

# Evaluation of Residential Rainwater Harvesting in Poland Based on 50-Year Time Series for 19 Cities

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## Abstract:

This article evaluated the decentralized rainwater harvesting (RWH) for 19 locations across Poland, for 1969–2018 historical rainfall data. A hypothetical residential rainwater harvesting system in selected locations was simulated by water balance modeling. A computational water balance model was developed to investigate the residential RWH performance with respect to 50-year daily rainfall data, runoff capture, rainwater storage, and residential water demand. The simulation results were used to characterize the water balance and long-term behavior of RWH system. The long-term behavior and harvesting performance were conducted as benchmarking metrics for all analysed cities.

**Keywords:** Rainwater harvesting; water demand; water saving efficiency; water balance model.

## I. INTRODUCTION

Rainwater harvesting (RWH) is increasingly becoming an alternative water source for many directions of its use, as a consequence of the current water scarcity problem. RWH systems shall be therefore applicable in various fields, and here we can distinguish urban RWH systems [1–3], systems for industrial purposes [4] and local or individual RWH systems [5, 6]. RWH systems may be a part of stormwater management strategies [3, 7] at both urban and regional scale [1, 2, 8]. RWH is beneficial not only to water supply systems but also to flood risk management as a way of reducing stormwater runoff in urban areas [9, 10]. The local storage of rainwater leads to stormwater runoff reduction from urban areas, which in turn relieves drainage systems [8, 11].

For individual applications, the RWH system collects rainwater from impervious surfaces (mainly from the roofs) and then stores it in a tank with a given capacity. The rainwater will be consumed in-situ, directly in residential and can, with success,

replace the tap water in covering the demands for non-potable purposes, i.e. washing, cleaning, toilet flushing or garden watering. The rain and tap water consumption is essential for water balance and performance of the RWH system.

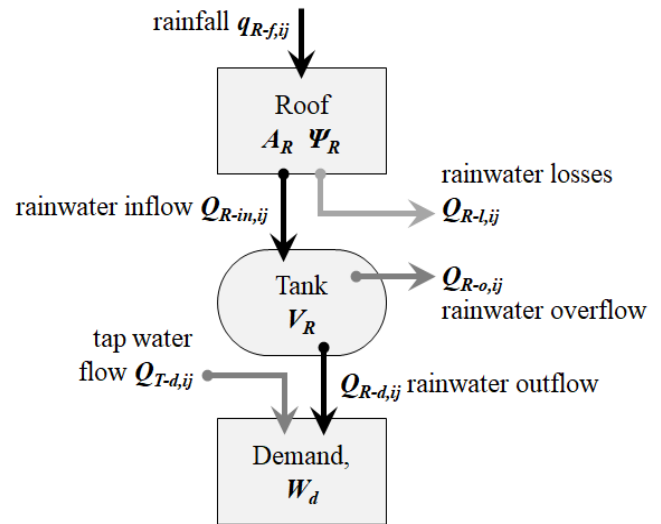
The main criterion for rainwater system evaluation is harvesting performance. The performance of residential RWH system can be defined as the share of used rainwater in relation to the total water consumption in the household and as the time reliability determined on the basis of the number of days in the year when the RWH system was able to meet the water demand [12]. The performance metrics depend mainly on rainfall pattern, water consumption profile and sizes of rooftop and rainwater tank [10, 13, 14].

The long-term rainfall time series is crucial for proper evaluation of RWH performance as they are essential in estimating the rainwater inflow to the tank [15, 16, 17]. To best reflect the rainfall phenomenon, sufficiently long data records are required.

According to the World Meteorological Organisation [18], 30 years of observation is the minimum period for hydrological calculations. Long-term simulations based on historical data allow better reflection of changes in RWH system operation and capturing the potential climate change impacts. The core of the long-term simulation is the water balance model, combining together the values of rainwater inflow to the tank, the outflow from the tank to cover the water demand and on this basis. The operation of RWH system should allow for maintaining a balance between water supply and demands [15]. However, it needs to be mentioned that some portions of rainwater will not be stored due to the limited capacity of the tank. The remaining water will be lost through the overflow. On the other hand, when there will be a shortage of rainwater, the remaining water demand will be covered by tap water. The simulation of reservoir operation with respect to time is so-called behavioral analysis [19].

## II. METHODOLOGY AND DATA USED

The aim of the paper was the long-term evaluation of residential rainwater harvesting in Poland. The analysis was performed for the 50-year period for 19 cities. The foundation for the analysis was the implementation of the water balance model based on the behavioral algorithm to simulate the flows of water through the harvesting system. On the basis of historical precipitation data from the time span 1969–2018, the simulation input database was prepared for all analysed locations. The water balance model was processing the hypothetical RWH system with respect to 50-year daily rainfall data, runoff capture, rainwater storage, and residential water demand. The simulation output data reflected the long-term performance and behavior of 19 investigated RWH systems as benchmarking metrics.



**Fig. 1.** The block diagram of the water balance model for rainwater harvesting system

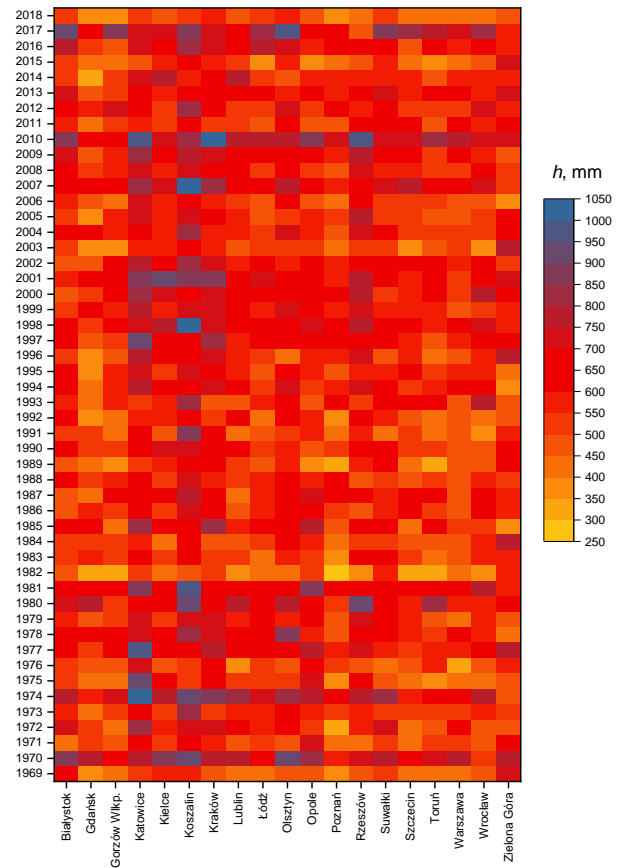
The water demand model was operated in day-step mode, as described in the block diagram in Fig. 1. The developed algorithm was carried out for all 19 locations (marked as  $i = 1..19$ ) and 50 years (marked as  $j = 1969..2018$ ). The rainwater inflows  $Q_{R-in,ij}$  were calculated based on the rainfall amounts  $q_{R-f,ij}$ , the roof area  $A_R$  and the surface runoff coefficient  $\Psi_R$ . The rainwater storage was determined as the in-, out- and overflows balance in tank volume  $V_R$ . The harvesting performance was defined as a share of rainwater outflow  $Q_{R-d,ij}$  in household water demand  $W_d$ . The tap water flows  $Q_{T-d,ij}$  were supplied when the  $Q_{R-d,ij}$  flows are insufficient to meet the residential water demand  $W_d$ . The simulation took into consideration the rainwater losses as the  $Q_{R-l,ij}$  and  $Q_{R-o,ij}$  flows. The simulation output data provides all information in day, month and annual scale. Basing on the  $Q_{R-d,ij}$  and  $Q_{T-d,ij}$  flows, the days when rainwater will be sufficient for covering the total daily water demand (rainwater days - RWD) and the days when the daily demand need to be completely covered by tap water (tap water days - TWD) were defined.



**Fig. 2.** The 19 analysed cities on map of annual precipitation in Poland

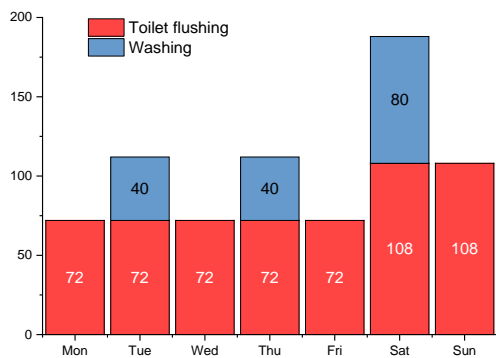
The archival rainfall data obtained from the Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB) was used as input data for the developed model. As a result, a wide range of data was obtained, covering 50 years of observations in the time span 1969–2018 for each of the 19 analyzed cities (Fig. 2). Such wide and long-term rainfall database is particularly valuable due to the fact that such data is usually difficult to access. The precipitation data was recorded with 1-minute time interval. However, the model of the RWH system behavior required rainfall data with an 24-hour time step. Therefore, it was necessary to convert raw data from 1-minute time step to a daily interval.

The heat-map, prepared in pre-simulation stage, characterizes the time-spatial variation of annual rainfall amounts in the years 1969–2018 for 19 analyzed Polish cities (Fig. 3). The color scheme indicates the dry year 1982 and the most humid year 2010. The long-term values of average annual precipitation ranged from 510 mm/year in Gdańsk to 729 mm/year in Koszalin, with median of all 19 stations 586 mm/year. Absolutely the highest precipitation amounts 1021 mm were recorded in Krakow in 2010. At that time, many extreme meteorological and hydrological events took place in Poland, which were taken into account in daily water balance modelling. Meteorological drought and hydrological drought in Poland occur cyclically in periods of 5–10 years.



**Fig. 3.** Annual rainfall amounts in the years 1969–2018 in the analyzed cities

In all analyses the developed standard water demand profile was used, covering the washing and toilet flushing needs for a 4-person household. The developed weekly water demand profile includes the daily sub-profiles for every working day and weekend (Fig. 4). Each member of the family flushes a  $3/6 \text{ dm}^3$  four times a day on a working day and six times on weekends. The laundry is washed four times a week, with a water demand of  $40 \text{ dm}^3$  per cycle. The sum of water needs characterizes the water demand profile in litres per day ( $\text{dm}^3/\text{d}$ ) used in the long-term simulations. The annual water demand  $W_d$  profile was imported into the water balance model as input data.



**Fig. 4.** The weekly water demand profile for toilet flushing and washing, dm<sup>3</sup>/day

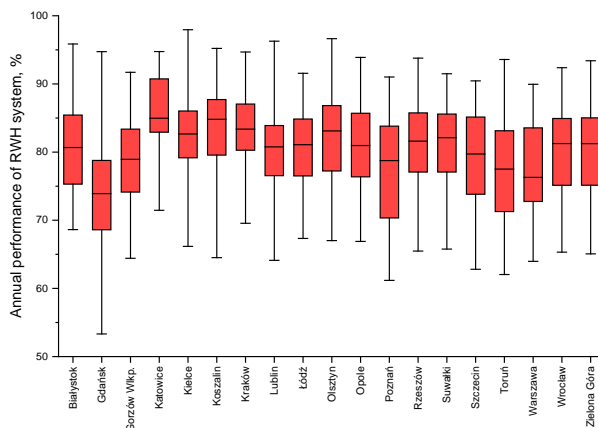
For evaluation of residential harvesting in Poland, the hypothetical residential RWH was investigated in 19 locations and rainfall conditions. The developed simulation algorithm is independent of the harvesting system construction and layout. The size of the catchment area  $A_R$ , the surface runoff coefficient  $\Psi_R$ , and the rainwater tank capacity  $V_R$  were implemented as required simulation input data. In the analyzed RWH model, the rainwater will be collected from the roof area  $A_R = 100 \text{ m}^2$ , with surface runoff coefficient  $\Psi_R = 0.95$ , stored in a typical rainwater tank with  $V_R = 1000 \text{ dm}^3$  and will be used locally. The RWH technical data were implemented as input data into developed model.

### III. RESULTS

The developed water balance model provides the RWH metrics in daily, monthly and annual scale. For a 50-year evaluation the annual RWH performance, the number of rainwater days ( $RWD_{ij}$ ) and tap water days ( $TWD_{ij}$ ) were analyzed by maximum, minimums and median for each year ( $i$ ) and location ( $j$ ). The simulation results were graphically presented in the form of box plots, in which the height of the box corresponds to the value of the quarter range, i.e. the difference between the first and third quartiles (50% of all observations). The second quartile (median) was presented as the horizontal line inside the box. The whiskers are limited to minimum and maximum values.

Figure 5 shows the annual RWH performance as a coverage of annual water demand for flushing toilets

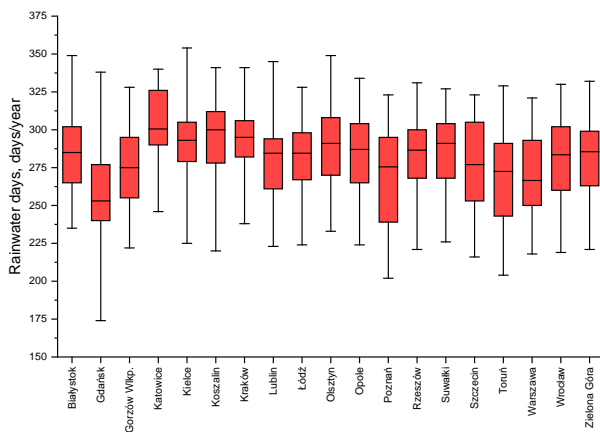
and washing expressed - for all 19 locations in the analysed multi-year period. The average degree of demand coverage at the national level amounted to favorably as much as 80.7% (minimum 65.0%, maximum 93.6%), whereby the differences between cities were usually minor. While analysing individual cities, the highest average coverage of water demands was recorded in Katowice - median equal to 85.0% (minimum value 71.5% in 2011, maximum value 94.7% in 1998), while the lowest in Gdańsk - median 73.9% (minimum value 53.3% in 1982, maximum value 94.7% in 1970). The highest annual coverage of needs equal to 97.9% was recorded in Kielce in 1970, with the lowest one in already mentioned Gdańsk (53.3%). The greatest diversity of annual performances was recorded in Gdańsk, where the minimum value is almost half the maximum one. This implies large discrepancies in tap water savings in individual years of operation. A beneficially low diversity was observed in Katowice and Łódź, where it ranges accordingly from 71.5% to 94.7% and from 67.3% to 91.6%, with a median of 85.0% and 81.1%, respectively. The highest median and short box oscillating around high values is favorable for achieving the highest performance of the RWH system. The whiskers are not decisive as reflecting the outliers - maximum and minimum values.



**Fig. 5.** The weekly water demand profile for toilet flushing and washing, dm<sup>3</sup>/day

The Figure 6 shows the box chart of rainwater

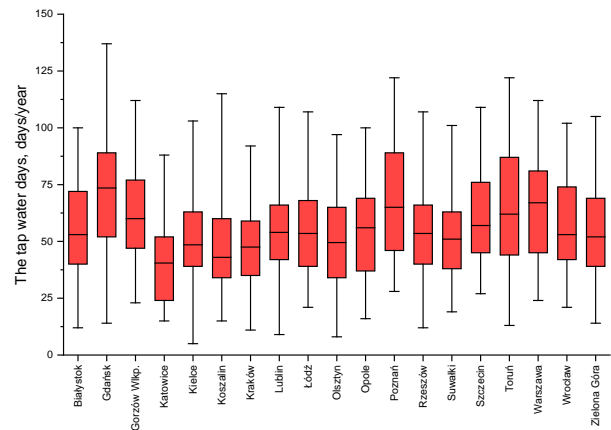
days (RWD<sub>ij</sub>) per year, in which the rainwater inflow  $Q_{R-i,ij}$  covered the water demand for toilet flushing and washing, including the overflow  $Q_{R-o,ij}$  episode days. The box-and-whisker plot reflects the RWH processing and annual performance. The average number of RWD in analysed 19 locations was beneficially as much as 284 days/year (minimum 221, maximum 335). The highest average result was recorded in Katowice, which coincides with the results from Figure 5. The median of 50 years was 301 days (minimum value of 246 in 2011, maximum value of 340 in 1998). The lowest long-term RWD is observed in Gdańsk - the median from 50 years is 253 (minimum value 174 in 1982, maximum value 338 in 1970). In the entire analyzed period, the highest annual result exceeding 354 was recorded in Kielce in 1970, which means that only 11 days/year the tap water was used to washing and toilets. The lowest number of RWD was noted in Gdansk (174), which translates to only 47% of the year.



**Fig. 6.** The weekly water demand profile for toilet flushing and washing, dm<sup>3</sup>/day

The graph in Figure 7 supplements the information in Figure 6 giving the number of tap water days (TWD) on which the water demand is met only by tap water. This unfavorable phenomenon occurs when RWH system is unable to provide any water for residential needs. The TWD days are unfavorable to the users, the environment and the system performance. It should be noted that in all 19 cities the annual TWD minimums are lower

than a month. On other days of the year the water demand was covered by tap and rainwater flows. These situations are beneficial for water savings and the environment, but decreases the annual rainwater harvesting performance.



**Fig. 7.** The weekly water demand profile for toilet flushing and washing, dm<sup>3</sup>/day

#### IV. CONCLUSIONS

In a 50-year analysis for 19 cities, it was shown that the basic RWH system can cover the residential water demand for flushing and washing at the annual level of 80.7%. For Polish conditions, the medians of rainwater performance ranged from 73.9% in Gdańsk to 85.0% in Katowice. The average whiskers spread (minimum-maximum) amounted to 28.6%, while the average height of the boxes was only 9.1% - from 6.6% in Kraków to 13.0% in Poznań. This results characterizes the analysed RWH system as very effective in Polish hydrological conditions.

The high RWH performance translated into the high number of days per year, in which the tap water for toilet flushing and washing was fully replaced by collected rainwater. The average number of RWD was an impressive 284 days/year - from 253 days in Gdańsk to 301 days in Katowice. Consequently, the number of TWD days, when only tap water was consumed, amounted to only 54 days/year on average - from 41 days in Katowice to 74 days in Gdańsk. In the remaining days, toilet flushing and washing required the use of both supply sources (27 days/year on average).

The long-term simulation results characterize the investigated residential RWH system as effective and meeting the expected assumptions regarding the harvesting performance, reducing environmental impact and water demand pressures. The performance of RWH should be assessed as sufficiently stable over such a long operation period. Only dry years lower significantly the ecological profit of residential rainwater harvesting.

The developed water balance model offers a universal and flexible tool for further analysis for other locations, rainfall data, RWH layouts and simulation steps.

The residential RWH systems reduce the operation costs and environmental impact of water supply. Due to a number of benefits, RWH should be promoted as an efficient solution in urban and rural areas.

## REFERENCES

1. A. Campisano et al., "Urban rainwater harvesting systems: Research, implementation and future perspectives," *Water Res.*, vol. 115, pp. 195–209, 2017.
2. A. C. Castonguay, C. Urich, M. S. Iftexhar and A. Deletic, "Modelling urban water management transitions: A case of rainwater harvesting," *Environ. Modell. Softw.*, vol. 105, pp. 270–285, 2018.
3. M. Di Matteo et al., "Controlling rainwater storage as a system: An opportunity to reduce urban flood peaks for rare, long duration storms," *Environ. Modell. Softw.*, vol. 111, pp. 34–41, 2019.
4. A. C. B. Thomé, P. G. Santos and A. G. Fisch, "Using rainwater in cooling towers: Design and performance analysis for a petrochemical company," *J. Clean. Prod.*, vol. 224, pp. 275–283, 2019.
5. H. Pavolová, T. Bakalár, D. Kudelas and P. Puškárová, "Environmental and economic assessment of rainwater application in households," *J. Clean. Prod.*, vol. 209, pp. 1119–1125, 2019.
6. N. İ. Şahin and G. Manioğlu, "Water conservation through rainwater harvesting using different building forms in different climatic regions," *Sustain. Cities Soc.*, vol. 44, pp. 367–377, 2019.
7. N. Alamdari, D. J. Sample, J. Liu and A. Ross, "Water supply and runoff capture reliability curves for hypothetical rainwater harvesting systems for locations across the U.S. for historical and projected climate conditions," *Data in Brief*, vol. 18, pp. 441–447, 2018.
8. M. J. Deitch and S. T. Feirer, "Cumulative impacts of residential rainwater harvesting on stormwater discharge through a peri-urban drainage network," *J. Environ. Manage.*, vol. 243, pp. 127–136, 2019.
9. N. Alamdari, D. J. Sample, J. Liu and A. Ross, "Assessing climate change impacts on the reliability of rainwater harvesting systems," *Resour. Conserv. Recy.*, vol. 132, pp. 178–189, 2018.
10. S. Zhang, J. Zhang, T. Yue and X. Jing, "Impacts of climate change on urban rainwater harvesting systems," *Sci. Total Environ.*, vol. 665, pp. 262–274, 2019.
11. A. Palla, I. Gnecco and P. La Barbera, "The impact of domestic rainwater harvesting systems in storm water runoff mitigation at the urban block scale," *J. Environ. Manage.*, vol. 191, pp. 297–305, 2017.
12. S. Zhang, J. Zhang, X. Jing, Y. Wang, Y. Wang and T. Yue, "Water saving efficiency and reliability of rainwater harvesting systems in the context of climate change," *J. Clean. Prod.*, vol. 196, pp. 1341–1355, 2018.
13. V. Notaro, L. Liuzzo and G. Freni, "Reliability Analysis of Rainwater Harvesting Systems in Southern Italy," *Procedia Engineer.*, vol. 162, pp. 373–380, 2016.
14. C. M. Silva, V. Sousa and N. V. Carvalho, "Evaluation of rainwater harvesting in Portugal: Application to single-family residences," *Resour. Conserv. Recy.*, vol. 94, pp. 21–34, 2015.
15. A. Adham, J. G. Wesseling, M. Riksen, M. Ouassar and C. J. Ritsema, "A water harvesting model for optimizing rainwater harvesting in the wadi Oum Zessar watershed, Tunisia," *Agr. Water Manage.*, vol. 176, pp. 191–202, 2016.
16. M. S. Geraldi and E. Ghisi, "Influence of the

length of rainfall time series on rainwater harvesting systems: A case study in Berlin,” *Resour. Conserv. Recy.*, vol. 125, pp. 169–180, 2017.

17. M. M. Haque, A. Rahman and B. Samali, “Evaluation of climate change impacts on rainwater harvesting,” *J. Clean. Prod.*, vol. 137, pp. 60–69, 2016.
18. WMO, *Calculation of Monthly and Annual 30-year Standard Normal*. World Meteorological Organization, Geneva, 1989.
19. D. Butler and A. M. Fayyaz, *Water demand management*. Iwa Publishing, 2005.