception by the canopy and plant stems (Gill *et al*., 2007 ; Zhang *et al*., 2012). The use of urban greenspace has gradually been recognized as a measure to reduce runoff and lessen the negative effects of urbanization on the hydrology of urban areas (Bartens *et al*., 2008 ; Zhang *et al*., 2012). Zhang *et al* (2015) modelled the effect of urban greenspaces on rainwater runoff reduction in Beijing. Their study showed that surface runoff controlled by urban green spaces decreased from 23 % in 2000 to 17 % in 2010 attributed to composition changes in urban green spaces. Grass almost totally eliminated surface runoff while trees and their associated tree pits in 9 m^2 Manchester plots reduced surface runoff by as much as 62 % annually compared to asphalt (Armson *et al*., 2013). Yao *et al*. (2015) analysed the role of urban greenspace in potential runoff reduction using the Soil Conservation Service Curve Number method found that green zones (vegetation > 60 %), which occupied only 15.54 % of the total area contributed > 30 % of runoff reduction while urban function zones with > 70 % developed land showed less mitigation of runoff. Their results suggest that urban greenspace has significant potential for runoff mitigation. Inkilainen *et al*. (2013) showed from their study of a low-intensity residential area in the humid subtropical climate that vegetation has a significant influence on the regulation of throughfall and potential stormwater runoff.

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3 The effect of vegetation type on infiltration rate and hydraulic conductivity in an urban area

3.1 Introduction

This chapter addresses objective 2: to characterise infiltration rates and hydraulic conductivity on designated fragments/ sites in Bedford, Luton and Milton Keynes, UK. This led to the outlining of a sub-objective, which is to assess the infiltration rate and hydraulic conductivity of the urban vegetation type in relation to soil type. Firstly, the background of the study area is highlighted, then the outline methodology is shown and finally, the results are discussed and some conclusions drawn.

3.2 Background of the study area

The study was carried out across three towns located in close proximity to each other: Luton (medium sized industrial town), Bedford (smaller county town) and Milton Keynes (planned new town) in south east England as selected for the larger research project. Together they comprise an urbanised area of about 174.5 km^2 (Figure 3.1). The towns differ in their areal extent, level of urbanization, and population densities (Table 3.1). The urban hydrological cycle of these towns is expected to be different in the amounts of run-off, water infiltration and evapotranspiration in relation to the varying percentage of sealed and permeable surfaces, underground and surface drainages present in the towns relate to the land cover and land use. The level of urbanization comes with an expansion of total impervious area, in the form of footpaths, rooftops, carparks and road surfaces.

Table 3.1
Basic Information of Study Areas (source; Wikipedia the free dictionary)

Town	Co-ordinates	Population	Area km^2
Luton	51˚ 53’ N, 0˚ 25’ W	240,000	55.75
Bedford	52˚ 58’ N, 0˚ 28’ W	79,190	29.25
Milton Keynes (inc.Newport Pagnell)	52˚ 02’ N, 0˚ 45’ W	226,180	89.5
Total		545,370	174.5

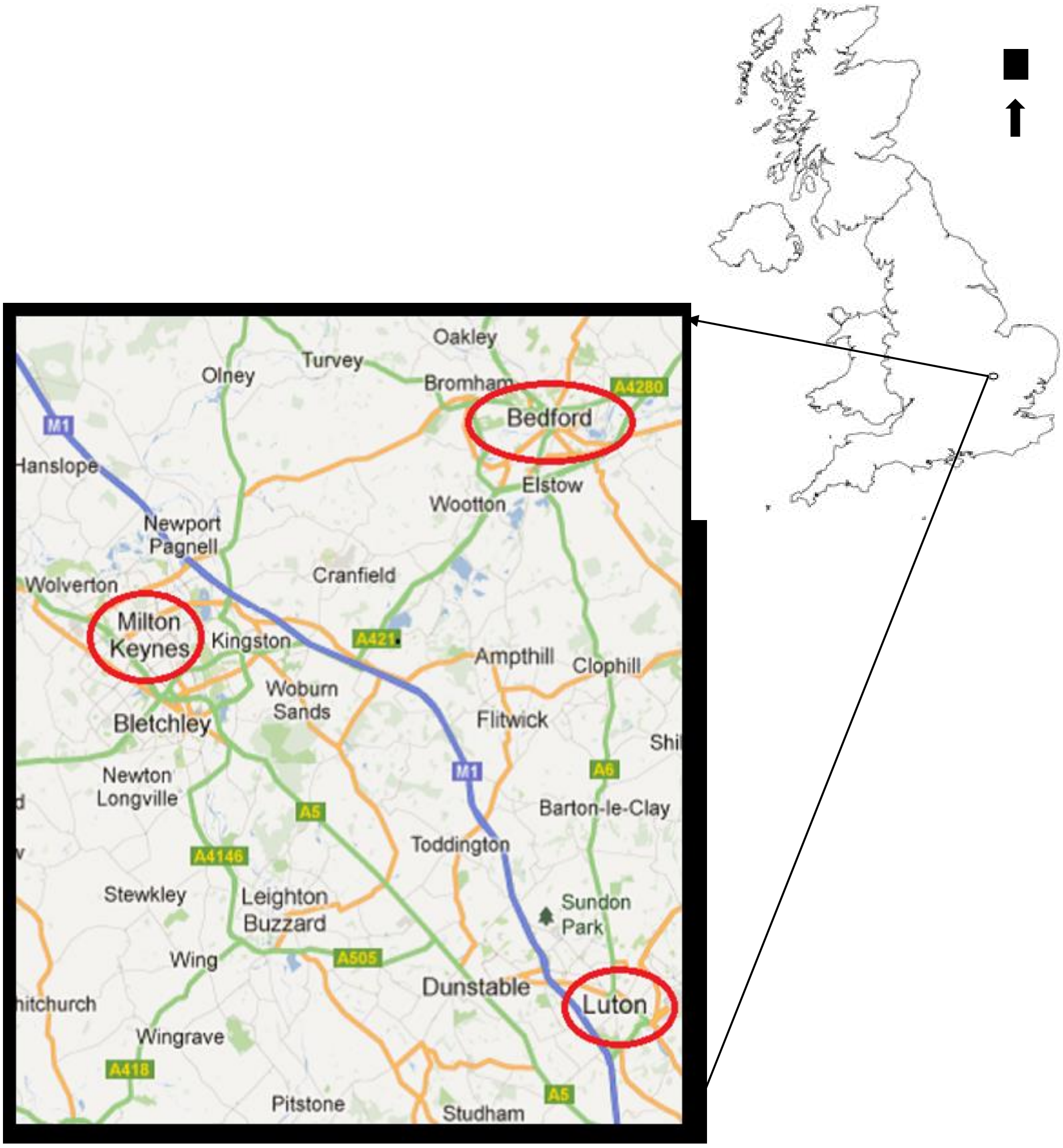

Figure.3. 1 Location of the three study sites: Milton Keynes, Bedford and Luton, UK (Google maps).

3.3 Methodology

3.3.1 Fragments and sampling locations

In this study, urban greenspaces are measured as urban areas now covered with vegetation, private or public, natural or maintained, as opposed to areas that are paved or have buildings on them. Community parks, forested lands are examples of greenspaces that occur in the study area. Identification of a ‘fragment’ for this study is an area of contiguous greenspace. Fragment is defined as an area of at least 100 m^2 with vegetated ground covering. It represented a variety of size, shape, composed of multiple land use. The methodology and selection of fragments was carried out at the University of Exeter, the vegetation structural category was also done in University of Sheffield, due to the scale of the project (as explained in Section 1.1) to meet the multi-disciplinary nature of the project. In summary, the fragments were selected by the calculation of two measures of urban form: the percentage building cover extracted from LiDAR and Ordnance survey data and percentage vegetation cover computed from LiDAR data. Each measure was divided into five categories for an even spread of the different urban forms across the urban mix. In the towns of Bedford, Luton, and Milton Keynes, UK, 112 fragments were marked out. A total of 78 fragments were surveyed out of the 112 fragments. At each site measurement for infiltration rate and calculation for estimate of unsaturated hydraulic conductivity was carried out on a 5 x 5 m subplot located within the fragments. The location of the subplot within the fragments was selected by simple random sampling method. The measurements was in three replicates, 234 results were recorded in all for the three towns. This resulted in three values per subplot which was averaged to get a final value of the subplot, except where negative value(s) were recorded (report on negative results is attached Appendix A.1). Table 3.2 shows the total number of fragments (excluding plots with negative results) with results for analysis.

The field work was carried out from the 2nd of July to 9th of August, then continued on the 6th, 19th to 25th of November 2013. The work lasted 34 days. Appendix A.2 shows the sampling sites, town, topsoil texture and vegetation structure.

Table 3.2
Number of sites according to vegetation and soil type

		Soil type				
		Clay	Clay loam	Sandy loam	Silty clay loam	Total
Vegetation types	**MG**	6	4	8	1	19
	MH		2		1	3
	S	7	5	1	1	14
	TMG	7	3	1		11
	TUH	1	1			2
	UH	5	4	5		14
	W/T	7	4		1	12
	Total	33	23	15	4	75

MG managed grass, MH managed herbaceous, S shrub, TMG trees over managed grass, TUH trees over unmanaged herbaceous, UH unmanaged herbaceous, W/T woodland/trees

3.3.2 Vegetation structure categories

The main vegetation structural types are as shown below within the fragment.

Vegetation structure categories:

I. Ground storey
    a. Managed grass
    b. Unmanaged grass & herbaceous
    c. Planted herbaceous
II. Shrubs / saplings < 2 m
III. Trees / Shrubs > 2 m

There are 5 base categories, these can be combined into 9 possible categories: I alone, I + II, I + III [where I can be a, b or c, but no combination of any of them]. Based on the categories. Table 3.3 shows the classification of vegetation adopted for the study.

Table 3. 3
Vegetation structures, combination and acronyms used for study.

Base categories No combination		**Possible categories**	
		With shrubs	With trees
Ground story	Managed grass, (**MG**)	Shrubs over managed grass, (**SMG**)	Trees over managed grass, (**TMG**)
	Unmanaged herbaceous, (**UH**)	Shrubs over unmanaged grass, (**SUH**)	Trees over unmanaged herbaceous, (**TUH**)
	Planted/managed herbaceous, (**MH**)	Shrubs over managed herbaceous, (**SMH**)	Trees over managed herbaceous, (**TMH**)
Shrubs/saplings < 2m, (**S**)			
Trees/shrubs > 2m, (**W/T**)			

As mentioned, site selection was carried out by the F3UES project group on urban ecosystem characterisation, focused on delineation of greenspaces into fragments with the urban ecosystem which excluded soil series data. A topsoil map (Figure 3.2) was generated using the coordinates of the sampling sites and relied upon to classify the soils of the study area. The topsoil texture data layer from Landis, Cranfield University was overlaid on the topographical map of the area. However, whilst the soil map was used for the soil classification the results should be treated with caution. This is due to the spatial variability commonly associated with urban areas which means that the identified soil type may not be present at the field or sub-field scale (Dane and Topp, 2002).

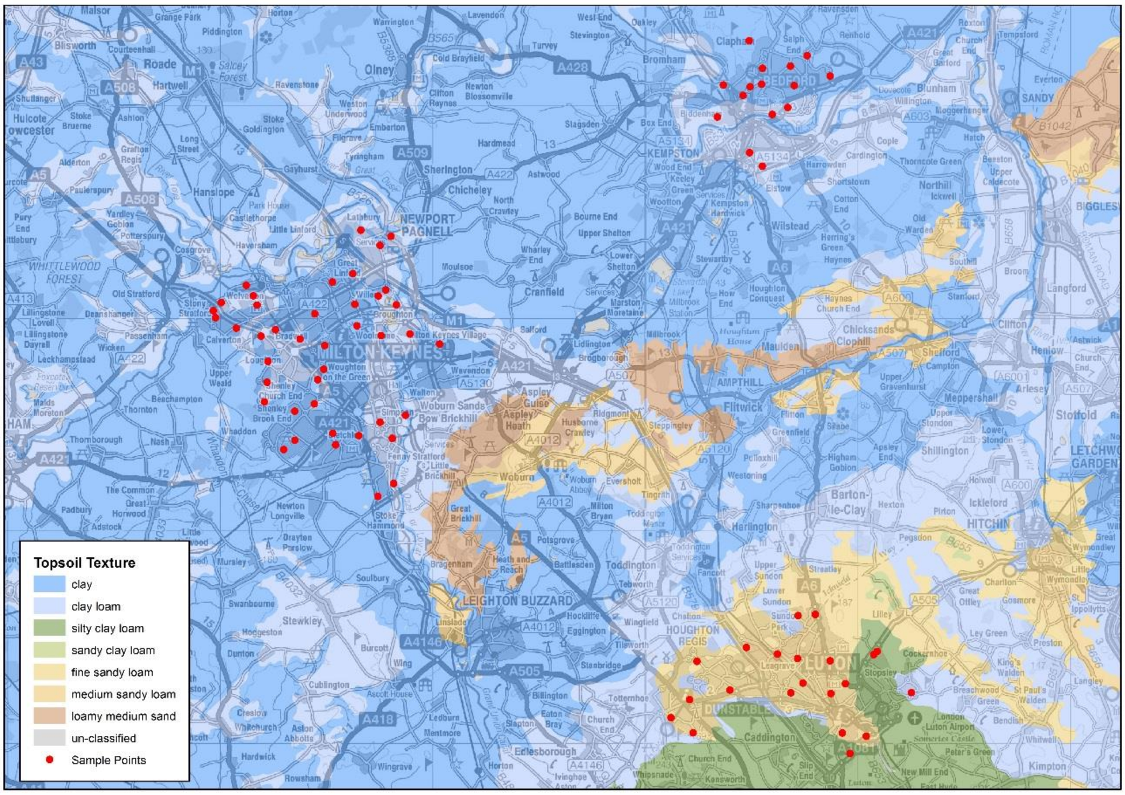

Figure 3. 2 Location and topsoil texture of sample fragments (Landis, Cranfield University, 2013).

3.3.3 Measurement of infiltration rate and unsaturated hydraulic conductivity

The vegetation structural types within fragments were measured for infiltration rate and unsaturated hydraulic conductivity. The measurement was carried out using the same instrument and site preparation procedure.

The Decagon mini disk portable tension infiltrometer (Figure 3.3) was used. The instrument was used to measure the infiltration of water into the topsoil cover (0 – 0.2 m). To determine an estimate of the unsaturated hydraulic conductivity, negative pressure is exerted on the soil surface. The Decagon mini disk infiltrometer excludes macro pores that fill at greater porewater pressure from the flow process, hence only measuring flow in the soil matrix.

It is constructed of a polycarbonate tube that is of total length 32.7 cm, graduated water cylinder of 21.2 cm, external diameter of 3.1 cm and internal diameter of 2. 5 cm with water volume of 135 mL, a 4.5 cm base diameter of semi-permeable stainless steel sintered disk. An adjustable steel tube of 10.2 cm is installed above the sample chamber to regulate the suction rate. The mini disk infiltrometer has tension values from 0.5 to 7 cm. The mariotte tube is 28 cm. The cylindrical tube was filled up with water and the rubber stopper installed, the steel tube was adjusted to the desired tension value, in this case 2 cm as recommended in the Minidisk Infiltrometer User's Manual (Decagon Devices, 2012). The bottom of the infiltrometer has a porous sintered stainless steel disk which will not allow water to leak in open air. The disk was placed on the soil surface. The soil surface at each location was made smooth and levelled by clearing away any cover that would not allow a good contact between the soil and the infiltrometer base with minimal disturbance to the soil surface (Figure 3.3 showing the mini disk infiltrometer on one of the sites). The volume change in the cylindrical tube was recorded at regular intervals of five minutes, for an hour based on literature search and prior pilot study. The data from the infiltration measurement was plotted using the excel spread sheet software following Decagons mini disk infiltrometer instruction manual (Decagon Devices, 2012), to calculate for the unsaturated hydraulic conductivity. The hydraulic conductivity is calculated using the method proposed by Zhang (1997) which is simple and works well for measurement of infiltration into dry soil and recommended by the infiltrometer supplier (Decagon-Devices, 2012). The method requires using the measured cumulative infiltration versus time and fitting the results to the function:

$\mathrm{I} = C_1 t + \mathrm{C}_2\sqrt{t}$ ……………………………………………………………………equation1

where: I is infiltration, t is time, C_1 and C_2 are fitted coefficients.

The unsaturated hydraulic conductivity of the soil (K) is then computed from;

$\mathrm{K} = \frac{C_1}{A}$ ………………………………………………………………………………...equation 2

where A is a dimensionless coefficient relating the van Genuchten moisture retention parameters. Details on calculations on how to determine hydraulic conductivity using the mini-disk infiltrometer is presented in Appendix A.3.

It is a quick way to determine estimates of hydraulic conductivity and infiltration rates. Minidisk infiltrometer is a standard tool for evaluation of soil hydraulic properties especially those related to pores and soil structures as influenced by vegetation on the soil surface (Holden et al., 2001). This method was chosen also in preference to the double ring infiltrometer as it requires less water and is easier to move from site to site. The rings of the double ring infiltrometer are heavy to move and need large amounts of water (McKenzie and Coughlon, 2002). An added advantage of the tension infiltrometer is, it is less expensive, and provides unsaturated hydraulic conductivity measurements as well as steady state infiltration rates (Yan *et al*., 2005; Li *et al*., 2005; Lichner *et al* ., 2007; Glenn and Finley, 2010; Hathaway-Jenkins, 2011; Orfanus *et al*., 2014).

While measurements were carried out on all plots of the study in replicates, not all of the measured results for estimated unsaturated hydraulic conductivity gave positive values. From the 234 sample points 20 of the results gave negative values (Appendix A.1). The negative results were excluded from the analysis of results.

In the context of this study, the following sub-hypothesis was developed for this chapter:

Null – Urban vegetation types have no significant effect on infiltration rate and hydraulic conductivity.

Alternative – Urban vegetation types have a significant effect on infiltration rate and hydraulic conductivity.

3.3.4 Statistical analyses

The above hypothesis was tested based on the results and analysed to determine whether the null hypothesis can be rejected. The objective of the analysis was to quantify any differences in infiltration rate and unsaturated hydraulic conductivity between vegetation types. All the data were analysed quantitatively using the IBM SPSS

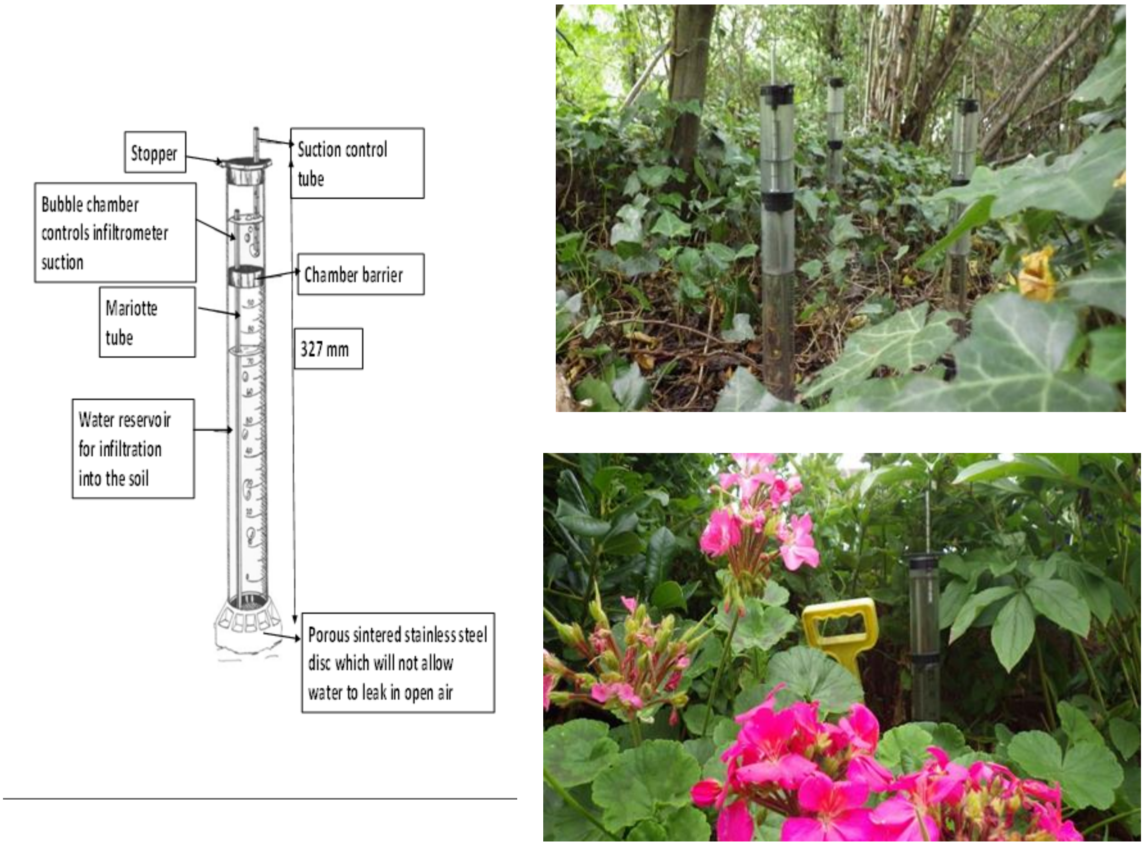

Figure 3. 3 Diagram and photograph of the Decagon minidisk infiltrometer (Decagon devices, 2012 and Piwuna, 2013)

Statistics (IBM Corp. IBM SPSS Statistics for Windows, Version 22.0.0 Armonk, NY: IBM Corp.). Descriptive analyses and data checking operations were run for outlier detection and normal distribution of data. Where normal distribution of data did not occur various data transformation attempts using square root, log, reciprocal and reverse score were used. Analysis was carried out on raw data where transformation attempts did not improve the normality of the data and results are taken as valid (www.statistics.laerd.com, Rivas Casado, 2014, Pers.Com). Data was analysed for statistical significance ($p < 0.05$) using a one-way Welch ANOVA to determine vegetation type effects on infiltration rate and unsaturated hydraulic conductivity. Where a difference was observed the Games-Howell post-hoc analysis was undertaken to evaluate statistical significance between means.

The experimental design was unbalanced and so there were different number of vegetation types for the soil types as shown in Table 3.2. Using ANOVA for statistical analysis allows for an unbalanced design and permits unbiased conclusions to be drawn. However, not all vegetation types were included for analysis based upon soil type.

3.3.5 Limitations on evaluation of the data

As in all experimental studies, some limitations and factors in data collection can affect the results obtained which include:

There were limitations with the data collected thereby restricting the output of the research especially where the results may be unable to fully determine the effect of vegetation types on infiltration rate and hydraulic conductivity. Not all vegetation types were present in every soil texture, posing a problem in terms of comparison of urban vegetation types and on conclusions which could be drawn from the analysis.

Antecedent soil moisture content, bulk density and soil organic matter were not measured on the sites for correlation analysis.

The measurements of this study was carried out at two different months of July and August when soils are generally dry and in the month of November when the soil was wet leading to temporal variability in soil hydraulic properties caused by soil moisture changes, that is, different antecedent moisture content altering hydraulic flow (Pirastru et al., 2013).

The effect of spatial variation of soil types including soil depth and surface conditions on hydraulic properties was also a shortcoming (Turner, 2006).

Another limitation is the high probability of lateral flow affecting infiltration rate values.

The same equipment was used for measurements of infiltration rate and unsaturated hydraulic conductivity. Any experimental errors would affect all parameters measured.

3.4 Results

The measurements did not yield a complete set of results. The number of replicate vegetation type varied according to soil type and there were no replicates of the silty clay loam soil Table 3.2 and Table 3.4.

Table 3 4
Mean unsaturated hydraulic conductivity and infiltration rate for the different vegetation types. Numbers in brackets are the total number of measurements for each sample site

Sample No.	**Topsoil texture**	**Veg.type**	**Unsaturated hydraulic cond. (3) mm d^{-1}**	**Infiltration rate (3) mm h^{-1}**
AB 43	Clay	W/T	48.98	23
AB 44	Clay	W/T	19.43	8
AC 44	Clay	UH	97.23	23
AD 42	Clay	TMG	12.59	8
AE 46	Clay	MG	155.25	23
AF 41	Clay loam	TMG	70.68	33
AF 44	Clay loam	TMG	102.16**	8
AF 45	Clay loam	UH	142.73	38
AG 35	Clay loam	MG	42.6	15
AG 37	Clay loam	W/T	31.6	10
AG 39	Clay loam	MG	323.06	11
AH 42	Clay	W/T	105.64	23
AI 30	Clay	MG	35.78**	41
AJ 31	Clay	W/T	-	
AJ 34	Clay	UH	39.4	8
AK 37	Clay loam	UH	5.93**	15
AL 38	Clay	S	93.8	20
AM 34	Clay loam	W/T	142.2	26
AM 40	Clay	MG	45.57	15
AM 46	Clay	W/T	-	
AO 44	Clay	W/T	19.75	10
AO 47	Clay	S	38.71	20
AP 42	Clay	W/T	34.12	10
AR 33	Clay	UH	-	

Sample No.	Topsoil texture	Veg.type	Unsaturated hydraulic cond. (3) mm d^{-1}	Infiltration rate (3) mm h^{-1}
AR 41	Clay loam	W/T	13.58*	13
AR 45	clay	W/T	9.25	8
AS 44	clay	UH	3.61	8
AT 34	clay	MG	85.66	15
AT 42	Clay loam	TMH	288.25	87
BS 5	Sandy loam	UH	73.28	25
BU 3	Sandy loam	MG	63.25	18
BU 6	Sandy loam	S	37.45	8
BV 10	Sandy loam	TUH	121.07	35
BX 64	clay	UH	126.84	33
BY 7	Sandy loam	MG	237.57	45
BZ 11	Sandy loam	UH	138	38
BZ 63	clay	TMG	102.37	18
CA 65	clay	TMG	408.32	38
CA 69	clay	W/T	19.07	8
CB 57	Clay loam	S	112.48	19
CB 64	clay	TMG	122.41	30
CB 66	clay	S	116.5	12
CC 11	Silty clay loam	MG	42.07**	13
CC 62	Clay loam	S	124.07	15
CD 7	Clay loam	UH	512.97	250
CE 10	Sandy loam	MG	383.65	8
CE 14	Sandy loam	MG	399.65	30
CE 63	Clay loam	UH	30.59	23
CE 64	clay	S	15.95**	13
CE 67	clay	TMG	68.88	20
CF 8	Sandy loam	MG	716.57	100.7
CF 67	clay	TUH	33.78	8

Sample No.	Topsoil texture	Veg.type	Unsaturated hydraulic cond. (3) mm d^{-1}	Infiltration rate (3) mm h^{-1}
CG 14	Sandy loam	MG	450.13	57
CH 7	Sandy loam	S	42.14	11
CH 10	Sandy loam	UH	146.38	15
CH 65	Clay	S	48.63	8
CI 3	Sandy loam	TMG	326.88	49
CI 8	Sandy loam	UH	42.33	11
CJ 1	Silty clay loam	W/T	88.44	53
CK 3	Sandy loam	MG	94.75	20
CL 11	Silty clay loam	MH	128.75	37
CM 11	Silty clay loam	S	17.65	10
CP 7	Clay loam	MH	117.21	38
AJ 41	Clay loam	TMG	5.77*	10
AL 43	Clay	MG	228.39**	18
AM 32	Clay	S	54.45	13
AN 31	Clay	S	5.04	8
AP 32	Clay	MG	175.3	11
AP 51	Clay loam	MG	94.65	23
AR 26	Clay	TMG	164.23	15
AR 50	Clay loam	UH	35.88	13
AS 27	Clay loam	TUH	77.45**	15
AS 31	Clay loam	MG	51.09	18
AS 50	Clay loam	S	31.37	18
AV 42	Clay	TMG	65.46	15
AW 40	Clay	S	130.34	25
BX 61	Clay loam	S	29.59	10
BZ 57	Clay loam	S	97.39	28

MG managed grass, MH managed herbaceous, S shrub, TMG trees over managed grass, TUH trees over unmanaged herbaceous, UH unmanaged herbaceous, W/T woodland/trees. ** site had one negative value * site had two negative value

3.4.1 Infiltration rate

The mean infiltration rate for each vegetation type across the entire area measured is shown in Figure 3.4. From the results the infiltration rates were variable in all the vegetation types, but most infiltration rates were < 30 mm h^{-1}. The managed herbaceous (MH) had the largest value of 29 ± 14 mm h^{-1} infiltration rate, while the trees over unmanaged herbaceous (TUH) had the smallest value of 12 ± 5 mm h^{-1}. However, the greatest within class variability in infiltration rate was observed for the managed grass (MG) 26 ± 21 mm h^{-1}. Even though mean values were not the same for the vegetation types no significant difference was observed between the different vegetation types on infiltration rate. This may be due to high variation between individual replicates within vegetation types and the confounding effect of soil type.

The results of the ANOVA related to the soil types of the area showed that there is a variation in values but these variations were not significantly different between the vegetation types (Figure 3.4 b, c, d). On the clay soil both the managed grass (MG) and trees over managed grass (TMG) had the largest value of 20 ± 11 mm h^{-1} while the woodland/trees (W/T) had the smallest value of 13 ± 7 mm h^{-1} infiltration rate. On the clay loam soil woodland/trees (W/T) had the largest value of 35 ± 35 mm h^{-1} while unmanaged herbaceous (UH) had the smallest value of 17 ± 4 mm h^{-1} infiltration rate. On the sandy loam soil the managed grass (MG) had the largest value of 34 ± 19 mm h^{-1} while the unmanaged herbaceous (UH) had the smallest value of 20 ± 12 mm h^{-1} infiltration rate.

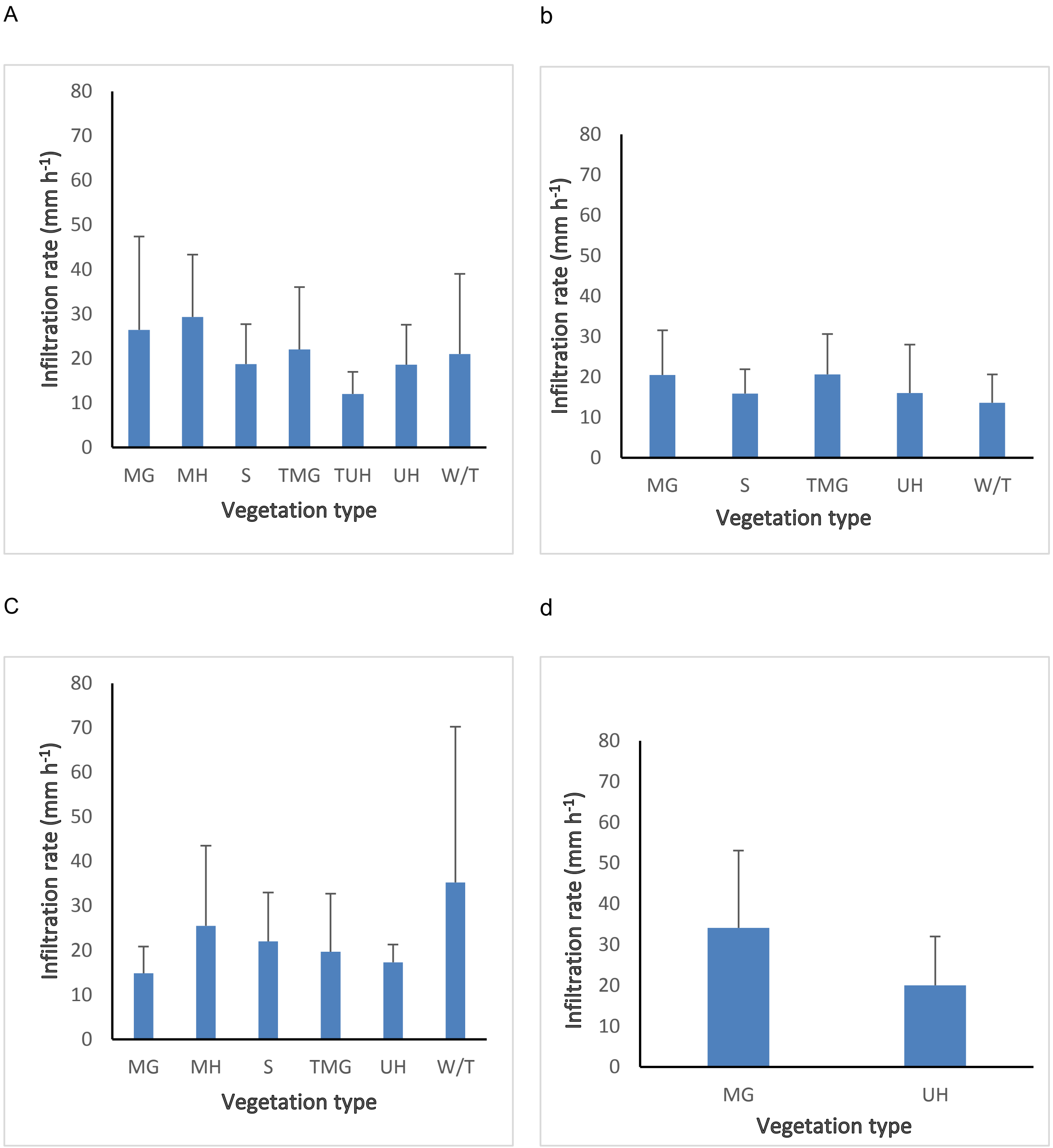

Figure 3. 4 The mean infiltration rate at an hour of entire sampled area (a), clay soil (b), clay loam soil (c), sandy loam soil (d) of the different vegetation types MG managed grass, MH managed herbaceous, S shrub, TMG trees over managed grass, TUH trees over unmanaged herbaceous, UH unmanaged herbaceous, W/T woodland/trees. Error bars indicate standard deviation of the mean

3.4.2 Unsaturated hydraulic conductivity

Figure 3.5a presents mean of estimated unsaturated hydraulic conductivity for each vegetation type totalled across the entire sampled area.

Analysis comparing the vegetation types on individual soil types of the area showed a significant difference ($p = 0.05$) in unsaturated hydraulic conductivity between managed grass (MG) (308 ± 223 mm d^{-1}) greater than unmanaged herbaceous (UH) (88 ± 51 mm d^{-1}) on the sandy loam soil (Figure 3.5 d). However, there was no significant differences observed between vegetation types for unsaturated hydraulic conductivity on other soil types which may be due to the high variation between replicates of the same vegetation types (Figure 3.5. b, c). On the clay soil managed grass (MG) had the largest range of 108 ± 60 mm d^{-1} and woodland/tree (W/T) had the smallest range of 36 ± 31 mm d^{-1}, on the clay loam soil unmanaged herbaceous (UH) had the largest range of 144 ± 246 mm d^{-1} and trees over managed grass (TMG) had the smallest range of 101 ± 43 mm d^{-1}.

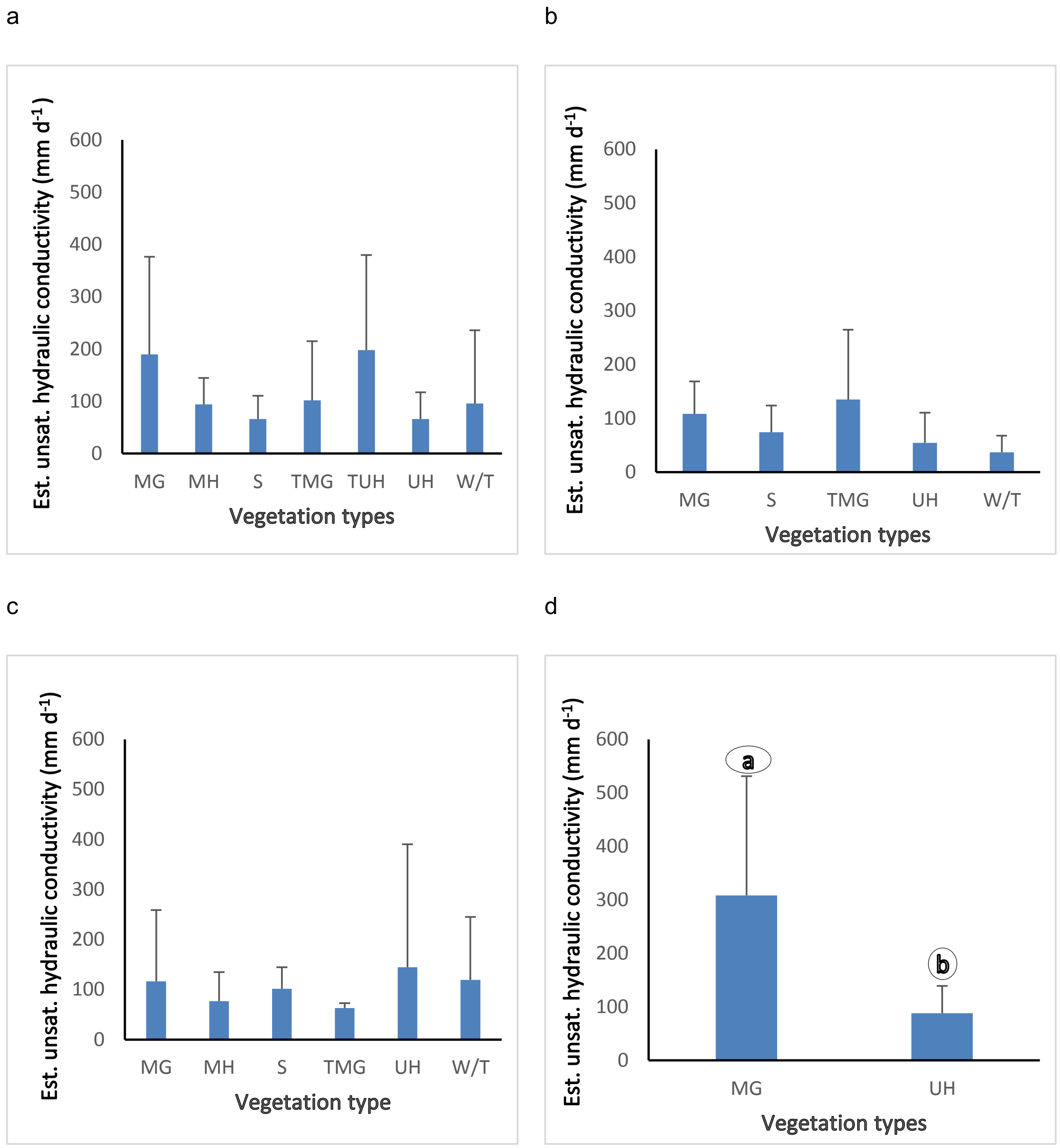

Figure 3.5 The mean estimated unsaturated hydraulic conductivity of entire sampled area (a), clay soil (b), clay loam soil (c), sandy loam soil (d) of the different vegetation types MG managed grass, MH managed herbaceous, S shrub, TMG trees over managed grass, TUH trees over unmanaged herbaceous, UH unmanaged herbaceous, W/T woodland/trees showing significant differences with different letters on bars. Error bars indicate standard deviation of the mean.

3.5 Discussion

3.5.1 Infiltration rate

Soil structure has been asserted as the most important parameter affecting infiltration rates (Brady and Weil, 1991). In general, the water infiltration of soils is achieved and controlled by macro pores, even though these represents only a small portion of the total porosity (Moret and Arrue, 2007). Macro pores, however, can be created and changed either by biological processes which include root growing or decaying, worm burrowing, soil fauna or by physical processes which include shrinking and drying and soil aggregate development (Neary et al., 2009). Plants influence the complex dynamics of soil aggregation: biotic influences of soil aggregation by plants include biochemical composition of plant residues through plant species, physical fragmentation of soil aggregates by plant root penetration and production of organic acids in the rhizosphere (Bronick and Lal, 2004). Enhanced infiltration rate is essential in helping to reduce run-off. Many studies have found that the infiltration rate of a soil was mainly controlled by both vegetation characteristics and soil physical properties (Fischer et al., 2014 and Leung et al., 2015). Vegetation with extensive fibrous roots producing high levels of micro aggregation increasing infiltration rate (Chan and Heenan, 1996). It was anticipated that there will be a difference in infiltration rate as a consequence of different root types which alter the soil structure associated with the different vegetation types. According to the analysis of the results there is no significant difference in infiltration rates between vegetation types even on different soil types, this was also found in the studies by Hathaway-Jenkins (2011) using the Decagon mini-disk infiltrometer on infiltration rate of arable fields which showed little difference between organic and conventional land management with different crops. Leung et al. (2015) found in their studies comparing the infiltration rate between grass-covered and tree-covered soil on a compacted completely decomposed granite, statistical analysis showed that there was no distinct difference. However, the wide variation between replicates of the vegetation type suggest that the variation maybe due to the difference in antecedent soil moisture content of the soil with depth.

3.5.2 Hydraulic conductivity

It was anticipated that there would be a difference in unsaturated hydraulic conductivity as a consequence of different root types which alter the soil structure associated with the different vegetation types. Vegetation with tap roots have a higher hydraulic conductivity. The trees over unmanaged herbaceous (TUH) had the largest range of 197 ± 182 mm d^{-1} estimated unsaturated hydraulic conductivity, whereas the shrubs (S) and unmanaged herbaceous (UH) had the smallest range of 66 ± 51 mm d^{-1}. Even though average values differed for the vegetation types no significant differences was observed between the different vegetation types on unsaturated hydraulic conductivity due to high variation between replicates of the same vegetation type and the confounding effect of soil type. Significant differences between the vegetation types on the sandy loam soil and the non-significant difference on the clay and clay loam soils for the same vegetation types would suggest that the effect of vegetation type is closely related to the soil type. However, as shown by the results, there was a difference between vegetation types due to soil type: the coarse textured characteristic of the sandy loam soil having a higher permeability due to large pore spaces compared to the other soils types. The non-significant difference on the clay and clay loam soils suggest that the changes in vegetation type did not alter the soil pore structure in the range of the tension value of -2 cm used. This was also found by Pirastru et al, (2013) in their study on sandy soils for unsaturated hydraulic conductivity using the tension infiltrometer at a water tension of -1 cm between forested and grassed plots showing no statistically significant difference. Boxell and Drohan (2009) also found using the minidisk infiltrometer at a water tension of -1 cm on alluvial aprons that difference in unsaturated hydraulic conductivity between the grass *Bromus tectorum* and shrub *Artemisia tridentate* was not significant. Leung et al. (2015) showed from their studies of effect of roots on hydraulic conductivity on compacted completely decomposed granite that grass-covered and tree-covered sites were not significantly different also. In their study Li et al. (2008) analysed unsaturated hydraulic conductivity between different shrubs and grasses (*T.scrpylloides, H. spinose, G. pumila and F. scariosa*) and found no significant differences, but the analysis between vegetated surface, rocky and bare surface showed vegetated surface significantly different using the tension infilrometer at water suction of -3 cm and -6 cm. The study by Clark and Zipper (2016) found a different result from the one found in this study; using the minidisk infiltrometer at a water tension of -2 cm, reforested area had greater unsaturated hydraulic conductivity than grassed areas on the same soil type.

3.6 Conclusion

This study provides an attempt under the limitations by a multidisciplinary project at highlighting the infiltration rate and hydraulic conductivity due to different vegetation type found within the urban ecosystem. The main conclusions drawn are:

There was evidence to support the suggestion that unsaturated hydraulic conductivity is greater on managed grass than unmanaged herbaceous on a sandy loam soil; such a difference might reduce runoff generation allowing the null sub-hypothesis to be rejected.

The analysis of the data for infiltration rate supports the suggestion that the different urban vegetation types compared to commonly managed grass does not change infiltration rates (regardless of soil texture) and hydraulic conductivity significantly on clay soil in agreement with other results but equally it is not detrimental, allowing the null sub-hypothesis to be accepted.

Furthermore, the absence of a trend of the vegetation types on different soil types suggests that infiltration rate and hydraulic conductivity are affected more by soil type.

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4 Plot scale studies on effect of urban vegetation type on soil properties

4.1 Introduction

The purpose of this section of the study was to address objectives 3 and 4, outlined in Chapter 1; to characterise experimental site based on the soil type, vegetation diversity and management, and to measure and evaluate the effect of vegetation and its management on topsoil moisture content, water infiltration rate and hydraulic conductivity. The field scale research (Chapter 3) demonstrated that urban vegetation types has a significant effect on unsaturated hydraulic conductivity dependant on soil type, but does not have a significant effect on infiltration rate. However, species diversity and richness under different management may generate different effects.

In this regard measurements were carried out to determine topsoil moisture content, water infiltration rate and hydraulic conductivity in order to assess how urban vegetation has an effect on the measured parameters. Plot scale experimental methodology to studies are, in general, part of a broader research project aimed at improving the knowledge of interrelationships between processes relating hydrological, climatic, biological, ecological and geomorphological factors (Wainwright *et al.*, 2000; Moreira *et al.*, 2011). An advantage of plot scale studies is that of allowing for specific process monitoring at small scale, providing a basic description of the most significant aspects (Michaelides *et al.*, 2009). This plot scale study allowed greater control of soil texture. The measurements for this phase of the studies were carried out at two seasons to assess changes in time of vegetation manipulation on soil moisture content, infiltration rate and hydraulic conductivity. These studies were also intended to provide data for the modelling (Chapter 5).

4.2 Methodology

The experimental site selection and design was carried out by the Sheffield University team of the F3UES Project. The experimental manipulation entailed the alteration of biodiversity (taxonomic and structural).

4.2.1 Experimental design

The experimental treatment was designed to represent an order of increasing species richness, that is, floristic diversity and increasing structural height difference (Table 4.1). The manipulations have been grouped into "no", "some" and "many" floral diversity and "short", "medium" and "tall" structural levels. Each plot represents a combination of the two manipulations (Figure 4.2 & 4.3) as follows:

I. **Floristic diversity – common flowers and grasses (species list of names in Appendix B.1)**
   - No – 4 to 5 species
   - Some – 9 to 13 species
   - Many – 16 to 21 species

II. **Structural diversity – by frequency of cutting/mowing**
   - Short- once in every four weeks , 50 mm
   - Medium – twice in the season, 500 mm
   - Tall– once in the season, 1000 mm

At each site 10 plots were marked out, seeds were sown on 9 of the plots for the manipulation and 1 for non-manipulated (standard mown amenity grass taken as a control) studies.

4.2.2 Experimental site selection, location and background information

Eleven sites from the towns described in Section 3.2 were selected for the plot level of experimental studies. However, only six of the sites had a complete experimental design. (Abbyfields, Brickhill Heights, Chiltern Avenue and Jubilee Park, in Bedford; Birmingham Road, in Luton and the Cranfield site).

The experimental site for this study was set up at Cranfield University located in a residential area (52° 4' 40"N, 0° 37'36"W), East of England, UK (Figure 4.1). The site covers a total area of about 8500 m^2. The site was selected for the study based on (a) a reconnaissance survey of all BESS project sites (reconnaissance survey report is presented in Appendix B.2), (b) vegetation germination on designated plots (c) ready access to site, and as well as (d) safety of investigator.

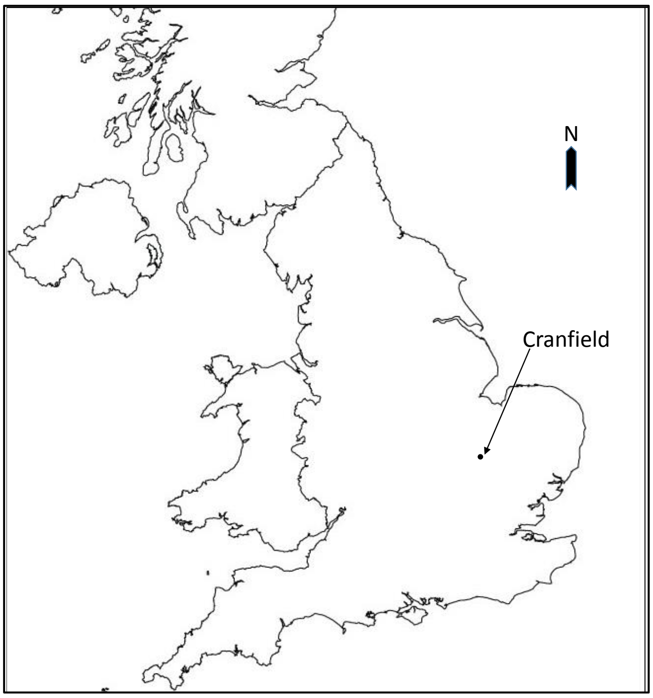


Figure 4.1 Location of Cranfield, UK

The site consists of plots with a 50 m length by 10 m width dimensions each (Table 4.1). The vegetation were planted in April 2013, the order of the plots at the site is random to reduce variances due to experimental error. Each manipulated plot excluding the non-manipulated was cultivated using a rotavator to a depth of 0.15 m before seeding (forbs 4 g m^2 and grass 20 g m^2) was carried out. Figure 4.2 shows an overview of the site and layout of the plots. The manipulated plots as indicated in Section 4.2.1 for structural diversity were managed by conventional mowing, while the non-manipulated plot was also managed by conventional regular bi-monthly mowing.

Table 4.1
Type of vegetation and number of species sown on each plot and their associated reference codes on the Cranfield site.

Plot identification	Structural and floral combination
1, I, MFT	Many flowers tall, Mix 6, 16 forb species & 5 grass species
2, C, MFS	Many flowers short, Mix 2, 12 forb species & 4 grass species
3, G, NFT	No flowers tall, Mix 8, 5 grass species
4, E, SFM	Some flowers medium, Mix 3, 7 forbs species & 4 grass species
5, H, SFT	Some flowers tall, Mix 5, 8 forb species & 5 grass species
6, B, SFS	Some flowers short, Mix 1, 5 forbs species & 4 grass species
7 ,F, MFM	Many flowers medium, Mix 4, 14 forb species & 4 grass species
8, A, NFS	No flowers short, Mix 7, 4 grass species
9, D, NFM	No flowers medium, Mix 7, 4 grass species
10,Non-manipulated	Non -manipulated vegetation, 4 grass species

Figure 4.2 Overview of Experimental plots in September 2014, Cranfield

increasing species diversity

Plot 8: No flowers shorts - 4 grass species

Plot 6: Some flowers short – 5 forb + 4 grass species

Plot 2: Many flowers short – 12 forb + 4 grass species

Increasing height

Plot 9: No flowers medium – 4 grass species

Plot 4: Some flowers medium – 7 forb + 4 grass species

Plot 7: Many flowers medium – 14 forb + 4 grass species

Plot 3: No flowers tall – 5 grass species

Plot 5: Some flowers tall – 8 forb + 5 grass species

Plot 1: Many flowers tall – 16 forb + 5 grass species

Plot 10: Non-manipulated

Figure 4.3 Picture of plots and combination of three levels of floristic and structural diversity of manipulation plots

4.2.3 Field site soil physical properties

Soil samples were collected from the site from the 13th - 15th October 2014 to determine soil properties aimed at fully characterising the site existing baseline properties for any confounding effects. The samples were collected randomly at a depth representative of the topsoil layer (0 - 0.2 m) of the soil. Three replicate soil samples were taken from each experimental plot. The methods used for the analysis of the soils were based on British Standards in the Cranfield Soils Laboratory, Cranfield University.

4.2.3.1 Bulk density and Porosity

Bulk density was determined to characterise the level of surface soil compaction. Bulk density reveals the ease of root penetration and water transmission which can be altered by management practices and land use. The bulk density is affected by texture, structure, compaction and Soil organic matter content. Soil sample was collected as undisturbed soil cores at 0 – 0.05 m depth using bulk density core metal rings of both 55 x 45 mm or 54 x 20 mm diameter and height respectively. The sample completely filled the ring. Bulk density (BD; g cm^{-3}) was determined by oven-drying method (BS 7755-5.6, 2010). Porosity (*P*) was calculated from BD and particle density (PD) assuming PD to be 2.65 g cm^{-3} using the equation and relationship (Equations 3).

$P = 1 - \left(\frac{BD}{PD}\right) \times 100$……………………………………………………………equation 3

4.2.3.2 Topsoil texture

The soil texture was assessed to confirm the soil type, the soils ability to retain water and the ease with which air and water may pass through the soil. A hand auger sampler was used for the collection of samples which were extracted vertically. The sample was bulked in a plastic bag and mixed thoroughly to obtain a representative value. All samples were air dried and large organic debris were removed. The sample was then homogenized in an agate mortar and sieved through a 2 mm sieve. Soil texture was determined using the sieving and pipette method (BS 7755-5.4, 1998) which separates the soil into three fractions: sand (0.05 – 2.0 mm), silt (0.002 – 0.05 mm) and clay (< 0.002 mm) and by plotting these values onto a soil textural triangle the texture can be established. This method was used preferentially to the hydrometer and hand texturing, according to Hathaway-Jenkins (2011) it is the most accurate direct sampling method.

4.2.3.3 Soil organic matter

To ensure similar soil organic matter content and therefore fair enhancement of absorbed water retention, it is expressed as a percentage of the mass of organic matter to the mass of the dry soil solids. A hand auger sampler was used for the collection of samples which were extracted vertically. The sample was bulked in a plastic bag and mixed thoroughly to obtain a representative value. Composite samples were air dried, ground and sieved through a 2 mm and analysed for organic matter content and results based on loss on ignition analysis (BS EN 13039, 2000). This method in general does not give results with a high level of accuracy, due to assumptions including, that all the soil organic carbon will be oxidised at 430°C used for heating of the samples (Rosella et al., 2001).

4.2.4 Field Methodology

The data collection was structured so as to show any changes in time. The timing of data collection was planned so as to have results at the end of the dry and middle of the wet period. This is aimed at knowledge of the variability over time due to applied treatments and the controlling factors.

These measurements were carried out on each of the ten plots on the site. A space of 0.5 m was given along the length and breadth of each of the plots to avoid possible edge effects, thereby avoiding chances of non-representation of what is on the plot.

The field measurements and soil sampling were taken over a short period so as to minimize the temporal variability in soil hydraulic properties associated with soil moisture changes.

4.2.4.1 Vegetation height

Vegetation height is the distance from the soil at its base to the highest point reached with parts of the plant in their natural position. On each plot readings of maximum and minimum vegetation height were taken using a meter stick at each point of measurement. A total of 360 measurements were taken on the site, 36 pairs of measurements on each plot in September 2014.

4.2.4.2 Vegetation cover

A 1 m x 1 m square quadrat frame with divisions every 10 cm was placed, three times randomly on each experimental plot (Figure 4.4), and number of plant species within each grid was recorded and coverage was determined, expressed as the percentage coverage of each species on the plot. Additionally, percent vegetation cover was also visually estimated. This was carried out in June 2015 when all the floral species were in bloom to aid species identification.

Figure 4.4 Quadrat (1 x 1 m2) on the Some Flowers Short (SFS) plot

4.2.4.3 Soil moisture content

Soil moisture content (SMC) was measured using a hand-held digital soil moisture meter – Hydrosense II (Campbell Scientific) (Figure 4.5).

Volumetric soil moisture content was measured at a depth of 0 – 0.2 m to cover for top soil surface. Soil moisture content was measured at two different periods:

1. In September 2014 when the soil was expected to be dry - A total of 360 measurements were taken on the site, 36 points per plot and
2. Repeat in December 2014 when the soil was expected to be wet.
3. SMC was measured to assess the effect of antecedent soil moisture content on infiltration rate and saturated hydraulic conductivity and to estimate field capacity following the method used by Zotarelli *et al*. (2016). In October 2015 alongside infiltration measurement - three points on each plot on:
    I. The same day of taking infiltration measurement.

II. The same day (21st October 2015), a day after a full day of rainfall event.

III. A day after infiltration measurement

Figure 4.5 Hydrosense II on the Many Flowers Medium (MFM) plot on the Cranfield site

4.2.4.4 Infiltration rate and Hydraulic conductivity

For the infiltration rate measurement and hydraulic conductivity estimates, two in situ methods were used:

1. Decagon mini disk infiltrometer
    - In September to October 2014, using water pressure - 2 cm - A total of 90 measurements was carried out on the site, nine measurements per plot, the same measurement was repeated
    - In November to December 2014, using water pressure -0.5 cm.

The water pressure of -2 cm was used as recommended by the user manual guideline, but when the soil was wet the -2 cm water pressure did not allow infiltration. Suggesting the smaller pore diameter were saturated with water and so -0.5 cm was used to allow infiltration through smaller pores.

2. Double-ring infiltrometer

- In October 2015 when the soil is expected to be wet – A total of 10 measurements was carried out.

Measurement of infiltration rate and calculation of estimated unsaturated hydraulic conductivity using the Decagon mini disk infiltrometer and its advantages are outlined in Chapter 3, Section 3.3.3. The double-ring infiltrometer was used for estimating the cumulative infiltration and infiltration rate by constant head method described by Gregory et al.(2005) and Bean et al (2007). The method is based on the operation of two open stainless steel rings. Both rings are 250 mm high and a 280 mm diameter inner and a 530 mm diameter outer ring arranged concentrically and hammered to a depth of at least 50 mm into the ground surface. A graduated rule was driven into the surface within the inner ring. Both rings were filled with water to a referenced level initially and maintained at that level after every reading so as to maintain a constant water head. The purpose of the outer ring is to reduce errors in the measurement caused by lateral movement of water through the soil. Replicate measurements were not carried out as ratio of the plots size to the infiltrometers are taken to be a fair representation of the plot. The rings of the double ring infiltrometer are heavy to move, measurement takes time and is tedious requiring considerable effort and time in setting up a further constraint due to the length of study (McKenzie et al., 2002; Maheshwari, 1996).

The results of the log-log cumulative infiltration measurements were fitted to Kostiakov (Equation 4 and 5) and Philip's (Equations 6 and 7) empirical equations to select the model that provides a good fit for the data. Estimated field saturated hydraulic conductivity (K_{fs}) values was determined as an average from the last five minutes of the steady state infiltration rate.

Kostiakov

$F_t = at^n$ Kostiakov equation for cumulative infiltration…………………..equation 4

where F_t = cumulative infiltration at time t (mm), t = time (h), a (mm h^{-1}) and n (dimensionless) constant.

Differentiation of equation 1 gives:

$I_t = ant^{n-1}$ Kostiakov equation for infiltration rate……………………equation 5

where I_t = infiltration rate at time t

Philip's

$F_t = at^{0.5} + bt$ Philip's equation for cumulative infiltration………………equation 6

where F_t = cumulative infiltration at time t (mm), t = time (h), a (mm $h^{-0.5}$) and b (dimensionless) are constants.

Differentiation of equation 3 gives:

$I_t = 0.5\ a\ t^{-0.5} + b$ Philip's equation for infiltration rate………………………equation 7

where I_t = infiltration rate at time t and t = time (h)

To determine objective 4 - to measure and evaluate the effect of vegetation and its management on topsoil moisture content, water infiltration rate and hydraulic conductivity the following sub- hypothesis was tested:

Null hypothesis: Urban vegetation species and its management have no effect on soil moisture content, infiltration rate and hydraulic conductivity.

Alternative: Urban vegetation species and its management have an effect on soil moisture content, infiltration rate and hydraulic conductivity.

4.2.5 Statistical analyses

The above hypothesis was tested based on the results and analysed to determine whether the null hypothesis can be rejected. The objective of the analysis was to quantify any differences in soil moisture content, infiltration rate and hydraulic conductivity between vegetation types. Testing for the interaction effects of treatments between the treatments was not possible because of the insufficient number of replicate and control plots. All the data were analysed quantitatively using the IBM SPSS Statistics (IBM Corp. IBM SPSS Statistics for Windows, Version 22.0.0 Armonk, NY: IBM Corp.). Descriptive analyses and data checking operations were run for outlier detection and normal distribution of data. Where normal distribution of data did not occur various data transformation attempts using square root, log, reciprocal and reverse score were used. Analysis was carried out on raw data where transformation attempts did not improve the normality of the data and results are taken as valid (www.statistics.laerd.com, Rivas Casado, 2014, Pers.Com). The soil physical properties data were analysed for statistical significance ($p < 0.05$) using a one-way ANOVA to compare the means of the values. The statistical analysis for soil moisture content, infiltration rate and hydraulic conductivity, the experimental design involved two levels of treatment: floral and structural, therefore a two-way ANOVA was used to compare means of the values. Where a difference was observed based on the homogeneity of variances as assessed by Levene's test, the Tukey HSD or Games-Howell post-hoc analysis was used to evaluate statistical significance between means.

4.3 Results

The experimental design was unbalanced for complete statistical analysis to be carried out. The experimental design allowed for only pseudoreplicates to assess the effect of structural and floristic diversity; interaction effects of structural and floristic diversity on urban vegetation species on soil moisture content, infiltration rate and hydraulic conductivity could not be determined; infiltration rate and saturated hydraulic conductivity results using the double ring infiltrometer had no replicates for plots and so results should be taken with caution.

Except for estimated unsaturated hydraulic conductivity measurements carried out at 5 mm suction, for the analysis of results not all values could be used. From the 90 measurements carried out for infiltration rate a total of 82 and 41 were used for 20 mm and 5 mm suctions respectively; for estimated unsaturated hydraulic conductivity a total of 76 values was used for 20 mm suction. The excluded results are discussed in Appendix A.1. Infiltration rate after one hour of infiltration into the soil was used for discussion. This length of time was chosen because observed steady state infiltration rate varied for the plots from 34 minutes to 121 minutes.

4.3.1 Soil properties

4.3.1.1 Topsoil texture

Table 4.2 presents average values of the particle size composition: sand fractions were lower in the NFS (20 %) than in the NM (33 %). The other plots had a similar sand content value. Silt contents were higher in NFS (35 %) than the MFT and MFM (both 30 %). The highest clay content was on the SFT (52 %) significantly higher than in the

MFS, NFS, MFM, NFM and the NM plots. The soil texture value of the plots were plotted onto a soil textural triangle (Figure 4.6).

Table.4.2
Mean sand, silt and clay (in %) distribution of each experimental plot with standard deviation in brackets.

Plot name	Sand % (n = 3)	Silt % (n = 3)	Clay % (n = 3)
Many flowers tall	27(6.46) $^{a, b, c}$	30 (0.60)^{b}	42(4.91)$^{a, d}$
Many flowers short	31(1.27) $^{b, c}$	31(2.16) $^{a, b}$	37(0.90) ^{a}
No flowers tall	27(3.26) $^{a, b, c}$	32 (1.28)$^{a, b}$	40 (4.01) $^{a, c}$
Some flowers medium	27(1.38) $^{a, b, c}$	31(3.14) $^{a, b}$	42(4.37) $^{a, b, d}$
Some flowers tall	23 (4.12)$^{a, b, c}$	25 (2.46)$^{a, b}$	51(1.81) ^{d}
Some flowers short	21(4.69) $^{a, b}$	44 (17.27) $^{a, b}$	35 (12.59) ^{a}
Many flowers medium	27 (0.86)$^{a, b}$	30 (0.84)^{b}	43 (0.76) $^{b, c}$
No flowers short	20 (7.14) ^{a}	35 (0.60) ^{a}	45 (6.89) $^{a, b, c, d}$
No flowers medium	26 (1.38) $^{a, b}$	32 (0.98) $^{a, b}$	42 (0.51) ^{b}
Non- manipulated	33 (4.96) ^{c}	34 (6.82) $^{a, b}$	33 (2.70)^{a}

Different superscript letters in the same column indicate significant difference at $p < 0.05$ in the mean between the treatments following the one way ANOVA

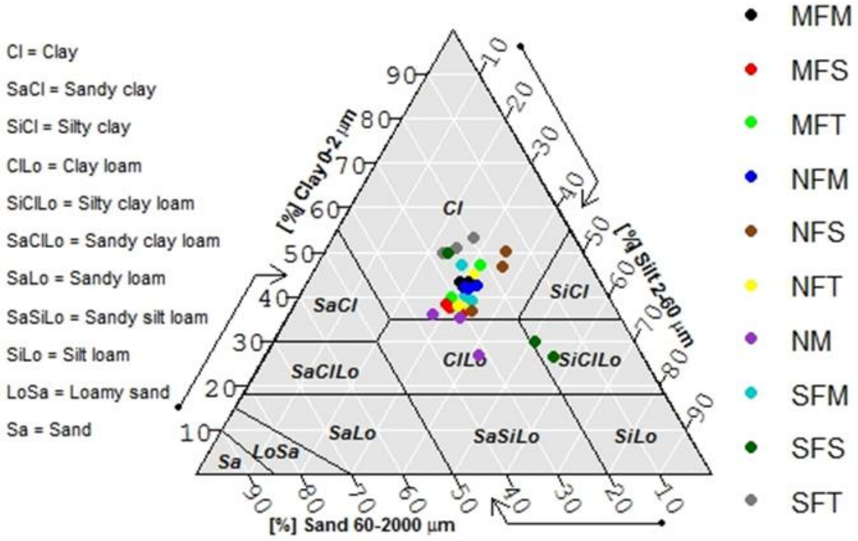


Figure 4.6 Soil texture of the experimental plots based on the SSEW soil texture classification system.

Furthermore, sand varied between the plots by up to 13%, silt by 5% and clay by 18% highlighting the heterogeneous composition of the topsoil texture of the site

4.1.1.1 Bulk density (BD), Porosity (*P*) and Soil organic matter (SOM)

The plots had mean bulk density which ranged from 0.80 to 1.2 g cm^{-3} and mean porosity ranging from 54 to 70%, while mean soil organic matter ranged from 10 to 15%. Bulk density on the SFT (0.91 g cm^{-3}), SFS (0.90 g cm^{-3}) and MFM (0.85 g cm^{-3}) plots were significantly lower than on the MFS (1.17 g cm^{-3}) plot. Porosity increases as bulk density decreases and vice-versa (Table 4.3), a relationship shown in equation 5, Section 4.2.3.1. Soil organic matter on MFT (15%) plot was significantly higher than SFM (10%), NFT (11%), and SFS (11%); NM (14%) was significantly higher than SFM (10%) (Table 4.3). The SOM values were high, which may be related to the method of analysis as highlighted in Section 4.2.3.3.

Table.4.3
Mean soil physical properties for nine experimental and one non-manipulated plot for bulk density (BD), porosity (*P*) and soil organic matter (SOM) of experimental site.

Plot name	**BD** (g cm^{-3}) n = 3	***P*** (%) n = 3	**SOM** $^{+}$ (%) n = 2
Many flowers tall	1.05$^{a, b}$	60$^{a, b}$	15^{c}
Many flowers short	1.17^{b}	56^{b}	12$^{a, b, c}$
No flowers tall	1.05$^{a, b}$	60$^{a, b}$	11$^{a, b}$
Some flowers medium	0.95$^{a, b}$	64$^{a, b}$	10^{a}
Some flowers tall	0.91^{a}	65^{a}	12$^{a, b, c}$
Some flowers short	0.90^{a}	66^{a}	11$^{a, b}$
Many flowers medium	0.85^{a}	68^{a}	14$^{a, b, c}$
No flowers short	0.98$^{a, b}$	63$^{a, b}$	12$^{a, b, c}$
No flowers medium	1.03$^{a, b}$	61$^{a, b}$	13$^{a, b, c}$
Non- manipulated	0.97$^{a, b}$	63$^{a, b}$	14$^{b, c}$

+Results based on loss on ignition analysis. Different superscript letters in the same column indicate significant difference at $p < 0.05$ in the mean between the treatments following the one way ANOVA

4.3.2 Vegetation height and cover

The grass mix and meadows were allowed to fully establish, so as to achieve a good overall ground cover and manipulated structural plant heights (Section 4.2.1) before taking measurements. The results for vegetation height is shown in Table 4.4 while the results for vegetation cover shows all the plots have > 95% cover (Appendix B.3).

Table.4.4
Mean and standard deviation of minimum and maximum vegetation height (mm) according to structural and floristic diversity in September and December 2014.

Combination of manipulation(groups)		n = 36			
		Minimum vegetation height mm		Maximum vegetation height mm	
		Mean	*SD*	Mean	*SD*
Non - manipulated		8.3	0.3	28.3	0.85
Structural diversity levels	Floristic diversity levels				
Short	No	18.6	1.2	86.7	1.9
	Some	15.9	0.7	81.7	2.5
	Many	15.3	0.8	72.1	1.9
Medium	No	20.7	1.0	73.7	2.5
	Some	7.7	7.4	68.5	2.3
	Many	20.6	1.3	209.1	11.4
Tall	No	12.4	1.4	830.5	38.1
	Some	8.7	11.4	885.3	27.8
	Many	8.8	15.2	885.3	27.7

4.3.3 Soil moisture content

The mean soil moisture content varied on the manipulated plots from 20 to 23% in September and from 46 to 49% in December. The NM had a mean of 22% in September and 44% in December (Table 4.5). The difference in mean soil moisture content is related to the temporal variations, September being a dry period characterised by very low precipitation and increased evapotranspiration, while December is when generally water content ranges between field capacity and saturation. There was a marginal significant difference ($p < 0.05$) among urban vegetation types due to structural diversity in September, the tall greater than the medium and short. There was no significant difference due to floristic diversity in both September and December (Appendix B.4).

Table.4.5
Mean and standard deviation (pseudoreplicates) of soil moisture content according to structural and floristic diversity in September and December 2014.

Combination of manipulation(groups)	**Soil moisture content n = 36**			
	September		December	
	Mean %	*SD*	Mean %	*SD*
Non – manipulated	22.4	5.9	44.4	3.5

Structural diversity levels	Floristic diversity levels				
Short	No	22.2	4.7	48.1	1.3
	Some	22.4	4.9	45.9	2.8
	Many	20.6	4.6	47.8	1.6
Medium	No	21.5	4.8	46.2	2.3
	Some	22.8	5.3	48.6	1.1
	Many	23.3	4.0	47.3	2.0
Tall	No	19.9	5.1	46.2	2.3
	Some	20.8	5.6	47.8	1.9
	Many	20.5	4.7	48.5	1.2

The mean soil moisture content value varied from 37% to 49% on the experimental plots when measured on the same day that saturated hydraulic conductivity measurement was carried out (Table 4.6). However, there was no significant difference between vegetation types due to the variability between replicates.

Table.4.6
Means of bulk density, porosity, and soil moisture content (SMC) on different days of measurements) of each experimental plot.

Plot name	BD (g cm^{-3}) n = 3	*P* (%) n = 3	SMC on day of infiltration measurements (%) n = 3	
Many flowers tall	1.05$^{a, b}$	60$^{a, b}$	45^{a}	15/10/15
Many flowers short	1.17^{b}	56^{b}	41^{a}	14/10/15
No flowers tall	1.05$^{a, b}$	60$^{a, b}$	46^{a}	12/10/15
Some flowers medium	0.95$^{a, b}$	64$^{a, b}$	45^{a}	8/10/15
Some flowers tall	0.91^{a}	65^{a}	49^{a}	19/10/15
Some flowers short	0.90^{a}	66^{a}	41^{a}	20/10/15
Many flowers medium	0.85^{a}	68^{a}	37^{a}	13/10/15
No flowers short	0.98$^{a, b}$	63$^{a, b}$	44^{a}	23/10/15
No flowers medium	1.03$^{a, b}$	61$^{a, b}$	42^{a}	17/10/15
Non- manipulated	0.97$^{a, b}$	63$^{a, b}$	41^{a}	17/10/15

symbols stand for: ρa (bulk density, P (total soil porosity). Different superscript letters in the same column indicate significant difference at $p < 0.05$ in the mean between the treatments following the one way ANOVA

The mean soil moisture content measured on infiltration spot a day after infiltration measurement was carried out ranged from 43 to 50% (Table 4.7). The difference in mean between plots did not show a change that can be related to the applied treatments on plots. Soil moisture content was significantly higher ($p < 0.05$) in NFM (50%) and SFS (50%) than in other treatments.

SMC after a day (22/10/2015) of rainfall was also carried out to determine any difference in moisture content on the assumption that each plot had an equal amount of the rainfall. The SMC mean was not significantly different between plots but had a range from 35 to 48% (Table 4.7). The lowest mean value may have been influenced by a very low sampling point value (25%).

Table.4.7
Mean soil moisture contents (SMC) a day after infiltration measurements and a day after a rainfall event of 2.6 mm on the 21/10/2015.

Plot name	SMC a day after on infiltration spot (%) n = 3	SMC after a day (22/10/15) of rainfall (%) n = 3
Many flowers tall	$49^{d, e, f}$	48^{a}
Many flowers short	$46^{b, c,}$	44^{a}
No flowers tall	$45^{a, b}$	47^{a}
Some flowers medium	$49^{c, d, e, f}$	48^{a}
Some flowers tall	$47^{b, c, d}$	43^{a}
Some flowers short	$50^{e, f}$	35^{a}
Many flowers medium	43^{a}	45^{a}
No flowers short	$48^{c, d, e, f}$	46^{a}
No flowers medium	50^{f}	46^{a}
Non- manipulated	$47^{b, c, d, e, f}$	43^{a}

Different superscript letters in the same column indicate significant difference at $p < 0.05$ in the mean between the treatments following the one way ANOVA

The change in soil moisture content between the two times of measurement (September and December) was tested by effect size to determine the soils ability for water intake comparing the manipulated plots to the non-manipulated (Figure 4.7). Soil moisture increased significantly on manipulated plots compared to the non-manipulated. The NFS wetted up more than the non-manipulated.

The results in Table 4.8 shows the significant relationship using the Pearson's correlation between the soil moisture content and clay content.

Table.4.8
Significance levels (p-value) of soil moisture and clay content derived from Person's correlation

Variables	***r* value**	**Sign. ($p < 0.05$)**
SMC_{dry} & CLAY	-0.16	0.66
SMC_{wet} & CLAY	0.62	0.05
$SMC_{@FC}$ & CLAY	-0.19	0.60

SMC - soil moisture content, FC – field capacity

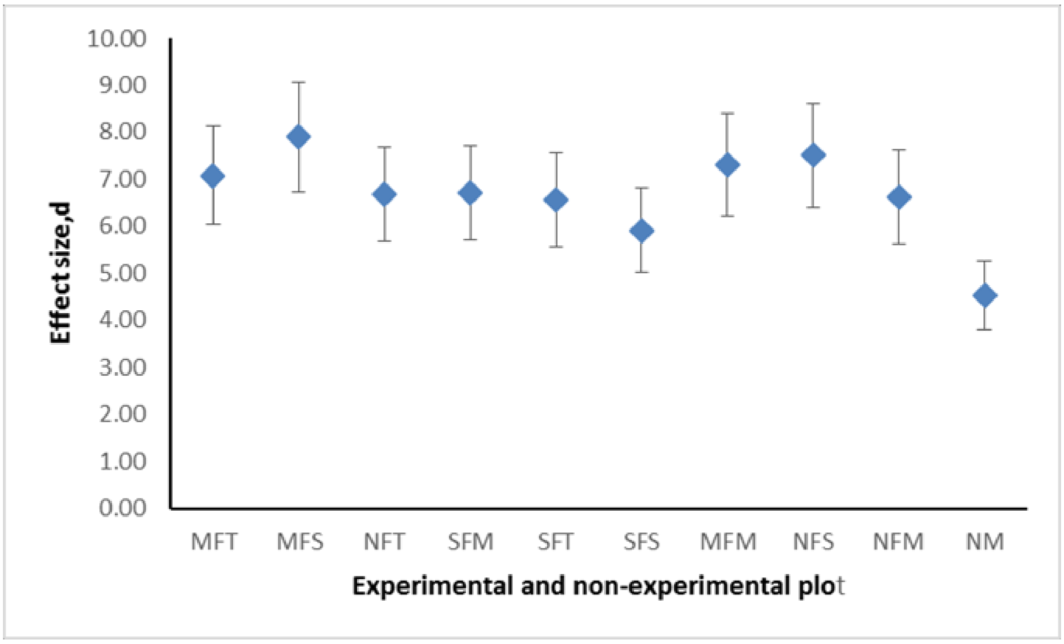


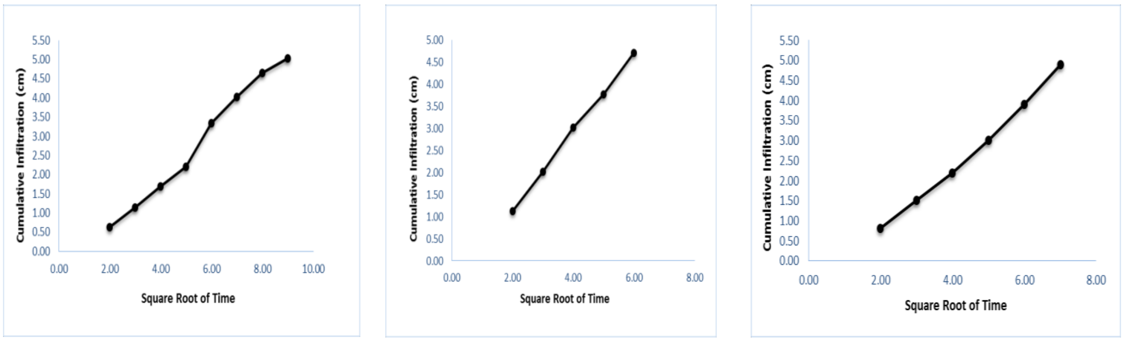
Figure 4.7 Mean effect size, d on soil moisture content for the nine manipulated and one non-manipulated plot. Error bars show ± 95 % confidence interval.

4.3.4 Hydraulic parameters

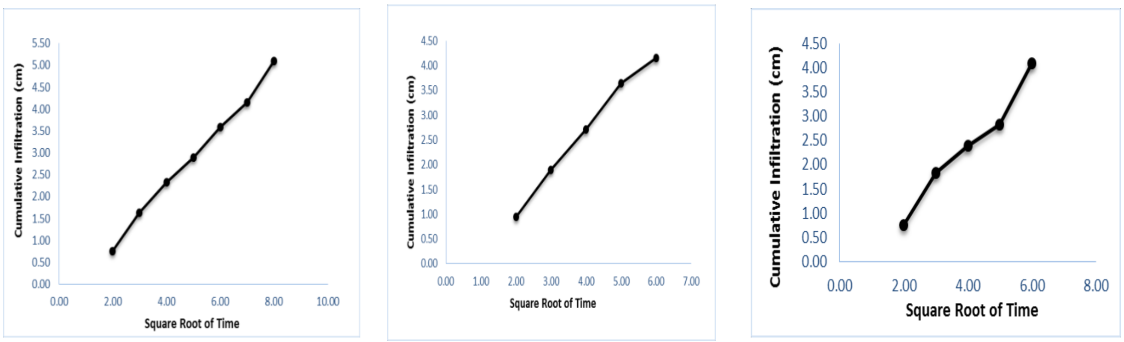
The cumulative infiltration was plotted against the square root of time for each measurement carried out and values for infiltration rate and unsaturated hydraulic conductivity was determined. The results suggest that the smaller diameter pores range dominate flow under unsaturated conditions. Figure 4.8 shows representative plots for each of the manipulated and non-manipulated plots using the 5 mm tension

4.3.4.1 Infiltration rate

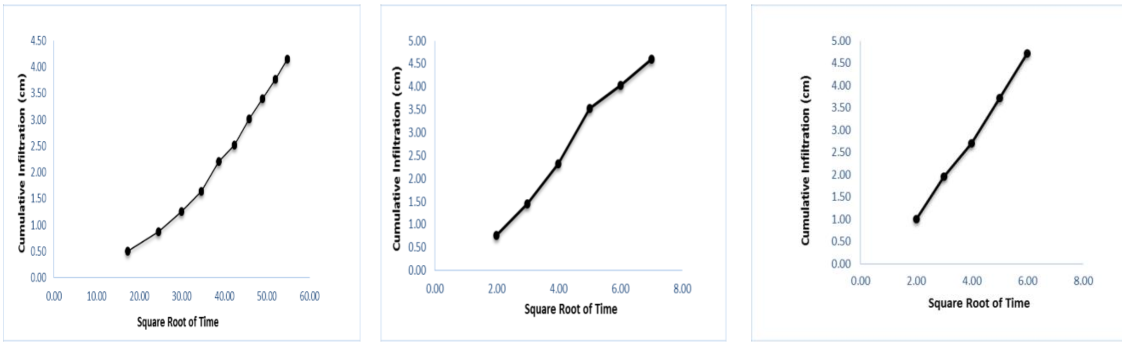
The mean infiltration rate at one hour on manipulated plots ranged from 5 to 25 mm h^{-1} and 41 to 100 mm h^{-1} using 20 mm tension (when the soil was dry) and 5 mm tension (when the soil was wet) respectively (Table 4.9). On the non-manipulated plot infiltration rate was 4 and 70 mm h^{-1} using 20 and 5 mm tension respectively. Infiltration rate under saturated conditions (using the double ring infiltrometer) ranged from 176 to 1771 mm h^{-1} and 172 mm h^{-1} for manipulated and non-manipulated plots (Figure 4.9). There was no significant difference due to structural and floristic levels of diversity (Appendix B.5).



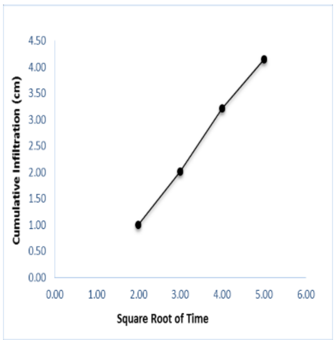
Plot 8: No flowers short Plot 6: Some flowers short Plot 2: Many flowers short



Plot 9: No flowers medium Plot 4: Some flowers medium Plot 7: Many flowers medium



Plot 3: No flowers tall Plot 5: Some flowers tall Plot 1: Many flowers tall



Plot 10: Non-manipulated

Figure 4.8 Representative plots of cumulative infiltration amount against square root of time for experimental plots using the Decagon minidisk infiltrometer at 5 mm tension.

Table.4.9
Mean and standard deviation of infiltration rate, at one hour, according to manipulation of structural and floristic diversity and non-manipulated plots in September and December 2014 with number of samples in brackets (pseudoreplicates).

Combination of manipulation groups		Infiltration rate (mdi)		Infiltration rate (dri)
		Sept.(20 mm tension)	Dec.(5 mm tension)	
		Mean mm h^{-1}		mm h^{-1}
Non - manipulated		4.34 ± 21(9)	70.36 ± 27.11(6)	144.0 (1)
SDL	FDL			
Short	No	7.99 ± 9.2(7)	62.73 ± 8.94(2)	57.0 (1)
	Some	9.88 ± 5.3(8)	65.58 ± 24.20(5)	224.8 (1)
	Many	9.29 ± 4.1(8)	67.87 ± 21.17(3)	187.8 (1)
Medium	No	19.74 ± 9.4(9)	91.31 ± 22.86(3)	209.7 (1)
	Some	7.93 ± 5.3(8)	45.47 ± 36.42(7)	227.9 (1)
	Many	10.11 ± 8.1(9)	99.80 ± 33.20(4)	158.4 (1)
Tall	No	24.66 ± 18.1(9)	78.50 ± 29.24(3)	167.6 (1)
	Some	5.12 ± 4.4(8)	40.68 ± 26.81(6)	66.1 (1)
	Many	8.50 ± 8.1(7)	89.81 ± 22.16(2)	190.2 (1)

SDL – structural diversity levels, FDL – floral diversity levels. mdi – decagon mini disk infiltrometer, dri – double ring infiltrometer

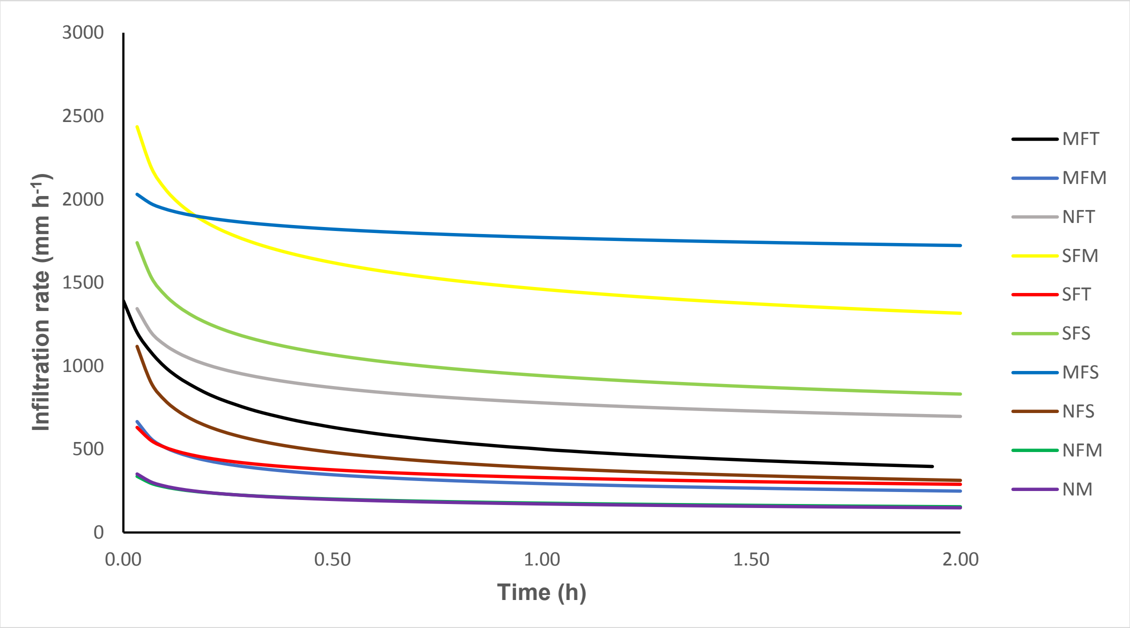


Figure 4.9 Infiltraton rates on the ten experimental plots, Cranfield using the double ring infiltrometer

4.3.4.2 Hydraulic conductivity

The estimated mean unsaturated hydraulic conductivity on manipulated plots ranged from 31 to 109 mm d^{-1} and 274 to 1378 mm d^{-1} using the 20 mm and 5 mm tension respectively (Table 4.10). On the non-manipulated plot estimated unsaturated hydraulic conductivity was 17 and 1094 mm d^{-1} using the 20 mm and 5 mm tension respectively. The estimated saturated hydraulic conductivity ranged from 287 to 1378 mm h^{-1} and 89 mm h^{-1} for manipulated and non-manipulated plots respectively using the double ring infiltrometer. There was no significant difference in hydraulic conductivity as a function of structural and floristic diversity (Appendix B.6).

Table.4.10
Mean and standard deviation (pseudoreplicates) of estimated unsaturated hydraulic conductivity at both 20 mm and 5 mm suction according to structural and floristic diversity in September and December 2014.

Combination of manipulation groups		Est. unsaturated hydraulic conductivity (mdi)		Est. saturated hydraulic conductivity (dri)
		20 mm tension	5 mm tension	
		Mean mm d^{-1}		mm h^{-1}
Non - manipulated		16.55 ± 11.30(7)	1094.0 ± 160.20(9)	891.7 (1)
SDL	FDL			
Short	No	101.47 ± 120.9(8)	1184.00 ± 431.40(9)	286.7 (1)
	Some	65.26 ± 46.34 (9)	976.33 ± 556.07(9)	976.3 (1)
	Many	46.76 ± 30.39(9)	905.67 ± 261.17(9)	976.3 (1)
Medium	No	64.58 ± 78.56(5)	1378.33 ± 144.64(9)	1370.7 (1)
	Some	31.29 ± 14.16(6)	310.67 ± 164.02(9)	1378.3 (1)
	Many	56.25 ± 47.16(8)	1211.47 ± 4.38(9)	944.7 (1)
Tall	No	109.20 ± 47.04(8)	944.37 ± 130.24(9)	905.7 (1)
	Some	74.22 ± 58.86(7)	274.72 ± 43.06(9)	310.7 (1)
	Many	79.39 ± 88.29(9)	1370.71 ± 629.70(9)	1184.0(1)

SDL – structural diversity levels, FDL – floral diversity levels, mdi – decagon mini disk infiltrometer, dri- double ring infiltrometer

The large variations in hydraulic conductivity measurements that exist between replicates could be a reason for the lack of significant difference between treatments.

Estimated hydraulic conductivity values were determined using both the minidisk and double ring infiltrometers.

4.3.5 Limitations of the data

There were limitations in the data collected on the experimental site. This restricted the outcome of conclusions for the research, like root density for each plot.

The soil moisture content, infiltration rate and hydraulic conductivity showed no significant difference due to structural and species richness of vegetation which could be due to lack of replicate sites.

The interaction effect of species richness and structural diversity was not assessed also due to the lack of replicate sites.

4.4 Discussion

4.4.1 Soil properties

Soil particle size composition results showed that the soil on all the experimental plots are clay except the SFS plot, a silty clay loam which could be due to the possibility of an error in measurement for the SFS plot. Furthermore, the significant difference in particle size between plots highlights the heterogeneous composition of the topsoil texture of the site. The difference in particle size suggests also that the measured hydraulic activity would be higher on the NM which has higher sand content than on the NFS when the soil is wet and meso and macropores are filled with water. The measured soil properties, BD and SOM also showed significant differences that could affect plot response. Measurements were taken once, so representative of pre-existing soil conditions. The experimental plots had a range of BD considered not generally compacted as soils with BD > 1.5 g cm^{-3} are considered to be compacted restricting root growth (Ossola *et al.*, 2015). The insignificant difference between manipulated and non-manipulated plots suggests that the soil structure which was altered by tillage on the manipulated plots may have deteriorated and also that the possible compaction due to wheels of the mower was not significant to increase the soil compaction.

In conclusion, the plots have been shown to belong to the clay soil type minimizing variation in soil properties, except the plot that is silty clay loam, suggesting that the subsequent soil properties measured could be influenced by this variation.

4.4.2 Soil moisture content

Changes in soil water content among plots was explained in terms of temporal effects, but the difference in the soils ability to intake water, (as measured by determining the effect of size on the difference between plots in mean soil moisture content), suggests that the difference in soil moisture content is also due to the difference in soil structure related to the applied tillage on the manipulated plots. The other likely mechanism responsible for this change in soil moisture content maybe the higher clay content on some of the plots which is the constituent that produces a larger surface area within the soil structure with more micro pores for water absorption (Brady, 1990). There was a significant relationship between soil moisture content in wet soil and percentage clay content.

Another likely mechanism maybe that the manipulated vegetation on the plots may have contributed to the alteration of the soil structure by the penetration of plant roots creating bio-pores resulting in higher water storage on the plots.

4.4.3 Infiltration rate

In general, decreases in infiltration rate has been associated with increasing clay content (Ketema and Yimer, 2014), but this pattern is not seen on the experimental plots. The lowest infiltration rate result using the double ring infiltrometer and clay content is on the NM plot 169 mm h^{-1} while the plot with the highest clay content SFT, has 335 mm h^{-1} infiltration rate. There was an insignificant relationship between infiltration rate and percentage clay content. However, this contradicts the findings of Moya, (2014) in which soil texture proved to be a physical characteristic that greatly affects the rate of water infiltration into the soil. The large variations in infiltration rate that existed between replicates could be a reason for the lack of significant difference between treatments. The large variation in infiltration rate also suggests that the soil texture below 0.2 m depth maybe different on the plots. The antecedent soil moisture content could have also been a factor contributing to the low infiltration rate, the antecedent moisture content on SFT was 49% while that on the NM was 41%.

The plot with the highest infiltration rate SFM of 1441 mm h^{-1} has antecedent moisture content of 45% and high saturated hydraulic conductivity 1309 mm h^{-1} with the NM having the lowest infiltration rate and hydraulic conductivity suggesting a preferential flow due to macro pores present from plant roots or earthworm paths.

The different plots had varying times of reaching steady state infiltration rate which ranged from the earliest 34 minutes in the SFS and maximum of 121 minutes in both the NFM and NM plots. Infiltration rate decreased at higher negative pressure under unsaturated conditions. In dry clay soil increase in infiltration rate may also be controlled by a structural change not related to tillage suggesting the presence of cracks in the soil.

Flow of water through pores under saturated conditions is also higher than under unsaturated conditions also suggesting the possibility of an effect due to vegetation type altering the soil structure. There was an insignificant relationship between infiltration rate measurements using the minidisk infiltrometer and bulk density. This was not the case with the double ring infiltrometer measurements where the relationship was marginally significant suggesting soil macropores affecting infiltration rate. Macleod et al (2013) found from their study that differences in infiltration rate are due to differences in the spatial organization of soil, commonly referred to as soil structure.

4.4.4 Hydraulic conductivity

The different vegetation type with levels of structural diversity did not show any effect on hydraulic conductivity. Gregory et al (2010) also using a tension infiltrometer on clay soil assessed the effect of different grass species on hydraulic conductivity and found that the hydraulic conductivity of capillary matrix was affected but the macro pore structure was not affected, therefore there was no difference between grass species.

Estimated soil hydraulic conductivity decreased at higher negative pressure under unsaturated conditions. According to Gallage et al. (2013) hydraulic conductivity of an unsaturated soil is a variable which is largely a function of the water content or the matric suction of the unsaturated soil. In an unsaturated soil, the hydraulic conductivity is considerably affected by the degree of saturation (or water content) of the soil. According to them, in unsaturated soil air first replaces some of the water in the larger pores, causing the water to flow through the smaller pores with an increased tortuosity of the flow path. Increase in the matric suction of the soil leads to a decrease in the pore volume occupied by the water. This leads to the further resistance to water flow when the air-water interface draws closer and closer to the soil particles. As a result, the hydraulic conductivity, with respect to the liquid (water) phase, decreases rapidly as the space available for the water flow declines. Soil hydraulic conductivity was higher in wet soil condition than in dry soil condition suggesting that the wetting process facilitates soil expansion which effectively decreases soil bulk density (Hu *et al*., 2012).

Hydraulic conductivity of clay soils is normally considered to be low and to be varied depending on soil compaction (Benson and Trast, 1995). This contradicts the findings of the study in which hydraulic conductivity had an insignificant relationship with bulk density.

Estimated hydraulic conductivity was highest under saturated conditions from double ring infiltrometer measurements. This could be due to the creation of preferential flow by roots of the vegetation cover in the soil (Halabuk, 2006; Stekauerova *et al.*, 2006).

However, the experimental design met a number of limitations, which restricted statistical analyses.

4.5 Conclusions

The experimental study in contrast to the field scale study measured the effect of species richness and structural diversity. The objective was to characterise experimental site based on the soil type, vegetation diversity and management, and to measure and evaluate the effect of vegetation and its management on topsoil moisture content, water infiltration rate and hydraulic conductivity. The main conclusions which can be drawn are the following:

1. The study site was selected so that measurements would be on a homogenous soil so that measurements are considered a fair test by removing the potential of soil physical properties influencing hydraulic properties but the results showed the heterogeneous spatial variability of soils.
2. The infiltration rate and hydraulic conductivity vary for the different species richness and its management, even though not significantly different. Hence, there is no detrimental effect of changing vegetation type.
3. The soil moisture content was significantly different between the manipulated and non-manipulated plot, attributed to the management effect of tillage on the manipulated plot altering the soil structure to increase pore spaces.
4. The variation in infiltration rate and hydraulic conductivity are due to an alteration in soil structure attributed to the species diversity, as there is no evidence of soil textural effect since the soil was clay.

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5 Research synthesis and conclusions

This research has sought to address an aspect of the effect of greenspaces on soil hydrology within the urban ecosystem. The aim of this study as stated in Section 1.1.1 , is to determine the effect of urban vegetation type, species and its management within urban ecosystems to deliver a water regulatory service (with soil moisture content, water infiltration rate, hydraulic conductivity as indicators) . This was addressed by carrying out the study in two phases that set out to test the main hypothesis.

The field surveys (fragments) of Phase 1 carried out in the towns of Bedford, Luton and Milton Keynes, and the experimental plots (manipulated vegetation) of Phase 2 carried out in Cranfield, UK provided understanding of the soil parameters (infiltration rate, hydraulic conductivity, and soil moisture content) within the urban ecosystem. The data were analysed using statistical analysis (Chapter 3 and 4). This research has focused on three factors which can be altered through changing vegetation:

1 Change in infiltration rate
2 Change in hydraulic conductivity
3 Change in storing of water (soil moisture content)

In Chapter 3 the null sub-hypothesis states that urban vegetation types have no significant effect on infiltration rate and hydraulic conductivity: Results presented in the chapter indicate that there was indeed no change in infiltration rate between urban vegetation types (categories included trees, shrubs and grass; Section 3.2.2) and so the hypotheses was accepted. However, unsaturated hydraulic conductivity changed between the urban vegetation types dependant on the soil type, this was shown by the managed grass having higher unsaturated hydraulic conductivity value than unmanaged herbaceous on a sandy loam soil, and so the hypotheses was rejected.

In Chapter 4 the null sub-hypothesis states that urban vegetation species (selected perennial forb and grass species: Appendix B.1) and its management have no effect on soil moisture content, infiltration rate and hydraulic conductivity: Results presented in the chapter indicate that soil moisture content changed due to applied management of tillage non clay soil, therefore the hypotheses was rejected. This was shown on the results comparing soil moisture content on the manipulated (0.15 m tillage applied) and non-manipulated (no tillage) plots.

Species richness and plant height did not change soil moisture content, infiltration rate and hydraulic conductivity on clay soil. The result showed that the values varied, but was not significantly different between the treatments. Therefore the hypotheses was accepted.

5.1 Research limitations

The research project has looked at soil properties at different scales: field and plot. This was important in the F3UES study for the biodiversity and flows aspect of the study; however, it was not necessary for the study of soil hydrological properties. The differences in soil texture on the field scale study produced an unbalanced design, which was not encountered in the plot scale study. This shows the importance of soil texture as a factor to consider within an experimental design to enable best statistical analysis. The inability to measure soil physical properties including bulk density for better results and discussion of the field study phase for clearer conclusions.

The lack of infield measurements of runoff rate and volume to simulate scenarios and determine runoff generated.

5.2 Effect of urban vegetation type and its management on soil hydrological properties

This section will integrate the main findings relating to the effect of vegetation type and its management on soil hydraulic and hydrological properties from the field and plot scales.

5.2.1 Infiltration rate

The results showed that urban vegetation type had no detectable change in infiltration rates in the urban ecosystem. The field scale study (Chapter 3) that tested the sub-hypotheses (Section 3.3.3) showed the infiltration rates under urban vegetation plants (managed grass, managed herbaceous, shrubs, trees over managed grass, trees over unmanaged herbaceous, unmanaged herbaceous, and woodland/trees) were not significantly different regardless of soil texture. The plot scale experimental study (Chapter 4) on clay soil also shows no difference between vegetation types (urban grass species) related to species richness and plant height. Both results suggesting that there is no difference due to urban vegetation, species richness and its management. Fischer *et al*. (2014) measured infiltration capacity on plots containing

1,4 and 16 plant species on sandy loam soil in Jena, Germany, even though a different soil type, the results showed no significant difference due to increase in species richness. The same study showed legumes increased infiltration capacity while it decreased on the grass plots. They related the lack of difference due to species richness to the effect of roots indirectly supressing modification of the soil structure and significant difference between the vegetation types to roots directly modifying the pores of the soil.

This research has also shown other insights that are not part of the set out objective. It showed that infiltration rate using the minidisk infiltrometer (0.5 cm suction) is about half the rate using the double ring infiltrometer on all the manipulated plots, with the exception of two of the manipulated plots. This highlights a confirmation on the fact that infiltration rate values are dependent on the methods used to measure infiltration rate (Mohanty *et al*., 1994; Reynolds *et al*., 2000).

In summary, the results showed that infiltration rate did not change with vegetation type, increased species richness and its management, even though there is a variation in infiltration rate values for the different vegetation types. However, the values are higher using the double ring infiltrometer than the minidisk infiltrometer, suggesting the presence of macropores created by the vegetation type at the soil surface. It is therefore concluded that where the use of a double ring infiltrometer is not convenient, lower suction values for minidisk infiltrometers should be used for studies where the effect of vegetation type is aimed at determining the altering effects of the plant on soil structure.

This study also corroborates other studies in showing that initial soil moisture content has an effect on infiltration rate (Fischer et al., 2015; He et al., 2009), as evidenced by situations that wet soil had a lower infiltration rate. Even though infiltration rate is faster in soils with larger pores, compared to the finer textured soils (Section 3.4.2), increase in soil infiltration rate can be associated with vegetation type that alters the soil structure and creates large (possibly continuous) pores from the roots, as these increases the infiltration rate of the soil.

In conclusion, there is no change in infiltration rate related to the urban vegetation species or increase in floral and structural diversity, regardless of soil texture suggesting infiltration rate on top soil surface is not altered by vegetation type.

5.2.2 Hydraulic conductivity

The field scale study (Chapter 3), which included an evaluation of the effect of vegetation type on hydraulic conductivity, showed that managed grass has a higher unsaturated hydraulic conductivity (308 ± 223 mm d^{-1}) than unmanaged herbaceous (88 ± 51 mm d^{-1}) on sandy loam soil. This suggests the presence of more or bigger pores on the managed grass soil surface from the roots, therefore conducting more water flow. The shorter more fibrous nature of the grass creating connecting macropores compared to the taproot nature of the unmanaged herbaceous. The plot scale experimental study (Chapter 4) on clay soil showed no difference in hydraulic conductivity related to urban vegetation species structural and floral diversity. Both studies (Chapter 3 and 4) show a lack of difference in hydraulic conductivity related to vegetation type and urban vegetation species manipulation on a clay soil.

The difference of hydraulic conductivity shown by vegetation type on sandy loam soil and lack of difference in other measured soil types (clay loam and clay) of the study was attributed to the dominant effect of soil texture, which could have masked any differences due to vegetation type. Generally, clays have lower hydraulic conductivity because they contain clay particles that are smaller than sandy loam soils, which have larger soil particles (Benson and Trast, 1995). However, the measurements on grassed swales with soil texture (loamy sand, loam, and silt loam) found significant difference of mean field saturated hydraulic conductivity (Ahmed *et al*., 2015), highlighting the effect of soil texture on hydraulic conductivity, in comparison to the results of this study on the sandy loam soil between vegetation types.

This research has also shown other insights that are not part of the set out objective of the study. In terms of hydraulic conductivity under unsaturated soil conditions determined using the minidisk infiltrometer values for the manipulated vegetation, this research on clay soil on plots with manipulated and non-manipulated plots showed that unsaturated hydraulic conductivity is about half the value of estimated unsaturated hydraulic conductivity using the double ring infiltrometer method, thus suggesting that soil macro pores created by plant roots, rather than bulk density, contribute to hydraulic conductivity amongst the urban vegetation types on clay soil.

In summary, the results show that hydraulic conductivity differs according to vegetation type, with notable difference related to soils that have more porous texture and structure. Indeed, Ossola et al. (2015) also show that in habitat complexity and its effect on hydrological processes on sandy soils, low complexity parks have lower saturated hydraulic conductivity than high complexity parks due to the presence of fewer soil macro pores.

5.2.3 Soil moisture content

Soil moisture content was not measured for the field scale study (Chapter 3). The plot scale experimental study (Chapter 4) showed that volumetric soil moisture content was significantly different between treatments after gravitational water was drained. However, there was no change due to species richness or plant height. However, this does not mean that no difference exists, as the lack of difference may be related to the short duration and time specific design of this study.

There was a general difference recorded in soil moisture content due to seasonal variation on the plots, and there was also a difference in soil moisture content between the manipulated and non-manipulated plot due to the tillage applied suggesting an alteration in the soil structure which creates more macro pores.

5.3 Effect of urban vegetation type on delivery of ecosystem services

This study looked at the effect of urban vegetation on hydrological functions of the urban ecosystem through water regulation to provide an ecosystem service. Urban ecosystems and their services need to be managed in the face of increasing urbanization and climatic change. The increase in urbanization and climatic changes include increased sealed surfaces and an increase in intense rainfall events. Therefore, the effect of urban vegetation type, species richness, plant height and its management on soil hydrological processes is important for ecosystem service. This section will integrate the principal findings of these hydrological processes (Chapters 3 and 4). The research determined that vegetation type had an effect on hydraulic conductivity on sandy loam soil. However, soil moisture content, infiltration rate, and hydraulic conductivity even though vary under different vegetation types on clay soil but, there was no observed change that can be attributed to urban vegetation type or increased species richness and its management.

5.3.1 Groundwater recharge

It has long been established that vegetated areas could contribute to solving the declining groundwater levels in many cities (Hino *et al.*, 1987), which result from impermeable surfaces and high abstraction of water (Law *et al.*, 2009; Bolund and Hunhammar, 1999). This is because, contrary to sealed surfaces, the ground surface of vegetated areas allows water to percolate through. This research has shown that different urban vegetation types and increasing species richness lend support to this correlation due to the observed infiltration rate and hydraulic conductivity values. The research has also shown that hydraulic conductivity was different due to vegetation type on a sandy loam soil, which suggests that in order to maximise water flow within the unsaturated zone, soil texture has to be considered as a contributory factor. This was also found in the review study by Redfern *et al.* (2016) on measured urban rainfall and runoff across south east UK, with a comparative study on permeable soils and clay soils. Therefore, the amount of water that percolates to the groundwater varies with soil texture. For example, in this study the managed grass on the clay soil had a mean infiltration rate of 20 mm h^{-1} on the clay loam 16 mm h^{-1} and 32 mm h^{-1} on the sandy loam, mean hydraulic conductivity of about 108 mm d^{-1} on both clay and clay loam soil, and 300 mm d^{-1} on sandy loam soil, highlighting the difference which could be due to the different soil textures. In order to increase the benefits of the greenspaces in improving hydrological processes, land managers could focus on improving the soil pore space for higher water infiltration.

Overall, there was a benefit for changing vegetation type shown in this study. The field study showed that hydraulic conductivity increased under managed grass on sandy loam soils. This increase in hydraulic conductivity would help to increase water flow under the ground surface reducing the likely occurrence of runoff. Vegetation type did not change the other hydraulic properties as shown in this study, equally there was no detrimental effect.

5.4 Implications for urban greenspaces management

Urban greenspaces are somewhat permanent components of the urban landscape along with urbanization. This research has shown that there are no indications that the planting of different urban vegetation type in greenspaces would negatively affect soil hydraulic properties. Therefore, the benefits related to its aesthetic value, cost of maintenance and increase in biodiversity should be considered. However, there is an increased benefit of higher hydraulic conductivity on the sandy loam soil improving the movement of water into the soil. The research also showed that species richness and plant height also do not have a negative effect on hydraulic properties and soil moisture content.

Tillage was assumed to be the reason for the change in soil moisture content between the manipulated and non-manipulated plots on the clay soil, therefore improving soil moisture content but having no effect on other hydraulic properties of the soil.

However, from the research presented, urban areas having problems of either drought or excess runoff, the urban vegetation used for this study and the mix of species and its management would not improve the negative hydrological situation. Other authors have shown that trees increase infiltration rate improving groundwater recharge and reducing runoff. Another consideration for greenspaces is that of people's preferences for greenspaces, as some people prefer only well managed greenspaces as they perceive for example the tall, high floral diversity greenspaces as unsafe (Jorgensen et al., 2002).

5.5 Wider implications of the study

This research provides empirical data on the effect of greenspace manipulation on soil hydrology within the urban ecosystem. The conclusions from the study show that urban vegetation type, species diversity, and structural diversity have no detrimental impact on the hydraulic functioning of urban ecosystems and so should be encouraged for use in greenspaces of urban ecosystems for the other aesthetic or ecological values. The study contributes to the use of greenspaces in the delivery of a regulatory ecosystem service.

This collected data provides scientific evidence on infiltration rates, hydraulic conductivity and soil moisture content for urban vegetation types under clay, clayloam and sandy loam soils that can be used to inform greenspace management. It contributes knowledge on the effect of urban vegetation type, species richness and height on soil hydrology that was previously unknown.

5.6 Further work

This study has highlighted areas that further work is required to be able to effectively apply the findings of this study in the use of greenspaces for ecosystem service delivery within the urban ecosystem.

1. In particular the evaluation of the same measured soil properties on a different soil type with manipulated vegetation. This is to confirm soil texture effect on the measured soil properties.

2. To investigate the effect of plant root length and density of species used. The aim is to verify how it contributes to the presence of pores in the soil.

3. To study the soil physical properties beyond the topsoil layer. This may show limiting soil conditions below the topsoil layer.

4. The determination of infield amounts of runoff generated from manipulated plots.

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APPENDIX

APPENDIX TO CHAPTER 3

A. 1 Negative results

There was an occurrence of negative values for hydraulic conductivity when measurements were taken using the Decagon mini-disk infiltrometer.

Possible reasons for negative values

The results were checked for a possible explanation of the negative results. Three main possible sources of errors were identified as follows:

1. **Mathematical error**

a. The relationship of cumulative infiltration to time using the Kostiakov's and Philip's equations was used on randomly selected sampling points to determine the infiltration rates. The results showed that the calculated value compared well to the recorded data.

Kostiakov's equation

When plotted on a log-log plot the cumulative infiltration data shows a straight line relationship which can then be described by Equation 1.

$$I_t = a\,t^n$$ Equation 1

Where I_t is the cumulative infiltration at time *t*, *t* is the time, and *a* and *n* are constants. The values of *a* and n are usually derived from the intercept and the slope of plotting a log v log graph

$$\log I_t = \log a + n \log t$$

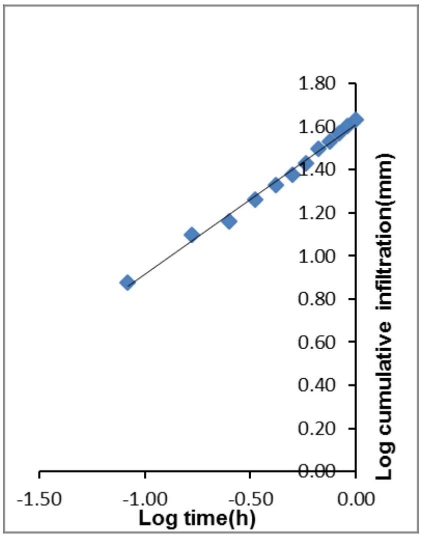
Equation 2

An example using BZ 63- 2a which is for trees over managed grass, figure 1a,

at log t = 0, log a = 1.61, therefore a = $10^{1.61}$ =40.73mm/h and n is 0.6977,

Thus cumulative infiltration at any time can be estimated from I_t = 40.73 $t^{0.69}$

Checking at time t = 0.50 h, $I_t = 24.84$ mm from Kostiakov's equation compared to 23.90 mm from data.



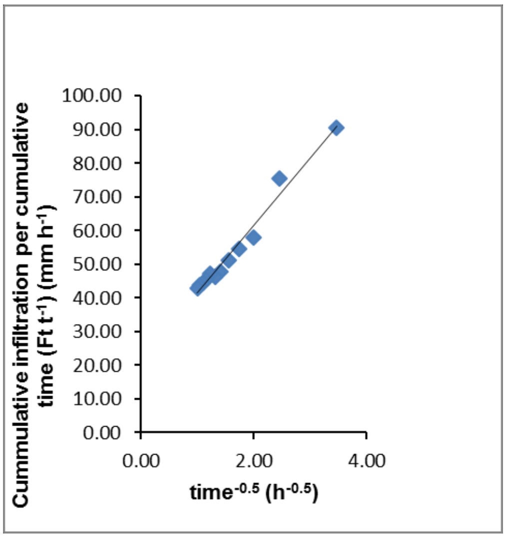


Figure 1a: Relationship between log of the cumulative infiltration rate and the log of the time based on Kostiakov's equation.

Figure 1b: Relationship between the average infiltration rate divided by the time (Ft/t) and time to the power of -0.5($t^{-0.5}$) based on Philip's equation.

Philip's equation

The Philip (1954) equation for infiltration adds a constant rate to the power term (Equation 3).

$$I_t = C_2 t^{0.5} + C_1 t$$

Equation 3

Where I_t is the cumulative infiltration at time *t*, *t* is the time, and C_1 and C_2 are constants related to the soil.

Dividing Philip's equation by t gives:

$$\frac{I_t}{t_t} = C_2 t^{-0.5} + C_1$$

Equation 4

Thus, there is a linear relationship between the average infiltration rate, F_t/t, and $t^{0.5}$. When plotted on a graph C_1 and C_2 can be found from the intercept and slope of the best fit line respectively. Using the BZ 63-2a which is for trees over managed grass, figure 1b shows a = 20 and b = 21.5. Thus cumulative infiltration can be calculated at any time from

$I_t = 20t^{0.5} + 21.5t$. Checking at time t =0.50h, Philip's equation gives It = 24.95 mm compared to the recorded data of 23.90 mm.

A major criticism of the Kostiakov approach is that as t becomes large the change in cumulative infiltration with time (or infiltration rate) becomes very small, implying that no more water will enter the soil. In fact, the infiltration rate tends towards a constant.

b. The relationship of cumulative infiltration to the square root of time was plotted, using results of randomly selected sample points to determine the parameters related to soil sorptivity and hydraulic conductivity as proposed by Zhang (1997). This is the method used by decagon devices for the minidisk infiltrometer to determine hydraulic conductivity. The results confirmed the negative values for the negative values and positive values for the positive values. A further check on curve fitting was assessed.

Curve fitting

Using sample AI 31a which was for woodland on a clay soil as an example the values of C_2 and C_1 were derived by fitting a second order polynomial to the relationship between cumulative infiltration and square root of time. This showed that the plotted values did not have the expected parabola shape of a concave after fitting the second order polynomial equation but gave instead a convex shape (Figure 2a & b).

The recorded reading showed a high initial infiltration volume and then much lower values for the subsequent values. The values were adjusted, to confirm the effect if any of the initial high infiltration values against time. The first ten minutes of the measurement were cancelled and readings recorded from the fourth reading correcting for the initial high difference between values. The fourth volume reading was recorded as the initial value at zero minutes. The graphs gave the expected parabola shape of a concave. The parameters related to soil sorptivity and hydraulic conductivity became positive and also the hydraulic conductivity value. But, the Decagon devices manual suggests that for reliable hydraulic conductivity values 15 – 20ml of water needs to be infiltrated into the soil. All the adjusted values were less than 15ml.For the AI 31a example used in the report; it was 13ml.These suggests that the new values from the adjustment were not reliable.

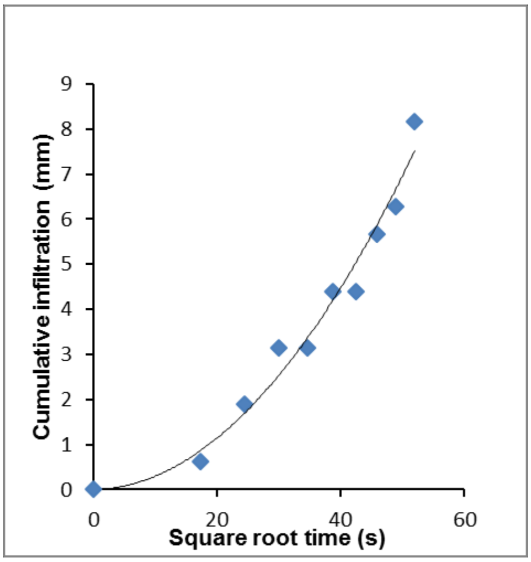


Figure 2a Relationship between cumulative infiltration and square root of time, of adjusted values fitting the second order polynomial equation showing concave fitting for positive values

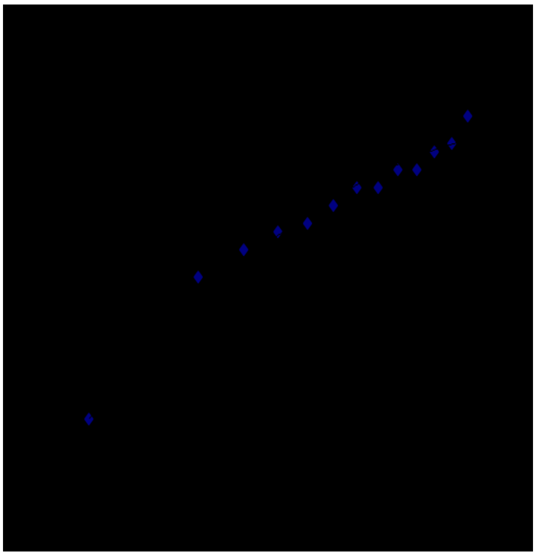


Figure 2b: Relationship between cumulative infiltration and square root of time fitting the second order polynomial equation showing convex fitting for negative values

On the basis of random selection from sampling points, some positive results were treated with the removal of the first ten minutes to confirm the degree of error introduced by adjusting the values and establish if any confidence on the adjusted positive values. Figures 3a & b show that the positive hydraulic conductivity value is maintained but the value of the figure changes. The non-adjusted with K = 4.040 X 10^{-5}, while the adjusted has K = 6.456 x10^{-5}.

The non-adjusted and adjusted values were plotted to determine the slope of the x-coefficient. The regression line has a slope of 2.2; this means that on average the adjusted values are larger than the non-adjusted values, so clearly, the adjustments make a difference to the estimates of unsaturated hydraulic conductivity. The mean of the adjusted values is 1.6times that of the non-adjusted values, confirming that the adjusted values are not reliable (figure 4).

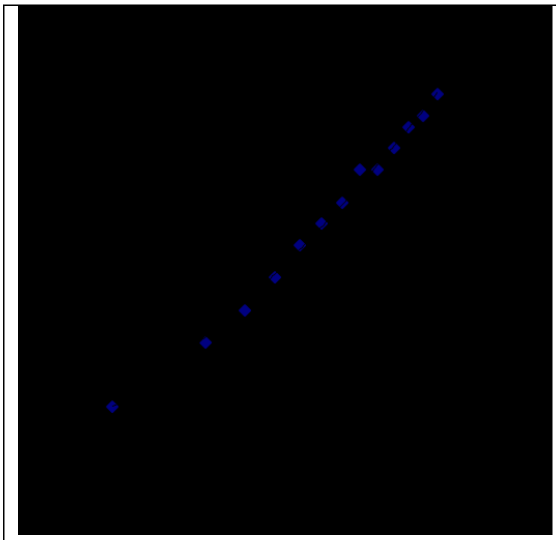


Figure 3a: Relationship of cumulative infiltration against square root of time with a positive unsaturated hydraulic conductivity value.

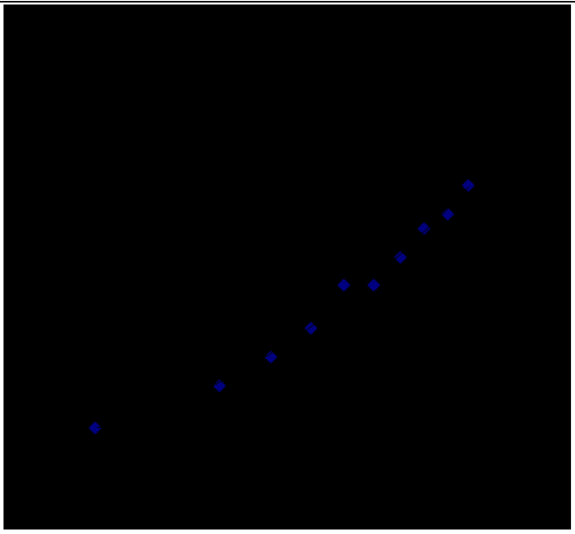


Figure 3b: Relationship of adjusted cumulative infiltration against square root of time with a positive unsaturated hydraulic conductivity value.

2. Measurement technique

The chi –test for the negative results gave p = 0.15, in the topsoil and p = 0.13, in the vegetation structure confirming that the negative values are random and do not have a pattern. The negative sampling points all had an initial high infiltration volume range between 10 and 19ml and then a very low volume range between 1 and 2ml infiltration volume for all immediate subsequent readings.

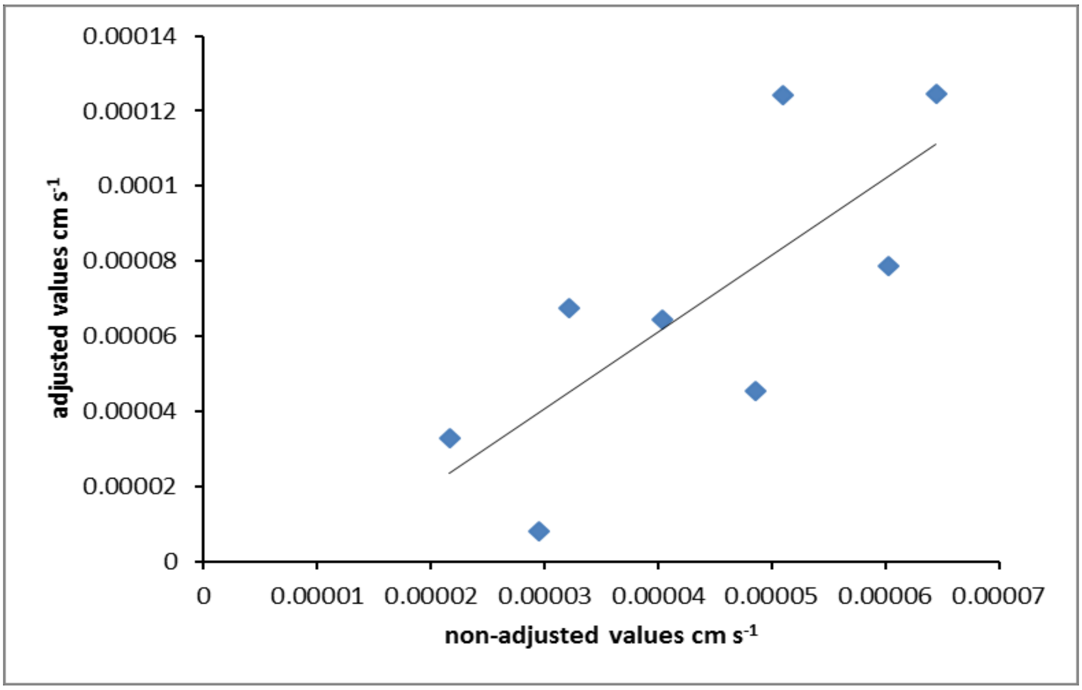


Figure 4 Relationship between adjusted and non-adjusted values of the estimated unsaturated hydraulic conductivity

The replicate measurements on each sampling site were carried out simultaneously. The sampling sites with a negative result either had negative values for all the replicate sampling points or one negative and two positive or two negative and one positive

The positive results measured for sampling sites with similar conditions of soil type and vegetation cover with the negative results suggest that the technique and instrument are suitable for the sampling of sites.

3. Instrument

The minidisk infiltrometer is designed to measure infiltration through the soil matrix, avoiding the macro pores.

The instruments used were labelled so that the same instrument was used for each of the sampling points at each site. Chi test for instrument confirmed that the negative results from measurements are random and not due to the instruments (table 7 in appendices).

6 Soil condition

Figure 5 shows the value of K_{unsat} for two soil conditions at two different soil water pressure heads. The graph show data from two [plots that were collected in September and December 2014. It can be seen that k_{unsat} increases as water pressure increases from -2 to -0.5 cm. It can also be seen that the values and variations show a sharp increase from -2 to -0.5 cm, reflecting a preferential flow phenomenon observed by other researchers. This can be attributed to the spatial variation of macro pores which includes grass roots and worm holes and structural cracks that act as preferential flow paths at pressure heads close to saturation. The variation in k_{unsat} indicated that the subsurface water flow at the plots was mostly driven by gravity through preferential flow paths at pressure heads close to saturation, this has also been observed by Lin et al, 1997.

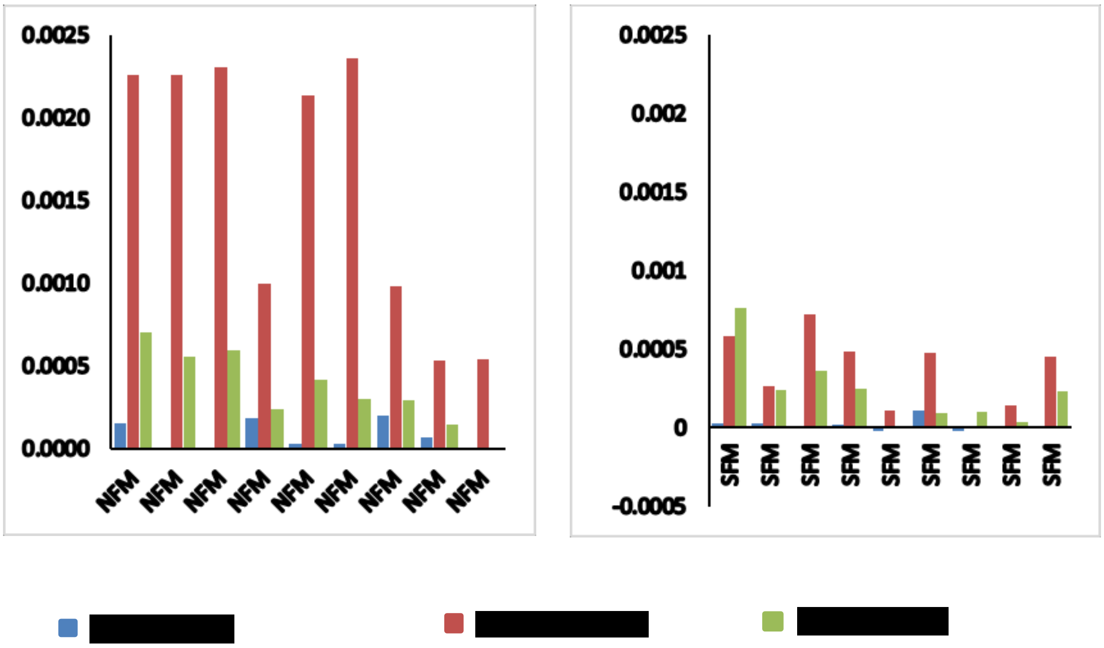


Figure 5 Plot of estimated unsaturated hydraulic conductivity values at different pressure heads for different antecedent soil moisture condition on no flowers medium (NFM) and some flowers medium (SFM) plots

Reynolds (2008), recommends that the negative values should not to be used in the analyses of results .Hence, the negative results were regarded as missing values and not used for all statistical calculations and analysis.

The negative results measured may have been due to;

1. The 2cm suction rate used on all the soil types. The user manual suggests the use of a suction rate of 0.5cm for compact soils where infiltration is slower. Though the negative results are random, none occurred on the sandy loam soil, but occurred on the soils with some clay content whose infiltration is slow, the highest frequency of occurrence being on the clay soil.
2. Porous medium heterogeneities or strong water content gradients as suggested by Reynolds, 2008.
3. Macrostructure collapse under the infiltrometer during the infiltration measurement and inadequate or changing hydraulic connection between the infiltrometer and the infiltration surface. As the porous medium wets up there is a decline in porous medium strength which combined with the weight of the infiltrometer can lead to a macrostructure collapse?
4. Vibration of the infiltrometer caused by the wind and the decreasing weight of the infiltrometer as the later empties out of the reservoir leads to inadequate or changing hydraulic connection.

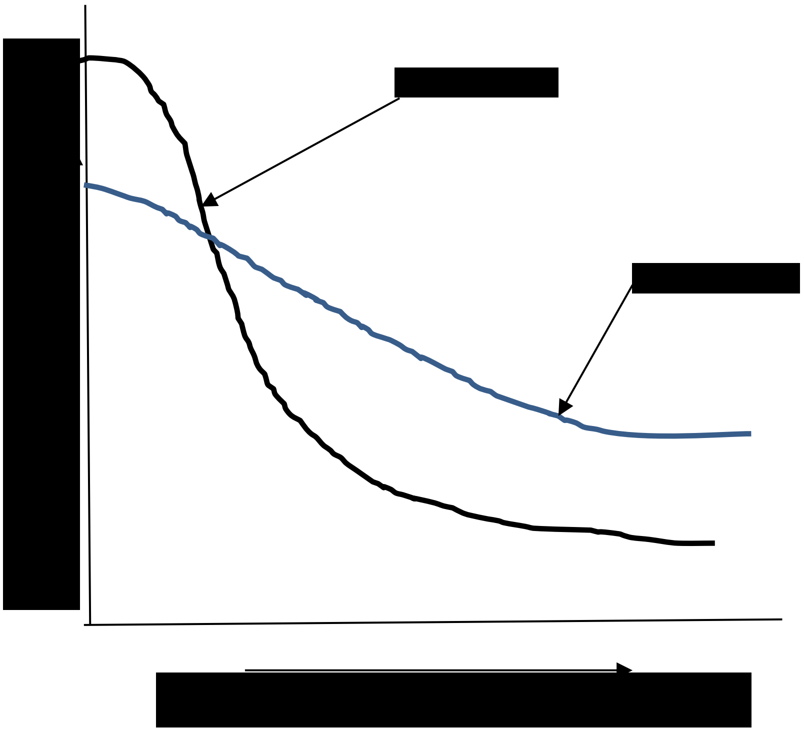
The mentioned problems 3 and 4 can be reduced by supporting the equipment with a large tripod which clamps solidly to the reservoir. This was not done by the investigator.

5. Shallow flow restricting layers or jiggling of the infiltrometer during the measurement (Decagon Devices, 2012).

Further literature search suggested the use of lower suction values for taking measurements in clay soils.

The measurement was taken at 2cm suction in September, repeat measurement for the month of December was carried out using a lower suction of 0.5cm. All the results were positive. Repeat measurements were taken at 2cm suction on two randomly selected plots and the results were still positive. Comparison of the values showed the highest values are the 0.5cm suction, followed by the 2cm suction readings taken in December 2014 and the lowest values being the 2cm suction values taken in September 2014.

According to Hillel, (1982) unsaturated conductivity of soils decreases with increasing suction (Figure 7).



A further explanation as given by Gallage et al.,(2013) is that hydraulic conductivity of an unsaturated soil is a variable which is largely a function of the water content or the matric suction of the unsaturated soil. In an unsaturated soil, the hydraulic conductivity is considerably affected by the degree of saturation (or water content) of the soil. According to them, in unsaturated soil air first replaces some of the water in the larger pores, causing the water to flow through the smaller pores with an increased tortuosity of the flow path. Increase in the matric suction of the soil leads to a decrease in the pore volume occupied by the water. This leads to the further resistance to water flow when the air-water interface draws closer and closer to the soil particles. As a result,

Figure 7: Dependence of conductivity on suction in soils of different

the hydraulic conductivity, with respect to the liquid (water) phase, decreases rapidly as the space available for the water flow declines.

A. 2 Estimated unsaturated hydraulic conductivity results

SUMMARY OF RESULTS - USING DECAGON MINI- DISK INFILTROMETER

02 JULY - 9TH AUGUST / 06TH ,19 - 25TH NOVEMBER 2013

SERIAL NO.	DATE OF FIELD VISIT 2013	SAMP NO.
1	31/07/2013	AB 43
2	31/07/2013	AB 44
3	08/08/2013	AC 44
4	08/08/2013	AD 42
5	15/07/2013	AE 46
6	02/08/2013	AF 41
7	02/08/2013	AF 44
8	02/08/2013	AF 45
9	16/07/2013	AG 35
10	09/08/2013	AG 37
11	08/08/2013	AG 39
12	16/07/2013	AH 42
13	23/07/2013	AI 30
14	23/07/2013	AI 31
15	09/08/2013	AJ 34
16	03/07/2013	AK 37
17	09/08/2013	AL 38
18	22/07/2013	AM 34
19	09/07/2013	AM 40
20	05/08/2013	AM 46
21	05/08/2013	AO 44
22	05/08/2013	AO 47
23	15/07/2013	AP 42
24	04/07/2013	AR 33

SERIAL NO.	DATE OF FIELD VISIT 2013	SAMPLE NO.	TOWN	LAT.	LONG.	TOPSOIL TEXTURE	VEG. TYPE	ONE	TWO	THREE	AVERAGE mm d^{-1}
25	31/07/2013	AR 41	MILTON KEYNES	52.04	-0.72	CLAY LOAM	W/T	-0.000046313	-0.000022408	0.000015713	13.58
26	10/07/2013	AR 45	MILTON KEYNES	52.06	-0.73	CLAY	W/T	0.000018166	0.000000219	0.00001373	9.25
27	10/07/2013	AS 44	MILTON KEYNES	52.06	-0.71	CLAY	UH	0.000008731	0.000001851	0.000001943	3.61
28	02/07/2013	AT 34	MILTON KEYNES	52.01	-0.71	CLAY	MG	0.00016284	0.000068928	0.000065673	85.66
29	22/07/2013	AT 42	MILTON KEYNES	52.04	-0.70	CLAY LOAM	TMH	0.00034132	0.00037016	0.0002894	288.25
30	25/07/2013	BS 5	LUTON	51.88	-0.53	SANDY LOAM	UH	0.00013184	0.000039539	0.000083076	73.28
31	25/07/2013	BU 3	LUTON	51.87	-0.52	SANDY LOAM	MG	0.000074155	0.000068429	0.000077036	63.25
32	17/07/2013	BU 6	LUTON	51.89	-0.52	SANDY LOAM	S	0.000034897	0.000048592	0.000046544	37.45
33	24/07/2013	BV 10	LUTON	51.90	-0.51	SANDY LOAM	TUH	0.00012738	0.00014337	0.00014964	121.07
34	01/08/2013	BX 64	BEDFORD	52.15	-0.49	CLAY	UH	0.000042269	0.00018332	0.00021484	126.84
35	25/07/2013	BY 7	LUTON	51.89	-0.49	SANDY LOAM	MG	0.00036771	0.00025753	0.00019967	237.57
36	30/07/2013	BZ 11	LUTON	51.91	-0.48	SANDY LOAM	UH	0.00012114	0.00014536	0.00021265	138.00
37	08/07/2013	BZ 63	BEDFORD	52.14	-0.47	CLAY	TMG	0.0001666	0.00003557	0.00015327	102.37
38	11/07/2013	CA 65	BEDFORD	52.15	-0.47	CLAY	TMG	0.00031649	0.00030663	0.00079466	408.32
39	01/08/2013	CA 69	BEDFORD	52.17	-0.47	CLAY	W/T	0.000003863	0.000028384	0.000033953	19.07
40	07/08/2013	CB 57	BEDFORD	52.11	-0.46	CLAY LOAM	S	0.000071875	0.0000674	0.00025129	112.48
41	07/08/2013	CB 64	BEDFORD	52.15	-0.46	CLAY	TMG	0.00011467	0.0001315	0.00017888	122.41
42	06/08/2013	CB 66	BEDFORD	52.15	-0.46	CLAY	S	0.000048762	0.000088538	0.0002672	116.50
43	18/07/2013	CC 11	LUTON	51.91	-0.46	SILTY CLAY LOA	MG	0.000051035	0.000046345	-0.000018122	22.83
44	12/07/2013	CC 62	BEDFORD	52.13	-0.45	CLAY LOAM	S	0.000000125	0.00015076	0.00027992	124.07
45	17/07/2013	CD 7	LUTON	51.89	-0.45	CLAY LOAM	UH	0.00052119	0.00077235	0.00048759	512.97
46	05/07/2013	CE 10	LUTON	51.90	-0.44	SANDY LOAM	MG	0.00073695	0.00003602	0.00055914	383.65
47	24/07/2013	CE 14	LUTON	51.92	-0.44	SANDY LOAM	MG	0.00014612	0.00089209	0.00034945	399.65
48	06/08/2013	CE 63	BEDFORD	52.14	-0.44	CLAY LOAM	UH	0.00003303	0.0000311	0.00004207	30.59
49	07/08/2013	CE 64	BEDFORD	52.15	-0.44	CLAY	S	0.000031996	-0.000009185	0.000004919	7.99
50	01/08/2013	CE 67	BEDFORD	52.15	-0.44	CLAY	TMG	0.000068077	0.00011722	0.000053885	68.88
51	19/07/2013	CF 8	LUTON	51.89	-0.44	SANDY LOAM	MG	0.00116833	0.00063926	0.00068049	716.57
52	06/08/2013	CF 67	BEDFORD	52.16	-0.43	CLAY	TUH	0.000037562	0.00003044	0.000049274	33.78

SERIAL NO	DATE OF FIELD VISIT	SAMPLE	TOWN	LAT	LONG	TOPSOIL	VEG. TYPE	ONE	TWO	THREE	AVERAGE
53	24/07/2013	CG 14	LUTON	51.92	-0.43	SANDY LOAM	MG	0.00056663	0.00056663	0.00042968	450.13
54	30/07/2013	CH 7	LUTON	51.89	-0.42	SANDY LOAM	S	0.00007482	0.000018086	0.000053419	42.14
55	24/07/2013	CH 10	LUTON	51.90	-0.42	SANDY LOAM	UH	0.00010158	0.00034664	0.00006004	146.38
56	07/08/2013	CH 65	BEDFORD	52.15	-0.41	CLAY	S	0.000077373	0.000057867	0.000033627	48.63
57	18/07/2013	CI 3	LUTON	51.87	-0.41	SANDY LOAM	TMG	0.0002171	0.00041154	0.00050636	326.88
58	19/07/2013	CI 8	LUTON	51.89	-0.41	SANDY LOAM	UH	0.000044499	0.000019789	0.0000827	42.33
59	18/07/2013	CJ 1	LUTON	51.86	-0.41	SILTY CLAY LOA	W/T	0.000064826	0.00009891	0.00014334	88.44
60	18/07/2013	CK 3	LUTON	51.87	-0.40	SANDY LOAM	MG	0.00007922	0.000098983	0.00015078	94.75
61	26/07/2013	CL 11	LUTON	51.91	-0.39	SILTY CLAY LOA	MH	0.00025999	0.000060227	0.00012682	128.75
62	26/07/2013	CM 11	LUTON	51.91	-0.39	SILTY CLAY LOA	S	0.000011401	0.000009705	0.00004018	17.65
63	30/07/2013	CP 7	LUTON	51.89	-0.37	CLAY LOAM	MH	0.00019482	0.000055692	0.00015646	117.21
64	06/11/2013	AJ 41	MILTON KEYNES	52.04	-0.78	CLAY LOAM	TMG	-0.000006333	-0.000019521	0.000006681	5.77
65	06/11/2013	AL 43	MILTON KEYNES	52.05	-0.77	CLAY	MG	0.00012581	-0.000001774	0.00040286	151.75
66	06/11/2013	AM 32	MILTON KEYNES	52.00	-0.76	CLAY	S	0.00006543	0.000095463	0.000028161	54.45
67	20/11/2013	AN 31	MILTON KEYNES	52.00	-0.76	CLAY	S	0.000006615	0.000007912	0.000002975	5.04
68	20/11/2013	AP 32	MILTON KEYNES	52.00	-0.74	CLAY	MG	0.000064806	0.000064481	0.00047941	175.30
69	19/11/2013	AP 51	MILTON KEYNES	52.09	-0.74	CLAY LOAM	MG	0.00012064	0.00005959	0.0001484	94.65
70	22/11/2013	AR 26	MILTON KEYNES	51.98	-0.73	CLAY	TMG	0.000079849	0.00031278	0.000177625	164.23
71	19/11/2013	AR 50	MILTON KEYNES	52.08	-0.72	CLAY LOAM	UH	0.000031041	0.000063997	0.000029553	35.88
72	25/11/2013	AS 27	MILTON KEYNES	51.98	-0.72	CLAY LOAM	TUH	0.000001963	0.00017731	-0.000007209	49.55
73	20/11/2013	AS 31	MILTON KEYNES	52.00	-0.72	CLAY LOAM	MG	0.000015365	0.00010214	0.00005988	51.09
74	19/11/2013	AS 50	MILTON KEYNES	52.09	-0.72	CLAY LOAM	S	0.000042084	0.00006403	0.000002821	31.37
75	19/11/2013	AV 42	MILTON KEYNES	52.06	-0.72	CLAY	TMG	0.000038026	0.000030259	0.00015902	65.46
76	20/11/2013	AW 40	MILTON KEYNES	52.04	-0.68	CLAY	S	0.00013861	0.0002346	0.000079365	130.34
77	22/11/2013	BX 61	BEDFORD	52.13	-0.49	CLAY LOAM	S	0.000049195	0.00003191	0.000021641	29.59
78	22/11/2013	BZ 57	BEDFORD	52.12	-0.47	CLAY LOAM	S	0.00020726	0.000080579	0.000050328	97.39

MG - managed grass, **MH** - managed herbaceous, **S** - shrub, **TMG** - trees over managed grass, **TUH** - trees over unmanged herbaceous, **UH** - unmanaged herbaceous, **W/T** - woodland/tree

A. 3 Calculation of unsaturated hydraulic conductivity from infiltration

Infiltration is the process of water entry into the soil. During infiltration events, the water enters the soil in response to potential gradients of water potential and gravitational potential. The water potential term is governed by the dryness of the soil and the pore structure of the soil. These two factors combine to form a sorptivity factor which is made up of the combined influences of capillary action and adhesive forces to soil solid surfaces. The gravity term is a constant for different soils and is due to the impact of the pore size, continuity and distribution on the rate of water flow through soil under the influence of gravity.

The initial water infiltration rate is largely governed by the sorptive forces of the dry soil, this is then replaced once the soil wets up by the gravitational forces. Thus equations describing infiltration can be made. These include

$$I = C_2 t^{0.5} + A\, t$$

where:

I is infiltration, t is time

C_2 is sorptivity , A is a constant for different soil types.

The hydraulic conductivity is calculated using the method proposed by Zhang (1997) which is simple and works well for measurement of infiltration into dry soil. The method requires using the measured cumulative infiltration versus time and fitting the results with the function

$$\mathrm{I} = C_1 t + \mathrm{C}_2 \sqrt{t}$$

where :

I is infiltration

T is time

C_1 is a parameter related to hydraulic conductivity, C_2 is the soil sorptivity which is function of,

$$C_1 = \frac{I - C_2 \sqrt{t}}{t}$$

values were obtained by plotting the measured cumulative infiltration against the square root of time and fitting a second order polynomial equation trend line. The slope and intercept of the curve are C_1 and C_2 respectively.

The unsaturated hydraulic conductivity of the soil (K) is then computed from ;

$$\mathrm{K} = \frac{C_1}{A}$$

where A is a dimensionless coefficient relating the van Genuchten moisture retention parameters n and α from soil water retention curve for a given soil type to the suction rate and the radius of the infiltrometer disk. A is computed from :

$$A = \frac{11.65\,(n^{0.1} - 1)\exp(2.92(n - 1.9)\,\alpha h_o)}{(\alpha r_o)^{0.91}}$$

for $n \geq 1.9$

$$A = \frac{11.65\,(n^{0.1} - 1)\exp(7.5(n - 1.9)\,\alpha h_o)}{(\alpha r_o)^{0.91}}$$

for $n < 1.9$

where

r_o is the radius of the disk and h_o is the suction at the disk surface.

n and α are van Genuchten parameters for the 12 soil texture classes (Decagon Devices User's Manual,2005).

For this study the following table 1 shows the van Genuchten parameters used;

Table 1
van Genuchten Parameters for the 4 Topsoil Texture Classes and A values for the 2.25cm disk radius and suction value of 2cm (Decagon Devices Manual,2005)

Texture	α	n	A
Clay	0.008	1.09	4.30
Clay loam	0.019	1.31	6.64
Sandy loam	0.075	1.89	3.91
Silty clay loam	0.010	1.23	8.51

APPENDIX TO CHAPTER 4

B.1 Vegetation species of grass and forbs seeded on manipulated plots.

The vegetation manipulation is aimed at difference in vegetation type using the forbs and grass species. There are 29 forb species: Achillea millefolium, Anthriscus sylvestris, Arctium minus, Centaurea nigra, Centaurea scabiosa, Daucus carota, Dipsacus fullonum, Echium vulgare, Galliun album,Galium verum, Gernium pratense, Hypercium perforatum, Knautia arvensis, Leontodon hispidus, Leucanthemum vulgare, Linaria vulgaris, Lotus corniculatus, Malva moschata, Medicago lupulina, Ononis spinosa, Plantago lanceolata, Plantago media, Primula veris ,Prunella vulgaris, Ranunculus acris, Rumex acetosa, Tanacetum vulgare, Trifolium pratense, Vicia cracca; and ten grass species: Agrostis castellana, Festuca rubra, Festuca rubra ssp.commuta, Lolium perenne, Poa pratensis, Agrostis capillaris, Dactylis glomerata, Phleum pratense,Schedonorus arundinaceus,Schedonorus pratensis.

B.2 Reconnaisance survey report

Field Reconnaissance Report

Introduction

The Millennium Ecosystem Assessment (MEA, 2005) defined ecosystem services as the benefits that people get from ecosystems, both natural and managed. These services are grouped into provisional, regulative, cultural or supporting services necessary for the well-being of humans (Constanza et al, 1997). The Natural Environment Research Council (NERC) is funding a research looking into Biodiversity and Ecosystem Service Sustainability (BESS) aimed at giving some answers on the functional role of biodiversity in key ecosystem services and the delivery of these services at the landscape scale. There are four landscapes being studied.

The urban landscape group, Fragments, functions and flows- the scaling of biodiversity and ecosystem services in urban ecosystems (F3UES) as a part of its study set up nine experimental and one demonstration site for studies. The research into the effects of green spaces on hydrology within the urban ecosystem would be based on studies carried out on these experimental plots. The sites have varying manipulation of vegetation and its management through a patterned mowing regime in the towns of Bedford, Luton and Cranfield. Only six of the nine sites have the complete number of nine experimental and one control plot being considered to be used for the study. The six sites were surveyed on the 21st – 23rd of July 2014.

Project title

Effects of green spaces on hydrology within the urban ecosytems.

Site Investigation aim and objectives

The aim of the survey is to select sites to be used for the study based on justified reasons. Other considerations include the length of study period left (a year and six months), funding and limited manpower available for the study. The afore mentioned would not allow for the scale of study where all the sites would be studied. There are ten sites in all but only six are suitable for further reconnaissance survey.

The following objectives are the reason for the reconnaissance survey field visit:

  - Visual physical observation of the growth and establishment of the plants on the plots.
  - Physical assessment of site location in terms of;

    I. location within the city for estimating proximity to bus stations,
    II. level of access unto sites,
    III. safety of working alone on site
    IV. Distance between sites
    V. Topographical nature of site

- To carry out hand method of soil texture determination and collect representative samples of the 0-15cm and 15 – 30 cm depth of soils for laboratory analysis.
- Practice how to use the Theta probe soil moisture kit on field.

Field methods

The ten plots are each 12.5m x 20m = 250m^2 on all the sites, except the Cranfield site where the plots are 10 x 5m each = 50m^2. This was confirmed using the long measuring tape by random selection of plots.

Location

A hand held Global Positioning System (GPS) unit was used to record the coordinates of the sites. The coordinates were used to create a map of the area showing the location of the sites in the towns and the proximity between sites and the Cranfield University where the Cranfield plots are located (which is also the set-out location for the investigator and laboratory for dropping samples in fridge) refer to figure 7. The other sites are located at Luton (Bramingham road), in Bedford, Brickhill heights, Chiltern Avenue, Jubilee Park and Abbey fields which are 33.5,19, 17.5, 15.5 and 14kms respectively away from Cranfield University.

Accessibility

All the sites are public centred making it safe for work alone on site and are easily accessible by public road and footpaths.

Topography

In general the relief of all the areas are low. Table 1 shows a summary of the general description of surveyed sites.

General topographical description of sites

Site name	Description
Abbey fields	Roughly flat surface
Brickhill heights	Hill
Chiltern avenue	Undulating surface
Jubilee Park	Hill and slope
Cranfield Plots	Low hill
Bramingham road	Low hill and slope

Vegetation

Different variety of forbs and grasses are grown on the plots. On each site the nine plots each represent a different mix of the plants with three of the plots having the same management pattern manipulated by the frequency of mowing regime. The first set of three plots is mowned once a month, twice in the season and the last group once in the season. The vegetation include the Red Clover(Trifolium pratense),Vipers Bugloss(Echium vulgare),Yarrow(Achillea),Black knapweed(Leucanthenum vulgare). The following figures 1-6 show some of the plants grown on the plots.

<table>
<tr>
<td>
Figure 1: Leucanthenum vulgare (Ox – eye daisy), rumex asetosa(common sorrel) and Daucus carota (wild carrot)</td>
<td>
Figure 2: Malva moscata(Musk mallow)</td>
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<tr>
<td>
Figure 3: Dipsacus Fullonum(common Teasel)</td>
<td>
Figure 4: Achillea (Yarrow)</td>
</tr>
</table>

 **Figure 5: Phleum pratense(Timothy grass)**	 **Figure 6: Echium vulgare(vipers gloss)**

Figure 7: Map showing the six site locations in Bedford, Cranfield and Luton.

Sample collection

Samples for soil texture were collected as close as possible about 5cm outside the experimentally plotted area. Two samples were collected per site at 0-15cm and 15-20 cm depth; the two depths were selected to know the type of topsoil,0-15cm which is the layer of interest and what soil type lies beneath the topsoil as a second layer at 15-

30cm. A hand auger was used to bore into the soil and contents emptied into clearly labelled sample bags. Figure 8 is picture of a hole made by the auger to 30cm depth. Hand method of soil texture was carried out on the field while the packaged samples have been kept in the fridge of the laboratory for analysis. Figure 9 shows how the hand texture method used on field. Table 1 gives a summary of the soil texture based on hand texture which

is a subjective method. The method adopted was from the practical hand out of the Cranfield University Soil Plant Environment Science module,2012/2013.

Figure 8: Hole from augering to 30cm

Figure 9: Hand texture method, Cranfield Plots

Table 2: Summary of soil texture sites based on hand texture method

Town	Site name	Soil depth	
		0 – 15cm	15 – 30cm
Bedford	Abbey fields	Silt loam	Silt loam
	Brick hill heights	Silt loam	Silt loam
	Chiltern Avenue	Loamy sand	Silty clay loam
	Jubilee Park	Clay loam	Clay loam
Cranfield	Cranfield Plots	clay loam	Clay
Luton	Bramingham road	clay loam	Clay

Sites

The growth and establishment of the vegetation on plots was captured in pictures along with pictures of some of the species as seen on the field. On each site pictures of all the plots were taken. Figures 10 – 21 are selected pictures from all six sites showing the vegetation mixes and overview of the sites.

Figure 10: Low diversity tall herb (plot 6H), Abbey fields

Figure 11: High diversity meadow (plot 10F), Abbey fields

Figure 12: High diversity tall herb (plot4 Brick hill heights

Figure 13: Overview of Brick hill heights site

Figure 14: Tall grassland (plot 8G),Chiltern

Figure 15: Overview of Chiltern Avenue

Figure 16: High diversity meadow (plot 10F) Jubilee Park, Bedford

Figure 17: Over view of Jubilee Park, Bedford

Figure 18: Low diversity meadow (plot 4E), Cranfield

Figure 19: Overview of the Cranfield site, Cranfield University

Figure 20: Standard mown amenity grass (plot 6A), Luton

Figure 21 : Overview of the Luton site

Equipment Practice

The theta probe equipment will be used for taking soil moisture content measurements on the field. Practice measurements were carried out on the field to familiarise with operation of equipment and output of results.

Summary of soil type on Sites

Site name	**Accessibility**	**Vegetation seeding**	**Soil type**				**Plots**
			Investigator(hand texturing)	**Soil map**	**Unit name**	*** Expert Dr J Hannam (hand texturing)**	
Abbey Fields	14 km from University, bus service is very brief and limited	All the plots were reseeded in April 2014	Silt loam	Clay loam	Efford 1	Clay loam	All plots in one area ,but not all plots vegetation are established as at

							time of visit
Brick hill heights	19km from University, about 1hour 45minutes by bus	Plots seeded in May 2013	Silt loam	Clay	Evesham 3	Clay loam	All the plots are not in one area, they are split into two areas about 500-600 m apart. All plot vegetation are established
Chiltern avenue	17.5km from University, about 1hour 30minutes by bus	Plots seeded in May 2013	Loamy sand	Clay	Evesham 3	Clay loam	All plots in one area, and are established
Jubilee Park	15.5km from University, bus service stop is far from location	All the plots were reseeded in April 2014	Clay loam	Clay loam	Efford 1	Clay loam	All plots in one area,but not all plots vegetatio

							n are established as at time of visit
Cranfield Plots	Easily accessible on foot	Plots seeded in May 2013	Clay loam	Clay	Hanslope	Clay	All plots in one area, and are established
Bramingham road	33.5km from University, about 2hours by bus	Plots seeded in April 2013	Clay loam	Medium sand	Moulton	Clay loam	All plots in one area, and are established

- Hand texturing with Dr J. Hannam was carried out on collected field soil samples in the Cranfield University soils laboratory using the Soil classification chart.

Conclusion

The survey shows that the suitable sites for selection are the sites with grown vegetation on all the plots as a primary consideration; Brick hill heights, Chiltern Avenue, Cranfield Plots and Bramingham Road. Selection of sites to suit research design, ease of access from University to site and travel cost would be based on findings from the survey results of the suitable sites for further investigation. Suggestions are included in the phase two plan report.

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Millennium Ecosystem Assessment (Program) and Millennium Ecosystem Assessment (2005), Ecosystems and Human Well-Being: Our Human Planet: Summary for Decision Makers, Island Pr.

B.3 Results of vegetation cover using the square grid

		Forbs																				
Plot ID		Achillea millefolium (Yarrow)	Anthriscus sylvestris (cow parsley)	Arctium minus (Burdok)	Centaurea nigra (Black knapweed)	Centaurea scabiosa (Greater knapweed)	Daucus carota (Wild carrot)	Dipsacus fullonum (Teasel)	Echium vulgare (Vipers Bugloss)	Galium album (mollugo)(Hedge Bedstraw)	Galium verum (Lady's Bedstraw)	Geranium pratense (Meadow Cranesbill)	Hypercium perforatum (St. John's Wort)	Knautia arvensis (Field Scabious)	Leontodon hispidus (Rough Hawkbit)	Leucanthemum vulgare (Oxeye Daisy)	Linaria vulgaris (Common Toadflax)	Lotus corniculatus (Birds Foot trefoil)	Malva moschata (Musk Mallow)	Meditago lupulina (Black Medick)	Ononis spinosa (Spiny Restharrow)	Plantago lanceolata (Narrow-leaved Plantain
Non-manipulated	**Expected(Sown)**																					
	Observed	1													2			3		2		2
No-flowers short	**Expected(Sown)**																					
	Observed						1											1	+			
Some-flowers short	**Expected(Sown)**	*																*		*		
	Observed	30														2		14				
Many-flowers short	**Expected(Sown)**	*									*				*	*		*		*		
	Observed	7												3		1		7		4		
No-flowers medium	**Expected(Sown)**																					
	Observed	35																				
Some-flowers medium	**Expected(Sown)**	*			*						*			*	*							
	Observed	29			63										5			33				
Many-flowers medium	**Expected(Sown)**		*			*	*				*	*	*	*	*	*			*			
	Observed	33			7	10	2							4		13						
No-flowers tall	**Expected(Sown)**																					
	Observed	23			1													32				
Some-flowers tall	**Expected(Sown)**	*	*	*	*			*								*						*
	Observed							10														
Many-flowers tall	**Expected(Sown)**	*	*	*	*			*	*	*				*		*	*		*		*	*
	Observed	1			2		1	+		10				3		25		7		1	26	1

										Grass											
Plot ID		Plantago media (Broad-leaved Plantain)	Primula veris (Cowslip)	Prunella vulgaris (Selfheal)	Ranunculus acris (Buttercup)	Rumex acetosa (Sorrel)	Tanacetun vulgare (Tansy)	Trifolium pratense (Red Clover)	Vicia cracca (Tufted Vetch)	Agrostis castellana (Highland bent)	Festuca rubra (Slender creeping Red Fescue)	Festuca rubra ssp.commutata (Chewing's Fescue)	Lolium perenne (Perrenial Ryegrass)	Poa pratensis (Smooth stalked Meadow)	Argostis capillaris (Common bent)	Dactylis glomerata (Cocksfoot)	Phleum pratense (Timothy)	Schedonorus arundinaceus (Tall Fesue)	Schendonorus pratensis (Meadow Fescue)	Poa annua (Annual Meadow grass)	white clover
Non-manipulated	**Expected(Sown)**												*		*				*	*	
	Observed			3	2			20			10		67	2	70	2			70	57	
No-flowers short	**Expected(Sown)**									*	*		*	*							
	Observed			3				30		1	65		80	2							
Some-flowers short	**Expected(Sown)**			*		*				*	*		*	*							
	Observed																				
Many-flowers short	**Expected(Sown)**	*	*	*	*	*		*		*	*		*	*							
	Observed	2						20		9			11								
No-flowers medium	**Expected(Sown)**									*	*	*			*						
	Observed																				
Some-flowers medium	**Expected(Sown)**	*						*		*	*	*			*						
	Observed				4						22				85						57
Many-flowers medium	**Expected(Sown)**		*					*	*	*	*	*			*						
	Observed							42		5											
No-flowers tall	**Expected(Sown)**											*				*	*	*	*		
	Observed							6	5		7						63		24		13
Some-flowers tall	**Expected(Sown)**					*					*					*	*	*	*		
	Observed																				
Many-flowers tall	**Expected(Sown)**					*	*	*			*					*	*	*	*		
	Observed			1	+	4		1	1	3	11					3	2	4			

Plot ID		Moss & Lichen	Bare earth	EXTRA'S	Argostis stolonifera	Bellis perennis	Centarrium erythraea	Potentilla reptans	Rubus caesius	Veronica serpyllifolia	Odontites vernus	Crex flacca	Festuca arundinacea	Picris echioides	Prunus spinosa	Potentilla reptans	Luzula campestris	Holcus lanatus	cerastium fontanum	Senecio jacobaea	Taraxacum sp	Vegetation cover %
Non-manipulated	**Expected(Sown)**																					
	Observed	2			+	1			+					1		3	+	3	+	1	1	100
No-flowers short	**Expected(Sown)**																					
	Observed		+																			100
Some-flowers short	**Expected(Sown)**																					
	Observed	3	+																			100
Many-flowers short	**Expected(Sown)**																					
	Observed	4	3																			97
No-flowers medium	**Expected(Sown)**																					
	Observed																					100
Some-flowers medium	**Expected(Sown)**																					
	Observed	1	+																			100
Many-flowers medium	**Expected(Sown)**																					
	Observed	3	2																			98
No-flowers tall	**Expected(Sown)**																					
	Observed	2	2																			98
Some-flowers tall	**Expected(Sown)**																					
	Observed	45	1																			100
Many-flowers tall	**Expected(Sown)**																					
	Observed	60	2				2	3	3	+	+	2	3		+							98

B.4 Statistical analysis of manipulations on soil moisture content

Table 4.5

Two-way ANOVA statistical analysis soil moisture content due to structural and floristic manipulations on the experimental plots

	P - value for treatment effects	
	Soil condition	
Manipulations	dry	wet
Structural diversity	0.09	0.97
Floristic diversity	0.57	0.63

B.5 Statistical analysis of manipulations on infiltration rate

Two-way ANOVA statistical analysis of infiltration rate at 1hour due to structural and floristic manipulations on the experimental plots using the minidisk infiltrometer (mdi) and double ring infiltrometer (dri).

	P - value for treatment effects		
	Soil condition (mdi)		dri
Manipulations	dry	wet	
Structural diversity	0.69	0.60	0.60
Floristic diversity	0.19	0.11	0.53

B.6 Statistical analysis of manipulations on hydraulic conductivity

Two-way ANOVA statistical analysis of estimated unsaturated hydraulic conductivity (k_{unsat}) due to structural and floristics manipulations on the experimental plots using the minidisk infiltrometer

	P - value for treatment effects	
	Soil condition	
Manipulations	dry	wet
Structural diversity	0.06	0.85
Floristic diversity	0.06	0.13