

Hydrological function of a thin extensive green roof in southern Sweden

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Abstract The runoff from and the water balance of a thin extensive green roof with sedum-moss have been studied. The soil cover is about 3 cm underlain by a thin drainage layer. The water balance is determined on a monthly basis. The runoff from the green roof is much reduced compared to runoff from hard roofs because of evapotranspiration. The annual runoff is rather close to that of natural river basins. Although most rainy days there is no or little runoff from the roof, the highest observed daily runoff values are close to the daily rainfall. Runoff is initiated when the soil is at field capacity, which for the studied roof corresponds to 9 mm storage. After that, on a not very short time basis, the runoff equals the precipitation. The reduction of the daily runoff can be described in a simple way knowing the daily precipitation, potential evaporation and storage capacity of the green roof.

Keywords Green roof; sedum-moss; urban runoff; water balance

Introduction

Green roofs with some form of vegetation cover are becoming popular today, maybe mainly for aesthetic reasons and as being part of a sustainability trend. Houses with green roofs were common hundreds of years ago, especially where the climate is wet as, for example, in Iceland. The vegetation on the roofs used to be grass or moss. The objective of using vegetation on the roofs was for insulation. In climates where the potential evaporation during summer much exceeds the precipitation, a thick soil cover is required to keep grass alive. This means a heavy load on the house construction. However, sedum and mosses can stand long periods of drought, see, for example, [Rusinska and Balcerkiewska \(1978\)](#). Using this kind of vegetation instead of grass, the soil cover can be thin.

In principle there are two classes of green roofs: intensive and extensive. Intensive green roofs have a thick soil layer, > 30 cm. Large plants grow on these roofs, which sometimes are called roof gardens. The soil cover of extensive roofs can be down to a few cm and can therefore only sustain low and durable plants such as succulents. When the soil cover is very thin, green roofs can be put on existing buildings without reinforcement.

A reason for building green roofs today is still their insulation effect, but there are many other reasons for having green roofs. The main objectives for green roofs are: 1) insulation, 2) reduction of heat island effect, 3) biodiversity, 4) creating blue-green urban streaks or zones, 5) aesthetics, 6) reduction of stormwater runoff and 7) improving stormwater quality.

Today, the interest is more focused on the cooling potential of green roofs than on their insulation effect during cold weather. [Niachou et al. \(2001\)](#) and [Onmura et al. \(2001\)](#) studied the passive cooling by determining heat and moisture fluxes. The air temperature within a city is higher than outside the city, and the air is drier. Green roofs can be a way to battle urban heat islands, as discussed by [Brake \(2001\)](#). Vegetation on roofs attracts birds, butterflies and insects. Thus biodiversity in the city increases. [Maeda \(1993\)](#) discusses

habitats for birds in a city and the need for green areas. Green roofs can be parts of urban greenways or blue-green zones in a city. [McGuichin and Brown \(1995\)](#) showed how urban greenways, relying much on open water, could be established in Guelph, Ontario. [Gómez et al. \(2001\)](#) studied the role of green zones in Valencia, Spain, emphasising people's comfort with respect to the urban climate.

For town planners the main reason for building green roofs is probably the aesthetic one. They often refer to them as eco-roofs. For the exhibition Bo-01 in Malmö many houses were built with extensive green roofs. Another example from Sweden is the Library in Linköping. The city hall of Chicago is a more famous example as is the library in Vancouver. [Thompson \(2000\)](#) gives more examples of green roofs on official buildings. Most of the examples given are, however, roofs which require some maintenance.

Green roofs can also be part of the stormwater system, see, for example, [Sieker \(1998\)](#). The water balance is changed rather much if rainwater is stored on the roofs to evapotranspire, instead of running off directly. Even when there is considerable runoff from a green roof, it may be delayed relative to the most intensive rain and relative to the runoff from other surfaces so that smaller stormwater pipes can be used compared to when there is no vegetation on roofs. [Zimmer and Geiger \(1997\)](#) have described how to design a multi-layered infiltration system based on green roofs and porous pavements.

In Augustenborg, Malmö, Sweden, the stormwater from roofs and other impermeable and semi-permeable surfaces has been disconnected from a combined system. Instead it is to be handled locally to be reduced as much as possible or to run off in an open stormwater system. Green roofs are a part of this system, the intention being to reduce the annual runoff and also to reduce the runoff peaks. The runoff is measured in the open canal-pond system and from green roofs with different vegetation. The present paper reports results from a study of the hydrological function of an extensive sedum-moss covered roof: the total runoff and the monthly water balance are analysed, and also the storage on the roof during storm events.

The experimental station of Augustenborg

Augustenborg is a residential area located in the central part of Malmö city in southern Sweden. The area was planned and constructed in the 1940s–1950s, and was at the time considered a modern and innovative project based on community concepts from Great Britain and USA. Fifty years later, however, poor maintenance and insufficient renovation had caused it to degrade. Therefore, in 1998 it was decided to comprehensively revitalise the area; a project termed Eco-city Augustenborg was initiated. This is a summarising name for a number of sub-projects aimed at making the area ecologically, socially and economically sustainable. The sub-projects include installation of facilities for recycling 90% of the wastes produced, renewal of parks and green areas in cooperation with the inhabitants, and renewal of the stormwater system.

A main objective of Eco-city Augustenborg is to find new and improved solutions for stormwater management. The combined sewer system in the area has long been under heavy pressure and flooding has plagued the area, in many cases damaging basements and other facilities. To alleviate the situation the entire system has been reconstructed. The stormwater has been disconnected from the existing combined system as much as possible. Instead it is delayed and transported in a network of open canals and ponds; stormwater is allowed to spill over and infiltrate near the small canals; rainwater is retained on green roofs. Small canals convey the runoff from each residential property to larger canals that cross the area along bicycle- and footpaths. The larger canals lead to ponds located next to residential buildings. Further downstream there are infiltration areas, which can be flooded during major events. The aim is to reduce the stormwater runoff from Augustenborg into the combined sewer system by at least 70%. [Stahre \(2002\)](#) has shown many examples of integrating

stormwater facilities in the urban environment in Malmö. The Augustenborg example is the most spectacular, especially since the new system is applied to an old already built part of the city.

The new open stormwater system consists of canals, ponds and infiltration surfaces, and roofs with vegetation. Many hard roofs have been converted into extensive green roofs. To date, 9500 m² of extensive green roofs have been installed in a municipal industrial complex located upstream in the Augustenborg area. A large part consists of demonstration surfaces. Some of the green roofs have been reserved for research purposes. Different roof sections have different vegetation, grasses, sedum, mosses and herbs, different soil thickness, type of drainage layer and different slopes.

The precipitation onto, and the runoff from, one of the extensive green roofs are presented in this paper. The measurements are continuous with a time resolution of 5 min. There is a tipping bucket rain gauge with depth resolution 0.1 mm on the roof and a meteorological station, which registers air temperature, wind, relative humidity and different kinds of radiation. The runoff water from the roof is transferred via a hose to a barrel beneath the roof, in which the level is measured. The runoff observations from the roof as presented in this paper started in mid-July 2001 and continued through 2002. The daily runoff was also measured from other roof sections by manual observations of the water level in barrels beneath the roofs. All the roofs are 5 m². Since the area of the barrels is 0.25 m², 1 mm runoff from the roof corresponds to an increase of 20 mm in the barrel. A photo of the test roofs is shown as [Figure 1](#). The figure shows the character of the vegetation and it also shows the meteorological station and the runoff collecting system.

Characteristics of the roof and the soil

The thin green roof is sedum-moss, the character of which is seen in [Figure 1](#), with an about 3 cm soil substrate layer on top of a thin 1 cm crushed stone drainage layer. The roof section



Figure 1 Photo of the experimental roofs at Augustenborg. The hoses lead to barrels beneath the roof. The meteorological station is to the right

is 4 m long and 1.25 m wide sloping 2.6%. On the bottom there is a membrane protecting the original roof. The soil substrate is 5% clay, 5% crushed limestone 8–12 mm, 43% crushed roof tiles 8–12 mm, 37% sand and 10% organic material.

The soil characteristics were determined in the laboratory in conventional ways. Before the laboratory tests were performed, the vegetation was cut, but the dense root system was kept. By measuring the volume of a sample and weighing it, the soil density including the roots was determined. Because of a dense root system the soil sticks together and samples from the surface down to the full 3 cm depth can easily be taken. The weight was determined first after the sample had been saturated, then after free drainage, then after 5 days in a dry atmosphere, and finally after micro-oven drying to constant weight. The weight of water removed was converted to volume. The condition after free drainage was considered to represent field capacity. It was assumed that the soil moisture of the thin soil reduced to the wilting point after 5 days at normal dry room temperature. Since it is difficult to completely saturate a soil sample, the porosity was also determined by comparing the bulk mass density (oven-dried mass divided by field volume) and the particle mass density (oven-dried weight divided by the volume of the solid particles determined from water displacement). Both methods showed that the porosity was 60–70%. Repeated measurements showed that the field capacity was 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 is thus about 9 mm.

Runoff hypothesis and expected results

From a hydrological point of view a roof with vegetation functions differently from a hard roof. Rainwater is retained and evapotranspiration takes place from the vegetation, while the rainwater runs off directly from the hard roof. As long as the soil moisture is below field capacity, there is hardly any runoff from a green roof. After field capacity is reached, runoff occurs. The soil is thin, so that already when the rain is light, some part of the soil becomes saturated and water flows in the soil substrate as a very shallow saturated sub-surface flow or in a thin film between the vegetation. When runoff is produced by a mild rain of long duration, the soil is saturated as long as the rain is continuous and then the soil moisture remains close to field capacity over extended periods. In the summer the soil often dries out between storms. In a few days the soil can dry out to near wilting point conditions. Then, when a storm occurs, rain water is stored in the soil–vegetation until field capacity is reached, when runoff is initiated. However, more water is stored to balance the relation between storage and runoff; the more intense the runoff, the more the storage as sub-surface water and overland flow water. When the rain ceases, the water on the roof which is in excess of that at field capacity is drained by gravity. Further reduction of the water storage is attributed to evapotranspiration.

Two time frames can be associated with the runoff reduction from green roofs. A short time frame is considered for the runoff response to an individual storm event, and a longer one for the seasonal runoff reduction. Especially in periods with high potential evaporation the runoff from green roofs is reduced compared with the precipitation. The response to short-term storms, and thus the peak flow, must depend much on how wet the roof soil–vegetation is prior to the rainfall, and thus on the antecedent precipitation. The reduction of the runoff as compared with that from a hard roof, when a second big storm follows a previous big storm, is, however, likely to be minor. Still, the very peak ought to be reduced compared to that from a hard roof, because the time required for the rain water to move vertically and horizontally in the soil substrate and in the vegetation is longer than the time required for the rain to flow down a hard roof.

Whereas the event-based timeframe is associated with the peak loads on sewers, the second, longer, timeframe is a seasonal one, associated with total loads over extended

periods. Seasonal differences in performance of the green roofs may be expected due to varying potential evapotranspiration and differences in dominant rainfall generating mechanisms. In southern Sweden, frontal rainfall associated with cyclone passages prevails over most of the year (fall, winter and spring). These events typically extend over several hours with low rainfall intensity, and are separated by dry periods of 3–5 days. This means that a green roof will not dry out completely between rainfall events, but some moisture remains. In summer, convective, short, high-intensity showers prevail. These are generally separated by longer dry periods. During summer the potential evaporation exceeds the monthly precipitation. Evapotranspiration takes place during the dry periods and the full buffering capacity of the green roof is likely to be available. This reasoning points at a seasonal variation in long-term runoff reduction, with the highest reduction during summer and the lowest during winter. This pattern has indeed been found in German studies (e.g. Köhler *et al.* 2001).

Previous studies of storm event response

There is not much to be found in the English literature on the hydrological behaviour of green roofs. From an experimental 1.3–2.6 m² roof study in Philadelphia, Miller (1998) reports that there was no runoff from a 7.6 cm thick (including vegetation, soil and drainage layer) roof cover unless storms exceeded 15 mm. For precipitation events between 15 mm and 25 mm the runoff lagged rainfall significantly. The maximum observed 5-min rain intensity was close to 1.0 mm/min, while the maximum 5-min runoff intensity was 0.3 mm/min. The pilot-scale experiment continued for 9 months. Miller reports a maximum roof water storage of almost 60 mm.

Köhler *et al.* (2001) have measured the runoff from two large 360 m² extensive green roofs with 5 cm and 12 cm soil thickness near Berlin. The total retention was 30 mm in the thin soil and 40 mm in the thick soil, when the precipitation depth over 3 days was 55 mm. They also studied the runoff from 8–10 cm thick experimental 2 m² green roof plots sloping 2%. When analysing a short intense storm of 10.5 mm in 15 min, it was found that runoff from these plots was initiated, when 4.5 mm of rain had fallen. The total runoff generated by the storm event was 6 mm. Thus, after initiating runoff the accumulated runoff equalled the accumulated precipitation.

Schmidt and Teschner (2000) have measured the runoff from green roof plots with different soils and also the runoff from 10-year-old roofs with high organic content in the soil. They found that a daily rainfall of 26 mm produced more runoff, 15–20 mm, from the green roof plots with soil substrate of coarse grains than from old roofs with organic soils, from which only little runoff was observed, <3 mm.

Previous studies of water balance

Köhler *et al.* (2001) measured the water balance of the Berlin roof mentioned above through 1997 and 1998. There was a clear seasonal effect for the runoff reduction relative rainfall. In November–March the runoff was near the precipitation. In the warmer part of the year, April–October the monthly runoff was 30–70 mm/month less than the precipitation, if of course the monthly precipitation was that large.

Also Schmidt and Teschner (2000) studied roof runoff in Berlin over extended time. In the period June 1997–January 1998 the precipitation was 280 mm. The runoff from a conventional roof was almost the same as the total precipitation, but the total runoff from green roofs with 10 cm soil of different substrates was only about 100 mm. The runoff from 10-year-old vegetated roofs was also measured and was about 50 mm.

In Philadelphia Miller (1998) measured rainfall and runoff from roof plots over 9 months. While the total rainfall was about 1100 mm, the runoff was only 400 mm.

Green roof water balance

The runoff from the thin sedum-moss roof in Augustenborg was measured from mid-July 2001 through December 2002. Individual rain events were studied as well as the overall water balance. The monthly water balance for a full year (August 2001–July 2002) is given in [Table 1](#). For the whole period the precipitation was 720 mm and the runoff 370 mm, which means that the evaporation was 310 mm. The water balance of the green roof was rather similar to that of small rural basins, for which the precipitation was 720 mm, the runoff 260 mm and the evaporation 460 mm. In September–March the evaporation losses corresponded to the potential evaporation. In the summer months the runoff was 30–50 mm less than the precipitation.

Daily runoff

The daily roof runoff in Augustenborg has been less than the precipitation except for a few days, when it rained for several consecutive days; those days the runoff equalled the precipitation. The highest daily rainfall observed during 2002 was 28 mm and the highest runoff was 27 mm. There were three more days with runoff around 20 mm. In 2001 the highest daily runoff was about 20 mm, after several consecutive days of rainfall in September. For these days the runoff was close to the precipitation. The precipitation and the runoff for 2001 are shown in [Figure 2](#) and for 2002 day by day in [Figure 3](#).

Hourly runoff

After field capacity is reached, the runoff as a mean over some time should equal the precipitation. An example is shown in [Figure 4](#) from 5 May 2002. No runoff occurs for the first few hours. At hour 4 runoff begins, and from hour 5 the runoff equals the precipitation. The maximum hourly rainfall this day was 6 mm, which was also the maximum hourly runoff. The highest observed hourly rainfall in 2002 was 16 mm and the highest runoff 15 mm. In 2001 the highest hourly rainfall was 11.5 mm and the runoff 11 mm. When rain falls on a dry roof, only a little runoff is generated. For example, 13 mm of rain during one hour on 2 August 2002 only generated 1 mm runoff.

Table 1 Monthly water balance of green roof in Augustenborg, 2001–2002

Month	Precipitation (mm)	Runoff (mm)	Evapotranspiration (mm)
August-01	89	48	41
September-01	110	76	34
October-01	43	17	26
November-01	50	29	21
December-01	37	25	12
January-02	76	62	14
February-02	69	56	13
March-02	29	13	16
April-02	28	5	23
May-02	52	13	39
June-02	64	8	56
July-02	58	26	32
12 month	705	378	327
12 month rural	710	260	450

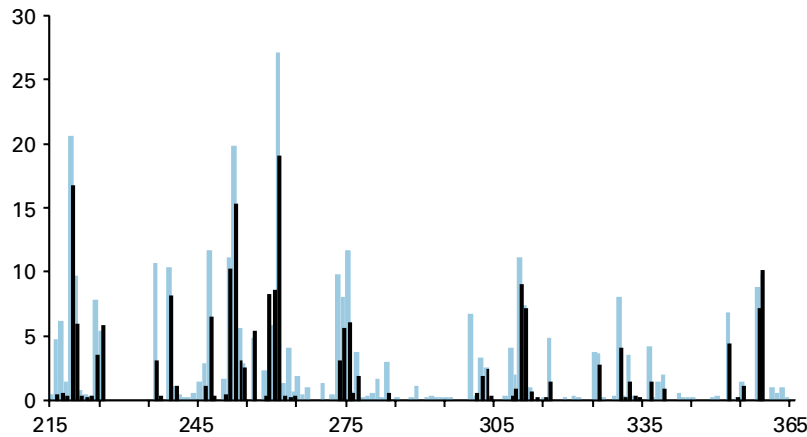


Figure 2 Observed daily mm rainfall (light grey) and runoff (black) for Julian days in 2001 from a green roof in Augustenborg, Malmö

Roof storage

Runoff from a green roof does not occur until the roof soil is at field capacity. When analysing storms occurring after dry periods, it is found that runoff is always initiated after 9–10 mm of rain, which, as shown above, is the difference between storage at field capacity and the wilting point. After runoff is initiated, on a not very short time basis, the runoff equals the precipitation. However, on a shorter time basis there is storage on the roof, which can be related to the runoff and the rain intensity variations. An example is shown in [Figure 5](#) from July 2002. It rained the previous evening and again from 8 in the morning. After initiation of runoff the storage on the roof remained 9–10 mm, but increased during those periods with intense rainfall. The storage as computed from the difference between precipitation depth and runoff depth reached 12 mm.

For some few occasions, when the rain intensity was rather constant over 30 min and the runoff almost equalled the rain intensity, it was possible to relate the storage to the rain intensity. As seen in [Table 2](#) the storage increases with rain intensity.

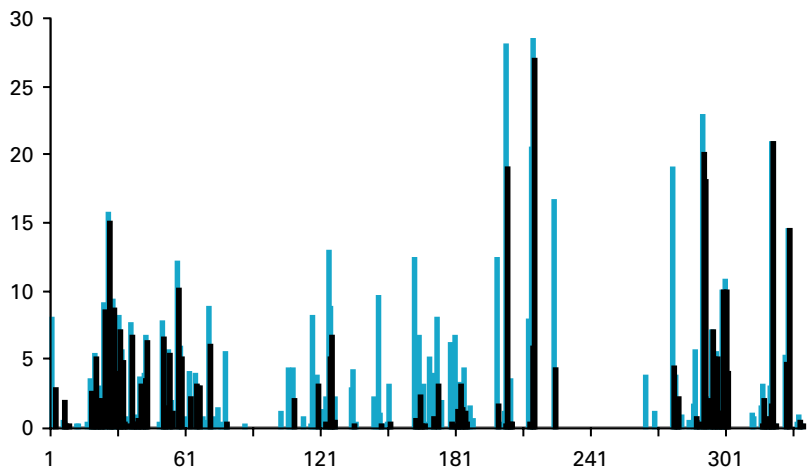


Figure 3 Observed daily mm rainfall (light grey) and runoff (black) for Julian days in 2002 from a green roof in Augustenborg, Malmö

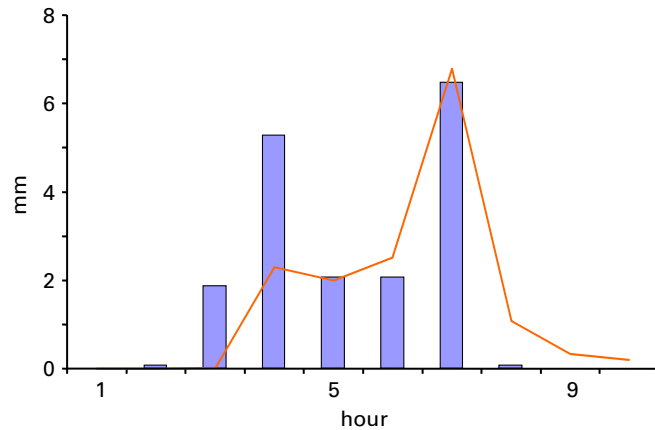


Figure 4 Hourly precipitation (bars) and runoff (line) from a thin green roof in Augustenborg, 5 May 2002

Simulation of daily runoff

On a daily time perspective, assuming that the rain has ceased or decreased to low intensity, all water in excess of the field capacity can drain and run off. Thus over a day the storage possibility on a green roof is the difference between the storage at field capacity and the storage prior to a rainfall. Assuming a green roof to be uniform with the same field capacity and the same soil cover thickness all over, a simple description of the hydrological function of a green roof on a daily basis can be given. The daily water balance is then

$$S < S_{FC} : dS/dt = p - q \quad q = 0; \quad S = S_{FC} : q = p$$

where S is storage in excess of that at the wilting point per unit area in the soil and the vegetation on the roof, p is precipitation, e is evapotranspiration and q is runoff. The maximum storage (on a daily basis, i.e. after drainage) corresponds to field capacity conditions and is S_{FC} . The actual evaporation, e , is less than the potential one, pe , and is related to the storage. The simplest approach for determining the actual evapotranspiration is to assume that the actual evapotranspiration corresponds to the potential one as long as there is water available in the thin soil, and if not there is no evapotranspiration at all.

This approach or simple model was used on the Augustenborg rainfall observations. The potential evaporation was crudely determined from meteorological data using the Priestly–Taylor method. The comparison between simulated and observed daily runoff is shown in

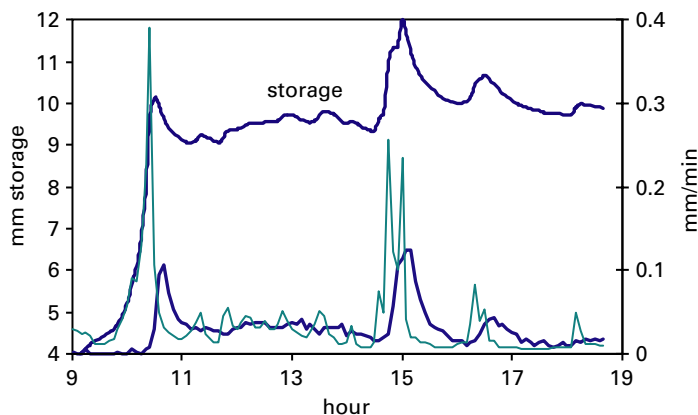


Figure 5 Rain (thin line) and runoff (thick line) and water storage on a thin green roof in Augustenborg, 22 July 2002

Table 2 Relation between water storage on the roof and rain intensity, when almost steady-state conditions prevail

Rain intensity (mm/min)	Storage (mm)	Storage in excess of runoff generation
0.10	9.5	0.5
0.10	10	1.0
0.15	11	2.0
0.25	12	3.0
0.30	12	3.0
0.40	13	4.0

Figure 6 for the period August–September 2001. The low peaks were computed too low and the highest peaks slightly too high. The storage capacity is somewhat related to rain intensity, even when rain over such a long period as a day is considered.

Conclusions

The evapotranspiration from a green roof with vegetation is high, in some months close to the potential one, which has the effect of greatly reducing the monthly runoff compared with the runoff from hard roofs. The annual runoff from a 3 cm sedum-moss roof in southern Sweden is about half of the precipitation and almost corresponds to the runoff from small agricultural basins. The maximum roof storage determined as the difference between precipitation depth and runoff depth for a storm event is 9–10 mm for the studied roof. After this amount of water has been stored on the vegetated roof, the runoff on a time resolution of an hour or longer corresponds to the rainfall. The reduction of the daily runoff can be related to the field capacity and the initial storage on the green roof. It is possible to simulate the daily runoff from daily precipitation and evaporation assuming that all water in excess of the storage at field capacity spills over. During a short storm, water producing runoff in excess of field capacity it is temporarily stored in the soil and in the vegetation, which means that the peak is delayed and reduced. If the peak flow from green roofs needs to be determined, the runoff process must be studied in more detail.

Acknowledgements

The open stormwater system in Augustenborg was built due to much effort by Dr Peter Stahre from Malmö Commune, who wanted to solve the flooding problem at the same time as the stormwater could add aesthetic and recreational values. The initiative for the green roof exhibition was taken by Peter Lindqvist, who together with Pär Söderblom arranged that some of the roofs

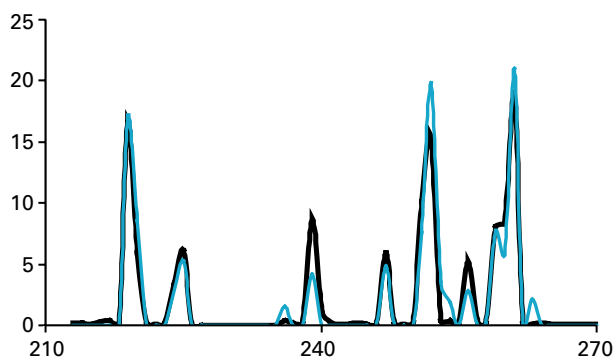


Figure 6 Comparison between simulated (light grey) and observed (black) daily mm runoff from a green roof in Augustenborg, Malmö; Julian days in 2001

could be used for research purposes. Lars-Erik Widarsson forwarded old information from Malmö Commune about Augustenborg and contributed through many discussions. The research carried out by the authors was possible due to a grant from FORMAS.

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