MODELLING GREEN ROOF STORMWATER RESPONSE FOR DIFFERENT SOIL DEPTHS

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ABSTRACT

Green roofs have been proposed as a way to mitigate stormwater run-off in urban areas due to the possibility of retrofit to existing buildings. The amount of run-off is influenced by the, humidity, evapotranspiration, as well as soil type and depth. A modelling approach was undertaken to evaluate the response of different soil depths to cumulative rainfall and the efficiency in stormwater flow rate attenuation. The soil hydraulics were modelled using HYDRUS-1D software developed for modelling water flow in variably saturated porous media. Model runs were carried out for three quarterly scenarios to determine run-off peak flow rates and the overall retention, based on evapotranspiration rates of succulent plants and rainfall registers from Auckland, New Zealand. The soil depths modelled ranged from 5 to 160 cm. The results revealed, that the efficiencies in peak flow attenuation by the shallowest soil considered were reduced under extreme and longer rainfall events by 3%. Therefore shallow soil or extensive green roofs may, on a wide scale, overcome the performance of deep soils due to their lighter weight which adds limited loads to existing roof structures thereby making them suited to retrofit greater numbers of buildings.

Key words: Green roofs, Modelling, Stormwater run-off.

1 - INTRODUCTION

The increasingly rapid process of urbanisation has led to substantial changes in the permeability of land and the use of soil (Berndtsson, 2010). Green areas are being replaced by buildings, driveways and pavements; thereby changing the original permeable conditions, to impervious surfaces. Consequently, there has been a considerable increase in rainwater run-off, leading to the risk of floods and decreased groundwater recharge (Lamond et al, 2012).

A number of alternative options have been proposed to restore the hydrology of urban areas to their original state as much as possible. Examples include the maintenance of green areas and recovery or restoration of deforested areas, which help to attenuate the effects of stormwater discharges in urban areas (Wilkinson et al, 2014). The adoption of green roofs is posited as an alternative or complementary measure to cope with this problem (Berndtsson, 2010). Green roofs differ from other types of solutions, such as bio infiltration systems and constructed wetlands, as they are not limited by space availability, since they can be retrofitted to existing buildings, which according to Dunnett and Kingsbury (2004) represents about 40–50% of the impermeable surfaces in urban areas.

When compared to a conventional roof, green roofs change stormwater run-off by attenuating and delaying the peak flow of water (Berndtsson, 2010). Around sixty per cent of peak flows on a vegetated roof were delayed up to 10 minutes when compared to peak flows from conventional roofs, because a certain amount of water is buffered in the soil layer of green roofs (Berndtsson, 2010). Some of this water is drained, and part is retained according to soil field capacity (Berndtsson, 2010). The water retained is subsequently removed from the soil through the evapotranspiration process (Berndtsson, 2010).

Typically four different layers are found in green roof systems: vegetation; soil; a filter to avoid the loss of soil particles; and drainage material. These systems play a significant role in rainfall retention due to water uptake by plant roots and the soil. According to Hilten et al. (2008), green roofs retain stormwater and thus attenuate the peak flow rate compared to that from impervious surfaces. Many studies have evaluated the efficiency of green roofs in the reduction of total rainfall volume and flow rate (Monterruso et al., 2004; Mentens et al., 2006; Carter and Jackson, 2007; Van Woert et al., 2005; Hilten et al., 2008; Simmons et al., 2008; Palla et al., 2009; She & Pang, 2010; Voyde et al., 2010a; Buccola and Spolek, 2011; Nardini et al., 2012; Fassman-Beck et al., 2013; Yio et al., 2013; Wong and Jim, 2014). This efficiency varies from 40 to 90% according to the individual depths, types and moisture conditions of soil. However, those authors have not performed evaluations of stormwater response for a wide range of soil depths. As an example, Van Woert et al. (2005) considered three shallow soil substrates (2.5 cm, 4.0 cm and 6.0 cm), where the results did not vary significantly. Buccola and Spolek (2011) and Nardini et al. (2012) performed their studies based on two soil depths of 5 cm / 14 cm and 12 cm / 20 cm respectively. Fassman-Beck et al. (2013) and Yio et al. (2013) analysed four substrates with a maximum depth of 15 cm (5 cm, 7 cm, 10 cm and 15 cm), and Wong and Jim (2014) considered soil depths of 4 cm and 8 cm. It is important to highlight that all the studies cited above comprise mostly extensive systems and no depths beyond 20 cm were evaluated. Thus, the present work aimed to evaluate the influence of soil depth in runoff retention and peak attenuation, gathering in the same study, for the same soil substrate, a range of depths from 5 cm to 160 cm which comprises extensive and intensive green roof systems.

Depending on the soil depth, green roof systems can be classified either as intensive or extensive. According to studies compiled and performed by Berndtsson (2010) the intensive system is comprised of soil layers greater than 10 cm depth, and is thus able to support the growth of small plants to trees. However, it is heavier, requires more maintenance, and in most cases the building structure has to be designed to support this additional load. Extensive green roof systems, in contrast, comprise thinner layers of soil and lighter vegetation, and thus can be retrofitted to most existing buildings without additional strengthening. Although lighter than intensive systems, it is not expected that extensive roofs will perform better with regards to water retention capacity and flow rate attenuation. However, given that most existing buildings were not designed to support a substantial extra load, extensive green roof systems might be applied to a larger overall area, thus overcoming the higher efficiency of the intensive green roof system due its greater depth.

Previous studies show that green roofs can mitigate stormwater run-off (Berndtsson, 2010), however the extent of such mitigation depends on soil depth (intensive or extensive green roof system), moisture content, and rainfall distribution. Studies undertaken in Germany reported that intensive and extensive green roofs had annual run-off reductions equal to 65-85% and 27-81% of annual precipitation respectively (Mentens et al., 2006). These results are supported by additional studies cited in Berndtsson (2010). However, the exact values of the percentage reduction achieved must be viewed with caution due to the different conditions experienced in the different studies. Thus, in order to evaluate the influence of soil depth in the mitigation of stormwater run-off, under same soil type and variable meteorological conditions, a modelling procedure is employed, to reduce potential experimental discrepancies, such as variations in soil structure, and setup imprecision.

Numerical models have been developed to assess the hydrologic performance of green roofs in terms of total volume and flow peak reduction, such as EPA's Storm Water Management Model (SWMM), SWMS-2D (Šimůnek et al., 1994), Hydrus-1D (Šimůnek et al., 2013) among others. SWMM is a dynamic rainfall-runoff simulation model used for simulation of runoff quantity and quality from primarily urban areas. SWMS-2 and Hydrus-1D numerically solve Richards' equation in order to simulate water flow in variably saturated porous media. Hydrus-1D was adopted in this work for one–dimensional modelling of soil water transport considering different soil depths. This is a public domain, Windows-based modelling software, with an interactive graphics interface for data, pre- and post- processing. Additionally, this software has been used in other green roof applications performed to date (see Yang et al. 2015; Hakimdavar et al. 2014; Liu & Fassman-Beck 2014; Palla et al. 2012; Hilten et al. 2008 and Hilten & Lawrence 2008).

This study consists of an evaluation of stormwater run-off attenuation by green roofs predicated on modelling techniques and rainfall registers from Auckland, New Zealand. Soil depths of 5 cm, 10 cm, 20 cm, 40 cm, 80 cm and 160 cm, planted with succulent Sedum species are considered in the modelling. Besides being common in many parts of the world, succulent Sedum species tend to be low growing plants that provide good soil coverage (Voyde et al., 2010b). They require low maintenance due to their resistance to drought, temperature, solar radiation, rainfall and wind. Furthermore, succulent Sedum species grow rapidly, are lightweight, shallow rooting, and have low fire risk. Succulents store carbon dioxide in their tissue, and this allows the plants to close stomata during the day to conserve water, and open stomata at night, to absorb carbon dioxide under cooler temperatures. As a result of this characteristic, succulents can survive under drought conditions (Voyde et al., 2010 a); a characteristic that makes them attractive in countries where rainfall can be variable, such as Australia and Brazil.

2 – **METHODS**

2.1 - Model overview

The version of HYDRUS used in this research is HYDRUS-1D, version 4.16 (Šimůnek et al., 2013). HYDRUS-1D is a numerical simulation program for one-dimensional soil moisture fluxes in a soil column of unit area. This programme numerically solves the Richards equation for variably saturated water flow and advection-dispersion type equations for heat and solute transport.

In HYDRUS-1D, a soil column of chosen depth, which its geometric characteristics, and hydraulic parameters are specified by the user, is discretised into elements. Time simulation, time steps range and iteration limits, head pressure and water content tolerances are set also as model parameters. Initial and boundary conditions are based on terms of pressure head or water content, sources and sinks. Whenever included in the modelling, sources and sinks such as precipitation and evapotranspiration fluxes, can be considered constant or inputed as a time data sequence. Šimůnek et al. (2013) presents a complete description of the model.

2.2 - **Governing equations**

A modified form of the Richards equation, using the assumptions that the air phase does not play a significant role in the liquid flow process and that water flow due to thermal gradients can be neglected, describes the water movement through the soil on the green roofs. This equation relates change in soil moisture content over time to hydraulic conductivity and pressure head.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] \qquad \text{(Equation 1)}$$

Where θ is the volumetric water content [L^3L^{-3}]; t is time [T]; h is the pressure head [L]; z is the vertical coordinate [L]; and K is the unsaturated hydraulic conductivity function [LT^{-1}], described on equation 3.

In order to obtain a predictive equation for the unsaturated hydraulic conductivity function in terms of soil retention parameters, the present work considers the soil-hydraulic functions of van Genuchten (1980) based on the statistical pore-size distribution model of Mualem (1976).

The van Genuchten (1980) relationships are given by:

$$\theta(h) = \begin{cases} \theta_s & h \geq 0 \\ \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha h)^n]^m} & h < 0 \end{cases} \qquad \text{(Equation 2)}$$

$$K = K_s \sqrt{S_e} \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad \text{(Equation 3)}$$

Where θ_s and θ_r are the saturated and residual water content [L^3L^{-3}]; K_s is the saturated hydraulic conductivity [LT^{-1}]; $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$ is the effective saturation; n, $m=1-1/n$ are dimensionless parameters and α is an empirical soil parameter [L^{-1}].

2.3 – Modelling parameters

All soil depths modelled were discretised into 100 elements. A sandy loam soil was chosen due to its good drainage capacity; a requirement for succulent species development. In its internal data bank HYDRUS-1D provides properties of different soil types. However, the soil hydraulic parameters used in the present study according to Rawls and Brakensiek (1982) work, are as follows: saturated soil water content (θ_S) is 0.453; residual water content (θ_r) is 0.041; van Genuchten parameter (n) is 1,322; van Genuchten parameter (α) is 0.068 cm^{-1}; and the saturated hydraulic conductivity is Ks = 4.42 cm/h.

The selection of the soil parameters was based on work by Braun and Schadler (2005), where the combinations of different soil hydraulic functions (Brooks and Corey, 1964; Campbell, 1974; van Genuchten, 1980) and different soil parameters (Clapp and Hornberger, 1978; Rawls and Brakensiek, 1982; Carsell and Parrish, 1988) were compared. According to Braun and Schadler (2005) the best results, compared with observational data, are observed when van Genuchten (1980) hydraulic functions and Rawls and Brakensiek (1982) soil parameters are used together.

The precipitation data comprise five years of rainfall records (2008-2012) from Redvale Auckland, New Zealand freely available for public use, and provided by Block Busters NZ (http://www.blockbusters.co.nz/). From this data, three quarterly rainfall scenarios were selected in order to evaluate the green roofs stormwater attenuation response (Table 1).

Table 1 – Description of the rainfall scenarios

Scenario	Period (day/mm/yyyy)	Number of days	Rainy days (>0.5mm)	Cumulative precipitation (mm)/ period	Highest precipitation (mm) / day
1	01/06/2008 – 26/08/2008	87	60	665.6	59

2	01/05/2010 – 27/07/2010	88	47	554.6	114
3	01/07/2012 – 26/09/2012	88	67	512.2	87

In terms of a stormwater management perspective, it was not intended to evaluate a seasonal variability in rainfall patterns, but to present three quarterly scenarios that depict critical rainfall conditions of highest accumulated rainfall volume (Scenario 1: June to August 2008 - 665.6 mm); highest rainfall depth (Scenario 2: May to July 2010 - 114 mm) and highest number of rain events (Scenario 3: July to September 2012 - 67 days). With the exception of scenario 2, that starts in the middle of the Autumn, scenarios 1 and 3 comprise mostly New Zealand (Auckland) winter (southern hemisphere) conditions that characterise the wettest season, though having regular rainfall distribution through the year. This allows the researchers to evaluate green roof performance with regards to mitigation of stormwater run-off, based on real conditions where the effects of subsequent rainfall events can be considered.

Water content values at each element in soil column were set as initial conditions and assumed a constant water content over the soil depth. In order to simulate initial dry conditions, it was supposed to be equal to residual water content (θ_r).

The evapotranspiration (ET) rates were estimated based on the work of Voyde et al. (2010b), who determined experimentally daily and hourly evapotranspiration rates of Sedum species for New Zealand green roofs. According to these authors, evapotranspiration has a great relevance for stormwater management, since it is the mechanism by which retention capacity is recovered by the system between storm events. In other words, it is the process of water transfer from the soil to the atmosphere.

According to Berghage at al. (2007), with regards to drought resistant plants, it has been hypothesised that by conserving water, succulents would provide relatively little storage recovery via transpiration when compared to evaporation from bare soil. However, Berghage at al. (2007) stated that these plants provided up to 40% of the total stormwater retention response, as they use water rapidly when it is available and then conserve it under stressed conditions. In other words, the transpiration has a relevant role in ET under well-watered soil conditions, and when the water supply is limited, plants stop transpiring and the evapotranspiration and evaporation levels become similar. Additional studies performed by Rezaei and Jarrett (2006) indicated that, depending on the seasonal condition, planted plots transferred from 34% (winter) to 51% (summer) more water via ET when compared to bare soil.

In order to quantify the ET rates, Voyde et al. (2010b) presented an empirical regression model, based on correlation between measured ET rates and rainfall data. These authors established, according to equation 5, that ET decays exponentially over time (in days) after it reaches its' maximum levels during wet soil conditions (rainfall events).

$$ET = 3.0544\, e^{-0.0861t} \qquad \text{(Equation 5)}$$

Where, ET is the evapotranspiration rate in mm/day, and t is time in days after a rainfall event.

However, according to Voyde et al. (2010b), maximum evapotranspiration rates are re-established under well-watered soil conditions, which happen with rainfall events greater than or equal to 10 mm/day. Thus, the efficiency of green roofs in stormwater retention strongly depends on the frequency and the volume of rainfall. Additional investigation of the relationship between ET rates and temperature, soil moisture and relativity humidity would provide a more mechanistic approach to ET estimation. Nevertheless, Equation 5 provides a simple and practical tool for estimating daily ET.

All parameters described in this section provided the basis for the modelling results. From the soil hydraulics perspective, these parameters play a fundamental role in the water balance calculation for green roofs. With regards to the stormwater retention capacity, soil water storage is regulated by the difference between inflows (rainfall) and outflows (run-off and ET) in the soil element. However, the relation between run-off and rainfall rates is the key factor in determining the efficiency of green roofs and is presented in the following section.

3- RESULTS AND DISCUSSION

The outflow and retention green roof performance for three rainfall scenarios are evaluated for urban drainage purposes. Sets for cumulative rainfall and run-off, and the efficiency (%) in rainfall peaks attenuation are compared graphically through an individual model run according to the different soil depths analysed.

The following results show the cumulative rainfall and cumulative run-off according to soil depth, and the green roofs' efficiency in rainfall peaks attenuation for the three different rainfall scenarios, for soil depths of 5 cm, 10 cm, 20 cm and 40 cm, herein denominated as Green Roof 5, 10, 20 and 40 cm respectively. Besides the evidence of higher efficiency for the higher depths considered (80 cm and 160 cm) the overlap between green roof run-off and rainfall peaks make their individual association difficult.

The results comprise one figure for each scenario and are divided in two parts. The cumulative rainfall and soil run-off for each of the soil depths (5 cm to 160 cm) is represented in the lower part, and the efficiencies in rainfall peaks attenuation for soil depths of 5 cm, 10 cm, 20 cm and 40 cm, as well as rainfall depths (mm) are expressed graphically on the upper part. It is important to note that the percentage efficiency represented in the column bars of the graphs, refers to peaks of successive rainfall only, and not to individual rain events.

The efficiencies in overall stormwater retention were determined through the relationship between the cumulative run-off curves and the cumulative rainfall volume. For each scenario, the average of the efficiencies observed in the rainfall peak attenuation is presented.

3.1 - Scenario 1

Figure 1 evaluates the green roof’s response to well-watered soil conditions between June and August 2008, where during sixty rainfall events a total amount of approximately 666 mm was reached.

The overall stormwater retention efficiencies were 26%, 27%, 29%, 33%, 40% and 54% according to soil depths of 5 cm, 10 cm, 20 cm, 40 cm, 80 cm, and 160 cm respectively. As expected, efficiencies increased with soil depth.

Regarding the efficiency in rainfall peaks attenuation, Green Roof 5 cm presented an average of 38%. The lowest efficiency observed of 5% for the highest rainfall event (59 mm - 30/07) is correlated to the highest levels of rainfall in the period of the simulation. No soil outflow was observed (100% efficiency) to low rainfall peak events (4 mm). Green Roof 10 cm, besides having a slight higher average efficiency of 43% in comparison to Green Roof 5 cm, presented a similar efficiency (6%) to the highest rainfall event. An overall retention (no outflow) was observed for Green Roof 10 cm to 5 mm rainfall events.

Green Roof 20 cm presented an average efficiency of 53%, performed better than the observed average efficiency for Green Roof 5 cm and Green Roof 10 cm. Although the overall retention (100% efficiency) was the same when compared to Green Roof 10 cm, the efficiency to the highest rainfall peak event (59 mm) increased slightly to 7%. Green Roof 40 cm increased even more the average efficiency in rainfall peak attenuation to 66%, demonstrating that it does not follow a linear relationship with soil depth. There was no soil outflow from, rain events lower than 10 mm, and the lowest efficiency observed was 11%.

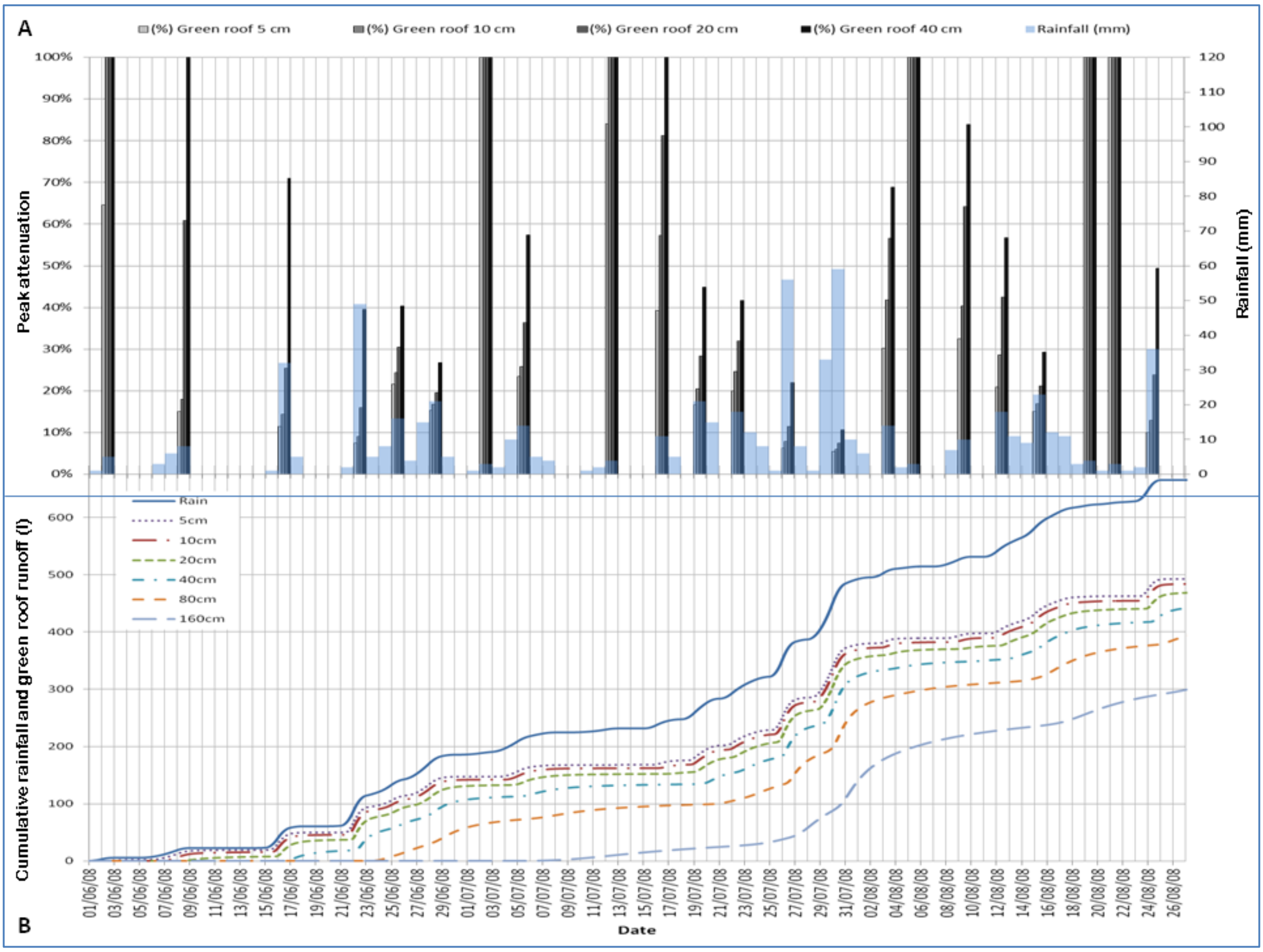

Figure 1 – Scenario 1: (a) Green roofs efficiency in rainfall peaks attenuation for 5 cm, 10 cm, 20 cm and 40 cm-thick soil. (b) Cumulative rainfall and soil run-off for each one of the soil depths (5 cm to 160 cm).

3.2 - Scenario 2

Figure 2 considers the response to an extreme rainfall event (114 mm), preceded by a dry period and followed by lower rainfall occurrences, during a quarterly period between May and July 2010.

The overall stormwater retention efficiencies were 26%, 27%, 30%, 35%, 44% and 62% according to soil depths of 5 cm, 10 cm, 20 cm, 40 cm, 80 cm, and 160 cm respectively.

Green Roof 5 cm presented 43% average rainfall peak attenuation efficiency in rainfall peaks attenuation of 43%. The lowest efficiencies observed to the highest rain event of 114 mm (21/05) was 3%, and no outflow of water from the soil (soil water outflow) was observed (100% efficiency) during rainfall peak events of up to 4 mm. Green Roof 10 cm was able to promote an overall retention (no soil water outflow) up to 6 mm rain events. The average efficiency and lowest efficiency for the highest rainfall events were 51% and 4%, respectively. Green Roof 20 cm had an average efficiency of 60%. No soil outflow occurred up to a 7 mm rainfall event, and the lowest efficiency was 5%. Green Roof 40 cm had its average efficiency increased to 69%. Soil outflow was not observed up to 8 mm rainfall, and for the highest rainfall event (114 mm) the efficiency reached 15%.

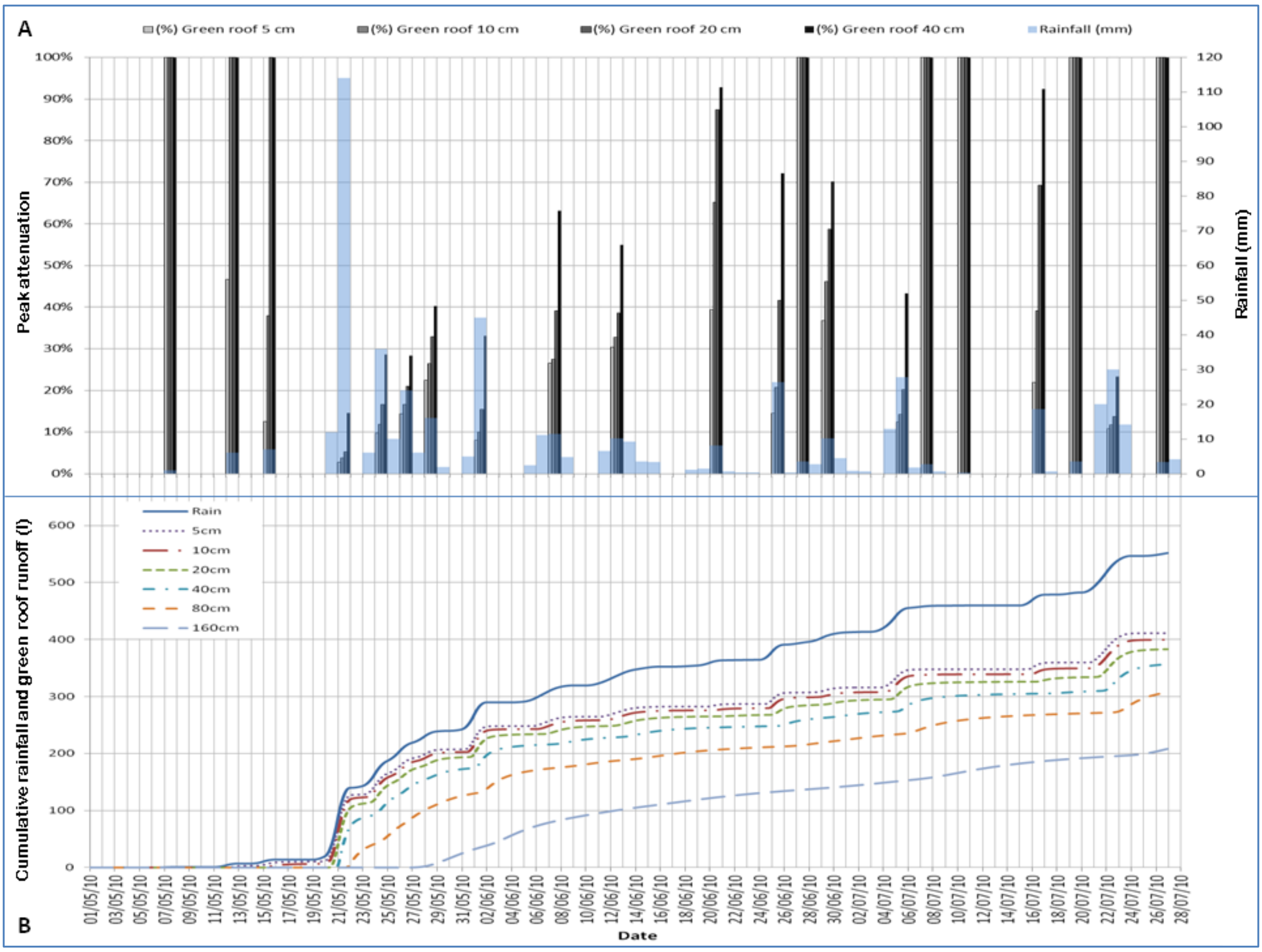

Figure 2 – Scenario 2: (a) Green roofs efficiency in rainfall peaks attenuation for 5 cm, 10 cm, 20 cm and 40 cm-thick soil. (b) Cumulative rainfall and soil run-off for each one of the soil depths (5 cm to 160 cm).

3.3 - Scenario 3

Figure 3, assesses the response to the greatest number of rain events (67) and the least amount of total precipitation (512 mm) during a quarterly period between July and September 2012.

The overall stormwater retention efficiencies were 32%, 34%, 37%, 41%, 49% and 65% according to soil depths of 5 cm, 10 cm, 20 cm, 40 cm, 80 cm, and 160 cm respectively.

It was observed for Green Roof 5 cm an average efficiency of 49% in rainfall peak attenuation, a total retention (no outflow) to rainfall events up to 6 mm, and an efficiency of 4% to the highest rainfall event (87 mm – 03/09). Green Roof 10 cm had its average and the lowest efficiencies increased to 54% and 5% respectively. However, similar to Green Roof 5 cm, it also presented total retention (no soil outflow) to rainfall events up to 6 mm. Green Roof 20 cm, in spite of showing the same response to total retention, presented the average and the lowest efficiencies equivalent to 63% and 7%. Green Roof 40 cm increased even more the average and the lowest efficiencies to 74% and 19%. Additionally this soil depth showed overall flow retention performance considerably better than the previous ones, being able to promote soil outflow retention up to 18 mm rainfall.

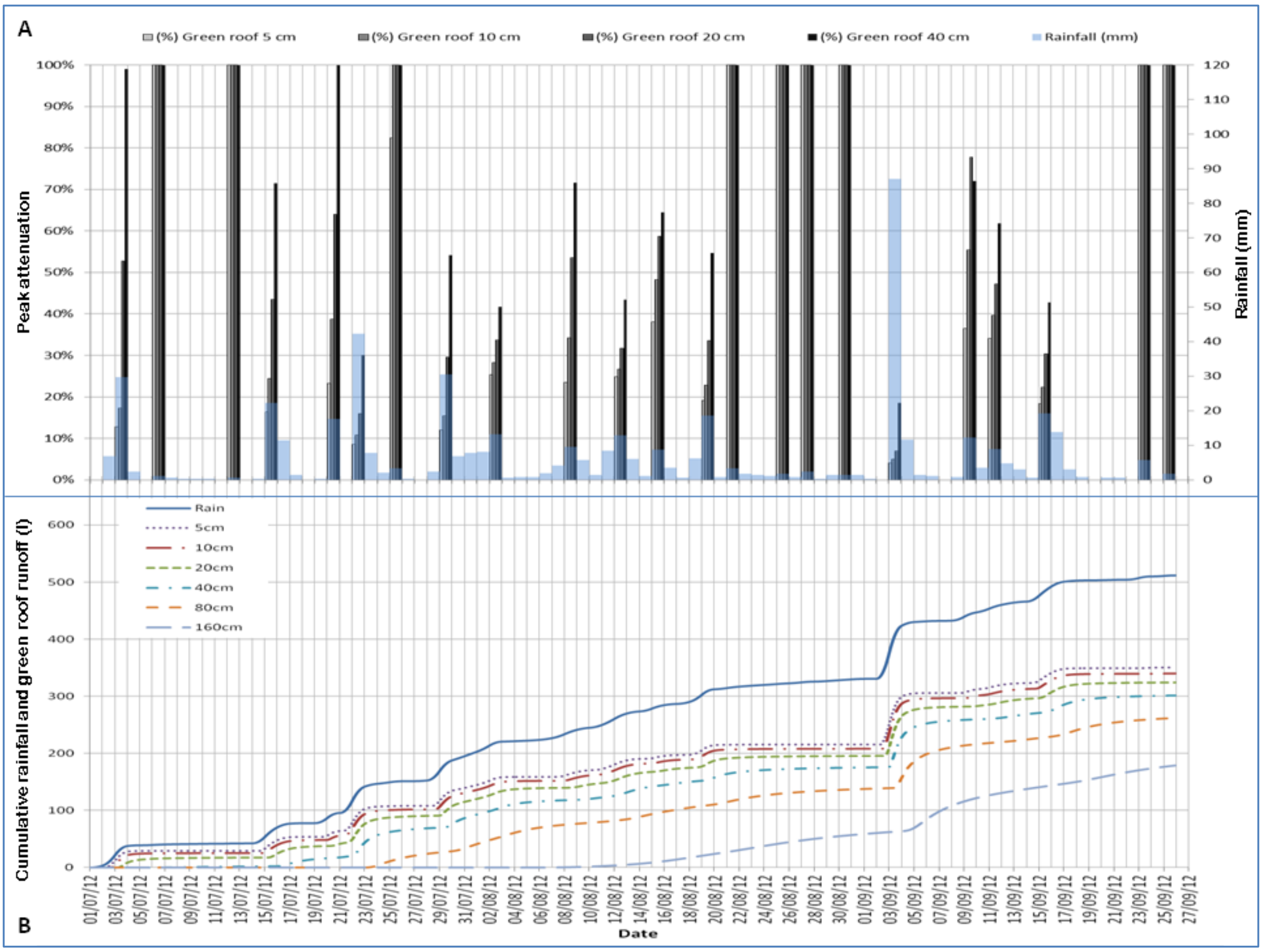

Figure 3 – Scenario 3: (a) Green roofs efficiency in rainfall peaks attenuation for 5 cm, 10 cm, 20 cm and 40 cm-thick soil. (b) Cumulative rainfall and soil run-off for each one of the soil depth (5 cm to 160 cm).

3.4 - Results overview / Discussion

A comparison among the percentage efficiencies according to scenarios is summarized in Table 2. In general, the stormwater retention and rainfall peak attenuation varied proportionally with soil depth and inversely to the total rainfall.

Table 2 – Green roofs stormwater retention efficiencies (%) in relation to total rainfall

Scenario/Total rainfall (mm)	Soil depth					
	5 cm	10 cm	20 cm	40 cm	80 cm	160 cm
1 – (665.6mm)	26%	27%	29%	33%	40%	54%
2 – (552.2mm)	26%	27%	30%	35%	44%	62%
3 – (512.2mm)	32%	34%	37%	41%	49%	65%
Average	**28%**	**29%**	**32%**	**36%**	**44%**	**60%**

The lowest retention capacity (26%) was observed for the shallowest soil and for the highest level of precipitation, whereas the highest retention capacity (65%) followed an inverse order in terms of soil depth and the amount of precipitation. Soil depths of 5 cm and 10 cm presented fairly similar efficiencies, which represent about half of the retention capacity of 160 cm soil depth. The stormwater retention capacity increased with the soil depth according to a linear pattern, and for the same soil depth the efficiencies reduced with the amount of total rainfall.

Table 3 presents an evaluation of green roof efficiency on rainfall peak attenuation according to soil depths from 5 cm to 40 cm.

Regarding to the average efficiencies it was observed the lowest one (38%) for Green Roof 5 cm during the wettest scenario (scenario 1), and the highest one (74%) was observed for Green Roof 40 cm under lower precipitation levels. For the all soil depths tested, it was found that the efficiencies reduce as precipitation levels increase (Scenario 1 to 3).

Table 3 – Rainfall peaks attenuation according to soil depth.

Green Roof (cm)	Scenario 1 (total rainfall – 665.6mm)		Scenario 2 (total rainfall – 552.2mm)		Scenario 3 (total rainfall – 512.2mm)	
	Lowest efficiency % (Max. rainfall – 59 mm)	Average efficiency (%)	Lowest efficiency % (Max. rainfall – 114 mm)	Average efficiency (%)	Lowest efficiency % (Max. rainfall – 87 mm)	Average efficiency (%)
5	5	38	3	43	4	49
10	6	43	4	51	5	54
20	7	53	5	60	7	63
40	11	66	15	69	19	74

As far as rainfall peaks attenuation is concerned, these efficiencies also vary according to a linear pattern with soil depth, and inversely proportional to the amount of total rainfall.

The lowest efficiency (3%) occurred to the highest rainfall depth (114 mm) and to the shallowest soil tested (Green Roof 5 cm). Comparing each one of the scenarios for the same soil depth, scenario 2 presented the lowest efficiencies observed, with exception of Green Roof 40 cm which had its lowest efficiency in scenario 1. This might be attributed to the overlap of soil outflow due to previous rainfall events in deeper soils. Although Green Roof 40 cm presented a performance relatively higher in relation to the first three soil depths evaluated, no considerable differences amongst the shallower soils (5 cm, 10 cm and 20 cm) were observed.

Previous soil moisture conditions have a relevant role in peak flow attenuation since, wetter soils can store less water and because hydraulic conductivity increases with soil moisture content. The following figure shows this effect for each scenario.

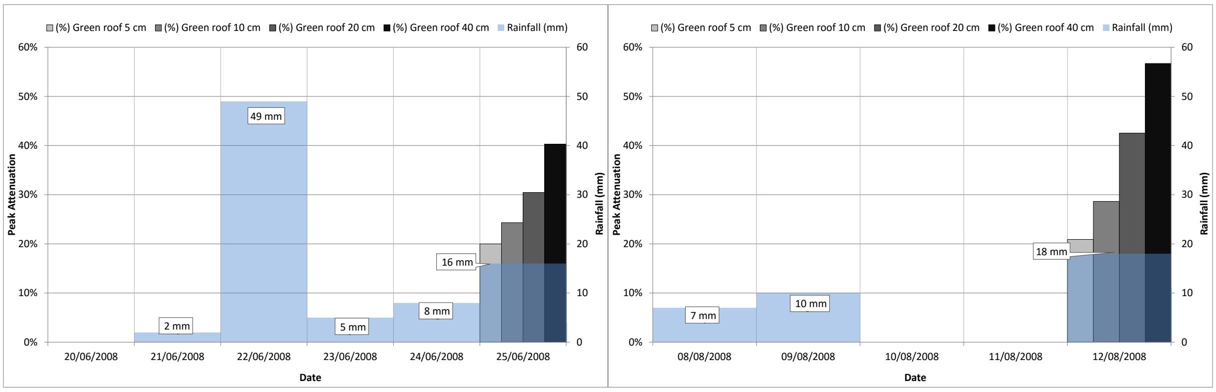

Figure 4 - Influence of previous soil moisture conditions in peak flow attenuation - Scenario 1.

As shown in figure 4 for scenario 1, even under a slightly lower amount of precipitation, is observed on June 25, due to higher rainfall volume in the four preceding days, a peak flow attenuation lower than the one observed on August 12. The same tendency is also evident for scenario 2 (figure 5), where the four dry days prior to June 25 provide a higher peak attenuation when compared to a lower rainfall amount occurred on May 26.

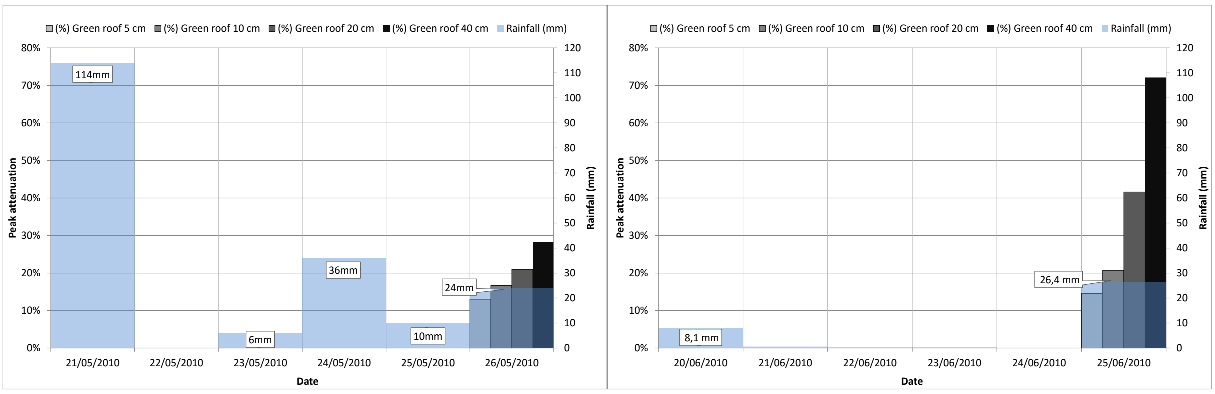

Figure 5 - Influence of previous soil moisture conditions in peak flow attenuation - Scenario 2.

For scenario 3 (figure 6), even having a slightly higher rainfall depth, the lower peak attenuation efficiencies on July 29 cannot be attributed to this fact, but to only one rainfall event prior to July 3, whose volume is much lower than the accumulated up to July 29.

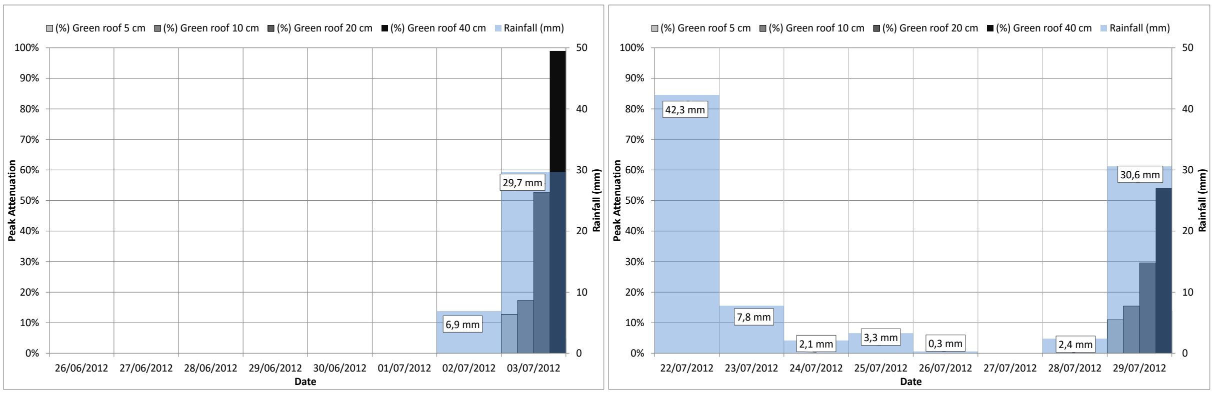

Figure 6 - Influence of previous soil moisture conditions in peak flow attenuation - Scenario 3.

Similarly to observed in Voyde et al. (2010a), the efficiencies in stormwater retention varied according to the period of the study. However, the efficiencies observed by these authors in field experiments for soil depths, varying between 5 cm and 7 cm, are significantly higher than the observed in the presented study. It is important to highlight that modelling does not consider all existing water retention, that happens in experimental procedures with elements such as: filter fabric; water retention mat; plastic retention cups, the area of drainage holes, as well as substrate components with water capacity retention, such as: pumice; coconut coir; or composted bark fines.

Simmons at al. (2008) evaluated the stormwater retention performance for three individual rainfall events of 10 cm soil depth for different green roof designs, considering, among other factors, the existence of a water retention mat, retention cup capacity, and the drainage hole area in the retention layer. Basically, under experimental conditions such as: a larger drainage hole area; lower retention cup capacity; and no existence of a water retention mat, an average efficiency of 17% was found, which is lower than the average of 29% observed in table 2 for same soil depth. However, it is important to emphasise that the results from Simmons et al. (2008) are from rainfall events of higher intensity than the existing in the modelled simulations.

Spolek (2008) evaluated the stormwater retention of three large green roofs portions (280–500 m^2) located on two different buildings in Portland, Oregon, U.S.A. For the green roof with a soil depth of 15 cm, planted with Sedum species, an average of 25 % was observed, which is lower than the modelled results presented herein.

The study presented herein comprises a theoretical approach, where the main objective was to evaluate the trend in stormwater response exclusively for different soil depths, but under identical composition / structure conditions. This would not be replicated easily in real/experimental conditions due to natural variations in soil composition, structure, compaction and moisture levels. All results present a conservative perspective, since modelling does not consider all existing water retention, that happens in experimental procedures elements such as: filter fabric; water retention mat; plastic retention cups, drainage holes area, as well as substrate components with water capacity retention. Compared to experimental measurements performed in New Zealand (Voyde et al., 2010a. Fassman-Beck, 2013), the modelling results show a lower efficiency for both rainfall retention and peak flow attenuation. It is most likely that this can be attributed to additional features included in the green roof design to enhance stormwater retention performance, such as drainage boards, mats with cups designed to store water, moisture retention mats, substrate layers with contrasting textures, absorption of the roof/slab surface, and the distance to the downpipe rainwater outlets.

For instance, in the present work, the effects of the green roof in rainfall retention and peak attenuation are compared directly to the amount of precipitation and do not consider any additional loss or absorption. According to the work performed by Mentens et al. (2006), even in a non-green roof surface the runoff is not equivalent to the total precipitation, showing an average retention of 19% for non-green roofs that must be due to mortar absorption and water puddle formation. From the results presented in table 2, the stormwater retention for a 10 cm soil depth, which lies in the range of extensive green roofs illustrated in Mentens et al. (2006), is about 29%, which means a runoff of 71% of total rainfall. As aforementioned, applying to this runoff, an additional retention of 19% for non-green roofs, the actual runoff would be about 57%; slightly higher than the average of 50% observed by Mentens et al. (2006).

Extra loads applied per square metre to an existing structure is related to soil type and depth. Considering a typical sandy loam soil with dry density of 1,600 kg/m^3, a saturated density of about 2,000 kg/m^3 that comprises the extreme load situation is estimated. Based on this assumption, it is expected that a load limit of 100 and 3200 kg/m^2 is applied for soil depths from 5 cm to 160 cm, respectively. According to Liu (2011), as the design load of existing roofs varies between 50 and 200 kg/m^2, it is expected that green roof soil up to 10 cm depth will not require a structural upgrade. However, the use of lightweight substrate material with such as expanded clay, and pumice with slightly higher substrate depths may reproduce the same loads of single soil component. As an example, cited by Peck and Kuhn (2003), the green roof on the new library in Vancouver, British Columbia, Canada is about 36 cm depth, weighs 293 kg/m^2 under saturated conditions, and based on the British Columbia Building Code does not require a structural upgrade. Comparatively, the same depth of saturated sandy loam soil weighs 720 kg/m^2.

Where rainfall peak attenuation is concerned, according to green roof coverage, it is expected that the percentage of green roof coverage offsets the differences between soil depths. As far as the stormwater management perspective is concerned, shallower soils when applied in larger areas can have same efficiencies of deeper soil layers. For instance, figure 7 shows for scenario 1 the rainfall peak attenuation with the percentage of area covered, for green roofs' soil depths from 5 cm to 40 cm. Considering the efficiencies presented in table 3, a coverage of 60% would produce, for Green Roof 5 cm, 10 cm, 20 cm and 40 cm, an attenuation of 23%, 26%, 32% and 40% respectively. In other words, one can say that a 100% coverage of 5 cm soil depth would be equivalent to 88%, 72% and 57% coverage of 10 cm, 20 cm and 40 cm soil depth respectively. It is important to highlight that, for the same soil substrate, compared to a 5cm depth, which weighs about 100 kg per m^2, the load applied by 40 cm soil depth to an existing structure is eight times heavier, i.e., under water saturated conditions it is equivalent to 800 kg/m2. As aforementioned, this level of loading overcomes the design load of existing roofs, requiring a structural upgrade. Thus, the better capability in rainfall peak attenuation, does not guarantee that deeper soils comprise the most effective solution.

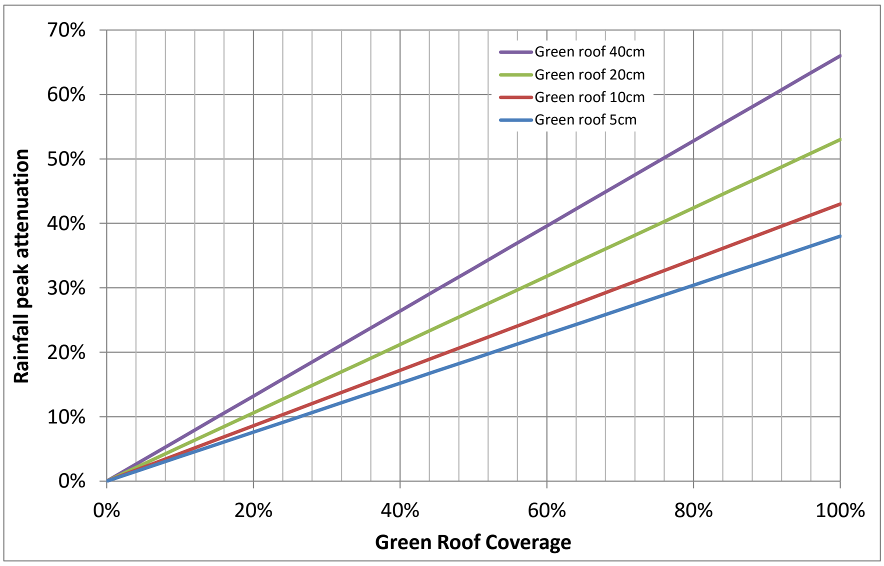

Figure 7 - Relation between rainfall peak attenuation and covered area (%) with green roofs.

4- CONCLUSIONS

From a conservative perspective, the more unfavorable conditions are based on high antecedent soil moisture conditions before extreme rain events. In these cases, the green roof's water retention capacity is diminished and efficiency in the rain flow peak attenuation is severely reduced.

The efficiency in reducing the peak flow rate of stormwater discharges increased proportionally to the soil depth according to a linear tendency, and showed dependency on previous soil moisture conditions. For all soil depths tested, the higher the intensity and duration of the rainfall event, the lower is the efficiency in reducing stormwater discharges. Under extreme rainfall events the lowest efficiencies did not vary significantly for the first three soil depths tested (5 cm, 10 cm and 20 cm).

Similarly, the cumulative run-off was shown to be sensitive to rainfall intensity, resulting in higher slopes in run-off curves during high precipitation levels. However, these slopes were less pronounced in deep soil. It is also noted that more similarities were found between cumulative rainfall volume and the cumulative run-off curves from shallow soils. During peak rainfall events, for soil depths from 5 cm to 40 cm, the cumulative run-off and rainfall curves exhibit quite similar slopes, which corroborate the lowest efficiencies observed in rainfall peak attenuation for intense precipitations.

The results presented herein are reasonably consistent with those observed in Mentens et al., (2006), Hilten et al., (2008), Simmons et al., (2008) and Berndtsson, (2010), as well as many authors cited in this paper, in regard to the inverse relationship between rainfall depth and the efficiencies in rainfall retention and peak attenuation. Hilten et al. (2008) evaluated the rainfall retention and peak flow attenuation for five simulated rainfall depths. Storms were simulated as independent events, and no soil moisture background from prior rainfall was considered. Thus, as expected their results show a better green roof performance than the results reported here.

The modelling study performed herein comprises a theoretical approach of the influence of soil depth in the efficiency of rainfall retention and peak attenuation. Due to the particularities of the green roof studies, such as, various types of soil, soil depth, and water retention systems adopted; it is observed that there is a wide range in these efficiencies.

Besides some similarities with experimental data presented by Simmons et al. (2008) and Spolek (2008), in general, the modelled results showed a lower efficiency compared to experimental data from Voyde et al. (2010a), Fassman-Beck (2013) and some others compiled in Berndtsson (2010). It is most likely that this can be attributed to additional features included in a green roof design to enhance stormwater retention performance, such as drainage boards, mats with cups designed to store water, moisture retention mats, substrate layers with contrasting textures, and other existing peculiarities in experimental procedures, such as absorption of the roof/slab surface, and distance to downpipe outlets. Based on Mentens et al. (2006) work, five non-greened roofs showed an average water retention of 81%. According to this, is expected that 19% of retention may occur due to mortar/slab absorption and water puddle formation. This circumstance reinforces the conservative results when only a single soil column is considered as a theoretical evaluation of stormwater retention.

In terms of a stormwater management perspective; the efficiency of stormwater retention and flow rate attenuation by green roofs on stormwater retention and flow rate attenuation is related to optimal soil depth, which, comprises the maximum depth supported by an existing structure without requiring a structural upgrade. Although deeper soils have higher efficiency, they are not considered the most suitable solution, since most existing buildings were not designed to support such additional loads without further strengthening. The actual efficiency in runoff attenuation will depend on the percentage of green roof coverage in urban areas. Importantly, the lower attenuation efficiency of shallower soils may be offset, if a greater area is retrofitted due to their lightweight characteristics. However, retrofitting housing with green roof technology requires a review of the existing roof structure to determine the excess loading capacity available. Whereas reinforcing the roof structure may not be viable economically, according to local regulations the load bearing capacity of the existing roof will regulate green roof soil depths. In other words it means that the suitability of the green roof retrofit will be subjected to admissible extra loads that can be applied per square metre to existing structures.

In terms of extra loads applied per square metre to existing structures, a Green Roof 40 cm besides providing a better overall performance than a Green Roof 5 cm in terms of stormwater retention and peak flow attenuation, comprises a structural load eight times greater that is likely to overcome the design load of existing roofs, requiring a structural upgrade. Therefore on a wide scale, better capability in rainfall retention and peak attenuation does not comprise the most effective solution.

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