Runoff detention effect of a *sedum* green-roof

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Abstract In order to estimate the detention effect (storage and peak flow attenuation) of a *sedum* green-roof, a comparison between the response of an impervious roof (runoff coefficient $C = 1$) and a green-roof has been carried out. Precipitation and runoff data from several controlled experiments (with wet initial conditions, i.e. approximately at field capacity) on a *sedum* green-roof were used for the analysis. For events with variable rain intensity, the green-roof's attenuation effect was as high as 65% for design storms. In contrast, events with constant intensity had increases in peak flows of up to 5%. The lowest detention volumes were observed for the experiments with constant rain intensity, for which a maximum of 29% of the rain volume was detained, whereas for rain events with variable intensity the detention volume was up to 52%. Simulations (using PondPack), based on a real case study, showed that green-roofs can be implemented in combination with other structural best management practices (BMPs) to obtain a desired detention. They can be used to reduce the size of other structural BMPs, and can occupy unused space that is readily available.

Keywords BMP; detention; green-roof; roof runoff; *sedum*

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Introduction

From the point of view of urban stormwater management, green-roofs are increasingly being used as a source-control measure because they detain and slowly release rainwater. Their implementation has other benefits such as: habitat creation for birds and insects (e.g. Scholz-Barth 2001); filtering of aerosols; energy conservation by providing thermal insulation (Eumorfopoulou and Avarantinos 1998; Köhler *et al.* 2002; Wong *et al.* 2003); improvement of local microclimate through evaporation; and reduction of rooftop temperatures (Köhler *et al.* 2002). The last three are related and can mitigate the urban heat island effect. Some authors (e.g. Scholz-Barth 2001) claim that green-roofs have a potential for controlling nutrients; however, the pollution reduction effect of green-roofs is still under investigation. It should be noted that the benefits of green-roofs are site-specific.

From the aesthetic point of view, green-roofs help to maintain a pleasant living environment and to maintain a balance between vegetation and urban infrastructure. Compared to other local stormwater management solutions, green-roofs require no additional space, which is an advantage in urban areas where land can be at a real premium. In fact, they have the potential to transform between 40 and 50% of the total impervious areas of cities, that is the space occupied by roofs, into usable space. An additional advantage is that they require little maintenance apart from occasional fertilization and initial irrigation for establishing plants, although this is only necessary if natural precipitation is insufficient. Recommendations for fertilization of green-roofs vary and there is no established practice. In a recent study on the influence of *sedum* green-roofs on water quality, Czemiel-Berdtsson *et al.* (2006) found that, during the two or three year establishment period (when the roofs are

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fertilized on occasions), stormwater quality can deteriorate as significant amounts of phosphate phosphorus can be released after fertilization. However, water quality impacts can be reduced by avoiding the use of easily soluable fertilizers.

From the point of view of stormwater management, it is of interest to know how green-roofs perform seasonally over the long term. Bengtsson (2002) used the water balance approach to study the hydrology of a *sedum* green-roof in Augustenborg, a residential area in Malmö, southern Sweden. *Sedum* is used in Sweden as the species has modest soil requirements and is resistant to drought and high exposure to wind and sun. For the *sedum* green-roofs at Augustenborg, it was found that annual roof runoff can be reduced by up to 50% due to evapotranspiration. Studies carried out in other countries show similar results. According to Köhler *et al.* (2002), evaporation from a green-roof in Germany (5 and 12 cm thick) accounted for 60–79% of the annual precipitation. Based on examples from cities such as Chicago, Philadelphia and Portland, Scholz-Barth (2001) claimed that, on average, 75% of roof runoff was retained by extensive green-roofs in the United States. The variation between reported results depends on the thickness of the soil layer and the type of vegetation.

As stated above, green-roofs can improve urban climate and stormwater management; however, the studies cited, with the exception of Zimmer and Geiger (1997), have not looked at individual rainfall events, which is a significant aspect for design. The objective of this paper is to analyse the detention effect of a *sedum* green-roof for individual rain events. To this end, controlled experiments on a *sedum* green-roof plot were carried out in Lund, southern Sweden. The basic approach of this analysis was to compare the response of a hard roof (runoff coefficient $C = 1$) to a green-roof. The idea is that, in urban environments, where a significant portion of the impervious area is covered by hard roofs and there are few opportunities to implement other kind of solutions to detain stormwater, green-roofs can be implemented as a means of local stormwater control.

Materials and method

A section of *sedum* green-roof (henceforth referred to as the plot) was placed in the carpark of the Department of Water Resources Engineering at Lund University. The plot (0.80 m × 1.93 m, $W/L = 0.41$) had a soil-vegetation layer of 0.04 m (soil layer 0.03 m) and an underlying geotextile layer. The soil was composed of 5% of crushed limestone, 43% crushed brick, 37% sand, 5% clay and 10% organic material. When dry, the total weight of the green-roof was 35 kg/m^2 and the soil porosity is 70%. The plot was placed on an impervious raised frame which allowed runoff collection. Artificial rains which mimicked both real and synthetic (i.e. design) rain events were applied over the plot using a sprinkler; runoff volumes were then measured directly at 1-min intervals using beakers. The experiments were carried out for different slopes (2°, 5°, and 8°) with wet initial conditions (i.e. at field capacity).

The rainfall distribution of three storm events used for the experiments is shown in Figure 1. Rain events (a) and (b) replicate real storms registered at the weather station *Turbinen* in Malmö which is located about 25 km from Lund. Figure 1(c) shows the 2-year design rain for Lund (Niemczynowicz 1984). In addition to these, several experiments with constant rainfall intensity (0.8, 0.97 and 1.0 mm/min) were also carried out.

Analysis of the detention effect

The concepts associated with detention are illustrated in Figure 2. The inflow hydrograph represents the runoff from a catchment area. The outflow hydrograph represents the discharge from a detention facility. The reduction in the peak discharge seen in the outflow hydrograph is referred to as attenuation, and the increase in the time to peak is referred to as the lag. The shaded area between the inflow and outflow hydrographs represents the storage

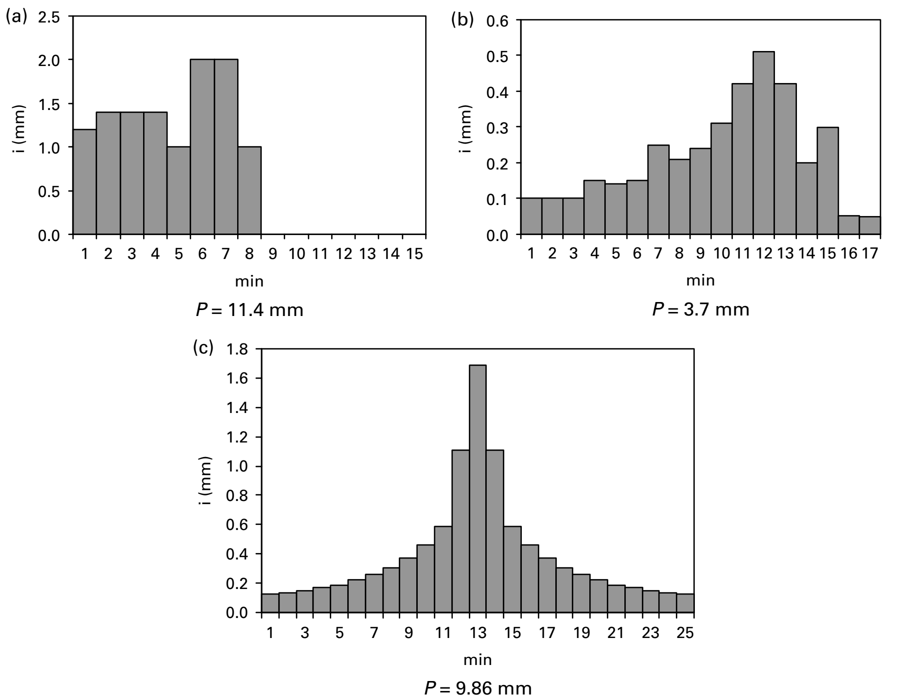

Figure 1 Storm events used for the experiments: (a) 2 August 2002, Malmö; (b) 22 July 2001, Malmö; (c) $Tr = 2$ yr for Lund. P indicates the total amount of precipitation

volume of the detention facility. When designing detention facilities, this is the storage volume required to achieve a desired detention effect. The maximum stored volume of stormwater in the detention facility occurs at the time where the two hydrographs intersect.

The very same detention effect is observed for a *sedum* green-roof if the inflow hydrograph is assumed to be the hydrograph that a determined storm event will produce on a hard roof, and the outflow hydrograph is assumed to be the runoff hydrograph for the same

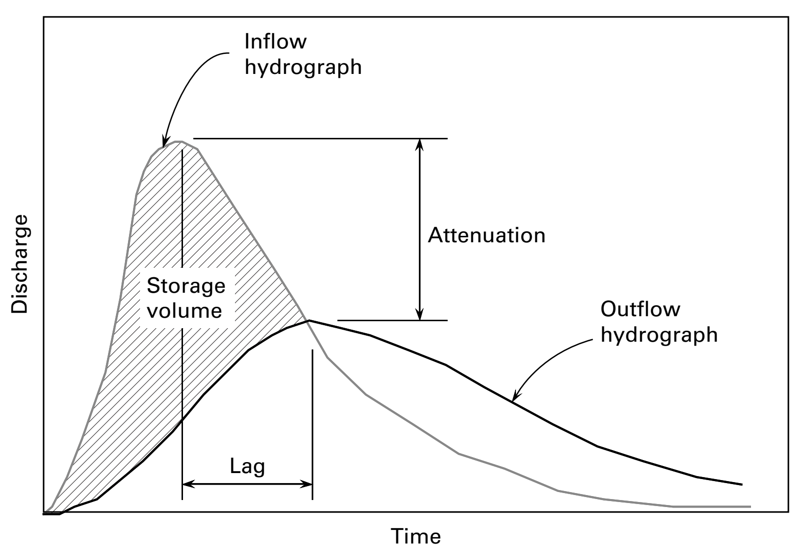

Figure 2 Inflow and outflow hydrographs for a detention facility

storm event from a green-roof. These assumptions are illustrated in Figure 3 which shows the hydrographs for some of the storm events used for the experiments.

With this picture of detention in mind, the detention effect (detained volume, peak flow attenuation and lag) of the *sedum* green-roof was analysed using the results from the experiments on the plot. In addition to the storms used for the experiments, the detention effect for Malmö's $Tr = 2$, 5 and 10-year design storms (VA-verket Malmö 1999) were estimated by using a unit hydrograph that was obtained in a previous study for *sedum* green-roofs (Villarreal and Bengtsson 2005).

A porosity of 70% means that voids fill around 18 mm of the roof layer; and, if about 10 mm of rain are necessary to initiate runoff when the soil is completely dry (Bengtsson 2002; Villarreal and Bengtsson 2005), then there will be a soil pore volume equivalent to 8 mm available to detain stormwater. The next step in this analysis was to estimate the detention effect of this volume of pores.

Using the hydrographs for each experiment, as well as the estimated ones for synthetic storms in Malmö, the detention volume was estimated. Additionally, peak flow attenuation was calculated by comparing the peak flows of these two hydrographs. The results are presented in Table 1.

Effective precipitation against detention volumes are shown in Figure 4. Two linear tendencies are identified: for events with constant rain intensity and for events with non-constant or variable intensity.

Discussion

For events with variable rain intensity the green-roof's attenuation effect is significant, being as high as 65% for design storms, and between 31 and 45% for the other storms (22 July 2001 and 2 August 2002) with variable intensity. For events with constant intensity, on the other hand, peak flows showed a slight increase of up to 5%; this is probably due to some overland flow as not all the water seems to have gone through the green-roof. The lowest detention

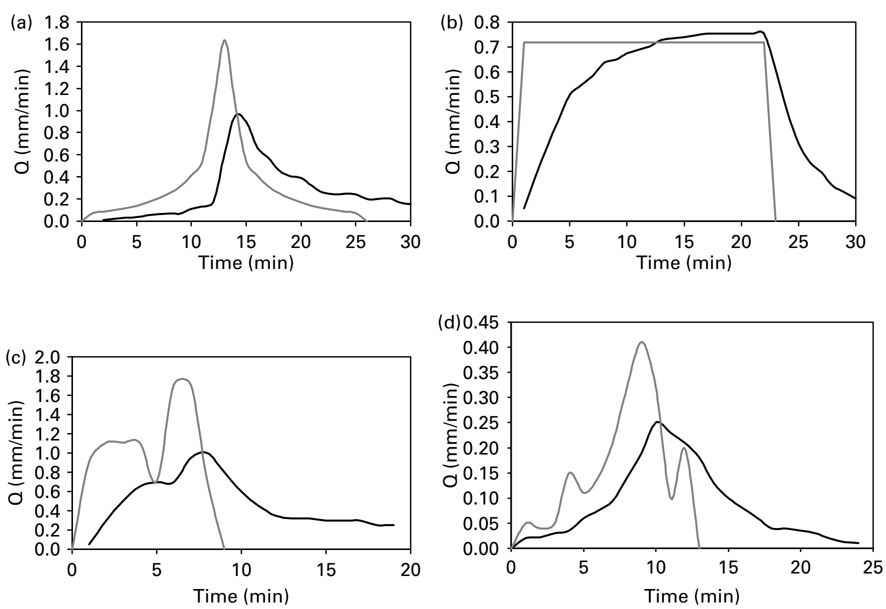

Figure 3 Hard roof "inflow" (grey line) and green-roof "outflow" (black line) hydrographs for (a) Lund $Tr = 2$ yr, (b) $-$ 0.8 mm/min, (c) 2 August 2002, (d) 22 July 2001

Table 1 Peak flows and detention volumes

Rain event	Effective precipitation (mm)	Peak flow (mm/min)		Detention volume (mm)
		Hard roof	Green-roof	
Slope 2°				
22 Jul 01	2.95	0.44	0.24	1.0
02 Aug 02	9.09	1.71	1.00	4.5
Lund $T = 2$ yr	7.37	1.60	0.70	3.0
0.64 mm/min (18 min)	11.50	0.64	0.62	3.3
Slope 5°				
22 Jul 01	1.82	0.39	0.24	0.7
02 Aug 02	9.42	1.89	1.30	4.7
Lund $T = 2$ yr	7.17	1.59	0.70	2.9
0.88 mm/min (12 min)	10.52	0.88	0.88	2.7
Slope 8°				
22 Jul 01	2.10	0.41	0.25	0.9
Lund $T = 2$ yr	7.95	1.61	0.84	3.6
0.72 mm/min (22 min)	15.80	0.72	0.75	2.7
0.87 mm/min (18 min)	15.68	0.87	0.91	3.1
Estimated with UH				
Malmö $Tr = 2$ yr	8.90	3.2	1.20	4.6
Malmö $Tr = 5$ yr	12.10	4.4	1.60	6.3
Malmö $Tr = 10$ yr	15.60	5.7	2.10	8.0
0.2 mm/min (17 min)	3.40	0.2	0.21	1.0
0.4 mm/min (17 min)	6.80	0.4	0.42	1.9
0.6 mm/min (17 min)	10.20	0.6	0.63	2.9
1.0 mm/min (17 min)	17.00	1.0	1.05	4.8
1.2 mm/min (17 min)	20.40	1.2	1.26	5.8

volumes were observed for the experiments with constant rain intensity: only between 20 and 29% of the rain volume is detained, whereas for rain events with variable intensity the detention volume is between 34 to 52%.

When comparing detention volume and effective precipitation two trends were observed (see Figure 4): one for storms with variable intensity and the other for constant intensity. For storms with variable intensity the detention volume seems to be independent of rain intensity during duration; what is important here is the effective amount of precipitation. For storms with constant intensity there are three possible "scenarios": (1) for the same duration and different rain intensity – the detention volume grows linearly; (2) for the same intensity and different duration – the same detention volume is observed; (3) for different intensity and different duration but same effective precipitation – detention volume remains approximately the same.

The difference between the behaviour of storms with variable intensity as compared to storms with constant intensity can be physically explainable as follows: for rain events with variable intensity the amounts of rainwater passing through the green-roof grow and decrease gradually which allows a better "accommodation" of the rainwater in the available space. Thus, the available space for detention within the green-roofs is better "used" for storms with variable rain intensity than for the ones with constant rain intensity.

The results from the analysis suggest that slope has no effect on the detention effect of this kind of green-roof. Lag effect was only present for events with variable rain intensity with a magnitude of only 1 min.

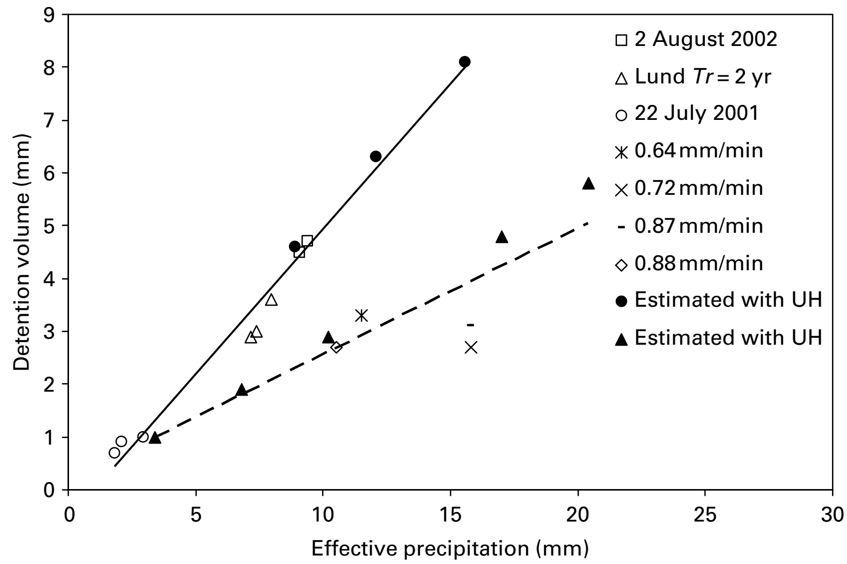

Figure 4 Relationship between effective precipitation and detention volume. Continuous line shows the trend for events with variable rain intensity; dashed line shows the tendency for events with constant rain intensity

Practical application

In Augustenborg, an inner-city suburb of Malmö on the southern tip of Sweden, two BMP elements for stormwater management have been implemented for a municipal property consisting of a paved yard, carpark and offices. The two BMP elements are *sedum* green-roofs and a 140 m long pond complex (volume 40 m^3). The outlet structure of the pond is a 0.10 m diameter pipe which has its invert level 0.20 m above the bottom of the structure; this means that the structure is able to retain 24 m^3. The pond forms a water feature which runs along the main front of the council offices bordering a small garden strip. *Sedum* green-roofs cover the offices of the council property (1450 m^2, about 31% of the area). Computer simulations using the academic version of PondPack (Haestad Methods 2002) were carried out to evaluate the role that green-roofs play in stormwater management at Augustenborg. PondPack is a surface stormwater modelling program capable of analysing a wide range of situations and infrastructure. Design hydrographs for return periods of $\frac{1}{2}$, 2, 5 and 10 yr were considered for the simulations; additionally the pond complex was considered to be empty. The green-roofs and pond complex are connected in series, that is, the outflow hydrograph of one structure became the inflow hydrograph of the structure immediately downstream. With the aim of estimating the effect of green-roofs, simulations were carried out for hard roofs (impermeable roofs) and for green-roofs, that is considering their available space for detention and retention.

The results indicate that, in the absence of the green-roofs, peak flows to the pond increased by 64%, 37%, 27% and 13% for design storms with recurrence interval of $Tr = \frac{1}{2}$, 2, 5 and 10 yr, respectively. The volume of the inflow hydrographs rose 52%, 30%, 26%, and 18% for the same return periods. Therefore, to offer the same level of detention and attenuation without green-roofs, the pond complex would have to be larger. According to the results for the $Tr = 10$ yr event, it is estimated that the pond complex should be at least 29% bigger than its present size.

Conclusion

The detention effect of a *sedum* green-roof was analysed by comparing measured output hydrographs to those calculated for a hard roof. It was shown that the detention effect can be significant; peak flow can be attenuated by as much as 65%. The methodology to estimate this effect can be used to estimate the detention effect of a green-roof as compared with any kind of hard roof (i.e. other values of the runoff coefficient C).

Augustenborg, an inner-city suburb of Malmö, was used as a case study. Measurements and model simulations showed that green-roofs can be implemented in combination with other structural BMPs. This has the benefit of reducing the need for land surface area given over to stormwater control. That is, green-roofs occupy otherwise unused space and, by reducing flow volumes and peak flows, can reduce the size of these other BMPs while achieving the same design criteria.

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