Evaluation of green roof hydrologic performance for rainwater run-off management in Hamburg

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Summary

Adaptation to the unpreventable consequences of climate change is one of the main challenges for cities in the coming decades. Especially for urban areas, where consequences of climate change will occur concentrated, there is a need for sustainable climate change adaptation measures. Our research focusses on one example of adaptation measures: green roofs. In addition to long-term economic benefits, they offer a wide range of benefits for urban ecosystems. Besides thermal benefits, like reduction of heating and cooling costs and reduction of the urban heat island effect, green roofs improve the urban water cycle, reduce air pollution, and enhance biodiversity. In Hamburg, heavy precipitation events regularly lead to overwhelmed urban drainage systems. Such events are expected to occur more often in the future with increasingly frequent (and intense) extreme precipitation events. Therefore, rainfall-runoff measurements of an extensive green roof on the HafenCity University building are carried out to determine the water retention capacity of the roof and to estimate the potential retention during heavy precipitation events. The long-term results show rainfall-runoff relationships under various weather conditions and are important for the development of future water management strategies and to overcome doubts about the effectiveness of green roof water retention, especially related to extreme precipitation events.

Keywords: green roof; climate change adaptation; water management; extreme precipitation

1. Introduction

There are several types of modern green roofs, consisting of the same principal elements: a waterproofing membrane covered with a growing medium and vegetation, which are installed on a rooftop. Other commonly used elements include root barriers and drainage layers (see Fig.1). In addition, filter layers are often integrated into the system between the substrate and drainage layer to avoid washing out of small-sized particulates. While the root barrier protects the waterproofing of the roof from penetration by plant roots, the drainage layers should be both able to retain rainwater and drain away the surplus water. Drainage layers can be industrially produced plastic frames as well as gravel layers. The substrate layer functions as growing medium for plants, by providing a rooting zone, and as water storage medium. It is typically a light-weight aggregate with both high water holding capacity due to high porosity, as well as good drainage properties. Substrate depth is an important property controlling water retention capacity, plant groth and subsequently, plant selection. Depending on substrate layer thickness or plant root-penetrable depth of the medium, two types of green roofs are distinguished. Extensive green roofs have a thicknesses of 8 to about 15 cm and intensive green roofs >15 cm. The types of plants used depend on the type of green roof and local climate. On extensive green roofs, due to regular drought stress, winter-hard, drought-tolerant and perennial plants like sedum species dominate. On intensive green roofs, grasses, shrubs and even trees can grow.

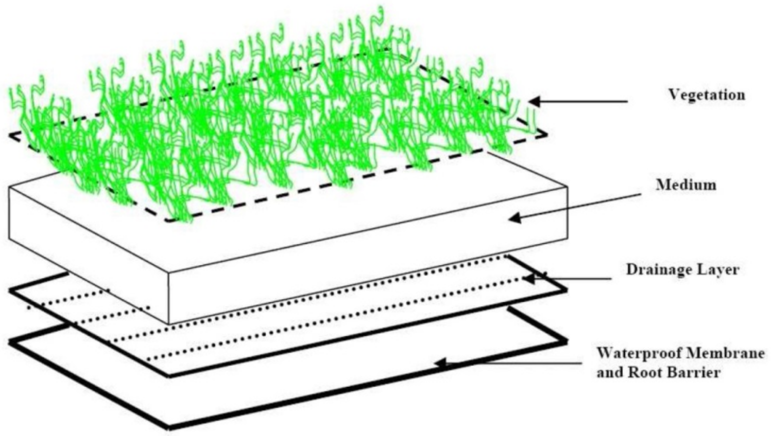

Fig. 1 Typical cross-section of a green roof system [1]

Several environmental and economic benefits are attributed to roof greening. Green roofs' installation costs are higher than those of standard flat or gravel roofs with 15 to 50 €/m² for extensive green roofs and from 50 €/m² upward for intensive green roofs, compared to about 10 €/m² for gravel roofs. In the long term, higher installation costs often pay off due to decreased sewage fees for utilised rainwater, lower repair costs due to higher durability (about 50 years) compared to conventional roofs (about 25 years) and energy savings. Furthermore, several cities like Hamburg promote green roofs with financial funding programmes to support widespread establishment. Further benefits are the reduction and attenuation of stormwater runoff due to water storage in the medium and on the plant surface, slow realease of rainwater out of the medium, transiration of plants and evaporation from substrate and plant surfaces. These lower the risks of urban floods and improve the urban water balance to approach a more natural condition (e.g. [2], [3], [4]). By thermally insulating and shading the roof surfaces and cooling through evapotraspiration, roof greening can reduce the costs of heating and air conditioning and the magnitude of the urban heat island effect (f.e. [5], [6], [7]). Green roofs also reduce noise levels (investigated numerically by [8]), reduce air pollution by filtering ([9], [10]) and provide wildlife habitats and enhance biodiversity ([11], [12], [13]).

The focus of this study, nevertheless, lies on the effectiveness of green roofs for urban rainwater management. Several studies regarding rainwater runoff retention state that the rate of rainwater retention for certain rainstorms depends on roof slope [14], substrate depth [4], rainfall characteristics like duration and intensity [15], season [16], soil moisture [17], roof age [18], plant species [12] and growing media type [19]. It is clear that over a whole year, green roofs with a substrate layer thickness of more than 6 cm can retain about 50% of precipitation and intensive green roofs with growing medium thickness >50 cm can retain up to >90% [20]. For urban rainwater management and especially dimensioning of sewage systems and prevention of flash floods due to sewage overflow, the retention capacity of green roofs in case of local extreme precipitation events is of interest. It is still not clear whether comprehensive implementation of green roofs can significantly affect rainwater retention and runoff reduction or delay the heavy rainfall events that cause flooding due to overcharged sewer systems. This problem is tackled by a comprehensive systematic review of literature on green roofs and water retention and a rainfall-discharge-measurement approach on the green roof of the HafenCity University (HCU) building.

2. Methodology

2.1. Systematic review

To get an overview of the published research regarding green roofs and their possible effects on rainwater management, a systematic review methodology, decribed in detail in [21], was applied. The overall research question "How effective are green roofs in reducing runoff into sewer system from heavy precipitation events?" was thus split up into the four main elements of the systematic review:

1. Population of interest or what problem is being addressed? (Green roofs)
2. Type of intervention or exposure? (Precipitation/runoff events)
3. What is the comparison/ comparator? ("conventional roofs")
4. What is the outcome or endpoint? (reducing and/or shifting runoff peak)

With these four elements (and synonyms), 9 different scientific databases from the fields of geosciences, environmental sciences and nature onservation, technics, architectural and urban studies were searched systematically. In this way, 70 studies were selected for the purposes of this study, of which the greatest number of studies originated from the USA (23), Germany (15), Canada (5), the United Kindom (4), Sweden (3) and Italy (3). Following, the results of the studies were entered into a database including the following features: Author(s), Location/Country, Latitude, Year(s), Experimental set-up, Size [m²], substrate depth [mm], drainage type, planted/non-planted, substrate, slope [%], Precipitation type, Yearly/period of study Precipitation, Yearly/study period retention, Winter retention, Summer retention, Rainstorm intensity [mm], Rainfall duration [min], Peak discharge coefficient, Volumetric retention, Runoff initiation [min], Peak delay [min], Initial conditions, Antecedent dry weather period [h], Water storage [mm]. Some refer to the overall water retention over a period (f.e. season or year) and some refer to single precipitation events. Thus, not all studies could provide data for all fields. With these data, water management related factors were analyzed and statistically tested to recognize significant dependencies between different factors.

2.2. Rainfall and runoff measurement system at HafenCity University building

The green roof of the HCU building is an extensive green roof vegetated predominantly with *sedum* and *phedismus* species (see Fig. 2). The substrate layer with 6 cm thickess is made of clay tiles mixed with organic compounds. The drainage layer (high-density-ployethylene, 2 cm thickness) is combined with an overlying filter layer. The green roof has a size of about 2200 m², of which about 600 m² of the roof drain into the measurement system.

Precipitation on the roof and runoff from the roof are measured separately. A Lambrecht rain gauge including a tipping counter with a resolution of 0.1 mm is situated at the North-eastern part of the building. Runoff from the roof is drained from 3 roof outlets into a measurement box on the ground floor of the building. In this box (Fig. 3), 2 different discharge measurement systems are integrated. A tipping counter with 100 ml resolution records smaller discharges whereas an ultrasonic sensor records higher discharges (up to 60 l/s) via water level measurement in a Thompson-weir outlet. The measurement system was installed in March 2015 and has been recording Rainfall and runoff since then in a temporal resolution of 1 minute.

Fig. 2 View over the HCU green roof

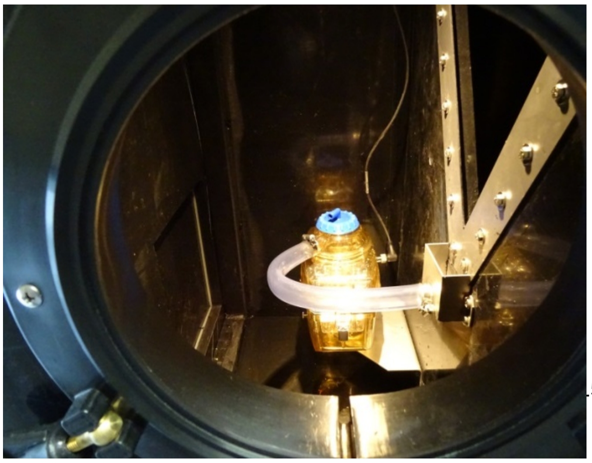

Fig. 3 View inside the runoff measurement box with V-weir (right) and tipping counter (middle)

3. Results

3.1 Systematic review

The systematic review results indicate a wide variety of properties characteristic of rainwater management (Tab. 1). Over all studies, the average yearly (or whole study period) water retention was 56%, ranging from 12% to 90% for an intensive green roof in sub-mediterranian Trieste, Italy [22]. The periodic retention rates differ within colder and warmer periods; average winter retention was 36% (12-69%) and summer retention 72% (32-100%). For single precipitation events investigated in the studies the average water retention of green roofs was 57%, ranging from zero retention to 100%. The average peak discharge coefficient, meaning the ratio of peak rainfall intensity [mm/min] to peak roof runoff [mm/min], was 0.4 (range: 0-1). The duration till runoff initiation from the green roof and peak delay from rainfall peak intensity to runoff peak intensity were delayed for 277 minutes (-8 – 2290 minutes) and 192 minutes (0 – 2000 minutes) on average.

Tab. 1 Rainwater and runoff related effects derived from systematic review

	Average	Maximum	Minimum
Year/study period average retention [%]	56	90	12
Winter retention [%]	36	69	12
Summer retention [%]	72	100	32
Volumetric retention rain event [%]	57	100	0
peak discharge coef-ficient	0.4	1	0
Runoff initiation [min]	277	2290	-8
Peak delay [min]	192	2000	0

Pearson-Correlation tests with data from the reviewed studies showed that runoff-retention describing factors (average retention, seasonal retention, retention single rain event, peak discharge coefficient, runoff initiation and peak delay) were significantly correlated ($p<0.05$) with the thickness of soil substrate (the thicker the layer the more retention), the soil moisture before the rain event (moister soil leads to less retention), the precipitation intensity and duration (higher intensity and duration leads to less retention), the roof slope (more slope, less retention), the season (more retention in warmer months) and latitude (less retention with higher latitude). No significant correlations could be proved with vegetation cover, plant species composition, growing media type and roof age.

3.2 Rainfall and runoff measurement system at HafenCity University building

Rainfall and runoff measurements on the HCU green roof were carried out starting at the end of March 2015 in 1-min temporal resolution. The results for longer periods and single rainfall events are described separately in the following sections.

3.2.1 Long-term green roof retention

During the period of study presented here (23.03.-10.12.2015) 668 mm precipitation were recorded whereof 277 mm were discharged. This means 59% of the rainfall was retained by the green roof (Tab. 2). As can also be seen in Tab. 2, June is the month with the most retention (74%) while the least (29%) water was retained during the first 10 days of December.

Tab. 2. Precipitation, discharge and retention measured at HCU green roof from 23.03.-10.12.2015. *indicates that the data are not for the whole month.

Month/period	Precipitation [mm]	Discharge [mm]	Retention [%]
March*	42	19	53
April	38	14	63
May	45	14	70
June	39	10	74
July	107	34	68
August	105	37	65
September	89	39	66
October	41	20	51
November	155	84	46
December*	7	5	29
Whole period	668	277	59

3.2.2 Single precipitation events' retention

Over the measurement period, several heavy precipitation events occurred in Hamburg. For urban stormwater management, the retention potential of local short-term events is especially interesting. During the study period 2 short events were recorded and evaluated (see Fig. 4). On may 5th 2015, 17 mm of precipitation in 60 minutes were recorded. During 5 minutes the measurement range of the rain gauge was exceeded, thus we assumed the maximum possible measurable precipitation amount for these minutes (1,8 mm/min). The recorded event corresponds to a return period of 1.7 years for Hamburg. In reality, this rain event was heavier than recorded. 8 mm of roof runoff was recorded, which corresponds to 53% retention. The peak discharge coefficient was 0.5. Another heavy precipitation event with 18 mm in 105 minutes was recorded on August 17th 2015 (return period for Hamburg: 2 years). Here, 50% was retained and the peak discharge coefficient was 0.25.

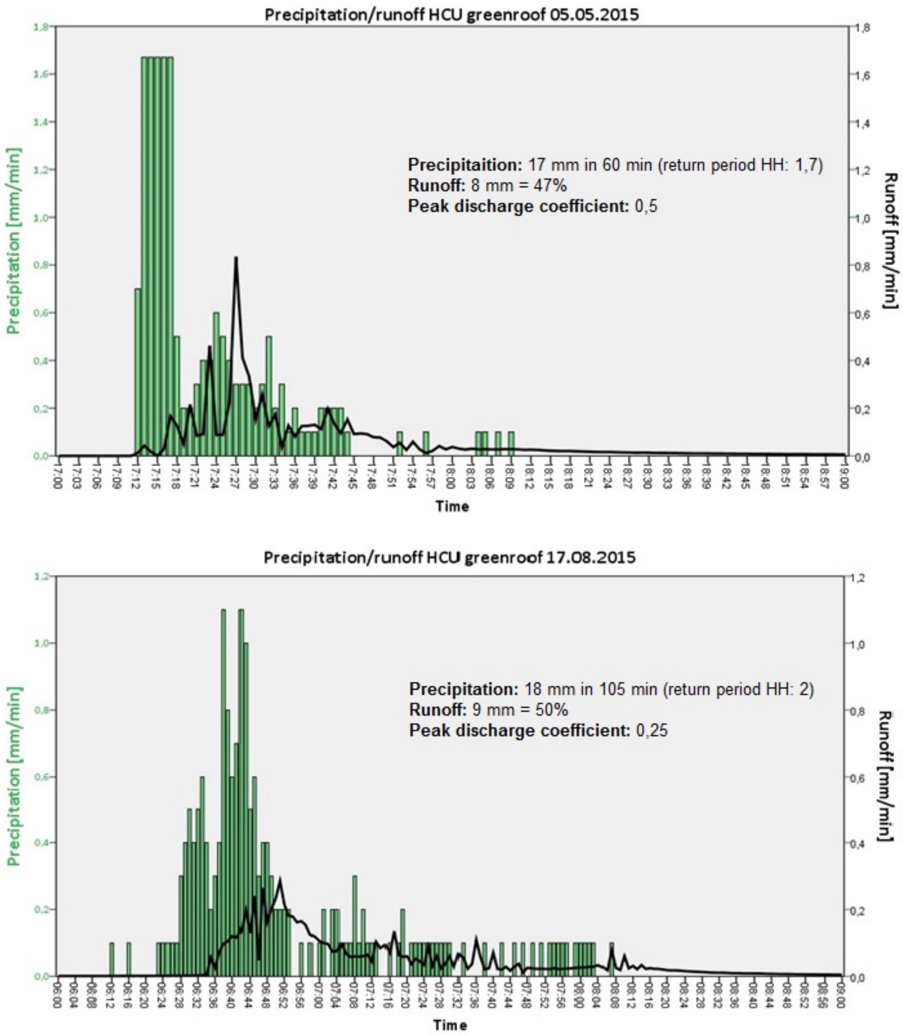

Fig. 4 Recorded heavy precipitation events on the HCU green roof (05.05.2015 and 17.08.2015)

4. Discussion

The results of the systematic review confirmed results of previous comparable studies of water management effects of green roofs ([16], [23], 24[]). Water retention over a year and in different seasons or months were reported as having the same order of magnitude (9-85% per year by [3]). Compared to the yearly retention values according to the FLL-guideline for green roofs ([20], see Fig. 5), the reviewed studies revealed greater retention performance of about 5-10% within each substrate thickness category, except the >100-150 mm category. This indicates a slight underestimation of the retention capacity of green roofs according to the guideline. The dependency of runoff retention on thickness of soil substrate, soil moisture content, precipitation intensity and duration, roof slope, season and latitude and their underlying causes are mostly known. In this meta-analysis, no significant correlations could be proved with vegetation cover, plant species composition, growing media type and roof age, which could be due to characteristics of the statistical method. For these attributes there are tendencies, but these could not be proved statistically significant due to the low number of published investigations on these attributes. For the whole picture, it is important to have these impacts of green roof characteristics in mind when targeting rainwater management. Nevertheless, even with knowledge of these characteristics it cannot be

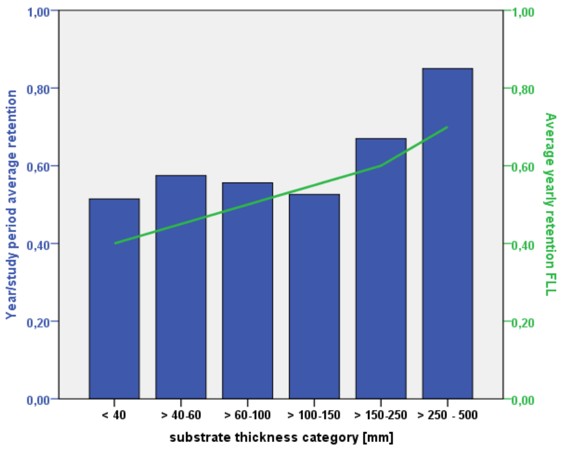

Fig. 5 Comparison of retention values of green roofs' substrate categories between FLL guideline and data from review

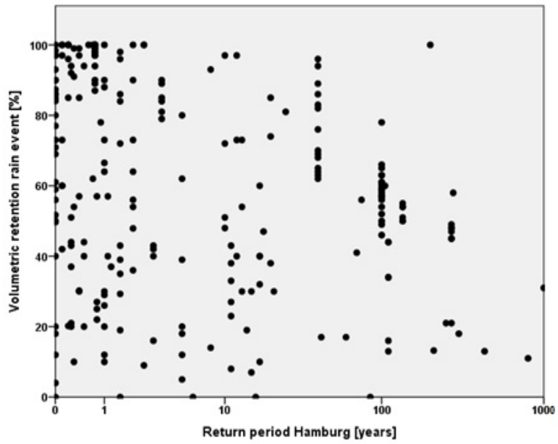

Fig. 6 Volumetric green roofs' retention of single rain events from reviewed studies (y-axis) and their comparison to Hamburg rain events expressed as return period (probability of occurrence) for Hamburg (x-axis, logarithmic)

guaranteed that desired effects will occur. For future rainwater management in cities and sewerage system design, the retention effects in case of heavy precipitation are of particular importance. It is still not cleared which amount of water can be retained and there are general doubts that green roofs, especially extensive ones, can contribute to decreasing urban flood risk in densely built urban quarters. At the moment, at least for Hamburg, green roofs are not considered to be an element of decentralized flood management practices. The review results, which include studies of green roofs all over the world, showed that it cannot be generalised whether green roofs have a significant retention effect or not. Figure 6 shows the outcome of an attempt to compare rain events from these studies with rain events from Hamburg. This was done by converting the rainfall amount [mm] and duration [min] of a single precipitation event into a return period for Hamburg. By applying specific extreme value statistics for heavy precipitation, every event was assigned a probability of occurrence (return period). For example a precipitation of 27 mm in 15 min had a return period of 100 years which means that the probability of occurrence is once in 100 years. It can be stated that there is a wide variety of volumetric retentions for most of the return periods. Even though the (linear) trend is slightly negative, which means that for greater return periods less retention would be expected, there are several events with return periods of, for example, 100 years where retention is over 50%. But nevertheless, there are also relatively small rain events (< 1 yearly) where there are retention values of less than 20%. This again indicates that the retention of green roofs is dependent on several technical and climatic values and that further research is needed in order to to generalize the effects influencing retention and to provide recommendations for stormwater management practices. The aim of the measurement system of the HCU green roof is to quantify these effects for the local climatic conditions of Hamburg. With ongoing measurement, a wide range of extreme precipitation events in the future will be recorded (return period of heaviest event up to now: 2 years, Fig. 4), which will lead to a better understanding of the underlying effects.

5. Conclusion

It has been demonstrated that green roofs can retain significant amounts of rainwater throughout the year (> 50%) and in this way have positive effects on the urban water cycle. But it is still unclear what amount of rainwater can be retained in case of extreme precipitaion events and therefore which contribution they can provide for urban stormwater management. By analysing precipitation events and related green roof retention it could be shown that there is a wide variety of characteristics (technical and climatological) that influence retention on a roof. Accordingly, no general statements towards retention capacity with increasing precipitation intensities and durations can be given. Therefore, the green roof measurement campaign on the HCU green roof is intented to collect data of a wide variety of (extreme) rain events and retention to draw conclusions for urban stormwater management. It would for example be interesting which type of green roof is suitable for comprehensive installation on roofs due to its cost-effectiveness and can retain large portions of heavy precipitation events to relieve the existing sewage network.

6. Acknowledgements

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