

ACTA UNIVERSITATIS SZEGEDIENSIS

PARS CLIMATOLOGICA
SCIENTIARIUM NATURALIUM
CURAT: JÁNOS UNGER

ACTA CLIMATOLOGICA

TOMUS LIII.

SZEGED (HUNGARIA)

2019

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University of Szeged, Faculty of Science and Informatics
(H-6720 Szeged, Aradi vértanúk tere 1.)

The issues are available on
www.clima.u-szeged.hu/acta-climatologica

Acta Universitatis Szegediensis: **ISSN 0324-6523**
Acta Climatologica: **ISSN 0563-0614**

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MODELING OPTIONS FOR RAINWATER HARVESTING DEVELOPMENTS IN A PUBLIC INSTITUTION AS PART OF SUSTAINABLE URBAN WATER MANAGEMENT SOLUTIONS

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Summary: The water cycle of cities is very different from that of natural areas, and it is characterized by artificial energy flow processes and materials. Due to the high concentration of population, weather extremes in urban areas can cause greater personal and economic damage than in rural areas. Besides extreme amounts of precipitation, which is only one type of extreme weather events, it is important to be prepared for drought and dry periods (which are typical in Szeged and the southern region of the Great Hungarian Plain). During these periods, urban vegetation requires additional irrigation due to the urban artificial environment and the special species composition. This irrigation water basically means potable water resources. It is not a sustainable way to protect potable water resources, therefore any solution that can alleviate this situation is a major improvement. In our study, we modeled a rainwater harvesting system which is established in an elementary school in Szeged. We paid special attention to the quantitative and time distribution properties of the potential precipitation available for the rainwater harvesting system.

Key words: urban hydrology, EPA SWMM, sustainable urban water management, rainwater harvesting

1. INTRODUCTION

Due to the anthropogenic changes, climatic and hydrological analyses in cities require a different approach. The extreme weather conditions of climate change are enhanced and emphasized by the urban environment, and therefore their examination is highly important. (Unger and Gál 2017). The changed land cover does not only contribute to the occurrence of urban flash floods, but also reduces drought tolerance in urban vegetation due to the reduced infiltration (Gayer and Ligetvári 2007, Buzás 2012). In times of climate uncertainty, we need to think in systems and prefer complex rainwater treatment rather than simple rainwater drainage (Fig. 1). There is no doubt about the importance of rainwater drainage because of the high concentration of urban population, which is associated with significant risks of urban flash floods with high runoff volumes (Romnée et al. 2015). However, the uncertain precipitation distribution is what makes the rainwater retention systems necessary (Barron 2009). Urban vegetation is basically man-made, whether private or public, and therefore requires artificial irrigation during drought and dry periods.

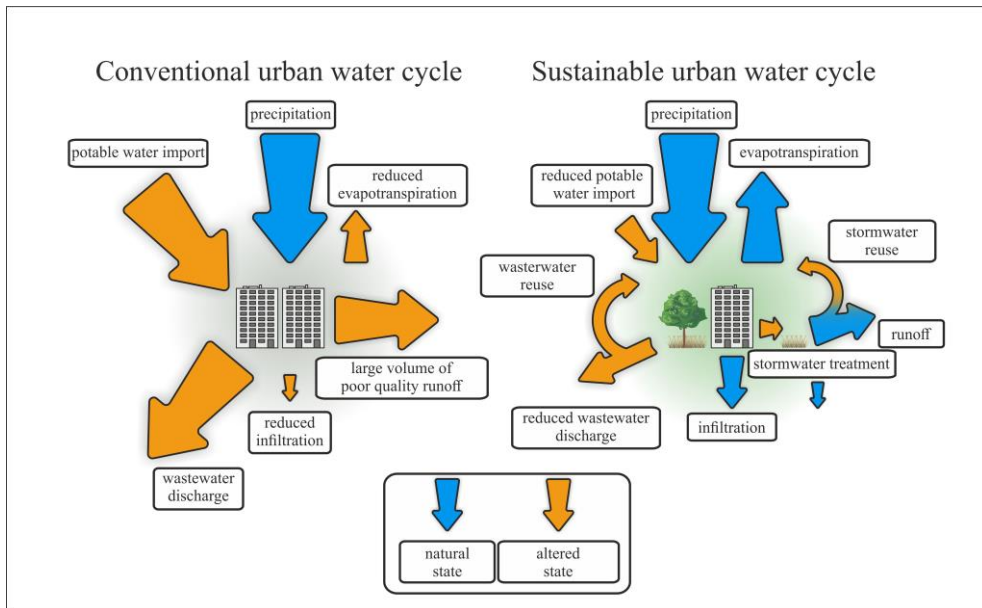


Fig. 1 The conventional and the sustainable urban water cycle (based on Hoban and Wong 2006)

Rainwater harvesting is not a solution which is used alone, but it can play an important role as part of various planning systems. The most notable of these are LID (Low Impact Development), SUDS (Sustainable Urban Drainage Systems) and WSUD (Water Sensitive Urban Design) (Department of Water 2007, Dietz 2007, Credit Valley Conservation 2010, Fletcher et al. 2015). In addition, nowadays there are pioneering initiatives such as “Smart Cities” projects or the “Sponge City” project in several cities in Asia and Europe, which carries the promise of retaining rainwater in its name (Liu et al. 2015).

In our study, we attempted to model the performance of a rainwater harvesting system located in the area of a public institution (an elementary school) in Szeged and examine the processes during the collection. Rainwater harvesting modeling is an outstanding tool to examine a harvesting system performance (Fewkes 2000, Fewkes and Butler 2000, Rossman 2015, Rossman and Huber 2016a, 2016b).

2. STUDY AREA

We carried out our investigation in Szeged, the largest city in the southern region of the Great Hungarian Plain (168,000 inhabitants (KSH 2013)). It has specific climatic and urban structure features. The area is characterized by low annual rainfall (497 mm), high sunshine duration, and, consequently, high sensitivity to drought (Balázs et al. 2009). The intensity of precipitation is very variable, and in the long, dry, summer periods heavy rainfalls are frequent which, according to climate change trends, may be even more severe in the future.

Our specific plot is the yard of an elementary school and the roofs of the building, which are located in the north-western part of Szeged. The total area of the yard together with

the roofs is 1 km², most of which composes the schoolyard. The model we used works with catchment areas. In this study, the schoolyard and 12 roofs (Subcatchments 1-13, hereafter SC1-13) were defined as one catchment area (Fig. 2). Defining the exact relations of the roof-to-roof connections is extremely important. The volume of water carried from a particular roof to another can have a determinative influence on the volume of water that can be potentially collected from a catchment.



Fig. 2 The study area with the subcatchments

The rainwater harvesting system consists of four rain barrels (each with 520 liters capacity), which are connected to SC4 and SC7 in a two barrels per catchment distribution. These two roofs and SC2 are almost completely flat roofs, while the other roofs are tilted. In the case of SC7, the harvesting system is only supplied by rainfall on the roof surface, while in the case of SC4, it has onflows from the tilted SC3 roof, which is an additional source of water.

3. DATA AND METHODS

We used the EPA SWMM model for the rain harvesting simulation. SWMM is a highly complex tool for performing various hydrological and hydraulic examinations. It can be used to investigate surface runoff, evaporation, and pollutants washoff. It includes an LID module that can be used to model green roofs, rain gardens or rainwater harvesting solutions (Elliott and Trowsdale 2007, Jayasooriya and Ng 2014).

The model requires the daily or hourly resolution of meteorological parameters, which include minimum-maximum temperature, precipitation intensity and wind speed. The modelled period was 2015, the source of data was the South-Hungarian Regional Center of the Hungarian Meteorological Service Synoptic weather station and the databases of the Department of Climatology and Landscape Ecology (Szeged) (Unger et al. 2017). Several precipitation sources can be attached to the model system, but due to the size of the area, one source was used in this study. In addition to the meteorology file, we also needed spatial data to provide a framework for examining runoff and evaporation (Rossman 2015, Rossman and Huber 2016a, 2016b).

Spatial data contain basic spatial parameters (e.g. area), but many other parameters also had to be specified in addition in order to run the model accurately. The model uses a subcatchment system, thus modeling processes take place within a small watershed. The following features should be provided for each subcatchment: impervious/pervious surface ratio, slope, percentage of potential depression storage, Manning's roughness coefficient (Rossman 2015), percentage of flow between subcatchments, receiver of runoff from the subcatchment, and its properties. Some of the data were evaluated through field surveys, and a part of the data (coefficients) were derived from literature data (Table 1). In Table 1 N-Imperv is Manning's n for impervious area, N-Perv is Manning's n for pervious area. Dstore-Imperv/Perv is the depth of depression storage on impervious and pervious area. %Zero-Imperv is the percent of impervious area with no depression storage and Percent Routed is the percent of runoff routed between sub-areas. Besides defining the connections between the roofs, it is also necessary to define the end points of the system. In this case, the model drains water outside the system directly from the roofs, so that there are no surface open channels that complicate surface runoff values (Rosa et al. 2015, Rossman 2015, Rossman and Huber 2016a, 2016b).

Table 1 Data sources and values

Data	Source	Flat roof	Tilted roof	Schoolyard
Area	orthophoto/field survey	SC specific	SC specific	SC specific
Width	orthophoto blueprint	SC specific	SC specific	SC specific
% Slope	blueprint	SC specific	SC specific	SC specific
% Imperv	orthophoto/field survey	100	100	36.46
N-Imperv	literature data blueprint	0.013	0.014	0.013
N-Perv	literature data blueprint	0.1	0.1	0.15
Dstore-Imperv	literature data blueprint	1.9	1.9	2.54
Dstore-Perv	literature data blueprint	2.54	0.05	3.8
% Zero-Imperv	literature data blueprint	20	90	12
Percent Routed	orthophoto/field survey blueprint	100	100	100

For the collecting system, it is necessary to define the height of the barrels (930 mm), the drain delay time (hours), and the flow coefficient, which together can determine the efficiency of the system. As the barrels in this case are relatively small, it is necessary to consider drainage times (flow coefficients: 2-5 mm h⁻¹), since without this (because of the small size of the barrels) the system would expect a continuous overflow after the first filling of the barrel. Therefore, we would not be able to determine how efficiently the system would collect water.

With these data, tests can be run for a specific time period or for complete annual periods. In the present study, we ran the model for a complete year (2015) to get an overview of the volume of the collected water throughout the year and the intensity of rainfall and runoff.

4. RESULTS

4.1. Summary results

The modeling provides basic information on the volume of water entering the SC, surface runoff, and surface evaporation. Heavy rainfalls occurred during the year in January, March, August, and October. The surface runoff was also high in these months, but evaporation was high only in March and August due to higher temperatures. Evaporation in this case is not affected by vegetation as SC1, which has vegetation surfaces, is not shown in the figure because of the significantly higher volumes (Fig. 3).

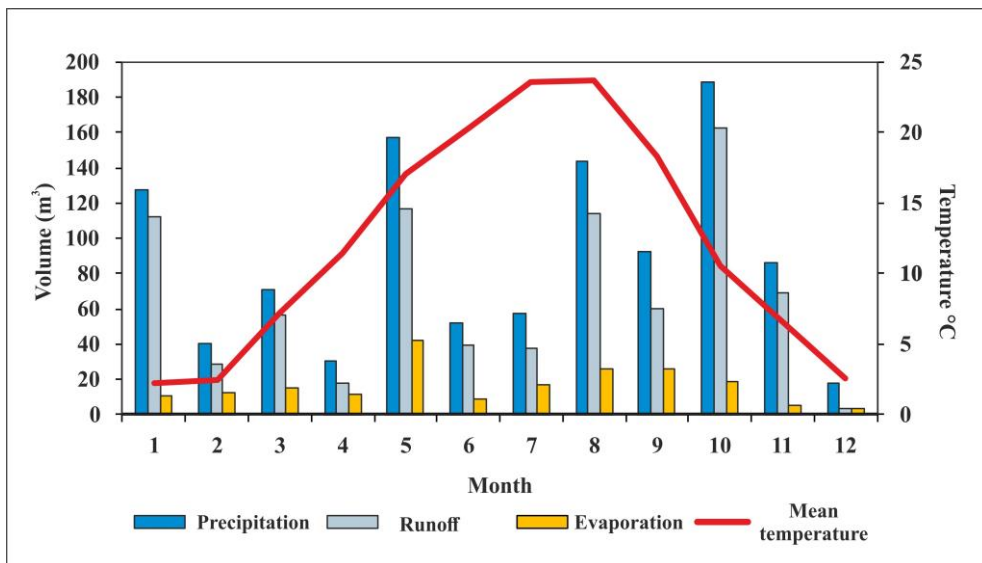


Fig. 3 The runoff and evaporation of the study area's roofs

In the case of SC1, we should consider the infiltration process, which accounts for a significant volume of precipitation. Nearly 66% of the schoolyard is covered by pervious

surfaces, which contributes to high infiltration efficiency. Surface runoff does not reach 40% in any month, and it is basically around 20% (Fig. 4).

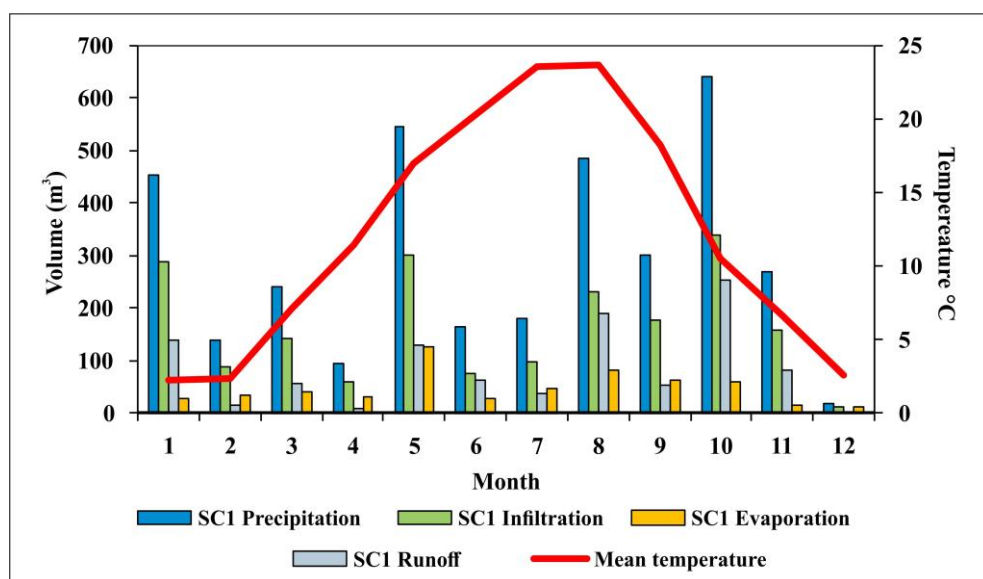


Fig. 4 The runoff and evaporation of the schoolyard (SC1)

4.2. Rainfall event results

These results provide information on the quantitative and temporal characteristics of rainfall events. We can obtain information about the event duration, the total volume of rainfall during the event, and event mean volumes. On the whole, we can get an overview of the quantities and the extent of precipitation events during the year. According to the literature, almost 30% of precipitation events in Hungary do not exceed 1 mm h^{-1} , while almost 48% belongs to the category of precipitation events with a value below 5 mm h^{-1} . 10 mm h^{-1} rainfalls, which have a greater impact on the daily lives of cities, account for a much smaller proportion of precipitation events. Their proportion decreases with increasing intensity. The length of the events is a minimum of an hour, as we used one-hour resolution data for modeling.

During the year, the model isolated 117 precipitation events, and calculated with a 5-hour separation time (it is the minimum time between two observed precipitation events). The longest precipitation event lasted 38 hours, with a 13-month return period, meaning that it does not occur at all or only once a year in similar meteorological conditions. 27 precipitation events lasting at least or more than 10 hours occurred during the year. Their return time decreases while their volume decreases, thus their percentage of occurrence also increases. As it can be seen in the figure, the highest proportion of precipitation events are beneath 5 hours (55%). Furthermore, 15- and 5-hour rainfall events have a relatively high proportion (35%). However, longer precipitation events are negligible (Fig. 5).

The total volume of events gives information about the events total precipitation/runoff. Basically, it can be emphasized that 7 mm precipitation events and those beneath them are the most numerous. Within this, precipitation events below 5 mm, but above

1 mm dominate. The largest amount of precipitation was 45 mm, it fell in 38 hours and began on October 10. Of the total precipitation events above 10 mm, 13 were during the year, while there were 52 precipitation events with 1 mm rain (Fig. 5).

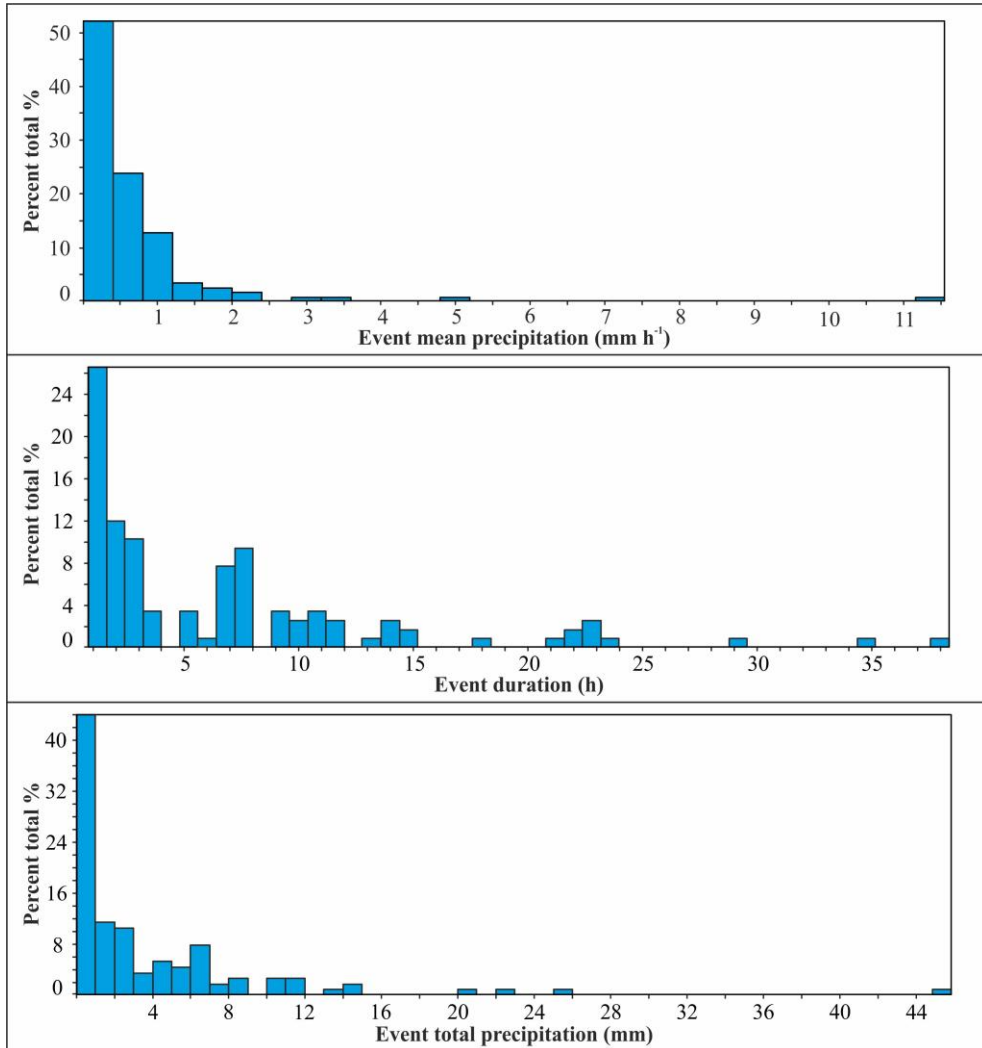


Fig. 5 The characteristics of rainfall events

We can give information about the hourly intensity of the precipitation during the event from the event mean values, i.e. the average volume of precipitation during a time interval (hour). Fig. 5 shows that the average intensity of precipitation events in 92% of the cases is below 1.5 mm h⁻¹. There are only a few events with higher intensity, for example, only one of the largest events of 11.5 mm h⁻¹ occurred. However, it is worth comparing the length of the event and the hourly averages. The duration of the three highest intensities of precipitation was 1 hour in each case. Specifically, during that event when 11.5 mm

precipitation fell in one hour, that type of precipitation can make it extremely difficult to control runoff (Fig. 5).

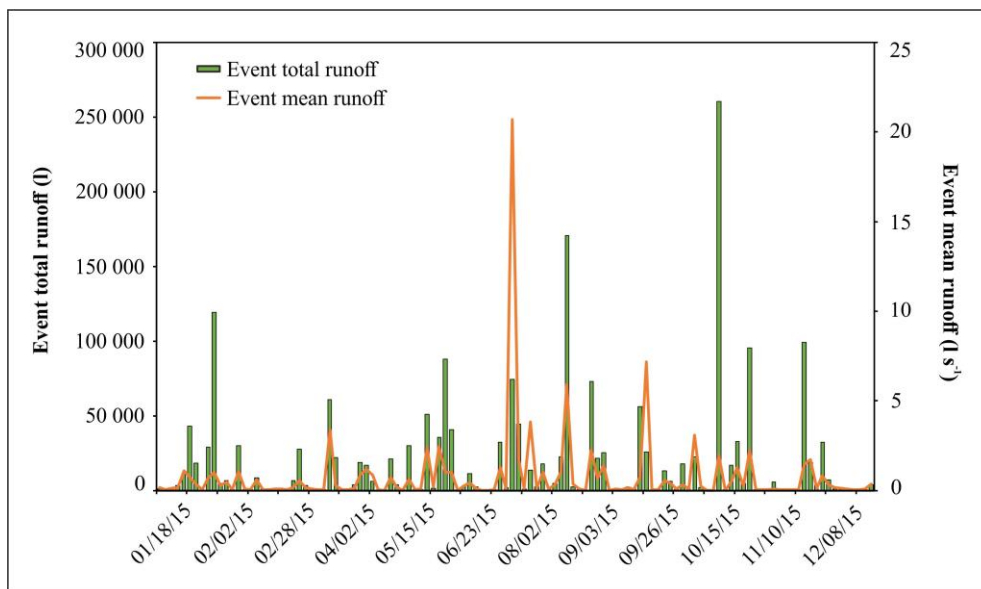


Fig. 6 Event mean and total surface runoff values

In the case of the surface runoff, we get a similar picture of the runoff events as the precipitation events, since the runoff is based on the volume of precipitation. The length of the events is similar to the length of precipitation events, but their volume may be significantly lower. It is due to evaporation on the one hand, and in the case of SC1, it is due to infiltration. By comparing the total volume of events and the average of the events, we can get a picture of the intensity of each event. Similarly, to precipitation trends, the runoff events are longer in the autumn and winter, their total volume is greater, but they fall in a longer time interval (Fig. 6).

Summer events are basically shorter, but their runoff intensity is much higher than in other periods. Two events are highlighted which are more extreme during the year. One is the July event, which had a moderate volume, but the highest average runoff. Based on this, the intensity of runoff can also be very high during the year. The other event was in October, but here the low average runoff was associated with high volume, which is a long-lasting, but less intense event (Fig. 6). In the future, it may be important to explore the impact of such different events on the process of rainwater harvesting, as the intensity and volume of runoff can affect the recharge of rainwater catchments.

4.3. Rainwater harvesting efficiency examination

In order to understand the processes at the two roofs (SC4, SC7) better, it is necessary to be aware of the volume of water flowing on them. The volume of precipitation falling on the two roofs is almost the same, but there are significant differences in the volume of runoff due to the onflow from the SC3 roof. This difference is also visible in the volume of runoff,

which shows more than a double difference. In contrast, there is no notable difference in the volume of evaporation. Thus, the excess onflow cannot be offset by the potential evaporation of the roof (Fig. 7).

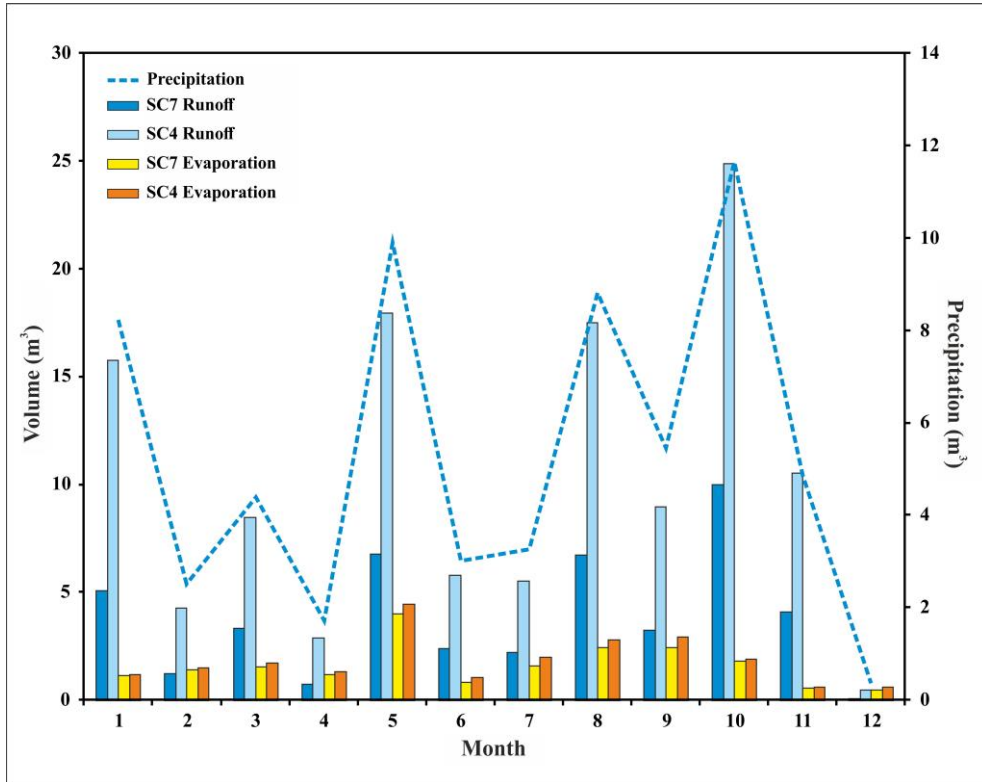


Fig. 7 The runoff and evaporation of roofs with the harvesting systems

The model can be used to calculate the volume of water potentially available for rainwater harvesting from precipitation on roofs. Thus, this volume does not contain the evaporated precipitation. The model calculates a specific storage level for each rain barrel, which is the height of the barrel (in this case 930 mm). Because of the small size of the barrels, it is necessary to calculate drainage times because the system cannot count the volume of water flowing into the barrels after the first filling, and we would only be given the data on the volume of overflow. In our study, we calculated two different drainage times ($2/5 \text{ mm h}^{-1}$), between which we did not find significant difference. However, there is a significant difference between the overflow of the two roofs, which is much more significant in the case of the SC4 due to the onflow from the tile roof (Fig. 8). Fig. 8 also shows that during the July and October events mentioned above, there were significant overflows from the roofs, which represent more than the double of the volume of SC4.

54-56% ($63\text{-}66 \text{ m}^3$) of the potential rainwater could be collected on SC4, which could fill the 2 barrels 121-128 times. In contrast, for SC7, 80-83% ($35\text{-}36 \text{ m}^3$) of the potentially available runoff could be collected, which could be able to fill the 2 barrels 67-69 times. It

shows that the efficiency of SC4 is lower than that of SC7, which is due to the overflow, but it could still collect nearly a double absolute amount compared to SC7.

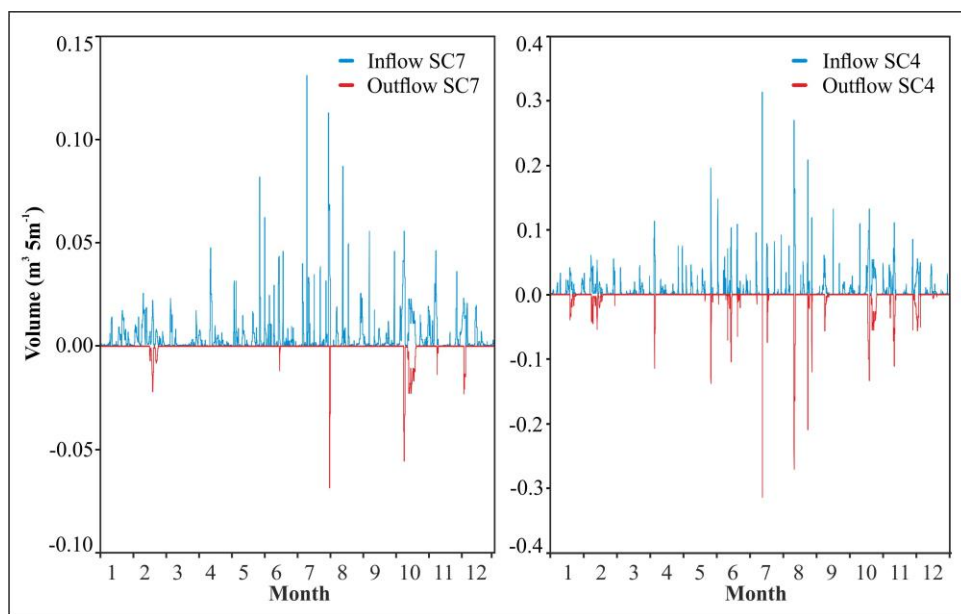


Fig. 8 The overflow of the roofs with harvesting systems

The first filling of the barrels indicates the rate at which the precipitation can fill them. This first filling for SC4 was 432 hours from the start of the study, while it occurred after 548 hours for the same volume of discharge in SC7. It also indicates that the inflow to the SC4 results in a higher load leading to a faster overflow of the barrel.

The volume of the water coming from the two rooftops (about 100 m³) can make a significant contribution to the irrigation of the school's green space, which has been based on potable water so far. It could save 65 200 HUF of potable water per year (calculated at 2018 prices). Of course, not only the irrigation of the vegetation can be replaced by rainwater, but also flushing the toilets can be done with it. However, it requires the installation of a more sophisticated system that can provide adequate volume of rainwater from other roofs.

5. CONCLUSIONS

The dry and droughty periods of the southern region of the Great Hungarian Plain can put a heavy load on private and public green spaces. Due to the uncertainty in the amount and occurrence of precipitation, it is important to retain the available precipitation. In order to facilitate the spread of rainwater harvesting systems, it is important to perform tests to prove their efficiency. With the help of water catchment modeling, we can estimate the volume of water collected by the planned system, and we can perform these tests on completed systems.

However, in order to evaluate the efficiency and usability of the systems, it is important to have a good understanding of the basic processes of the models. With the help of the SWMM model, we can examine the processes that affect the use of collecting barrels. Basically, the study showed that events of low volume and intensity dominate throughout the year. An exception to this is a couple of events that were either exceptionally large or high in intensity. While smaller and low intensity rain events do not cause problems in the operation of the collecting system, significant overflows are to be expected in the case of large and prolonged rainfalls.

The information available on harvesting systems can be useful to public institutions, as we can also provide information on the volume of water collected and cost estimates for the savings. With this information, we can also help to improve our approach to saving water.

Acknowledgements: Supported by the UNKP-18-3 New National Excellence Program of the Ministry of Human Capacities. The authors' special thanks to the Department of Physical Geography and Geoinformatics and the Department of Climatology and Landscape Ecology for the provided data.

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