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THE LONG-TERM BEHAVIOR OF RESIDENTIAL RAINWATER HARVESTING SYSTEMS IN 1969–2018 RAINFALL TIME SERIES

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Abstract - Increasing pressures on water demand and availability of water resources due to progressive urbanization, industrial development, population growth and climate change require looking for water sources. A significant part of the water demand in residential buildings can be reduced as a result of replacing tap water with rainwater. This study aimed to investigate the potential of rainwater harvesting (RWH) system performance for polish climate conditions, on the example of two cities: Białystok and Wrocław. The inflow, outflow and the storage volume of rainwater were evaluated on the basis of water balance model including 1969–2018 rainfall data and water consumption estimated for two purposes: toilet flushing and washing. The simulations revealed that RWH system is able to cover ~80% of annual water demand. The accumulated rainwater can fully cover the water demandfor two-thirds of the year. Therefore, RWH systems can definitely play a significant role as an alternative water source and should be implemented as a common practice in urban development.

Keywords - Rainwater Harvesting, Water Demand, Water Saving Efficiency, Water Balance Model.

I. INTRODUCTION

Progressive urbanization, industrial development and population growth have a significant impact on water demand and availability of water resources [1]. This problem is also intensified by climate change, which is the issue outlined in the IPCC Report [2]. Increasing water supply pressures demand the application of solutions related to water management optimization, and here two types of activities can be distinguished. The former are based on activities promoting the reduction of water consumption (including using devices with lower water demand). The latter group of solutions is to look for alternative water sources [3]. A significant part of the water demand in residential buildings can be reduced as a result of replacing tap water with rainwater for purposes that do not require potability. In addition, this water can be purified in order to be suitable for all uses [4].

Rainwater harvesting (RWH) allows water to be collected directly in households. RWH systems operate by collecting rainwater from surfaces such as roofs or terraces, and then transporting water to tanks or cisterns. The collected water is then used to cover the needs inside buildings (e.g. for flushing toilets, doing laundry) or outdoors (e.g. for car washing or irrigation in gardens). It is worth noting that typical consumption of domestic water, according to [5] for various purposes is as follows: 40% in sinks and bathtubs; 25% for flushing toilets, 13% for washing, 12% in the kitchen, 5% for watering home gardens and 5% for cleaning [6]. RWH systems allow to provide from 12 to even 100% of the water demand for the household [7]. Beyond the obvious benefits of water saving, RWH systems are beneficial from the point of view of storm water drainage systems, especially in relation to climate change. The projected increase in intensity of rainfall [2] may lead to urban floods in the future. RWH systems allow the reduction of storm water runoff from urbanized areas, enabling to alleviate the pressure on urban drainage systems [8, 9]. Accumulation of rainwater in urban areas has also an impact on reducing the costs associated with the operation of water supply including, inter alia, reducing energy demand in the process of preparing tap water of adequate quality and its delivery to consumers [3, 10]. Due to a number of benefits, RWH has been recently promoted as a common practice in many countries, not only in arid regions, but also in areas with good water balance conditions. Some countries have even ordered the implementation of RWH systems in newly designed buildings (i.a. Australia, China, Jordan) [1, 8, 11, 12].

Performance of RWH systems depends primarily on the spatial and temporal rainfall pattern, the size of catchment area, water consumption pattern, and the size of the rainwater tank [8, 11]. It will also depend on the scope of its use (e.g., domestic - potable or non-potable; irrigation) [3]. The main variable in the designing of RWH systems are rainfall data, because on their basis the amount of accumulated rainwater from the analyzed catchment is determined [4, 12, 13]. Long-term rainfall time series best reflect the rainfall phenomenon over time. According to the World Meteorological Organization recommendations [14], rainfall data from at least 30-year period is considered as a representative time series. In recent years, many studies on the effectiveness of RWH systems have been conducted using historical rainfall data [8]. Consideration of long-term time series of rainfall data allows to provide information on changes in RWH system behavior. It may also more realistically reflect the impact of climate change than synthetic rainfall data downscaled from Global Climate Models [1].

In recent years, there has been an increase in the number of studies on RWH systems [15, 16]. In [3], the broad review of them are presented. Although these studies have shown the potential efficiency of RWH, the effectiveness of this technology should be investigated for various climatic conditions. The objective of the present study was the investigation of the hypothetical RWH system behavior for a household located in 2 cities in Poland, based on the 50-year rainfall data, considering the use of rainwater for non-potable uses: toilet flushing and washing.

II. MATERIALS AND METHOD

To assess the long-term behavior of residential rainwater harvesting in Poland, two cities were selected as the study area, namely Wrocław and Białystok (Fig. 1). The simulations of hypothetical residential RWH system were conducted using the 50-year historical data. The 1969–2018 long-term time series provides proper information on RWH operation in analysed locations. The water balance model was developed comprising the water demand and supply sites.

Figure 1: Two analysed cities on map of annual precipitation.

In simulation of the RWH behavior, the 4 residents were assumed. On this basis, the water demand for toilet flushing and washing was estimated, as in this study the rainwater use was restricted to these two purposes. For toilet flushing, the dual flushing device with 3/6 dm^3 per flush were adopted for calculations. For each person, 4 times per day on working days and 6 times per day on weekends were assumed. In case of water consumption for washing, it needs to be mentioned that it depends on class and capacity of the washing machine. Modern devices have the mean water consumption at the level of 40 dm^3 per cycle and this amount was taken to further analysis. It was assumed that typical 4-member family do the laundry 4 times per week (1 time on Tuesdays, 1 time on Thursdays, and 2 times on Saturdays), which results in 208 times per year. Based on the assumptions made, a profile of weekly water consumption for toilet flushing and doing laundry was developed (Table 1).

Day of the week	Washing, dm^3/day	Toilet flushing, dm^3/day
Monday	0	72
Tuesday	40	72
Wednesday	0	72
Thursday	40	72
Friday	0	72
Saturday	80	108
Sunday	0	108
Total weekly	160	576
demand	736	

Table 1: Water demand profile for washing and toilet flushing.

The simulation algorithm was developed as independent from the RWH system layout. It was assumed that rainwater will be collected from the roof with an area of 100 m^2 and stored in a typical rainwater tank with a capacity of 1000 dm^3. The surface runoff coefficient from the roof was assumed at the level Ψ=0,95, as the consequence of estimating the rainwater losses at approximately 5% to i.e. evaporation. In order to estimate the inflow of rainwater to the tank, the archival rainfall data for Wrocław and Białystok obtained from the Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB) was used. The hourly-step data range included 50 years of observations from the time span 1969–2018. Such a long measuring series guarantee the possibility of checking the system performance in both dry and wet years.

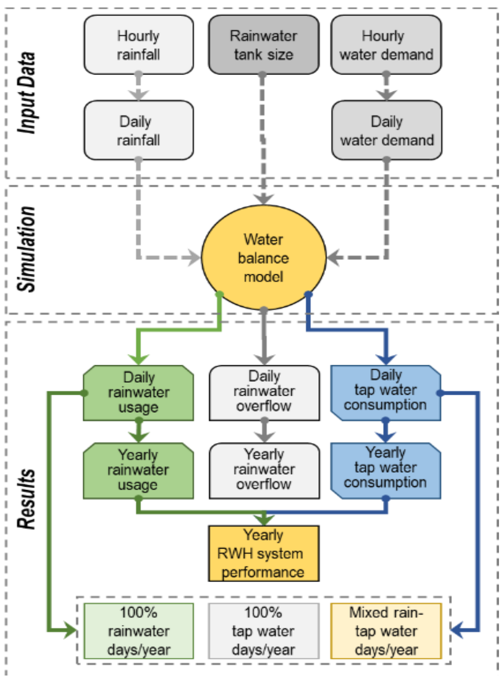

Figure 2: The block diagram of the long-term simulation of rainwater harvesting systembehavior.

Figure 2 presents the algorithm of RWH system performance and the block chart of conducted calculations. Based on historical data of daily rainfall from 1969–2018, the volume of water flowing into the tank each day was calculated, which - together with the estimated water demand for flushing toilets and washing - constituted the basis for the simple water balance for the analyzed system.

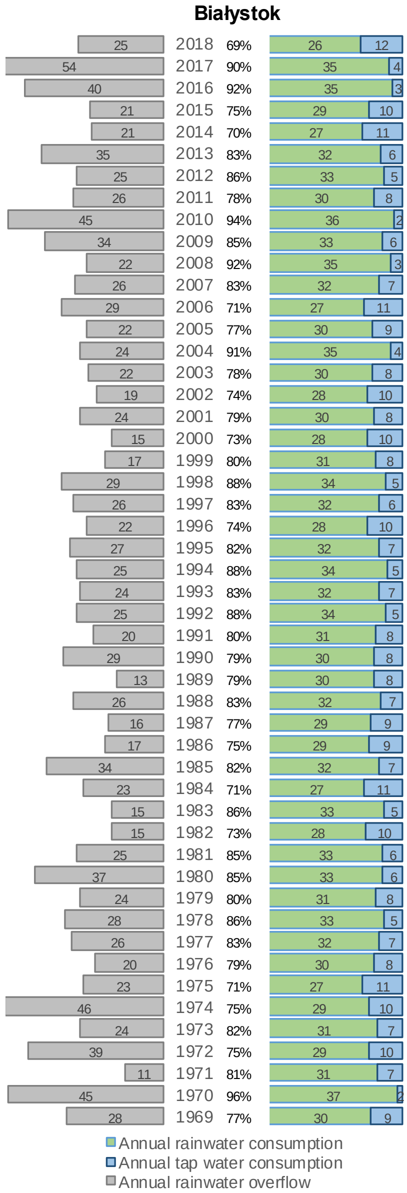

Figure 3: The RWH system behavior and performance in Białystok, m^3/year.

With a given volume of the rainwater storage tank, the rate of rainwater used for washing and flushing toilets will depend on the precipitation pattern. The results provide detailed information about rainwater consumption (used), rainwater overflow (lost), tap water consumption. Based on water balance the 100% rainwater usage days, 100% tap water usage days and mixed rain-tap water usage days were specified in each analysed year in Wrocław and Białystok, respectively.

III. RESULTS

As a simulation results the yearly rainwater harvesting performance and rainwater usage days were given in both analysed cities. The RWH system performance for the analyzed 50-year period are presented in Figure 3 (for Białystok) and Figure 4 (for Wrocław).

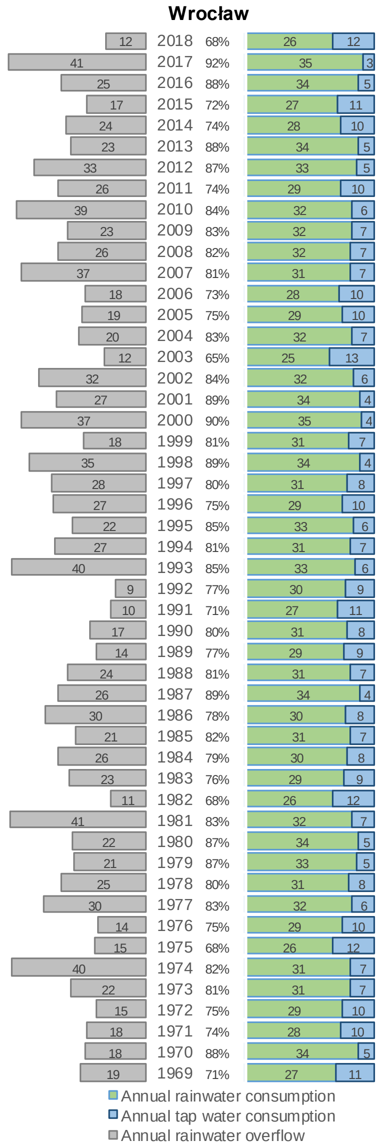

Figure 4: The RWH system behaviorand performance in Wrocław, m^3/year.

The yearly harvesting performance was defined as the proportion of water demand and used rainwater volume in individual years (in cubic meters per year). The green bars represent the rainwater volume consumed to cover the water demand in household, equivalent to the amount of tap water savings. The blue bars show the volume of tap water needed to cover the remaining demand. The gray bars on the left side illustrates the volume of rainwater that would not be collected in the tank (discharged by overflow), equivalent with rainwater losses.

For both cities, it can be seen that rainwater covers most of the water demand for washing and toilets flushing in each year. The volume of tap water required to cover the remaining demand is only a fraction of the total water consumption.

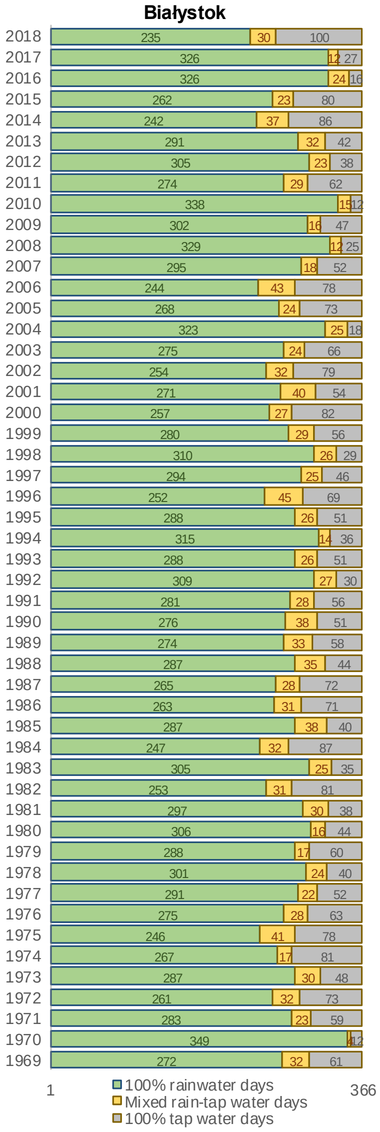

Figure 5: The 100% rainwater, 100% tap water and mixed rain-tap water usage days in 1969–2018 long-term behavior of RWH system in Białystok, days/year.

Based on these results, the contribution of rainwater in total water consumption was estimated for each year. The results were convergent for both cities. For Wrocław, rainwater would be able to provide on average 80% of the total water demand (for flushing toilets and laundry) - with a minimum value of 65% for 2003 and a maximum value of 92% for 2017. In Białystok, on average, 81% of the water demand would be covered with rainwater (with a minimum equal to 69% in 2018 and a maximum equal to 96% in 1970). In case of water that has not been collected in the tank, significant discrepancies in volumes of lost rainwater can be seen. For Białystok, the average volume of rainwater discharge was 26.1 m^3/year (with a minimum value of 11.3 and a maximum of 54.1 m^3/year). For Wrocław, on the other hand, the average discharge volume was 24.1 m^3/year (minimum equal to 9.2; maximum equal to 41.2 m^3/year). Considerable volumes of rainwater discharged by overflow are observed. There was no clear trend over the analyzed 50-year period.

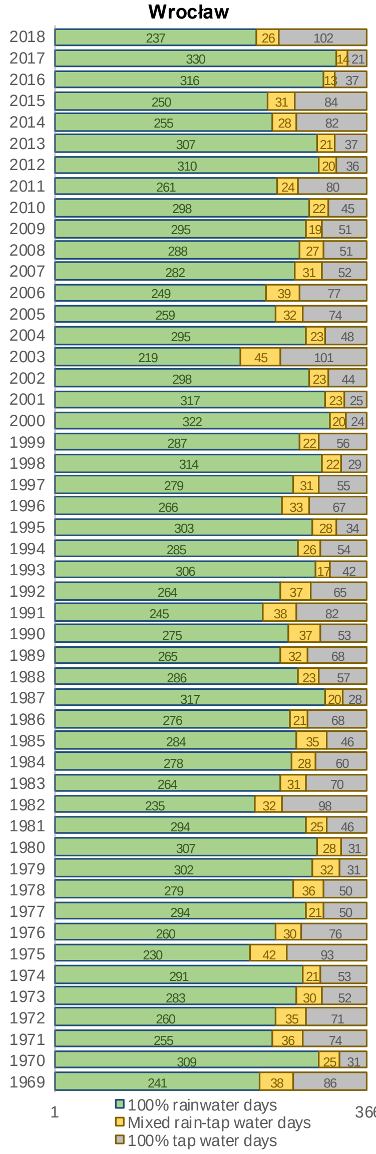

Figure 6: The 100% rainwater, 100% tap water and mixed rain-tap water usage days in 1969–2018 long-term behavior of RWH system in Wrocław, days/year.

For each year, the number of days on which rainwater would cover the water demand completely was also determined (100% rainwater usage days), as well as the number of days on which only tap water could cover water consumption (100% tap water usage days). The remaining days were those in which the demand for toilet flushing and washing was covered by both rainwater and tap water (mixed rain-tap water usage days). A graphic illustration of these calculations is shown in Figure 5 (for Białystok) and Figure 6 (for Wrocław).Both when the RWH system is located in Białystok and Wrocław, there is a significant prevalence of days when the water demand would be fully covered by harvested rainwater. The average number of 100% rainwater usage days for Białystok was 284 days/year, while for Wrocław 280 days/year. The number of days on which the tank was emptied and, as a consequence, the demand for water could only be covered by tap water, was on average 54 days for Białystok, while for Wrocław 55. These results are very similar. The smallest share in the year are days with a mixed use of tap and rainwater from the RWH system. The results show no clear trend throughout the period considered (1969–2018).

IV. CONCLUSION

In this study, the long-term behavior and performance of RWH system was investigated. Two polish cities were selected as the study area: Wrocław and Białystok. In order to assess the potential water saving efficiency, a simple water balance model was applied with the use of historical hourly rainfall data from the time span 1969–2018 (for both locations). Usage of such long real-life precipitation data allows providing proper information on changes in RWH operation.

The simulations of residential RWH system behavior in revealed that it is able to provide good potential performance when taking into account the covering of water demands for water for toilet flushing and doing laundry. In this case, the mean water-saving efficiency of 81% can be reached for Białystok and 80% for Wrocław – almost equal values. In the calculation results it can be seen that considerable volumes of rainwater discharged by overflow are observed for both cities. However, there was no clear trend for the analyzed 50-year period.

The number of days on which rainwater would cover the water demand completely was also determined, as well as the number of days on which only tap water could cover water consumption. The analysis of conducted research showed that in most days it was possible to fully cover the water demands with the accumulated rainwater in the RWH system. This allows for a significant reduction in tap water consumption. The average number of these days for Białystok was 284 days/year, while for Wrocław 280 days/year. On the other hand, the number of days on which the water demand could be covered only by tap water, was on average 54 days/year for Białystok, while for Wrocław 55 days/year. Obtained results were similar for both analyzed cities.

The major conclusion from the conducted research is that rainwater harvesting definitely can play a significant role as an alternative water source for households in Poland. The estimations of rainwater harvesting performance should encourage the implementation of these systems as a sustainable practice in future urban development.

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