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TRENDS IN DAILY CHANGES OF PRECIPITATION ON THE EXAMPLE OF WROCŁAW

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ABSTRACT: The study analyzed 8295 daily rainfalls recorded in Wrocław from 1960 to 2017. The frequency of daily precipitation in a year was determined in nine categories: from very weak (less than 1.0 mm) to disastrous (over 100 mm). In addition, the precipitation trends were determined by linear regression and the Mann-Kendall test. Analysis of the variability of the number of days with precipitation of particular categories showed a statistically significant downward trend for moderately strong precipitation (10.1-20.0 mm). In case of other categories of precipitation, the tests did not show statistically significant changes.

KEY WORDS: rainfalls, urban flooding, urban hydrology

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Introduction

One of the most important infrastructures in the urbanized area is the rainwater drainage system, which drains excess rainfall from the catchment area to a natural watercourse like a river or a lake – away from urban areas. The construction of rainwater drainage systems is one of the most expensive investments in infrastructure. Such systems are usually designed to last at least 50 years or even 100 years.

Rainwater drainage should protect against the effects of extreme rainfall causing significant economic and social losses. However, it is not possible to achieve its fully reliability, neither now nor in the future, due to the stochastic nature of precipitation. Safe design of sewerage systems is aimed at ensuring an adequate standard of drainage of the area, which is defined as adapting the system to accept forecasted maximum rainwater streams with a frequency equal to the allowed (socially acceptable) frequency of their flooding on the area (Kotowski, 2015). The standard EN 752 (2017) limits the permissible frequency of sewer overflow to once every year for areas of very low importance (e.g. roads and open spaces located away from buildings), to, among others, once every 5 years for areas of medium importance (e.g. roads and open spaces located near buildings), up to once every 50 years for areas of very high importance (e.g. critical infrastructure). Examples of project criteria for outflows according to EN 752:2017 are presented in table 1.

Table 1. Examples of design sewer flooding criteria for standing floodwater

Impact	Example locations	Examples of design sewer flooding frequency, years
Very low	Roads or open spaces away from buildings	1
Low	Agricultural land	2
Low to medium	Open spaces used for public amenity	3
Medium	Roads or open spaces adjacent to buildings	5
Medium to high	Flooding in occupied buildings excluding basements	10
High	Deep flooding in occupied asements or road underpasses	30
Very high	Critical infrastructure	50

Source: EN 752, 2017.

The issue of drainage of rainwater from urbanized areas has gained special significance in recent years. On the one hand, the continuing sealing of the surface area results in increased rainwater runoff coefficients, which in turn leads to hydraulic overloading of rainwater drainage systems or combined sewer systems (Kotowski, 2015). On the other hand, more and more attention is given to climate change, especially in the context of global warming and the increased occurence of extreme weather events (Schiermeier, 2011; Walsh et al., 2016; Dai, 2011; Kundzewicz et al., 2012), although there is no consensus as to their causes (Dąbrowski, Dąbrowska, 2012). The increase in the average annual temperature on the globe causes increased water circulation in the hydrological cycle and influences, among others, the frequency of extreme precipitation. Due to global warming and anthropogenic activities, extreme precipitation will become more common and will have a negative impact on the functioning of rainwater drainage systems (Kaźmierczak, Kotowski, 2014; Fleig et al., 2015). Potential problems with the functioning of sewage systems related to climate change include flooding of surfaces and basements, increased number and volume of stormwater, as well as increased volume of sewage flowing into the sewage treatment plants (Saboia et al., 2017; Ahmed et al., 2016; Kotowski, 2013).

Urban infrastructure planners and designers should use the forecasted changes in the occurrence of intense precipitation to adapt urban drainage systems as part of the reconstruction of aging infrastructure. To meet the combined challenges of climate change and urbanization, carefully selected adaptation measures that would require technical, economic and political commitment are needed (Semadeni-Davies et al., 2008; Yazdanfar, Sharma, 2015; Arnbjerg-Nielsen et al., 2013). The technical adaptive solutions include increasing diameters of sewers, constructing retention reservoirs and separating sewage into domestic wastewater and rainwater (Fratini et al., 2012; Kirshen et al., 2015). However, it should be noted that the current practice of drainage of land involving the discharge of rainwater away from urban areas is increasingly being put into question (Wong, Brown, 2009; Spatari et al., 2011). Green infrastructure is mentioned increasingly as one of the adaptation solutions aimed at utilizing rainwater at the place of intake (Fratini et al., 2012; Hostetler et al., 2011). The adaptation of urban infrastructure determined by the changing climate will become increasingly important to enable safe living in the cities in the future.

The aim of this work is to analyze the variability of daily precipitation recorded in Wrocław between 1960 and 2017. The frequency of daily precipitation in a year was classified from very weak (less than 1.0 mm) to disastrous (over 100 mm). In addition, the precipitation trends were determined using linear regression and the Mann–Kendall test for predicting their future frequency.

Materials and methods

Daily precipitation records from the Institute of Meteorology and Water Management (IMWM) meteorological station from the time span 1960-2017 were used as a research material. The meteorological station of IMWM in Wroclaw is a part of national measurement and observation network at hydrological and meteorological service. The station coordinates: 51–06 N, 16–54 E; terrain altitude: about 120 m above sea level. The classification of daily rainfall was made using the Olechnowicz-Bobrowska criterion (Olechnowicz-Bobrowska, 1970), extended by the criteria presented in the paper (Lorenc et al., 2012). As a result, daily precipitation was divided into 9 categories, depending on their sum (table 2).

Table 2. Criteria of daily rainfall

Rainfall criteria	Daily sum, mm
Very weak	0.1-1.0
Weak	1.1-5.0
Moderate	5.1-10.0
Moderately strong	10.1-20.0
Strong	20.1-30.0
Dangerous	30.1-50.0
Constituting flood hazard	50.1-70.0
Flood	70.1-100.0
Disastrous	≥ 100.1

Source: Lorenc et al., 2012.

The classic linear regression and the non-parametric Mann–Kendall test were used to detect trends in the changes in precipitation time series. This test answers the question as to whether the values measured in the time series $\{x_1, x_2, \ldots, x_n\}$ have a tendency to gradually increase or decrease (Schiermeier, 2011). The Mann–Kendall test analyzes the sign of the difference between successively measured measurement values. The newly measured value is compared to all previously measured values, which gives a total of n(n-1)/2 of possible data pairs, where n is the number of observations. Statistic S of the test is calculated using the following formula:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right). \tag{1}$$

By substituting $(x_j - x_i) = \theta$ we get:

$$\operatorname{sgn}(\theta) = \begin{cases} 1 \text{ for } \theta > 0 \\ 0 \text{ for } \theta = 0 \\ -1 \text{ for } \theta < 0 \end{cases} . \tag{2}$$

If the statistic S is positive, the newly measured values are greater than those measured earlier, which indicates an upward trend in the measured values x. Otherwise, there is a downward trend. The rate of the change of the analyzed trend in time can be described by the directional coefficient of the straight line expressed by Sen's slope estimator:

$$\beta = \text{mediana}\left(\frac{x_j - x_i}{j - i}\right), \tag{3}$$

calculated for every $i<j$, where $i = 1,2, \ldots, n-1$ and $j = 2,3, \ldots, n$.

Changes (increases or decreases) at a materiality level above 95% are considered statistically significant. A change with the significance level from 90 to 95% is assumed to be close to statistical significance, while changes with the significance level from 75 to 90% are considered as a tendency to change. Changes at the level of significance below 75% are considered as irrelevant and without a specific direction of change (Pińskwar, 2010).

Results

In Wrocław in the years 1960-2017 a total of 8295 days with precipitation were registered, of which 7491 were classified (according to the classification presented in table 2) as very weak, weak or moderate. The number of instances of daily precipitation with a volume exceeding 10 mm was much lower (804 in total). The summary of the number of days with precipitation in individual categories registered in Wrocław in the years 1960-2017 is presented in table 3.

Table 3. Number of days with precipitation according to criteria

Rainfall criteria	Number of days with precipitation	Average number of days with precipitation
Very weak	2892	49.86
Weak	3497	60.29
Moderate	1102	19.00
Moderately strong	581	10.02
Strong	139	2.40
Dangerous	71	1.22
Constituting flood hazard	11	0.19
Flood	2	0.03
Disastrous	0	0.00

Source: author's own work.

The linear regression ($y = ax + b$) and the Mann–Kendall test were used to determine the trends of the change in the number of days with precipitation representing individual categories in the years 1960-2017. Due to the very small number of days with daily precipitation exceeding 70 mm, the precipitation representing the last three categories was grouped for further analysis. The calculation results are presented in table 4 and in figure 1. The trend line is marked red for linear regression and blue for the Mann–Kendall test.

Table 4. Trends in the number of days with precipitation according to criteria

Rainfall criteria	Linear regression			Mann–Kendall test		
	R^2	*a*	Significance level	*S*	*β*	Significance level
Very weak	0.010	0.054	54.8%	54	0.000	27.8%
Weak	0.001	-0.021	22.5%	-52	-0.028	26.8%
Moderate	0.017	-0.036	66.4%	-147	-0.034	67.4%
Moderately strong	0.092	-0.056	98.0%	-297	-0.044	95.5%
Strong	0.020	-0.013	71.2%	-194	0.000	81.4%
Dangerous	0.000	-0.000	1.7%	63	0.000	34.0%
Constituting flood hazard, flood and disastrous	0.000	0.000	7.4%	-19	0.000	13.7%

Source: author's own work.

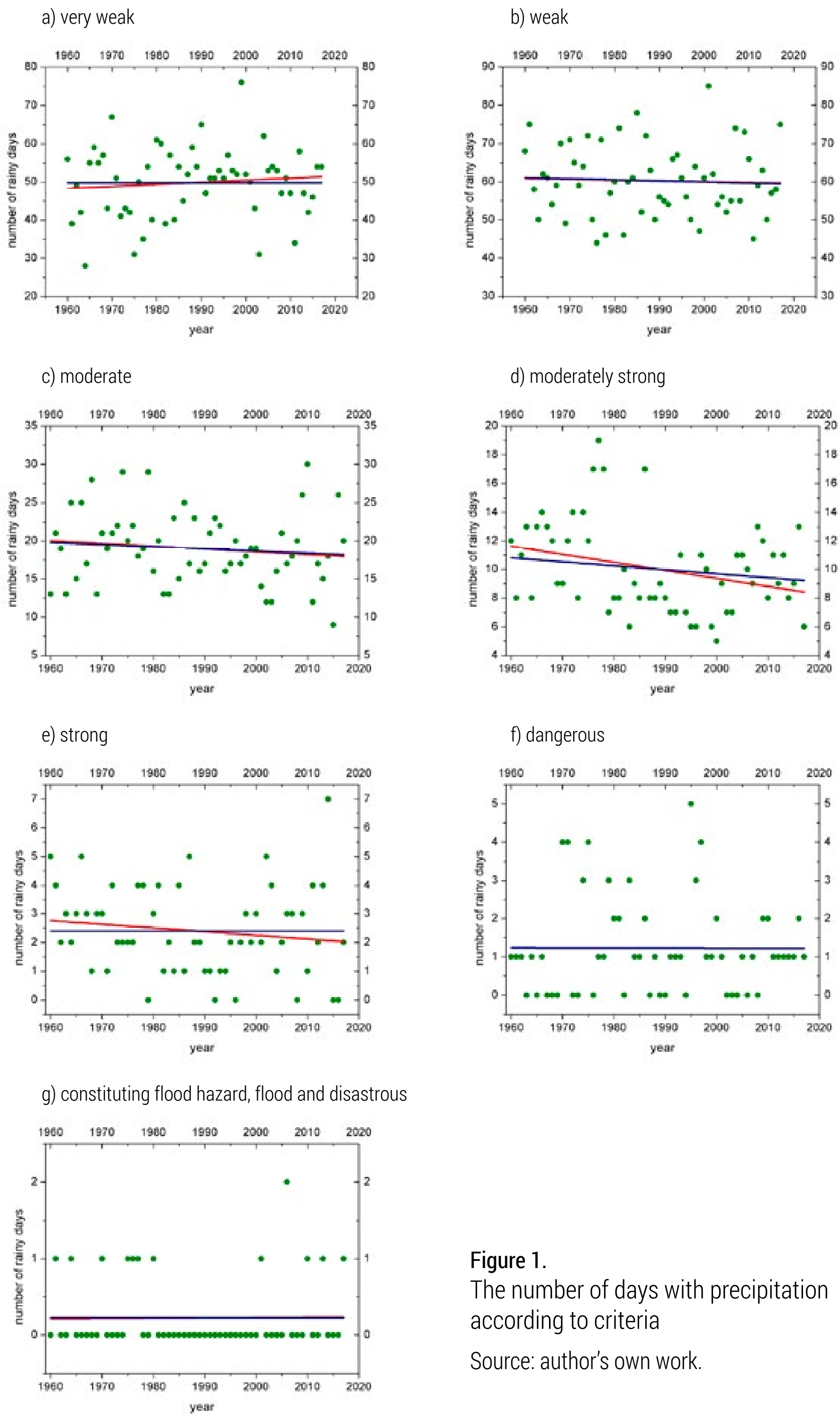

Figure 1.
The number of days with precipitation according to criteria

Source: author's own work.

Analysis of the changes in the number of days with precipitation of particular categories (table 4) showed a statistically significant downward trend for moderately strong precipitation (10.1-20.0 mm). In case of other categories of precipitation, the tests did not show statistically significant changes in precipitation in Wrocław in the years 1960-2017.

Summary and conclusions

The study analyzed daily precipitation recorded in Wrocław in the years 1960-2017. In total, 8295 days with precipitation were recorded during this period, of which 90.3% were days with very weak (0.1-1.0 mm), weak (1.1-5.0 mm) and moderate precipitation (5.1-10.0 mm) that occurred 2892, 3497 and 1102 times, respectively. Consequently, such precipitation occurs, on average, 50, 60 and 19 times a year.

Moderately strong precipitation (10.1-20.0 mm), strong precipitation (20.1-30.0 mm) and dangerous precipitation (30.1-50.0 mm) occurred 581, 139 and 71 times respectively, i.e. 10, 2.4 and 1.2 times a year on average. Precipitation constituting flood hazard (50.1-70.0 mm) and flood precipitation (70.1-100.0 mm) occurred only 11 and 2 times, while disastrous precipitation (above 100.0 mm) was not recorded during the analyzed period.

Analysis of the variability of the number of days with precipitation of particular categories showed a statistically significant downward trend for moderately strong precipitation (significance level of 98.0% and 95.5% – for linear regression and Mann–Kendall test respectively). A drop in the number of days with moderately strong precipitation was approx. 0.5 per decade. In case of other categories of precipitation, the tests did not show statistically significant changes.

It should be noted that for urban hydrology the most important is the short-term precipitation, with duration spanning from several minutes to several hours. These are the most intense rainfalls that can cause hydraulic overloading of drainage systems. Analysis of the changes in the duration of short-term rainfalls shall be the goal of further research that will complement this work.

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The contribution of the authors

Bartosz Kaźmierczak – 40% (concept and objectives, literature review, research).

Marcin Wdowikowski – 30% (concept and objectives, literature review, research).

Joanna Gwoździej-Mazur – 30% (objectives, literature review, research).

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