

Pluvial conditions in Wrocław, Poland

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Abstract. The paper presents rainfall conditions for the city of Wrocław (Poland) in the multi-annual period 1960–2017. A decreasing tendency of annual precipitation totals on the level of -12.5 mm/decade and decreasing trend of the monthly total in November of -2.9 mm/decade has been shown. In remaining months, no statistically significant change trends were observed. The maximum daily rainfall amounts were recorded in summer months: 56.4 mm in June, 74.4 mm in July and 67.5 mm in August. The analysis of variability in the number of precipitation with daily amounts exceeding 10 mm showed statistically significant decreasing trends – a decrease in the number of days in the amount of 0.69 per decade (linear regression). In the case of rainfall exceeding 20 mm and 30 mm no statistically significant trends were noted – the number of days with such heavy precipitation is practically constant and amounts to an average of 3.84 and 1.44 precipitation per year.

1 Introduction

From the point of view of urban hydrology, the most important climate features are atmospheric precipitation [1, 2]. For the proper recognition of pluvial conditions of urban areas, a climatological analysis of multi-annual series of rainfall data is necessary [3–5]. According to the recommendations of The World Meteorological Organization, a minimum period of 30 years should be adopted for climatological studies [6].

The latest research on climate change in Europe on the basis of over 50 years of summer measurement series indicates that maximum daily rainfall, depending on the altitude above sea level, are highly variable and range from 37.6 to 520 mm. The number of short-term but intense rainfall increases continuously, and since 1960, on 89% of measurement stations more than one case of daily precipitation greater than 50 mm has been registered [7, 8].

In Poland up to 2010, an increase in the number of days with precipitation is observed, with an explicit fluctuation of monthly and annual precipitation totals. Trends of changes are usually statistically irrelevant, regardless of whether the trends are downward or upward

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[9, 10]. In the paper [11] a decreasing tendency of annual totals change was shown for Wrocław.

The aim of this study is to characterize the pluvial conditions of the city of Wrocław. The work includes the analysis of daily rainfall totals recorded at the synoptic station in Wrocław over a 58-year period. Both daily and monthly totals of precipitation were analyzed, as well as a number of days with precipitation.

2 Materials and methods

The meteorological station of the Institute of Meteorology and Water Management (IMWM) in Wrocław is a part of national measurement and observation network at national hydrological and meteorological service. The station coordinates are: 51–06 N, 16–54 E; terrain altitude: about 120 m above sea level. In this study, daily precipitation records from this IMWM meteorological station from 1960–2017 long-term period were used as a research material.

In order to determine trends of changes in rainfall time series, both linear regression and non-parametric Mann-Kendalls test were used [12, 13]. Changes (increases or decreases) at a significance level above 95% are considered as statistically relevant. Changes at the significance level from 90 to 95% are assumed to be close to statistical significance, while changes in the significance level from 75 to 90% are assumed to be a tendency to change. Changes at the level of significance below 75% are considered statistically insignificant and consequently without a specific direction of change [9].

The classification of monthly rainfall amounts was made using Kaczorowska criterion [14]. Monthly precipitation totals were divided into 7 categories, depending on the percentage of the multi-annual average: extremely dry (less than 25%), very dry (25–49%), dry (50–74%), normal (75–125%), wet (126–150%), very wet (151–175%) and extremely wet (above 175%).

In order to determine the intensity of rainfall, the Olechnowicz-Bobrowska criteria were used [15], extended by the criteria given in [16]. As a result, daily precipitation were distinguished: very weak (0.1–1.0 mm), weak (1.1–5.0 mm), moderate (5.1–10.0 mm), moderately strong (10.1–20.0 mm), strong (20.1–30.0 mm), dangerous (30.1–50.0 mm), constituting flood hazard (50.1–70.0 mm), flood (70.1–100.0 mm) and disastrous (above 100 mm).

3 Results

The average annual sum of the analyzed precipitation series amounts to $H = 568$ mm. For comparison, on the multi-annual period 1971–2000, which appears in many climatological studies, i.e. the Climate Atlas of Poland [17], a corresponding precipitation total is equal to 570 mm, while for the earlier 1961–1990 the sum amounts to 590 mm and for the current period of 1981–2010 the average precipitation total is 537 mm.

The course of annual rainfall totals and their trend is presented in Fig. 1. Linear regression and Mann-Kendalls test reveal no statistically significant change trends, but only a declining trend (–12.4 mm/decade and –12.6 mm/decade respectively). Due to very similar values of directional coefficients, trend lines determined by both methods are practically overlapping.

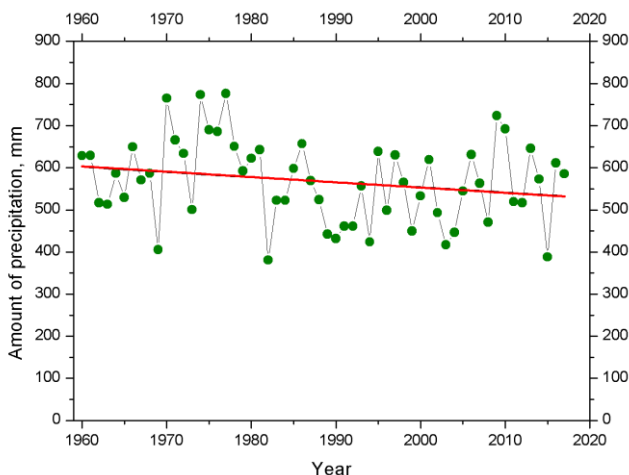


Fig. 1. Annual precipitation in Wroclaw in 1960–2017.

In the years 1974–1981, the longest period of precipitation higher than average occurred, with the maximum (over the whole analyzed period) annual precipitation of 776.2 mm (208.6 mm above the average) in 1977. The longest period with lower than average rainfall amounts occurred in years 1988–1994, with the minimum annual rainfall of 380.8 mm (186.8 mm below the mean) observed in 1982. Deviations from the average amount of precipitation are shown in Fig. 2.

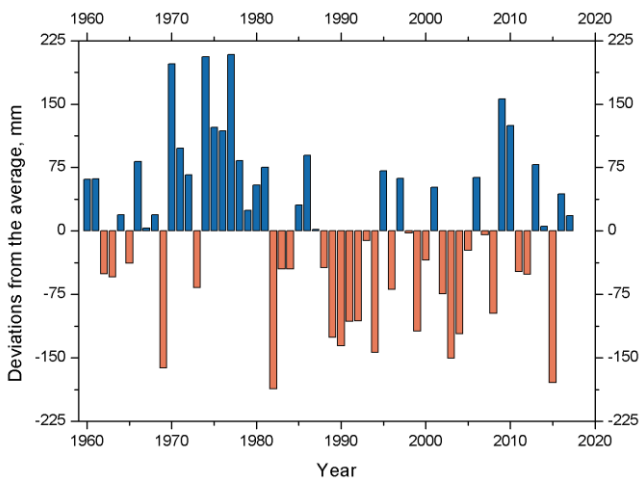


Fig. 2. Deviations from the average annual precipitation in Wroclaw in 1960–2017.

A summary of average, maximum and minimum monthly rainfall totals is presented in Table 1. The table also shows the percentage of monthly rainfall in the annual total (h / H) and the years in which the maximum and minimum values occurred.

Table 1. Monthly rainfall totals against the background of the annual total (I–XII) in Wrocław in 1960–2017.

Month	Average value		Maximum value		Minimum value	
	<i>h</i> , mm	<i>h</i> / <i>H</i> , %	<i>h</i> , mm	Year	<i>h</i> , mm	Year
I	28.5	5.0	95.7	1976	5.0	1964
II	25.4	4.5	47.8	1966	1.5	1978
III	31.0	5.5	74.1	1992	3.5	1974
IV	35.3	6.2	79.0	1989	5.1	2007
V	61.4	10.8	140.5	1965	6.0	1988
VI	71.9	12.7	185.4	1975	13.8	1962
VII	88.7	15.6	250.8	1980	10.8	1994
VIII	70.6	12.4	229.3	2006	4.0	2015
IX	47.3	8.3	109.5	1979	7.4	1982
X	38.9	6.9	128.4	1974	2.6	2010
XI	37.5	6.6	102.8	1970	0.0	2011
XII	31.1	5.5	100.0	1974	4.0	1972
I–XII	567.6	100.0	776.2	1977	380.8	1982

For monthly rainfall amounts, the lowest average values are recorded in the winter (31.1 mm in December, 28.5 mm in January and 25.4 mm in February), and the highest in the summer (71.9 mm in June, 88.7 mm in July and 70.6 mm in August). Very important (in relation to averages) are the maximum values, which were respectively 100.0 mm, 95.7 mm and 47.8 mm for winter months and 185.4 mm, 250.8 mm and 229.3 mm for summer months. The minimum, average and maximum monthly rainfall amounts, as well as their median and percentiles of 25% and 75% are shown as a box plot in Figure 3.

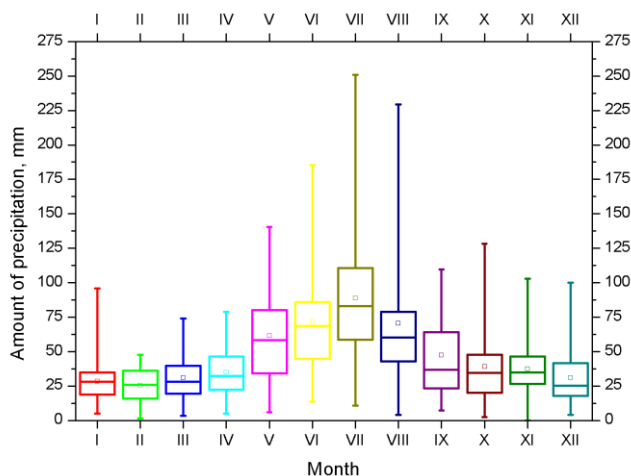


Fig. 3. Wrocław Monthly precipitation in 1960–2017.

In 1960–2017, the monthly precipitation totals were qualified according to the accepted classification: 32 times as extremely dry (4.6%), 93 very dry (13.4%), 129 dry (18.5%), 258 normal (37.1%), 66 wet (9.5%), 52 very wet (7.5%) and 66 extremely wet (9.5%). Most often the most dry month was October (6 times), very dry September (12 times), dry December (16 times), normal June (28 times), wet March and December (8 times each), very wet February (8 times) while the extremely wet September (10 times). The structure of variability of monthly precipitation totals with reference to the average perennial values according to the adopted classification is shown in Figure 4.

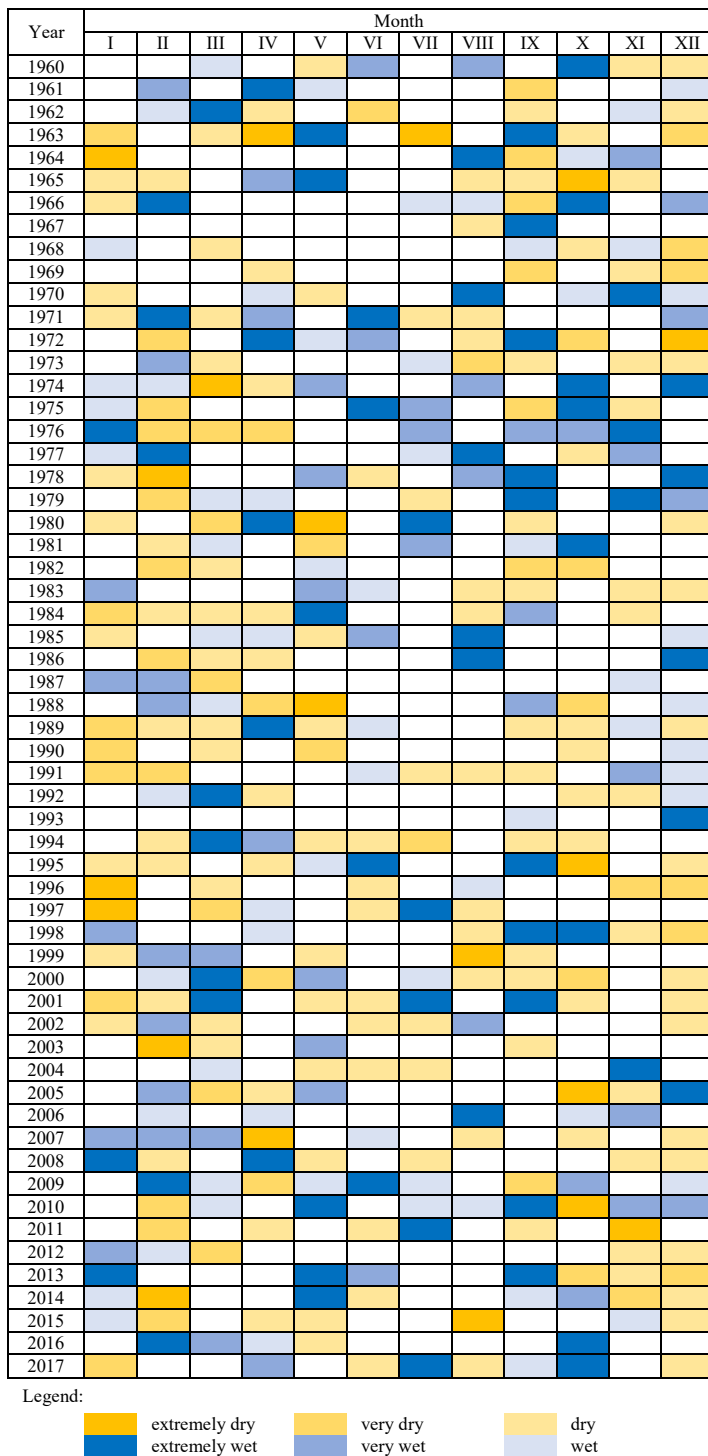


Fig. 4. The range of rainfall classes calculated by means of the Kaczorowska classification.

Analysis of variability of precipitation sums in individual months did not show statistically significant change trends except for November, for which a downward trend

of -2.9 mm/per decade (linear regression) was calculated. In addition, declining trends close to statistical significance were demonstrated in June and August and growing in January (Mann-Kendalls test).

The average and maximum daily rainfall values recorded in Wrocław in particular months of the year in 1960–2017 are summarized in tab. 2.

Table 2. Daily sums of rainfall in Wrocław in the years 1960–2017.

Month	Average value	Average maximum value	Absolute maximum value		Minimum maximum value	
	<i>h</i> , mm	<i>h</i> , mm	<i>h</i> , mm	Year	<i>h</i> , mm	Year
I	0.92	7.2	20.0	1982	1.6	1964
II	0.90	7.2	19.5	1960	0.8	2014
III	1.00	9.6	23.5	1999	1.1	1974
IV	1.18	11.7	24.3	1989	2.8	2007
V	1.98	16.6	41.5	1984	2.0	1988
VI	2.40	22.9	56.4	1961	5.3	1992
VII	2.86	27.6	74.4	2001	5.0	1994
VIII	2.28	23.2	67.5	1964	2.2	2015
IX	1.58	15.9	47.4	2010	3.1	2009
X	1.26	12.5	34.3	1974	1.0	2005
XI	1.25	11.1	38.3	1970	0.0	2011
XII	1.00	8.1	32.0	1974	1.1	1972
I–XII	1.55	39.1	74.4	2001	17.2	2008

The smallest average daily totals are recorded in the winter months (1.00 mm in December, 0.92 mm in January and 0.90 mm in February), and the highest in the summer months (2.40 mm in June, 2.86 mm in July and 2.28 mm in August). The course of average daily sums in the following days of the year is shown in Figure 5.

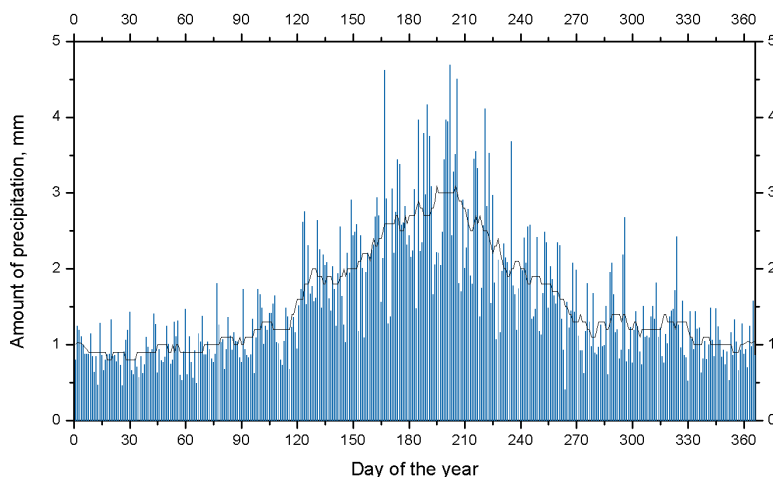


Fig. 5. The course of average daily sums in subsequent days of the year in Wrocław from 1960 to 2017 (black line – moving average from 15 days).

The maximum daily rainfall amounts in a given month are many times higher than the average values. In the winter months they are 32.0 mm, 20.0 mm and 19.5 mm respectively, and in summer 56.4 mm, 74.4 mm and 67.5 mm respectively. The course of maximum

daily totals recorded in Wroclaw in the years 1960–2017 in the following days of the year is shown in Figure 6.

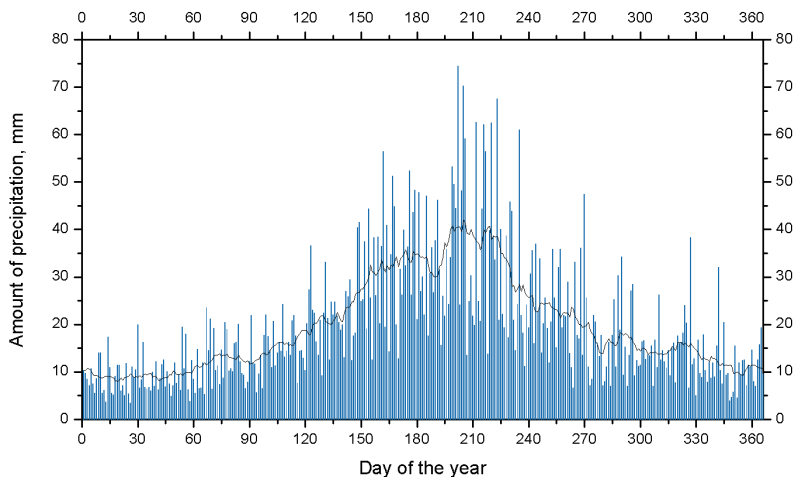


Fig. 6. The course of maximum daily totals in subsequent days of the year in Wroclaw from 1960 to 2017 (black line – moving average from 15 days).

The lowest values (among daily maxima from a multi-year period) of 3.4 mm were recorded on 03.01.2006 and 26.01.2008. The absolute maximum of 74.4 mm was recorded on 20.07.2001. It should be noted that this sum accounted for 84% of the monthly average for the month of July.

In Wroclaw in the years 1960–2017 a total of 8295 days with precipitation were recorded, of which the highest were classified as very weak (0.1–1.0 mm), weak (1.1–5.0 mm) and moderate (5.1–10.0 mm) – which occurred respectively 2892, 3497 and 1102 times. Daily rainfall exceeding 10 mm was already less: 581 moderately strong (10.1–20.0 mm), 139 strong (20.1–30.0 mm), 71 dangerous (30.1–50.0 mm), 11 constituting flood hazard (50.1–70.0 mm) and 2 floods (70.1–100.0 mm). In the analyzed period no disastrous daily precipitations (over 100 mm) were recorded.

Table 3. Average number of days with fall of individual categories in Wroclaw in 1960–2017.

Month	Very weak	Weak	Moderate	Moderately strong	Strong	Dangerous	Constituting flood hazard	Floods
I	5.67	6.12	1.00	0.28	0.00	0.00	0.00	0.00
II	5.28	4.66	1.24	0.21	0.00	0.00	0.00	0.00
III	4.69	5.47	1.17	0.41	0.09	0.00	0.00	0.00
IV	3.40	4.55	1.47	0.67	0.12	0.00	0.00	0.00
V	3.26	4.93	2.10	1.40	0.40	0.09	0.00	0.00
VI	3.47	4.97	1.93	1.48	0.34	0.26	0.05	0.00
VII	3.09	4.57	2.14	1.76	0.66	0.38	0.05	0.03
VIII	3.24	4.07	1.88	1.45	0.33	0.31	0.09	0.00
IX	3.28	4.79	1.66	0.78	0.28	0.12	0.00	0.00
X	3.59	4.59	1.53	0.74	0.12	0.03	0.00	0.00
XI	5.17	5.60	1.62	0.57	0.05	0.02	0.00	0.00
XII	5.74	5.98	1.26	0.28	0.02	0.02	0.00	0.00
I–XII	49.86	60.29	19.00	10.02	2.40	1.22	0.19	0.03

Days with rainfall exceeding 10 mm occur most often during the summer, especially in July. The winter months are characterized by the highest frequency of very weak and weak precipitation. The comparison of the average number of days with precipitation of individual categories registered in Wroclaw in the years 1960–2017 is presented in tab. 3.

Analysis of the variability of the number of precipitation with daily sums exceeding 10 mm (Fig. 7) showed statistically significant decreasing trends – a decrease in the number of days by 0.69 per decade (linear regression). In the case of rainfall exceeding 20 mm and 30 mm, no statistically significant trends were recorded – the number of days with such heavy rainfall is practically constant and amounts to 3.84 and 1.44 precipitation per year (on average).

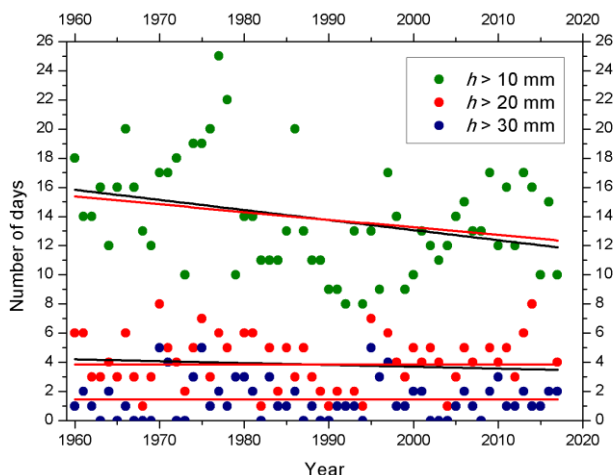


Fig. 7. Number of days per year with precipitation exceeding 10, 20 and 30 mm in Wroclaw in the years 1960–2017 (black line – linear regression, red line – Mann-Kendalls).

4 Conclusions

The work assessed rainfall conditions in Wroclaw based on measurement data recorded in 1960–2017. The analyzes presented allowed to formulate the following conclusions:

- in line with the rain zone's rainfall regime, the highest values of monthly and daily sums are found in Wroclaw in the warm season of the year (V–X);
- annual precipitation show a statistically insignificant decreasing tendency of approx. 12.6 mm changes per decade;
- there is a strong temporal and spatial differentiation of the degree of humidity of individual months in the multi-year analysis;
- negative deviations from the norm of individual months occur more frequently than positive anomalies, which corresponds with the decreasing tendency of changes;
- the most frequent rainfall in Wroclaw are weak, very weak and moderate precipitation – usually occurring in winter;
- days with precipitation greater than 10 mm occur most often in the summer period (in particular in July), statistically significant trends of decreasing numbers of days with precipitation above 10 mm have been demonstrated;
- the number of days with precipitation exceeding 20 and 30 mm over the years does not change.

From the point of view of urban hydrology, rainfall with sums exceeding 20 mm in a short up to several hours will be particularly dangerous. Analysis of trends in the occurrence of such rainfall should be the subject of subsequent analyzes.

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