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An investigation into the storm water retention capabilities of two experimental mesocosm substrates and their practical use on green roof design.

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Executive Summary

With a growing population and our rapidly urbanising landscape the issue of sustainability is at the forefront of the topics which need to be addressed by today's society. Recent flooding throughout the United Kingdom has brought the problem of stormwater management to the headlines and never has the need to develop sustainable solutions to stormwater run-off been so important. Green roofs offer such a solution, they fit well into modern infrastructure and provide benefits both environmentally and economically. The use of green roofs as storm water retention devices has been widely addressed within recent literature, however their implementation across the United Kingdom has been slow in comparison with the rest of Europe. Nevertheless, it is likely that green roofs will experience a change in acceptance by the commercial sector once more is known about their performance and sustainability (Arthur and Wright, 2005).

The aim of this study was to highlight the ability of green roofs to reduce run-off from experimental mesocosms located at the University of Birmingham and to compare the ability of two different substrates to retain precipitation, whilst critically reviewing the current literature surrounding green roof urban design. With the use of laboratory analysis, data recorded from the mesocosms, and the development of a model two substrates types used on the mesocosms were compared. The results showed that the brick mesocosms retain on average 54% of the precipitation and the demolition aggregate 37%. A delay in the hydrograph peak was observed from both substrates further indicating their importance as run-off retention devices. Although the brick only appeared to delay run-off significantly more than the demolition aggregate when there was extremely heavy rainfall (>1.8mm / 5min). Model simulations indicated that as the vegetation cover develops across the mesocosms the retention capacity of both substrates should increase.

These results demonstrate the ability of green roofs to reduce stormwater flow into urban rivers diminishing the likely hood of flooding whilst taking the first step in rehabilitating our aquatic ecosystems severely damaged by urbanization (Carter and Rasmussen, 2006). It has been recommended that this research should continue on a larger spatial scale over a longer time period to fully understand the effect substrate type and vegetation cover has on stormwater retention.

Acknowledgements

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Chapter One

Introduction

1.1 Introduction

One of the main issues associated with urban areas is stormwater run-off. The urban hydrological system has to cope with a highly fluctuating amount of surface run-off water which can become extremely high during periods of rainfall but will remain low under normal conditions (White, 2002. cited in Mentens et al., 2006). Urban areas generate considerably more stormwater run-off than natural areas of the same size due to a greater percentage of impervious surfaces that impede water infiltration (VanWoert et al., 2005). Consequently stormwater mitigation is an important consideration in any new development. From meeting the Environment Agency run-off targets to reducing an areas susceptibility to flooding, methods for reducing run-off must be incorporated into designs from an early stage.

Prompted by the need to mitigate the effects of rapid urbanisation in relation to stormwater management new legislation has been introduced to aid the management of stormwater run-off. Urban drainage design in general has been revolutionized by the wider acceptance of Sustainable Urban Drainage Systems (SUDS) and greater public concern regarding pluvial flooding within the context of climate change (Arthur & Wright, 2005). With the implementation of the Water Framework Directive (WFD) requiring all water bodies to reach "good" status by 2015 the role of green roofs are imperative. SUDS links with the WFD ideologically, by encouraging sustainable and holistic design of urban drainage and stakeholder involvment, the use of green roofs epitomizes this. SUDS also provide a pratical means of achieving aims set out in Making Space for Water and the Planning Policy Statement 25 (PPS 25) (Communities and Local Government, 2006) both documents which aim to reduce the risk of flooding.

Green roofs have the ability to meet the criteria outlined in recent legislation in reference to the development of urban areas. They have the potential to transform between 40% and 50% of the total impervious areas of cities into usable space (Villarreal and Bengtsson, 2005) and increase the ratio of greenery to population (Wong et al., 2003). Originating in Germany, countries such as Japan, Canada and the USA have all utilised green roofs for their environmental and economic benefits in city centres (Kidd, 2005). With most technological advances been made in Germany, the sector has rapidly grown to a £39 million industry (Livingroofs.org, 2007).

1.2 Aims and Objectives

1.2.1 Aims

i. To critically review the current literature surrounding green roof urban design;
ii. To compare the potential of two different substrate types (Brick and Demolition Aggregate) at reducing stormwater run-off;
iii. To critically review the methods of hydrological modelling for simulating storm water run-off from green roof systems, whilst formulating a model to simulate run-off.

1.2.2 Objectives

The specific objectives required to meet the aims stated above include:

i. To have critically reviewed current literature with focus on green roof urban design.
ii. To have critically assessed the ability of two substrate types (Brick and Demolition Aggregate) at reducing storm water run-off, through the use of real time data and laboratory experiments.
iii. To have critically reviewed green roof hydrological modelling approaches and formulated a model in Excel to simulate run-off from the experimental mesocosms.

1.3 Hypotheses

i. A positive relationship exists between the propagation of green roofs as run-off reduction tools as widely demonstrated within current literature.

ii. Green roofs with a greater percentage vegetation cover will reduce run-off more effectively than those with a more sparse vegetation cover.

iii. Green roof substrate material with a large percentage of pore space will retain water more effectively than those with a smaller percentage of pore space.

Chapter Two

Research Background

2.1 Green Roofs

The literature reviewed in this Chapter will allow aim and objective (i) set in Section 1.2 to be met.

2.1.1 Green Roofs an Introduction

A green roof is a lightweight, engineered roofing system that allows for the propagation of rooftop vegetation while protecting the integrity of the underlying roof (Spala et al., 2007). Green roofs provide benefits both environmentally and economically. However, stormwater run-off mitigation is considered a primary benefit due to the prevalence of impervious surfaces in urban and commercial areas and failing stormwater management infrastructures (Liptan, 2003 cited in VanWoert et al., 2005).

High evapotranspiration from a vegetated roof can reduce the annual run-off to less than half the precipitation (Bengtsson et al., 2005 cited in Berndtsson et al., 2006). The temporal storage of water in soil and vegetation on the roof reduces peak flow, which prolongs the time-of-concentration. As a result, local urban flooding and combined sewer overflows (CSOs) can be lessened. Fewer CSOs, in turn minimises the impact of the urban run-off on the natural water recipients (Berndtsson et al., 2006).

The various layers of a green roof perform the different functions of a natural soil, giving the nutritional elements, storing water, and allowing transpiration and drainage to occur (Lazzarin et al., 2005). As long as the soil moisture is below field capacity, there is hardly any run-off from a green roof (Bengtsson et al., 2004). However, the response of a green roof to short-term storm events, and thus peak flows, will depend upon how wet the roof soil-vegetation is prior to the rainfall, and thus on the antecedent precipitation (Bengtsson et al., 2004).

2.1.2 Previous Studies of Green Roof Responses to Storm Water

Bengtsson et al (2004) aimed to find new and improved solutions for stormwater management reducing stormwater run-off reaching the combined sewer system by at least 70%. The water balance approach was used to study the hydrology of an extensive *Sedum* green roof. Measurements were continuous with a time resolution of 5 minutes, recording run-off and meteorological data. It was found that annual run-off can be reduced by up to 50% due to evapotranspiration from a green roof with high vegetation cover. Studies in other countries have demonstrated similar results. In Mentens et al's (2006) review of literature, it was demonstrated that rainfall-retention capacity on a yearly basis can range from 75% for intensive green roofs to 45% for extensive roofs. An American study by DeNardo et al (2003) found an average 40% reduction in run-off from a *Sedum* green roof and in Kidd's (2005) Australian study 42% of stormwater was found to be retained annually by an extensive green roof.

2.1.3 Vegetation and Substrate Use

Vegetation is integral to the use of green roofs as run-off reduction tools. The plants with their biological functions, such as photosynthesis, respiration, transpiration and evaporation absorb a significant proportion of solar radiation and rainfall. Plants also help to mitigate the greenhouse effect, filter pollutants, mask noise, prevent erosion and calm their human observers (Spala et al., 2007).

The selection of plants to be established on a green roof can be considered the most vital component, and as such the hardest to perfect (Kidd, 2005). The characteristics of vegetation typically used in green roof systems include:

- Drought tolerant;
- Shallow root systems;
- Regenerative qualities;
- Resistance to direct radiation, frost and wind.

(Modified from Kidd, 2005)

Seasonal differences in the performance of a green roof may be expected due to varying potential evapotranspiration (Bengtsson et al., 2004) which will be influenced by the weather conditions and vegetation type. The substrate used on a green roof will influence a roofs ability to mitigate run-off as it is important in retaining water and anchoring vegetation. Therefore, the depth of the substrate layer is crucial, and will also influence the classification of the green roof. The substrate used must allow healthy plant growth, which is achieved if water in soils is easily available to roots, whilst providing enough oxygen for respiration (Handreck and Black, 2005). It is widely accepted that the ideal substrate for use on a green roof is comprised of a balance of lightweight, well-drained material, which has adequate water and nutrient retention capacity and will not break down over time (Getter and Rowe, 2006).

2.1.4 Classifying Green Roofs

Green roofs are classified into intensive and extensive roofs. Intensive roofs have a deep growing medium, which allows the use of large species of trees and shrubs. They are generally quite costly and require extra structural design to the building (Livingroofs.org, 2007) and will require significant ongoing maintenance. Intensive green roofs are usually landscaped environments for recreation which are publicly accessible and may also include storage of rainwater for irrigation. Examples include Canary Wharf Estate at Canada Square and Cannon Street Station, London.

Extensive green roofs in comparison have a thin growing medium and require minimal maintenance. In general they do not require irrigation although some may require irrigation when initially seeded (Livingroofs.org, 2007). In contrast to intensive green roofs they can be considered less costly. Examples include Barclays HQ, London and Canary Wharf, East London.

2.1.5 Further Benefits of Green Roofs

Aside from their storm water retention capacity green roofs provide a multitude of benefits. Much literature focuses on the implementation of green roofs from the viewpoint of urban heat island mitigation (Spala et al., 2007; Köhler et al., 2002; Takebayashi and Moriyama, 2006; Bass et al., 2002). Green roofs do not act as cooling devices themselves but as insulation devices, reducing the heat flux through the roof (Palomo Del Barrion, 1998) and thus reducing air conditioning costs. As a result green roofs offer a sustainable green surface improving urban climate, by minimising heat island effects and simultaneously protecting biodiversity (Spala et al., 2007).

Improving biodiversity is an important aspect of green roofs. Green roofs may function as "stepping stone" habitats connecting isolated habitat pockets with each other which promote urban biodiversity (Kim, 2004 cited in Schrader and Böning, 2006). As extensive green roofs are inaccessible to the public, they can provide undisturbed habitat for micro organisms, insects and birds (Getter and Rowe, 2006). Further to their potential for promoting biodiversity vegetated roof run-off water quality studies performed in Germany indicated nutrient and heavy metal removal by green roofs (Köhler et al., 2002). Results have implied that contaminants can be retained in green roof material or taken up by plants (Berndtsson et al., 2006).

It is apparent that vegetated roofs can fit well into the concept of a modern green city (Berndtsson et al., 2006). The benefits outlined, provided by both extensive and intensive green roofs are important in their development and their continuing application across our urbanised landscape.

2.2 Modelling

2.2.1 Introduction

In order to understand the processes which influence the hydrological function of green roofs and thus the experimental mesocosms, it was considered important to review the literature which surrounds the use of hydrological models. This section will fulfil part of aim and objective (iii) set in Section 1.2.

2.2.2 Previous Green Roof Modelling Studies

In relation to the ability of green roofs to mitigate storm water run-off Carter and Jackson (2006) demonstrated with the use of hydraulic modelling that widespread green roof implementation can significantly reduce peak run-off rates, particularly for small storm events. Carter and Jackson's primary objective was to examine the effect green roofs can have on stormwater run-off volumes at a variety of spatial scales in an urbanised watershed in Georgia, USA. The stormwater outflow of the receiving waterbody under hypothetical roof greening scenarios was modelled. The Soil Conservation Service (SCS) curve number method was the infiltration and run-off model chosen due to its simplicity and widespread use amongst engineers and watershed managers (Carter and Jackson, 2006). Changes in hydrology due to green roofing scenarios were found to be clearly dependent upon the size of the green roofs and storm events. A change in hydrology across the watershed with the implementation of green roofs was found to be minimal for storm events greater than 2-year, 24hr event. The analysis recommended the use of vegetative roofs as an abstractive stormwater best management practice in urban watersheds to replicate the interception and evapotranspiration aspects of the water cycle found in less disturbed environments. However, the hydraulic modelling suggests that green roofs alone cannot solely be relied upon to provide complete stormwater management at the watershed scale.

2.2.3 Soil Drainage Models

In formulating a model to represent the drainage rate through the experimental mesocosm it was important to not only review the limited literature surrounding the hydraulic modelling of green roofs, but to review the literature and application of soil drainage models most of which are in relation to agricultural systems.

Agricultural system models require the input of soil properties, weather data, plant parameters, and management practices, for all of which uncertainty is a major concern. The more complex a model, the more parameters it requires and the more sensitive its simulation results are to uncertainty in input parameters (Ma et al., 2007). The major requirements of process-based models are detailed soil hydraulic properties such as the soil water retention curve and the soil matrix saturated hydraulic conductivity for the specific site. Ma et al used variability in measured soil hydraulic properties to conduct sensitivity analyses of the RZWQM-DSSAT hybrid model after calibration for a long-term study in Iowa, USA. The studies objective was to conduct sensitivity analysis on how experimental errors in hydraulic parameter measurements affected simulation results of RZWQM, and to evaluate them in comparison with default soil parameters based on soil texture from Rawls et al (1982) (Ma et al., 2007). It was concluded that wherever possible it is recommended to use local soil information and accurate vegetation bulk density measurements as this defines the magnitude of saturated soil water content which in turn determines drainable porosity. Therefore specifying the importance of calculating the correct vegetation density in soil hydraulic models can be considered crucial.

2.2.4 Vegetation and Drainage Capacity

The main factor governing plant water use is the evaporative demand or the evaporation potential of the atmosphere around the plant foliage. The level of evaporative demand and hence the plant water use is directly influenced by: solar radiation; air temperature; relative humidity; and wind speed (Kidd, 2005). As a result vegetation density is a crucial component in the ability of any green roof to retain potential run-off. Modelling is important in analysing the factors governing plant water use. Few experimental works and accurate models are available in literature to explain the evapotranspiration phenomena (Lazzarin et al., 2005) and much of the literature refers to the modelling of the thermal and energetic behaviour of green roofs.

The capacity of vegetated surfaces to intercept and store water is of great practical importance. To hydrologists, the most important aspect of interception relates to its effect on site and catchment balances (van Dijk and Bruijnzeel, 2001) and in this instance the ability of a vegetated green roof to intercept rainfall. Bellot et al (1999) and Ashman and Puri (2003) found that plants increase the infiltration capacity of soils by means of macropores caused by root systems, thus limiting run-off. In contrast, a proportion of the rainfall is lost by interception in the plant canopy, reducing the soil water content by actual evaporation in proportion to the plants' biomass (Bellot et al., 1999). Bellot et al's study in Alicante, Spain modelled soil water content and evapotranspiration, over a range of vegetation types using data series for the year 1997. The model applied a negative exponential approach to estimate actual evaporation as a function of hydraulic conductivity and total evaporation. The main conclusion was the relevance of the vegetation type in estimating actual evaporation, drainage and soil water content.

Peters-Lidard et al (2001) investigated the scaling properties of soil moisture, given its importance in land-atmosphere interactions. It was hypothesised that the multiscaling behaviour inferred from simulated soil moisture and latent heat flux is a relationship which is a function of average soil moisture. It is thought that this transition is governed by scaling properties which in wet conditions control infiltration (porosity, field capacity, leaf area index) to properties which in dry conditions control drainage (residual moisture content and soils-topographic index) and evaporation (wilting point and leaf area index) (Peters-Lidard et al., 2001). The spatial structure, soil moisture and surface heat fluxes for a 5cm depth of soil in the Washita watershed, USA were investigated from 1992 – 1994. A spatially distributed water and energy balance model was used and shown to reasonably represent soil moisture and latent heat flux during the experimental period confirming the importance of soil moisture on land-atmosphere interactions. The investigation was conducted on a large spatial scale but the scaling properties analysed can be considered just as important on small scale green roof developments.

2.2.5 Vegetation Cover

Much literature relates to agricultural practices, crop evapotranspiration and the calculation of crop co-efficients. In particular the FAO irrigation and drainage paper 56 (Allen et al., 1998) specifies the importance of calculating the correct crop co-efficient value to incorporate into calculations of crop evapotranspiration. The crop co-efficient varies predominantly with the specific crop characteristics and only to a limited extent with climate. This enables the transfer of standard crop co-efficient values between locations and climates. The crop co-efficient integrates the effect of characteristics that distinguish a typical field crop from the grass reference, which has a constant appearance and a complete ground cover. Consequently, different crops have different co-efficients. After rainfall or irrigation, the effect of evaporation is predominant when the crop is small and scarcely shades the ground (Allen et al., 1998), as is the case for newly seeded extensive green roofs. For such low cover conditions the co-efficient is largely determined by the frequency with which the soil surface is wetted (Allen et al., 1998). However, as the crop develops, the ground cover, soil height and leaf area will change (Allen et al., 1998) and these differences in growing stages will results in differences in evapotranspiration rates. Drainage capacity will therefore vary with plant growing stage, the resulting change in evapotranspiration and root system development (Handreck and Black, 2005) all of which should be considered in the development of a model to simulate drainage.

2.2.6 Root Systems

Due to their influence upon the hydrological functioning of soils, root systems are an important component within the modelling process. Coelho et al (2003) stated that crop growth yield simulation models require a sub-model of root growth that should contain an adequate description of the root system by considering its growth and interactions with shoot growth and the soil environment. Most modelling approaches are based on one of the following assumptions: (*i*) that plant roots are uniformly distributed in homogenous soil layers and all roots have the same ability for uptake; or (*ii*) that plant root length is always sufficient for resource uptake in rooted soil layers. In structured soils, an overestimation of water uptake is likely to be expected (Wang and Smith, 2004).

As can be seen there are a multitude of factors which must be considered in the development of a model to simulate drainage. Much of the literature reviewed relates to agricultural models, therefore there is a research gap in relation to the modelling of substrate type and drainage from green roofs. This thesis will attempt to critically assess some of the questions surrounding the use of varying substrates on green roofs and their ability to mitigate run-off effectively. With the development of a model to simulate discharge from the experimental mesocosms the factors reviewed within the literature in relation to vegetation, evapotranspiration and drainage will be considered.

Chapter Three

Experimental Methodology

3.1 Site Description

3.1.1 Experimental Mesocosms

The experimental mesocosms are located on the Arts Building of the University of Birmingham's Edgbaston Campus. The site consists of seven substrate types with five replicates of each (Table 3.1.1).

Treatment Number	Substrate Type
1	Demolition aggregate with no mulch
2	Demolition aggregate with a loam mulch
3	Demolition aggregate with a loam mulch containing compost
4	Crushed brick with a loam mulch
5	Solid municipal incinerator bottom ash with a loam mulch
6	50:50 Demolition aggregate: crushed brick with a loam mulch
7	50:50 Demolition aggregate: solid municipal incinerator bottom ash with a loam mulch

Table 3.1.1 Substrate treatment types

The mesocosms are identical except for their substrate treatment. Each mesocosm consists of a plywood deck (2.44 x 1.22m) with timber curbs at each side with a 50mm outlet in one corner. On top of the plywood deck is a layer of polyester reinforced PVC that acts as a water and root proof layer. Above the PVC is a composite drainage-reservoir board, to enable plant uptake during long periods without rain, and to allow the free drainage of water. A fleece layer is placed above the board to limit the amount of fine sediment that can wash through the mesocosm and cause blockages (Figure 3.1.1.1).

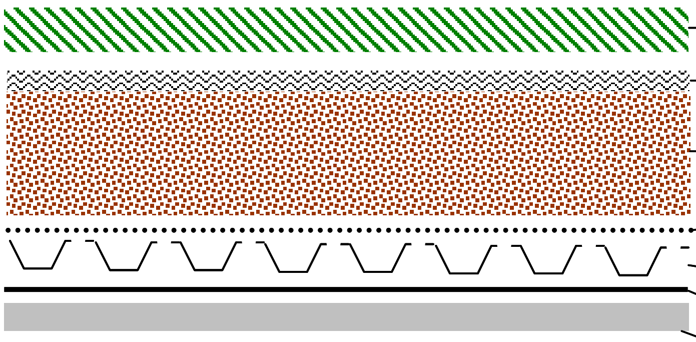

Figure 3.1.1.1 Schematic diagram of green roof system (Bates et al., 2006)

The sediment layer consists of ~10cm of inorganic substrate, with ~1cm of mulch on the treatments specified. The crushed brick and ash provide the coarsest substrate and the demolition waste the finest. The demolition aggregate was sourced from demolished buildings and is principally made up of concrete, crushed brick, mortar, ceramics, roof tiles, glass, stone and other such materials.

The analysis will only consider two treatment types: The crushed brick with a loam mulch and demolition aggregate with loam mulch, both of which contain a soil moisture probe (see Appendix A.1 for locations).

3.1.2 Vegetation Mix

On the 15th of March 2007 the mesocosms were seeded with 1.5g/m^2 of species mix known to do well on green roofs and commonly associated with brownfield sites in Birmingham (Appendix A.2 for species mix). A lack of rainfall prevented the mix from seeding and as a result the mesocosms were re-seeded with 1g/m^2 of the same mix (without the *Sedum acre*).

3.1.3 Watering

Due to a lack of rainfall after seeding the mesocosms were watered on seven occasions during May to encourage plant growth. The mesocosms were never allowed to dry out and on each occasion were watered with 13.1 litres per mesocosm, equivalent to ~5mm of rainfall.

3.1.4 Data Logging

A weather station records wind direction and speed, rainfall, temperature, relative humidity and air pressure. A pyranometer provides solar radiation measurements. Weather information, soil moisture probe and discharge readings, are automatically transferred every 5 minutes to the Data Logger DT80 situated on the roof.

3.2 V-Notch Weir

3.2.1 Experimental Set Up

Water falling on the mesocosms which is not retained by the substrate or lost through evapotranspiration will be piped to a v-notch weir. The five demolition aggregate mesocosms are piped to v-notch weir 1 and the five brick mesocosms to v-notch weir 2. The angle of the v-notches are integral to the calibration, these angles were measured with a protractor and are specified in Table 3.2.1. Using the protractor to measure these angles was the most practical method but human error may have resulted.

v-notch	Angle of notch
1	38^{o}
2	36^{o}

Table 3.2.1 V-notch weir angles

The water level behind the v-notch will be automatically measured by an ultrasonic distance transducer. The ultrasonic sensor did not have a built in temperature sensor to compensate for the change in sound speed in air due to temperature variations, and as a result the values produced maybe subject to some degree of error. A baffler was inserted into the v-notch reservoirs to prevent the inflow of water into the weir disturbing the surface of the water.

3.2.2 Calibration of V-notch Weir

V-notch weir 1 was calibrated in situ on the 11^{th} of July, v-notch weir 2 was calibrated in situ on a prior occasion. The most crucial aspect of the calibration were the no flow values, the water level when there is no flow out of the v-notch. The water heights recorded require this value to be subtracted to account for the space underneath the v-notch outlet. To record this value the water level in the weir was left to stabilise and the values recorded by the ultrasonic transducer over a period of 15 minutes were noted and an average calculated.

A plastic storage tank was placed above the v-notch with a hose connected to an outlet tap, a hole at the top of the tank allowed excess water to flow out and a constant head to be maintained. After the ‘no flow’ level was ascertained eight subsequent flow rates were recorded. For each flow rate the hose was placed inside a measuring cylinder and the time taken for the water level to reach 500ml or 1000ml (for the higher flow rates) was recorded and repeated three times. The hose was then placed in the v-notch weir and over a period of 15 minutes (after the water level had stabilised) the flow levels sampled by the sensor and recorded by the data logger were noted. The hose was placed back in the measuring cylinder and the flow rates noted to ensure the discharge had not fluctuated. Average flow rates were calculated. Due to the use of a stopwatch to record the time taken to fill the measuring cylinders human error may have resulted.

Prior to calibrating, Cd (co-efficient of discharge) was estimated to be used in the calibration equation (Equation 1). The Cd value is a correction factor applied to correct for effects such as viscosity, turbulence and non-uniform flow distribution within the v-notch reservoir (Bos, 1989 cited in Van den Elsen). The Solver function in Excel was then used to calculate a more accurate Cd value in relation to the recorded data.

The flow out of the weir is proportional to the height of water above the bottom of the v-notch and is calculated by the following calibration equation:

$$Q = Cd\left(\frac{8}{15}\right)\sqrt{2g}\,\tan\left(\frac{\theta}{2}\right)H^{\frac{5}{2}}$$

Equation 3.2.2 Calibration Equation

Where:	Q	=	Flow Rate (l/min)
	Cd	=	Co-efficient of discharge
	θ	=	Angle of notch
	H	=	Height of water above the base of notch (mm)
	g	=	Gravity

3.2.3 Calibration Results

Figure 3.2.3 indicates the comparison between the measured and predicted values for water height and discharge into the v-notch weirs at low flow rates. The measured values are values recorded in situ on the roof. Predicted values are those which have been calculated using the new co-efficient of discharge produced from the calibration. It was considered appropriate to compare the predicted and observed values at low flow rates as discharge into the weir will be small most of the time and therefore it was important that the v-notch produced accurate results.

It is clear from Figure 3.2.3 that the measured and predicted values are similar for both v-notch 1 and v-notch 2. At the lowest recorded discharge the values correspond well although discharge is slightly under predicted. However, the difference between the measured and predicted values increases with increasing discharge and discharge becomes over predicted. Nevertheless this is of minor concern as discharge is unlikely to exceed 1.0 litre/min. Therefore, the co-efficient of discharge produced from the calibration produces satisfactory values for the small flows which will be expected from the experimental mesocosms.

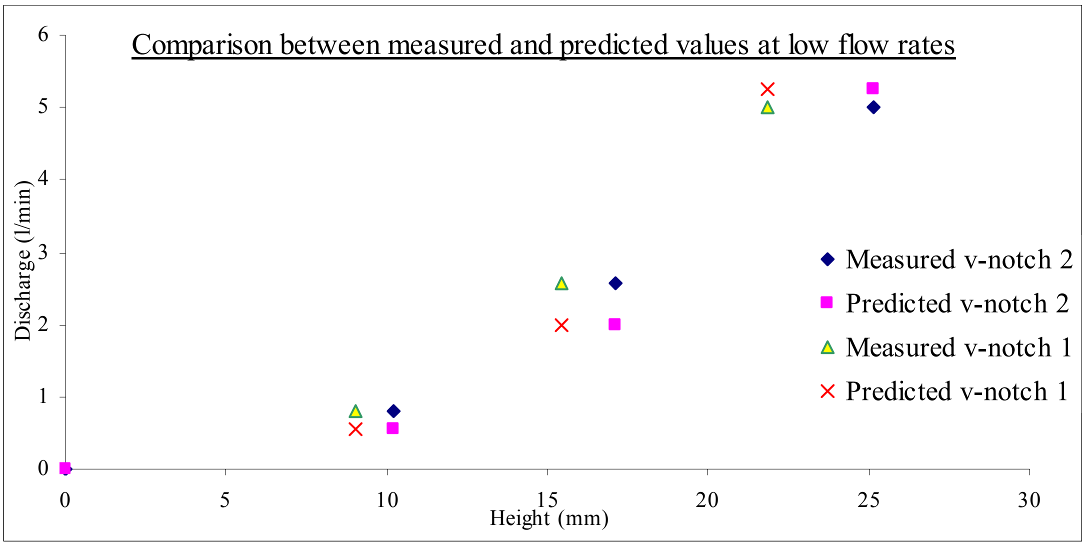

Figure 3.2.3 V-notch weir ultrasonic sensor calibration, comparison of predicted and recorded values

3.3 Soil Sampling

This section will cover the laboratory analysis of the two substrates. A full methodology of the laboratory analysis can be found in Appendix B.

The substrate analysis was undertaken with the aim of causing minimal disturbance to the experimental mesocosms. This was problematic as the sample sizes required to undergo the laboratory analysis were relatively large and as a result some of the vegetation was destroyed. All of the sample collection and laboratory analysis was undertaken with the aid of Adam Bates.

3.3.1 Determination of Particle Size

Particle size distribution gives a broad indication of the physical and chemical properties of soils (Rowell, 1994). It was therefore relevant to determine the particle sizes in order to compare the substrates.

3.3.2 Determination of Overall Density of Soil Particles and Overall Dry Bulk Density

It was necessary to determine the overall density of the soil particles to compare the two sets of mesocosms. Particle density focuses on the soil particles alone and not the total volume that the soil particles and pore spaces occupy in the soil. Bulk density includes the volume of the solid (mineral and organic) portion of the soil including the spaces where air and water are found. Particle and bulk density data were used to calculate the pore space (porosity). This provides information on the amount of space occupied by air and water in the samples, important in determining which substrate is better at retaining water and supporting plant, animal and microbial life (Rowell, 1996).

3.3.3 Determination of Water Content at Field Capacity, and Permanent Wilting Point

The amount of water held within the substrate may help determine how well plants will grow. The amount of water stored in the substrate for plant growth is termed ‘plant available water’. This is the amount of water that the soil can store between the ranges of field capacity (when the soil is saturated) and wilting point (when the soil is too dry to supply water to the plant) (Ashman and Puri, 2003). Calculating the permanent wilting point and field capacity will allow comparisons to be made between the substrates, readings generated from the soil moisture probe and the results from the laboratory analysis.

3.4 Vegetation Cover

A full methodology of how the vegetation analysis was undertaken can be located in Appendix C.

3.4.1 Vegetation Cover Sampling

It was important to analyse the change in vegetation cover over the period of time being investigated (15/05/2007 – 16/08/2007) in order to see if a relationship exists between vegetation cover and run-off. The analysis was under taken using the programme Image Pro Plus, which provides an estimation of percentage vegetation cover. The vegetation cover results will be incorporated into the modelling process to determine its influence on the water retention capacity of the mesocosms.

Chapter Four

Results

4.1 Introduction

This chapter will present the results and describe any evident trends, a critical analysis of the results can be found in Chapter 5 'Discussion'. As the run-off from each set of mesocosms drains into a combined reservoir it was considered appropriate to present the data from the substrate analysis in the same format, i.e. one average value calculated from the 5 replicates for each substrate. Where specified the demolition aggregate mesocosms are referred to in the figures and tables as 'Dem Loam'.

4.2 Soil Analysis Results

4.2.1 Particle Size

It is clear from Figure 4.2.1 that the demolition aggregate mesocosms have a higher percentage of large particles. Approximately 20% of the material removed from the demolition aggregate mesocosms was smaller than 16mm, in comparison with 70% from the brick mesocosms. Both the brick and demolition aggregate mesocosms contained a similar percentage of particles between the sizes 0.5mm and 2.0mm, 3.86% and 3.92% respectively. The brick mesocosms although having a smaller make up of large particles produced the greatest grain sizes.

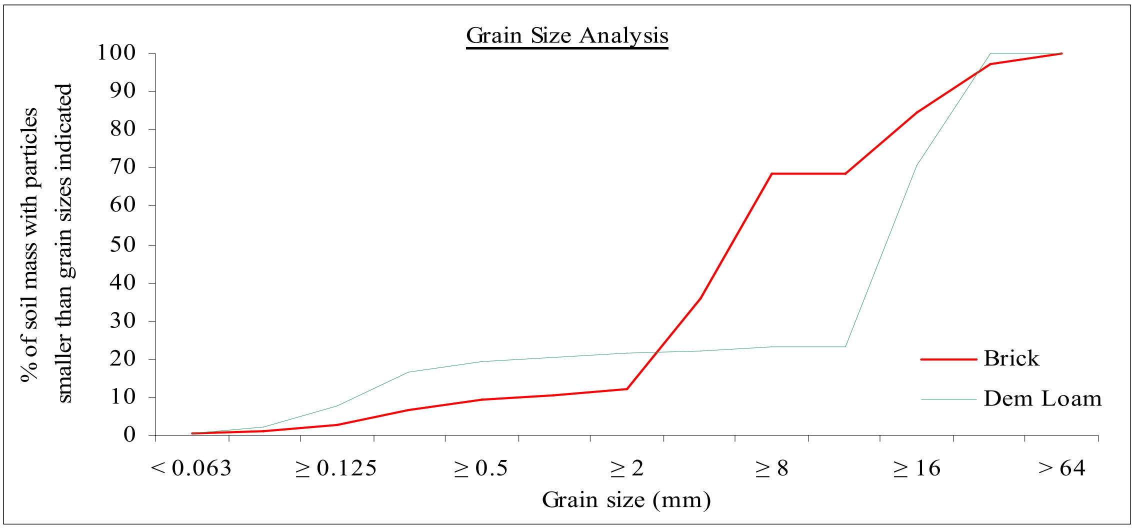

Figure 4.2.1 Grain size analysis

4.2.2 Pore Space

Bulk density and particle density data found in Table 4.2.2 have been used to calculate percentage pore space. It is clear that the particle density values are very similar for each mesocosm. Bulk density is greater for the demolition aggregate mesocosms, 2.37g/ml in comparison with 1.74g/ml calculated for the brick. Soil Porosity is greater for the brick mesocosms with an average value of 31% pore space, compared with 6% for the demolition aggregate.

Results	Brick	Dem Loam
Dry Mass of Excavated Soil (g)	1093.94	1355.68
Overall Dry Bulk Density (g/ml)	1.74	2.37
Particle Density (g/ml)	2.55	2.52
Soil Porosity (%)	31.0	5.88

Table 4.2.2 Pore space investigation results

4.2.3 Permanent Wilting Point and Field Capacity

Utilising the pore space results and calculating the water content in the substrate at permanent wilting point and field capacity it was possible to illustrate the percentage make up of the two substrate types (Figure 4.2.3 and 4.2.3.1). At permanent wilting point the brick mesocosms contain 6% water in comparison with the demolition aggregate mesocosms which contain 2% water.

At field capacity the brick mesocosms contain approximately 20% water in comparison with the demolition aggregate mesocosms which contain 12% water. The demolition aggregate pore space is clearly full as there is a greater percentage of water than there is available poor space.

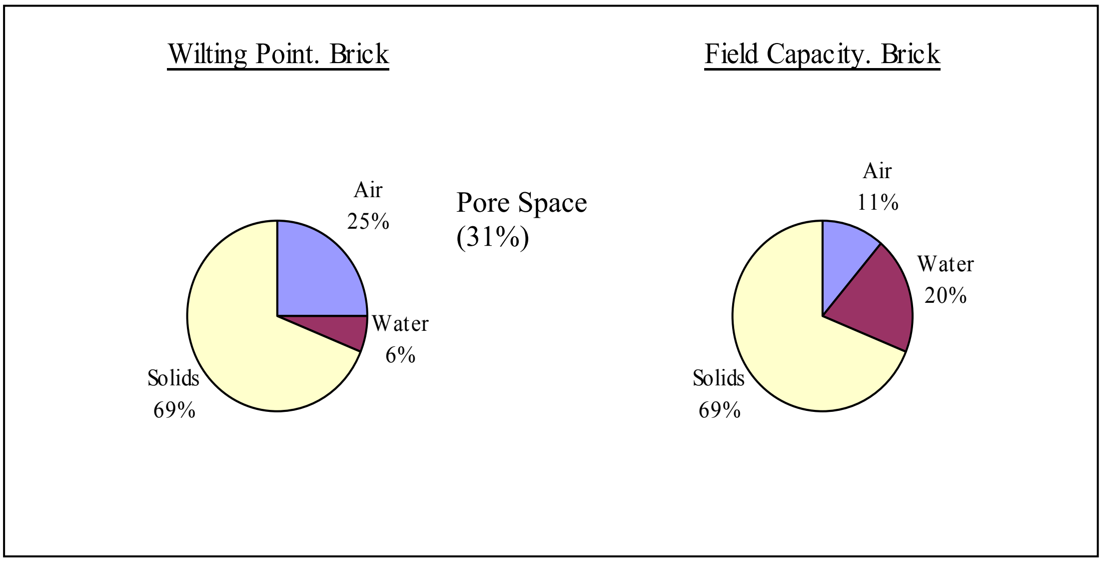

Figure 4.2.3 Composition of brick substrate at permanent wilting point and field capacity

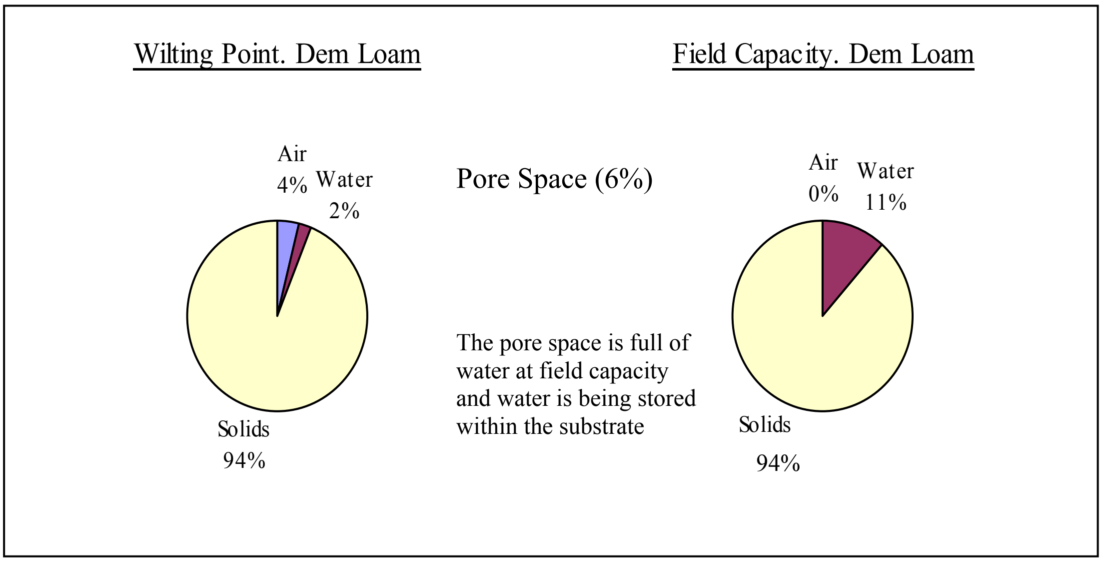

Figure 4.2.3.1 Composition of demolition aggregate substrate at permanent wilting point and field capacity

4.3 Vegetation Cover

4.3.1 Vegetation Cover Results

The demolition aggregate mesocosms have a greater vegetation cover than the brick mesocosms (Figure 4.3.1). After a 3 month growing period there is only an average of 0.42% vegetation cover for the brick and 1.93% for the demolition aggregate. By the end of July both set of mesocosms have almost doubled in percentage vegetation cover. For the brick there is little change in cover by the end of July and surprisingly for the demolition aggregate vegetation cover appears to have reduced.

The error bars in Figure 4.3.1 are based on the standard deviation of the average vegetation cover values for each substrate. The demolition aggregate vegetation cover has the largest errors (standard error of 0.59 and 0.97 for the 28th of June and 30th of July respectively). The error is also large for the brick on the 30th of July (0.54).

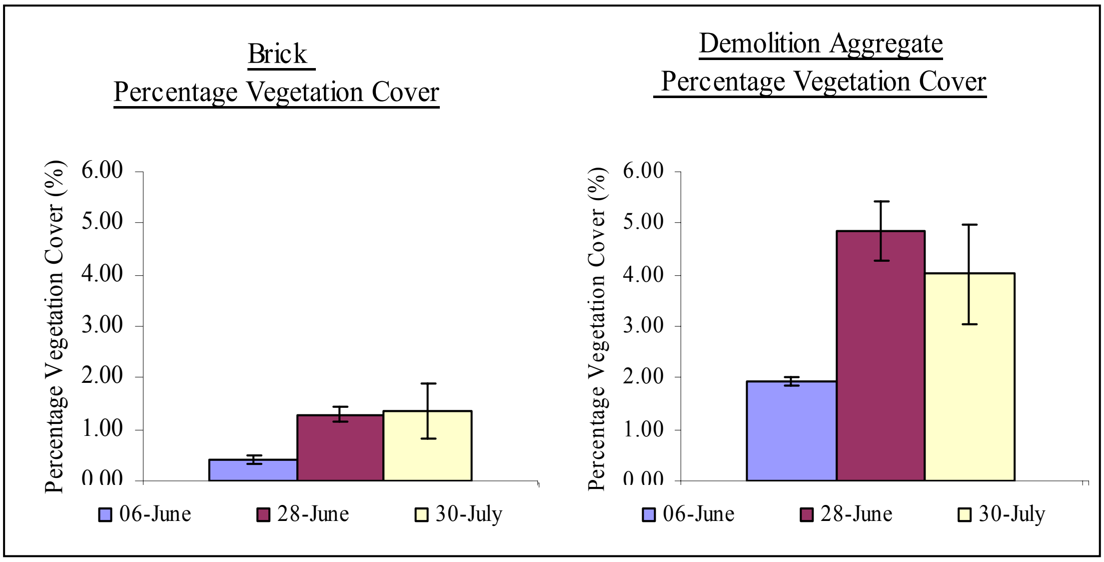

Figure 4.3.1 Percentage vegetation cover from Image Pro-Plus analysis, brick and demolition aggregate

4.4 Experimental Mesocosm

4.4.1 Rainfall and Discharge Produced

From a numerical analysis of monthly rainfall and run-off data it is clear that run-off is greatest from the demolition aggregate mesocosms (Table 4.4.1) and that the brick mesocosms retain a larger percentage of rainfall. The brick overall retained an average of 54% of the precipitation recorded compared with 37% retained by the demolition aggregate.

Month	Total Rainfall (mm/5min)	Total Brick Run-off (l/m^2)	**% Retained by mesocosm**	Total Dem Loam Run-off (l/m^2)	**% Retained by mesocosm**
June	210.78	130.15	**38 %**	159.42	**24 %**
July	192.08	109.71	**43 %**	116.25	**39 %**
August (1/8/07 – 16/08/07)	15.38	2.73	**82 %**	8.00	**48 %**

Table 4.4.1 Total amount of run-off produced from each set of mesocosms

It is clearly visible from the 4 graphed occasions that the demolition aggregate mesocosms produce run-off before the brick mesocosms (Figures 4.4.1.1, 4.4.1.3, 4.4.1.5 and 4.4.1.9).

For the period show in Figure 4.4.1.2 the demolition aggregate mesocosm has a greater soil moisture content than the brick. The demolition aggregate soil moisture content reaches a peak value of 35% compared with a value of 15% for the brick. The soil moisture content for the demolition aggregate remains more constant and stable than that of the brick. Both soil moisture readings rise at similar gradients after the rainfall event which peaked at 0.64 mm/5min at 11:00 on the 26/05/07 (Figure 4.4.1.1). It is clear that during the period of no rainfall after that which fell at 23:00 the mesocosms were unable to dry out. Therefore when the rain occurs again at 5:00 the soil moisture content increases little and run-off occurs for both substrates. A small peak occurs for the brick soil moisture content which corresponds with a peak in rainfall of 0.96 mm/5min at 2:00 on the 27/05/07. This peak is not observed in the demolition aggregate soil moisture reading. Figure 4.4.1.1 further illustrates how some large rainfall events have lower peak discharges than intermediate events.

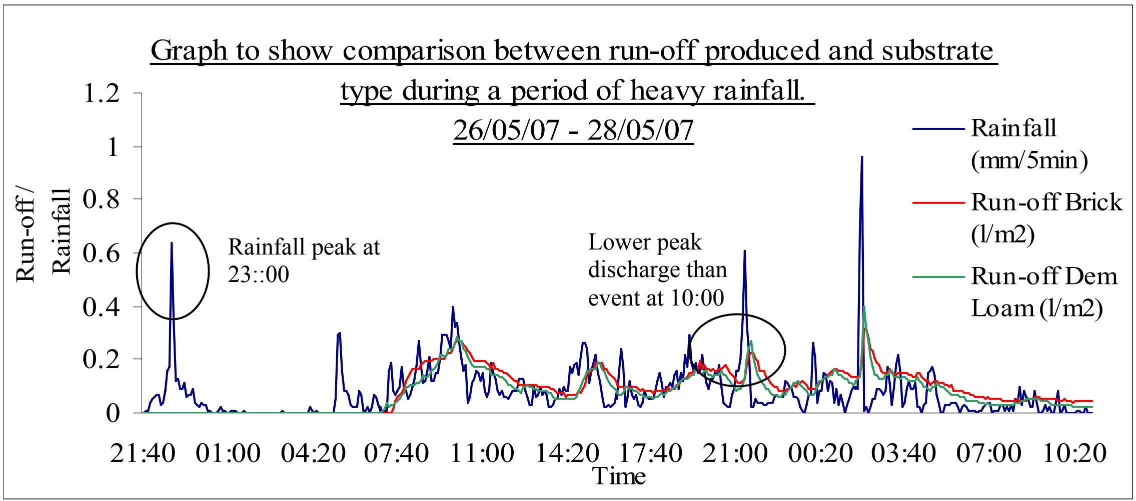

Figure 4.4.1.1 Rainfall and run-off comparison (26/05/07 – 28/05/07)

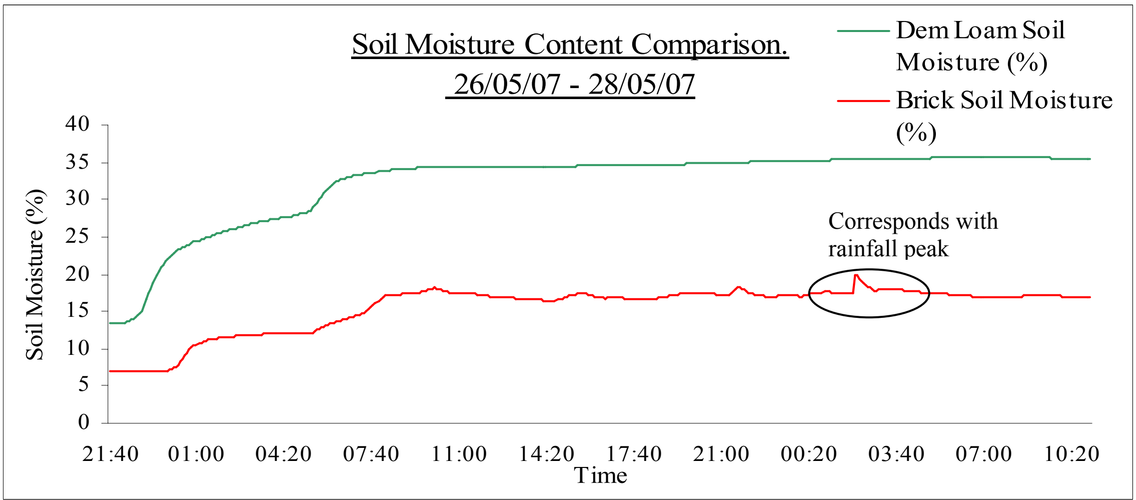

Figure 4.4.1.2 Soil moisture comparison (26/05/07 – 28/05/07)

Figure 4.4.1.3 illustrates rainfall occurring for a short period between 12:50 and 17:30 on 28/05/07 and peaking at 13:25 at 1.72 mm/5min. The run-off produced from this short rainfall event peaks approximately at 14:40 at a value of 0.11 l/m^2 for the brick mesocosms. Run-off from the demolition mesocosms peaks prior to this at 13:45 with a value of 0.09 l/m^2. The soil moisture values for the 2 substrates remains fairly constant at around 35% for the demolition aggregate and 17% for the brick (Figure 4.4.1.4). The soil moisture content does not start to decrease until 24 hours after precipitation peaked, at which point both substrates decrease at similar rates.

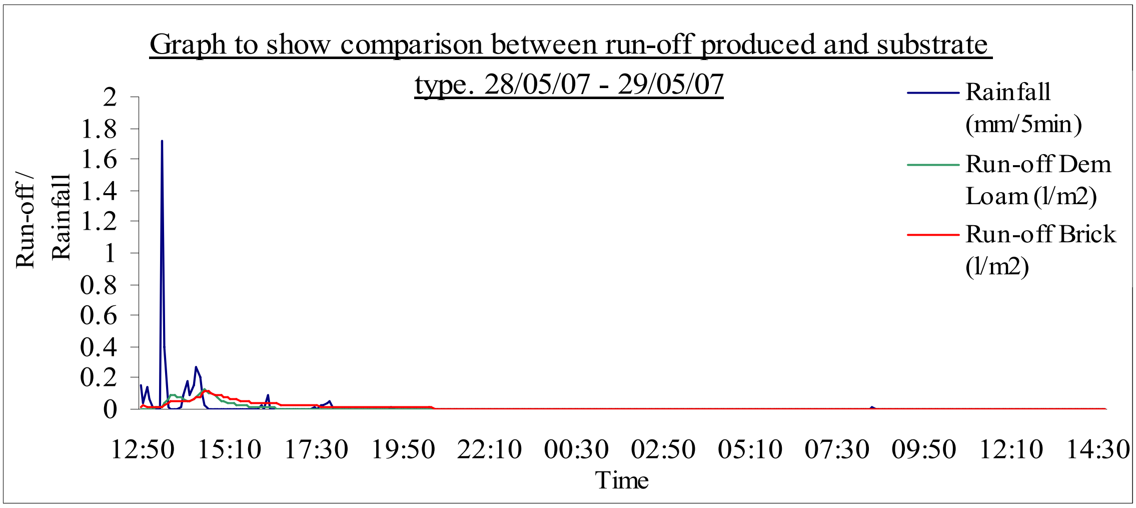

Figure 4.4.1.3 Rainfall and run-off comparison (28/05/07 – 29/05/07)

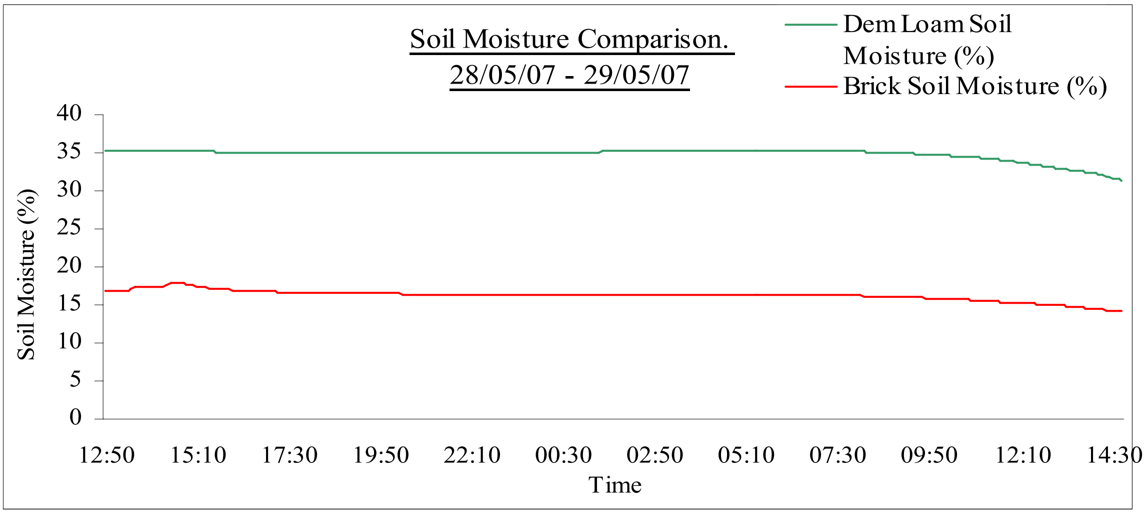

Figure 4.4.1.4 Soil moisture comparison (28/05/07 – 29/05/07)

It is apparent that run-off lags the peak rainfall events and that the hydrograph peak is significantly attenuated. This is clearly illustrated in Figure 4.4.1.5. At 14:55 (20/7/07) rainfall peaks at 1.91 mm/5min however run-off does not peak until 15:20 at a rate of 1.09 l/m^2 for the brick mesocosms. The brick only appears to delay run-off significantly more than the demolition aggregate when there is extremely heavy rainfall (>1.8mm / 5 min). For the period graphed in Figure 4.4.1.6 the soil moisture content remains stable for demolition aggregate slightly increasing over time. The brick soil moisture content however fluctuates more with small peaks and troughs coinciding with those in the rainfall data.

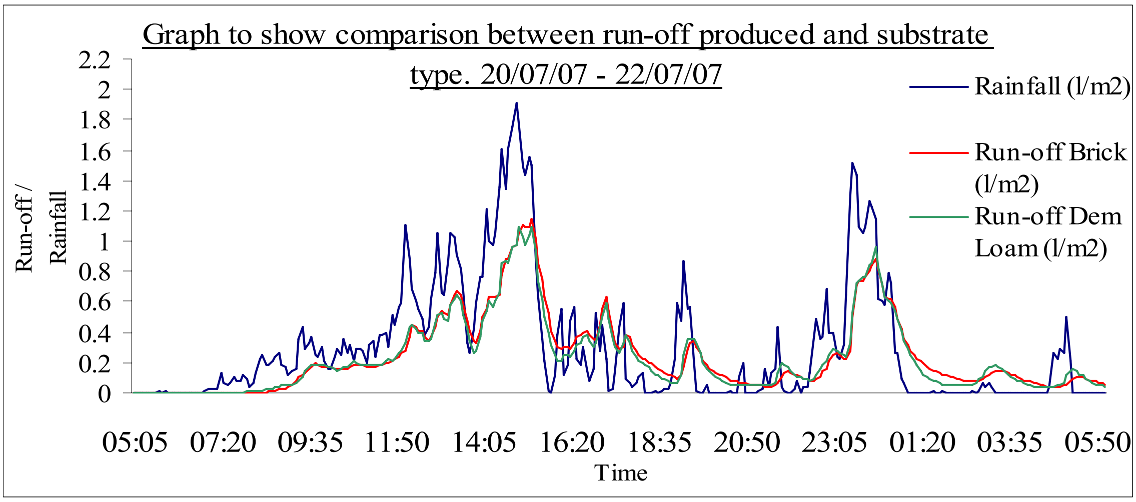

Figure 4.4.1.5 Rainfall and run-off comparison (20/07/07 – 22/07/07)

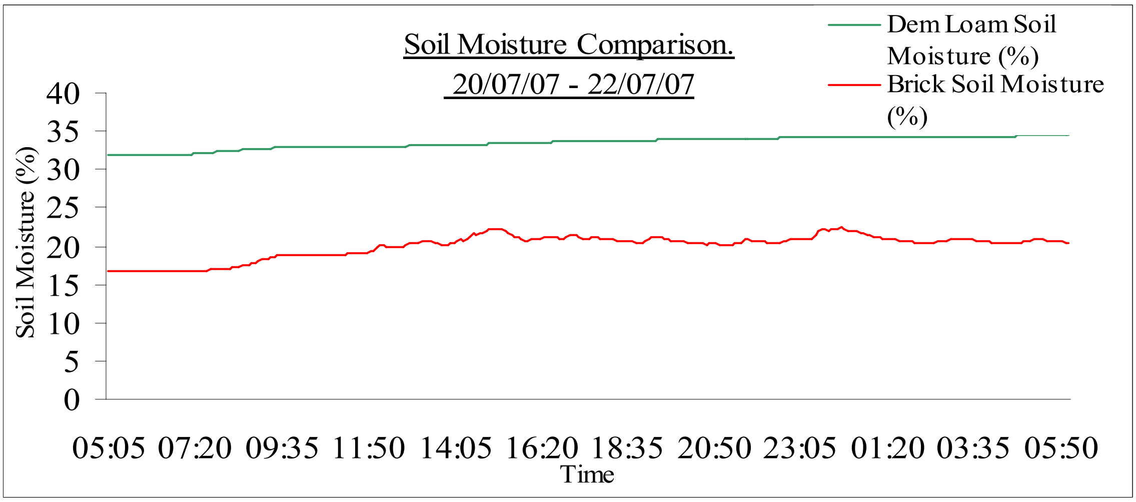

Figure 4.4.1.6 Soil moisture comparison (20/07/07 – 22/07/07)

The data generated from the mesocosms clearly indicates that more run-off occurs from the demolition aggregate mesocosms than the brick. Soil moisture content is generally greater for the demolition aggregate than the brick by approximately 20%. However, from the end of July the weather improved considerably and a change in the soil moisture composition was noted. For the period illustrated in Figure 4.4.1.7 and 4.4.1.8 rainfall only occurs for a short 2 hour period in the early morning on the 2/08/07 when the opportunity was taken to analyse permanent wilting point. Unusually in comparison to previous readings the brick soil moisture content exceeds that of the demolition aggregate. It was confirmed by laboratory analysis that on this occasion the brick contained 6% water and the demolition aggregate 2%, both of which are consistent with the readings produced by the soil moisture probe (Figure 4.4.1.8).

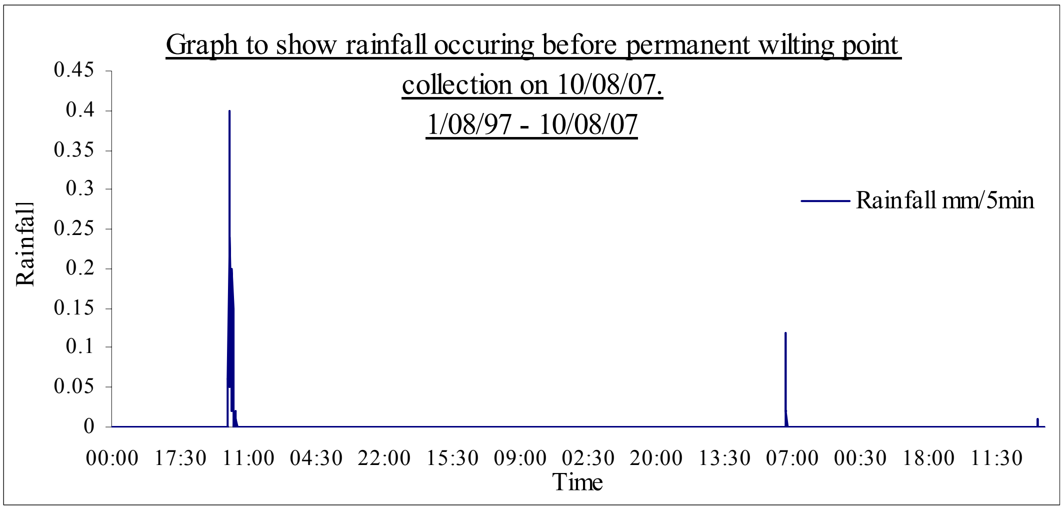

Figure 4.4.1.7 Rainfall and run-off comparison at permanent wilting point (1/08/07 – 10/08/07)

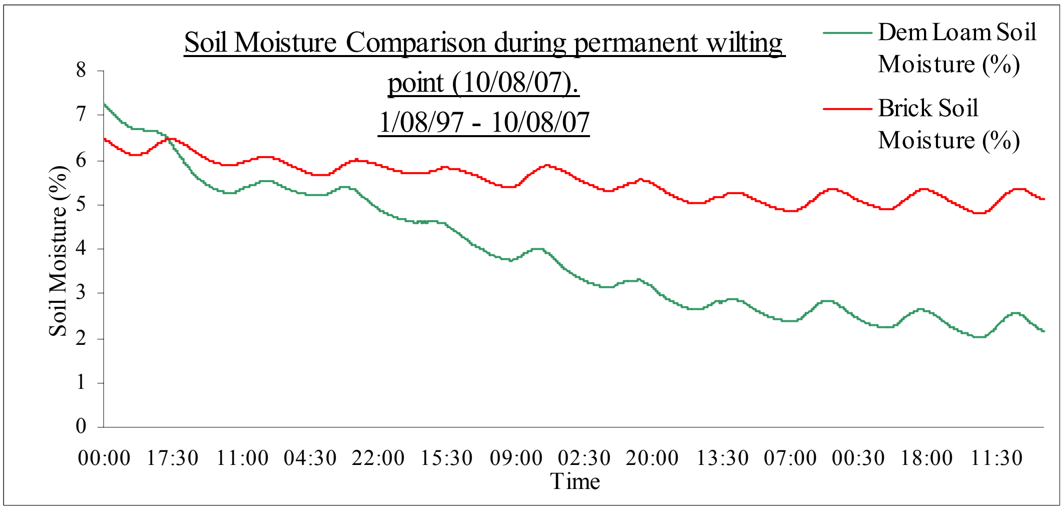

Figure 4.4.1.8 Soil moisture comparison at permanent wilting point (1/08/07 – 10/08/07)

In order to understand the interactions between rainfall, run-off and soil moisture content samples were taken at field capacity. It is important to note that before the 14/08/07 graphed in Figures 4.4.1.9 and 4.4.1.10 was a very dry period with temperatures reaching 30 ^{0}C, when the permanent wilting point analysis took place. It is clear from Figure 4.4.1.9 that because the mesocosms were so dry little run-off was generated from the large rainfall event at 08:25, and discharge only occurred from the demolition aggregate mesocosms. It is interesting to note the rapid increase in soil moisture content after the large rainfall event, illustrating the retention capacities of the substrates. The demolition aggregate still has a greater soil moisture content than the brick which is puzzling as the field capacity results concluded that there was only 11% water held in this substrate in comparison with 20% for the brick, this is not confirmed by Figure 4.4.1.10 and as a result suggests some form of error either in the laboratory analysis from the soil moisture probes.

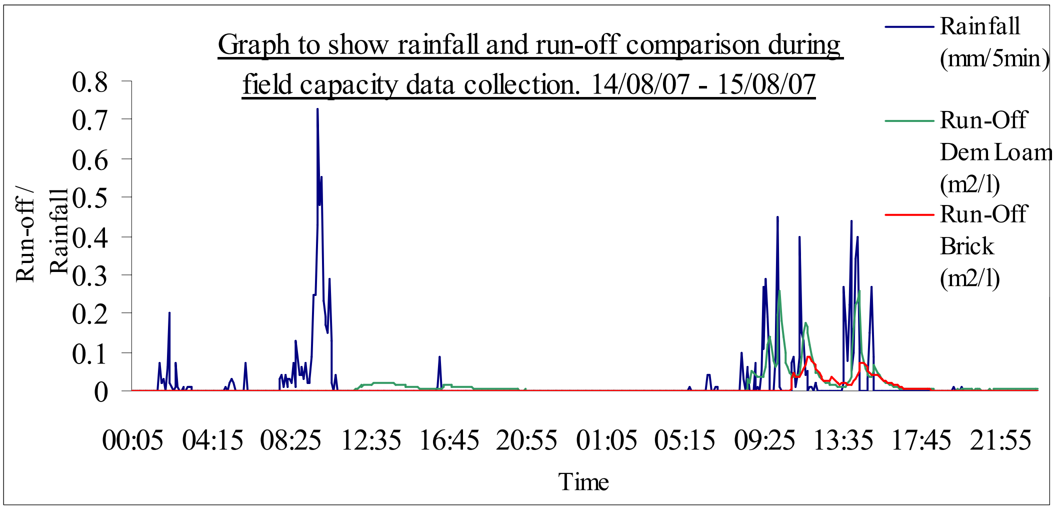

Figure 4.4.1.9 Rainfall and run-off comparison at field capacity (14/08/07 – 15/08/07)

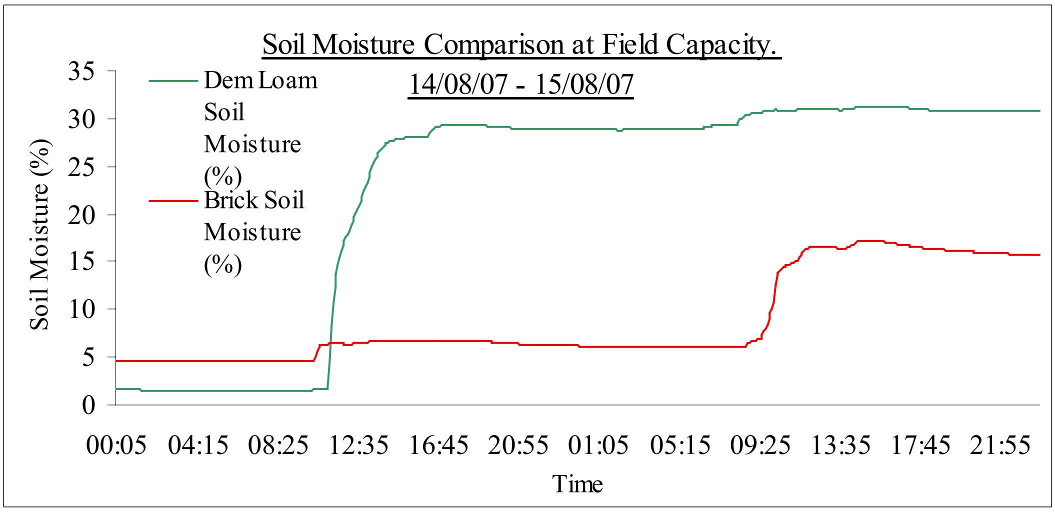

Figure 4.4.1.10 Soil moisture comparison at field capacity (14/08/07 – 15/08/07)

Chapter Five

Discussion

5.1 Introduction

The results presented in Chapter 4, and discussion presented in this Chapter allows aim and objective (ii) set in Section 1.2 to be met. A comparison of the results produced from each set of mesocosms will allow conclusions to be drawn on their value of reducing run-off from roofs in urban areas.

5.2 Interpretation of Soil Analysis

5.2.1 Particle Size

Particle size distribution is an important soil characteristic and will have an effect on soil properties such as the availability of moisture and permeability.

Sands will often provide a good supply of nutrients for plant usage, retaining nutrients well preventing leaching (Rowell, 1996). The brick mesocosms had approximately a 10% make up of sand and the demolition aggregate 17%. Although sand is beneficial it can become water logged during heavy rainfalls due to poor drainage and can also become very hard when dry (Rowell, 1996). As the demolition aggregates contained a higher percentage of sand it is likely that during periods of very dry weather the soil will have a lower water content than the brick as was illustrated in Section 4.2.3 Figure 4.2.3.1. As 77% of the demolition aggregate soil is made up of medium to course gravels and pebbles, it is likely that water will be lost more easily due to the reduced volume of soil (Rowell, 1996), and as illustrated run-off will be more likely from the demolition mesocosms. In contrast only 28% of the soil from the brick mesocosms is medium to course gravels and pebbles

As the substrates used on the experimental mesocosms contain little soil, most of the particles need to be in the size range of 0.2 – 3.0 mm diameter to allow good vegetation development (Handreck and Black, 2005). The demolition aggregate soil particles in this size range are around 12% and in comparison the brick comprises only 7%. This may have negatively influenced vegetation development on the brick mesocosms.

5.2.2 Pore Space, Permanent Wilting Point and Field Capacity Interpretation

The brick mesocosm contained a greater percentage of poor space and thus can more easily be filled with water (Taro et al., 2001), increasing the retention capacity of the brick. Particle density which has been used to calculate soil porosity is fairly consistent for each mesocosm, as neither substrate is much heavier than the other. The reduced pore space and high percentage of gravels and pebbles in the demolition aggregate mesocosms may contribute to increased discharges observed from this substrate. When considering green roof design it is important ensure the substrate has a higher proportion of large pores than do natural soils so the roots are supplied with an appropriate amount of oxygen (Handreck and Black, 2005). Therefore vegetation cover on the mesocosms maybe influenced by the availability of large pores and the ability of the substrate to retain water during long dry periods. As the brick mesocosms can hold water for longer, plant productivity maybe positively influenced during these dry periods, this however was not investigated.

The samples removed for the field capacity analysis were taken during a period of heavy rainfall and it was assumed that field capacity had been reached, however on closer inspection this is debatable. The results indicate that more water is stored in the brick mesocosms than in the demolition aggregate illustrating why more discharge occurs from the demolition mesocosms, proving hypothesis (ii) set in Section 1.3 to be correct. As the demolition mesocosms are holding more water than there is space available within the pores it is likely that water has been absorbed and retained within the substrate. However as the brick only contained 20% water out of a pore space capacity of 31% it is unlikely that field capacity has been reached for the brick substrate. As the field capacity results do not correspond with the results produced from the soil moisture probe it is clear that an error has occurred with the soil moisture probes. During installation it was necessary to surround the brick moisture probe with coarse sand to ensure the probe was in contact with some material. This may have resulted in more moisture around the probe than the rest of the sediment and thus inaccurate results.

5.2.3 Vegetation Cover Interpretation

Vegetation growth has occurred more rapidly for the demolition aggregate mesocosms than the brick. A number of factors may have influenced this result. Firstly the demolition aggregate mesocosms maybe more favourable to plant growth as they contain more beneficial size particles (0.2 – 3.0 mm in diameter) which will not clog pores between the bigger particles. Secondly there maybe a limiting nutrient in the brick mesocosms which is slowing plant growth, but this is unlikely as both sets of mesocosms contain the same loam mulch. Thirdly water availability within the brick mesocosms maybe negatively effecting vegetation growth. However the large errors observed during the vegetation analysis and large differences in vegetation cover between the substrates might be attributed to the limitations of Image Pro Plus. It was not always possible to highlight fully the vegetation cover due to colour similarities with the mesocosm substrate and the *Sedum*, indicating why the errors increased as the *Sedum* developed.

As investigated a variety of factors may have influenced the vegetation cover results. Nevertheless without further analysis over a longer time scale it is not possible to come to a conclusion to why the brick mesocosms contain a much reduced vegetation cover in comparison with the demolition aggregate. Therefore it was not possible to prove hypothesis (ii) set in Section 1.3 to be correct.

5.3 Rainfall, Run-off and Soil Moisture Content Interpretation

The results show that run-off is greater from the demolition aggregate mesocosms. However, why the demolition aggregate, which has a greater proportion of finer grain sizes in comparison to the brick stores more water but always has a greater run-off generated sooner than the coarser brick is puzzling. It is a possibility that the coarser brick drains into the storage board at the bottom of the mesocosm, but the sand in the demolition aggregate blocks this off. A further possibility for the earlier breakthrough from the demolition aggregate is the combination of heterogeneity, the greater capillary contribution to the down flow of water during a rainfall event and the contact between the filter at the base of the mesocosm with the finer material. There will be a certain complication arising from the geometry of the filter layer material that will concentrate the breakthrough at specific points and will make it easier to break the surface tension at the underside of the filter cloth. The finer sediments such as clay washed into the filter material may also have an impact. These effects are likely to be small-scale and unfortunately due to time constraints it was not possible to investigate them further.

Some large rainfall events have lower peak discharge rates than intermediate events, which supports the finding of Carter and Rasmussen (2006) who observed the same relationship. During a large rainfall event discharge maybe attenuated substantially more than during an intermediate event due to the soil moisture content of the substrate. If the soil moisture content is already approaching field capacity run-off will occur almost immediately after the event. In contrast if the soil moisture content is approaching wilting point and rainfall occurs there will be an additional retention capacity in the mesocosm. Most stormwater retention occurs at the beginning of storms as the substrate absorbs the initial rainfall until it reaches saturation, at which point run-off from the mesocosms and from an un-vegetated roof will be similar. This indicates that the mesocosms essentially act as a retention instrument for a particular water volume rather than detaining and slowly releasing stormwater after percolation through the soil (Carter and Rasmussen, 2006). The brick only appears to delay run-off significantly more than the demolition aggregate when there is extremely heavy rainfall (>1.8mm / 5min), this maybe due to the large pore space in the brick which can retain more water.

The fluctuations observed in the soil moisture content readings maybe attributed to the ability of the brick substrate to dry out more quickly than the demolition aggregate. As run-off occurs more rapidly for the demolition mesocosms it is likely that after drainage has stopped, the medium at the very bottom of the mesocosm will remain saturated (Handreck and Black, 1996) and may result in higher soil moisture content readings for the demolition aggregate. It is puzzling to why the brick produces less discharge than the demolition aggregate but also has a lower soil moisture content, as it would be expected that the brick would have a higher soil moisture reading as it retains more water. The soil moisture probe readings further proved to be inaccurate as the readings produced did not correspond with the laboratory analysis of field capacity. The laboratory analysis indicated that the brick substrate retained more water at field capacity than the demolition aggregate but this was not confirmed by the moisture probe readings. Nevertheless the laboratory analysis of permanent wilting point did correspond with the results produced from the soil moisture probe, and the results coincided with published values by Rowell (1996), and Ashman and Puri (2003) amongst others.

It is important to consider the substrate moisture content before rainfall events. If the water content is low before a period of heavy rain the retention capacity of the mesocosm will be at its highest as there is space to store water (VanWoert et al., 2005). The results produced in this investigation are consistent with those produced by VanWoert et al (2005) who noted such a relationship between soil water content and rainfall. This relationship is particularly apparent prior to the field capacity analysis as there had been a very dry period which enabled the mesocosms to reach permanent wilting point and as a result the retention capacity of both the substrates was likely to be at a maximum.

5.4 Value of Green Roofs for Run-off Mitigation

It is clear that both sets of mesocosms retain a large percentage of the precipitation recorded with on average 54% of the precipitation retained by the brick and 37% by the demolition aggregate, these results correspond closely with those produced by Kidd (2005) and DeNardo et al (2003) who found on average 42% and 40% respectively of precipitation to be retained by an extensive green roof. Therefore proving hypothesis (i) set in Section 1.3 to be correct.

Several studies have shown a delay in peak flow of run-off from a green roof when compared with a standard roof (VanWoert et al., 2005; Arthur and Wright, 2005; Kidd, 2005), it is apparent that a delay in onset of run-off from the mesocosm is evident when compared to the rainfall events. From this investigation it can be implied that substrate type plays an important role in water retention. However, the retention capacity will ultimately be dependent upon the substrate moisture content prior to precipitation. Evaporation of water requires energy, making the climatic environment the major factor in determining the amount of water stored by the substrate (Foth, 1984). Furthermore findings indicate that vegetation has much less of an effect on aiding water retention when compared with substrate further confirmed by VanWoert et al (2005).

Nevertheless an increase in vegetation cover may significantly reduce run-off as discussed by Bengtsson (2004), this will be further explored through model simulations.

Chapter Six

Modelling

6.1 Introduction

This chapter will fulfil aim and objective (iii) specified in Section 1.2. In order to effectively analyse the ability of the experimental mesocosms to retain precipitation and thus reduce run-off it was considered appropriate to develop a model in Excel. A numerical model was created to predict the hydrological response of the mesocosms to real rainfall events. In order to reduce complexity and due to time limitations one period of rainfall from 13/06/07 to 17/06/07 was used throughout the model simulations.

6.2 Hypotheses

i. An increase in vegetation cover will correspond with a decrease in run-off from the mesocosm.
ii. Implementing bypass flow will help illustrate the ability of the model to effectively model drainage and soil moisture content of the mesocosms.

6.3 Model Development

A standard linear model was produced to model the effects of bypass flow, evaporation and vegetation cover on the experimental mesocosms. In the context of the model water is held in a soil moisture store, precipitation will add to the store, and evaporation from the soil and any vegetation will deplete the store. When full, excess precipitation is routed out of the mesocosm and recorded as run-off. The model was run with a number of varying scenarios, the use of a two stage reservoir model and a single reservoir model were investigated amongst other variables.

The most difficult item to measure was actual evapotranspiration (AE), and in general a conceptual quality called ‘potential evapotranspiration’ (PE) which intends to be a measure of the energy available for evaporating and transpiring water (Lerner et al., 1990). It should be noted that good evapotranspiration data is equally as important as good precipitation data (Lerner et al., 1990). Unfortunately in this experiment as is the case with most others, evapotranspiration was not measured. For the preliminary runs of the model PE was estimated and used as a constant value for each time step throughout the simulations. AE was calculated using the soil water depth i.e. moisture content of the soil (measured as % saturation) and the PE value.

After the preliminary runs of the model it was considered important to incorporate the effect of vegetation cover on the retention capacity of the mesocosms. This was important as the primary control produced by vegetation is the evaporation rate. Therefore to reduce complexity it was considered appropriate that the canopy store (percentage vegetation cover) would be affected by PE and the soil moisture would be affected by AE.

6.4 Results and Analysis

A comprehensive version of all of the modelled scenarios can be found on the CD located in Appendix D. In this section only the most relevant results are presented or those which are most appropriate to allow a comparison between the mesocosms.

6.4.1 Vegetation Cover

The model was run with varying percentage canopy covers ranging from 5% to 100% for a dual reservoir system. The 5% cover produced the best result and a realistic figure for what might be expected on the mesocosms over the coming months. The model performed well for the brick substrate storage as is illustrated in Figure 6.4.1. The estimated values correspond with the peaks in the observed water depth but the model under predicts water depth for both the substrates, and does not provide realistic results for the demolition aggregate (Figure 6.4.1.1).

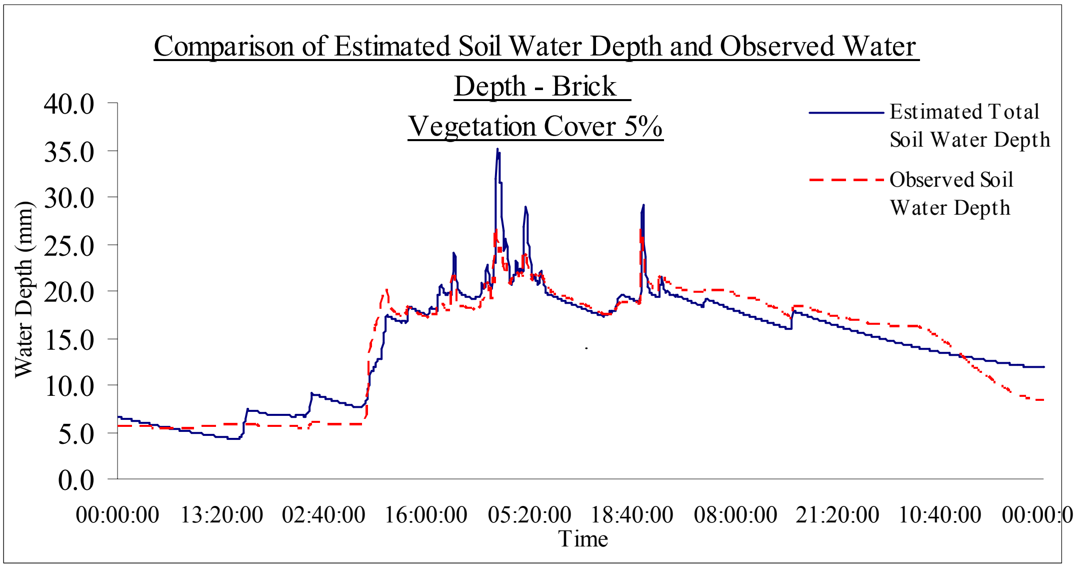

Figure 6.4.1 Comparison between model simulation and observed results for soil water depth at 5% vegetation cover, for brick mesocosms

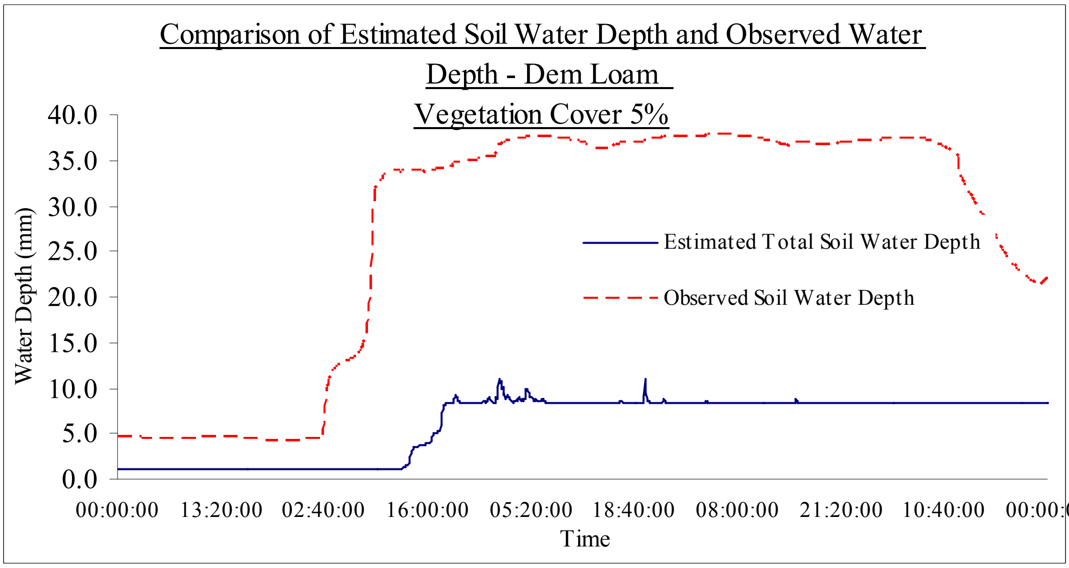

Figure 6.4.1.1 Comparison between model simulation and observed results for soil water depth at 5% vegetation cover, for demolition aggregate mesocosms

The model works better for drainage from both substrates (Figures 6.4.1.2 and 6.4.1.3), the fit however appears better for brick. Once again the estimated values fit realistically with the peaks in the observed data. For both substrates the model fails to recognise the initial peak in drainage. It is possible that the model is not sensitive enough to account for such a small change in discharge and it can be observed from both Figures that drainage occurs too quickly for the data simulated by the model, as the simulation is only working to meet the peaks in the data set.

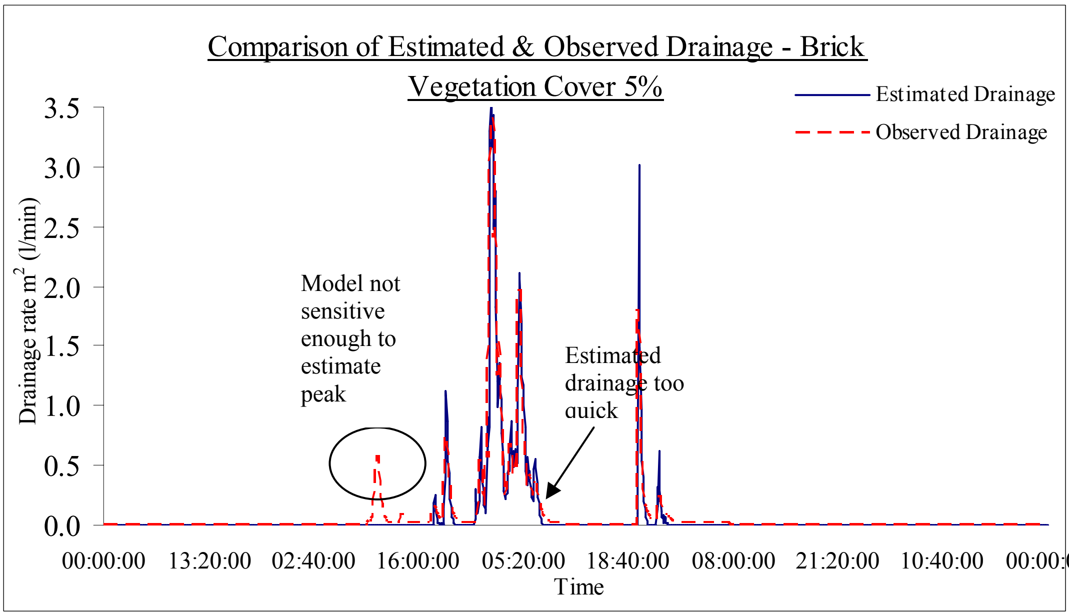

Figure 6.4.1.2 Comparison between model simulation and observed results for drainage at 5% vegetation cover, for brick mesocosms

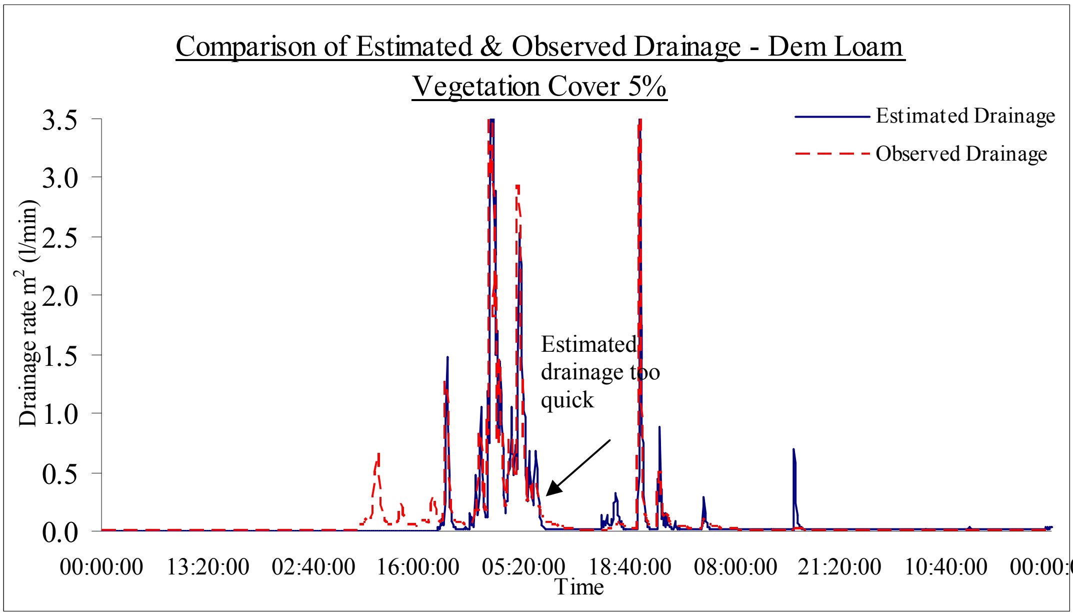

Figure 6.4.1.3 Comparison between model simulation and observed results for drainage at 5% vegetation cover, for demolition aggregate mesocosms

As the percentage vegetation cover increased the model did not perform as well and a number of errors were noted with the data produce. Firstly negative values for the soil water depth were produced for the demolition aggregate when the simulation was run without vegetation. It was thought that by adding another drainage route that in theory the modelled results should improve. This proved to be effective and the problem was resolved. However, as discussed drainage appeared to be occurring too quickly from both set of mesocosms. In order to investigate the problem further the rainfall for the modelled period was graphed and compared with the discharge produced. From this it was concluded that there was an error in the data as there was not enough rainfall occurring for the recorded drainage to occur.

In order to examine the effect vegetation cover would have on the model results the co-efficient, drainage and storage capacity values for each vegetation cover were kept constant (previously they varied whilst using the solver function). It is clear from Figure 6.4.1.4, that as vegetation cover increases discharge decreases. More water is being intercepted by the vegetation canopy and retained or evaporated back into the atmosphere. Two of the percentage vegetation cover results from Image-Pro Plus have been included, the discharge results however do not increase anymore than that for the 10% cover. This is likely to be due to the sensitivity of the model, as values this small will not affect the model. It can therefore be said that an increase in vegetation cover will correspond with a decrease in discharge from the mesocosms proving hypothesis (i) to be correct.

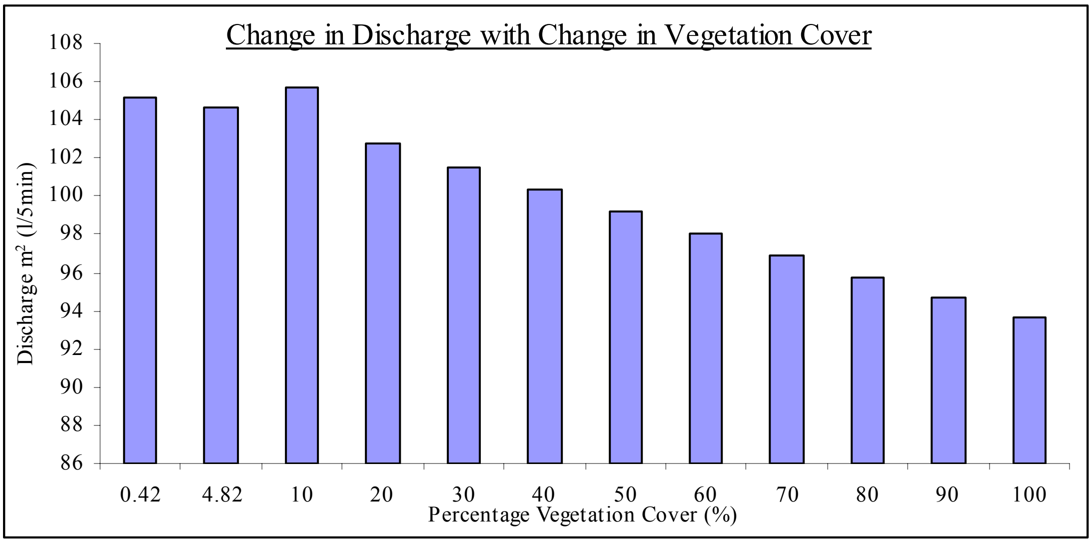

Figure 6.4.1.4 Change in discharge with vegetation cover observed through model simulations

It can be concluded that there is the need for more specific vegetation cover data to develop a more comprehensive model. Including crop co-efficient values, vegetation type and plant growing stage as specified by Handreck and Black (2005) and Allen et al (1998), may help to develop the model. Without this information it is not possible to investigate further the effect of vegetation cover on the water retention capabilities of the mesocosms.

6.4.2 Bypass Flow

The model was run for both a dual and single reservoir system for bypass flow. Bypass flow will occur in the model when a specified level of precipitation set by the user is reached. The results illustrated are those from a dual reservoir bypass systems, those produced for the single reservoir system were very similar and as a results not considered necessary to include.

A number of bypass flow levels were modelled ranging from 0.5mm/5min to 7.0 mm/5min. Once again the model performed best for the water depth in the brick mesocosms (Figure 6.4.2). The drainage from the mesocosms does not correspond as well with the observed data, and the soil moisture probe does not appear to be reacting well to small changes in precipitation as identified in Figure 6.4.2.1. An error with the soil moisture probe may not been the cause of such a result. The water may not have had time to move down through the substrate to the probe and as a result has not been recorded. The model will not accurately predict the time it takes for the water to move down through the substrate and as a result the data produced will not have been influenced by this time lag. Evaporation used to calculate the water depth and drainage values produced by the model maybe too high and a more detailed calculation of AE and PE maybe required.

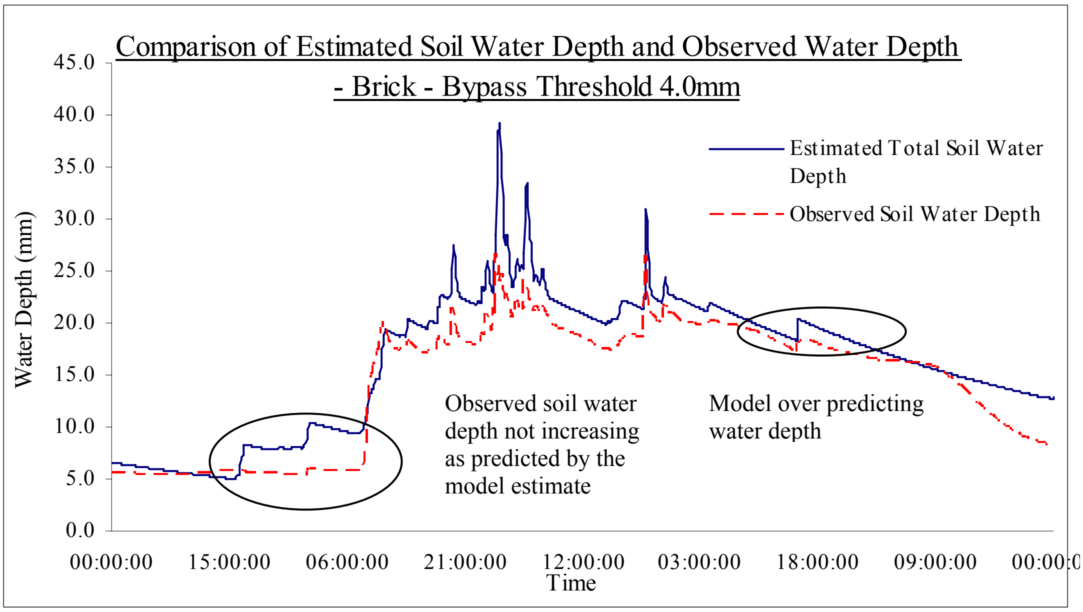

Figure 6.4.2 Comparison between model simulation and observed results for soil water depth at a bypass threshold of 4.0mm, for brick mesocosms

Comparing the bypass flow results with a simulation run with no bypass flow illustrates the effect of this constraint (Figure 6.4.2.1 and 6.4.2.2). Implementing bypass flow reduces the models estimate of soil water depth as would be expected, confirming that the model is operating correctly. Without bypass flow there is a better fit between the estimated and observed values for water depth (Figure 6.4.2.1) but in places soil water depth is now under predicted.

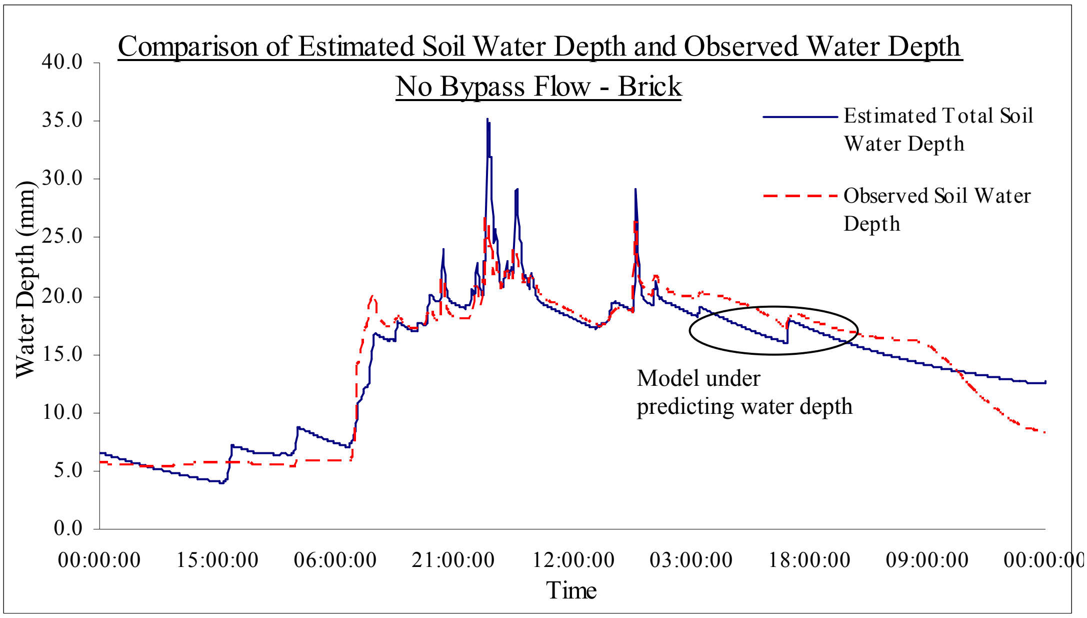

Figure 6.4.2.1 Comparison between model simulation and observed results for soil water depth at no bypass flow, for brick mesocosms

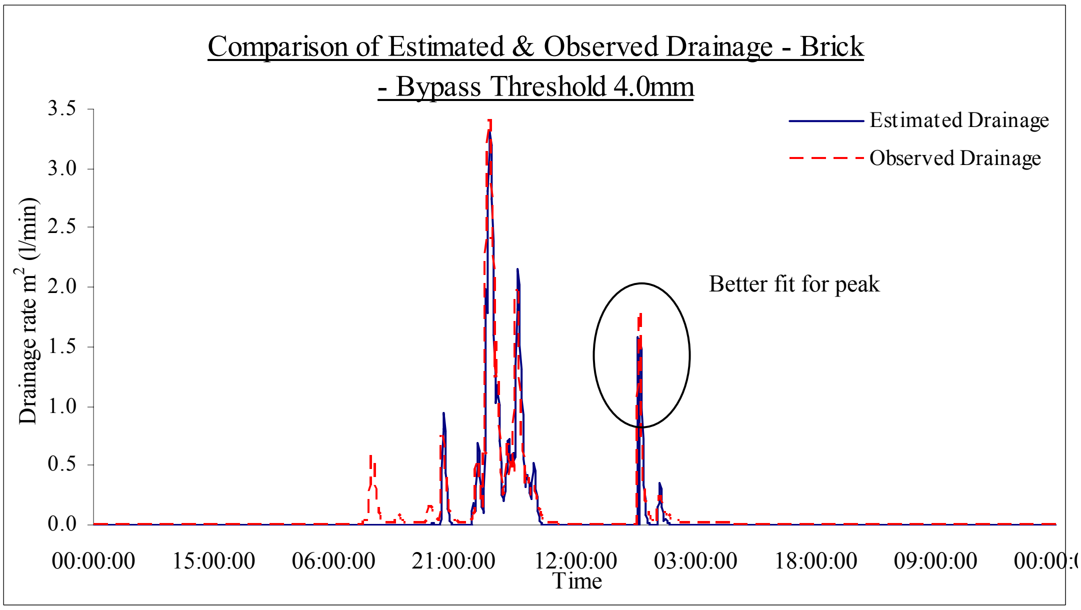

Figure 6.4.2.2 Comparison between model simulation and observed results for drainage at a bypass threshold of 4.0mm, for brick mesocosms

Comparing the estimated and observed results for the drainage with and without bypass flow (Figures 6.4.2.2 and 6.4.2.3) it is clear that the drainage model is a better fit with bypass flow, as the peaks are greatly over predicted when there is no bypass flow.

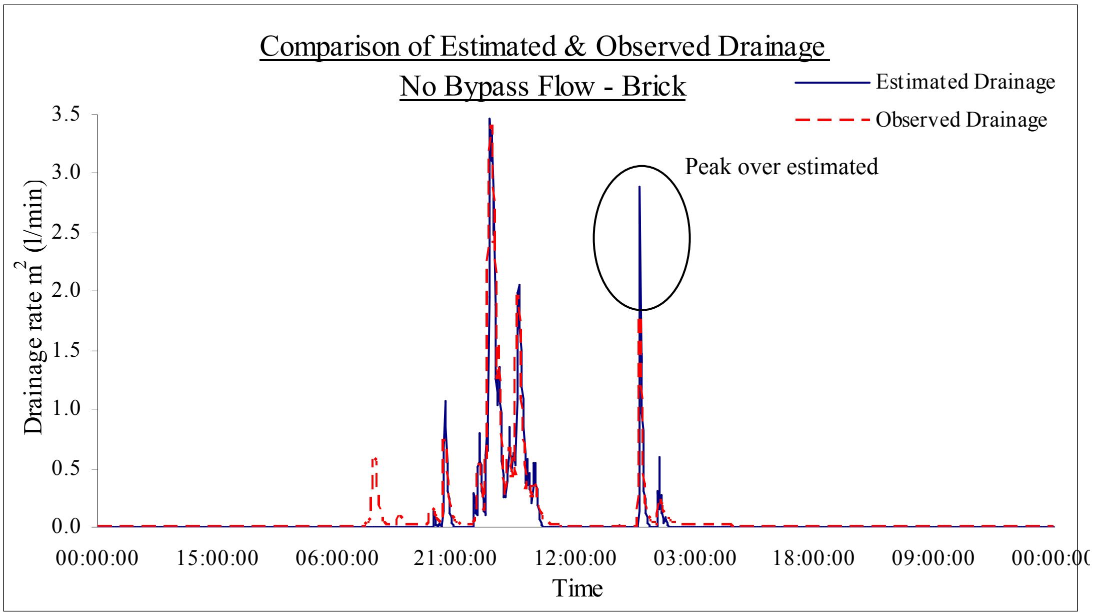

Figure 6.4.2.3 Comparison between model simulation and observed results for drainage at a no bypass flow, for brick mesocosms

The model does not correspond well with the observed data for the demolition aggregate mesocosms as is illustrated in Figure 6.4.2.4 and 6.4.2.5. Once again the model under predicts soil water depth. The results produced are unusual as the estimated water depth values correspond with the peaks in the observed discharge but the observed water depth values do not correspond with these peaks. This adverse result maybe a result of the precipitation error previously discussed. However, the soil moisture probe may not be sensitive enough to pick up the change in water depth as quickly as it is predicted by the model.

It was not considered necessary to display the demolition aggregate results with a model simulation without bypass flow as the observed and estimated results were still very different.

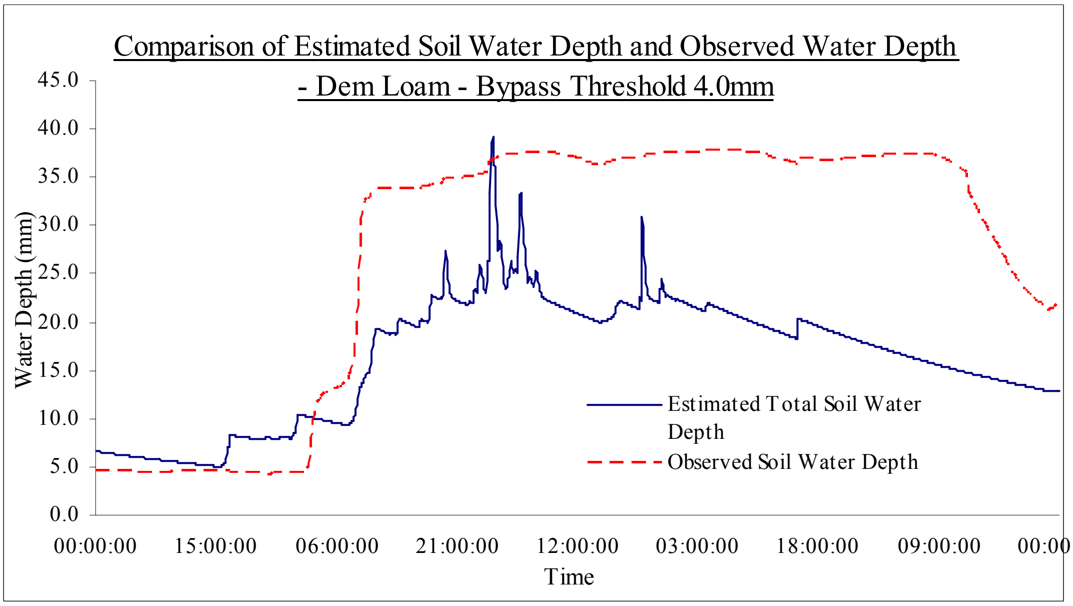

Figure 6.4.2.4 Comparison between model simulation and observed results for soil water depth at a bypass threshold of 4.0mm, for demolition aggregate mesocosms

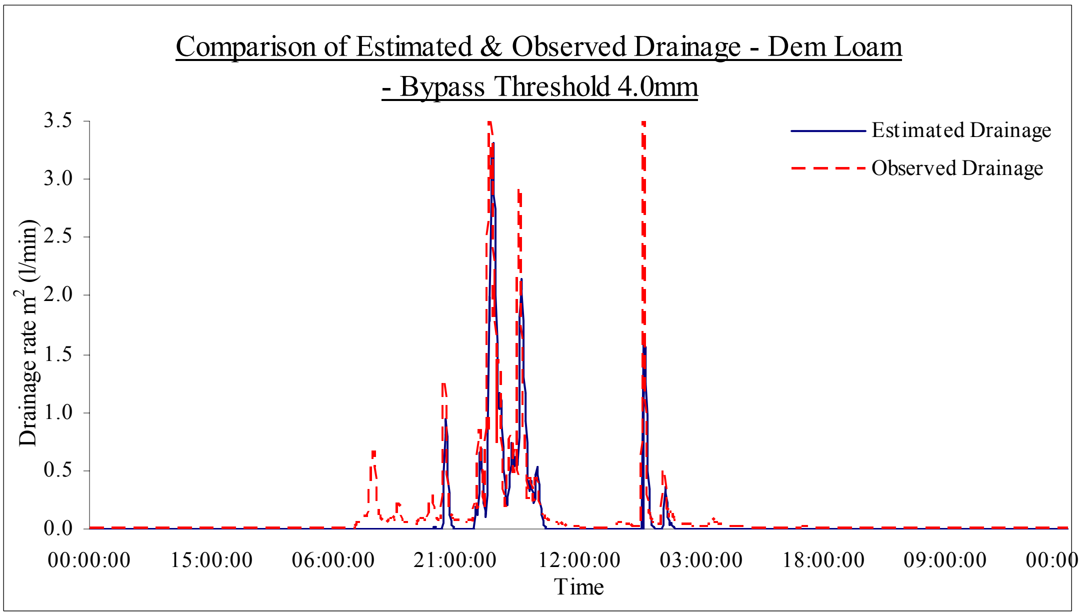

Figure 6.4.2.5 Comparison between model simulation and observed results for drainage at a bypass threshold of 4.0mm, for demolition aggregate mesocosms

Implementing bypass flow confirmed that the model was functioning correctly. Therefore hypothesis (ii) was confirmed to be correct.

The results produced from the model simulations confirm the findings of Carter and Jackson (2006) that vegetated roofs are a good rainwater abstractive tool. It was not possible to investigate the influence that green roof size has on stormwater retention with the use of this model. It is likely that the results produced from this small scale mesocosm study will be applicable to large scale roof greening.

6.5 Model Inadequacies

The model does not consider variations in evapotranspiration for changes in climatic conditions and diurnal variations. In reality evapotranspiration does not occur at night or during very dry periods as stomatal controls will shut off evapotranspiration (Mocko and Sud, 1998). However, with a short time scale available for the development of the model and the need for simplicity it was not feasible to change AE and PE. For a number of the modelling scenarios PE was calculated as greater than AE which in reality is not possible, but this was considered a minor issue and a decision was made to leave the calculations how they were. As discussed the model does not consider the time it will take for water to drain down through the mesocosms and be recorded as drainage. The drainage through the mesocosms will be influenced by the substrate type and by the plant root systems as discussed by Coelho et al (2003). A sub model for the plant root system was not included and as a result drainage occurs too quickly for many of the simulations.

As discussed by Ma et al (2007) model complexity will influence uncertainty in input parameters and may negatively affect the results produced by the model. Running longer simulations may have reduced the error in the results as they should decrease over time, but it is unlikely that the result would have significantly improved and this was not implemented. Although the model developed for this study is limited and has a large number of inadequacies it can be consider more usefully than an over complex model with increased uncertainty.

Chapter Seven

Conclusion

7.1 Introduction

Laboratory experiments and direct comparisons between the results produced from each set of mesocosms have been used to assess the ability of the two substrate types to mitigate run-off. The impact of the substrate type has further been quantified through the development of a model. Four out of the five hypotheses set have been proven to be correct with the exception of the vegetation results produced from the Image Pro Plus analysis which were inconclusive.

7.2 Main Research Findings

The results of this research project show that the brick mesocosms retain more water than the demolition aggregate mesocosms. Over the time period analysed the brick retained an average 54% of the precipitation recorded in comparison with an average of 37% for the demolition aggregate. Substrate type is therefore an important consideration in the development of a green roof system and should be carefully considered. Although the brick only appears to delay run-off significantly more than the demolition aggregate when there is extremely heavy rainfall (>1.8mm / 5min), in total the amount of run-off recorded from the brick mesocosms is reduced in comparison with the demolition aggregate. The reason for the greater retention capacity of the brick was found to be due to the large percentage of pore space in comparison with the aggregate and thus more space for water retention.

The analysis of the substrate type and drainage using the model was inconclusive. It was proven through the development of the model simulations that the model functioned correctly for the brick mesocosms but the same could not be said for the demolition aggregate. The implementation of bypass flow improved the model outputs for some scenarios but not others. It was not possible to fully model the effects of vegetation cover, as the impact of root depth, vegetation type and growing stage were not fully known. Model simulations nevertheless did confirm that as vegetation cover increases discharge from the mesocosms decreases.

Finally it can be concluded that the implementation of sustainable urban drainage systems such as green roofs can provide significant attenuation of run-off from roofs in urban areas and help meet the aims set out in the WFD and Environment Agency run-off targets. Although green roofs are an attractive alternative, it is probable that conventional roof surfaces will continue to dominate domestic installations. Nevertheless, it is likely that green roofs will experience a change in acceptance by the commercial sector once more is known about their performance and sustainability (Arthur and Wright, 2005). The conclusions drawn from this research project illustrate the importance of substrate type in relation to green roof development.

Chapter Eight

Limitations and Recommendations

8.1 Limitations

It became evident whilst analysing the results downloaded from the data logger that there may have been inaccuracies in the results recorded by the soil moisture probes and weather station. This is a significant limitation of the project, and should be considered if any further analysis with the same equipment is undertaken. The calibration of the v-notch weirs will be subject to some degree of human error due to the methods used to measure the discharge into the weirs.

Much of the laboratory analysis involved the weighing of the green roof material using unreliable equipment and as a result some of the volume and weight measurements may be inaccurate. This is of minor concern as the aim of the laboratory analysis was to provide a rough estimate of the substrate characteristics to allow a comparison to take place. When collecting the samples for permanent wilting point and field capacity it was hard to tell if such conditions had been reached, in an ideal situation these experiments would have been repeated over a number of occasions to produce more accurate results.

8.2 Recommendations

The limitations highlighted can be reduced in order to produce more accurate results. To reduce the potential error associated with the data recorded by the data logger it is recommended that the v-notch weirs and soil moisture probes are re-calibrated.

To gain a complete understanding of the ability of the two substrate types to retain precipitation, monitoring must be undertaken over a greater period of time and at a watershed scale. Increasing the investigated time scale may aid vegetation cover analysis once the vegetation has developed.

In relation to the model, more comprehensive input parameters need to be incorporated to improve the models sensitivity and allow more detailed simulations to be run. Additional research is now required to further investigate the ability of green roofs to reduce run-off on a larger spatial scale. Furthermore this research should highlight the advantages of green roofs as sustainable run-off reduction tools.

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Appendix A

Figure A.1 Mesocosm Locations

Figure A.2 Mesocosm Seed Mix

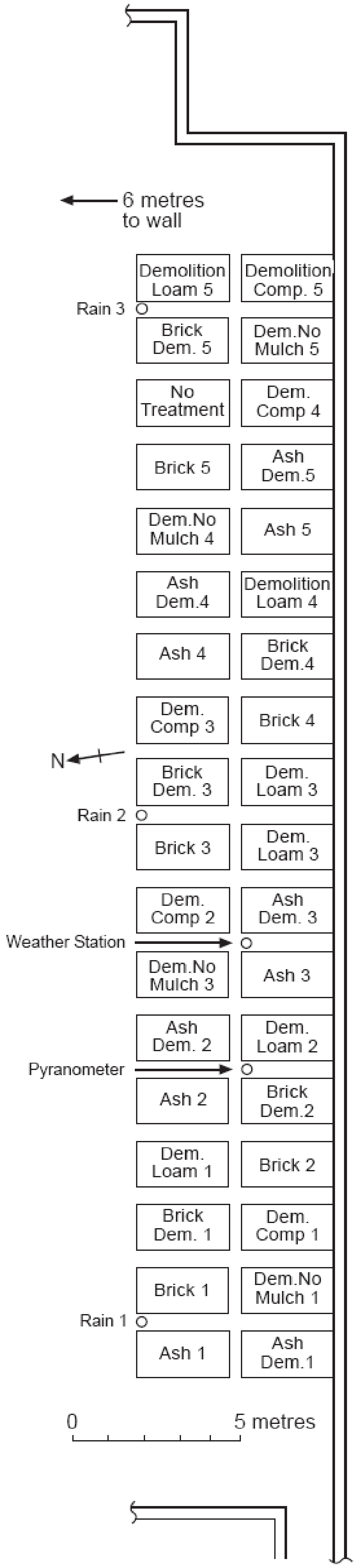

Figure A.1 Mesocosm Locations **(Bates et al., 2006)**

%	Latin name	Common English name	Typical habitat
5.6	*Agrimonia eupatoria*	Agrimony	Grassy places in fields & hedgerows
5.6	*Agrostemma githago*	Corn cockle	Cultivated & waste ground
4.7	*Anthyllis vulneraria*	Kidney vetch	Grassland, dunes, cliff tops, waste ground, usually calcareous
4.7	*Centaurea cyanus*	Cornflower	Traditionally native to cornfields, now mainly in waste places
4.7	*Centaurea nigra*	Common knapweed	Grassy places, rough ground & waysides
2.8	*Daucus carota*	Wild carrot	Grassy & rough ground mostly on chalky soils and near the sea (stunted)
4.7	*Echium vulgare*	Viper's-bugloss	Open grassy places, cliffs, dunes, shingle, rough ground on light calcareous soils
5.6	*Knautia arvensis*	Field scabious	Dry grassy places on light soils
4.7	*Leontodon hispidus*	Rough hawkbit	Basic, often calcareous grassland
3.8	*Leucanthemum vulgare*	Oxeye daisy	Grassy places, especially rich soils
0.9	*Linaria vulgaris*	Common toadflax	Rough & waste ground, stony places, banks, open grassland
4.7	*Lotus corniculatus*	Birdsfoot trefoil	Grassy & harsh places, mainly well-drained soils
1.9	*Origanum vulgare*	Wild majorum	Dry grassland, hedgebanks & scrub, usually on calcareous soils
1.9	*Papaver dubium*	Long-headed poppy	Arable ground, roadsides & waste places
3.8	*Papaver rhoeas*	Common poppy	Arable ground, roadsides & waste places
4.7	*Plantago media*	Hoary plantain	Neutral & basic grassland
4.7	*Prunella vulgaris*	Selfheal	Grassland, lawns, wood-clearings, rough ground
4.7	*Ranunculus bulbosus*	Bulbous buttercup	Dry grassland & fixed dunes
4.7	*Reseda lutea*	Wild mignonette	Disturbed, waste & arable land esp. calcareous soils
5.6	*Sanguisorba minor ssp minor*	Salad burnet	Calcareous or neutral grassland
4.7	*Silene vulgaris*	Bladder campion	Grassy places, open & rough ground
0.9	*Verbascum thapsus*	Great Mullein	Waste and rough ground, banks & grassy places esp. sandy and chalky soils
3.8	*Viola tricolor*	Wild pansy	Waste, marginal & cultivated ground
6.3	*Sedum acre*	Biting stonecrop	Barish ground on sandy soils

Table A.2 Mesocosm Seed Mix

Appendix B

Methodology – Laboratory Analysis

B.1 Determination of Particle Size

Table B.1.1 Wentworth Class

Figure B.1.2 Schematic of Axis Location

B.2 Determination of the overall density of soil particles

B.3 Determination of the overall dry bulk density

B.4 Determination of water content at the approximate field capacity, and at approximate permanent wilting point

B.1 Determination of Particle Size

(Modified from Rowell, 1994)

1. A representative sample of between 1000g – 1400g was removed from the 10 experimental mesocosms (5 from the demolition aggregate and 5 from the brick).
2. The samples were oven dried for approximately 24 hours at 105 ^{0}C and weighed.
3. Each sample was mechanically sieved through 9 size fractions from 63µm to 16mm on the Wentworth Scale (see Figure B.1.1) for 5 minutes on an intermittent setting.
4. Each size fraction was removed and individually weighed.
5. Anything greater then 16mm in size was measured by hand along its B axis (see Figure B.1.2 and separated into 3 size ranges (16 – 32mm, 32 – 64mm, and > 64mm) and again weighed.
6. The weights were complied and graphed to indicate the differences in sediment size between the two substrate types.

Size Range (Metric)	Aggregate Name (Wentworth Class)
> 256 mm	Boulder
62 – 256 mm	Cobble
32 – 64 mm	Very course gravel / pebble
16 – 32 mm	Course gravel / pebble
8 – 16 mm	Medium gravel / pebble
4 – 8 mm	Fine Gravel / pebble
2 – 4 mm	Very fine gravel / granules
1 – 2 mm	Very coarse sand
0.5 – 1 mm	Course Sand
0.25 – 0.5 mm	Medium sand
125 – 250 µm	Fine sand
62.5 – 126 µm	Very fine sand
3.90625 – 62.5 µm	Silt / Mud
< 3.90625 µm	Clay / Mud
< 1 µm	Colloid / Mud

Table B.1.1 Wentworth Class

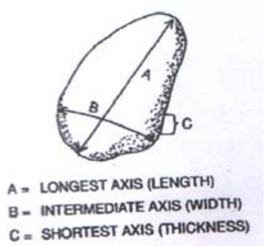

Figure B.1.2 Schematic of axis location (Potyondy and Bunte, 2002).

B.2 Determination of Overall Density of Soil Particles

(Modified from Rowell, 1994)

1. The sample taken from each experimental mesocosm for the sediment size analysis was used.
2. The samples were oven-dried and added to two pre-weighed beakers.
3. The beakers and samples were re-weighed.
4. Water was added to the beakers to fully cover the sample, and the beakers placed on a hot plate to boil gently for approximately 30mins, or until it was clear that the air has escaped from the sample.
5. The samples were removed to cool in a bath of tepid water and poured into a 2000ml pre-weighed measuring cylinder with water added to reach the 2000ml mark.
6. The samples were then weighed and put through a sieve to remove the water to allow them to easily be returned to the mesocosms.
7. The following were calculated:
    a. The volume of water in the measuring cylinder = mass boiled sample – mass of dry sample (1m = 1g of water)
    b. The volume of soil particles in the measuring cylinder = 2000ml – volume of water in the measuring cylinder
    c. The particle density = mass of dry soil / the volume of the soil particles

B.3 Determination of Overall Dry Bulk Density

(Modified from Rowell, 1994)

1. The 10 holes from which the soil was removed for the determination of the over all density of soil particles were used as they provided a depth down to the filter layer.
2. The hole was lined with a flexible plastic sheet.
3. Oven-dried, graded sand (pre-sieved to 500 – 700 µm) of a known volume was used to fill the hole from a funnel with a falling height of approximately 3cm until it was level with the surrounding soil surface. (The amount of sand used to fill the hole is the volume of the hole).
4. The following were calculated:
    a. Soil Porosity (%) = 1 – (Dry Bulk Density / Particle Density) x 100

B.4 Determination of Water Content at Approximate Field Capacity, and at Approximate Permanent Wilting Point

(Modified from Rowell, 1994)

1. A representative sample of soil was taken from the 10 mesocosms at approximate field capacity and at approximate permanent wilting point.
2. Between 400g and 700g of soil was weighed, placed in a crucible and dried in an oven at 105 ^{o}C. The samples were placed in a desiccator to cool and re-weighed. The drying was repeated until a constant mass was reached.
3. The water content (g H_2O g^{-1}) at approximate field capacity or permanent wilting point will be equal to the mass of water lost/mass of oven dried soil. The value will be given as a percentage i.e. g H_2O / 100g oven-dry soil.

Appendix C

Methodology – Vegetation Analysis

C.1 Vegetation Cover Analysis – Image Pro-Plus

C.1 Determination of Vegetation Cover

1. Using a large tripod constructed by Dr. Richard Greswell a digital camera was placed over the centre of half of the mesocosm being photographed. The tripod was then moved to the second half of the mesocosm and a photo taken again for that side.
2. A ruler and label were placed in each photograph to allow easy identification and to clarify scale.
3. Using the programme Image Pro Plus it was possible to analyse the percentage of the photograph covered by vegetation.
4. The segmentation function was used to highlight the vegetated areas in bright blue.
5. Using the histogram 'Hue' function it was possible to calculate the percentage cover of the areas highlighted. Fixed parameters were used for each photograph to ensure consistency. The movable axis used to calculate percentage cover were fixed at the same values throughout the analysis.
6. The hue was used as it refers to the gradation of colour within the optical spectrum, or visible spectrum, of light. "Hue" also refers to a particular colour within this spectrum, as defined by its dominant wavelength, or the central tendency of its combined wavelengths (Wikipedia, 2007). Therefore looking along the hue scale to see where the blue colour used to highlight the vegetation is located enabled the identification of where on the histogram the peak dictated by the vegetation cover would be located.
7. The two vegetation cover values for each mesocosm were then combined and divided by two to give a total percentage vegetation cover value for each mesocosm.
8. A problem arose due to the location of the tripod over the mesocosm. Each photograph taken contained a significant amount of space from outside the mesocosm. As a result before the analysis described took place the photos had to be cropped to ensure the percentage cover value only included the mesocosm and not the surrounding roof.

Appendix D

Results

D.1 CD 'Model Run's'

D.1 – CD of model simulations