STORAGE CAPACITY OF RAIN TANKS OPTIMIZED FOR THE LOCAL CLIMATE IN TWO METROPOLITAN AREAS OF SLOVAKIA

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Combating the adverse effects of drought and extensive precipitation in urban areas can be achieved by efficiently designed rain water harvesting systems such as green roofs, rain tanks, infiltration trenches, etc. Their performance, however, is inherently affected by local rainfall patterns. In this paper we focus on the rainfall regime at six locations within two metropolitan areas in Slovakia. Four sites are located in the capital of Bratislava and its environs, and two sites are located in the second largest city Košice. Using event-based statistical characteristics and an analytical probabilistic model, the optimal capacity of rain tanks for the metropolitan areas of Bratislava and Košice were estimated. The presented event rainfall statistics can facilitate the design of green infrastructure (e.g. vegetative roofs, rain gardens, infiltration trenches etc.), optimized irrigation of urban gardens and improvement of storm water management in these two metropolitan areas of Slovakia.

KEY WORDS: rain water harvesting, drought, green city, rain tanks

Introduction

The most recent scientific reports show (including IPCC) that increasing concentrations of greenhouse gasses affect the climate of the Earth, which is manifested by global warming and fast complex changes within the entire climatic system. Global warming has also its consequences in Slovakia and in the investigated regions of Bratislava and Košice. The observed upward trend in Earth's surface temperature is the most readily perceived manifestation of the ongoing climate change especially after the mid-1980s and the early 1990s in Slovakia. Whereas the global average temperature of the boundary-layer atmosphere increased since the start of the 20th century by 1°C (AR5 IPCC, 2013), the region of Central Europe, including Slovakia, witnessed a double increase in temperature (~1.7 to 2.0°C) over the same period. Based on climatic models, in the southern parts of Slovakia, the annual average of air temperature is very likely to increase by 0.8–0.9°C by 2025, and 2.0–2.5°C by 2050, compared to the climatic normal 1961–1990. But climate change is not limited only to increasing global and local air temperature. It brings a host of other manifestations and phenomena (e.g. droughts and extreme rainfall).
Combating the adverse effects of drought and extensive precipitation in urban areas can be achieved by efficiently designed rain water harvesting (RWH) systems such as green roofs, rain tanks, infiltration trenches, etc. Their

performance, however, is inherently affected by local rainfall patterns. Rain water harvesting (RWH) systems have been shown to be an alternative source of water in cities (Zhang and Guo, 2014; Cain 2010; Rahman et al., 2014). In general, the goal of introducing RWH systems into urban planning is to collect and store rain water. The most common uses of rainwater in cities include watering of public gardens, parks and to flush public toilets. Apart from the environmental benefits associated with saving water resources, RWS reduce water bills.
In this paper we focus on the rainfall regime at six locations in Slovakia. Four sites are located in the capital of Bratislava and its environs, and two sites are located in the second largest city Košice. Using event-based statistical characteristics and an analytical probabilistic model we estimate the optimal capacity of rain tanks for the metropolitan areas of Bratislava and Kosice. Despite the widespread use of rain tanks in Slovakia, the optimal capacity (volumes) of rain tanks is often anecdotal. The goal of this paper is to describe the local rain regime and climate in the metropolitan areas of Bratislava and Košice, and subsequently to provide a tool to estimate optimal capacity of rain tanks.

Material and methods

Source data and sites description

The rainfall data analysed in this paper were obtained

from the internal climatological databases of the Slovak Hydrometeorological Institute. In this study, 14–19 years (1991–2009) of pluviographic records measured at four rain gauges located within the city Bratislava, one gauge at Malý Javorník located some 20 km north from the city center in the Small Carpathians Mts., and two gaugess in Košice, were used. The geographical attributes of the rain gauges are listed in Table 1. The temporal resolution of the time series is one minute. The rainfall data cover the 'warm' part of the year when precipitation falls in liquid form (April–October), hence the cold season (November–February) was not analysed.

Local climate

The climate in the metropolitan area of Bratislava has been estimated for the period 1961–2010. According to the Koncek climate classification the area belongs to the warm (*T*) area which is characterized with an annual incidence of more than 50 warm days in the summertime (a summer day is a day when the maximum diurnal air temperature T_{max} surpassed 25°C), sub-region T1–T6 (warm, moderately humid with mild winters). The average annual temperature in this region is 10.1°C (determined for the climatic normal 1981–2010), the warmest month is July with average monthly temperature 20.5 to 21.6°C, the coolest month is January (average monthly temperature -0.8°C, average annual air temperature between 10.5 and 11.0°C). The annual incidence of summer days is 67.3 ($T_{max} \geq 25$°C), 18.4 tropical days ($T_{max} \geq 30$ °C), and 83.3 frost days (minimum diurnal temperature $T_{min} < 0$°C), 29 ice days ($T_{max} < 0$°C) and 0.4 arctic days ($T_{max} \leq -10$°C). The precipitation regime and its spatial variability in the area of Bratislava is affected by geography (Small Carpathians, Danubian and Morava lowlands). The average annual precipitation total is between 560 to 680 mm, with up to 60% of precipitation falling during the warm part of the year (April–September). Most precipitation falls between June and August, accounting to 170 to 200 mm. The average air temperature in Bratislava increased by almost 2°C since 1951 (the mean decadal increase in air temperature is 0.3°C/10 years). The annual precipitation total increased, on average, by 6–12 mm (comparison of 30-year averages estimated for 1951–1980 and 1981–2010 (16)) which is only a 2% increase. The number of frost days between the periods 1951–1980 and 1981–2010 dropped by 13 days (from 96 days to 83 days); on the other hand, the number of summer days

increased by 14 days, and the number of tropical days increased by 9 days (from 10 to 19). The diurnal maximum and minimum air temperature is expected to rise in the upcoming decades. By 2050, the number of summer days is expected to substantially increase by 25 days per year, the number of tropical days with increase by 15 days; while the number of frost days can decrease by 25 days and ice days by 15 days. The most important consequence in terms of the thermal comfort is the increasing incidence of heat waves with an earlier onset (in May) and occurring until mid-September. Due to the elevated water holding capacity of the atmosphere, the number of days with muggy weather will probably increase. The precipitation totals will slightly increase, especially in the cold part of the year. But with the increasing air temperature, evaporation will increase too. This will create conditions for conditions for longer lasting droughts in the investigated region. Torrential and long-lasting rains will become more frequent and more severe (by approximately 7–14% per every °C increase in air temperature). Changing temperature and precipitation regimes in the winter season will affect the snow cover. The number of days with snow cover is expected to decline. More severe and storms are also expected to occur in the future as a response to the increasing air temperature and humidity.

Rain event separation and event characteristics

Knowing the so called „minimum inter-event time" is essential in order to isolate statistically independent rainfall events. The minimum inter-event time (MIT), as defined by Restrepo and Eagleson (1982), is a rainless period separating two successive rains events. Two successive rains are considered as a single event if the rainless periods between two rains is shorter than the MIT value. The procedure of event selection is based on the premise that the inter-event times are exponentially distributed (Restrepo and Eagleson, 1982), and the arrival of independent events is thought to follow a Poisson process.

Every independent rainfall event can be described by various statistical characteristics such as total event volume, event duration, time between successive events, time-to-peak and maximum intensity (Wang et al., 2019; Dunkerley, 2008; 2015). In this paper, we present the event characteristics that are required for probabilistic analytical models proposed by Guo and Baetz (2007), i.e. mean event duration, mean event depth and mean inter-

Table 1.   **Basic geographic description of the analysed locations**

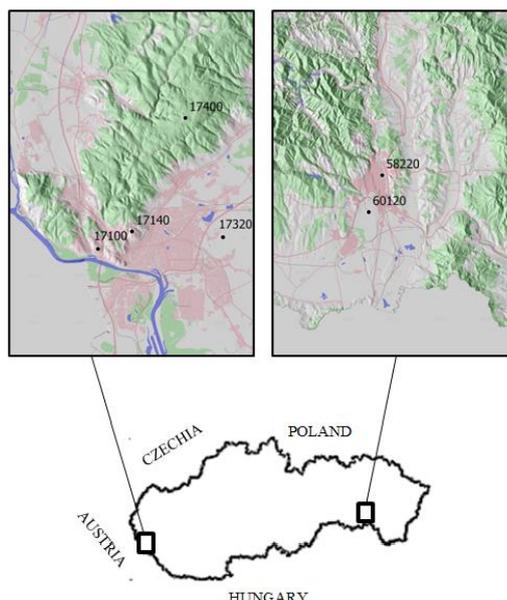| Station ID	Station Name	Latitude	Longitude	Record length	Altitude [m a.s.l]
17100	Bratislava–Mudroňova	48.15219	17.07034	14	205
17140	Bratislava–Koliba	48.16778	17.10611	15	283
17320	Bratislava–Airport	48.17028	17.2075	15	128
17400	Malý Javorník	48.25583	17.1525	15	575
58220	Košice–Mesto	48.72528	21.265	15	207
60120	Košice–Airport	48.67056	21.23861	19	229

Fig. 1.   Location of investigated metropolitan areas and rain gauges (left: Bratislava; right: Košice). The gauge names corresponding to the displayed gauge IDs are indicated in Table 1.

event time. These characteristics were calculated for each location from the series of previously separated rainfall events following the procedure described in Restrepo and Eagleson (1982) and Bedient et al. (2008).

Estimation of tank sizing and maximum water use rate

The local rainfall event characteristics were used as an input in an analytical probabilistic model proposed by Guo and Baetz (2007). Briefly, the capacity of a rain tank (Eq 1) and maximum daily water use rate (Eg 2) are defined as:

$$B = \frac{A\phi G}{\zeta G + A\phi\psi} ln \left[\frac{A\phi\psi \; e^{-\zeta \, v_{ff}}}{A\phi\psi \; e^{-\zeta v_{ff} - R(A\phi\psi + \zeta G)}} \right] \qquad (1)$$

where

A – rooftop catchment area (roof) [m^2];
B – rain tank volume [L];
R – desired reliability of tank in supplying water [-];
G – daily use rate [L day^{-1}];
ζ – distribution parameter of event depth v [mm^{-1}];
ψ – distribution parameter of inter-event time τ [hour^{-1}]
ϕ – dimensionless runoff coefficient [-];
v_{ff}– depth of first flush that is diverted from rain tank [mm].

The daily maximum use rate G_{max} [L day^{-1}] is defined as:
$$G_{max} = \frac{A\phi\psi}{\zeta} \left(\frac{e^{-\zeta \, v_{ff}}}{R} - 1 \right) \qquad (2)$$

The ζ and ψ distribution parameters in Eq. 2 were determined as the inverse of the mean of the event depth v and rainfall inter-event time τ, respectively (Guo and

Baetz; 2007). Usually, the first flush may be contaminated with e.g. dust and vegetation debris. The first flush v_{ff} is the rain water that is diverted from the downspout gutter just before the water enters the tank. To simulate tank sizes for a range of rooftop areas and reliability factors, Eq. 1 and Eq. 2 were applied pre-specified input parameters. The rooftop surface catchment areas was allowed to very between 25 to 250 m^2 in order to cover broad range of rooftop areas. The reliability factor R is here defined as a fraction of time when the desired water use rate (G_{max}) is guaranteed. R was allowed to vary from 0.2 to 0.8. These simulations were conducted for all six locations (Table 1), using the statistics of the mean event depth $\hat{v}$ and the mean inter-event time $\widehat{IET}$ (Tables 2). In the examples presented in Fig. 3, the reliability factor R was set to 0.4 and the rooftop catchment area A to 190 m^2, which are arbitrarily chosen design parameters.

Results and discussion

The analysed rainfall records were separated into statistically independent rainfall events that were later used to derive event-based statistical characteristics such as mean rainfall duration, mean event depth and mean inter-event time for each location. The empirical estimates of mean event depth and mean inter-event time are listed in Table 2. As rainfall is a highly spatially variable phenomenon, it is essential to investigate how the average rain event duration, total rain event volume and inter-event time vary in space. For example, the MIT values across the analysed locations range from 11 hours at Malý Javorník and 23.5 hours in the city of Košice (Table 2). The average event volume is a highly variable characteristics within the area of Bratislava (ranging

from 6.3 to 9.3 mm). In the case of Kosice, the average event volume ranges from 10.5 to 17.8. The other event characteristics show also a large spatial variability within and between the two metropolitan areas.

To show the applicability of the presented analytical probabilistic approach, a real-world situation is simulated for a hypothetical homeowner living in the vicinity of the Bratislava Airport wants to collect rain water and use it for irrigating a small backyard. Let us suppose that the house has a roof with surface area 190 m^2 and the expected daily use rate is 320 L day^{-1}. In all simulations, the runoff coefficient ϕ was set to 0.95. As shown in Fig. 3a, this will require a tank (or several smallest tanks) of almost 3 m^3. Note, that this particular location does not allow the homeowner to use more than 320 litres per day, supposing the reliability is set to 40%. i.e. 40% of time the requirements will be satisfied. If the house was located in Bratislava–Koliba, the same tank volume would allow the homeowner exploit 430 L per day. Similar comparisons can be readily made for other situations and locations (Fig. 2a–b).

The maximum daily use rates were also simulated for a range of reliabilities and rooftop catchment areas estimated for stations located in the Bratislava area (Fig. 3) and in Košice (Fig. 4). In general, the maximum daily use rate decreases exponentially with increasing reliability. Fig. 3 and Fig. 4 show that increasing the rooftop catchment areas does not lead to a substantial increase in the maximum daily use rate when the reliabilities are expected to be too high. Considering that a reliability of 0.8 means that water can be abstracted from the rain tank almost every day, the rain tank can provide very small amounts of water.

Apart from the application presented in this paper, the tabulated statistical properties of rainfall (Table 2) can be used in the design of water detention reservoirs (Bacchi et al., 2008), bioretention systems and infiltration systems (Guo and Hughes, 2001), vegetative roofs (Guo, 2016), sewer tanks (Balistrocchi et al., 2009), or to conduct hydrologic analysis of rainfall-runoff relationships in catchments (Guo and Adams, 1998). Although only the mean inter-event time and mean event depth were used in the estimation of proper sizing for rain tanks, the values of mean event duration and the mean number of events (Table 2) as presented as well, as these statistical properties of rain are essential for the design of drought mitigation measures mentioned earlier.

Fig. 5 is important in respect to the actual choice of rain tank volumes. The sizing of rain tanks was simulated an hypothetical house with a rooftop catchment of 190 m^2 (a typical urban family house in the investigated region), reliabilities from 0.1 to 0.8 (or 10 to 80%), daily water use rates 10 to 500 L day^{-1} (with 10-liter increments). Choosing the optimal size of a rain barrel is a trade-off between the desired use rate G and reliability R. For example, a reliability of 10% actually means that, on average, the tank volume will be completely depleted once in every 10 days. Increasing the reliability to 30 and 40%, the largest tank sizes will reach 1.5 and 4 m^2, respectively; depending on the location. Note that above the reliabilities of 40% the tank volumes are determined only to a certain limit.

This limit is displayed in Fig. 4 as white spots. These white spots indicate that the tank volume cannot be mathematically determined because the denominator in the logarithm of Eq. 1 becomes negative for high values of reliability. Thus, additionally increasing the tank volume would not guarantee more water in the tank, as rain-fall becomes the limiting factor. An extreme situation happens when the reliabilities are set to 80%. In this case, the rain tanks cannot provide more water than 10 liters of water from a 0.5 m^3 rain tank at Bratislava–Aiport and not more than 50 liters of water from a 1 m^3 rain tank in Košice–Mesto.
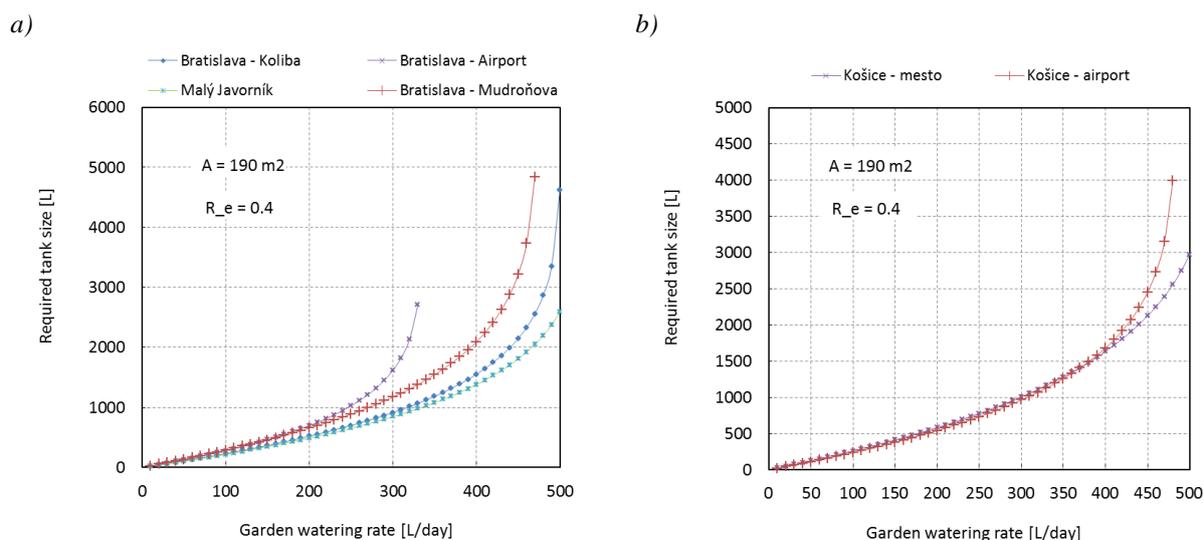
a)

b)

Fig. 2.   Required tank sizes calculated by Eq. 1 for four stations in the capital city Bratislava and Malý Javorník a); and b) for two stations at the second most-populated city (Košice).

Table 2. **Spatial variability of event characteristics (annual mean values): event depth $\hat{\nu}$, event duration $\hat{\tau}$, inter-event time $\widehat{IET}$, and number (incidence) of rainfall events $\hat{N}$**

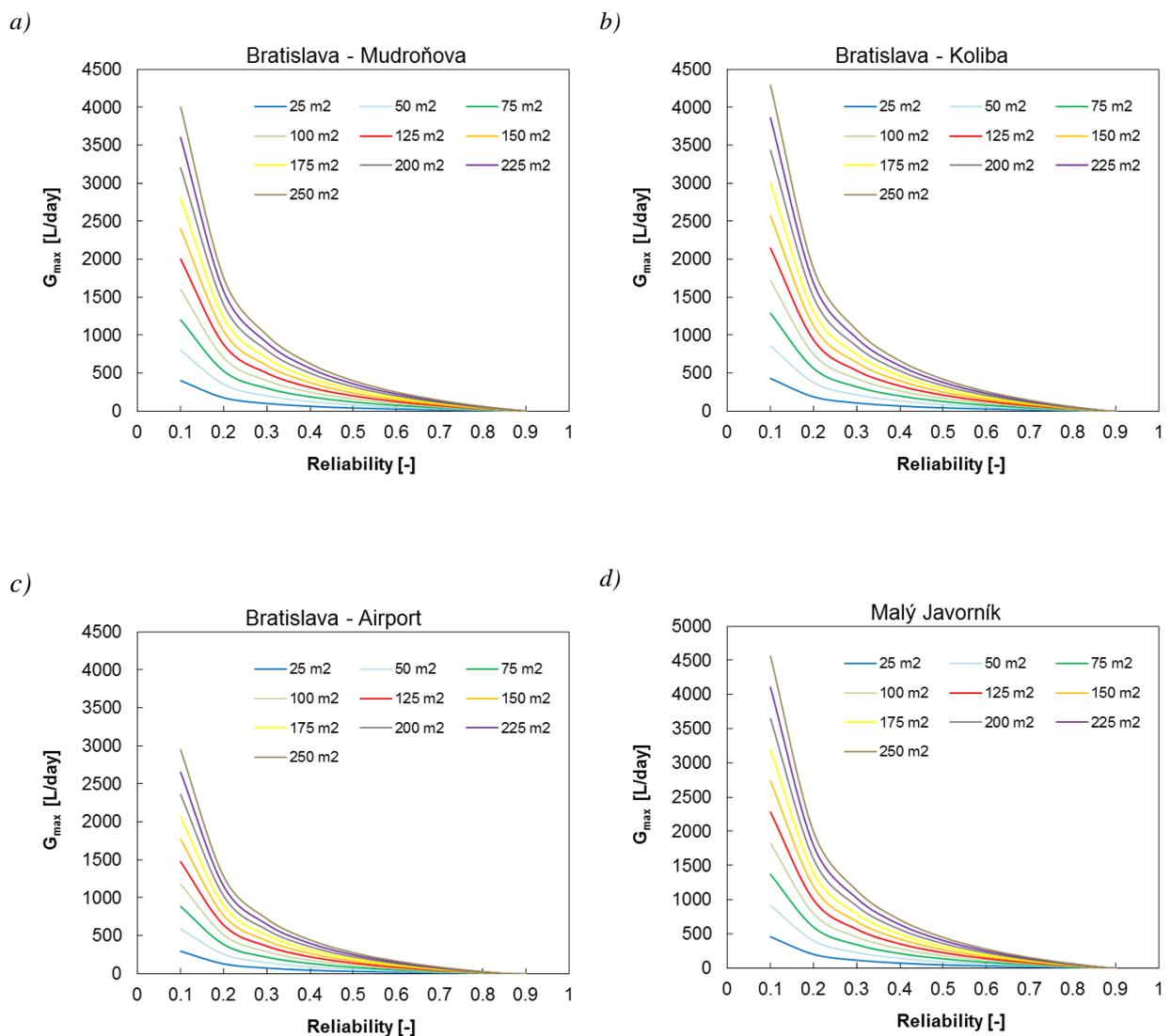| Station ID	Station Name	$\hat{\nu}$ [mm]	$\hat{\tau}$ [hrs]	$\widehat{IET}$ [hrs]	$\hat{N}$ [-]	MIT [hrs]
17100	Bratislava–Mudroňova	9.3	14.1	105.5	27.5	20.0
17140	Bratislava–Koliba	8.0	10.3	83.3	30.1	14.5
17320	Bratislava–Airport	6.3	8.9	91.1	29.9	14.5
17400	Malý Javorník	8.1	8.6	79.8	25.8	11.0
58220	Košice–Mesto	9.8	17.8	245.8	29.7	23.5
60120	Košice–Airport	8.0	10.5	215.1	31.2	16.5

Fig. 3. *Maximum daily use rates calculated by Eq. 2 for a range of reliabilities R ∈ (0.1–0.9) estimated for: a) Bratislava–Mudroňova; b) Bratislava–Koliba; c) Bratislava–Airport; d) Malý Javorník.*
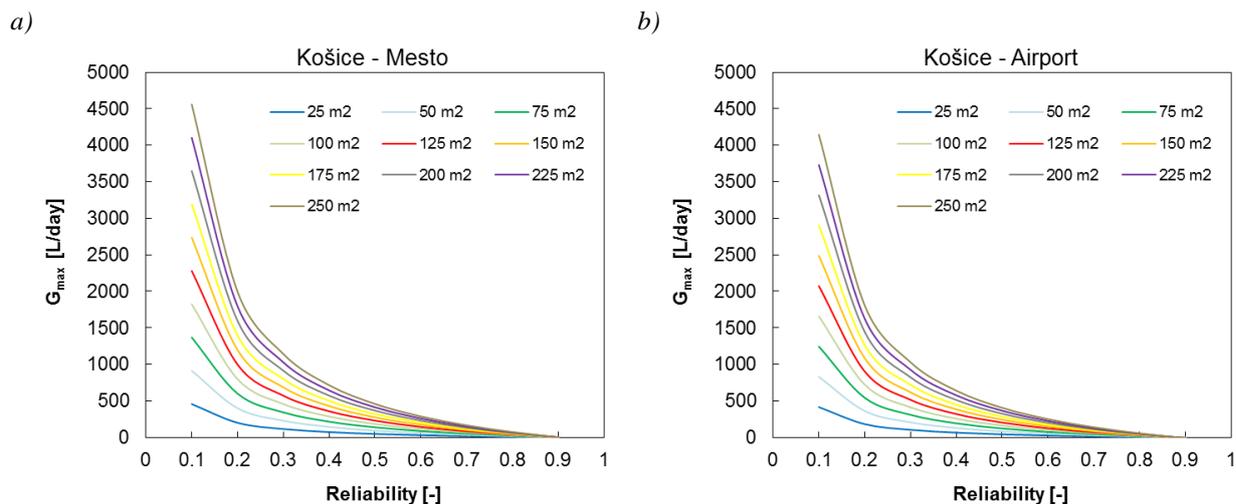
a)

b)

Fig. 4.   Maximum daily use rates (Eq. 2) simulated for a range of reliabilities
R (0.1– 0.8), rooftop catchment area 190 m², and first flush 1mm, estimated for: a) Košice
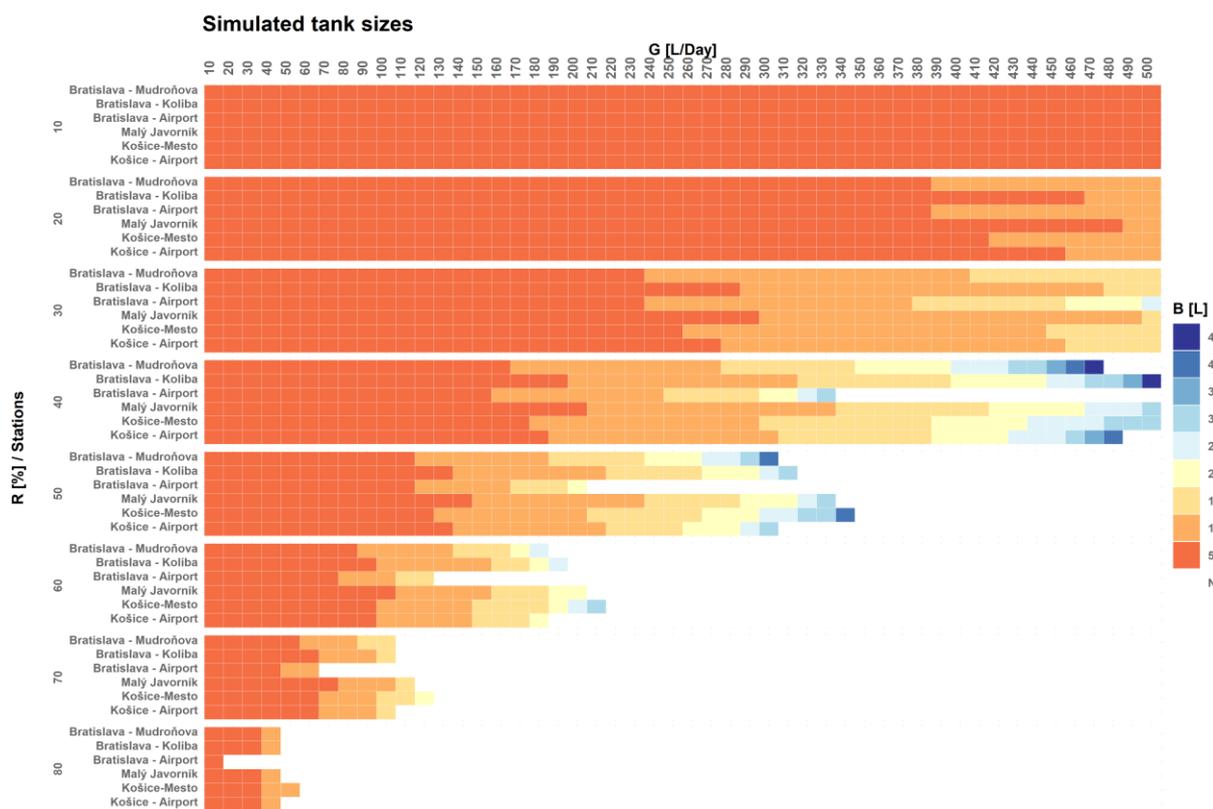– mesto; b) Košice – Airport.

Fig. 5.   Simulation results for a hypothetical rooftop area A=190 m², reliabilities
range from 10 to 80 %. The daily use rate G [L day⁻¹] are indicated in increments of
10 L day⁻¹.

Conclusions

By 2050 the number of days with extreme air temperatures is expected to substantially increase. On the local and national levels, there are several initiatives supported by the EU to combat the manifestations of drought in cities. The most important measures are green infrastructure and improvement of water retention structures in the urban environment as part of the urban green agriculture. The use of rooftop inexpensive rainwater harvesting systems increases the quantity of water for urban green architecture. In this study, six rainfall records were analysed in two major metropolitan areas in Slovakia to show local rainfall characteristics are detrimental in the design of rainfall harvesting systems. As a practical example, the analytical probabilistic approach was deployed to estimate optimal rain tank capacity for three sites in Bratislava, one site in the Small Carpathians and two stations in Košice. The model is parameterized on locally estimated event-based rainfall statistics: rainfall volume and inter-event time and rainfall. The rainfall records were separated into statistically independent rainfall events to derive the event-based rainfall statistics. The presented rainfall statistics can be used as design values directly by homeowners or municipalities that may assist homeowners in selecting the proper sizing of rain tanks without having to laboriously acquiring local statistics of rainfall. As analytical probabilistic models are gaining in popularity in the hydro-meteorological community, we are convinced that the presented statistical properties of rainfall can used also in the design of bio-retention systems, infiltration systems, vegetated roofs, and hydrologic analysis of rainfall-runoff relationships in catchments.

Acknowledgement

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