Brown Roof Hydrological Studies

by

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Abstract

Miniature brown roof tiles were produced with differing mixtures of aggregate infill, and subjected to a regime of storm event, created in the laboratory with the use of a rainfall simulator. Flows into and out of the boxes were recorded as well as the storage of water in the box during each experiment. The results of the experiments were used to calibrate and test a linear reservoir model, which was then used to successfully predict the response of the full-scale tiles to natural rainstorms.

Acknowledgements

I would like to thank Prof. Rae Mackay and Dr. Adam Bates for the impetus in getting this project rolling, Mick Riley for his continued encouragement and ideas and Dr. Richard Greswell for his endless ingenuity in the workshop.

Thank you to Mo, Derek, Jules and James for keeping me smiling, and to Frances for all her encouragement and support.

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1 Introduction

A study into the ecological and hydrological nature of brown roofs is currently in its early stages at Birmingham University. Brown roofs are a variation of the green roof, designed particularly to recreate the habitat of brown-field sites. With local planning laws encouraging the redevelopment of these sites, the habitats that they provide are slowly diminishing in number.

Green roofs have been installed on rooftops in continental Europe since the 1960s and are becoming increasingly common sights around the world. A green roof provides many benefits for a building and the surrounding environment, not least of which is the ability to retain rainfall from storm events and reduce the peak runoff delivered to storm drains from the roof. Brown roofs should behave in a similar manner, but whereas green roofs are intentionally planted with vegetation, brown roofs are often left to be colonised by wind-born seeds and mosses, as at real brown-field sites. As such, the potential for transpiration from brown roofs is much reduced, and any water held in the roof material will be held there much longer than that held in a green roof. In every other aspect however, brown roofs should provide adequate storm-water runoff reduction.

The primary aim of this project was to develop a good understanding of the hydrologic response of the brown roof boxes.

Objectives to meet this aim:

- A literature review of past research on the hydrological functioning of green and brown roofs.
- A detailed grain size analysis and estimation of the hydraulic properties of the materials to be used in the roofs.
- A detailed study of the hydraulic response of brown roof boxes to storm events.
- The development of a model to aid in the prediction of the response of the tiles to future rainfall events in Birmingham.
- An assessment of the design parameters of the brown roof tiles.

The initial intention of this project was to study the hydraulic characteristics of brown-roof tiles to be installed at Birmingham University in 2006. However, these tiles were not installed and the project shifted focus to studying the properties of the materials intended to be used on the roofs. A number of glass boxes were produced, to act as miniature roof tiles and a rainfall simulator created to mimic rainfall events in the laboratory. These boxes were filled with different mixtures of material intended to be used on the roofs. The flows into and out of the boxes were recorded, as was the storage of water in the boxes, during varied rainfall experiments.

A numerical model was created to recreate the experimental results derived and to predict the hydrological response of the brown roof tiles to real rainfall events.

2 Background

The brown roofs under consideration in this project are similar in concept to the slightly more well-known green roof.

2.1 Green roofs

The elementary definition of a green roof is a roof fully or partially covered with vegetation, however an instant distinction can be drawn between modern-day green roofs and older roofs. Whilst turf has been utilised as a roofing material in Europe (particularly in Scandinavia and the British Isles) for centuries, modern green roofs were first constructed in Germany in the 1960s. These roofs are intended to replace slate, felt or tiles as the outermost surface of a roof, and comprise a layer of soil or any other suitable growing medium overlying a waterproof membrane and root-resistant layer, to prevent plants from damaging the underlying roof structure. Plants are encouraged to grow on the roof and may either consist of those which must be regularly watered and fed, such as flowers (an intensive green roof) or those which do not require special maintenance, such as grasses and moss (an extensive green roof).

2.1.1 Human benefits

Although first used widely in continental Europe, the green roof industry is currently gaining momentum around the world with major projects under way in the United States (Liptan and Strecker, 2003), Australia (Kidd, 2005) and South America (Köhler et al., 2001). Today, green roofs are constructed for a variety of reasons, including financial and legislative incentives (local authorities in Britain (including the cities of Birmingham and Newcastle) are increasingly seeing green roofs as an opportunity to increase biodiversity in urban areas), as well as for the amenity space they provide. Many local

authorities in urban areas where sewers and storm water drains are connected (including Portland, Oregon and New York) encourage the construction of green roofs, as they have been shown to both delay peak flows of storm water runoff and reduce the overall discharge by as much as 75% through evapotranspiration. Green roofs help mitigate against the Urban Heat Island Effect (Bass et al., 2002), whereby the temperature in urban areas is noticeably increased over that of surrounding areas, often resulting in unpleasantly hot conditions in summer months. While traditional roofing materials absorb solar radiation and emit it back into the city, greened roofs reflect much more energy back into the atmosphere, utilise energy during photosynthesis and radiate less energy to their surroundings, leading to temperature reductions (for instance, green roofs in Chicago exhibit temperatures of up to 44˚F cooler than nearby black tar roofs).

2.1.2 Ecological benefits

As well as the aesthetic, financial and environmental advantages, green roofs have been shown to act as suitable habitats for many species of wildlife and plants, and may act as elements of wildlife corridors, allowing birds and insects to migrate between different habitats and breeding grounds.

2.1.3 Scientific Research

Much research has been conducted into the thermal properties of green roofs (Aravantinos et al., 1999; Del Barrio 1997; Liu and Baskaran, 2003; Niachou et al., 2005), which has also included modelling of the thermal effects (Lazzarin et al., 2005). Green roofs are known to provide improved insulation for buildings, thereby reducing temperature control costs. The vegetation on a green roof reflects more solar radiation back into the atmosphere than a traditional roof surface and evapotranspiration also helps to remove energy from the building beneath and emit it into the atmosphere.

The hydraulic response of green roofs to storm events has also received much attention recently. Many authors have been interested in the retention of storm water by green roofs during storm events (Forrester; Monterusso et al., 2004). Work has also been published on the factors which affect the retention of green roofs: the volume of precipitation during rainstorms has been shown to have a great effect on retention, with 87.6% of storm-water retained in light storms (<2.54cm total precipitation) compared with 47.2% retention for heavy storms (>7.62cm), (Carter and Rasmussen). The physical dimensions of the green roof, including media depth, slope of the roof and material used also play an important roll in determining the retention of a green roof (VanWoert et al., 2005; Bengtsson, 2005). A combination of low-slope, thicker media depth and green-roof material (which was compared against gravel) was found to produce the greatest retention.

The reduction of peak-discharge from storm events is of great importance for urban communities with drainage problems, where flash flooding or overflowing drains may cause environmental damage to homes and businesses. Research in Sweden on thin (3cm thick) roofs planted with sedum-moss reveal that peak runoff discharges can approach or even match daily precipitation in this style of roof (Bengtsson et al., 2004; Bengtsson, 2005) although whether this is the case with thicker roofs remains to be seen.

2.2 Brown roofs: a brief history

Brown roofs are a very recent development in the 'ecoroof' sector, the first of which were constructed in London in 2002. While a green roof may be built for aesthetic, financial or legislative reasons, brown roofs are first and foremost replications of an ecological habitat. With current British legislation promoting the development of new buildings on brown-field sites (Figure 2.1) in inner-city areas, brown-field locations are slowly disappearing from the urban environment. Although man-made and, at first-glance, not teeming with life, brown-field sites provide important refuges for wildlife in urban

environments and are often more ecologically diverse than the out-of-town, green-field sites which are being protected from development.

The world's first brown roof came about as a result of pressure from local ecologists in Southwark, South London, when a brown-field area was chosen as the site for a new performing arts centre. The roof was incorporated into the building design so that a species of bird rarely seen in Britain could continue to thrive in a local brown-field habitat. The centre went on to win the prestigious RIBA Stirling Prize the following year.

Figure 2.1 A brown field site on the perimeter of the University of Birmingham

It is advocated that brown roof materials

1) Be sourced from the same site, to minimise ecological trauma, increase chances of re-population, and reduce the need for obtaining material from external sources.

2) Be stored at ground level for a period of up to three months before installation at roof level, so as to allow the indigenous flora and fauna to re-establish themselves.

There are a number of scientific and social issues surrounding brown roofs, such as their success and necessity in the urban environment, and their merits relative to the highly efficient insulation and storm-water discharge reduction provided by green roofs.

2.3 Precipitation in Birmingham

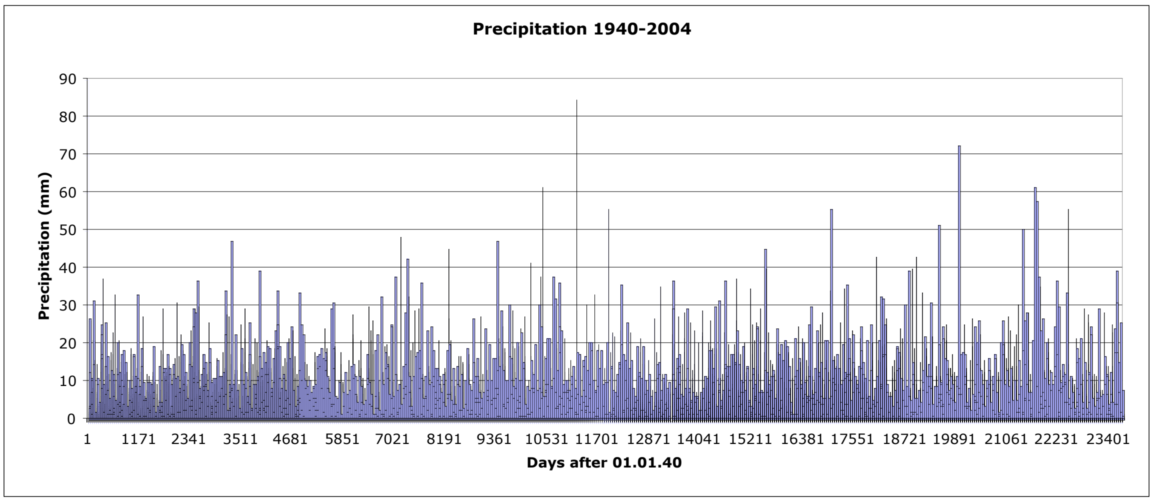

Figure 2.2 Daily precipitation at the University of Birmingham for the years 1940-2004

The hydrologic function of the brown-roofs in Birmingham will clearly be related to the precipitation in the city. Daily rainfall data from the past 65 years (Figure 2.2) and minute-data for the past five years recorded at the University of Birmingham Weather station on campus have been analysed to gain an understanding of the pattern of weather to be expected in the future. For the past five years data has been collected every minute from a tipping rain-gauge with a 0.2mm resolution, for a brief period in 2003 a 0.1mm resolution gauge was used but this was replaced with the 0.2mm gauge at the end of the year.

An analysis of the probability of rain events on a particular day exceeding a certain amount reveals that the chance of any rain at all is 0.5 (Figure 2.3). There is an inverse power-law relationship between size and probability. As much as 90mm of rain has been

recorded in a single day in Birmingham, but this type of event has only occurred once in over 60 years.

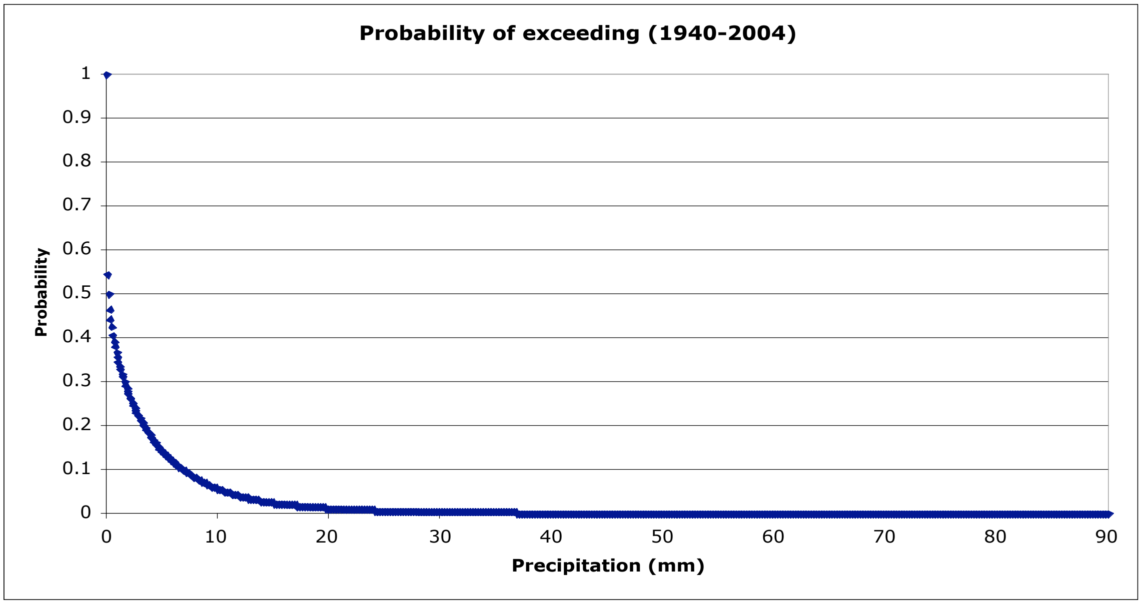

Figure 2.3 The probability of the daily rainfall exceeding a given value on any day. Notice there is a probability of 0.55 of any rainfall occurring.

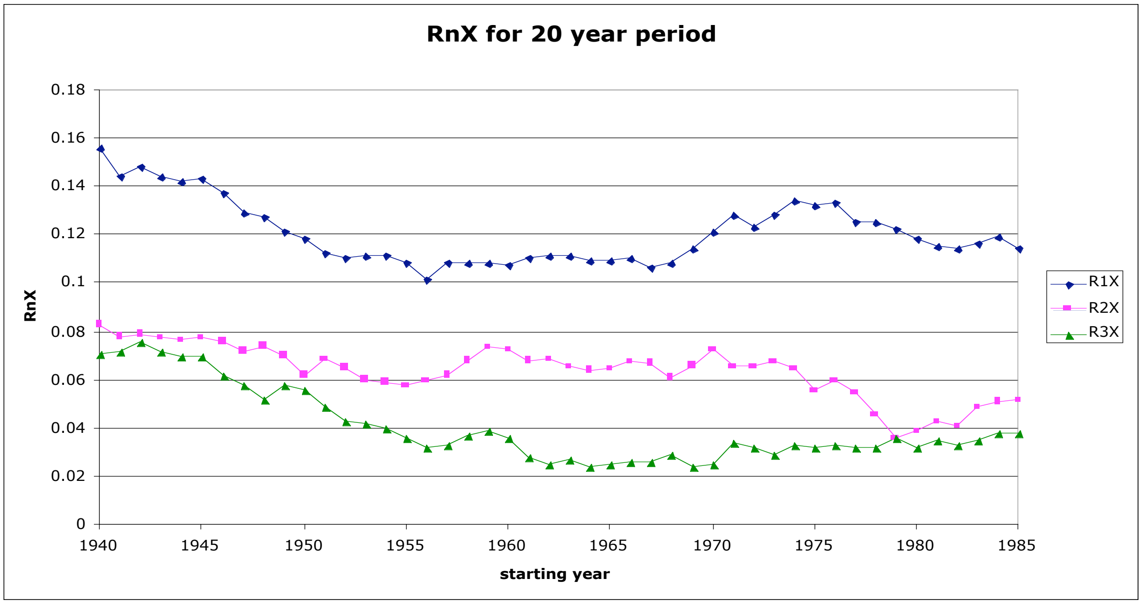

Figure 2.4 Autocorrelation coefficients for the 20-year periods beginning 1940 and ending 1985 (each period covers 20 years from the given start date). Coefficients greater than zero indicate correlation between above average events separated by n days.

An assessment of whether a day with greater than average precipitation will be followed by another day with greater than average rain can be achieved by performing an auto-correlation on the data (Figure 2.4). This analysis returns a number between -1 and 1 for a series of data, where a result >0 indicates that heavy rain will be followed by heavy rain, while a result <0 indicates that days with heavy rain are followed by days with very little rain.

Sampling a 20-year block of results and calculating the autocorrelation result for the periods 1940-1959, 1941-1960, 1942-1961 etc, reveals that there is a slight correlation between higher than average rainfall events (figure 2.4), suggesting that days with heavy rainfall are likely to be followed by days with more heavy rain, but that individual storms are also common but not quite so frequent.

2.4 Minutely recorded rainfall data

Alongside daily rainfall data, precipitation data recorded every minute at the university weather station was available for the years 2000-2005. For periods of the record the data has a resolution of 0.1mm, while for the majority the resolution of the rain gauge was 0.2mm.

The daily rainfall data for the period covered by minute-data (Figure 2.5) reveals that daily precipitation rarely exceeded 10mm, although on occasions, as much as 55mm was recorded in a single day. These heavy rain events do not necessarily denote high intensity storms, but may be the result of low intensity precipitation over an extended period of time. In the case of the 55mm event of 17th-18th July 2001 this was precisely the case. Throughout July 2001, only one occurrence of precipitation of greater intensity than 1mm/min is recorded (Figure 2.6). During the 17th-18th July rainfall (Figure 2.7), the highest intensity recorded is 0.4mm/min. However, there are approximately 13 hours of continuous rain, with only minor breaks, resulting in the vast quantity of rain precipitated that day.

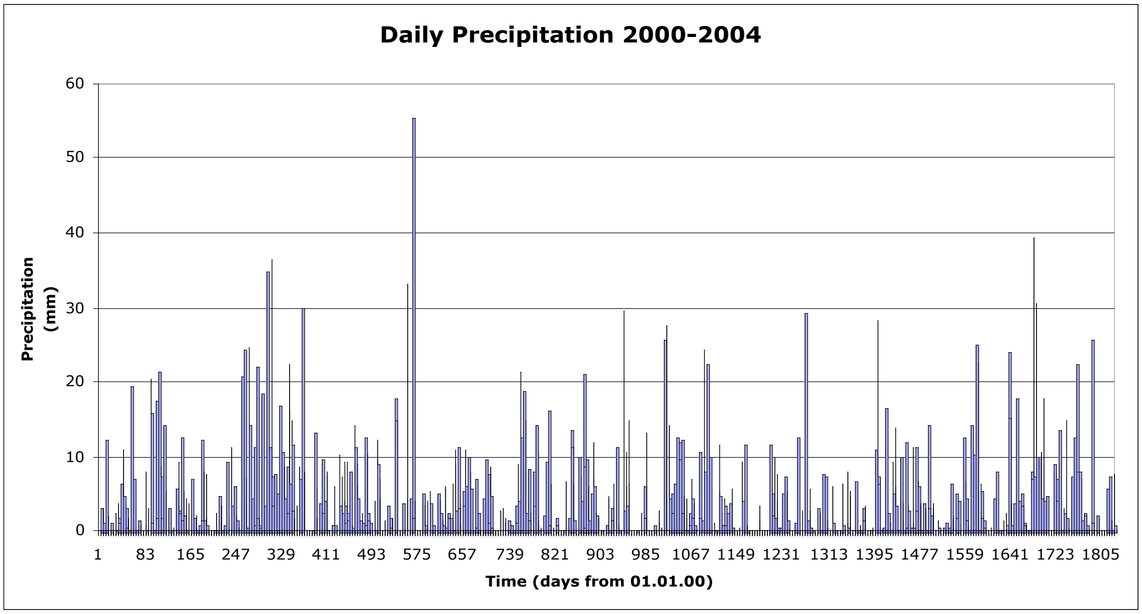

Figure 2.5. Daily precipitation recorded at the University of Birmingham 2000-2004

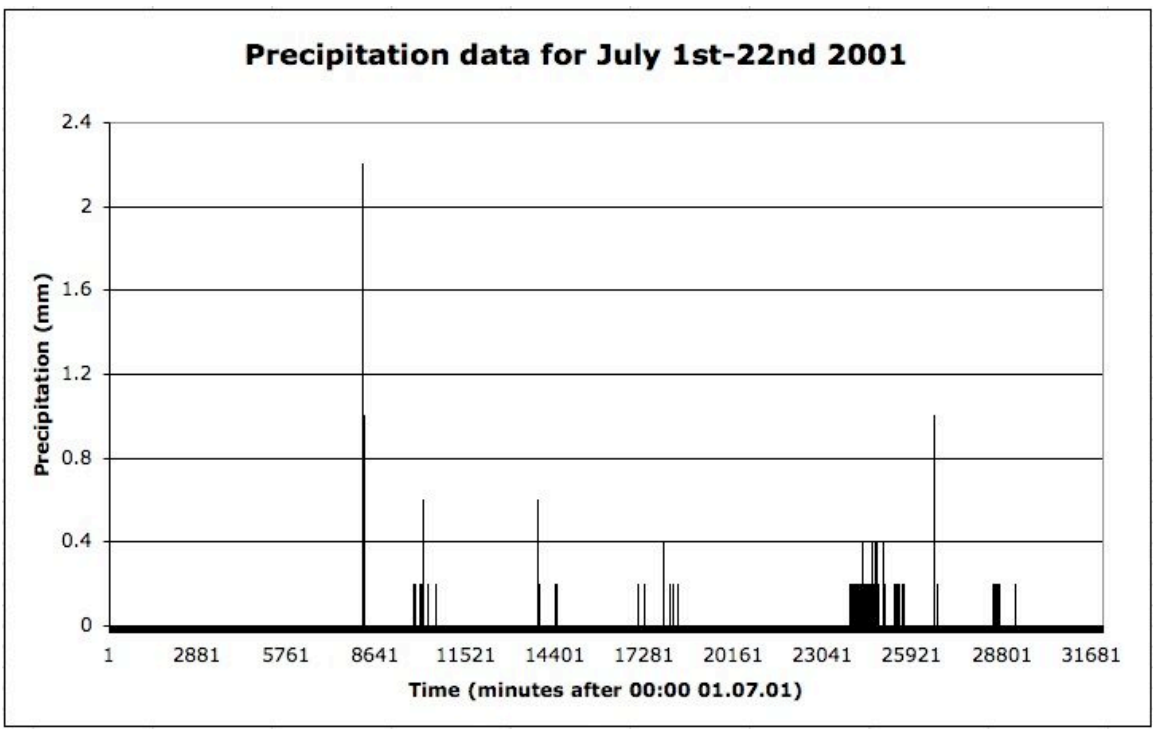

Figure 2.6 Precipitation recorded each minute during July 1st-22nd 2001

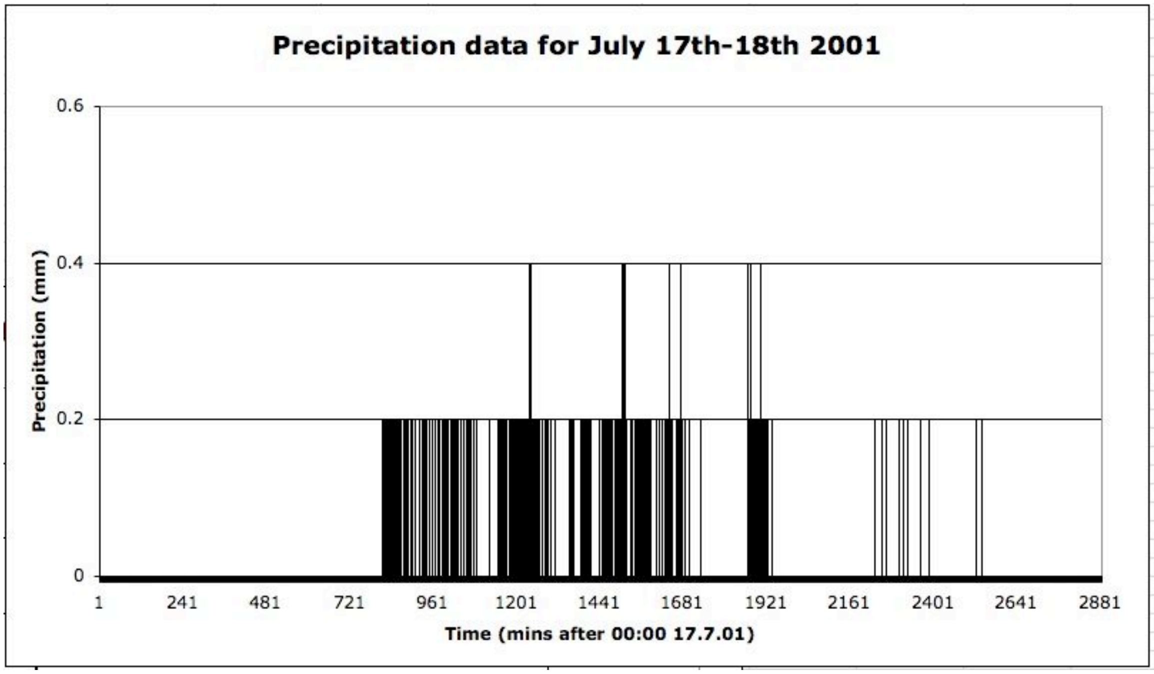

Figure 2.7 Precipitation recorded each minute over July 17th-18th 2001. Rain gauge resolution = 0.2mm/min.

The rain gauge and data logger in place at the weather station are not always reliable. The logger malfunctions from time to time and the data for entire days go unrecorded. The tipping rain gauge occasionally records anomalously high rates of precipitation. In March 2001 and December 2003, precipitation rates over 10mm/min were recorded, but the total volume of rain calculated for these events using the minute-data far exceeds the recorded daily totals. Otherwise, the highest intensity of rainfall recorded at the university in this period is 2.2mm/min in April 2000 during an intermittent storm lasting less than an hour totalling 5mm of rain.

A typical rainstorm in Birmingham may vary between two extremes: short sharp storms e.g. Apr 2000 (3mm in two minutes), and storms of extended duration and lower intensity e.g. May 2001 (13mm in 17 hours). The brown roof boxes should ideally be able to cope with either of these storm types.

3 Methods

3.1 Reduced-scale models of brown roof tiles

3.1.1 Glass boxes

Figure 3.1 Glass boxes constructed to hold the materials of miniature brown roof tiles.

In order to analyse the hydraulic response of a brown roof in an artificial environment, a series of small-scale mock-ups of the proposed, 2m x 1m, roof-tiles were constructed (Figure 3.1). For convenience and ease of observation these boxes were constructed of glass and filled with the same materials that will be used in the full-scale brown roof tiles.

3.1.2 Dimensions

The boxes were constructed with a surface area 300mm x 300mm, small enough that they could be easily manoeuvred, yet large enough to behave similarly to full-scale tiles. The boxes are 150mm high, in order to accommodate the underlying layers of the brown roof including 100mm of soil-mix and 10mm of top-soil.

3.1.3 Assembly

Figure 3.2 One corner of a glass box, with section removed to permit outflow. Each joint is sealed with waterproof silicone sealant.

The glass sheets that comprised the walls and base of the boxes were glued together with strong silicone sealant, in order to provide a watertight seal and a strong bond between

the sheets. Before assembly, one corner of the base sheets had been removed to allow water to drain from the bottom of the boxes (Figure 3.2).

3.1.4 Brown roof materials

3.1.4.1 Lining

The bases of the boxes were lined with waterproof material, overlain by a root-resisting layer, which will be used in the full-scale roof tiles. These materials are bituminous and covered on one side with fine flakes and coarse flakes of slate respectively.

3.1.4.2 Aeration layer

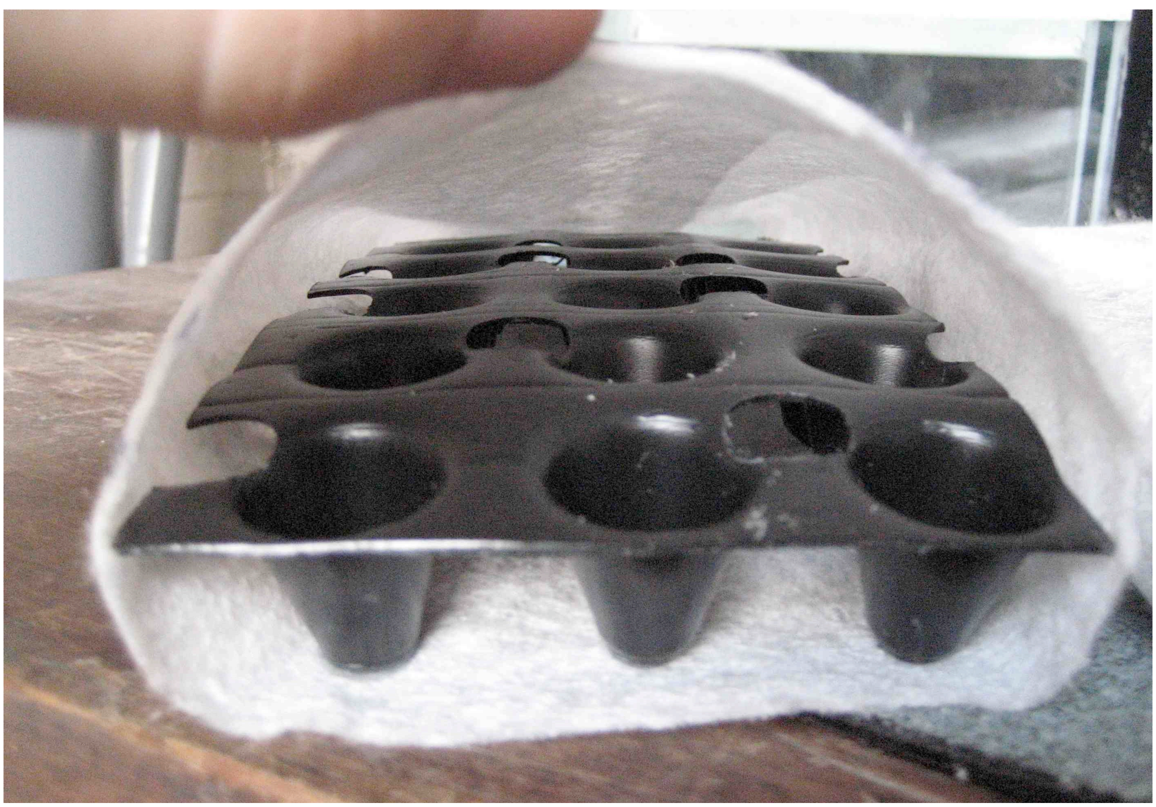

Figure 3.3 A section of the aeration layer, revealing the plastic cups which store water and the punched holes which allow overflowing water to pass through. Each cup is 2cm deep and holds 5ml of water. The plastic layer is surrounded by the filter material.

A pre-fabricated aeration layer lies on top of the root-resistant layer. This layer is intended to trap a small amount of water, for plants to draw on during long periods without rain. The aeration layer consists of a moulded plastic sheet with regularly spaced cups to pool water (Figure 3.3). The sheet is punctured by large holes in the sheet to allow water to flow through once the cups are filled. The plastic layer is wrapped with a fleecy, filter material designed to prevent fine particles from passing out of the system. The filter layer may be punctured by hair-thin roots, looking for water pooled in the cups. This layer was provided as a roll, 100mm wide and 4m long. The roll was cut into strips, 300mm x 100mm, which were placed side-by-side in the boxes. The edges of the filter material were sealed to the sides of the boxes with silicone sealant to prevent fines being washed down the sides. There was sufficient filter material surrounding the plastic to overlap the material of adjoining strips, preventing fines from flowing through the gaps.

3.1.4.3 Soil mix

As the brown roofs for this research are not being constructed on brown field sites, there is no ready supply of aggregate to be used as the soil mix. As such, a number of different aggregate types, which might prove to be suitable materials, were sourced from different locations.

Crushed concrete from demolished buildings was sourced from a demolition and aggregate recycling company in Birmingham. This material was pre-sorted into different grades by industrial sorting equipment. Bags of sand, 6-12mm, 12-20mm and 20-40mm material were chosen and mixed together in various ratios to produce suitably differentiated mixes of material.

Incinerator Bottom Ash (IBA), collected from the bottom of power station chimneys and Pulverised Fuel Ash (PFA), removed from the upward rising flue gases were sourced from a power station in the West Midlands. IBA contains a variety of particles ranging in

size from sand to small pebbles and consists primarily of siliceous material, but also contains fragments of glass, china, plastic and other detritus. PFA is composed of small, glassy spheres of silicon, aluminium and iron oxides. Its texture resembles that of cement. It was decided on inspection of the PFA that it would be unsuitable as a component of the soil-mix, but the IBA comprised a mixture similar to that of the crushed concrete aggregate and was used in one box mixed with the aggregate in 1:1 ratio. IBA and PFA are widely used in Britain and other countries throughout the world as secondary aggregates in road-building and construction. They provide both environmental and cost benefits, as they do not require the mining of virgin aggregate.

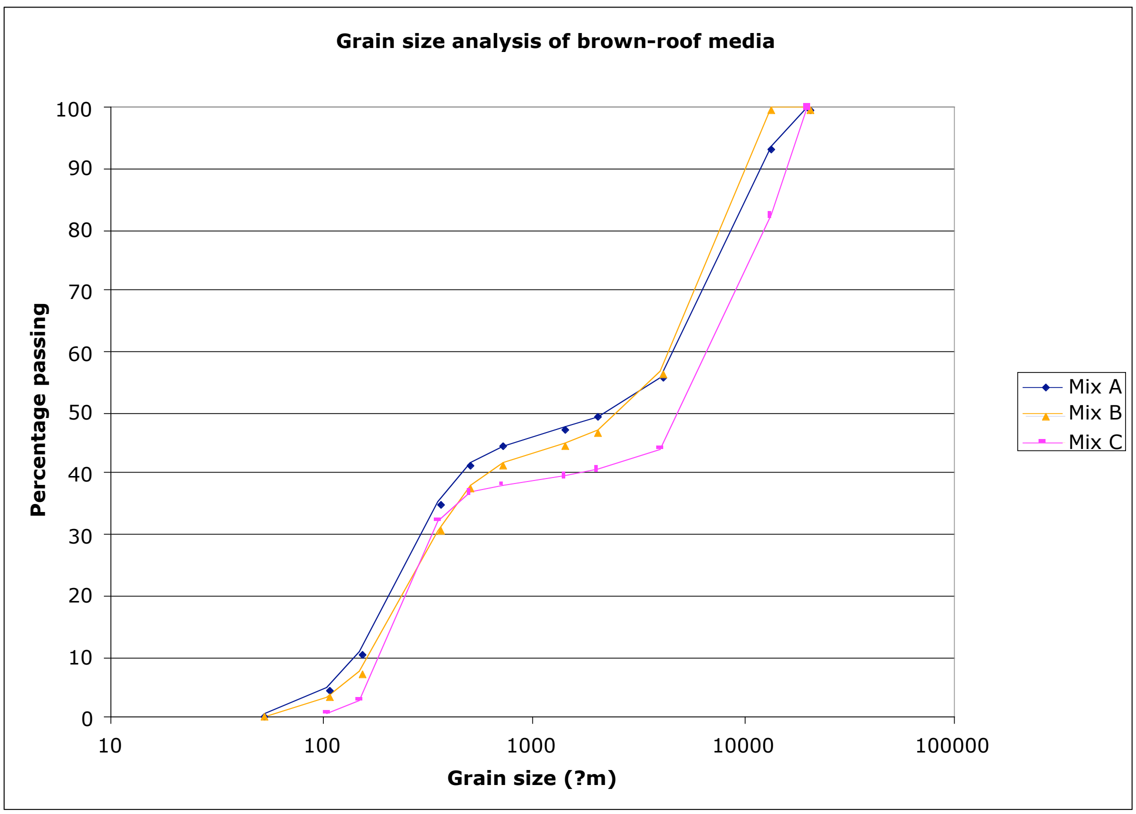

Figure 3.4 Grain size analyses of the three mixtures used in the brown roof boxes.

Three mixtures of material were produced to fill the brown-roof boxes. Mixture A consisted of 8000 cm^3 of a 1:1 mix of sand and 6-12mm crushed concrete, along with 1000cm^3 of 12-20mm material from the aggregate recycler. Mixture B was created by mixing sand and 6-12mm material in a 2:1 ratio. Mixture C contained 4500 cm^3

Incinerator Bottom Ash and 4500 cm^3 silica sand. Grain size analyses of samples of the three mixes are provided in figure 3.4.

Figure 3.5 Boxes containing mixture A (right) and Mixture B (left). Mixture A appears to hold considerably more sand.

Although mixture A contained half the volume of sand that is present in mixture B, the grain size analyses of these two mixtures appear to be virtually the same. To perform the grain size analysis, three samples from each mix were analysed. Samples of between 900 cm^3 and 1800 cm^3 were taken from a large bucket containing all of the material for each mixture. In-situ, a definite difference may be observed in the compositions of the two mixes however (Figure 3.5), so it may be that the samples analysed were not representative of the overall mixture. From the analysis, mixture C can be seen to

contain significantly less sand than Mixture A and more large grains (>10mmm) than Mixture B (Figure 3.4).

3.2 Rainfall Simulator

Natural rainfall has numerous defining properties, from the intensity and duration of rainfall events to the size, size distribution and velocity of individual raindrops (Assouline et al., 1997). Rainfall simulators typically attempt to recreate certain of the factors, depending on the reason for their construction (Rickson), although various external factors including wind velocity must be taken into account when designing a rainfall simulator (de Lima et al., 2002; Erpul et al., 1998)

Besides the deficiencies in precisely recreating natural rain, simulated rain also has many advantages, namely: control over timing, duration and intensity.

While fundamental studies of soil erosion may require rainfall simulators which only produce a single raindrop (Agassi and Bradford, 1999) the majority require multiple raindrops. These are typically separated into two fields, pressurized and non-pressurised (gravity-fed) simulators.

3.2.1 Pressurized simulators

Pressurized simulators emit raindrops from one, or a series of, nozzles and have the advantage of creating a uniform distribution of water over large areas, whilst at the same time, producing a wide distribution of drop sizes (Cerdà et al., 1997). Pressurized simulators have the added benefit of being able to produce a variable intensity over time (de Lima and Singh, 2002). Due to the small amount of apparatus required to construct a nozzle-type simulator, portable versions may be constructed which can be carried into the field or positioned over different plots of land (Cerdà et al., 1997, Hamed et al., 2002), whereas non-pressurized simulators are often permanent constructions, confined to the laboratory. One disadvantage of this type of simulator is that, due to the shape of the

water distribution from the nozzle, water is often provided to an area larger than that under investigation, hence these are not always practical for use in the laboratory

3.2.2 Non-pressurized

Non-pressurized rainfall simulators typically consist of an array of drop-formers fed by a tank of water. The raindrops fall under their own weight and therefore in order to closely resemble natural rainfall velocity distributions, the drop formers must be elevated to 10-15m above the intended surface. The drop formers may be yarn wool, hypodermic needles or glass capillary tubes. These will typically all be of the same diameter, producing only one size of raindrop, however, a fine mesh may be installed beneath the drop formers to break up large drops into many smaller ones. The intensity of rainfall events from non-pressurised simulators is generally controlled by varying the head of water in the tank feeding the drop formers, although the density of the drop formers in a given area will also affect this, and simulators with drop formers ranging from $80/m^2$ (Geagea et al., 2000) to over $1000/m^2$ (Battany and Grismer, 2000, Hignett et al., 1995) have been produced in the past.

3.2.3 Manufacturing a rainfall simulator

For the brown-roof box experiments, the ability to accurately monitor the volume of water precipitated onto the boxes was of prime importance. If a pressurized simulator had been chosen, it would have been necessary to collect all the water not falling onto the box, in order to calculate the proportion of water that was successfully reaching the target. This method posed a number of problems as far as the design of the boxes themselves was concerned and hence a non-pressurized simulator was produced which could be positioned such that all of the water leaving the simulator would land on the box.

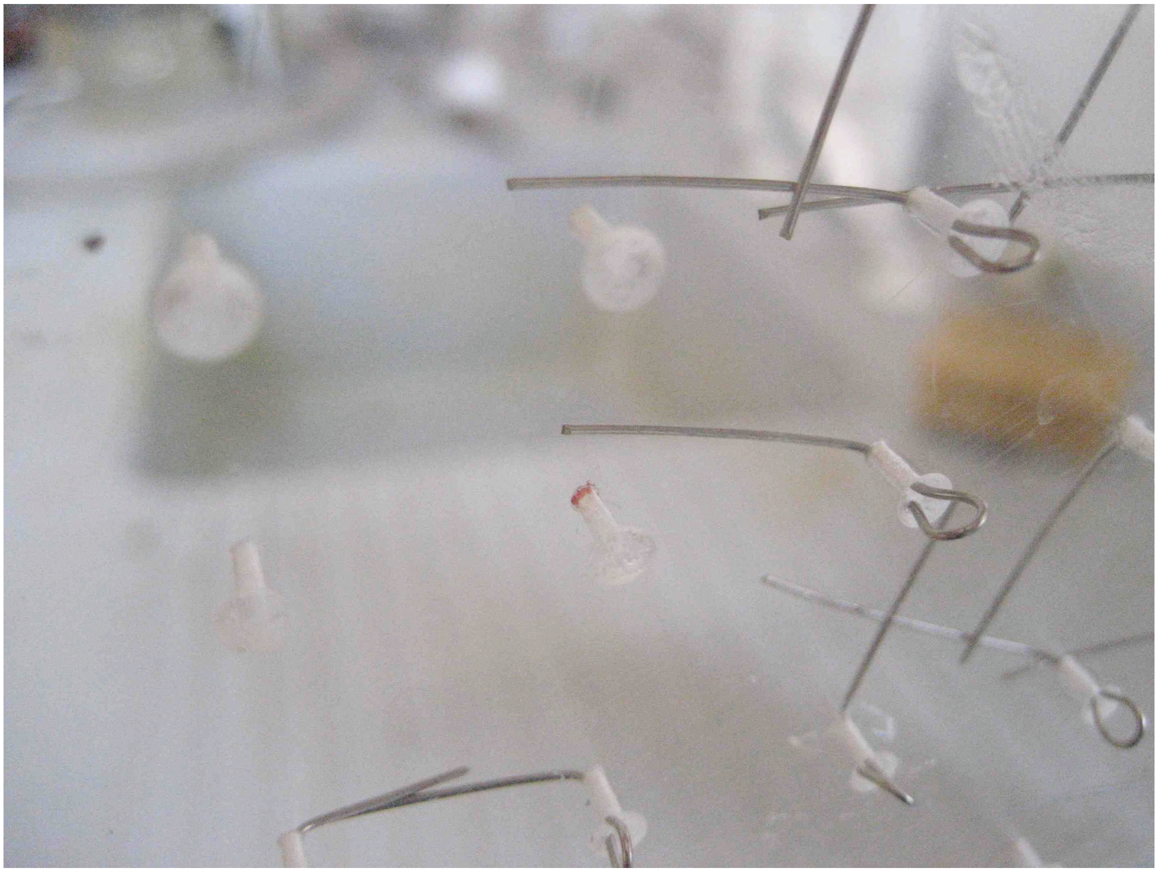

Figure 3.6 Capillary tubes drilled into the Perspex sheet have been countersunk and fitted with wire loops.

The rainfall simulator produced was based on that outlined in Bhardwaj and Singh (1992), created at the Indian Institute of Technology and expanded on by Singh et al. (1999). The design uses 1mm-diameter capillary tubes as the drop-formers for the simulator (Figure 3.6). These were drilled into a 300mm square sheet of 8mm-thick Perspex. The holes were drilled through the plastic with a 1mm thick drill at intervals of 15mm and each was countersunk to a depth of 2mm. Each tube was then threaded with short sections of annealed copper wire, coiled at one end to form loops for the drips to form on and bent at the other end to hold them in place. After testing different thicknesses of wire, it was found that 21 gauge wire (approximately 0.7mm) was the most suitable thickness to use, allowing water to flow past it at a moderate rate. Thicker wire permitted no water to pass, while thinner wire allowed too much. However, the precipitation rates created by the rainfall simulator were still twice the maximum rate of

1mm/min envisaged for the experiments, so half of the wires were removed and those holes covered over with waterproof adhesive tape (Figure 3.7).

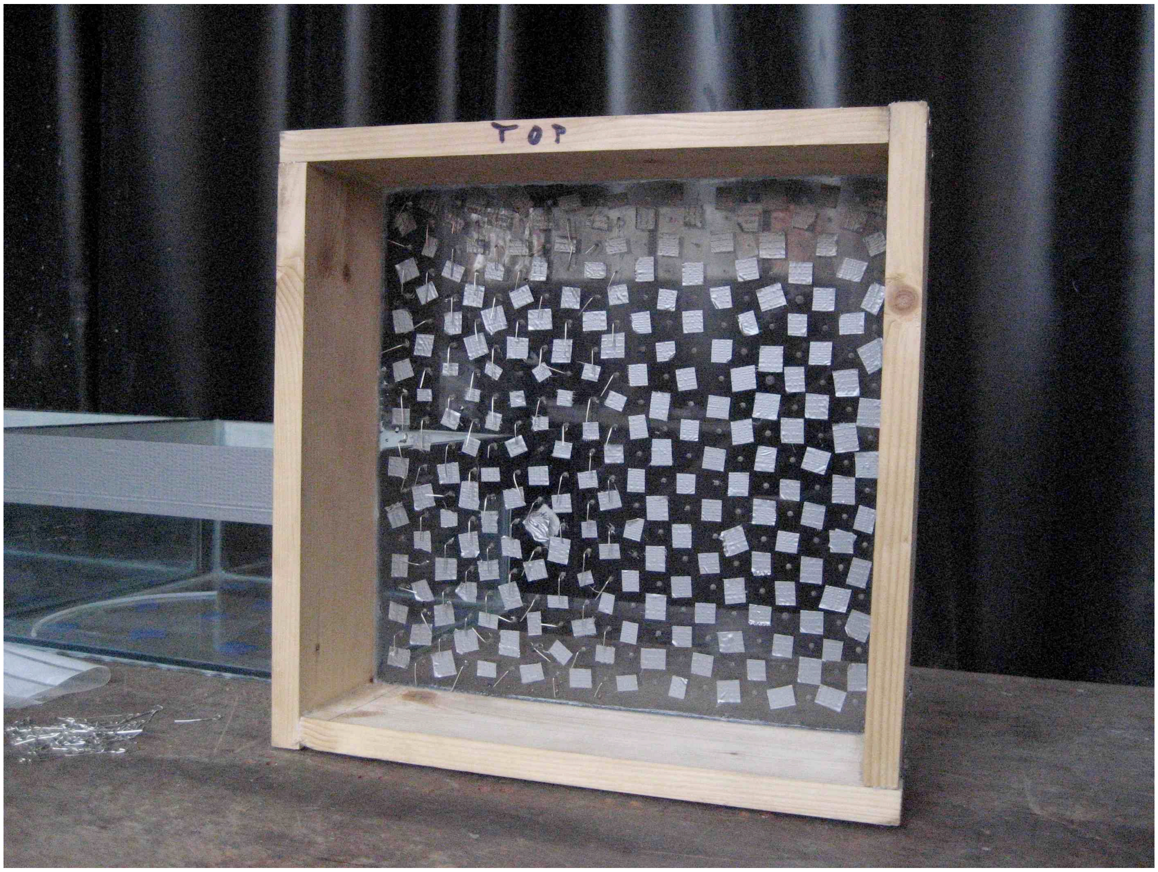

Figure 3.7 The completed rainfall simulator, with half of the drilled holes sealed with waterproof tape.

3.3 Monitoring equipment

3.3.1 Flow rate meters

3.3.1.1 Inflow

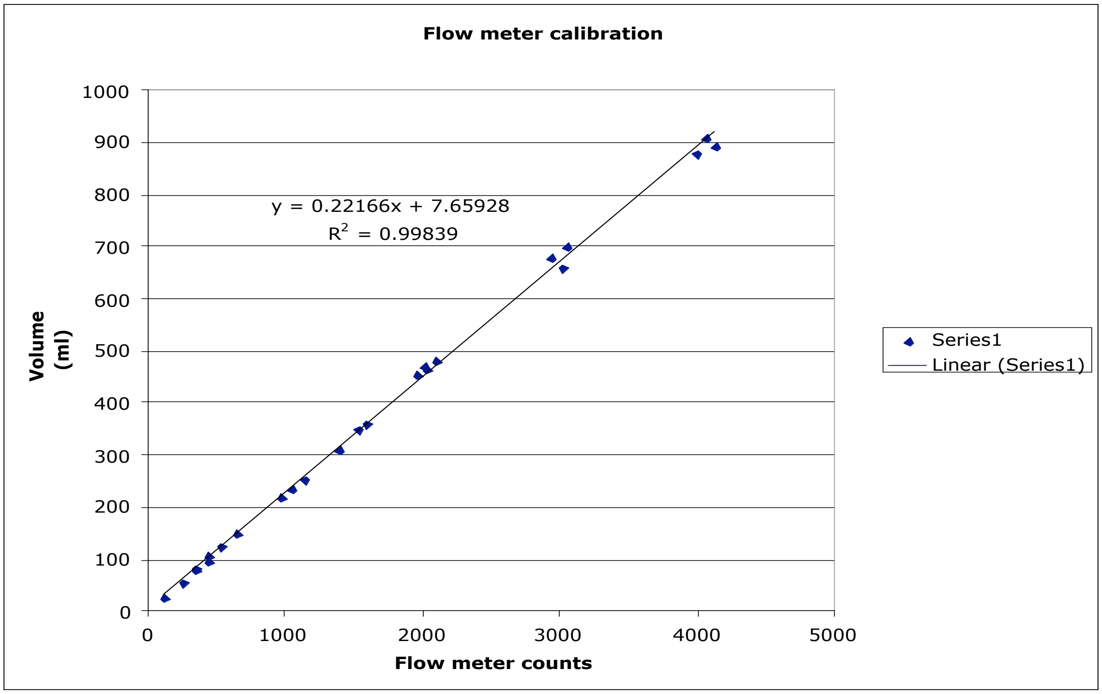

Figure 3.8 Flow meter calibration. The volume of water passing through the flow meter in a given time was contrasted with the number of counts recorded by the flow meter in that same time period.

An in-line flow meter was attached to the inflow pipe leading to the rainfall simulator to record the flow entering the equipment. The flow meter comprised a central turbine in between two lengths of piping. The total number of revolutions of the turbine and calculated revs/min could be displayed on an accompanying data logging device. The cumulative counter was found to be very reliable at measuring given volumes of water (Figure 3.8.), but the calculated counts/min were somewhat unreliable, changing dramatically over time when measuring a supposedly constant flow from the taps.

3.3.1.2 Outflow

Figure 3.9 The v-notch weir and ultrasonic sensor in place for the experiments. A large funnel directs water from the box into the weir. The baffler sits in between the funnel and sensor.

A V-notch weir, produced by Dr. Richard Greswell, was used to monitor the outflow from the brown-roof boxes (Figure 3.9). The weir was constructed from a small tub with a 45° V-notch cut out of one end, with a baffler inserted to prevent the inflow of water into the weir disturbing the surface of the water where it is measured.

Water level in the weir was recorded using an ultrasonic-sensor, which measures the distance from the sensor to a surface. The sensor reliably measured the surface height of water in the weir (Figure 3.10) over a suitable range of values.

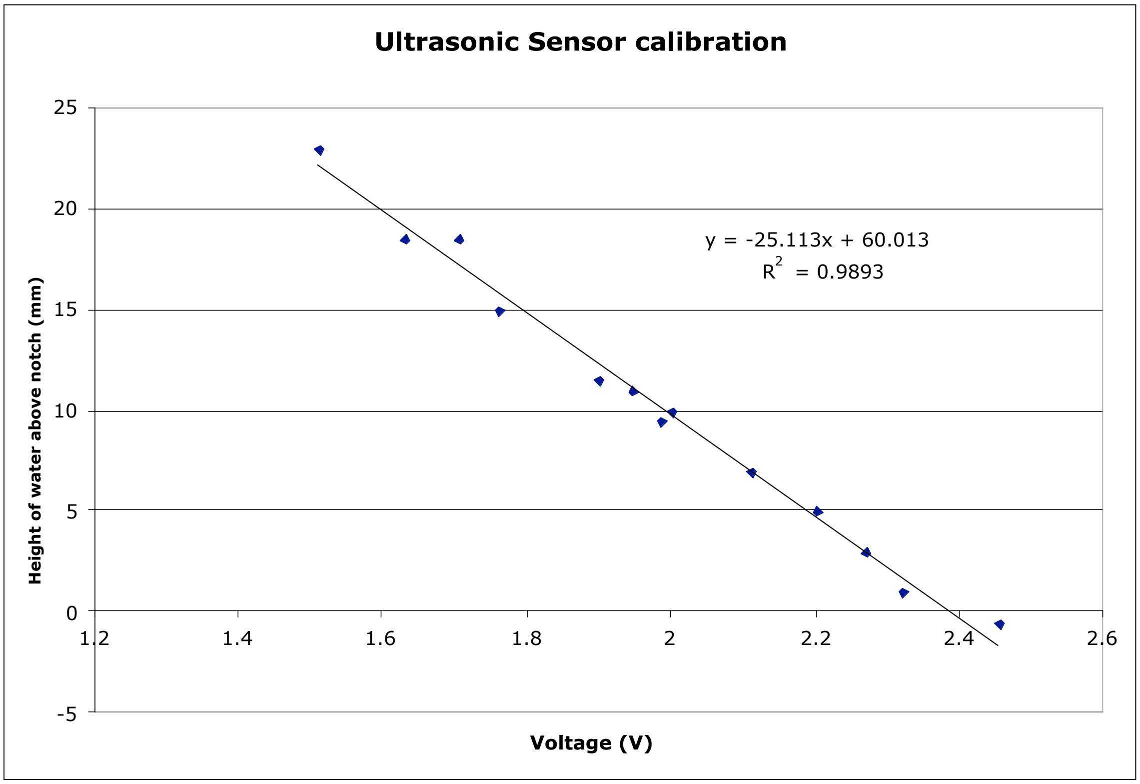

Figure 3.10 Ultrasonic sensor calibration. Output voltage from the sensor is compared with the height of water above the v-notch at that time.

Flow out of the weir is proportional to the height of water above the bottom of the notch and is calculated by the equation:

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

Where:Q = Flow rate (m3/s)

Cd = Coefficient of discharge

_ = Angle of notch

H = Height of water above base of notch (m)

The coefficient of discharge was calculated by experiment, by measuring the volume of water discharged from the weir in a given time, while the height of water was held constant. By the relationship above, Q^2 is proportional to H^5. The relationship between

these two factors is displayed in figure 3.11. The trend-line featured is linear and passes through the origin. While measurements at high flow rates appear to sit well on the line, those corresponding to lower rates < Q^2=1 l^2/min^2 do not fit the trend quite so well. The calibration suggests low flow rates are over-estimated.

Between four and twelve measurements of the flow rate were taken for each recorded depth of water, over time periods varying between ten and thirty seconds, hence the averages of these measurements may take into account some of the various errors in the experimentation and observation, e.g. errors in timing.

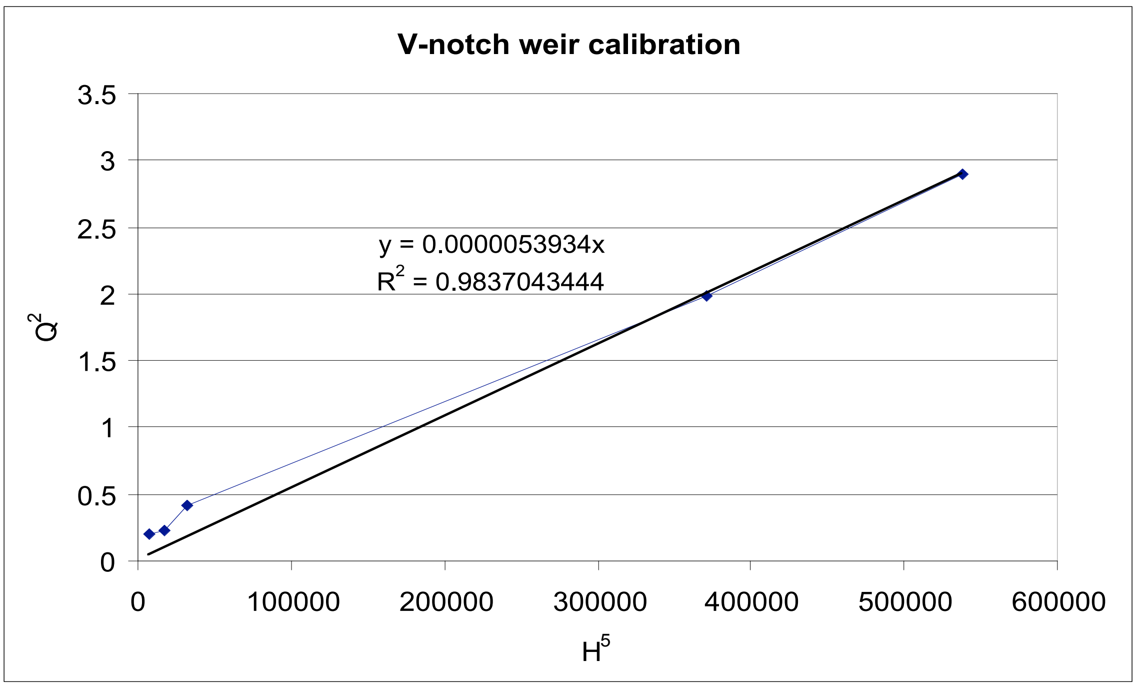

Figure 3.11 V-notch weir calibration. Flow out of the weir (Q) is compared with Height of water above the notch (H).

The flow into the weir was provided by one of the laboratory taps, which produced a steady flow-rate at high flow-rates, but was harder to control at the lower end of the scale. Measurement of the depth of water was performed using a steel rule before each flow measurement was undertaken. The measurement of depth was undertaken particularly

carefully and the human error in recording this value is estimated to be no more than ±0.5mm.

The tension effect observed at low flow rates may lead to significant error, since even with the water level above the notch no water flows out of the weir, due to the surface-tension of the water holding the water in place. In this case, it would be expected that the outflow associated with low depths of water would be less than predicted; however, the calibration experiment reveals that more flow than expected is recorded. This is likely a result of the outflow at low rates not having enough energy to form a stream of water exiting the weir, instead, the water dribbles down the side of the weir, negating the requirements of the theory behind the weir.

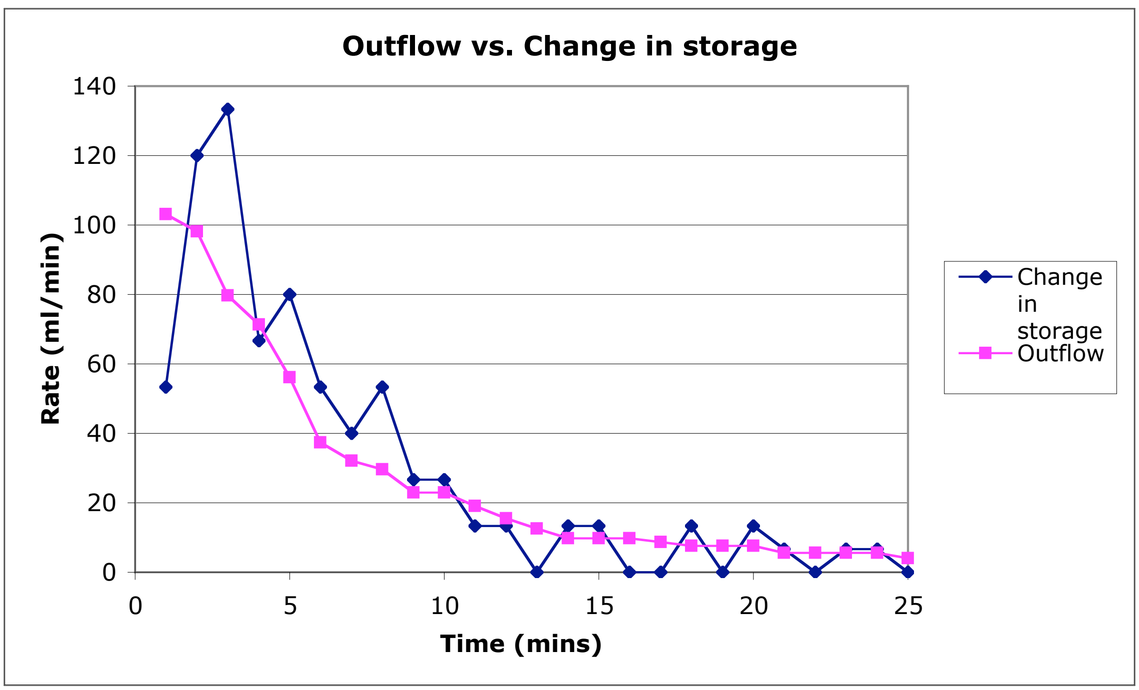

Figure 3.12 Outflow from the weir is compared with concurrent change in storage of the brown roof box. There was no inflow to the box at this time.

As the flow rates encountered in the brown-roof box experiments are in this low flow range (Q<1 l/min) this suggests that there may be difficulties using the weir for the experiments. However, during its use, the weir proved to be very effective at recording

the temporal variation in flow out of the brown-roof boxes, and after calibration, a measure of the quantity was also possible (Figure 3.12), which contrasts the outflow recorded at the weir with the contemporaneous rate of change of storage in a brown roof box.

3.3.2 Storage

The volume of water stored in the boxes was calculated by weighing the boxes during the experiments. It was necessary to use a set of scales with a fine enough resolution to be able to record the small variations in mass as water slowly trickled out of the box yet at the same time able to weigh masses greater than 20kg. As it proved difficult to find scales matching both these criteria, a fine set of scales, with a 1g resolution, capable of weighing up to 4kg was chosen.

The weight of the brown-roof boxes was effectively reduced by producing a cantilever for the boxes to sit on. The cantilever was constructed of wood in the shape of an isosceles triangle, in order to support the box at the broad end, and supply a force to the scales at a single point. By changing the position of the box along the lever, a different fraction of the mass would be recorded on the scales. A point was chosen, where the outflow from the box could be easily routed to the weir and the recorded mass was a suitable fraction of the total weight. In this position, 3/20ths of the total mass was recorded by the scales and a 1g variation in the mass recorded, corresponding to an absolute change in mass of 6.667g. This position was carefully marked, since a variation of even 1mm distance gave rise to ±2g variation in recorded mass, which propagates to a ±13g error in actual mass.

4 Results

4.1 Initial experiments

In most experiments, the rainfall simulator was suspended over an empty glass box and allowed to achieve a steady state head of water with an inflow from the laboratory tap. Once the head of water in the simulator had reached this steady state, a brown roof box to be analysed was placed below to collect the falling raindrops. Once the rain event had finished the rainfall simulator was either removed or in some instances, the tap turned off and the simulator allowed to drain of all water.

Figure 4.1 A brown roof box during the initial experiment on mixture C. Water is slowly moving through the box from top to bottom as can be seen from the change in colour.

The first experiment with the box containing mix A was intended to thoroughly wet the mixture so that subsequent rain events could start with a wetted box. Later experiments on mixes B and C investigated what happened when the box was wetted from dry and allowed to establish a flow-through of water, however in the case of mix A, when the first drops of water began to discharge from the box the inflow to the rainfall simulator was turned off. A small amount of water was left to drain into the simulator, but this produced very little outflow. This may be seen in figure 4.3, where a slight increase in the outflow appears after 15 minutes in an otherwise downward trend of the water held in the weir.

4.1.1 Mix A

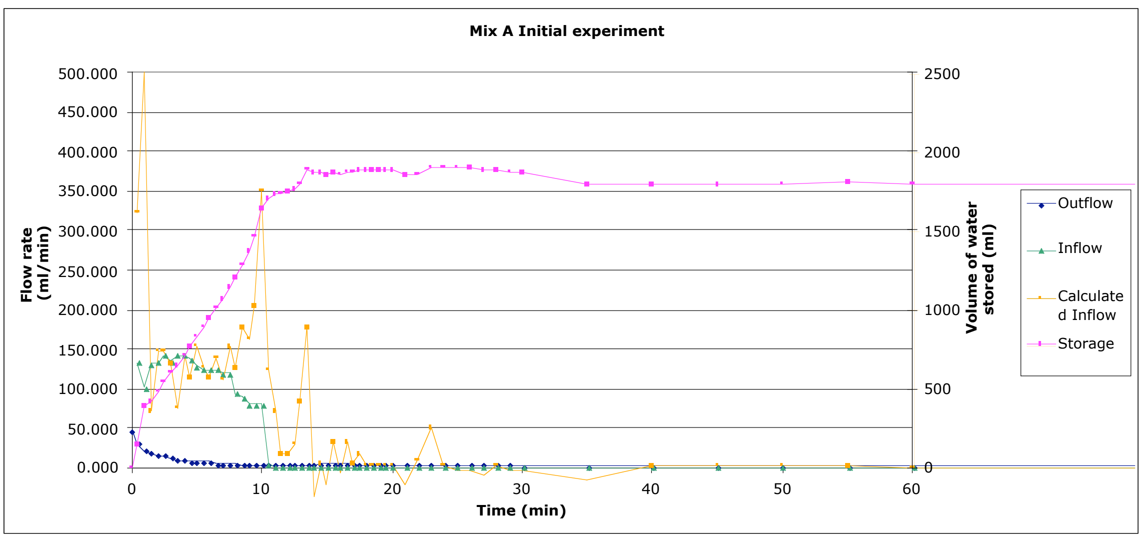

Figure 4.2 Record of initial experiment with mix A.

For this experiment the inflow of water to the rainfall simulator ceased 10 minutes after the start of the rain event. Initial inflow rate to the box was 150ml/min and the last raindrops fell 20 minutes later. Although it is not apparent in this record, the inflow from the laboratory tap was difficult to control satisfactorily, and although the simulator provided a steady flow of water to the brown roof boxes, resulting in a linear increase in storage (Figure 4.2), the flow recorded by the flow meter varied wildly in most

experiments and was not an accurate record of the water reaching the simulator at any time.

As the storage of water in the boxes and the outflow were being adequately recorded it has been possible to calculate estimates of the inflow to the boxes, however, due to the difference in scale between these two records, the calculated inflow shows a spiky trace for every experiment. This trace is still useful when compared with the measured inflow and with the records of storage and outflow from the boxes.

The record of this experiment shows an anomaly at its start, as an outflow of 50 ml/min is recorded before any water has reached the glass boxes. This trace reflects the water which had passed through the empty glass box before the start of the experiment and was still draining from the V-notch weir as the experiment began. In later experiments this trace has been removed from the graph record for clarity.

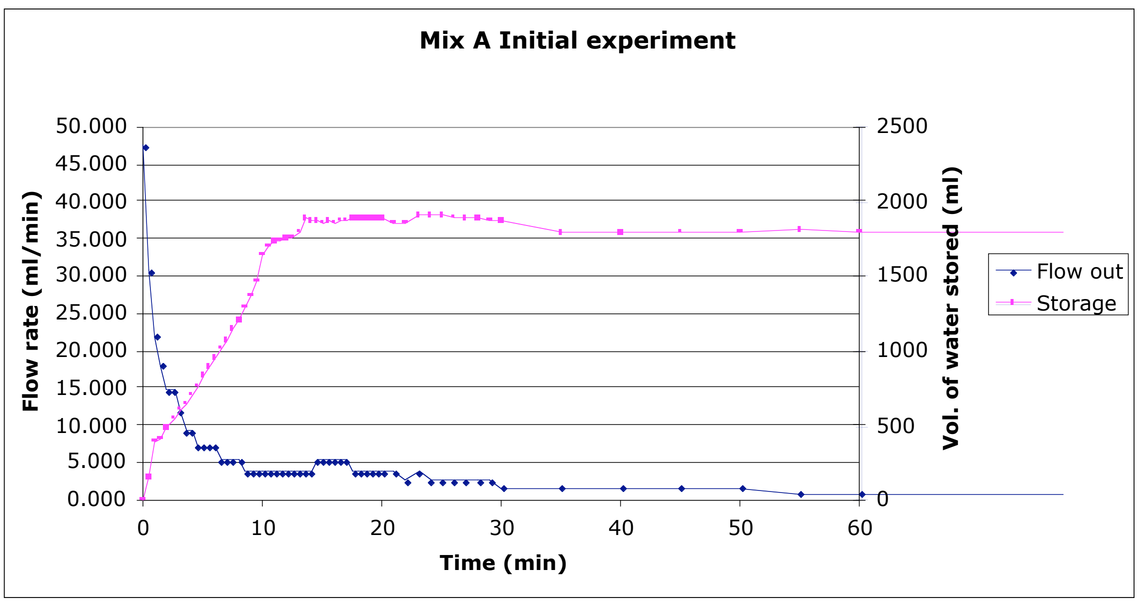

Figure 4.3 Storage and outflow recorded during the initial experiment with mix A showing a slight increase in outflow at t=15.

The record of the water stored in the box shows a steady rate of increase between t=1 and t=9 with sharp rises in the minutes before and after this period, perhaps due to an increased inflow from the rainfall simulator after it has been knocked, or a knock to the

measuring scales. In the 10 minutes following this, the storage remains roughly steady at 1900ml until t=23 when we begin to see a slow decrease over a period of 12 minutes until the volume of water stored has decreased to 1800ml. This decrease may be the result of water moving slowly through the soil mixture until it reaches the base of the soil layer where it can drain out of the box, or perhaps the drainage of water from the filter material which encases the aeration layer. When wet, this material can retain a significant volume of water, but given time, this water drains away.

4.1.2 Mix B

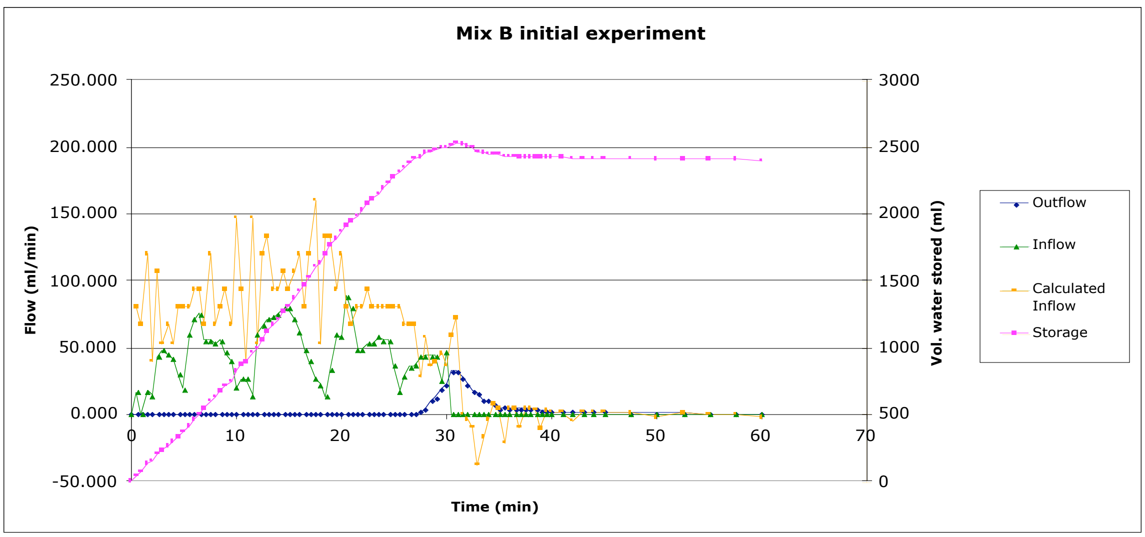

Figure 4.4 Recording of the initial experiment with mix B.

The initial storm on mix B was run at a rate of 100ml/min (50ml/min less than for mix A) and continued for 30 minutes (Figure 4.4). The first drops out of the box were observed after 25 minutes but there was no noticeable flow for a further 2.5 minutes. Peak flow from the box occurred at 30 minutes into the event, when there were 2500ml of water in storage. At this point the rainfall simulator was removed and the outflow began to decrease approximately one minute later. The storage quickly falls to 2450ml (greater than the quantity of water in storage in mix A after its initial experiment) at t=34, and 50ml is gradually lost over the subsequent 25 minutes.

4.1.3 Mix C

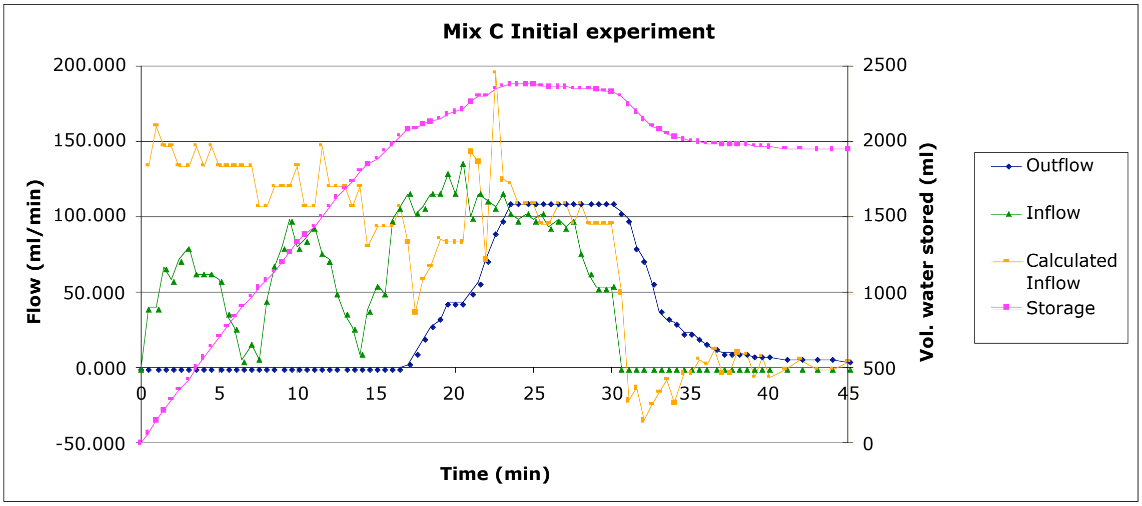

Figure 4.5 Recording of the initial experiment with mix C.

The initial storm event with Mix C featured an initial calculated inflow of 130ml/min, lowering to an average of 120ml/min after 7 minutes and then to 110ml/min after 14 minutes (Figure 4.5). Very slight breaks in slope are visible in the trace of storage corresponding to these changes, while more significant breaks in slope are observed at 17 and 25 minutes into the storm event where increases in the outflow are recorded.

At t=23.5 the outflow reaches a peak of 110ml/min and remains constant until the rainfall simulator is removed. The water held in storage decreased by 50ml over this period and it might be expected that the outflow would decrease in line with this. But as this is not the case, it seems reasonable to assume that something is impeding the flow of water out of the box. Higher flows of water had been recorded out of the other boxes, which suggests that this is not a problem with the flow meter, however it is hard to be certain of the real cause.

The rainfall simulator was removed after 30 minutes, at which point the rate of decrease of storage increased. The rate of decrease levelled off again as the output decreased in proportion to the storage. Flow from the box was only observed up until 33 minutes (flow=35ml/min), when a stream of fast drops was formed instead. The frequency of these drops decreased from approximately 2 per second at 35 minutes (23ml/min) to 1 per second at 40 minutes (7.5ml/min).

Over this period a total of 360ml of water drained from the box; 300ml in the first 5 minutes, 40 ml in the second 5 minutes and 20ml in the third.

4.2 Steady state experiments

In a number of experiments a steady state was achieved between inflow to the brown roof boxes and outflow. Under these conditions, storage in the boxes remains constant for extended periods of time.

4.2.1 Approaching steady state

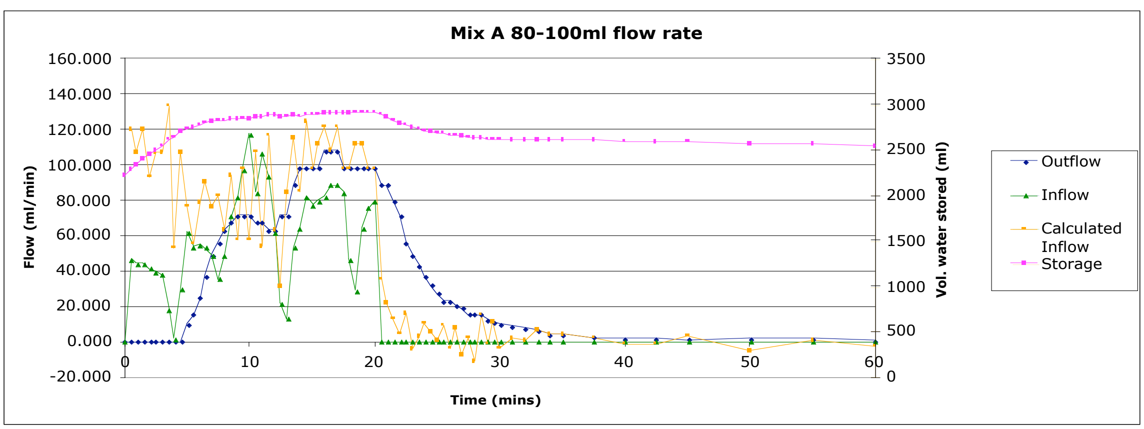

Figure 4.6 Record of an experiment on mixture A with an 80-100ml/min inflow rate.

During this experiment the weighing scales behaved slightly temperamentally and hence, the calculated inflow displays an excessively spiky trace (Figure 4.6). Problems with the inflow from the laboratory tap also caused the inflow to drop suddenly in the middle of the rain event leading to the slight reduction in outflow following t=10min.

With 220ml of water stored initially, a storm event averaging between 80ml/min and 100ml/min was created over the box containing Mix A. After 4.5 minutes the first outflow was observed and increases to 70ml/min after 9 minutes, while the rate of increase in storage decreases to a steady rate of 8ml/min which remains constant over the next 13 minutes until the rainfall simulator is removed. In this example the brown-roof box never reaches a steady-state condition.

When the input is removed from the system at t=20 the outflow was observed as non-continuous flow, however by t=20.5 the flow has already reduced to individual drips which become less frequent until t=30 when the last regular drops are observed. By this time, the storage has reduced to 2600ml. Over the next 30 minutes, 45ml of water are lost from the box, averaging 1.5ml/min.

4.2.2 Mixture A steady state

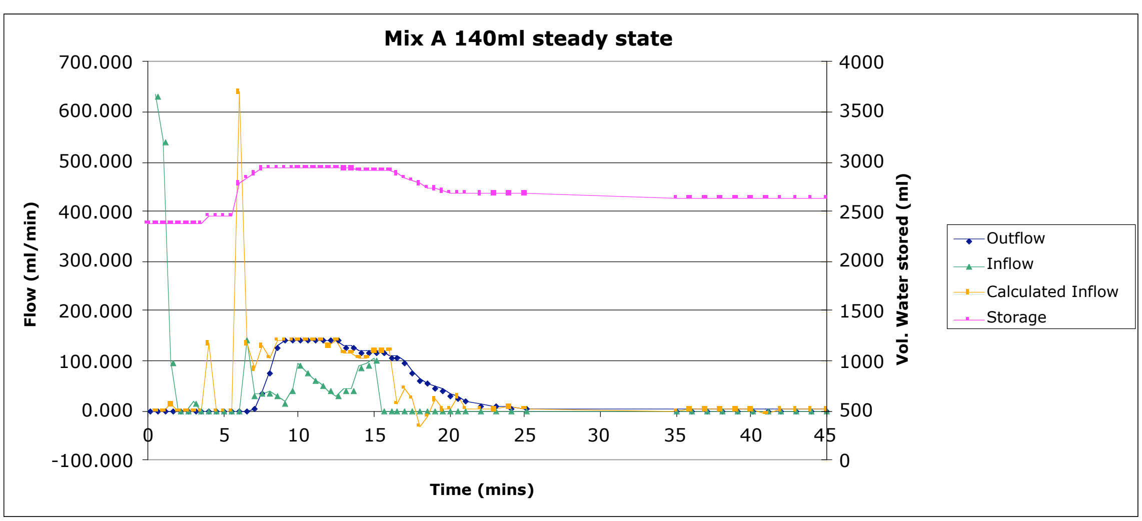

Figure 4.7 Record of an experiment on mix A with a 140ml/min inflow rate.

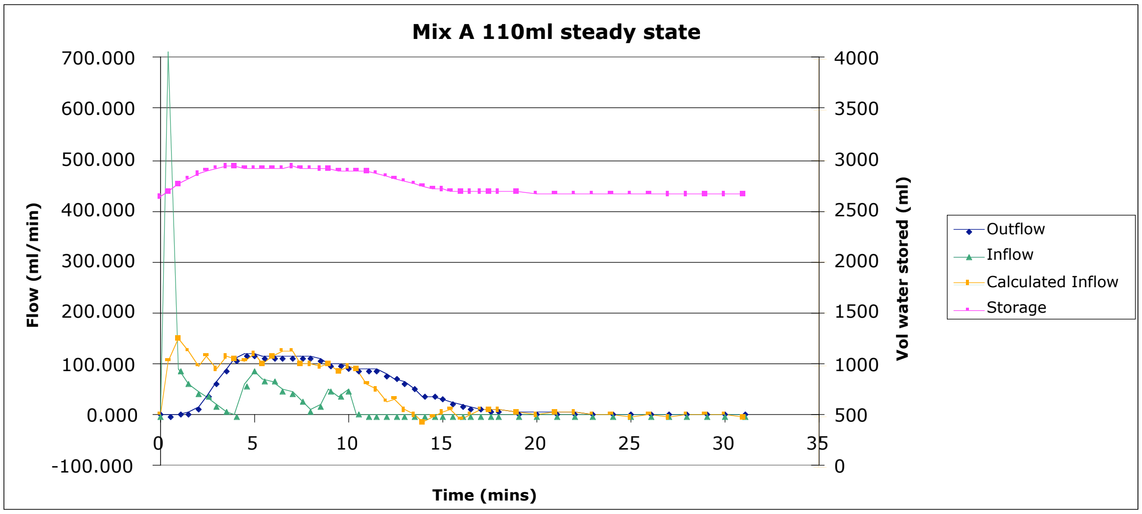

Figure 4.8 Record of an experiment on mix A with a 110ml/min inflow rate

Figures 4.7 and 4.8 illustrate situations where the brown-roof box reaches steady state of storage, with differing rates of flow through the system. While the rates of flow differ in these two examples, at 140ml/min in the first example and 110ml/min in the second, the volume of water held in storage is virtually the same in both circumstances at an average of 2940ml and 2920ml in the first and second examples respectively. These two experiments were conducted in quick succession of each other, with the second storm staring 30 minutes after the end of the first. While there was only 2400ml of water in storage at the start of the first experiment this increased to 2940ml during the event and eventually dropped to 2630ml following the event. With this starting volume, the second storm increased the volume stored to 2920ml and 20 minutes after the rain had ceased, the volume had decreased to 2650ml.

4.2.3 Mixture B steady state

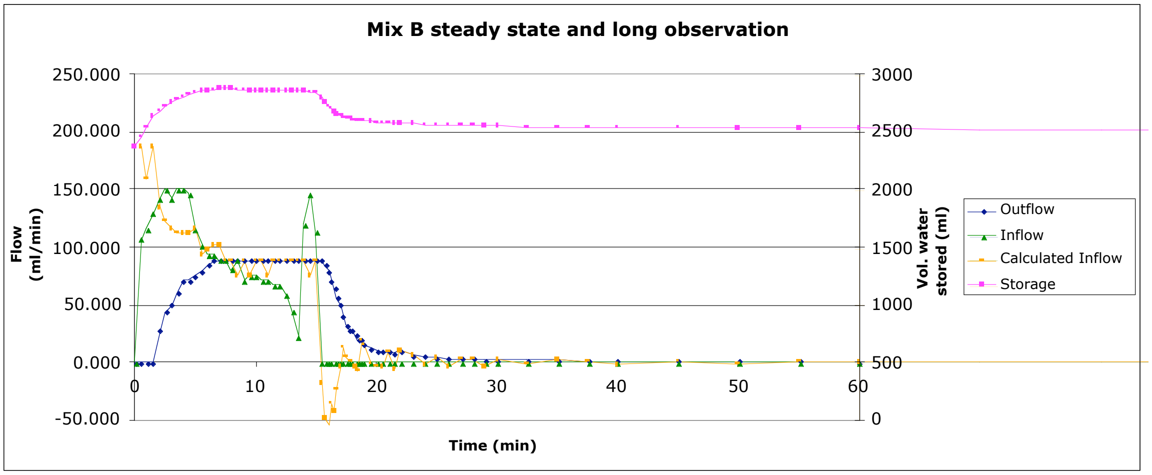

Figure 4.9 Record of an experiment on mix B with a 90ml/min inflow rate.

With an initial volume of 2350ml water stored in the brown-roof box, an initial input rate of 175ml raises the storage to 2700ml after two minute and outflow from the box is observed. The inflow subsequently decreases to 90ml/min while the outflow increases to 90ml/min at t=7. Steady state conditions ensue until the inflow is removed at t= 15 (Figure 4.9).

4.3 Observations of outflow following rain events

4.3.1 Mix A long observation

With an initial stored volume of water of 2140ml, an input of 100-120ml/min is applied to Mix A and the first output observed after 3 minutes when 2500ml of water is stored (Figure 4.10). After 6.5 minutes the outflow has increased to 80ml/min and there is a noticeable difference in the rate if increase of storage. The rainfall simulator is removed after 10 minutes and the decrease in storage recorded over the next hour. Immediately following the end of storm, the head of water held in the aeration layer was recorded as

3mm, 4mm and 8mm in the segments closest to the outflow hole, in the middle of the box and furthest away respectively and constant flow of water through the hole was observed. At this stage the recorded flow was still high at 80ml/min.

At t=17 these heads were recorded as 0mm, 0mm and 2mm and infrequent drips were observed, while the recorded outflow was 12ml/min. At t=35 there were very occasional drops from the box and the recorded flow was negligible at 0.5mm/min.

In the period between 10 and 20 minutes when recorded flow was greater than 5ml/min, the storage dropped from 2860ml to 2610ml, releasing 260ml of water from the brown-roof. In the following 40 minutes, a total of 110ml was released from storage, averaging 2.75 ml/min. During this time, very little water was seen to flow out of the box and the weir recorded less than 2.75ml/min flow for entire period after t=24.

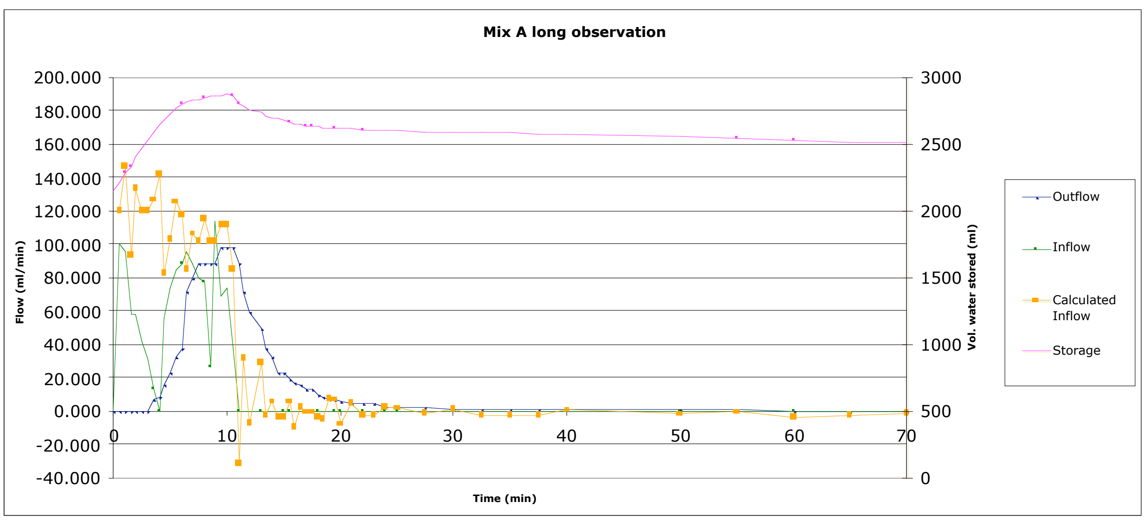

Figure 4.10 Record of long observation after rain event with mix A

4.3.2 Mix B long observation

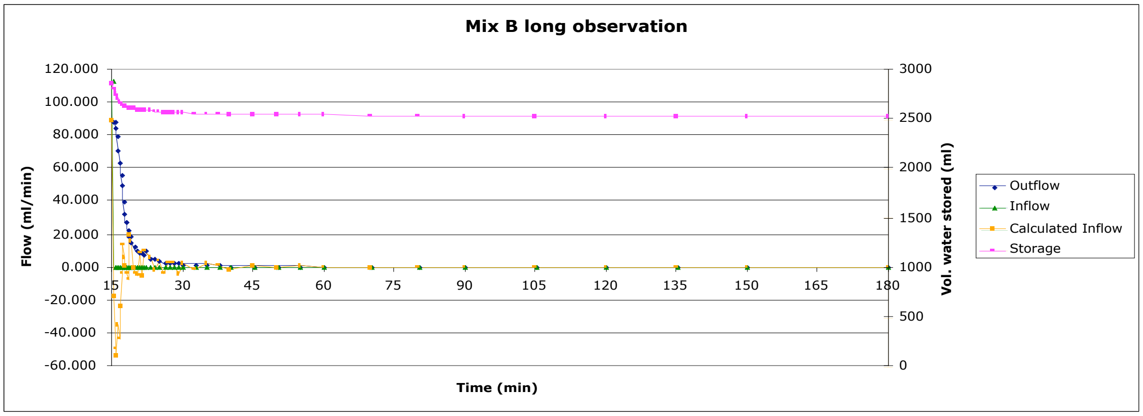

Figure 4.11 Record of long observation after a rain event with mix B

The decrease in storage following a steady state experiment with mix B was recorded until t=180. A steady flow of water from the outflow was observed during the storm and was still present up until t =16.5 (Figure 4.11). However, by t=17 the flow had reduced to individual drips. At t=22 all the pooled water had drained from the aeration layer and subsequently only occasional drips were observed. In the following 50 minutes, 50ml of water are lost from the box at a steady rate. However in the next 50-minute period (between t=70 and t=120) only 10ml water are lost. There was no observed change in storage during the last hour of observation, with 2515ml recorded throughout this entire period. Due to the conversion between the recorded weight on the measuring scales and the actual weight of the box, the scales are only sensitive to changes greater than 6.5ml, hence, the constant measurement is not an indication that no water was lost.

4.4 Double storm event

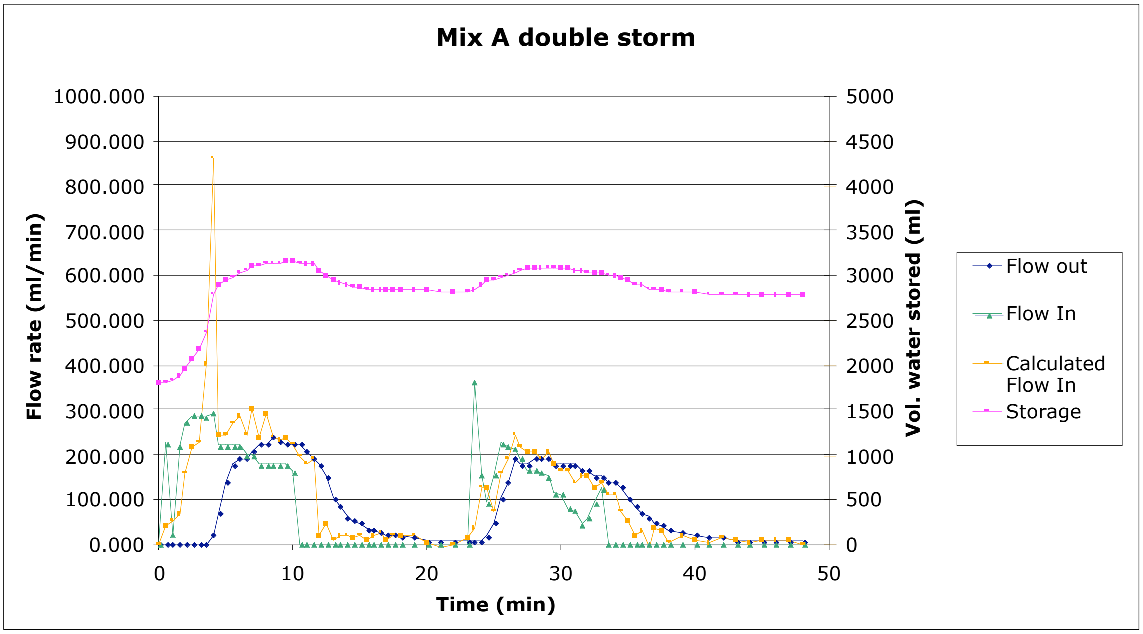

Figure 4.12 Record of a double storm event with mix A.

A double storm event was produced over mixture A, which initially held 1800ml of water (Figure 4.12). In this experiment the rainfall simulator was positioned over the box as it began to fill with water, without waiting for it to reach steady-state. This is revealed in the non-linear increase in storage over the first four minutes of the experiment, as the inflow increases from 0 to 300ml/min. After four minutes the storage has increased to 2800ml and the first outflow is recorded. Following this the rate of increase in storage decreases as the outflow increases. After 10 minutes the inflow to the rainfall simulator ceases and the flow into the box gradually falls to zero. At this point the volume of water held in storage in the box immediately starts to decrease (though slowly at first) as the outflow exceeds the inflow.

In this example it is obvious that the inflow measured with the flow meter is an inadequate record of the flow into the box as this trace drops below the measured outflow at t=7 minutes, when the volume of water in storage is still increasing.

Between t=11.5 and t=16, with no input to the system, the volume of water stored decreases and the rate of change of storage decreases as the outflow decreases. After t=16 the volume of water continues to decrease, but at a much reduced rate, 20ml is lost in 7 minutes, whereas 280ml were lost between t=11.5 and t=16.

4.5 Between experiments

A quick analysis of what happens between the recorded experiments gives a rough idea of which factors have been important in draining water from the boxes once the main outflows have ceased.

In separate intervals, 393ml of water is noted to have drained from mix A in a period of one day, while only 500ml has drained in a period of 5 days. From this it may be suggested that evaporation has not been the major factor in determining the outflow from the boxes at extremely low flows, as a more constant rate of evaporation might be assumed. While water will surely be evaporating from the surfaces of the boxes, most of the fluid leaving the boxes is likely to seep slowly out of the base, and in particular to escape from the aeration layer and filter material which have been observed to store significant quantities of water in separate tests.

4.6 Discussion of Experimental Results

The initial experiments on each mixture highlight that each has a minimum storage requirement before any water is released as outflow; effectively there is a field capacity which must be exceeded before any outflow is observed. The timing of the first out flow is complicated by the underlying aeration layer. When this layer is dry, it will absorb a significant volume of water, delaying the time at which we see water flowing out of the box. In addition to this, the separate aeration sections further delay the transfer of water out of the box, as the filter material which surrounds them impedes the flow between the segments and causes water to pool in those sections furthest from the outflow hole.

For mixture A the total volume of water stored before outflow is observed is 2600ml. However, we must take into consideration the volume of water held in the cups of the aeration layer. Each box contains 81 cups in total and by experimentation it was found that each cup holds 5ml ± 0.5ml, hence the total volume of water held in the aeration layer is 405ml ± 40.5ml. Mixture A then, can store 2195ml ± 40.5ml in the aggregate layer. This equates to a field capacity of 24.3mm ± 0.45mm of water. For mixture B, 2400ml total volume of water can be stored. Field capacity is then 22.2mm ± 0.45mm. For mixture C, 1950ml of water may be held, and field capacity is equivalent to 17.1mm ± 0.45mm of water.

The steady state flow characteristics achieved, reveal a maximum storage capacity, beyond which, any further input to the system is automatically output to the weir. For mix A, steady states were achieved with inputs equivalent to 1.22mm/min and 1.55mm/min. In both circumstances the corresponding storage during steady state was 2945ml, equivalent to 28.2mm ± 0.45mm of water. Mixture B held a maximum of 2855ml corresponding to 27.2mm ± 0.45mm.

Although the surfaces of the boxes were noticed to pool with water after extended periods of rain, none of the boxes flooded during any of the experiments, indicating that there is no potential for surface flow from the boxes. The surfaces of the boxes became quite pitted due to the nature of the simulated rain, falling in the same positions over and over. It is likely that this also led to armouring of the surface, causing small puddles of water to pool here.

The decay of outflow as the storage decreases provides an excellent opportunity to examine how the magnitude of outflow is affected by the storage in the aggregate. Figure 4.13 displays the recorded outflow contrasted with the volume of water in storage measured above the field capacity and reduced by a linear amount for the aggregate mix C.

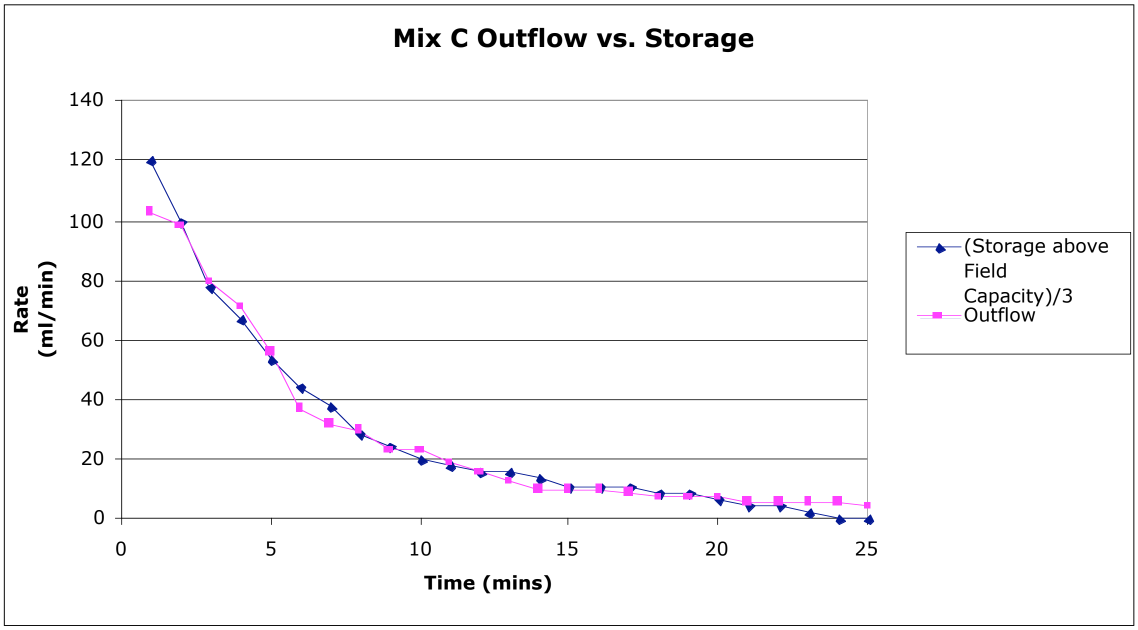

Figure 4.13 Outflow recorded at the v-notch weir contrasted with the volume of water in the box exceeding the field capacity, scaled down by a factor of 3.

Figure 4.13 reveals that the relationship between the outflow and storage measured above the field capacity in Mix A is linear with a factor of 0.344, i.e. outflow = 0.344*(S above F.C.), a similar factor to that seen in mix C. While the points between t=21 and t=27.5, corresponding to outflows between 90 and 20ml/min fit the trend, those points after t=27.5 show outflows greater than the recorded change in storage at these times. This result may be an effect of the surface tension effects of the water in the v-notch weir, holding water in the weir and giving an impression of greater flow than was actually occurring.

The important thing to gain from this however is that discharge is linearly related to the storage exceeding field capacity (Figure 4.14).

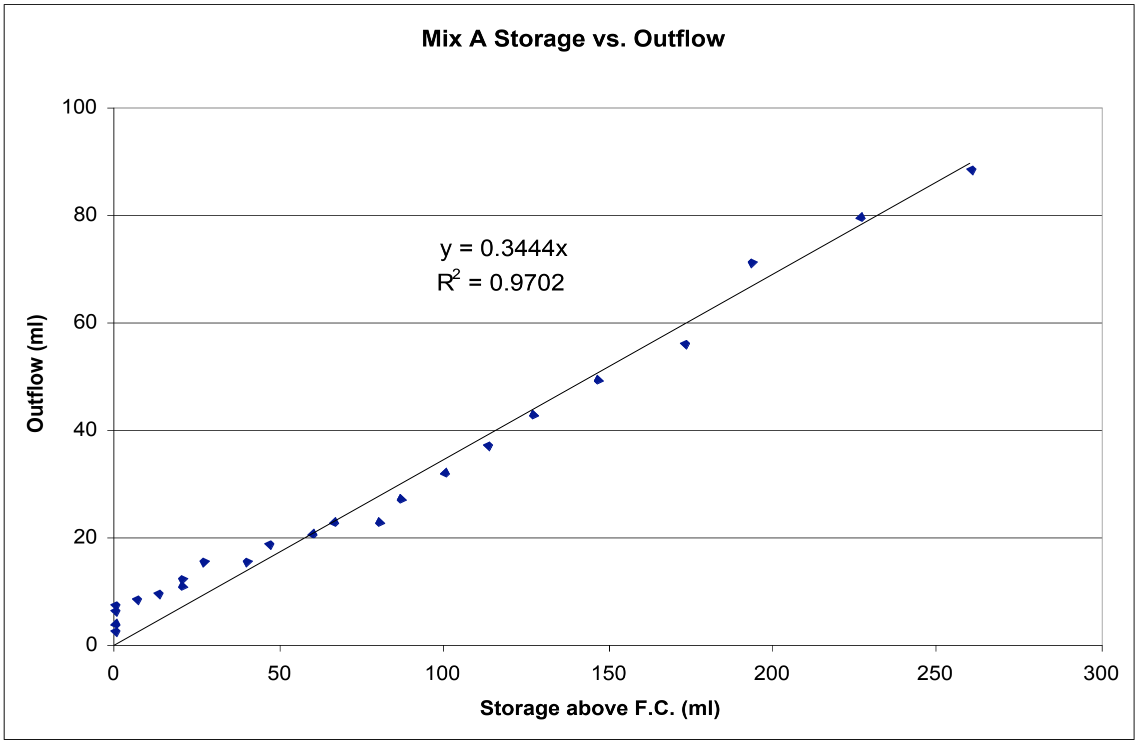

Figure 4.14 Outflow from the box compared with volume of water in storage exceeding the field capacity.

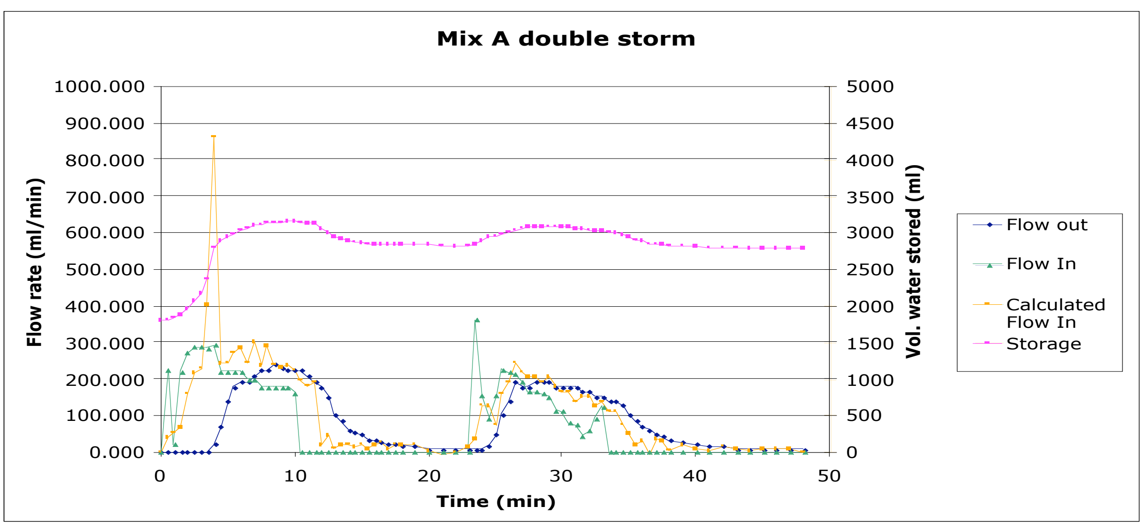

Figure 4.15 Record of a double storm event with mix A

The double storm presented in figure 4.15 is another clear indication that outflow will not occur while the storage is below the field capacity. During the first storm where the initial storage is well below the field capacity, there is a time-lag of five minutes before any outflow is seen. During the second storm, when the brown-roof has not had time to drain much water, the time-lag between the onset of the storm and the first appearance of outflow is reduced to one minute.

There can be no real assessment of the retention rate of the brown roof boxes from studying the results of these experiments as they have not been intended to recreate natural rainstorms, but instead to probe the hydraulic function of the boxes. As retention is related to storm intensity, there is no way to gain meaningful values from these experiments. However, the results of modelling used to predict the response of the tiles to natural rainfall events should give some indication of the retention rate under different rainstorm conditions.

5 Model

A computer model of the brown roof boxes will aid in the understanding of their hydraulic response and help to predict the behaviour of the roof tiles in future and their response to real events.

5.1 Conceptual model

The behaviour of the brown roof boxes is analogous to a simple system of linear reservoirs. When water is applied to the uppermost reservoir it will fill with water until some minimum level is reached, before it begins to discharge water into the next reservoir in the series. After the initial experiments with the boxes it was decided that a simple two reservoir model would be sufficient to model their behaviour. However after further experiments, it was decided to increase the number to four, with three side-by-side reservoirs representing the three sections of the aeration layer.

An additional reservoir has been added to represent the storage cups in the aeration layer, but these only play a role when the experiment is starting from a completely dry state. In other circumstances it is assumed that the cups are initially full of water.

The flow of water from the aggregate reservoir to aeration reservoirs is related by an experimentally determined factor to the volume of water in storage exceeding the field capacity.

The flow between aeration reservoirs and the flow out of the final reservoir are related to the difference in head between the reservoirs and a (large) proportion of this water allowed to pass through.

The change in storage of the box after the storage drops below the field capacity is most likely due to the evaporation of moisture from the boxes. This flux has not yet been quantified for the brown roof boxes.

5.2 Implementation

The model was designed to take the input from the laboratory experiments, which had been collected and recorded in Excel, hence the model was written with this in mind, using Visual Basic for Applications.

Input values are designated for individual timesteps in the model and the balance of storage and flows in each reservoir solved in the order of the flow direction within each timestep. This method, although simple to implement, is effective and efficient at solving this type of problem. During calibration experiments the model took no more than 2 seconds to run.

5.3 Calibration

Data collected from the laboratory experiments was used to calibrate the model. By providing the model with the calculated inflow from the experiments, the model was able to predict the storage and outflow for the duration of the experiment. It was possible to affect how the model responded by adjusting the values of field capacity and the coefficients of flow between the reservoirs used in the model.

A minimum value was set for the storage in each reservoir before flow to the next reservoir was initiated. The flow between reservoirs was then calculated as a fraction of the excess storage in the reservoir in that timestep. The coefficients were calibrated for each mixture used in the experiments, until the modelled results suitably matched those acquired from experimentation.

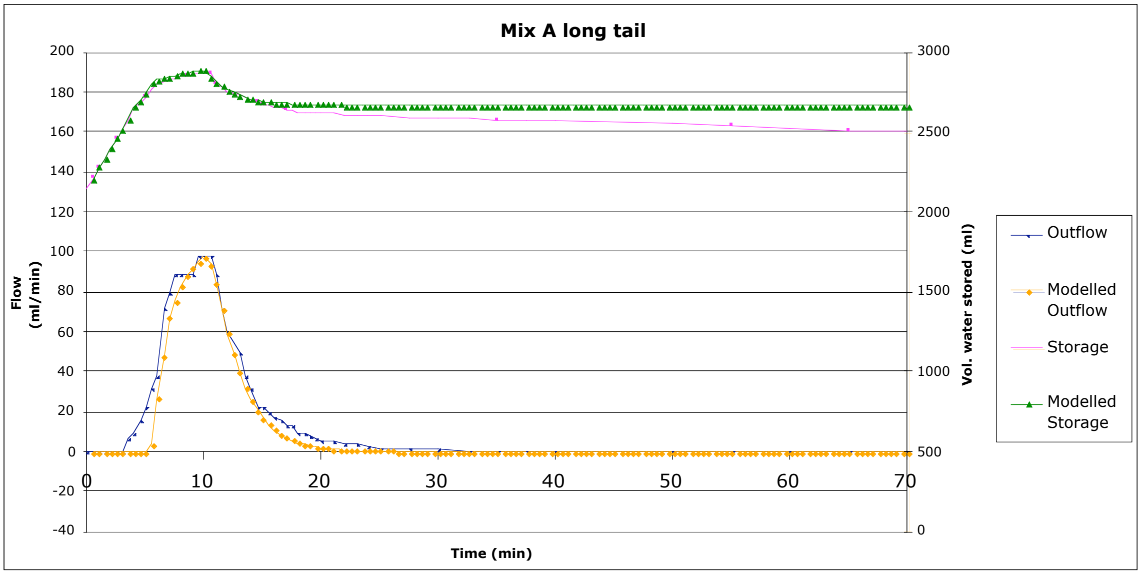

Figure 5.1 Output from the model contrasted with experimentally obtained data for a given rain event.

The results displayed in figure 5.1 highlight the experimental and modelled result for one experiment with mixture A. They reveal that the model is capable of accurately predicting the storage of the brown-roof box during the input and outflow periods of the experiment, but following the period of significant outflow (>10ml/min), the modelled storage shows barely any decrease while the recorded storage drops a further 180ml in the next 50 minutes. This slow, gradual decrease in storage is not taken account of in the model. Between experiments, the brown-roof boxes have shown varied rates of evaporation which have been difficult to quantify with respect to time. It would be possible to append a simple linear decrease to the modelled storage following rainfall events, but without accurate records of the temperature and other factors throughout this time it would be impossible to model this with any degree of certainty. The recorded decreases in storage have averaged between 0.05ml/min and 0.25 ml/min between the end of one experiment and the onset of the next.

The modelled outflow is shown to match the peak outflow recorded experimentally and to follow the rates of increase and decrease quite faithfully. As the rate of outflow decreases after the rain event, once it decays to low flows (<20ml/min) the predicted outflow drops off much more quickly than that recorded at the weir. Yet again this may

possibly be attributed to the surface tension effects observed in the weir, where these low flow conditions are observed to hold more water in the weir - giving an impression of greater flow than is actually flowing through the weir at that instant.

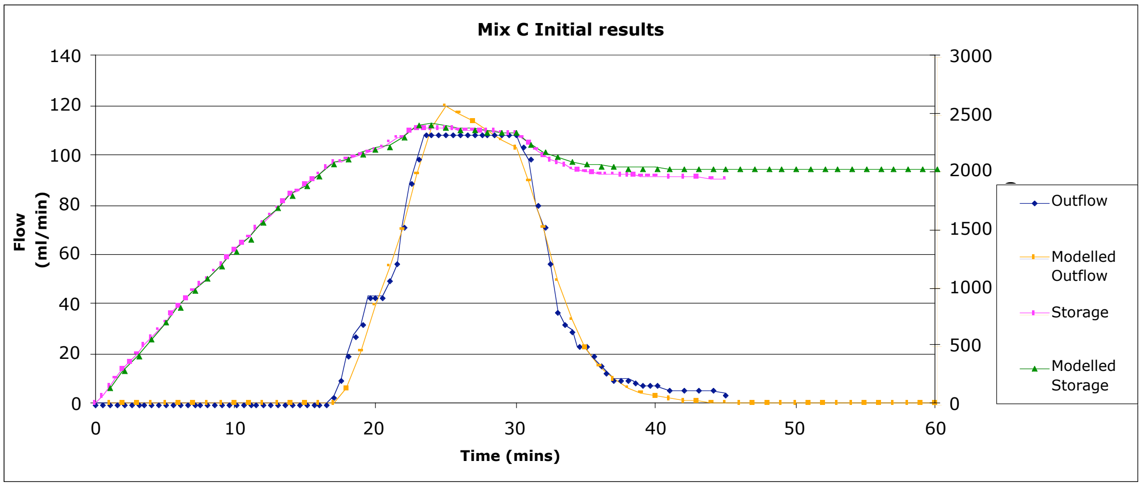

Figure 5.2 Output from the model contrasted with experimentally obtained data for a given rain event.

The calibration of mixture C (Figure 5.2) again reveals that the calibrated storage is not able to replicate the small decreases in storage subsequent to the rain event. The difference between the modelled and recorded figures is displayed in figure 5.3. While this difference is no more than 15ml during the first 20 minutes, when the storage in the box is increasing towards field capacity, during the next 10 minutes while box is almost in steady state, there are some major variations in storage (up to 35ml), but by t=30 the recorded and modelled figures are approximately the same. After this point, there is a marked increase in the difference between the two measurements which increases rapidly in the first three minutes and subsequently increases at a steadier, but reduced rate.

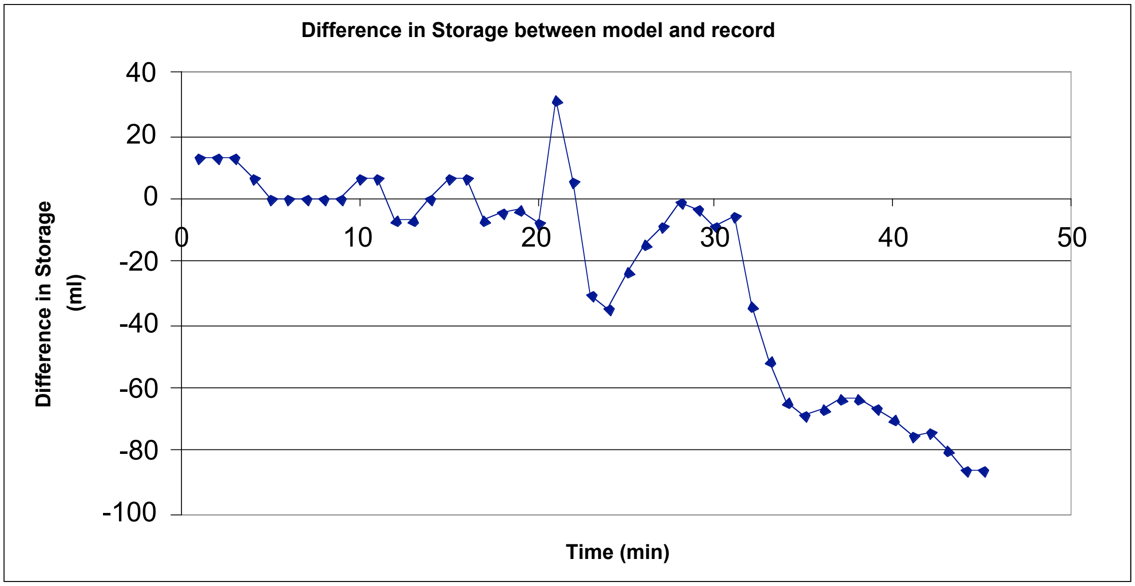

Figure 5.3 Difference in the storage predicted by the model and that observed during the experiment.

The calibrated outflow also estimates lower outflows than those recorded by the weir at low flow rates, another indication that the weir is recording anomalously high flow rates in these conditions.

One factor which is not replicated faithfully in this instance is the peak outflow during the storm. While the weir recorded a steady flow rate for a full eight minutes between t=23.5 and t=30.5, the model produces an increased peak at t=25, 10ml/min greater than the recorded flow. Subsequent to this, the modelled outflow decreases to a rate 6ml/min less than the recorded rate at t=30.

Using a model previously calibrated for Mix A, the calculated input for a double storm event was utilised to test the reliability of the model. In order for the model to predict the response of the boxes to certain inputs it must be also be supplied with information regarding the water in storage in the box prior to the rain event, namely the total volume of water contained within. Without further calibration, the predicted results largely match those recorded during experimentation (Figure 5.4). The initial storage is modelled extremely well, however, following each storm event the model retains more water than the actual boxes retained. The modelled outflows match those achieved by

experimentation in magnitude, but at present are offset by a time-lag of one minute in the later stages of the first storm and do not predict the high outflow at the beginning of the second storm. The modelled values are not dramatically different from the experimental results and could be seen to suitably predict the response of the brown-roof box.

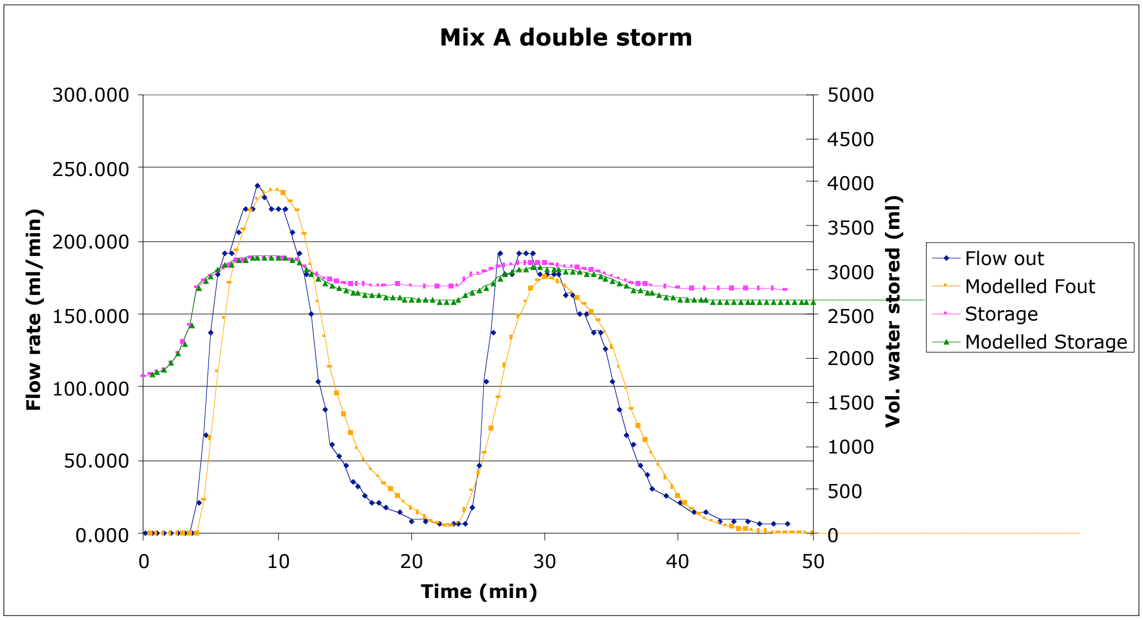

Figure 5.4 Modelled inflow and storage compared with that observed during experiment.

The calibration of the brown roof model reveals that it is able to accurately predict both the timings and magnitudes of the change in storage and outflow from the boxes over time, when supplied with input data for rain events. When supplied with data from real rain events the model should now be able to predict the response of the roof tiles to those particular circumstances.

5.4 Natural rainstorms

Sections of the rainfall data from storms recorded in Birmingham over the past six years were run through the model, to predict the response of the brown-roof tiles to future storm events.

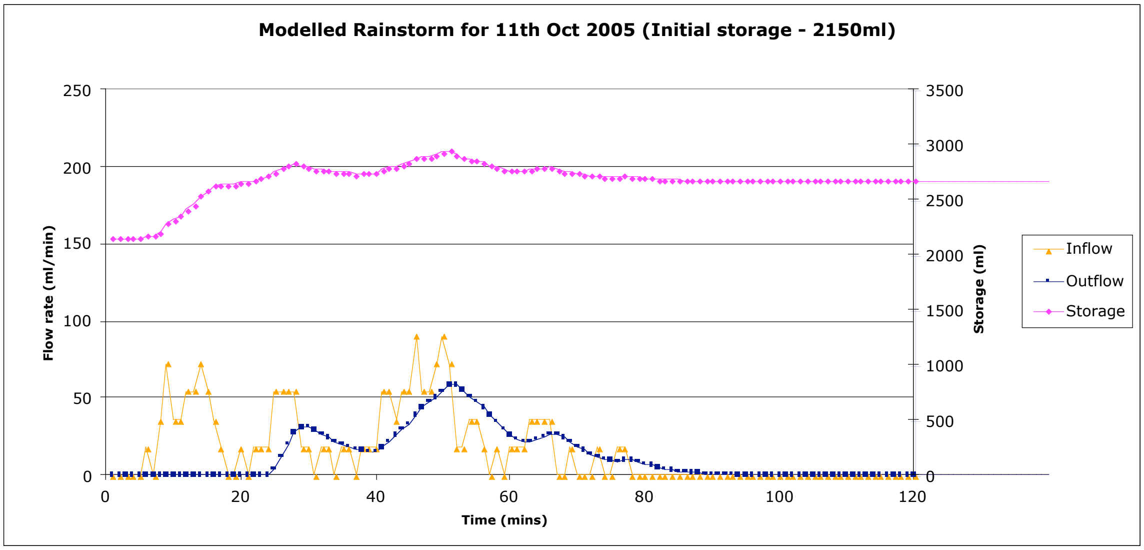

Figure 5.5 Modelled rainstorm using precipitation data from 11th October 2005 and initial storage of 2150ml.

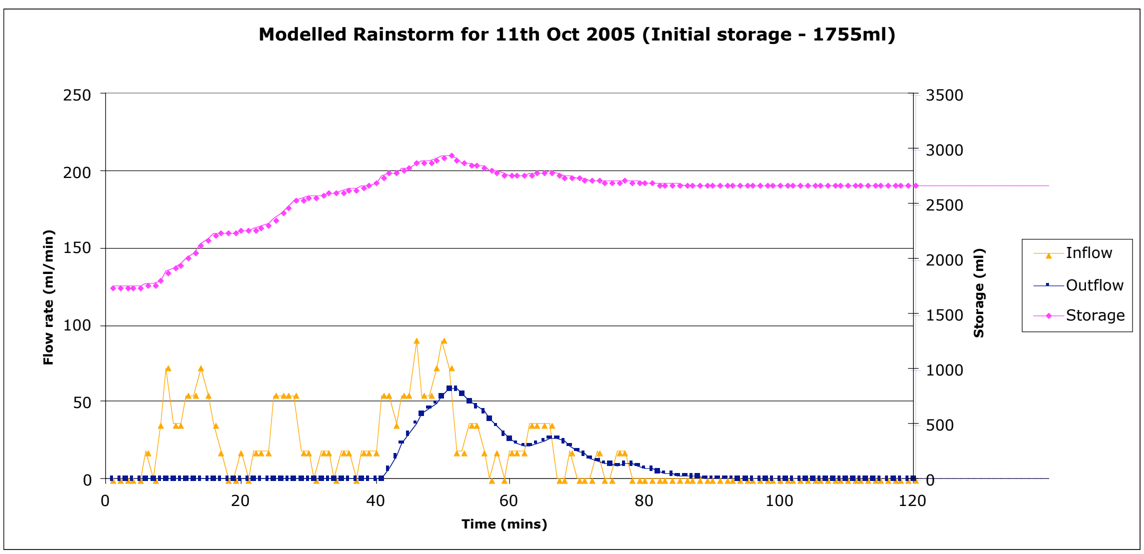

Figure 5.6 Modelled rainstorm using precipitation data from 11th October 2005 and initial storage of 1755ml.

A storm on 11th October 2005 produced 22.6mm of rain in 80 minutes, arriving in four distinct showers. This event was recreated in the model using various initial conditions for the brown-roof box (Figure 5.5, Figure 5.6). As can be seen from the results, the initial conditions in the box play an important role in the early stages of the storm,

however, during extended events, the same results are recreated during the latter stages of the storm.

In both scenarios depicted, there is a considerable time-lag between the onset of the rain event and the first outflow. In both cases the peak outflow is also reduced to 65% of the peak inflow. In the first scenario, total outflow from the system is 1520ml, while the total inflow is 2034ml, relating to retention of 25% of the precipitation. In the second scenario 1120ml of water is retained, a retention of 45%.

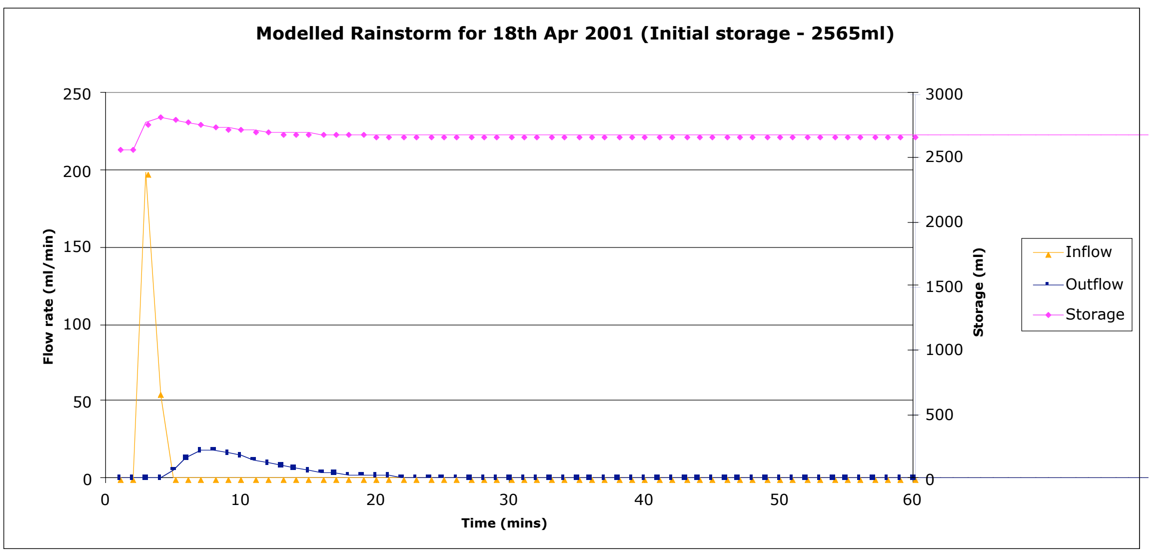

Figure 5.7 Modelled rainstorm using precipitation data from 18th April 2001 and initial storage of 2565ml.

Short and intense storms rarely produce outflow from the model unless the initial conditions are already very wet (Figure 5.7), in which case there must have been significant precipitation prior to the storm. In the 18th April example, peak outflow is 10% of the peak intensity.

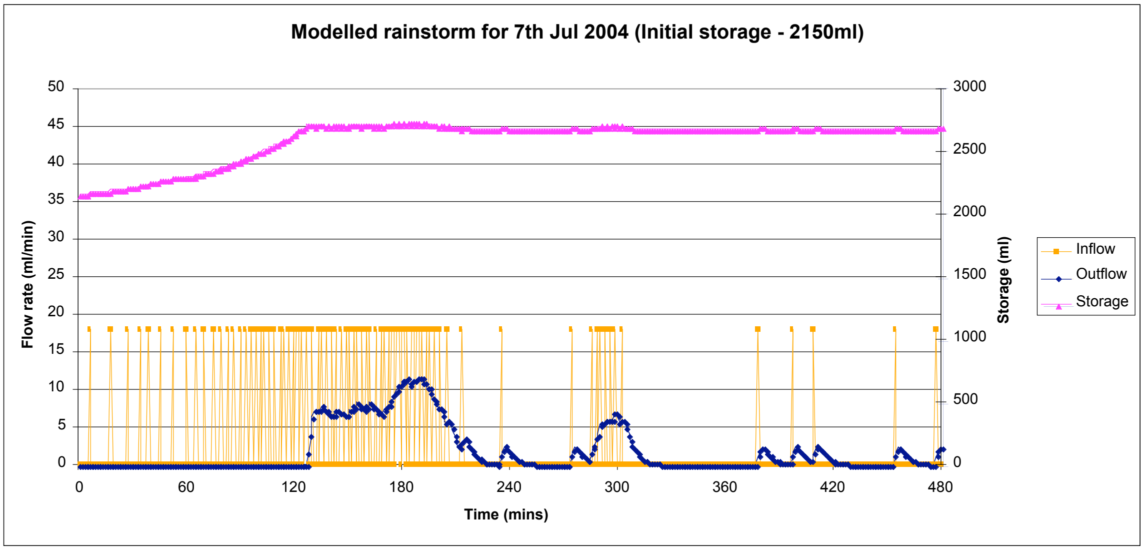

Figure 5.8 Modelled rainstorm using precipitation data from 7th July 2004 and initial storage of 2150ml.

Extended periods of very light rain may also result in outflow from the brown roofs (Figure 5.8). On 7th July 2004, 17.6mm of rain precipitated in just over 8 hours, at no more than 0.2mm/min. At this rate, the time taken for the box to reach field capacity may be as much as two hours or more, depending on initial conditions. Once field capacity is reached, the persistent rain keeps the box saturated at this level as long as the rainfall continues, with only minor outflow (<15ml/min) observed. The outflow rate never exceeds 56% of the inflow rate. Total input to the box is 1580ml rain. In the above example 930ml of outflow is recorded, corresponding to a total retention of 40%. This value will be highly dependant on the initial conditions of the brown roof.

5.5 Model Discussion

Although the model is simply implemented, it is a powerful tool for predicting the response of the brown-roof boxes to rain events. The model illustrates that the boxes function as linear reservoirs and confirms that a field capacity for each box must be overcome before flow is initiated and that this outflow is linearly related to the volume of water exceeding the field capacity.

As it proved difficult to separate the effects of evaporation from the general release of water by dripping from the box after each rain event, it was not possible to quantify these flows accurately and unfortunately this aspect of the hydraulics of the boxes has been omitted from the model. Due to this it is not possible to accurately predict the reaction of the boxes between rainfall events at present, but only predict the response to delineated storms.

The response of the model to real rainfall data suggests the brown-roof tiles will respond well to storm events outside the laboratory, predicting both reductions in peak discharges ranging from 10-65% and retention of rainfall of between 25 and 45%, dependant on the saturation state of the tiles at the beginning of the rainfall event.

6 Discussion

6.1 Experimental Results

The brown-roof box experiments provided important information on the functioning of the brown-roofs. The monitoring equipment recording inflow, outflow and storage was of great importance, allowing the calculation of the input to the boxes when the inflow meter proved unreliable. The rainfall simulator worked well, providing an even distribution of rain over the surface of the box without causing any to be lost to the outside. The flow rate out of the simulator was adjustable by limiting the amount of inflow it received from the tap, although this was hard to quantify given the inaccuracies of the in-line flow meter. The addition of marked outflow holes to the side of the simulator at heights corresponding to defined rainfall intensities would greatly improve the functionality of the simulator, but would require a method of channelling the excess water away.

From the experiments it has been confirmed that the boxes must hold a certain volume of water before outflow is initiated. This field capacity value was slightly different for the different mixtures of aggregate used in the boxes. The experiments also confirmed that outflow from the boxes is proportional to the volume of water in the aggregate which exceeds the field capacity. It is also found that the initial conditions of the storage in the aggregate are of prime importance to the response of the boxes to particular rain events.

It was not possible to accurately quantify the rate of decrease in storage during the periods between experiments from the data recorded and hence the action of the boxes when wet but under no rainfall has not been determined. In order to achieve this, the storage in the boxes would have to be recorded regularly over periods of up to at least seven days, possibly longer, while also monitoring the parameters which will affect evaporation from the boxes, namely air temperature, humidity, wind speed, etc.

6.2 Model

The brown-roof box model is a powerful tool for predicting the hydraulic response of the boxes to rain events. Given the correct initial conditions it can recreate the experimental results of a known rainfall event tolerably well with little to no difference in the magnitude of flows and storage and only minimal time lag between recorded and predicted outflows. This latter point may be due to the aeration layer reservoirs which were included in the model. These reservoirs were calibrated to work with certain experimental data, but may behave differently if the filter material is dry or wet at the onset of rain.

The model does not account for the change in storage between events, but it would not be difficult to incorporate this into the code. This would require additional inputs to the model including measurements of air temperature etc recorded concurrently with the other inputs, and further experimentation to quantify the relationships for the different mixtures.

Predictions of future events using the model suggest that the current design of the boxes will react well to storm events. Peak discharges during storms are reduced and often delayed by significant periods of time. The brown-roofs are also able to store large quantities of water which are retained after the event. The current predictions of peak reduction between 10 and 65% compare well with those for similar green roofs; however the retention of precipitation from these events (25-45%) is far less than that recorded with green roofs (45-85%), likely due to the lack of any vegetation in the boxes used for these experiments.

7 Conclusions

Brown roofs help to conserve habitats for both animal and plant species which make their homes in brown-field sites when these locations are re-developed. The roofs appear to share the same hydraulic benefits as green roofs, though without the same aesthetic appeal.

The brown roof boxes produced for these experiments were able to hold large volumes of water before any discharge was recorded. The field capacity of the boxes is related to the grain size distribution of the aggregate used and will also be affected by the depth of the material. Outflow from the boxes is proportional to the volume of water held in storage above the field capacity.

The brown-roof computer model ably predicts the response of the boxes to rain events when provided with correct initial conditions. The predictions of the response of the tiles to real rain events are positive. Peak discharges are reduced below the peak inflow intensity and water is retained in the aggregate and aeration layer cups after rain event. Using less material in the boxes or decreasing the sand content of the mixes is likely to reduce the field capacity of the boxes and will result in less retention and quicker and more intense discharge from the roofs.

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