ORIGINAL ARTICLE

The impact of climate change on rainwater harvesting in households in Poland

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Abstract

In water management, climate changes require adaptation, protection of existing resources and the search for alternative water sources. Rainwater harvesting (RWH) is increasingly becoming an alternative water source, applicable for many directions of its use. The aim of the research was to analyse the influence of long-term climate change on the potential for rainwater harvesting in households in Central Europe in Poland. The analysis of long-term climate changes impact on the household rainwater harvesting potential was conducted for the 50-year period for 19 cities in Poland. The water balance model was operated in a day-step mode, and the research was carried out in four "time scales approach". For the purpose of all analyses, a standard weekly water demand profile was developed. It includes the daily sub-profiles for every working day and weekend, covering the washing and toilet flushing needs for a 4-person household. In order to evaluate the long-term changes in residential harvesting in Poland, a hypothetical residential RWH was investigated in 19 locations and rainfall conditions. To illustrate the time-spatial variation of annual rainfall amounts in the analyzed period, the heat map was prepared as the pre-simulation stage. Results show that the design of RWH systems should be based on archival data and take into account the many years of rainfall changes. This will improve performance and secure benefits for the users of this system.

Keywords Rainwater harvesting system · RWH efficiency · Climate changes

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Introduction

In recent years, more and more attention is paid to climate change, especially in the context of global warming and of the increasing occurrence of severe weather phenomena (Dai 2011, Kundzewicz 2012, Schiermeier 2011, UN Report Climate changes). An increase in the average annual temperature on the globe causes an increased water circulation in the hydrologic cycle, as the maximum water vapour mass in the atmosphere increases, as per the Clausius–Clapeyron relation, by approximately 7% along with a 1 °C increase in temperature (Held 2006, Lenderink 2011, Pall 2006). Therefore, one should expect that an increase in the availability of moisture in the atmosphere will cause a change in the rainfall regime, and this also includes an increase in the intensity of extreme rainfall (Allan 2008, Fleig 2015, Saboia 2017, Trenberth 2011).

According to the European Environment, the annual precipitation trends have changed over the last century. Additionally, it depended on location. Northern Europe has become wetter (10–40% growth), and southern Europe has

become even 20% drier. Changes in water resources may, therefore, be a reason for reducing the availability of drinking water in some regions.

In water management, climate changes require adaptation, protection of existing resources and the search for alternative water sources. Rainwater harvesting (RWH) is increasingly becoming an alternative water source, applicable for many directions of its use. RWH systems can be applied in various fields, in forms of urban RWH systems (Campisano 2017, Castonguay 2018, Di Matteo 2019), systems for industrial purposes (Thomé 2019) and local or individual RWH systems (Pavolová 2019, Şahin 2019). RWH is favourable to water supply systems as well as to flood risk management, being a way of reducing stormwater runoff in urban areas (Alamdari 2018, Zhang 2019). This reduction, achieved through local rainwater storage, leads to the relief of drainage systems (Deitch 2019, Palla 2017). RWH systems may be, therefore, a part of stormwater management strategies (Alamdari 2018, Di Matteo 2019) at both urban and regional scale (Campisano 2017, Castonguay 2018, Deitch 2019).

Considering individual applications, the operation of the RWH system is based on collecting rainwater from impervious surfaces (mainly from the roofs) and storing it in a tank (of given capacity). The rainwater is then consumed in-situ–in residentials and will replace the tap water in covering the demands for non-potable purposes. Regular residential water requirements include cooking, cleaning, dishwashing, garden watering, laundry, showers, baths and toilet flushing. According to European statutes, if the RWH system provides water that meets bathing quality, it can replace over 50% of total tap water demand.

Harvesting performance constitutes the main criterion for rainwater system evaluation. For residential RWH systems, it is defined as the share of used rainwater in relation to the total water consumption in the household (Zhang 2018). The rainfall pattern, water consumption profile, and sizes of rooftop and rainwater tank are the main factors affecting the performance metrics (Zhang 2019, Notaro 2016, Silva 2015).

The proper evaluation of water saving efficiency is directly related to the long-term rainfall time series because they are crucial in estimating the rainwater inflow to the tank (Geraldi 2017, Haque 2016, Adham 2016). In compliance with the World Meteorological Organisation (WMO 1989), 30 years of rainfall observation is the minimum period for hydrological calculations. Such long data records are needed to best reflect the rainfall phenomenon. In terms of studies related to RWH, the long-term simulations based on historical data allow better reflection of changes in RWH systems operation, as well as capturing the potential climate change impacts. The core of such simulation is the water balance model, which combines together the values of rainwater inflow to the tank and the outflow from the tank to cover the water demand. The operation of RWH system should

allow for maintaining a balance between water supply and demands (Czapczuk 2015, Adham 2016). However, due to the limited capacity of the tank, some quantities of rainwater would not be collected and this remaining water will be lost through the overflow. On the other hand, when a shortage of rainwater will occur, the remaining water demand will be covered by tap water. The simulation of reservoir operation with respect to time is the so-called behavioural analysis (Butler 2005).

Poland is one of the European countries threatened with a water deficit. The area of Central and Eastern Europe, including Poland and Spain, has on average less than 200 mm of fresh water available each year, while demand for water is 3–10 times higher. It is important that 97% of water in Poland comes from precipitation. Therefore, water resources are characterized by high variability in the annual cycle (in the summer season, the precipitation can be several times higher than in winter), between individual years and areas of the country. The southern areas of Poland (upland and mountainous areas) are characterized by a greater number of them, while the central and northern part of Poland is suffering from their deficit. In recent years, the problem of water deficit has been intensified both by increasing anthropopressure and climate changes.

Rainfall variability in Poland has been described, among others, in the work (Czarnecka 2012), in which there was an analysis of the monthly precipitation value from 38 weather stations (excluding mountain stations) from the years 1951–2010. Slightly increasing tendencies in the spring and autumn seasons and decreasing tendencies in the summer and winter seasons have been indicated in the majority of the country (however, these were statistically insignificant). A decrease in the total precipitation values in the summer months has also been confirmed in the work (Skowera 2014), on the basis of research from 16 stations from the years 1971–2010 and in the work (Żmudzka 2009) on the basis of research from 50 stations from the years 1951–2000. In monograph (Pińskwar 2010), there has been an analysis of the value of precipitation from 22 stations with daily data from the years 1951–2006 and from 6 stations with monthly data from the years 1956–2009. On the basis of the analysis of the precipitation, one has noted a decrease in the total amount of summer precipitation in comparison with the winter precipitation, as well as of the total values of precipitation in the warm half-year in relation to the sum of precipitation in the preceding cooler half-year (especially in the western parts of Poland). In the case of the total value of the annual precipitation, one can observe trends of both signs.

The goal of the work is an analysis of the influence of long-term climate change (the observed changes in the precipitation values) on the potential rainwater harvesting for washing and toilet flushing needs for a 4-person household

in Poland. For the purpose of all analyses, a standard weekly water demand profile was developed. The analysis of long-term climate changes impact on the household rainwater harvesting potential was conducted for the 50-year period for 19 cities in Poland.

Materials and methods

A wide range of archival rainfall data obtained from the Institute of Meteorology and Water Management–National Research Institute (IMGW-PIB) was used as input data for the model. The foundation for the analysis was the implementation of the water balance model based on the behavioural algorithm to simulate the flows of water through the harvesting system. For all analyzed locations, the simulation input database was prepared based on historical precipitation data from 1970–2019. The water balance model was processing the hypothetical RWH system, having regard to the 50-year daily rainfall data, runoff capture, rainwater storage, and residential water demand. Benchmarking metrics for assessing the long-term performance and behaviour of all 19 RWH systems were represented by the simulation output data.

The water balance model was operated in a day-step mode, as described in the diagram in Fig. 1. The developed algorithm was carried out for all 19 locations (marked as $i = 1...19$) and 50 years (marked as $j = 1970...2019$). In practice, two algorithms are often used to describe the behaviour of the collecting system during a given time interval: the yield after spillage (YAS) and the yield before spillage (YBS). In this investigation, each simulation was tested by YAS algorithm, in which the withdrawal occurs before the rainfall:

$$Q_o = \max \begin{cases} V_{t-1} + A \cdot \Psi \cdot R_t - S \\ 0 \end{cases} \tag{1}$$

$$Y_t = \min \begin{cases} D_t \\ V_{t-1} \end{cases} \tag{2}$$

$$V_t = \min \begin{cases} V_{t-1} + A \cdot \Psi \cdot R_t - Y_t \\ S - Y_t \end{cases} \tag{3}$$

where Q_o (m^3) is the volume discharged as overflow from the storage tank at time step t, V_t (m^3) is the volume stored at time step t, R_t (m) is the rainfall at time t, A (m^2) is impervious surface area (m^2), Ψ–surface runoff coefficient, Y_t (m^3) is the yield of rainwater from the storage tank at time step t, D_t (m^3) is the water demand at time step t, and S (m^3) is the tank storage capacity.

The usual indicator used to evaluate the performance of a rainwater collecting system is the water saving efficiency (E). It is equal to the percentage of the overall demand supplied by the tank and it is given by the following equation (Gires 2009):

$$E = \frac{\sum_{t-1}^{T} Y_t}{\sum_{t-1}^{T} D_t} \cdot 100 \tag{4}$$

where T is the total time period under consideration. Equation provides a measure of how much water has been conserved in comparison with the overall demand and is also referred to as water saving efficiency (Fewkes 2000).

In the analyzed RWH model, the rainwater will be collected from the rooftop area $A = 100$ m^2, with surface runoff coefficient $\Psi = 0.95$, stored in a typical rainwater tank with $S = 1000$ dm^3 and locally used. The developed water balance model provides the RWH metrics in monthly and annual

**Fig. 1** The diagram of the water balance model for rainwater harvesting system
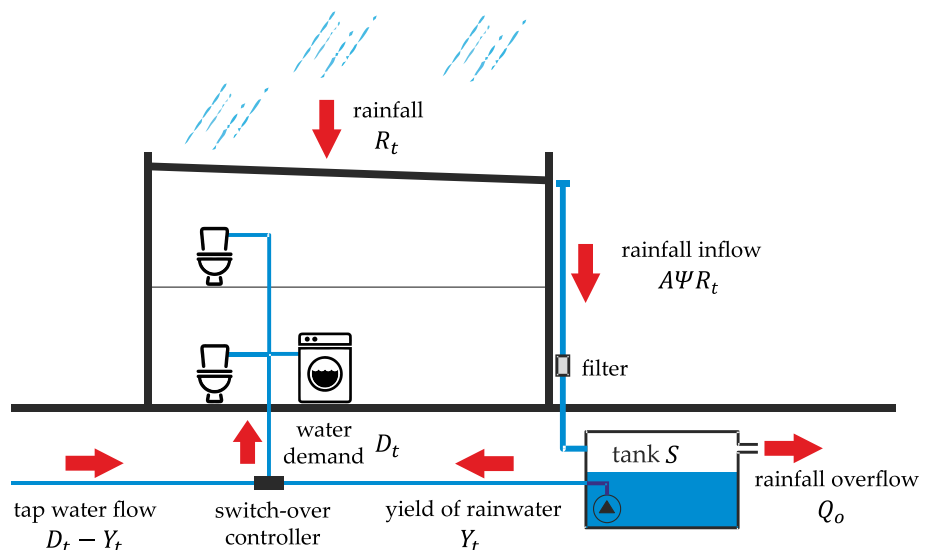
scale. The basic calculation step is 24 h. The water balance model uses a daily sum of precipitation from historical data and a daily water demand profile. On this basis monthly and annual metrics of rainfall and operation of RWH system are developed. The statisticaelaboration allows to determine and assess significant trends of changes 1970–2019 according to climate changes in Poland and to draw appropriate conclusions on a multiannual, annual, monthly and daily basis.

For the purpose of all analyses, a standard weekly water demand profile was developed. It includes the daily sub-profiles for every working day and weekend, covering the washing and toilet flushing needs for a 4-person household (Fig. 2). Each member of the family flushes a 3 or 6 dm³ (on the average 4.5 dm³) 4 times a day on a working day

and 6 times on weekends. The laundry is washed four times a week, with a water demand of 40 dm³ per cycle (Struk-Sokołowska 2020, Willis 2010, Freni 2019). The sum of water needs characterizes the water demand profile in litres per day (dm³/d) used in the long-term simulations. The annual water demand profile was imported into the water balance model as input data.

In order to evaluate the long-term changes in residential harvesting in Poland, a hypothetical residential RWH was investigated in 19 locations and rainfall conditions (Fig. 3). Precipitation is highly dependent on the shape of the surface. The average annual precipitation (from 1970–2019) in the analysed cities is 597.3 mm, with the lowest precipitation generally occurring in the central part of Poland and

Fig. 2 The weekly water demand profile for toilet flushing and washing, dm³/day
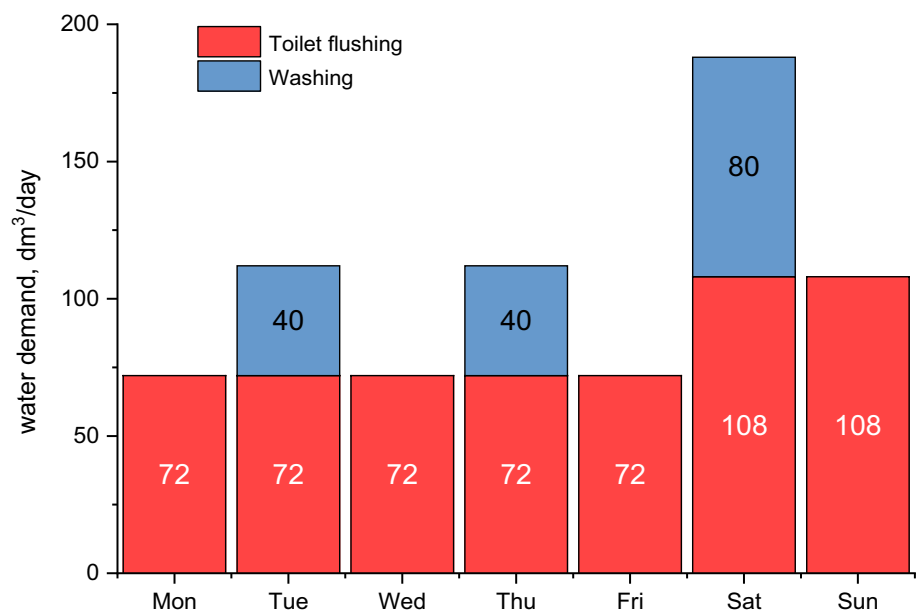
Fig. 3 The 19 analysed cities on the map of annual precipitation in Poland (average in 1971–2000) (Lorenc 2005)

the highest on the coast and in the Tatras (over 1000 mm). Among the towns analysed in the study, the lowest precipitation occurs in Gdańsk (512.7 mm) and Poznań (518.1 mm), and the highest in Koszalin (731.6 mm) and Katowice (724.6 mm).

To illustrate the time-spatial variation of annual rainfall amounts in the analyzed period (1970–2019) for all 19 cities, the heat map was prepared as the pre-simulation stage (Fig. 4). The preparation of the archive data was necessary as input data for the model used in the simulations. The analysis of the colour distribution of annual rainfall amounts shows the history of rainfall in Polish cities. Both dry and most humid years are visible.

The colour scheme indicates the dry year 1982 and the most humid year 2010, with average annual precipitation amounted to 424 mm and 791 mm, respectively. The long-term values of average annual precipitation ranged from 513 mm/year in Gdańsk to 732 mm/year in Koszalin, with a median of all 19 stations 598 mm/year. Absolutely the lowest precipitation amounts 275 mm were recorded in Poznan in 1982, whereas absolutely the highest precipitation amounts 1021 mm were recorded in Krakow in 2010. Many extreme meteorological and hydrological events took place in Poland at that time, and they were taken into account in daily water balance modelling. Meteorological drought and hydrological drought in Poland occur cyclically in periods of 5–10 years. All these factors describe the working conditions of RWH affecting its behaviour and performance. They are included in the prepared simulation.

The next step of the investigation was the preparation and analysis of the distribution of monthly precipitation levels (1970–2019) recorded in the Polish cities under consideration. An average annual sum of precipitation was also determined for all cities. The results are presented in Table 1.

In the case of monthly sums of precipitation, the lowest values were recorded in the winter months (an average of 40.9 mm in December, 35.6 mm in January and 28.2 mm in February) and the highest in the summer months (69.3 mm in June, 85.1 mm in July and 65.7 mm in August). This distribution is characteristic of Poland's climatic zone and occurs in all cities. It should be noted that the difference in the mid-month total precipitation between the towns with the largest and the smallest sums of precipitation is about double, i.e. in January from 25.6 mm in Gdańsk to 48.5 mm in Koszalin; in February-May from 18.0 mm, 23.1 mm, 28.6 mm and 48.6 mm in Gdańsk to 37.0 mm, 43.8 mm, 49.5 mm and 76.7 mm in Katowice; in June from 57.2 mm in Zielona Góra to 85.1 mm in Kraków; in July from 69.8 mm in Szczecin to 101.7 mm in Katowice; in August from 53.2 mm in Gorzów Wielkopolski to 80.1 mm in Koszalin; in September–November from 41.3 mm, 35.7 mm and 34.8 mm in Poznań to 76.7 mm, 67.6 mm and 63.2 mm in Koszalin, respectively; and in December from 31.9 mm in Wrocław to 58.7 mm in Koszalin.

The differential and distribution of monthly and annual sums of precipitation directly affect the performance RWH, differentiating them in particular localities and years. It should be noted that total precipitation is not the only factor determining the precipitation-related water saving efficiency.

The high amount of precipitation, which is characterised by a large amount of precipitation in a short period of time, will usually be used only to a small extent–the greater part of
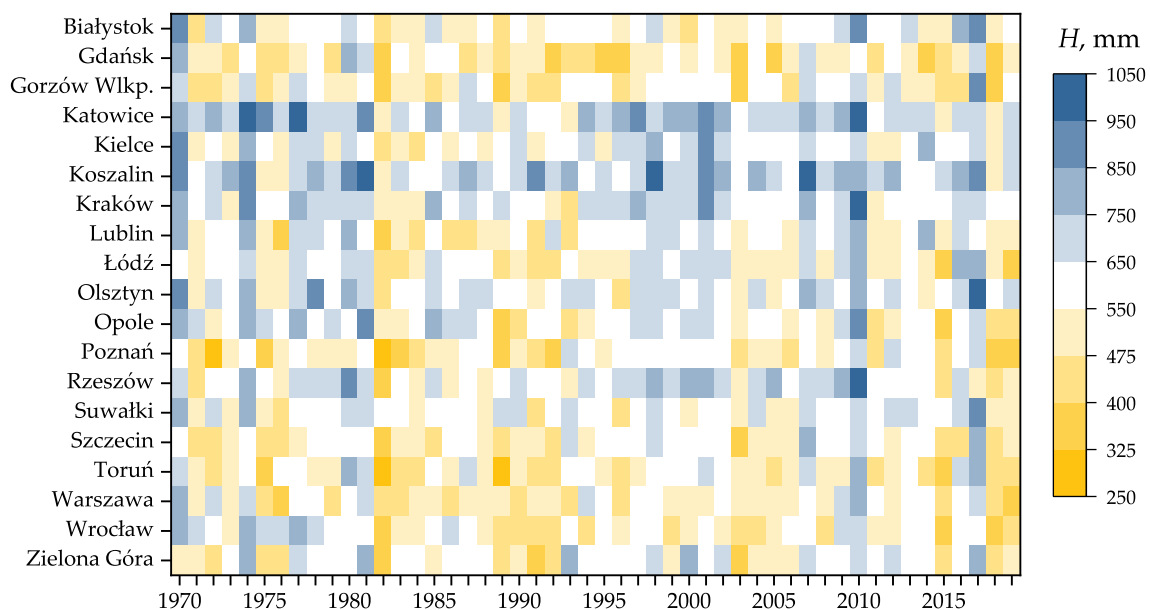
Fig. 4 Annual rainfall amounts in the years 1970–2019 in the analyzed cities

Table 1 Average annual and average monthly rainfall amounts in analysed cities

City	Average rainfall, mm												
	I–XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Białystok	602.2	34.0	26.7	32.6	36.9	61.9	67.8	89.8	68.9	56.4	47.5	39.8	39.9
Gdańsk	512.7	25.6	18.0	23.1	28.6	48.6	58.1	73.9	60.0	53.5	46.2	43.8	33.2
Gorzów Wlkp	547.1	39.1	30.0	35.8	34.2	53.0	62.1	70.4	53.2	44.7	39.1	41.4	44.0
Katowice	724.6	43.0	37.0	43.8	49.5	76.7	83.0	101.7	78.0	65.4	51.2	48.5	46.8
Kielce	618.7	38.0	30.2	37.0	39.4	61.9	66.9	90.8	73.8	54.7	43.1	41.1	41.8
Koszalin	731.6	48.5	35.4	42.5	37.3	52.3	78.9	90.5	80.1	76.7	67.6	63.2	58.7
Kraków	669.7	37.2	30.0	36.1	48.1	76.5	85.1	91.3	76.4	62.2	49.0	41.6	36.3
Lublin	587.8	32.2	27.8	33.5	41.6	64.6	66.9	79.7	65.0	57.9	44.5	37.4	36.6
Łódź	577.4	33.5	29.8	34.7	35.9	56.6	65.7	83.8	60.0	50.8	41.9	41.5	43.0
Olsztyn	640.8	40.4	28.2	37.3	37.6	54.2	76.9	83.7	68.0	60.5	56.3	50.1	47.7
Opole	605.5	33.8	28.2	33.3	40.0	63.1	76.0	88.5	68.2	56.8	41.7	39.1	36.8
Poznań	518.1	34.3	25.3	34.7	31.8	49.3	58.5	78.7	54.5	41.3	35.7	34.8	39.3
Rzeszów	635.8	32.3	28.1	34.7	45.1	74.5	81.7	93.4	65.9	60.1	46.7	36.2	37.2
Suwałki	607.7	36.6	27.2	35.5	35.9	52.5	70.4	88.8	68.7	53.9	52.2	44.2	41.8
Szczecin	547.6	38.6	29.5	36.0	34.3	51.0	60.0	69.8	55.4	45.0	41.7	42.6	43.7
Toruń	543.0	30.4	24.4	29.6	30.2	51.9	64.7	88.0	60.5	50.2	39.1	35.7	38.2
Warszawa	537.7	27.5	25.4	28.2	35.0	54.3	65.9	80.2	60.9	48.1	39.6	37.1	35.3
Wrocław	563.1	29.4	24.0	31.1	35.2	58.2	70.9	91.9	66.8	48.4	38.6	36.6	31.9
Zielona Góra	577.2	41.0	31.4	39.3	36.4	51.8	57.2	82.2	64.2	45.3	40.1	43.1	45.1
Average	597.3	35.6	28.2	34.7	37.5	58.6	69.3	85.1	65.7	54.3	45.4	42.0	40.9

it will be transferred out of the system. Therefore, a proportionally smaller water saving efficiency in relation to the sum of precipitation is to be expected in the months in which the most frequent precipitation occurs in Poland, i.e. June–August (VI–VIII) (Kaźmierczak 2015, Pińskwar 2019). Due to the hourly simulation step, this phenomenon is correctly taken into account by the proposed water balance model.

Simulations covering the period of 50 years in 19 Polish cities, taking into account the mentioned precipitation conditions, provided results determining the performance of hypothetical RWH. In order to determine trends of changes in water saving efficiency, linear regression was used (Wdowikowski 2016). Changes (increases or decreases) at a significance level above 95% were considered as statistically relevant. Moreover, changes at the significance level from 90 to 95% were assumed to be close to statistical significance, while changes in the significance level from 75 to 90% were assumed to be a tendency to change. Changes at the level of significance below 75% were considered statistically insignificant and consequently without a specific direction of change (Pińskwar 2010).

Results

Water saving efficiency

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 the minimum and maximum values.

Figure 5a shows the annual water saving efficiency as a coverage of analysed annual water demand for flushing toilets and washing expressed–for all 19 locations in the investigated multi-year period. The average degree of demand coverage at the national level amounted to favourably as much as 80.7% (minimum 74.4%, maximum 85.1%), whereby the differences between cities were usually minor. While analysing individual cities, the highest average coverage of water demands was recorded in Koszalin–average equal to 85.1% (minimum value 65.2% in 1982, maximum value 95.2% in 1998), while the lowest in Gdańsk–average 74.4% (minimum value 53.3% in 1982, maximum value 94.7% in 1970). The highest annual coverage of needs equal to 97.9% (with annual rainfall of 857.4 mm) was recorded in Kielce in 1970, with the lowest one in already mentioned Gdańsk (53.3%–with annual rainfall of 345.5 mm). 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 RWH operation. The highest median and short box oscillating around high values is favourable for achieving the highest water saving efficiency of the RWH system. The
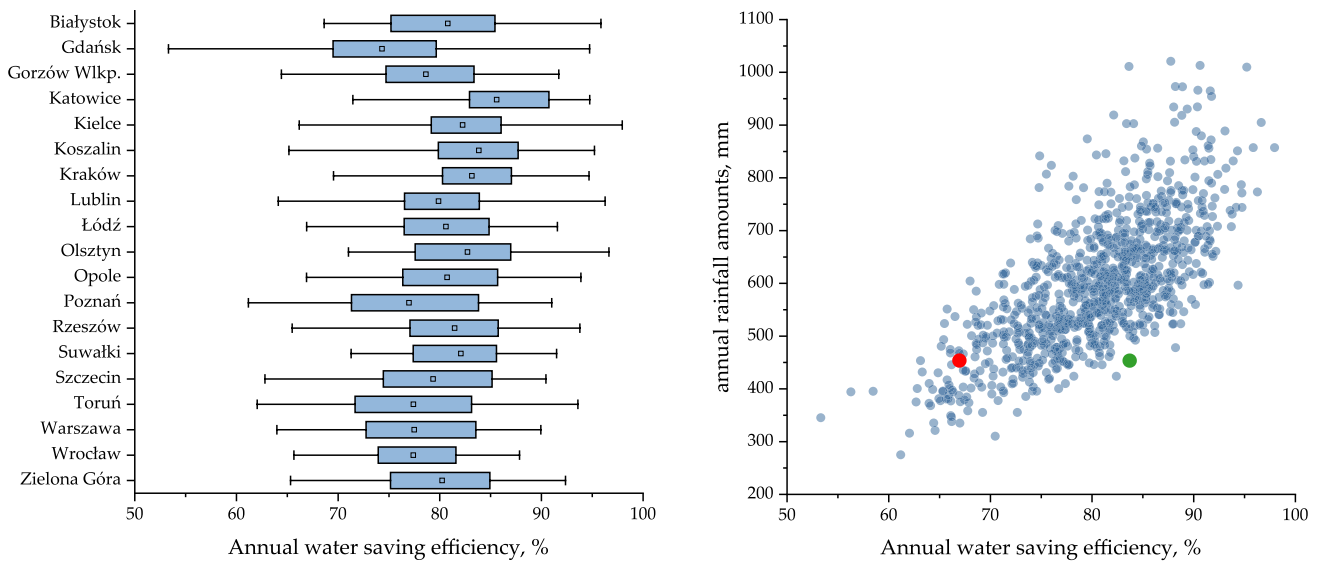
Fig. 5 Annual water saving efficiency of RHW system (1970–2019): **a** depending on the city; **b** depending on the total annual rainfall (green dot: Warsaw 1993; red dot: Warsaw 1996)

whiskers are not decisive, as reflecting the recorded outliers–maximum and minimum values.

Figure 5b illustrates the dependence of the annual RWH performance on the total annual precipitation in all simulated years and cities. The relationship is very clear, but the height and width of the cloud indicate that, as expected, the height of annual precipitation is not the only factor that affects water saving efficiency. For example, in 1993 and 1996, Warsaw had an identical annual rainfall of 453.6 mm (green and red dot in the figure), and the water saving efficiency was as high as 83.7% and only 66.9%, respectively (with a multi-year average of 77.5% at 538 mm rainfall). The course of the 1993 cumulative precipitation curve in Warsaw (Fig. 6a) is much more linear

than in 1996 (Fig. 6b), when many days with precipitation exceeding 10 mm were recorded. This translated into an average water saving efficiency per 100 mm of precipitation −18.5% and 14.7%, respectively.

The above analysis proves that the best performance from the point of view of RWH is years with not only a large amount of precipitation but also its successive growth during the year. Extreme cases in this respect were recorded in Toruń in 1989 and in Katowice in 1974, where in the first case, 310.4 mm of precipitation gave 70.5% water saving efficiency (on average 100 mm of precipitation covered as much as 22.7% of annual demand) and in the second case, 1011.2 mm of precipitation gave 83.6%
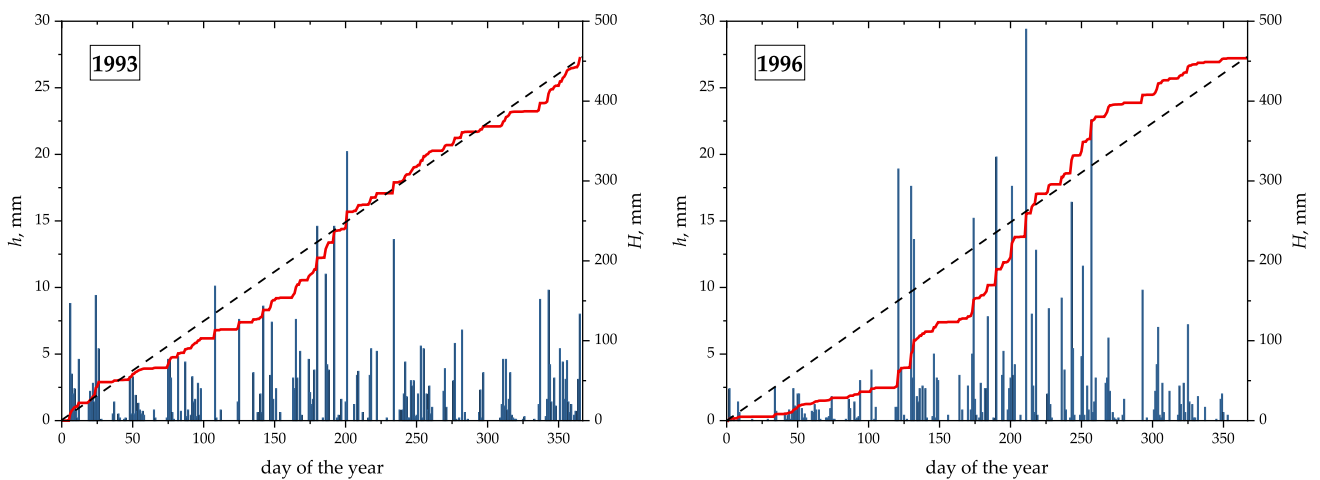
Fig. 6 Daily precipitation levels with the cumulative curve in Warsaw in 1993 and 1996

water saving efficiency (on average 100 mm of precipitation covered only 8.3% of demand).

The results of calculations of the average water saving efficiency on an annual and monthly basis for 19 analysed cities in the period 1970–2019 are presented in Table 2.

Same as the Fig. 5b, Fig. 7 presents the water saving efficiency in individual months of the year depending on the sum of precipitation recorded in the years 1970–2019 in 19 analysed localities. The graphical presentation of the results shows both the varied nature of precipitation in individual months described by the Polish climate and the difference in the water saving efficiency obtained for the same monthly sums of precipitation. For the analyzed hypothetical RWH system, the same in all locations, for the same average monthly precipitation, differentiation of harvesting performance was obtained. This means that, similarly to the annual sum of precipitation, the sum of precipitation in given months is not the only factor determining the water saving efficiency (although this dependence is also clear at this point).

Analysing the above results, it must be concluded that in order to determine the impact of climate changes on water saving efficiency, it is not possible to examine only trends in annual or monthly amounts of precipitation. The dependence of the water saving efficiency on the amount of precipitation, although clear, cannot be determined unequivocally, as an equally important factor as the sum of precipitation is its course over time (e.g. Fig. 6). Therefore, in order to analyse

the impact of climate change on the water saving efficiency, it is not necessary to examine the variability of precipitation totals, but the variability of the water saving efficiency of the modelled system (with assumptions).

The trends of change

Based on the simulated efficiency of the RWH system, its long-term variability in the context of climate change was determined. Calculated on the basis of archival data of RHW efficiency from 1970 to 2019 are shown in Table 2. The variation of water saving efficiency was calculated by means of linear regression and compiled in Table 3 as ΔE in % per decade. Statistically significant and close to statistically significant trends with a significance level above 90% were distinguished by colours. It should be noted that positive (blue) and negative (yellow) trends appeared in the table. The results were compared in two "time scales" as multi-year trends in monthly and annual precipitation changes in all 19 analysed Polish cities.

In the case of only one of the analysed locations, the annual water saving efficiency is characterised by a significant trend. In Opole, a decrease in −1.44% per decade was recorded. For this city in Fig. 8 presents the values and trend of annual water saving efficiency in the years 1970–2019 against the background of annual rainfall.

For the other cities, the changes in annual performance are statistically insignificant. This means that in the face of

Table 2 RWH performance

| City | Water saving efficiency (E), % | | | | | | | | | | | |
	I–XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Białystok	80.8	73.8	71.1	70.5	74.8	84.6	90.6	91.6	85.8	84.7	75.3	82.1	84.0
Gdańsk	74.3	61.5	56.6	55.1	65.4	75.2	84.6	86.8	82.6	83.0	76.7	85.0	78.6
Gorzów Wlkp	78.6	78.5	72.9	73.5	69.6	78.7	85.2	85.4	79.7	80.9	74.3	78.5	85.9
Katowice	85.6	82.5	79.7	78.7	82.7	88.9	94.8	94.1	90.9	88.1	79.0	83.7	84.0
Kielce	82.2	80.0	75.6	73.9	75.7	85.4	92.6	91.1	89.6	85.7	75.4	79.3	82.2
Koszalin	83.8	80.9	80.0	75.2	74.5	79.4	86.0	87.7	87.1	89.4	86.3	87.2	92.2
Kraków	83.2	76.1	74.3	72.5	80.8	90.3	94.5	93.7	90.7	87.7	77.9	80.9	78.0
Lublin	79.9	73.7	74.1	70.7	76.9	85.9	88.0	89.6	85.0	82.8	74.2	76.6	80.7
Łódź	80.6	77.2	72.6	71.3	75.7	83.5	86.2	89.9	88.2	83.6	74.8	80.2	83.7
Olsztyn	82.7	80.1	74.4	71.9	74.6	82.9	90.0	90.0	88.8	87.2	78.2	86.5	87.6
Opole	80.7	75.1	73.5	71.2	76.5	85.4	92.7	90.1	89.4	85.8	74.4	79.9	74.6
Poznań	77.0	75.3	67.7	69.5	69.9	78.2	84.3	86.8	81.7	81.0	70.1	76.2	82.3
Rzeszów	81.5	75.4	73.3	72.0	80.8	89.0	94.4	90.8	87.4	85.5	74.6	76.2	77.9
Suwałki	82.1	77.6	73.9	71.3	76.3	79.9	90.4	93.4	85.7	83.0	79.1	87.5	86.5
Szczecin	79.3	77.2	74.3	74.3	71.9	76.9	85.3	83.6	81.2	82.4	78.1	81.5	85.3
Toruń	77.4	73.1	66.2	67.4	68.6	79.0	88.9	87.5	84.0	80.0	72.4	80.0	81.3
Warszawa	77.5	68.2	67.6	65.0	74.4	83.1	87.7	89.1	86.7	81.6	71.8	77.6	76.8
Wrocław	77.4	71.0	64.6	68.6	73.7	80.8	88.6	92.1	84.2	84.0	71.8	75.8	72.6
Zielona Góra	80.2	81.0	75.2	77.6	72.9	77.6	87.3	88.9	80.6	82.1	72.9	79.9	86.6
Average	80.3	75.7	72.0	71.1	74.5	82.4	89.1	89.6	85.7	84.1	75.6	80.8	82.1
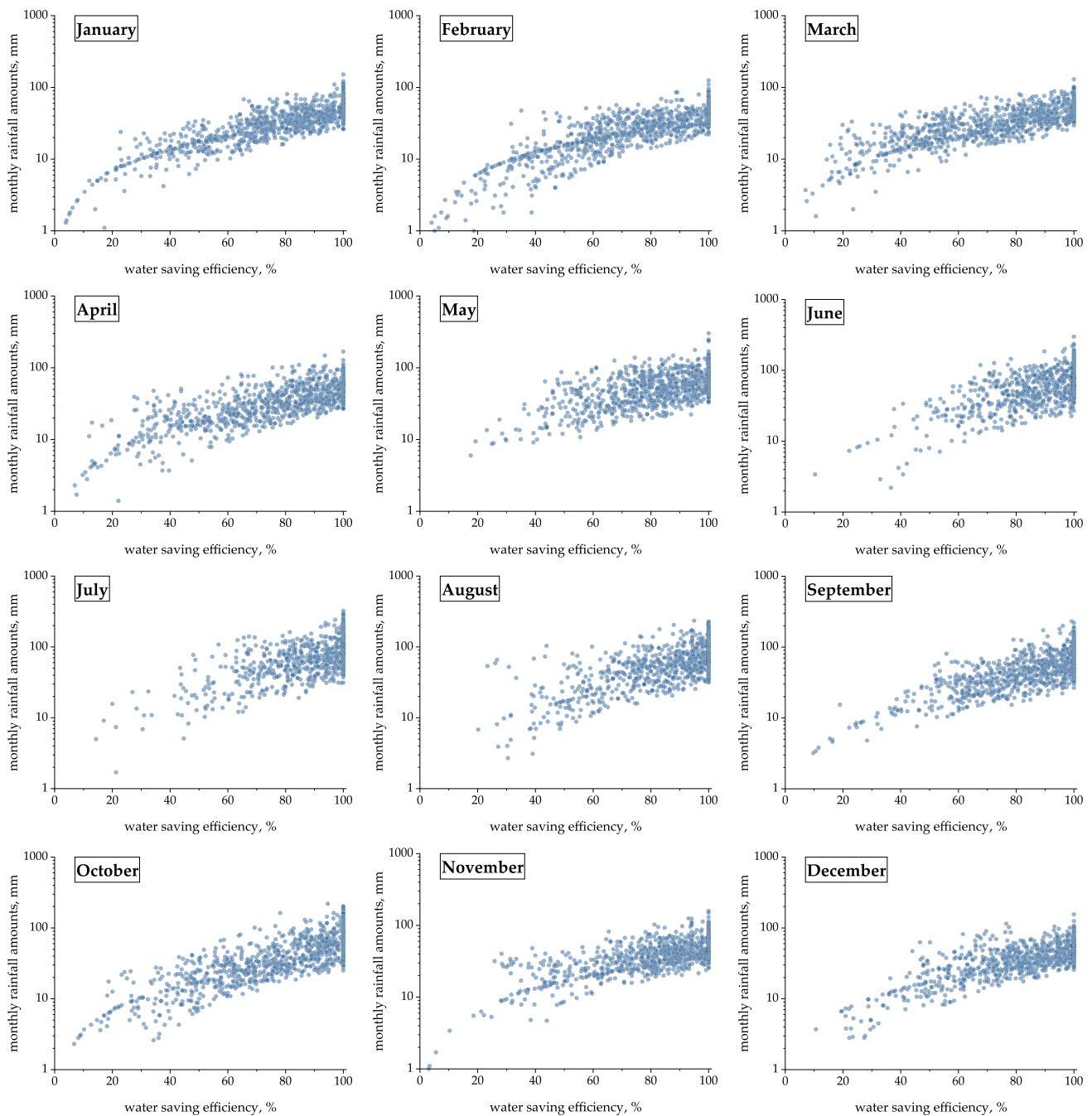
Fig. 7 Monthly performance of RHW system depending on the amount of rainfall

undisputed climate changes, since 1970, the average annual water saving efficiency has not changed in the case of 18 out of 19 analysed cities located in different regions of Poland.

At the level of analysis of monthly water saving efficiency averages the situation turns out to be more dynamic. In all analysed cities, there are positive and negative trends in monthly sums of precipitation, including as many as 24 statistically significant ones in the analysed period. Statistically significant changes in monthly efficiency appear in cities where no statistically significant change in annual efficiency was recorded. This interesting phenomenon means significant trends in the annual precipitation distribution.

The distribution of statistically significant trends (positive blue, negative yellow) in Table 3 shows no statistically significant annual changes (except for Opole, where a statistically significant decreasing trend was noted) and a statistically significant monthly increase in winter and decrease in summer. This confirms the observation of other authors from

Table 3 Trends of change of water saving efficiency (% per decade)

City	ΔE, % per decade											
	I–XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Białystok	0.03	3.04	2.80	2.37	− 0.69	− 0.85	− 0.20	0.65	0.57	− 2.52	− 2.13	− 1.20	− 1.50
Gdańsk	− 0.43	2.05	− 2.28	− 1.36	− 2.54	0.98	− 2.28	0.84	3.55	0.23	− 2.30	− 0.14	− 2.21
Gorzów Wlkp	0.47	4.39	1.16	1.71	− 2.91	− 2.49	− 1.66	2.39	2.23	− 1.07	1.19	− 0.65	1.04
Katowice	− 0.44	2.30	0.65	3.64	− 3.52	− 0.50	− 1.98	− 0.20	− 1.78	0.59	− 0.68	− 1.81	− 2.05
Kielce	− 0.12	1.58	1.82	3.33	0.07	0.80	− 1.14	− 1.05	0.36	− 3.02	− 0.63	− 1.83	− 1.86
Koszalin	0.56	3.72	− 0.16	1.63	− 0.27	0.79	− 0.61	− 0.16	2.30	− 1.10	0.35	− 0.64	0.66
Kraków	− 0.53	2.06	− 1.09	4.76	− 1.37	− 0.19	− 3.11	− 0.84	− 0.72	− 0.45	− 0.61	− 1.41	− 3.66
Lublin	0.06	3.42	2.87	4.64	0.90	− 0.58	− 2.56	− 0.71	0.08	− 4.24	− 1.63	− 0.79	− 0.74
Łódź	− 0.04	4.53	1.69	2.55	− 1.05	0.94	− 1.97	− 2.33	0.71	− 2.45	0.76	− 2.56	− 1.49
Olsztyn	0.40	2.43	1.36	1.51	0.56	0.34	0.27	1.69	1.40	− 2.07	− 0.83	− 0.67	− 1.33
Opole	− 1.44	0.13	− 2.12	1.30	− 2.81	0.32	− 2.26	0.59	− 1.50	− 2.36	− 1.97	− 3.47	− 3.53
Poznań	0.78	4.63	1.95	3.72	− 0.19	− 1.17	0.17	0.33	1.54	− 1.97	0.27	− 0.65	0.45
Rzeszów	0.54	2.96	3.38	5.48	1.21	0.08	− 0.92	− 0.96	1.18	− 1.71	− 0.82	− 1.00	− 2.46
Suwałki	0.36	2.79	2.65	1.60	− 1.37	− 0.54	− 0.08	1.53	2.76	− 1.12	− 0.64	− 1.68	− 1.61
Szczecin	1.03	4.31	0.46	2.89	0.44	− 0.73	0.59	0.70	2.13	0.34	1.23	− 1.01	0.78
Toruń	0.00	2.71	1.66	1.97	− 0.70	− 0.04	0.15	0.99	0.70	− 3.42	− 1.85	− 1.64	− 0.64
Warszawa	0.29	4.74	3.84	2.18	− 0.72	0.13	− 0.26	− 0.60	1.36	− 2.78	− 1.71	− 1.66	− 1.12
Wrocław	− 0.70	2.72	− 2.14	2.99	− 2.05	0.59	− 2.85	0.20	− 1.57	0.25	− 1.34	− 2.53	− 3.04
Zielona Góra	0.34	3.58	− 1.26	2.84	− 1.78	− 1.99	− 0.99	2.51	1.07	0.20	0.88	− 0.78	− 0.75
Average	0.06	3.06	0.91	2.62	− 0.99	− 0.22	− 1.14	0.29	0.86	− 1.51	− 0.66	− 1.37	− 1.32

shorter observation periods or smaller areas in Poland. In total, 24 statistically significant trends of monthly changes were determined in 16 cities. Only in Koszalin, Olsztyn and Suwałki, no statistically significant monthly changes occurred. The most significant trends occur in January (in 6 locations) and all are positive. Similarly, four positive trends occur in March. Significant negative trends occur in June (4 cities) and September (4 cities).

On the basis of the data from Table 3, graphs for statistically significant change trends have been developed. Figure 9 presents 24 statistically significant trends of changes in monthly efficiency compared to monthly precipitation totals (also with a trend line–blue).

Figure 9 shows evident trends in monthly water saving efficiency over the 50 years analysed from 1970 to 2019. Most of the trends in water saving efficiency correlate with changes in precipitation, although there are exceptions to this rule. Statistically significant trends of changes in water saving efficiency in Białystok, Kielce and Toruń in September are negative, although trends of changes in monthly total precipitation are positive in these locations in September. This clearly confirms that total precipitation is not the only factor determining water saving efficiency.

The use of valuable long-term data from 1970 to 2019 on precipitation provided full information on long-term changes in the potential of the RWH in 19 large Polish cities. Time scale approach in water balance modelling results investigation provided interesting and unexpected conclusions about the impact of perennial climate change on rainwater harvesting and trends in RWH operation and performance.
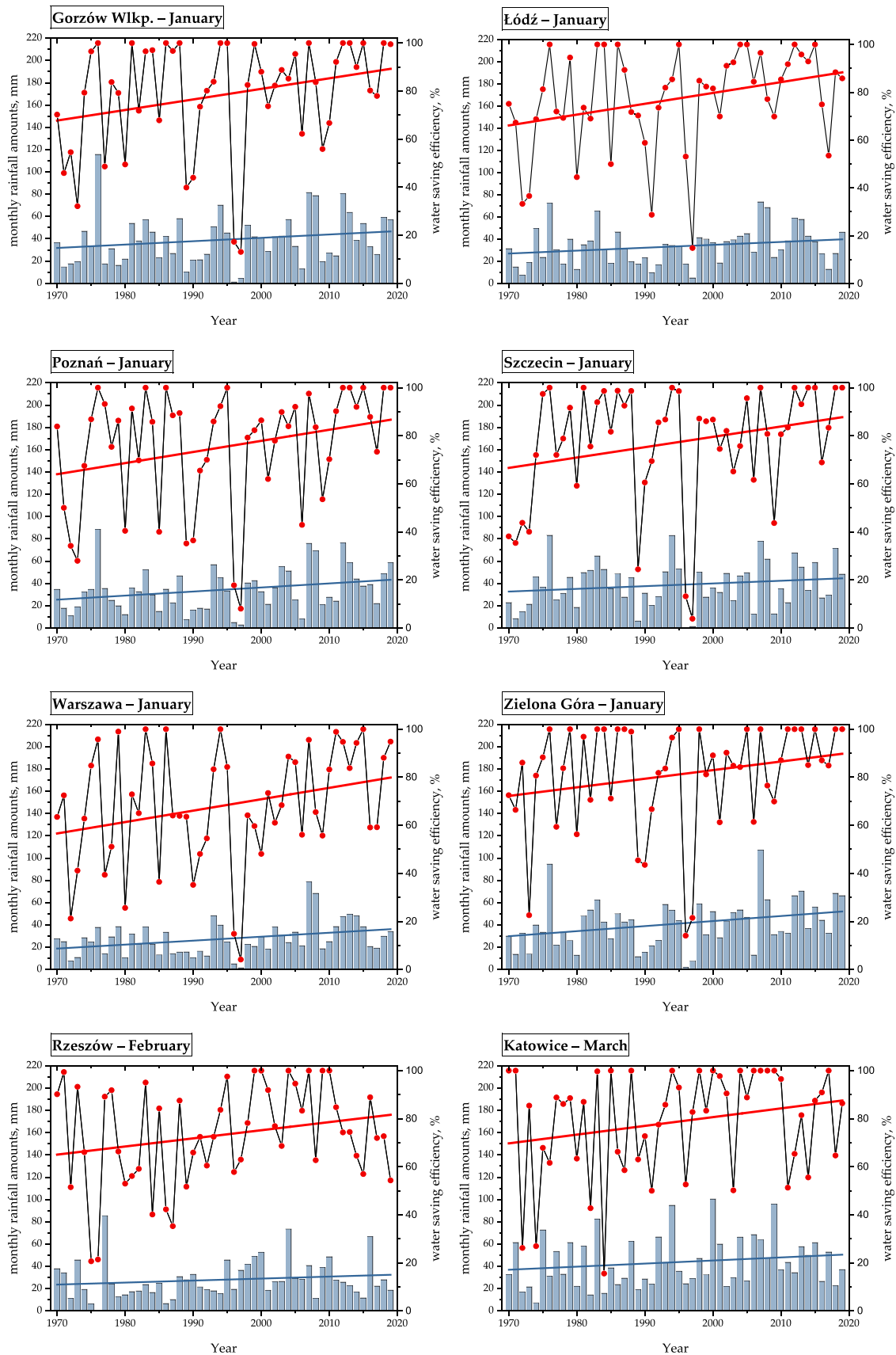

Fig. 8 Trend line of water saving efficiency (red line) and annual precipitation (blue line) in Opole between 1970 and 2019, annual efficiencies (red dots) and annual precipitation totals (blue bars)

Fig. 9 Statistically significant monthly changes (red line) in water saving efficiency (red dots) in individual cities in the years 1970–2019 and monthly amounts of rainfall (blue bars)
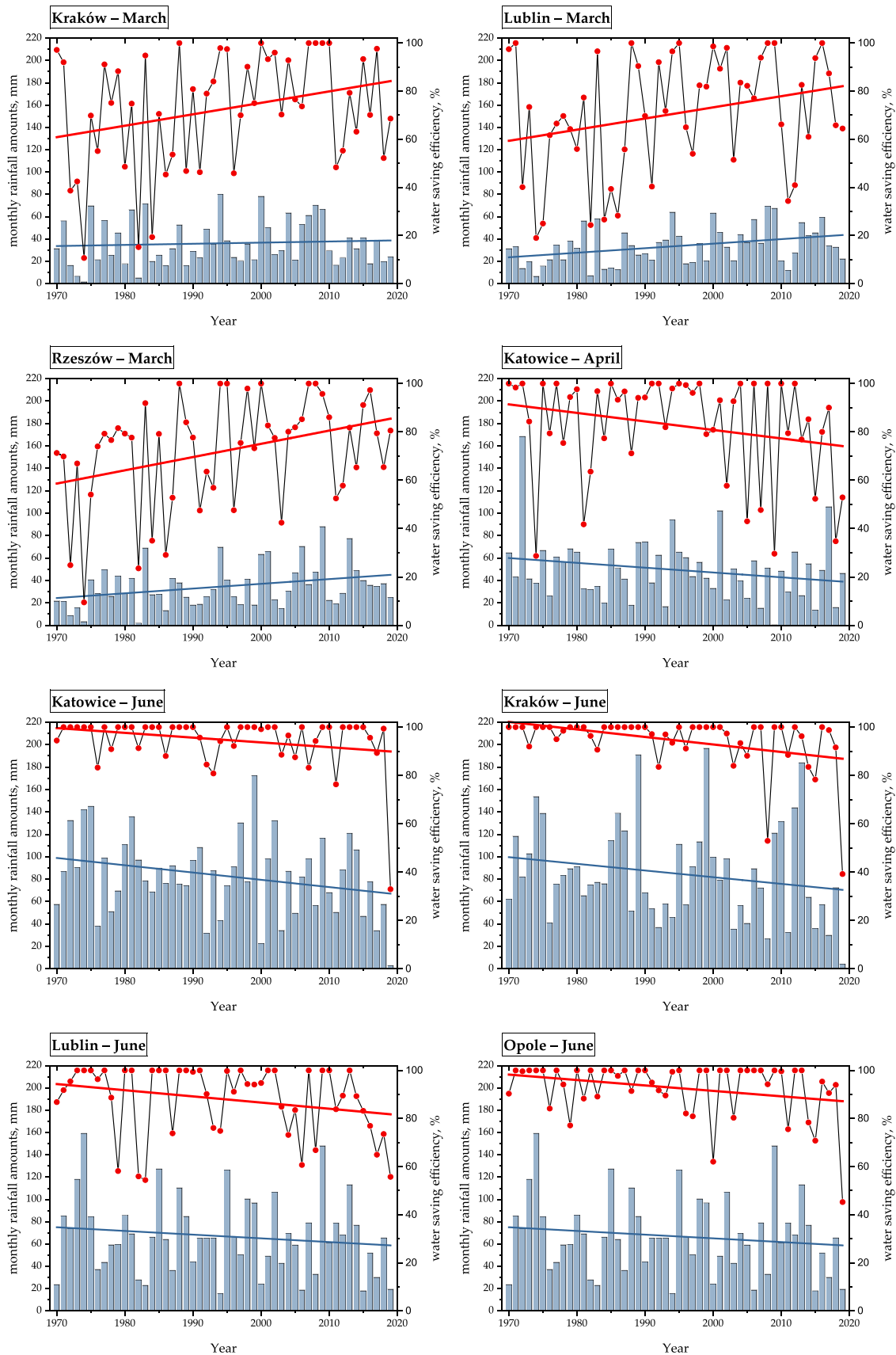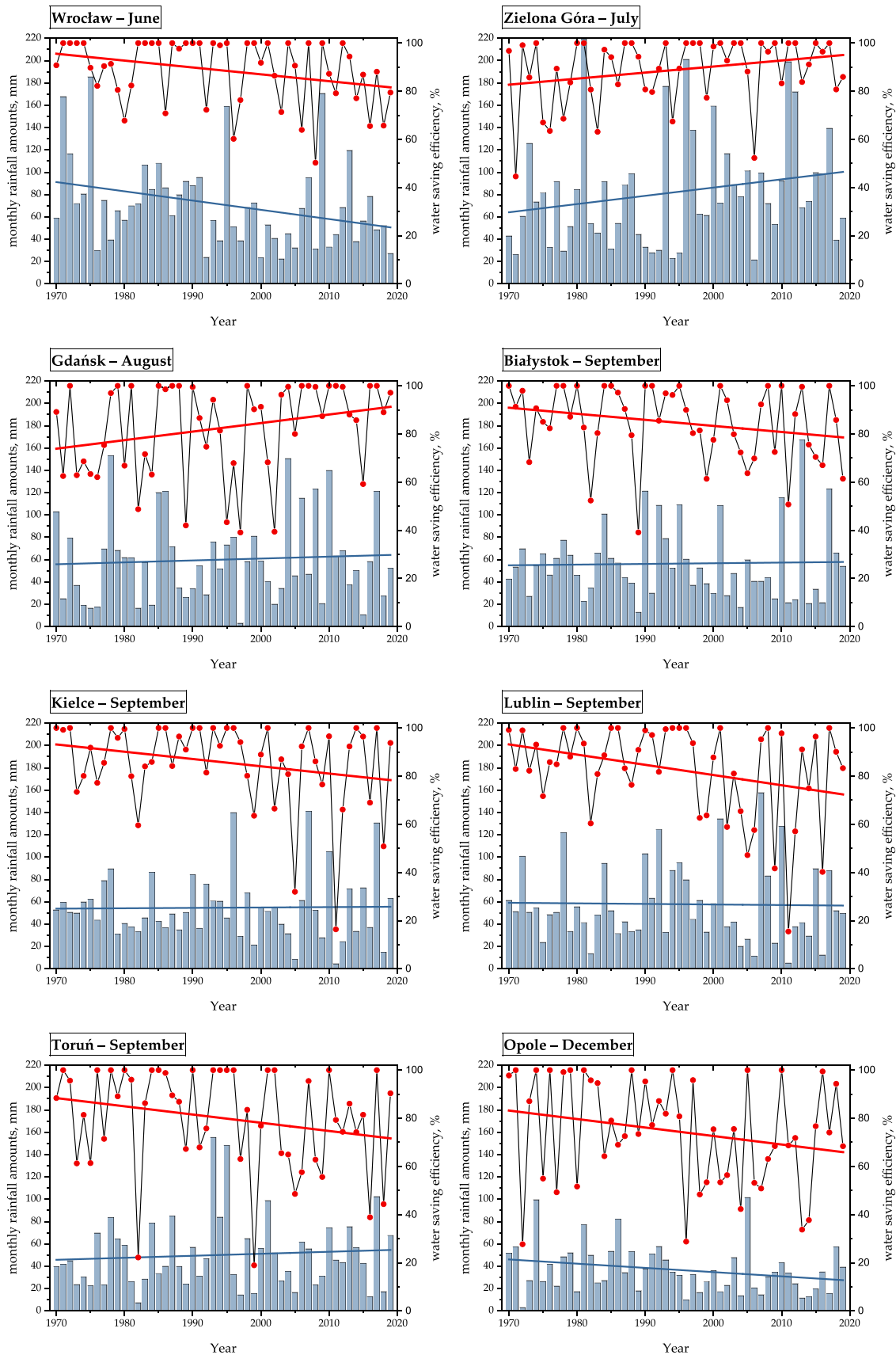
Fig. 9 (continued)

Fig. 9 (continued)

Conclusions

On the basis of the results of the research carried out the following conclusions were drawn:

- In the context of undisputed climate changes, statistically significant trends of changes in the average annual efficiency of the RWH system in 18 out of 19 analysed cities in Poland in the years 1970–2019 were not found. A statistically significant impact of climate changes on the annual water saving efficiency was found only in Opole. A decrease in efficiency by 1.44% per decade means clearly decreasing economic and ecological benefits for users of such a system during its operation. This is a negative trend.
- The analysis on a monthly basis provided more detailed information. In the analysed half of the century, statistically significant changes in the monthly efficiency of the RWH system were shown. A total of 24 significant monthly trends show an increase in efficiency in the winter months and a decrease in the summer months. For the residential RWH systems, this is a positive change reducing the seasonal difference between summer and winter precipitation. For garden watering RWH systems, it is an unfavourable change due to the reduced availability of water for watering at the beginning of the growing season. Research on water collected from roofs should be extended to include quantitative and qualitative analysis of its composition, including identification of heavy metals. Their results will confirm the suitability or disqualification of water collected in particular regions (especially highly industrialised ones) for domestic use and garden watering.
- Differences in statistical significance of annual and monthly trends of RWH efficiency in the analysed cities indicate that the sum of precipitation is not the only indicator influencing its efficiency. The course of precipitation is also important. Therefore, water saving efficiency trends should be analysed, not precipitation trends.
- The design of RWH systems should be based on archival data and take into account the many years of rainfall changes. This will improve performance and secure benefits for the users of this system.

Declarations

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