Green Roof Storm Water Retention –Monitoring Results

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ABSTRACT

A two year monitoring program in real meteorological conditions investigated the rainfall-runoff processes of 18 green roof constructions at large scale test segments of 12 m² and 24.5 m² size with different slopes and layer types. Results proved that green roofs reduce the annual and seasonal rain runoff considerably. The layer depth dominates the retention effect clearly compared to other construction details. Steeply sloped roofs as well as 2-layer-constructions tend to increase runoff in minor order. A substantial reduction of peak runoff could be observed for all constructions. Peak flow reduction does not clearly depend on depth or number of the layers or slope. Soil moisture and retention are predominantly influenced by evapotranspiration and the sequence of rainy and dry periods. The study proved green roofs to be highly effective on site tools for storm runoff reduction.

KEYWORDS

green roofs, monitoring, retention, runoff, storm water, water sensitive urban design

INTRODUCTION

Professional green roof systems have been available for about two decades. The systems range from thin layer systems with succulents to green rooftop gardens with bushes and even small trees. Urban ecology expects advantages regarding reduced storm water runoff and increased evaporation as well as positive effects on urban microclimate and ecology. Green roofs on private and industrial buildings are used in new developments and as retrofit options. Water sensitive urban design demands combinations of several options to reduce storm water runoff on single private and public properties and development areas.

Green roofs are one of the options for sustainable urban drainage systems (SUDS). They act as storage units imitating the hydrological behavior of the upper soil layer. Storage is provided for the most part by the pore volume of the substrate, by the drainage layer or system and by the surface of the vegetation layer. Runoff generally occurs with large time delay and significant reduction in peak flows and volume. The retention effect is influenced by the humidity and hydraulic conductivity of the substrate as well as the lateral flow characteristics of the drainage system.

For about 20 years the runoff characteristics of green roofs had been studied in western Europe, especially in Germany. In the years 1987 – 2003 several studies were reported in german mainly by Kolb, Lieseke and Mann. Mentens *et al.* (2006) give a short survey on that work. Kolb and Lieseke carried out several small scale studies focusing either on peak flow with saturated substrate during controlled experiments or annual and seasonal runoff during real weather conditions. A regression model (Mentens *et al.*, 2006) for annual runoff however suffers from weak representativity for low and high annual rainfall.

Test plot studies are reported by several authors. Mentens *et al.* (2003) studied runoff and evaporation from green roofs in small scale tests plots during real weather conditions. VanWoert *et al.* (2005) report on two detailed studies on runoff processes during real weather conditions in Michigan. LaBerge/Worthington (2005) investigated stormwater and temperature issues at 6 test roofs in Chicago. Stovin *et al.* (2007) give notice of a beginning research project in Sheffield studying green roofs under maritime climate conditions. Especially in the US and Canada in the recent years several large scale case study monitoring programs were run in different climatic conditions (for example Graham *et al.* 2003, Hutchinson *et al.* 2003, Johnston *et al.* 2004, Moran *et al.* 2004, Taylor 2006, Seters *et al.* 2007, Wachter *et al.* 2007).

The study this paper reports on was undertaken as part of an industrial development program for green roof construction in 1995-1997 (Uhl *et al.*, 2003). Real scale roofs were monitored in real weather conditions to study amongst others the following hydrological objectives:

- influence of the construction on stormwater retention and runoff process
- total runoff volume and peak flow of green roofs under real meteorological conditions
- process analysis and data acquisition for a long-term simulation model

In this paper the program is published internationally for the first time and new results of data analysis especially concerning urban hydrology are given.

MATERIAL AND METHODS

Test roofs

A two year monitoring program investigated the rainfall-runoff processes of 5 standard and 18 green roof constructions at large scale test segments of 12 m² and 24.5 m² size located on a 500 m² roof. Gravel, roof tiles and proofing membrane were selected as standard materials. The test segments were constructed as a cutout of the respective real roof construction. The following types (Table 1) were implemented:

- rectangular segments with 12 m² in size and linear outflow at the lowest side
- triangular segments with 24,5 m² in size and point outflow at the lowest point
- slopes 0 %, 1.7%, 26.8%
- extensive and intensive vegetation
- 1-, 2-layer systems
- 5-35 cm in height

The roof construction is based on a root resistant proofing membrane followed by a protection and storage geotextile (900 g/m²) for all green roofs except the intensively vegetated ones (D02, D03, D04). For the drainage layer broken expanded slate with grain sizes of 2/10 mm (Perl 2-10) and grain sizes of 8/16 mm (Perl 8-16) was used. Three types of substrate were investigated. Type “M” is a mixture of lava, pumice and expanded slate. Type “i” consists of expanded slate, lava, pumice, expanded clay, bark humus and garden compost. For Type “E” also expanded slate, lava, pumice, expanded clay, bark humus and garden compost were used. All roofs got initial plantings to establish special vegetations of the moss-sedum-haulm-type, the sedum-grass-haulm-type or the herbaceous perennial-grove-type each depending on the individual roof conditions.

The common typification of green roofs in Europe (Krupka, 1992; Kolb and Schwarz, 1999) was used:

- extensive green roofs: substrate layers with a maximum depth of about 15 cm
- intensive green roofs: substrate layers with a depth more than 15 cm

Table 1: Characteristics of the test roofs.

Nr.	**size**	**shape**	**outflow**	**slope**	**layer height** drainage/substrate	**materials** drainage/substrate	**vegetation**
-	**m^2**			**%**	**cm**		
D01	24,3	triang.	point	1.7	- / 8	- / M	extensive
D02	12,0	rectang.	linear	0	10 / 15	Perl 8-16 / i	intensive
D03	12,0	rectang.	linear	0	15 / 20	Perl 8-16 / i	intensive
D04	12,0	rectang.	linear	0	10 / 5	Perl 8-16 / E	intensive
D05	12,0	rectang.	linear	0	- / 5	- / M	extensive
D06	12,0	rectang.	linear	0	5 / 10	Perl 2-10 / E	extensive
D07	12,0	rectang.	linear	0	5 / 5	Perl 2-10 / E	extensive
D08	24,1	triang.	point	1.7	5 / 5	Perl 2-10 / E	extensive
D09	25,0	triang.	point	1.7	- / 10	- / E	extensive
D10	25,1	triang.	point	1.7	5 / 10	Perl 2-10 / E	extensive
D11	22,4	triang.	point	1.7	-	proofing membrane	none
D12	12,0	rectang.	linear	26.8	- / 10	- / E	extensive
D13	12,0	rectang.	linear	26.8	- / 15	- / E	extensive
D14	12,0	rectang.	linear	26.8	- / 15	- / E	extensive
D15	12,0	rectang.	linear	26.8	- / 10	- / E	extensive
D16	12,0	rectang.	linear	26.8	- / 5	- / E	extensive
D17	8,9	rectang.	linear	26.8	-	proofing membrane	none
D18	8,7	rectang.	linear	26.8	-	roof tile	none
D19	17,6	triang.	point	1.7	- / 8	- / M	extensive
D20	24,0	triang.	point	1.7	- / 5	- / gravel	none
D21	24,2	triang.	point	1.7	- / 8	/ M	extensive
D22	6,0	rectang.	linear	0	- / 5	gravel	none
D23	12,0	rectang.	linear	0	- / 8	M	extensive

Table 2. Measurement equipment.

variable	**equipment**	**number**	**location**
rainfall	tipping bucket 200 cm^2 heated, resolution 0,1 mm	1	on the roof, 0.3 m above roof and 4.3 m above ground
runoff	volumetric measurement system collection tanks of 200 and 500 l, swimmer system for water level measurements, resolution 1 mm, quick emptying by heaver system	34	in a air-conditioned room directly under the roofs
soil temperature	sensortype PT 100	15	roof no. 2, 3, 6, 7, 15, 17, 22, 23
relative humidity	Thiess hygro-thermo-sensor	3	0.3 m above roof
relative humidity and air temperature	Skye instruments SKH 2053	1	10 m above ground
wind velocity	Porton anemometer 0 - 60 m/s, heated	1	10 m above ground
wind direction	Porton wind direction 0 - 358°, heated	1	10 m above ground
global radiation	Skye Instruments SKL 2650	1	10 m above ground

Table 3. Seasons and rainfall.

			measured rainfall		
			period 1	period 2	total
season		**climate**	**mm**	**mm**	**mm**
summer	1.5. – 30.9.	warm/hot	441	368	809
spring + autumn	15.3.-30.4. and 1.10.-15.11.	cool	114	185	299
winter	15.11. – 15.3.	cold	131	143	274

Instrumentation

Rainfall, humidity, air temperature, global radiation, wind speed and direction were the measured meteorological variables. At 8 selected roofs soil temperature was monitored additionally. The roof runoff was monitored by volumetric systems using standardized collection tanks and swimmers for water level monitoring. The volumetric measurement system allowed a resolution of 0.05 (mm/(m²×min). Possible surface runoff of 26.8% sloped green roofs could be monitored separately. The measurement equipment is given in Table 2.

Scope of data material

Due to careful operation the monitoring program was continuous with only 5 missing days in two years. In accordance to former investigations (Lieseke, 1995) three seasonal conditions (Table 3) were defined to group and compare the data material.

RESULTS AND DISCUSSION

Annual and seasonal influences on the runoff coefficients

Annual and seasonal balances of rainfall and runoff were undertaken for the two year measurement data set. During the measurement program no direct surface runoff occurred.

The resulting runoff coefficients are shown in Figure 1 and are grouped for extensive green roofs in Table 4 and for intensive green roofs in Table 5. The runoff coefficient c_R is defined as the ratio between the sums of runoff and rainfall.

The annual c_R is in average32 % with a range of 23 % to 39 %, whereas the variability shown by the coefficient of variation 0.15 is relatively low.

The seasonal analysis clarifies the influence of different meteorological conditions. Under warm and hot conditions in summer the average c_R is 24 %, ranging from 16 % to 31 % with a higher variability. In winter runoff c_R range from 40 % to 60 % with an average of 51 %. The cool conditions in spring and autumn resulted in c_R between 27 % and 51 % and an average of 38 %. In cool and cold seasons the coefficients of variation of 0.13 and 0.15 indicate a low variability. Intensive green roofs (Table 5) showed very low c_R of 6 % and 11% during the warm and hot season. During the cold season 42 % and 47 % were within the range of extensive green roofs.

The low runoff coefficients in the summer seasons are remarkable when taking into account that nearly 2/3 of the rainfall fell in 10 of the 48 months measurement period. The evapotranspiration rates must have been sufficient for a quick drying of the substrates resulting in high retention capacities. In summer evapotranspiration and precipitation are stronger negatively correlated random processes. That causes a higher variability of runoff coefficients.

In the cool and cold seasons the higher runoff coefficients can be explained by lower evapotranspiration rates. The probability of higher humidity (i.e. lower retention capacity) of the substrates rises with decreasing evapotranspiration. As a seasonal effect higher runoff coefficients can be observed. The amount and the seasonal distribution of precipitation and evapotranspiration are both the important meteorological driving forces influencing the retention effect.

The annual runoff coefficients depend also on the seasonal distribution of rainfall and evapotranspiration. The annual runoff coefficients during the 2-year observation period are relatively low due to the above mentioned fact that about 2/3 of the precipitation fell in summer.

A seasonal analysis of precipitation and runoff coefficients is therefore obligatory for monitoring programmes. A transfer of runoff coefficients to other periods or locations has to ensure the comparability of the meteorological situation.

Table 4. Runoff coefficients of extensive green roofs (10.10.95-13.10.97).

no.	**size**	**slope**	**depth**	**substrate**	**form**	**runoff coefficient**			
						warm/hot	**cool**	**cold**	**year**
	m²	**%**	**cm**			**%**	**%**	**%**	**%**
D05	12.0	0	5	M	rectang.	24	44	55	33
D16	12.0	26.8	5	E	rectang.	30	43	53	36
D01	24.3	1.7	8	M	triang.	31	51	57	39
D19	17.6	1.7	8	M	triang.	30	36	44	31
D21	24.2	1.7	8	M	triang.	30	43	56	36
D23	12.0	0	8	M	rectang.	25	38	58	33
D07	12.0	0	5 / 5	E	rectang.	23	42	51	31
D08	24.1	1.7	5 / 5	E	triang.	31	47	54	38
D09	25.0	1.7	10	E	triang.	25	40	45	31
D12	12.0	26.8	10	E	rectang.	23	37	43	29
D15	12.0	26.8	10	E	rectang.	24	38	54	31
D04	12.0	0	10 / 5	E	rectang.	16	35	60	26
D06	12.0	0	5 / 10	E	rectang.	18	35	55	27
D10	25.1	1.7	5 / 10	E	triang.	24	37	55	31
D13	12.0	26.8	15	E	rectang.	17	30	42	23
D14	12.0	26.8	15	E	rectang.	18	27	40	23
average						24	39	51	31
median						24	38	54	31
minimum						16	27	40	23
maximum						31	51	60	39
standard deviation						5.1	6.1	6.5	4.8
coefficient of variation						0.21	0.17	0.13	0.15

Table 5. Runoff coefficients of intensive green roofs.

no.	**size**	**slope**	**depth**	**substrate**	**form**	**runoff coefficient**			
						warm/hot	**cool**	**cold**	**year**
	m²	**%**	**cm**			**%**	**%**	**%**	**%**
D02	12.0	0	10 / 15	I	rectang.	11	24	47	20
D03	12.0	0	15 / 20	I	rectang.	6	20	42	19

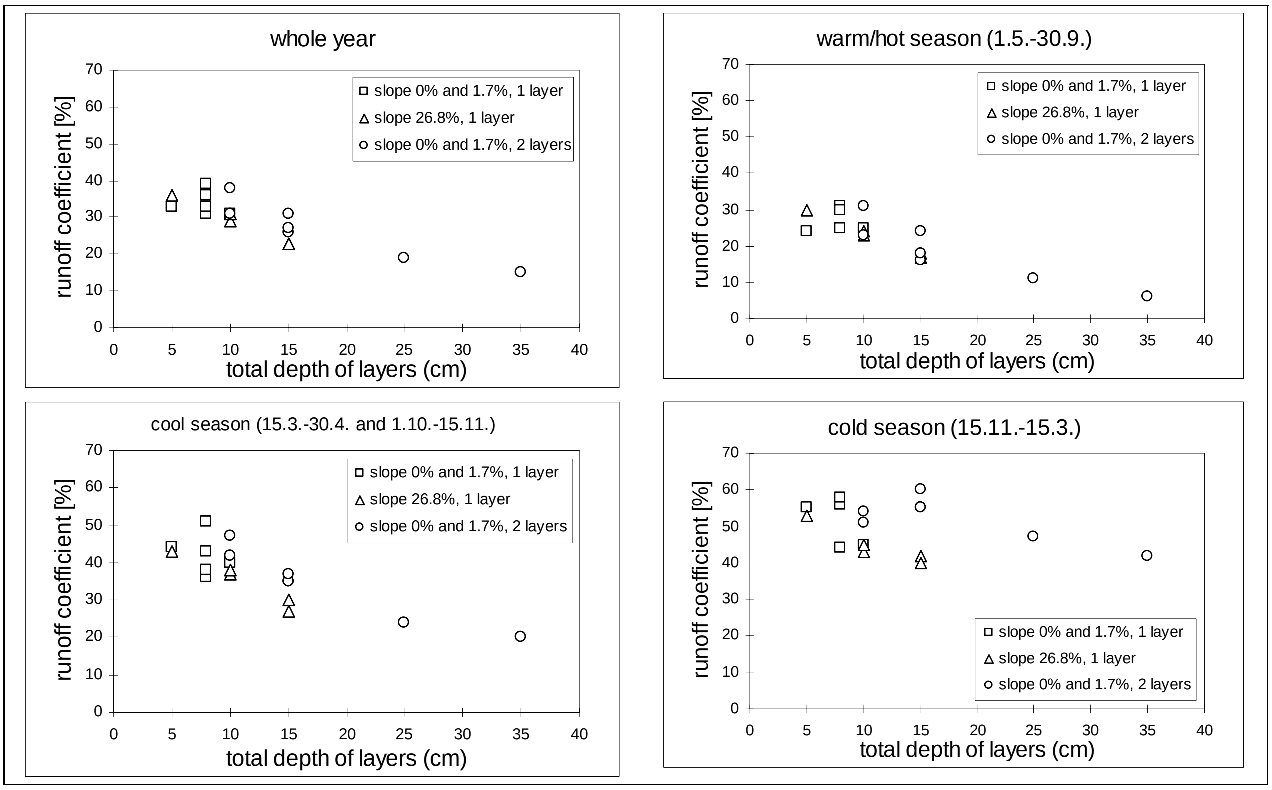

Figure 1. Annual and seasonal runoff coefficients.

Influences of the roof construction on annual and seasonal runoff coefficients

Figure 1 points out some interrelationship between construction details and retention effects of green roofs. Due to the limited number of test roofs a comparison of different types of construction is possible but without a strict monocausal analysis of any factor in every case.

Depth of layers. The total depth of substrate and drainage layer dominates clearly the retention effects. The annual data can be well fitted by linear regression functions between runoff coefficient c_R [%] and total depth s [cm] of layers for the given annual precipitation and its seasonal pattern:

$c_R = 39.927 - 0.7503\ s$ $R^2 = 0{,}81$ with $5\ \text{cm} \leq s \leq 35\ \text{cm}$ and slopes $\leq 1.7\ \%$

$c_R = 42.875 - 1.3143\ s$ $R^2 = 0{,}98$ with $5\ \text{cm} \leq s \leq 15\ \text{cm}$ and slopes of 26.8 %

The seasonal data show different linearity between c_R and s. The linear correlation coefficients for flat roofs (n=13) in the three seasons are R^2=0,79 (warm/hot), R^2=0,78 (cool) and R^2=0,25 (cold). For steep roofs (n=5) R^2=0,99 (warm/hot), R^2=0,95 (cool) and R^2=0,86 (cold) can be derived from the data.

The correlation between c_R and s is strong during warm/hot periods. Storage capacity is a linear function of pore volume and depth of the substrate and the drainage layer. After rainfalls high evapotranspiration rates lead to a quick achievement of high or full storage capacities of the roofs. The likelihood of same boundary conditions for storage at the beginning of the next rainfall event is very high. Linearity between c_R and s is therefore likely. During cool seasons also a high linear correlation indicates the layer depth to be predominant on the retention effect. In cold seasons the retention is often influenced by the antecedent rainfall because of the low evapotranspiration. More heterogeneous boundary conditions at the begin of any rainfall event result in lower correlation between c_R and s. Figure 3 indicates that for flat roofs other factors in addition to the layer depth begin to influence the retention with more evidence.

Drainage layer. The influence of the drainage layer can be studied by comparing roofs of the same size, type and slope and different layer construction. In the following the depths of the drainage and substrate layer are given in brackets. The runoff coefficients (Table 6) of the roofs D05 (-/5 cm) and D07 (5/5 cm) are nearly equal on an annual and seasonal basis. The greatest difference can be seen during winter with c_R = 55% (D05) and c_R = 51% (D07).

The roofs D09 (-/10 cm) and D10 (5/10 cm) showed nearly the same c_R–values during warm and cool seasons and on an annual basis. In the cold season the non-drained roof D09 had lower runoff coefficients (c_R = 45 %) than the drained roof D10 (c_R = 55%).

The high porosity of the drainage layer in general abets the dewatering of the substrate and accelerates the lateral flow process. This results in principle in higher runoff and therefore lower retention. This effect of the drainage seems to be relevant only during cold seasons. In the two given examples as well as the other data material clear differences between drained and undrained green roofs could not be identified. The drainage effect of the substrate layers themselves is obviously sufficient for dewatering the green roofs.

Slope. The influence of slope can be directly studied by a comparison of the runoff coefficients (Table 4) of the 5 cm one-layer roofs D05 (slope 0%) and D16 (slope 26.8%). During the warm and hot season the sloped roof D16 caused a 25 % higher runoff. During the cool and cold seasons both roofs had similar runoff. No direct surface runoff has been observed during high intensity rains.

The slope of the roof can influence lateral flow and evapotranspiration. Lateral flow can be increased by slope due to the higher potential energy. Evapotranspiration can be increased by additional solar radiation energy depending on slope and orientation of the roof (Mentens et al., 2003; Mentens et al., 2006). In summer evapotranspiration mainly influences the runoff coefficient. The similarity of runoff during the cool and cold seasons indicate that different de-watering due to the slope can not be the main reason for differences of the runoff coefficient. The effect of increased evapotranspiration however must be limited in summer due to the thin layer of only 5 cm. One reason for the increased runoff coefficient in summer might be that thin layer surface runoff during heavy rainfall infiltrates quickly again in the lower part of the roof near to the drainage section.

The equally constructed steep sloped roofs D12 and D15 as well as D13 and D14 have very similar c_R during all seasons so that reproducibility of the results can be assumed. Table 4 and Figure 1 point out that sloped roofs do not increase the annual and seasonal runoff coefficient in an noticeable way.

Type of drainage section. When comparing the two types of drainage sections in general the runoff coefficients of rectangular sections are lower than those of triangular sections. This can be observed at 8 cm one layer roofs (D21/D23), 5/5 cm two layer roofs (D07/D08) and 5/10 cm two layer roofs (D06/D10). In the triangular sections with 26.8 m² area short drainage pipe lead to a quicker de-watering of the section which results in higher values of c_R. The relevance of the effect is limited to warm/hot seasons. In these seasons the retentions effect of rectangular sections is higher.

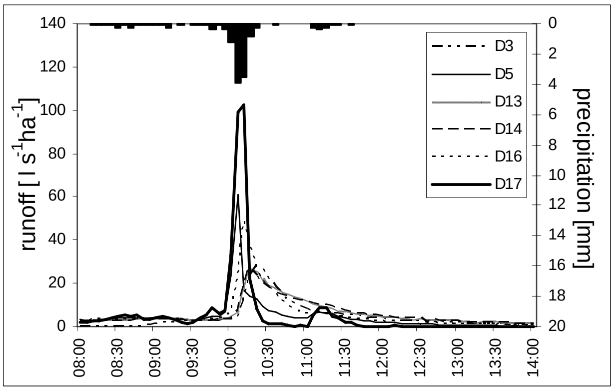

Figure 2. Hydrograph of an intensive rain.

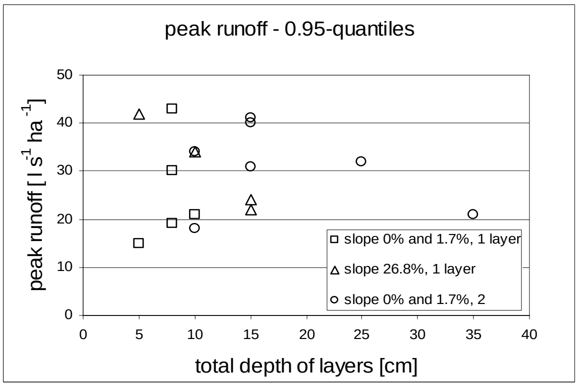

Figure 3. 0.95-quantiles of peak runoff.

Table 6. Retention capacity and peak flow of green roofs.

no.	size	slope	depth	retention capacity	peak runoff		
				maximum	0.9-quantile	0.95-quantile	maximum
	m²	%	cm	mm	L s⁻¹ ha⁻¹	L s⁻¹ ha⁻¹	L s⁻¹ ha⁻¹
D05	12	0	5	25	9	15	68
D01	24.3	1.7	8	25	10	30	39
D21	24.2	1.7	8	25	15	43	90
D23	12	0	8	35	8	19	30
D19	17.6	1.7	8	35	-	-	-
D09	25	1.7	10	40	12	21	46
D12	12	26.8	10	40	-	-	-
D08	24.1	1.7	5/5	25	14	34	44
D07	12	0	5/5	45	17	18	64
D04	12	0	10/5	45	25	41	85
D06	12	0	5/10	40	15	40	50
D10	25.1	1.7	5/10	40	15	31	42
D03	12	0	15/20	55	6	21	40
D02	12	0	10/15	50	13	32	54
D16	12	26.8	5	20	15	42	54
D15	12	26.8	10	35	14	34	39
D13	12	26.8	15	35	8	24	100
D14	12	26.8	15	40	10	22	33
minimum				25	6	15	30
maximum				55	25	43	100

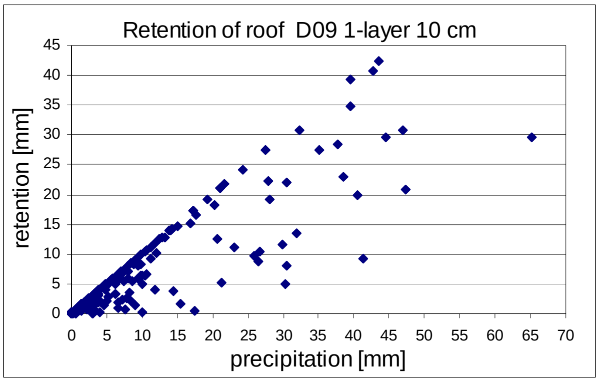

Figure 4. Retention of roof D09.

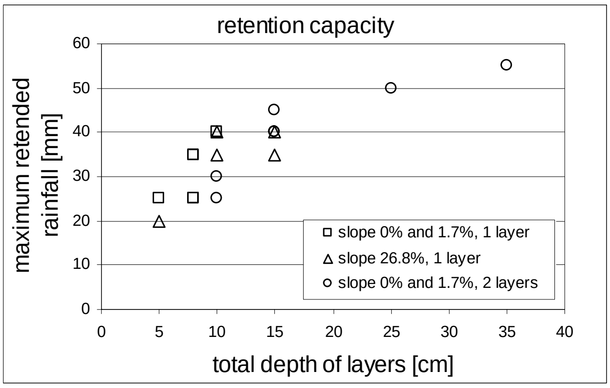

Figure 5. Observed retention capacity.

Single event runoff

Knowledge about single event runoff is important when green roofs are part of sustainable urban drainage systems (SUDS). Single event retention and runoff and especially peak runoff are important for dimensioning the whole retention and drainage system.

Hydrographs. Figure 2 illustrates typical hydrographs of selected green roofs and membrane covered roof (D17) for a 28.8 mm rainfall with two intensive peaks of 3.92 mm/5 min and 3.5 mm/5 min. Detention of runoff hydrograph, reduction of volume and reduction of peak flow can be observed in a typical way. Detention reduces peak flow on the membrane covered roof down to about 75 % of peak rain intensity. Both 5 cm layer roofs (D05, D16) show a quick response but with significant reduction of peak flow and volume by retention and detention. For the steep roofs D13 and D14 with a 15 cm layer a similar response was observed as for the flat intensive green roof D03 with a two layer system of totally 35 cm depth.

*Maximum retention capacity.*Figure 4 illustrates the retention being the difference between rainfall and runoff as a function of rainfall for roof D09. The bisector marks events without runoff and therefore full retention. From Figure 4 a maximum retention capacity of about 40 mm can be estimated for the given rainfall events. For the other roofs similarly estimated values for the maximum retention capacity are given in Figure 5. The maximum retention capacity depends stronger on the total layer depth than on the substrate depth itself. Other factors are not dominant. Steep slope and 2-layer-roofs tend to have some lower retention capacity than the other types.

Peak runoff. Detailed hydrograph analysis proved that peak runoff often is influenced by the retended water in substrate layer. Peak runoff is therefore strongly influenced by the antecedent rainfall and evapotranspiration process. Simple linear relationships between rainfall and peak runoff such as peak flow reduction factors are not suitable. Table 6 summarizes peak flow data of 47-49 events by means of simple statistical values. Peak runoff of green roofs with 0.0-quantiles of 6–25 L s^{-1} ha^{-1}, 0.95-quantiles of 15-43 L s^{-1} ha^{-1} and maximums of 30-100 L s^{-1} ha^{-1} were clearly lower than peak runoff of the membrane covered roof. This non vegetated roof had peak flows with a 0.9-quantile of 109 L s^{-1} ha^{-1}, 0.95-quantile of 128 L s^{-1} ha^{-1} and 213 L s^{-1} ha^{-1} maximum. Peak runoff reduction by green roofs are about 66-86 % regarding the 0.95-quantiles and 50-84 % regarding the maximums compared to a membrane covered roof. Figure 3 illustrates for the 0.95-quantiles that dominant individual factors for peak runoff reduction cannot be identified. In general 2-layer systems and steep sloped roofs tend to have some higher peak runoff than low sloped 1-layer systems. Lower lateral flow rates can be assumed as a reason for this. The depth of substrate does not influence peak runoff reduction substantially. Green roofs with 5-10 cm one-layer substrate can already reduce peak runoff considerably.

CONCLUSIONS

Green roofs reduce the annual and seasonal rain runoff considerably. The annual runoff coefficient ranged between 23% and 38%. During summer 16%-31 % and in winter 40%-60 % were observed for the runoff coefficient. The layer depth dominates the retention effect clearly compared to other construction details. Steep sloped roofs as well as 2-layer-constructions tend to increase runoff in minor order.

A substantial reduction of peak runoff could be observed for all constructions. The range of the 0.95-quantiles was 15-43 L s^{-1} ha^{-1} compared to 128 L s^{-1} ha^{-1} of a membrane covered roof. Peak flow reduction does not clearly depend on depth or number of the layers or slope.

Already a thin layer construction is likely to reduce peak flow substantially. For the reduction of peak runoff intensity infiltration into the substrate as well as lateral flow or even thin layer surface flow are the main detending processes. Runoff production is also influenced by the water content at the beginning of a new rainfall event.

Soil moisture and retention is predominantly influenced by evapotranspiration and the sequence of rainy and dry periods. Monitoring results therefore cannot be directly transferred into other climatic regions. This supports the need for process models focusing on runoff production and evapotranspiration. Further research should therefore include soil moisture and evapotranspiration in detail.

The study proved green roofs to be high effective on site tools for storm runoff reduction.

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