Peak flows from thin sedum-moss roof

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Abstract The runoff from real 3 cm thick sedum-moss roofs and from laboratory roof plots in southern Sweden is measured and analysed. Real rains and artificial storms are used for the analysis. The probability of high runoff is compared with the probability of high precipitation intensity. Intensity–duration–frequency curves for runoff are derived and it is found that the runoff of 1.5 year return period corresponds to rain of 0.4 year return period. The storage of water in the soil–vegetation cover on the roof is determined. The storage at field capacity, when runoff is initiated, is about 9 mm. Water in excess of that is temporary stored during storms. The runoff distribution during prolonged storms can be related to the mean rain intensity over 20–30 min. The influence of the slope and length of the roof on the runoff peak is investigated as is the effect of the drainage layer. Neither slope nor length seems to significantly influence the runoff distribution, which indicates that the vertical percolation process through the vegetation and the soil dominates the rainfall–runoff process. The presence of a drainage layer below the soil results in somewhat faster runoff compared to when there is no drainage layer, and thus results in an increased runoff peak.

Keywords Green roof; i–d–f curves; sedum-moss; stormwater; urban drainage

Introduction

Green roofs, although mainly built for aesthetic reasons, are today being used as facilities for handling stormwater in a sustainable way. It is known that the water balance is much improved compared to hard roofs, since evapotranspiration takes place. However, it is not known to what extent peak flows are reduced when green roofs constitute parts of stormwater systems.

If a roof is converted from a hard roof to a green roof, the soil has to be very thin so as not to increase the load on the roof very much. The soil may be as thin as 2–4 cm. Green roofs with a thin soil cover are called extensive green roofs. They do not require much maintenance. The vegetation used is sedum or moss, which can stand long periods of drought. The type of roof reported on here is such a thin extensive green roof.

Evapotranspiration occurs from the soil–vegetation on a green roof, and therefore the total runoff is much reduced compared to that from a hard roof, from which the runoff almost equals the precipitation. Studies from northern Europe (Köhler *et al.* 2001; Bengtsson *et al.* 2005) show that the runoff from thin extensive green roofs is only about half the annual precipitation. Rainwater is stored in the soil. In a warm period with little precipitation the runoff is minor. When rain falls on a dry green roof, there is no runoff until the soil reaches field capacity. From then on the runoff approaches the precipitation. Most small summer storms do not produce any runoff. A second intense storm may, however, produce a high runoff peak. Although, as was shown by Bengtsson *et al.* (2005), the hourly runoff is close to the hourly rainfall, the peak runoff over shorter intervals is reduced compared to the rain intensity. The peak runoff from a storm event depends on the rain intensity distribution. The relation between rain intensity and runoff over short time intervals after runoff has been initiated is investigated in this paper.

The precipitation onto and the runoff from a 4 m long thin green roof in Augustenborg, Malmö, Sweden were measured for two years with a time resolution of 5 min. The roof is covered by about 3 cm soil substrate with sedum-moss vegetation and is underlain by a fine gravel drainage layer. Since only a few storm events produced high runoff in the study period, studies were also made using artificial rains on the roof in Augustenborg and on a smaller laboratory experimental roof plot. The effect of the slope of the roof, the length and the drainage layer could be investigated. Statistics were performed on the precipitation and the runoff data. Intensity–duration–frequency curves were derived. The most intense events were analysed to estimate time of concentration for the roof.

Study area and experimental setup

In Malmö, integration of stormwater facilities in the urban environment has been a focus for a decade (Stahre 2002). Augustenborg, situated almost in downtown Malmö, is a residential area with some industrial buildings. After having had problems with combined sewer overflows for a long time it was decided to disconnect most of the stormwater from the combined sewer system and instead distribute the stormwater in an open system and handle much of the stormwater locally. The concept behind the new system was discussed by Stahre (2002). More details about the open system at Augustenborg are given by Villareal *et al.* (2004). As part of the new system most of the low industrial buildings were provided with green roofs. Some of the roofs are reserved for research purposes. Vegetation development, insulation effect and hydrology are studied. Runoff from the roofs generated by real rains was measured. Runoff was also generated applying artificial rains to the roofs.

The extensive green experimental roofs in Augustenborg are 4 m long, 1.25 m wide and are sloping by 2.6%. The runoff water from the roofs was collected via a flume and a hose into a barrel below each roof. From one of the roofs, the one reported on here, the runoff intensity was determined by automatic continuous recording of the water level in the barrel. The time resolution was set to 5 min. As a control the daily runoff was also measured from two other roofs, one identical to the first roof, the second differing only by not having a drainage layer. The readings of the water levels in the barrels below these two latter roofs were made manually during most of the study period, but in some periods of 2002 the recording was also automatic for the roof without a drainage layer. The area ratio roof–barrel was 20:1, which means that 1 mm runoff resulted in 20 mm increased level in the barrel. The vegetation on the roofs is sedum-moss, which grows on an about 3 cm thick soil substrate layer. The drainage below is a 1 cm crushed stone layer. The soil substrate consists of 5% clay, 5% crushed limestone, 43% crushed roof tiles, 37% sand and 10% organic material. Runoff was measured for $1\frac{1}{2}$ years (July 2001–Dec. 2002). The daily measured runoff was almost the same from all three roofs.

A meteorological station was mounted on the roof. Rain intensity, wind speed and direction and different types of radiation were measured. The rain intensity was measured with 5-min resolution with a tipping-bucket gauge. Each tip represented 0.1 mm. More details about the measurements, including a photo of the experimental roofs at Augustenborg, are found in the previous paper by Bengtsson *et al.* (2005).

Since there were only 6 events producing more than 1 mm runoff over 10 min, experiments were carried out with artificial rains to obtain more information about the rainfall–runoff response. High-resolution experiments were performed on the Augustenborg roofs and on a special laboratory experimental roof plot, which could be tilted at different angles. On the Augustenborg roof as well as on the experimental roof plot, water was applied manually to simulate design rains and to reproduce observed real rains.

In Augustenborg water was evenly, and at a constant rate, sprayed onto the roof. Two different intensities were used: 0.4 and 1.0 mm/min. The runoff was determined from the level in the barrel beneath the roof with a 1-min resolution. The Augustenborg experiments continued until the runoff intensity was constant. There are identical roofs at Augustenborg, so the experiments could be repeated the same day with almost identical initial conditions.

Most of the experiments with artificial rains were done on a special roof plot. The roof plot is, as for the Augustenborg roof, covered with about 3 cm sedum-moss vegetation. At the time of the experiments the sedum-moss vegetation had developed over one season only, as compared to that at Augustenborg where the vegetation had developed over two years. The roof plot is 2 m long compared to the 4 m long Augustenborg roof, and can be reduced to 1 m. The experiments were carried out with and without the drainage layer. The roof was tilted in different angles from 2.6% to 23%. Water from a bottle representing 1-min rain volume was sprayed evenly in time and space over the plot. The runoff water was collected manually in bottles downstream from the roof. Each bottle represented 1-min runoff.

The characteristics of the soil substrate were determined in the laboratory in conventional ways. As shown in a previous paper (Bengtsson *et al.* 2005), the porosity of the soil substrate with a developed root system is 60–70%, the field capacity is 40–50% and the wilting point about 15%. The available storage of water between the wilting point and field capacity for a 3 cm soil substrate with root system is thus about 9 mm. Another 6 mm or more is required to saturate the soil.

The saturated hydraulic conductivity was measured with a constant head permeameter. Since the soil is only 3 cm thick, 2–5 layers were put on top of each other in the permeameter. The hydraulic conductivity was found to be about 0.03 cm/s. The hydraulic conductivity of the drainage layer was measured to be 0.05 cm/s, but since the layer is thin and the gravel loosely distributed on the roofs, the effective hydraulic conductivity is likely to be different.

Early studies of daily and hourly runoff

In the water balance study of the green roof in Augustenborg (Bengtsson *et al.* 2005), it was found that about 9 mm of rain was required to initiate runoff from a dry roof. This value corresponds to the available water storage between the wilting point and field capacity. Once runoff is initiated the runoff over periods longer than 1 h almost equals the rainfall. The highest observed hourly runoff in 2001 was 11 mm and in 2002 15 mm. The hourly rainfalls at these two events just barely exceeded the runoff intensity. During these two years there was hourly runoff exceeding 4 mm only on four occasions. During all these events the runoff equalled the rainfall.

During the period studied (July 2002–December 2002), there were only 6 days when the daily runoff exceeded 9 mm. The highest daily runoff was 20 mm in 2001 and 27 mm in 2002.

Measurement results

Real storms-real roof

The observations of real events at Augustenborg were made from July 2001 through 2002. Rain and runoff intensities of 5–30 min duration were determined for all events. The number of events with rain exceeding 1 mm during 10 min was about 15. The corresponding number of runoff events was 6. Similar rain events could cause high or little runoff depending on the initial soil conditions. The highest 5-min rainfall was 1.2 mm/min which, however, hardly produced any runoff at all, since the roof initially was almost dry when the event occurred. The two events producing the highest runoff peaks were in early August 2001, when a storm produced 5-mm runoff corresponding to 0.48 mm/min, and in early August 2002, when a 5-min runoff of 0.43 mm/min was measured. The two storms were rather similar in character. The 5-min peak was 0.76 mm/min in 2001 and 0.62 mm/min in 2002. The 20-min rain intensity corresponded to 0.48 mm/min in 2001 and to 0.41 mm/min in 2002.

In Table 1 the 5–15-min runoff intensities are compared with rain intensities of different durations for the same storm event; the events could last for some hours, which means that the highest runoff intensities do not necessarily coincide with the timing of the highest rain intensities. Considering only events when the 10-min rainfall is at least 1 mm (0.1 mm/min), it is seen that the 5-min runoff intensity corresponds to the mean rain intensity over about 20–30 min or longer. It is also seen from the table that the 5-min rain intensity is not much higher than the 15-min rain intensity, indicating that the rainfall-produced runoff is distributed over a prolonged time.

Until the soil–vegetation system is at field capacity, water can be stored on the roof for a rather long time. Water is lost only through evapotranspiration. After field capacity is reached and it continues to rain, runoff is generated but also some excess storage is built up. This increase of the water storage on the roof is temporary over rather a short time, since the excess water varies with the rain intensity and is drained after the rain has ceased. The time for the whole roof, after initiating of runoff and thus after the soil–vegetation system has reached field capacity, to contribute to runoff is considered to be the time of concentration for the roof.

A detailed comparison between observed rainfall and runoff is done in Fig. 1 for an event on 7 August 2001. The rain peak over 5 min is 0.76 mm/min and the runoff peak is 0.48 mm/min. By assuming a constant concentration time for the roof of 15 min, the 5-min runoff can be computed as the mean rainfall over 20 min. In this way computed runoff is also plotted in Fig. 1. The fit is very good. The storage of water on the roof increased by 5 mm from the start of runoff until the peak occurred. The storage is computed from simple water balance, so the difference between rain and runoff is the change in storage.

Another example from October 2002 with lower intensities and longer duration is shown in Fig. 2. The runoff peak, 0.15 mm/min, is not so far from the rain intensity peak, 0.20 mm/min. The rain intensity exceeded 0.15 mm/min over 30 min, so there was no pronounced peak rain intensity. In Fig. 2 the mean rain intensity over 30 minutes is also shown. After two hours and about 16 mm of rain and 6 mm of runoff the mean 30-min rain intensity is close to the runoff. Before that the runoff is of low intensity. When the peak runoff occurred, the storage had increased to 13 mm, which is 4 mm in excess of the 9 mm field capacity.

Artificial storms-real roof

The storms generating intense runoff from the green roofs at Augustenborg were rather few and therefore it was difficult to determine the storage capacity of the roofs and the time of concentration only from the runoff observed from real storms. Therefore, artificial rains were applied to the roofs at Augustenborg. The experiments were performed when the roofs were dry after two weeks with no rain, and after they had been saturated and allowed to drain to field capacity. The storage capacity of the green roofs was estimated and the time to reach a steady-state condition, i.e. when the runoff equals the rain intensity, was determined. When artificial rain was applied to an initially dry roof the first runoff occurred after 9–10 mm of rain regardless of the rain intensity, which is in agreement with the results from the real rain observations.

The Augustenborg experiments continued until the runoff intensity was constant. The water never did reach above the vegetation. The time from initiation of runoff until the time when steady-state conditions were obtained was considered as the time of concentration. For an intensity 0.4 mm/min the time of concentration was determined to be 16–20 min, and for 1.0 mm/min to be 12–13 min.

When runoff occurs, the soil moisture is above field capacity and large parts of the soil substrate are saturated. Water is stored on the roof during a storm event. By comparing the

Table 1 Episodes with intense runoff from 3 cm sedum-moss roof in Augustenborg, Malmö, August 2001–December 2002. Rain intensity, *p*, and runoff intensity, *q*, mm/min with different durations

Year	Date	*p* 60 min	*p* 30 min	*p* 20 min	*p* 15 min	*p* 10 min	*p* 5 min	*q* 15 min	*q* 10 min	*q* 5 min
2001	Aug 7	0.22	0.39	0.48	0.57	0.67	0.76	0.45	0.47	0.48
	Sep 4	0.09	0.11	0.12	0.13	0.15	0.16	0.08	0.08	0.08
	Sep 8	0.04	0.07	0.08	0.11	0.15	0.20	0.07	0.07	0.08
2002	Feb 26	0.05	0.06	0.07	0.07	0.09	0.10	0.05	0.06	0.06
	Mar 12	0.06	0.08	0.10	0.11	0.11	0.12	0.06	0.06	0.07
	May 5	0.11	0.15	0.17	0.19	0.22	0.22	0.17	0.18	0.19
	Jun 13	0.09	0.14	0.18	0.19	0.24	0.26	0.05	0.05	0.05
	Jun 21	0.13	0.26	0.39	0.50	0.54	0.58	0.08	0.10	0.10
	Jul 22	0.11	0.17	0.21	0.25	0.31	0.39	0.10	0.15	0.16
	Aug 2									
	Morning	0.22	0.40	0.59	0.77	1.13	1.18	0.04	0.05	0.08
	Evening	0.07	0.10	0.11	0.11	0.12	0.14	0.06	0.06	0.06
	Aug 3									
	Morning	0.08	0.15	0.19	0.20	0.22	0.26	0.12	0.13	0.15
	Noon	0.26	0.32	0.41	0.47	0.51	0.62	0.29	0.38	0.43
	Oct 17	0.11	0.16	0.18	0.18	0.19	0.20	0.14	0.14	0.15

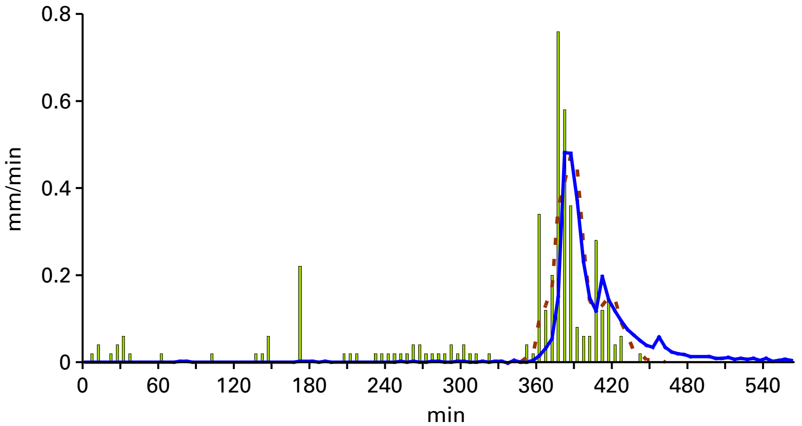

Figure 1 Rain (bars) and runoff (solid line) from 3 cm sedum-moss roof in Augustenborg, 7 August 2001, and simulated runoff (dashed line) as mean rain intensity over 20 min

accumulated applied rain and the accumulated runoff the variation of the storage of water in the soil–vegetation on the roof can be determined. The temporary storage, defined as the storage in excess of field capacity, on the roof in Augustenborg reached almost 8 mm during the 1 mm/min experiments, and was about 4 mm when the rain intensity was 0.4 mm/min.

Artificial storms-roof plot

On the laboratory roof plot it was possible to investigate the influence of the slope and length of the roof on the runoff distribution, and also the effect of the drainage layer. The artificial rains used represented constant rain intensity, a design rain with peak, and a short intense storm observed with 1-min resolution in July 2002 at the official meteorological station at Turbinen in Malmö. Rains observed at Augustenborg only had 5-min resolution, so they were not used. The design storm having a return period of about 1.5 years was derived from the Niemczynowicz (1982) data from Lund. The rain distributions can be seen in Figs. 3 and 4, when the generated runoff is discussed.

The experiments were first done with the same slope as in Augustenborg. As for the Augustenborg roof it was found that about 9 mm of water was required to generate runoff

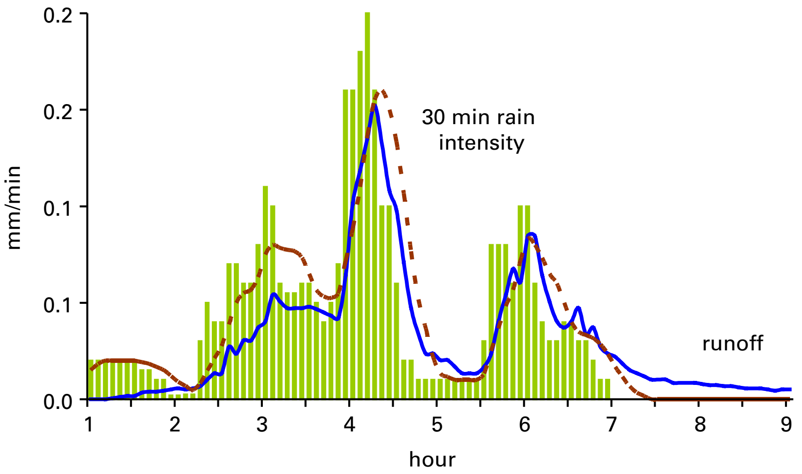

Figure 2 Rain intensity (bars) and runoff (solid line) from 3 cm sedum-moss roof in Augustenborg 17 October 2002, and simulated runoff (dashed line) as mean rain intensity over 30 min

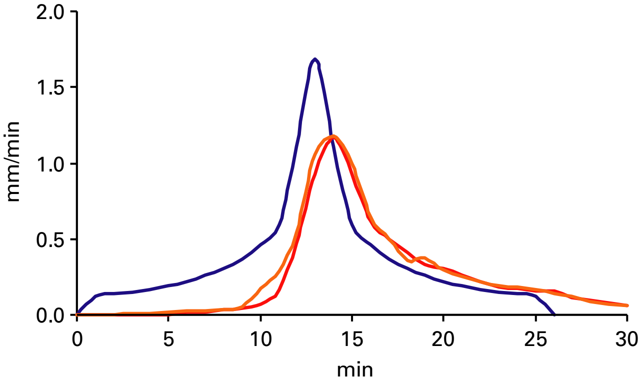

Figure 3 Runoff from 2 m long experimental green roof study plot with drainage layer sloping 3% and 20% (almost identical lower curves) as a result of artificial Lund design rain (upper curve). Excess storage 4 mm

when the roof plot was initially dry. The time to reach steady-state conditions, when starting from wet conditions, was found to be 12–15 min for a rain intensity 1.0 mm/min and 15–18 min for a rain intensity 0.4 mm/min. These are almost the same values as those obtained for the 4 m long roof in Augustenborg. The temporary storage during a storm was, however, found to be less for the roof plot than for the real roof in Augustenborg. The storage on the plot reached only 4.5 mm on the roof as compared to almost 8 mm in Augustenborg for 1.0 mm/min rain intensity, and for 0.4 mm/min intensity only 2.5 mm on the plot as compared to 4 mm in Augustenborg. Overland flow was not observed on the roof plot. It should be recalled that the vegetation system at Augustenborg had developed over a longer time than the young vegetation on the plot.

The Lund design rain, whose distribution can be seen in Fig. 4, had a 1-min peak intensity of 1.7 mm/min. The runoff peak from the roof plot generated by the design rain was 1.2 mm/min when the roof initially was wet. The 1-min runoff resolution is shown in Fig. 4. The 10-min rain intensity is 0.7 mm/min and the 10-min runoff is 0.6 mm/min. The maximum excess storage reached 4 mm. In the figure the runoff from two different experiments with different tiltings of the roof plot are shown. As is discussed later the influence of the slope of the roof on the runoff distribution is minor, which can be seen from the fact that the two hydrographs are almost identical.

The effect of the short intense observed storm was also simulated on the roof plot (Fig. 5). The storm lasted 18 min. While the peak rain intensity was 0.51 mm/min the peak runoff

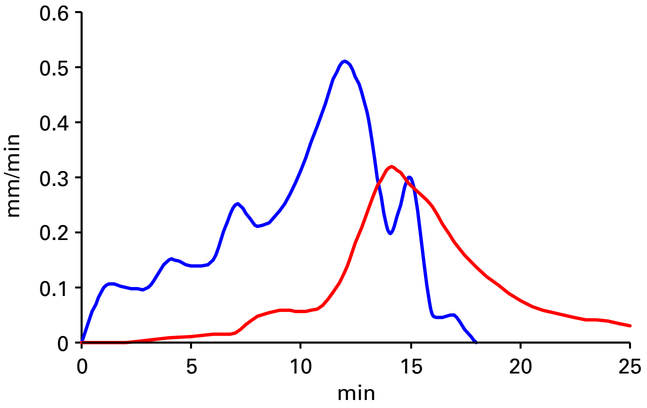

Figure 4 Runoff (lower curve) from experimental green roof with drainage layer sloping 10% produced by an observed shower (upper curve). Initially wet conditions. Excess storage 3 mm

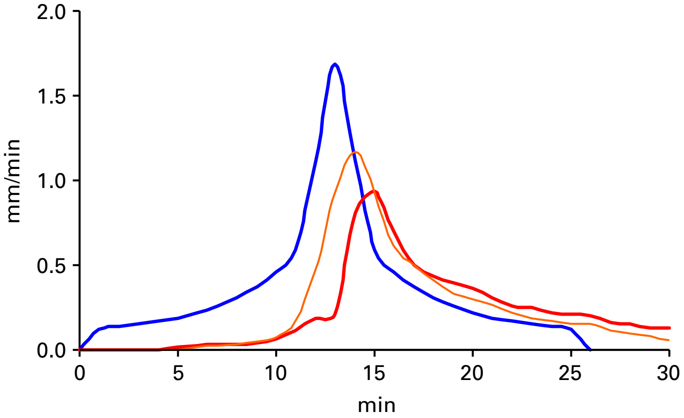

Figure 5 Runoff from 2 m long experimental roof plot sloping 7% with drainage layer (thin middle curve) and without drainage layer (lowest curve) generated by artificial design rain (uppermost symmetrical curve)

intensity was only 0.18 mm/min. The runoff peak corresponded to the mean rain intensity over 20 min. The excess storage was almost 3 mm.

All the experiments were repeated with steeper slopes for the roof. The runoff response remained almost the same for all slopes between 2.6% and 23%. A comparison between the 3% and 20% slope is shown in Fig. 3 for the design rain.

The plot was shortened to 1 m to see the effect of the roof length on the runoff response. For the design rain, the peak runoff increased a little from 1.2 to 1.3 mm/min when the plot was shortened, but the mean runoff over 5 min did not change. The time to reach steady state, when a constant rain of 1 mm/min was applied, was almost the same as for the 2 m long roof, which in turn was almost the same as for the 4 m long roof in Augustenborg. Thus, neither the slope nor the length of the roof seems to significantly influence the runoff response to intense rains.

The drainage layer was removed and all the experiments were repeated. When comparing the runoff from a roof with and without a drainage layer, it was found that the runoff peaks produced by the design storm and by the observed rain were lower when the drainage layer was removed. For the design storm the peak runoff reduced from 1.2 mm/min to 0.9 mm/min; the 10-min runoff reduced from 0.6 mm/min to 0.5 mm/min. The comparison is shown in Fig. 5. The excess storage was slightly higher for the roof plot without a drainage layer (about 4.5 mm) than from the plot with a drainage layer (4 mm).

The runoff response to the observed July shower was slower without a drainage layer than in the presence of one, although the peak did not differ very much: 0.16 as compared to 0.18 mm/min. The runoff was minor until the excess storage was about 2 mm.

As discussed above and seen from Fig. 5, the runoff response for intense storms was slower when the drainage layer beneath the soil substrate was removed. When comparing the runoff response of the roof plot with and without a drainage layer for rains with constant rain intensity, it was found that the time from initiation of runoff to reach steady-state runoff, defined here as the time of concentration, increased slightly by 2–3 min when the drainage layer was removed. Some water was observed on top of the vegetation at the very downstream end of the roof plot when rain of constant intensity 1.0 mm/min was applied.

Analysis of runoff response

It is clear that runoff is not generated from vegetated roofs until the soil is at field capacity. The initial storage can be considered to correspond to conditions at the wilting point. The laboratory tests showed that the difference between field capacity (45%) and wilting point

(15%) corresponds to 9 mm storage for the 3 cm soil substrate. Thus the runoff observations are in agreement with the soil characteristics determined in the laboratory.

During a storm the water storage in the soil–vegetation system exceeds the storage corresponding to field capacity. The storage is higher the higher the rain intensity is. The storage was from continuity calculated to be up to 8 mm in excess of that corresponding to field capacity. It is less when a roof is short.

The runoff response to rainfall shows no dependence on slope and very little dependence on the roof length. Thus, the runoff distribution in time must be a result mainly of the vertical movement through the thin soil and of the storage within the vegetation and in the soil. The vertical movement through a rather wet soil corresponds to the unsaturated hydraulic conductivity, which is a function of the soil moisture. The soil is heterogeneous with a dense root system, so a quantitative analysis is not possible. However, it can be stated that the higher the rain intensity is, the higher the soil moisture is and the faster the water can move through the soil.

Still, some qualitative analysis is possible. Using the available information about the soil characteristics (field capacity 45%, porosity 70%) it is seen that the maximum increase in soil moisture when rain water is percolating into soil at field capacity is 25%. If a pulse of 1 mm/min is moving into a soil being at field capacity, assuming homogeneous soil and neglecting capillary forces, the pulse moves with a velocity $1/0.25 = 4$ mm/min; the time for travelling through 3 cm soil is then $7\frac{1}{2}$ min. The runoff experiments indicate a longer time, but still travel times of this order of magnitude.

After infiltration and percolation the water must move in the drainage layer and in the soil–vegetation system as saturated flow. The hydraulic conductivity was determined to be 0.03 cm/s. If Darcy's law is applied it can already be seen that, for rain intensities much less than 1 mm/h, all the rain water from the Augustenborg roofs cannot be transported as subsurface flow. The soil cover is much too thin. Since overland flow has not been observed, it seems that Darcy's law is not applicable for horizontal flow in the macro-pore system of the soil. Also the almost non-existent relation between runoff response and roof slope indicates that Darcy's law is not applicable. Instead the horizontal flow is rather fast, especially in the presence of a drainage layer. The relation of travel velocity to slope must be less pronounced than linear.

The time of concentration computed from the experiments with constant rain intensity was dependent on the rain intensity and was in the range 12–20 min when the rain intensity was 0.4–1.0 mm/min. This is in agreement with the observed runoff distribution from real rains. The 5-min runoff generated by real storms could best be described with the mean rain intensity over 20 mm, cf Fig. 3, which corresponds to a concentration time of 15 min, when the rain intensity almost reached 1.0 mm/min. For the low intensity storm shown in Fig. 4 the rain intensity never exceeded 0.2 mm/min, and consequently the time of concentration was longer, about 30 min.

It was found that the runoff response to rainfall on the green roofs was faster in the presence of a drainage layer than without. The horizontal transport is faster in the drainage layer than in the soil substrate. The total travel time is, however, mainly determined by the vertical processes, so the total travel time does not differ very much. Still, if the rain has a peaked distribution, the runoff peak is reduced when there is a drainage layer compared to when there is not.

Rainfall and runoff statistics

Statistics can be used on the runoff without considering initial conditions. The observed data allow intensity–duration–frequency (i–d–f) curves to be determined. The i–d–f curves for rainfall and runoff from the Augustenborg green roof are given in Fig. 6. Since there are

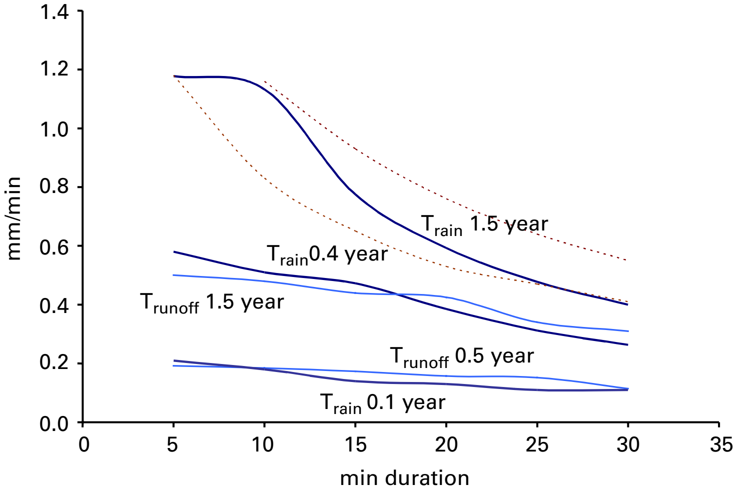

Figure 6 Intensity–duration–frequency curves (T_p for rain and T_q for runoff with return period in years as index) from 3 cm sedum-moss roof in Augustenborg, Malmö. Maximum rain and runoff represent 1.5 year return period. The dashed lines shows intensity–duration curves with return period 1.5 and 3 year as given by Niemczynowicz (1982)

observations for $1\frac{1}{2}$ years, the highest values are assumed to correspond to a return period of 1.5 years and the second highest values to a return period of 0.75 year and so on. By comparing with 1.5 and 3 year rain intensities derived by Niemczynowicz (1982), it is found that the highest observed rain intensities in Augustenborg have a return period higher than, but close to, 1.5 year.

In the intensity–duration–frequency figure, the rain and the runoff are shown. The highest runoff curve, which then should have a return period of 1.5 years, is rather close to the rain intensity–duration curve of return period 0.4 year. The runoff intensity–duration curve of return period 0.5 year follows the rain intensity–duration of return period 0.1 year. Comparing the two intensity–frequency curves of maximum rainfall and runoff, i.e. return period 1.5 years, it is seen that the runoff intensity with duration 10 min equals the rain intensity with duration 25–30 min.

The i–d–f curves derived here can be used for designing stormwater systems directly connected to extensive green roofs.

Design conditions

Water from a hard roof runs off almost directly as the rain falls on the roof. Runoff from a green roof does not occur until the green roof soil is at field capacity. After runoff is initiated, the rain on the green roof is delayed and attenuated before it appears as runoff. The return period of an event causing runoff peaks of the same magnitude is higher for a green roof than for a hard roof. The rain corresponding to a 2-year event is more intense for the green roof than for a hard roof. However, a green roof constitutes part of a stormwater system, where there might be other stormwater facilities, and where runoff is generated at least from hard roofs and impermeable surfaces. The different urban sub-systems should probably be designed for different events. However, when designing a downstream system, the same rain must be used as input over the whole drainage basin, unless the basin is big. Therefore, the concentration time and a design rain rather than design runoff based on statistics should be used for the design.

To see to what extent green roofs reduce the peak flow from an urban area a single example is shown. The best approach for design, when there are storage facilities within a stormwater system, is continuous modelling, but the effect of green roofs on runoff peaks is more directly seen from simple reasoning. It is first assumed that the contributing area to runoff is 50% impermeable ground surface and 50% hard roofs. The lateral inflow of overland flow from the impermeable ground surfaces and from the roofs to a pipe is uniform along the pipe. The floating time in the pipe is 5 min. The inflow from the roofs is direct, while the concentration time for overland flow on the ground to the pipe is 5 min. The design rainfall has a peaked distribution ($p(t) = 0.55|t|^{-0.7}$, when t is in min and p is in mm/min) corresponding to 5-min mean maximum intensity 1.0 mm/min, and 10-min mean maximum 0.6 mm/min. Using the approach of constant floating time, the maximum runoff at the downstream end of the pipe outlet is computed to be 0.9 mm/min. The full hydrograph is shown in Fig. 7.

After that it is assumed that half of the roofs are converted to green roofs. The concentration time for the sedum-moss roofs is chosen as 25 min for rain intensities 0.3–1.0 mm/min. The soil of the green roofs is assumed to initially be at field capacity. The new outflow hydrograph (50% hard ground surface, 25% hard roof, 25% green roof) is also shown in Fig. 7. The peak flow is reduced compared to when there are no green roofs and it is much delayed. The peak is 0.75 mm/min. The figure also shows the hydrograph if all the roofs were extensive green roofs: peak 0.6 mm/min. Still, the green roof contribution to the runoff is significant. The peak, if there would not be any runoff at all from the green roofs, would only be 0.45 mm/min, as is also shown in the figure. By placing the green roofs in a strategic way in an urban basin, it should be possible to obtain a considerable reduction of downstream peak flows.

Conclusions

While the probability of high intensity runoff from hard roofs is the same as the probability of high intensity rainfall, the probability of high runoff from thin green roofs is much lower. Rain on dry green roofs hardly produces any runoff at all. Runoff produced by rain on wet roofs is delayed and the runoff peak reduced compared to the rain intensity peak. In Augustenborg the runoff of 1.5 year return period from a 3 cm thick sedum-moss roof

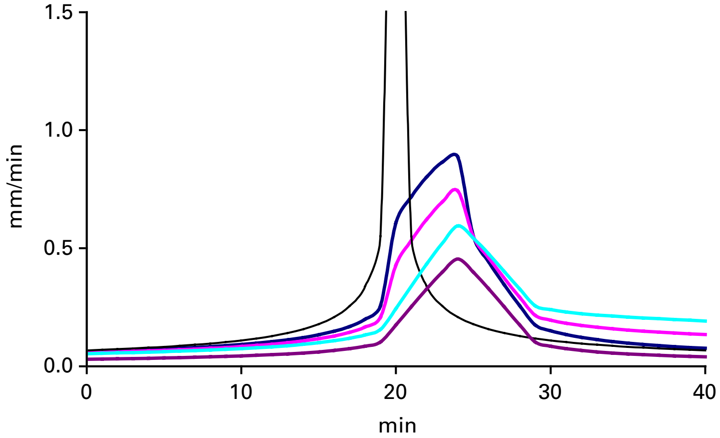

Figure 7 Computed hydrograph from an urban basin with concentration time 10 min, of which 5 min is floating time on the ground and 5 min floating time in pipes, resulting from a peaked design rain ($p(t) = 0.55|t|^{-0.7}$, shown as the very peaked graph; the 1 min intensity is 3 mm/min) when the contribution to runoff is from 50% impermeable surfaces on the ground and a) 50% roofs with direct runoff to the pipe (runoff curve with the highest peak), b) 25% roofs with direct runoff and 25% sedum-moss roof with 25 min concentration time (curve with second highest peak), c) 50% sedum-moss roof (all the roofs) (second lowest peak) and d) no runoff contribution from roofs (lowest peak)

corresponds to rain of 0.4 year return period, and runoff of 0.5 year return period corresponds to rain of 0.1 year return period. The runoff from individual storms can best be described as the mean of the rain intensity over 20–30 min. The runoff distribution is not much influenced by either the slope of a green roof or by the length. The concentration time is mostly related to the vertical movement through, and the storage in, the vegetation and thin soil substrate. The response is slightly faster and thus the runoff peak is higher with than without a drainage layer.

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