Green roof runoff experiments in Singapore

Ruissellement des toitures végétalisées : expériences à Singapour

Toine Vergroesen*, Umid Man Joshi**

* Deltares, Rotterdamseweg 185, 2629 HD Delft, The Netherlands (toine.vergroesen@deltares.nl)
Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands (a.j.j.vergroesen@tudelft.nl)

** National University of Singapore, 1 Engineering Drive 2, Singapore 117576 (cvejum@nus.edu.sg)

RÉSUMÉ

L'augmentation de l'amplitude et de la fréquence des ruissellements pluviaux urbains résulte de la combinaison du changement climatique, de la croissance démographique et de l'urbanisation. Des travaux de recherches ont montré que, sur une base annuelle, les toitures végétalisées peuvent significativement contribuer à la rétention des eaux de pluie, et que cette contribution dépend fortement des conditions météorologiques locales. Singapour a lancé des expériences précises de toitures végétalisées afin de déterminer et de quantifier à un niveau très détaillé les principaux processus de ruissellement des toitures végétalisées et leurs paramètres. Le présent article indique les résultats préliminaires obtenus avec deux toitures végétalisées comparées à une toiture conventionnelle de référence. Trois journées consécutives avec des hauteurs de pluie pratiquement identiques ont permis d'observer des différences notables de réduction des ruissellements (13,6 – 98,8%), de réduction des débits de pointe (41,9 – 98,9%), et de réduction des ruissellements retardés (0,2 – 20,2%) par rapport à la toiture de référence. La cause principale est la période de temps sec qui précède les évènements pluvieux. Pour l'ensemble des évènements pluvieux, les retards de ruissellement varient de quelques minutes à plusieurs heures. A Singapour, le retard de ruissellement joue un rôle important dans l'accroissement du débit de base.

ABSTRACT

Combination of climate change, population growth and urbanization will increase urban storm water runoff, both in magnitude and in frequency. Previous research already showed that on an annual basis green roofs can contribute considerably to storm water retention. It also showed that this contribution is highly dependent on local weather conditions. High resolution green roof experiments in Singapore are started to determine and quantify the leading green roof runoff processes and process parameters on a very detailed level. This paper presents the preliminary results for two green roofs compared to a conventional reference roof. Three consecutive days with almost similar daily rain depth show, all compared to the reference roof, a wide variety in reduction in runoff volume (13.6 – 98.8 %), reduction in peak runoff (41.9 – 98.9 %) and delay of runoff volume (0.2 – 20.2 %). Main cause is the antecedent dry weather period. Runoff delay times vary for all events between minutes and several hours. In Singapore runoff delay is very relevant for enlarging the base flow.

KEYWORDS

Experiment, green roof, rainfall, retention, runoff

1 INTRODUCTION

Figure 1 Some examples of green roofs in Singapore and The Netherlands

The world population still increases, as do the demands people make on their life-style. Next to that the urbanization process accelerated during the last decades. The increasing demand for houses, roads, parking lots, schools, shopping malls, etc. already led to enormous paved areas. Both processes will most likely continue for decades. Population scenarios of the UN predict an increase in the current world population of 6.8 billion people to 7.8 billion people in 2040 (lowest scenario) to 10 billion people in 2050 (highest scenario). Currently half the world population lives in cities. Urbanization scenarios predict an increase up to 70% in 2050. Without proper measures the process of paving the earth surface will keep on increasing rapidly. On the other hand more and more symptoms indicate a climate change. Sea level rises and extreme rainstorm events will occur more often and at a higher intensity. Combination of population growth, urbanization and climate change means that more often more water will have to be rapidly discharged into the surface water. The (extra) storage capacity of the surface water however often is limited.

Two obvious solutions for this problem are enlarging the storage capacity of the surface water, and reduce / delay the discharge of storm water to the surface water. Increasing the surface water area will enlarge the storage capacity, but conflicts with the decreasing available area. Therefore enlarging the storage area only seems feasible when it can be combined with other functions. Developments in that direction are building on water, and storing water in, under or on top of buildings. Reduction and delay of the rainfall runoff looks more promising. Examples of development in this field are infiltration facilities like swales, permeable roads and parking lots and green roofs. Infiltration facilities are more suitable for higher areas, in which also during wet periods the groundwater level lies far below the surface level. In principle green roofs are applicable almost everywhere.

Research already proved that green roofs can delay rainfall-runoff by several hours, and can reduce the total annual runoff volume as well as the average peak runoff significantly. Moran et al. (2004)

reported a long-term reduction in runoff volume by 62% of the total rainfall (901 mm in 9 months) and an average reduction in peak runoff by 78% of the maximum rainfall intensity. The paper shows a delay time of approximately 3 hours between the end of a rain event and the end of the runoff. VanWoert et al. (2005) noted for a setup with only 2.5 cm of growing media 60% retention of the long-term rainfall with a variation between 12% and 100% for distinct rain events. However the total rainfall was relatively low (556 mm in 14 months). The maximum recorded time between the end of a rain event and the last runoff was 14 hours. In their review on original measurements reported in 18 publications Mentens et al. (2006) noted that the rainfall-retention capability on a yearly basis may range from 45% for extensive green roofs (median substrate depth: 10 cm) to 75% for intensive green roofs (median substrate depth: 15 cm). Stovin et al. (2007) recorded for 11 events during spring 2006 an average volume retention of 34% of the total rainfall, and an average reduction in peak runoff by 57% of the maximum rain intensity. They concluded that the key hydrological determents were the antecedent dry weather period, the mean rainfall intensity and the rainfall depth. The paper showed an example with a much higher volume retention (61%), and a delay time of almost 4 hours between the end of the rain event and the end of the runoff. Uhl and Schiedt (2008) examined different sizes, slopes, substrates, layer depths and roof forms. They concluded that the reduction in annual runoff, which ranged between 61% and 77%, was clearly dominated by the layer depth compared to the other construction details. They observed a substantial reduction in the peak runoff for all constructions (63 – 88% of the maximum rainfall intensity), and concluded that the peak runoff was strongly influenced by the antecedent rainfall and evapotranspiration process, and hardly by the depth of the substrate or the slope of the roof. The paper shows a delay time of more than 2 hours between the end of a rain event and the last runoff.

For data collection Moran et al. (2004) collected the rain data were with a tipping bucket rain gauge and the flow data with a V-notch weir box with a level sensor. Both data were recorded in 5-minutes intervals. VanWoert et al. (2005) used rain gauge tipping buckets with a 5-minute interval, both for rainfall and for runoff. Stovin et al. (2007) recorded the rain data with a standard rain gauge. For the runoff data a collection tank with a high resolution pressure transducer was used. Though stated to use 5-second intervals, data in the paper were presented at 5-minute intervals. Uhl and Schiedt (2008) used a tipping bucket rain gauge and collection tanks with a swimmer system for water level measurements to measure to runoff.

Although previously performed research clearly proves the benefits of using green roofs to retain water (Moran et al., 2004; VanWoert et al., 2005; Mentens et al., 2006; Stovin et al., 2007; Uhl and Schiedt, 2008), quantifying the exact effects for specific situations and locations remains a problem. As long as the leading process parameters can not be determined, attempts to model the effects (Baraglioli et al., 2008; Martin, 2008) remain on the scale of a water balance study, as do consequently attempts to determine the exact effects on water quality (Berndtsson et al., 2006). Therefore high resolution research was started to try to determine the leading process parameters for roofs in general and green roofs in particular. Final goal of the research is to develop a proper modeling tool to help to quantify the effects of measures (like green roofs) on urban runoff.

2 JOINT RESEARCH OF SINGAPORE AND DELFT

The research described in this paper is the first result on this topic of the cooperation between the cities of Singapore and Delft in the Netherlands.

2.1 Singapore

To face storm water runoff problems Singapore developed an intensive drainage network. This drainage network, consisting mainly of concrete drains and canals, is designed to rapidly discharge extreme rainstorm events. Generally the drainage network functions really well. However, due to the often hilly surface level the drains and canals are mostly dry. When dry, the large concrete canals create a rather ugly view. Due to the rapid discharge most of the available water can not be used as well. Currently Singapore has to import a large part of its required drinking water, whereas in principle sufficient water is available. Therefore Singapore developed plans to embellish to city, and to be able to use a larger part of the available water. Closing the Singapore bays to create fresh water reservoirs (like Marina Bay) is part of these plans. However also the peak discharges have to be reduced and the base flows have to be distributed over a longer period of time. Green roofs can help realizing these goals. Research on green roofs in Singapore so far was limited to energy consumption (Wong et al., 2003a) and life cost analysis (Wong et al., 2003b).

Figure 2 Singapore. A main drainage canal in dry (upper left) and wet (upper right) conditions. The lower left picture shows the target view. The lower right picture shows the experimental setup.

2.2 Delft / The Netherlands

Currently in several Dutch cities green roofs are being constructed or planned. Next to that several researches on the effects of green roofs are ongoing. In the city of Rotterdam the roof of the office of the waterboard “Hoogheemschap van Schieland en de Krimpenerwaard” at the river Maas is being renovated. The waterboard took the opportunity to transform the traditional roof into a green roof. The Community of Rotterdam and the waterboard started a joint research on the effects of the green roof on water retention, climate control (both internal and external), sound insulation and environmental aspects. Deltares and TU Delft will carry out this research.

2.3 Singapore Delft Water Alliance

The Singapore Delft Water Alliance (SDWA) is a multi-national, interdisciplinary research Centre of Excellence for Water Knowledge, involving PUB (Singapore), National University of Singapore and Deltares (The Netherlands), established through an initiative of the National Research Foundation in Singapore. SDWA is hosted by National University of Singapore and provides research home to scientists and engineers from all partner organizations.

In the SDWA-framework, since the end of 2008 detailed experiments are conducted in Singapore on the effect of green roofs on the retention and the quality of the rainfall runoff. This paper focuses on runoff reduction and runoff delay.

3 DESCRIPTION OF THE EXPERIMENT

The entire experimental setup consists of five simulated square roofs of 1 by 1 meter (figure 2, lower right). Three of which are used in the experiment described in this paper.

3.1 Equipment

The slope of the roofs is set to 1 degree. A discharge gutter is situated at the lowest side of the roof.

The discharge from the roof flows through a hose into a tipping bucket flow gauge with a capacity of 1 liter per tip. The tipping bucket is situated on a high precision weighing scale. Every other second the measured weight is transferred to a data logger. The rainfall is measured by a tipping bucket rain gauge with a capacity of 8 milliliter per tip (corresponding to 0.01 inch of rainfall per tip). Every minute the number of tips is recorded by a data logger.

Figure 3 Experimental setup of the rain gauge (left) and flow gauge on weighing scale (right).

The tipping bucket of the rain gauge was tested in a lab by pouring in 160 ml of water at different flow rates. Outcome of this lab-test was that the higher the flow rates the lower the number of tips. Up to a flow rate of 4 tips per minute (corresponding to a rain intensity of 1 mm/min) the reduction in measured flow volume was within 1%. Beyond that flow rate the reduction in measured flow volume increased rapidly: 15% at 20 tips/min, 22% at 30 tips/min, up to 37% at 120 tips/min. This is the main reason for the chosen setup for measuring the runoff from the roofs, instead of just using tipping bucket rain gauges. In the experiment results however possible underestimation during severe rainfall is not taken into account.

3.2 Roof setup

For this experiment three roofs are used: two green roofs and one reference roof. All three roofs are covered by a concrete layer. On the two green roofs directly on top of this concrete layer a drainage layer is applied. The drainage layer is approximately 3 cm thick, consisting of Chinese hydroton. On top of the drainage layer thin filter fabric is applied to prevent the soil from clogging the drainage layer. On top of the fabric layer a layer of approximately 15 cm potting soil is applied. The weight of a 15 cm thick wet soil corresponds to the load capacity (3 kN/m^2) of the roof on which the experiments are carried out. Some simple tests with a water tap showed that the porosity of the drainage material is 40 – 45 %, and that the permeability exceeds 1300 m/d (corresponding to more than 1.5 10^{-2} m/s). Similar tests proved that the porosity of the potting soil is 45 – 50 % in dry conditions. In wet conditions (field capacity) approximately 20 % storage capacity remains. The permeability of the potting soil is approximately 20 m/d (2.3 10^{-4} m/s).

The roofs are planted with Sedum Gold Mound, a kind of sedum that is also growing well in the more moderate climates of Europe and North America. At the start of the experiment the complete setup was already operational for three months. During this period small changes to the initial setup like settling of the soil and growing of the plants have already occurred.

3.3 Time period

The experiment is carried out during three consecutive days with relevant rainfall (44.7 mm in total), preceded by a dry period of five days. The first day 16.5 mm of rainfall was measured, 15 mm of which fell in less than 15 minutes. The second day the recorded rainfall was 14 mm, divided over two periods with an almost equal rainfall depth (7.1 and 6.9 mm). The intensity of the first event was clearly higher than the intensity of the second event. During a period of more than three hours in-between these two events no rainfall was measured. The third day 14.2 mm of rain was recorded.

3.4 Results

Figure 4 and table 1 provide an overview of the measured rainfall and runoff. The average measured discharge from the reference roof is 92.2 % of the measured rainfall. The variation between the four events is only a few percent. However it has to be considered that the events during this experiment all had a relevant rainfall depth and intensity. Small rainfall depth will hardly be able to create runoff. An example of this is shown in figure 4, where the last rain on the third day (0.5 mm) did not lead to any additional runoff from the reference roof. If the rainfall intensity is low (like during a drizzle) relatively more rain will evaporate before it can runoff, resulting in a relative lower discharge.

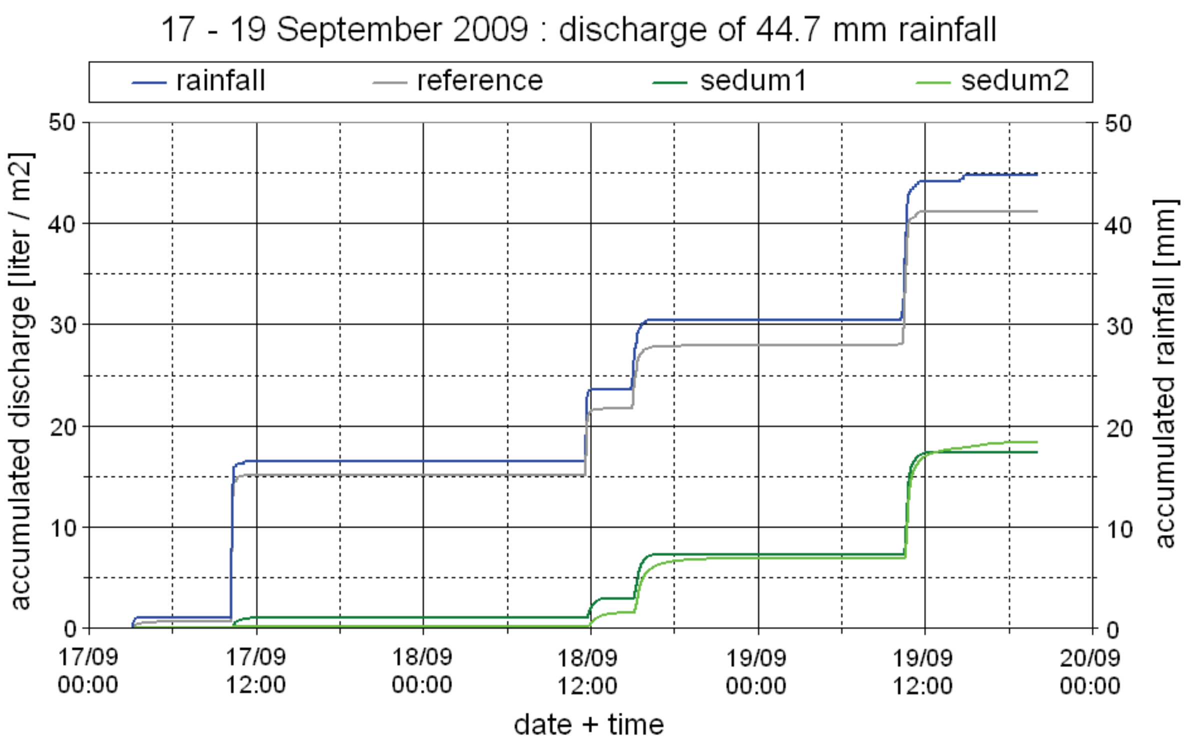

Figure 4 Measured rainfall and runoff during three consecutive days with rainfall.

Table 1 Measured rainfall and runoff.

day	event	rainfall [liter/m^2]	discharge [liter/m^2] from:					
			reference roof *		sedum1 roof **		sedum2 roof **	
1	1	16.5	15.0	91.2%	1.0	6.6%	0.2	1.2%
2	2a	7.1	6.6	93.5%	1.9	28.9%	1.3	20.3%
2	2b	6.9	6.2	89.9%	4.3	69.7%	5.3	85.8%
3	3	14.2	13.3	93.8%	10.1	75.6%	11.5	86.4%
total		**44.7**	**41.2**	**92.2%**	**17.3**	**42.0%**	**18.3**	**44.5%**

* percentage of the reference roof is related to the measured rainfall
** percentage of the sedum roofs is related to the discharge of the reference roof

The discharge from the sedum roofs proofs to be very dependant on the antecedent weather conditions, as well as on the rainfall intensity. In spite of its intensity the rainfall on the first day hardly produced any discharge from the sedum roofs. The morning rainfall was almost entirely used to replenish the soil moisture deficit. Caused by the preceding five day dry period, a large part of the moisture content was taken up by the sedum roots during the rest of the first day, thus creating a new soil moisture deficit. That is the reason that the discharge from the sedum roofs caused by the first shower on the second day was considerably less than the discharge caused by the second shower, in spite of the higher intensity of the first shower. Due to the higher intensity than the second event on the second day the event on the third day resulted in the relatively largest discharge from the sedum roofs. Table 1 shows that the discharge of the sedum roofs for this event is only 15 – 25% less than the discharge from the reference roof.

The discharge from the reference roof started almost directly after the rainfall started. After it stopped raining the discharge from the reference roof continues for a short while. Figure 5 shows that the discharge from the sedum roofs starts 5 to 10 minutes later than the discharge from the reference roof. Although this generally is called delay of the runoff, it is mainly caused by runoff reduction. The first part of the rainfall is not discharged, but used to replenish the soil moisture deficit.

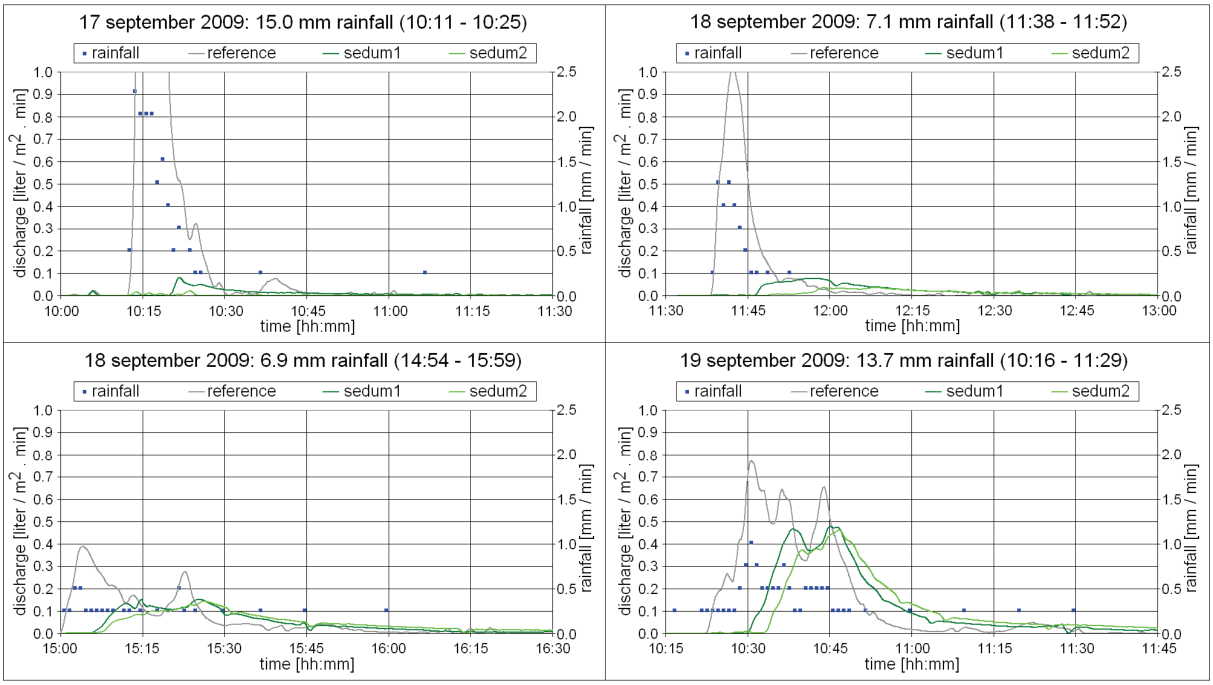

Figure 5 Measured discharge intensities of four rain events during three consecutive days. (Displayed are the trend lines of the moving average of 30 values)

Table 2 Measured reductions in peak runoff.

day	event	peak rainfall [liter/m^2.min]	actual peak runoff [liter/m^2.min] reference roof	sedum1 roof *		sedum2 roof *	
1	1	2.286	2.309	0.094	4.1%	0.025	1.1%
2	2a	1.016	1.072	0.080	7.5%	0.037	3.5%
2	2b	0.508	0.404	0.163	40.3%	0.146	36.1%
3	3	1.016	0.811	0.498	61.4%	0.471	58.1%
average		**1.207**	**1.149**	**0.209**	**18.2%**	**0.170**	**14.8%**

* peak runoff of the sedum roofs is related to peak runoff of the reference roof

In fact discharge can only be called delayed no sooner than the discharge intensity of the sedum roof becomes larger than the discharge from the reference roof. Figure 5 shows that in the experiments this happened more than 15 minutes later than the discharge of the reference roof started. The results show that the sedum roofs keep on discharging long after the reference roof stopped. The maximum measured time difference in the experiments was more than two hours.

Table 2 shows the measured peak runoff during the experiments. In general the values in this table exceed the maxima in figure 5, because in order to create a clearer view in this figure the moving averages of 30 values are displayed. The actual measured peak runoff therefore will be a little higher. The average reduction in peak runoff is 80 – 85%. Like the reduction in total runoff volume, the variation in reduction in peak runoff for the individual events is high.

Next to insight in reduction in runoff volumes and peak runoff, and insight in delay times, knowledge on the delayed water volume is important. Figure 5 gives an impression of these volumes. When the discharge intensity of a sedum roof exceeds the discharge intensity of the reference roof, the area between these two lines represents the delayed discharge volume. Figure 6 shows this principle. The green area in this figure is the delayed discharge volume. The size is the same as the grey area. The blue area is the volume that is discharged at the same time. The rest (the orange area) is the reduced discharge volume.

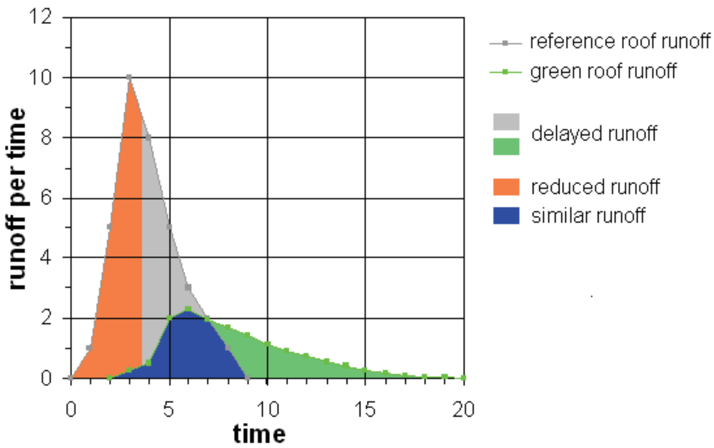

Figure 6 Principle of delayed discharge water.

Table 3 Measured delayed runoff volumes.

day	event	rainfall [liter/m^2]	runoff * [liter/m2] from reference roof		delayed runoff ** [liter/m2] from sedum1 roof		delayed runoff ** [liter/m2] from sedum2 roof	
1	1	16.5	15.0	91.2%	0.1	1.0%	0.0	0.2%
2	2a	7.1	6.6	93.5%	0.5	8.0%	0.5	7.5%
2	2b	6.9	6.2	89.9%	0.6	10.4%	1.2	20.1%
3	3	14.2	13.3	93.8%	1.4	10.2%	2.7	20.2%
total		**44.7**	**41.2**	**92.2%**	**2.7**	**6.5%**	**4.5**	**10.8%**

* percentage of the reference roof is related to the measured rainfall
** percentage of the sedum roofs is related to the discharge of the reference roof

Table 3 provides an overview of the delayed discharge volumes. During the experiments this volume varied from almost zero to more than 20% of the discharge from the reference roof. It clearly depends strongly on the antecedent weather conditions and on the duration and the intensity of the rainfall.

4 SUMMARY AND CONCLUSIONS

Green roofs can provide a relevant contribution to storm water retention in Singapore. The runoff volume can be reduced by more than 50%, the peak runoff even more. The runoff time can be increased by several hours. The delayed runoff volume (5 – 10%) is relatively small when compared to the reduction in runoff volume. However when compared to the base flow it can be a considerable contribution.

The variety of these numbers for separate rain storm events is high. Main cause of this variety is the so called “antecedent dry weather period”, ADWP, the time between two consecutive rain events. Smaller contributions are provided by differences in rainfall intensity and rainfall duration. Since the climate in Singapore is extremely constant, it can be assumed that contributions of other stochastically changing parameters to the variation of the runoff are negligible.

5 DISCUSSION

The size of the experimental roofs is 1 m^2 with an average flow distance to the gutter of half a meter. Most real roofs are a lot bigger. Due to the extreme permeable drainage layer, the vertical flow through the potting soil is normative regarding the discharge time. Therefore larger roofs only mean larger horizontal flow distances to the gutter. Time differences between flow through the drainage layer and flow over the reference roof are factors smaller than the vertical flow through the soil. This means that scaling the results of the experiments to real roofs by just multiplying the runoff volumes by the roof areas (in m^2) probably causes relatively small errors.

Roofs without a drainage layer can not be scaled in a similar way. In that case the horizontal flow to the gutter goes also through the soil, and enlarging this distance will lead to a substantial delay of the discharge. Lack of a drainage layer however can lead to (partly) submerged conditions, resulting in drowning of plants and surface runoff (thus reducing the discharge time). In those cases a (much) thicker layer of soil has to be used, and / or combinations of drought and wet loving plants need to be applied. Most existing roofs are not designed to carry such an extra load.

Due to the limited capacity of carrying extra load, on existing buildings mostly lightweight green roof constructions are applied, in which the plants are put in an only 4 to 6 cm thick layer of substrate. Nevertheless the reduction in total annual runoff of these roofs can be considerable. The actual delay of the runoff of these roofs is generally small.

When green roofs are taken into account in the design phase of new buildings, much thicker layers of soil can be used. Next to more variation in the applied vegetation (even smaller trees are possible), a much thicker soil can enlarge the reduction in runoff, but more important can extend the delay of the runoff considerably.

6 CONTINUATION RESEARCH

As already was mentioned in the introduction a research on the effects of green roofs is started in the city of Rotterdam. Two types of lightweight green roofs will be applied, and a part of one of the roofs will stay empty to function as a reference roof. In relation to this an experiment in Singapore will be set up to compare the rainfall-runoff of lightweight green roofs to the ones applied in the experiment described in this paper. Combination of the results of both experiments will be used to start to develop a reliable way of scaling results from experiments to different roof sizes.

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LIST OF REFERENCES

Baraglioli, A., Guillon, A., Kovacs, Y. and Senechal, C. (2008). *Studies on the quantity impacts of green roofs.* 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, 2008.

Czemiel Berndtsson, J., Emilsson, T. and Bengtsson, L. (2006). *The influence of extensive vegetated roofs on runoff water quality.* Science of the Total Environment 355:48-63.

Martin, K.M. (2008). *The dynamic stormwater response of a green roof.* University of Guelph, MSc. Thesis, November 2008.

Mentens, J., Raes, D. and Hermy, M. (2006). *Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?* Landscape and Urban Planning 77:217-226.

Moran, A., Hunt, B. and Jennings, G. (2004). *A North Carolina Field Study to Evaluate Greenroof Runoff Quantity, Runoff Quality, and Plant Growth.* 2nd Greening Rooftops for Sustainable Communities Conference, Portland, 2-4 June, 446-460.

Stovin, V., Dunnett, N. and Hallam, A. (2007). *Green roofs – getting sustainable drainage off the ground.* Proceedings of the 6th NOVATECH Conference, June 2007, Lyon, France, Conference Proceedings Vol 1, 11-18.

Uhl, M. and Schiedt, L. (2008). *Green roof storm water retention – monitoring results.* 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, 2008.

VanWoert, N.D., Rowe, D.B., Andresen, J.A., Rugh, C.L., Fernandez, R.T. and Xiao, L. (2005). *Green roof stormwater retention: effects of roof surface, slope, and media depth*. Journal of Environmental Quality, v34(3), 1036-1044.

Wong, N.H., Cheong, D.K.W., Yan, H., Soh, J., Ong, C.L. and Sia, A. (2003a). *The effects of rooftop garden on energy consumption of a commercial building in Singapore.* Energy and Buildings 35:353-364.

Wong, N.H., Tay, S.F., Wong, R., Ong, C.L. and Sia, A. (2003b). *Life cycle cost analysis of rooftop gardens in Singapore.* Building and Environment 38:499-509.