Changes in Maximum Rainfall Amounts in Wroclaw (Poland)

B. Kaźmierczak and K. Wartalska

***Abstract*—In the paper an attempt has been made to predict the maximum rainfall, authoritative for drainage systems dimensioning, particularly for 2050 in Wroclaw (Poland). Research material was represented by archival pluviographic records from the Institute of Meteorology and Water Management meteorological station, from the time span 1960–2018. From the research material, a number of 30 – 30-year measurement series were separated, which formed the basis for the development of probabilistic models of maximum rainfall. For statistical analyses, the rainfalls were selected with the use of the peak-over-threshold (POT) method. For such prepared data, an empirical probability of exceedance was attributed, followed by the identification of the parameters estimators of generalized exponential distribution (GED), using the maximum likelihood method. In order to verify the compatibility between the assumed – theoretical and the empirical distributions, a λ-Kolmogorow test was carried out. The applied Mann–Kendall test demonstrated the statistically relevant changes trends of equations parameters describing the dependency the two estimators (scale and location parameters) on rainfall duration. As a result, the equations were obtained, which allowed to determine the prediction model of maximum precipitation amounts, dependent on the duration, probability of exceedance and a year, on which the rainfall is calculated.**

***Index Terms*—Climate change, Mann–Kendall test, maximum likelihood method, time series.**

I. Introduction

Urban drainage should protect against the effects of extreme rainfall, submerging and flooding, however, due to the stochastic nature of rainfall and their high spatial and temporal variability, it is not possible to achieve its fully reliable operation [1]. The standard EN 752:2017 suggests to distinguish the allowable flooding frequency from sewers in a seven-step scale of the impact of threat on the environment – from C = 1 year (1 time per 1 year) for very low hazard areas, to C = 50 years (1 time per 50 years) for areas with very high risk (Table I).

Both progressive urbanization and climatic changes have a negative impact on the efficiency of the sewage systems operation, causing its increasingly frequent overloads, leading to local or urban flooding [2], [3]. The adaptation of the urban infrastructure, determined by the changing climate, will become more and more important so that our cities may be fit to live safely in the future [4].

TABLE I: 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 basements or road underpasses	30
Very high	Critical infrastructure	50

Research on future rainfall scenarios and their impact on drainage infrastructure have been conducted for many years around the world. The increase in the extreme precipitation occurrence will undoubtedly result in the need to update the height (DDF) or rainfall intensity curves (IDF) [5]-[7]. The quantification of the problem, as well as appropriate remedial planning, in order to minimalize the negative effects of such events in the future are urgently needed today [8]-[11].

II. Materials and Methods

In the work, based on rainfall observations in Wroclaw, an attempt has been made to predict the future maximum rainfall, authoritative for drainage systems dimensioning (designing on the prospect of 50–100 years). Research material was represented by archival pluviographic records from the Institute of Meteorology and Water Management Wroclaw-Strachowice meteorological station, from the time span 1960–2018 (59 years of observations).

In order to determine trends of changes in rainfall time series, both linear regression and non-parametric Mann–Kendall 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 [14].

Since rainfall models should be based on at least 30-year measurement period, and the principal purpose of the work

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was the forecast of the future rainfall based on observed trends, from the research material, a number of 30, 30-year measurement series were separated: 1960–1989, 1961–1990, …, 1989–2018. In this way, the 30 measurement series were created, which formed the basis for the development of probabilistic models of maximum rainfall. For statistical analyses, the maximum rainfalls were selected with the use of the peak-over-threshold (POT) method [15]–above the own cut-off limit, for 16 durations, recommended for precipitation models formulation, i.e.: 5, 10, 15, 30, 45, 60, 90, 120, 180, 360, 720, 1080, 1440, 2160, 2880 and 4320 min [16], [17]. For each of the 30 periods (from 1960–1989 to 1989–2018), the 30 highest rainfall amounts (for each of the 16 rainfall durations) were selected and ordered non-increasing. For such prepared data, using the maximum likelihood method "94", an empirical probability of exceedance was attributed [18], followed by the identification of the parameters estimators of the generalized exponential distribution (GED) [19]-[21], by which the maximum rainfall amounts for each of the 30 analyzed periods were described.

In order to verify the compatibility between the assumed – theoretical and the empirical distributions, a λ-Kolmogorow test was carried out [17]. Obtained results allowed to assume the null hypothesis about the GED theoretical distribution compatibility with the empirical data.

III. Pluvial Conditions in Wroclaw

The average annual sum of the analyzed precipitation series amounts to H = 565 mm. Linear regression and Mann–Kendall test reveal no statistically significant change trends, but only a declining trend (–12.4 mm/decade and –12.6 mm/decade respectively).

Analysis of the variability of precipitation sums in individual months did not show statistically significant change trends. Declining trends close to statistical significance were demonstrated in June, August and November and growing in January.

For monthly rainfall amounts, the lowest average values are recorded in the winter (31.2 mm in December, 28.2 mm in January and 25.0 mm in February), and the highest in the summer (71.5 mm in June, 88.6 mm in July and 69.7 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. Fig. 1 shows the monthly sums of rainfall amounts registered in Wroclaw in the years 1960–2018.

The smallest average daily totals are recorded in the winter months (1.01 mm in December, 0.91 mm in January and 0.88 mm in February), and the highest in the summer months (2.38 mm in June, 2.86 mm in July and 2.25 mm in August). 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.

In Wroclaw in the years 1960–2017 a total of 9248 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 3748, 3536 and 1113 times. Daily rainfall exceeding 10 mm was already less: 589 moderately strong (10.1–20.0 mm), 142 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.

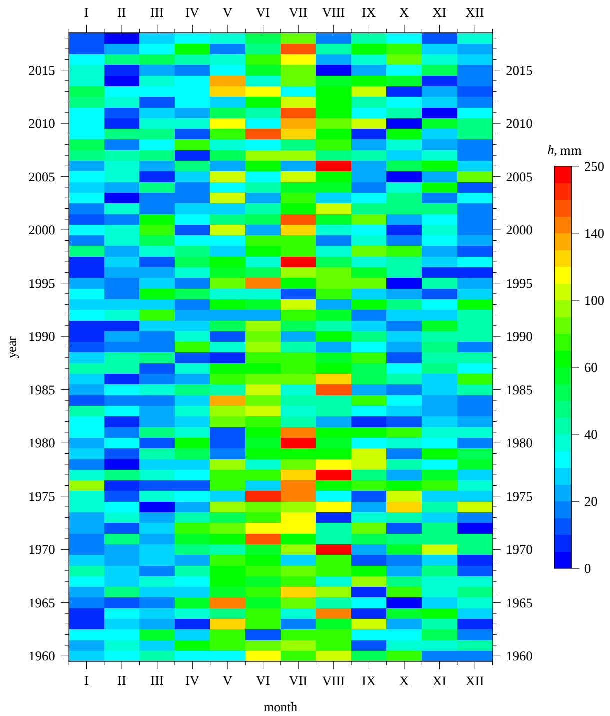

Fig. 1. Monthly sums of rainfall amounts.

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.

IV. A Probabilistic Model of Maximum Rainfall

Since rainfall models should be based on at least 30-year measurement period, and the principal purpose of the work was the forecast of the future rainfall based on observed trends, from the research material, a number of 30, 30-year measurement series were separated: 1960–1989, 1961–1990, …, 1989–2018. In this way, the 30 measurement series were created, which formed the basis for the development of probabilistic models of maximum rainfall.

In the first place the top 30 amount of rainfall was ordered decreasing (in 16 groups of time duration from 5 min to 3 days). Then there were successively assigned to it the empirical probability of exceedance according to (1) from p = 0.03 (for the highest value) to p = 0.97 (for the lowest value):

$$p = \frac{m}{N+1} \tag{1}$$

where m is the sequence number within a decreasing ordered string of the number of N.

Estimators parameters of the generalized exponential distribution were determined by maximum likelihood method (MLM), through a numeric maximizing likelihood function (or its logarithm), taking into account the range of variability of investigated parameters. Quantile of the random variable GED distribution takes the form of the following formula:

$$h = \mu - \frac{1}{\beta}\ln\left(1-(1-p)^{1/\alpha}\right) \tag{2}$$

First, the shape parameter was determined ($\alpha = 0.737$), and then the parameters β and μ were calculated. The exemplary parameters, calculated for the maximum rainfall recorded in Wroclaw in the first multi-year (1960–1989), are summarized in Table II.

TABLE II: THE ESTIMATION RESULTS OF THE GED DISTRIBUTION PARAMETERS FOR MAXIMUM RAINFALL IN WROCLAW IN THE TIMESPAN 1960-1989

t, min	α	β	μ	λ	BIC
5		0.485	6.6	1.27	97.0
10		0.262	8.9	0.60	131.3
15		0.165	10.0	0.98	162.7
30		0.148	13.8	0.60	165.1
45		0.135	14.9	0.52	169.9
60		0.114	15.1	0.65	179.8
90		0.098	16.1	0.81	180.7
120		0.093	17.9	0.68	185.7
180	0.737	0.082	18.9	0.71	201.8
360		0.083	24.2	0.79	202.7
720		0.078	30.8	0.56	205.2
1080		0.083	37.9	0.55	200.1
1440		0.066	40.3	0.58	217.3
2160		0.061	45.3	0.41	219.8
2880		0.056	48.1	0.54	219.5
4320		0.040	50.0	0.83	245.6

The dependence of the β and μ estimators on the precipitation duration, for rainfall recorded in Wroclaw in 1960–1989, is described by equations of the form (3) and (4) and is shown in Fig. 2.

$$\beta = 0.343(t-4.750)^{-0.25} \tag{3}$$

$$\mu = 4.551t^{0.294} \tag{4}$$

The quality of this distribution fit to the empirical distribution of the amount of rainfall in Wroclaw (1960–1989), with different parameters for particular rainfall durations, shown in h–h plot in Fig. 3.

High compliance of the results of calculations obtained with the use of formulated models with the measurement data (for each of the 30 data sets) allowed to consider the developed models as reliable and that could be the basis for generalization of research results.

The applied Mann–Kendall test demonstrated the statistically relevant changes trends of all equations parameters describing the dependency the estimators of scale and location parameters on rainfall duration. As a result, the equations were obtained, which, after placing to GED quantile, allowed to determine the prediction model of maximum precipitation amounts, dependent on: the duration, probability of exceedance and a year, on which the rainfall is calculated.

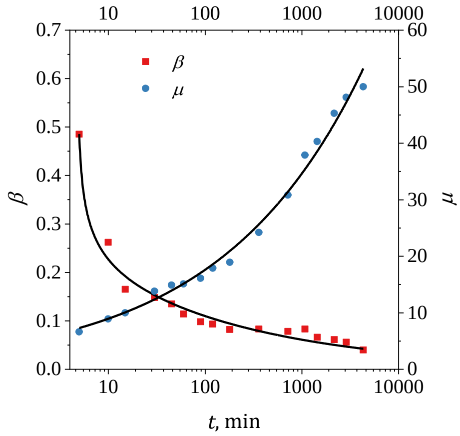

Fig. 2. Dependence of β and μ estimators on the precipitation duration.

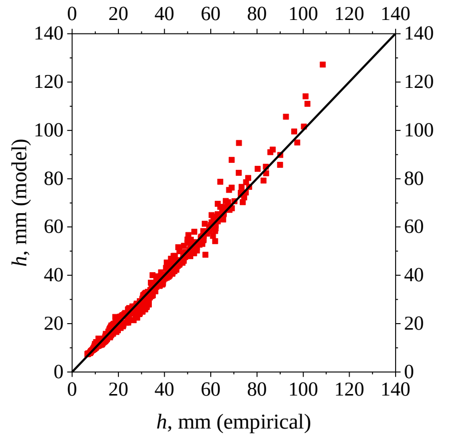

Fig. 3. h–h plot for the GED distribution for measurement data.

V. RESULTS

The examples of maximum precipitation amounts, for characteristic frequencies of occurrence (from $C = 1$ to $C = 50$ years) and 16 analyzed durations (from $t = 5$ to $t = 4320$ min), calculated for 2018 and forecasted for 2050 are presented in Tables III and IV.

TABLE III: MAXIMUM RAINFALL AMOUNTS (H, MM) CALCULATED FOR THE YEAR 2018

t, min	$C = 1$	$C = 2$	$C = 3$	$C = 5$	$C = 10$	$C = 30$	$C = 50$
5	7.8	9.2	10.2	11.5	13.4	16.4	17.8
10	9.5	11.7	13.3	15.4	18.3	23.1	25.3
15	10.7	13.2	15.0	17.5	20.9	26.4	29.0
30	13.0	16.1	18.4	21.4	25.7	32.5	35.7
45	14.5	18.0	20.6	24.0	28.8	36.5	40.0
60	15.8	19.5	22.3	26.0	31.2	39.5	43.3
90	17.7	21.9	25.0	29.1	34.8	44.0	48.4
120	19.2	23.7	27.0	31.5	37.6	47.6	52.2
180	21.5	26.5	30.2	35.1	42.0	53.0	58.2
360	26.1	32.1	36.5	42.4	50.5	63.7	69.9
720	31.7	38.9	44.1	51.1	60.8	76.5	83.9
1080	35.5	43.5	49.3	57.0	67.8	85.2	93.3
1440	38.5	47.0	53.3	61.6	73.2	91.9	100.6
2160	43.2	52.6	59.6	68.7	81.6	102.2	111.9
2880	46.8	57.0	64.4	74.3	88.1	110.3	120.7
4320	52.5	63.7	72.0	82.9	98.1	122.7	134.2

Fig. 4 presents, in the form of contour graph, the rainfall changes (Δh,%) observed so far and forecasted until 2050 for the occurrence frequency from $C = 1$ year and durations from $t = 5$ to $t = 4320$ min.

TABLE IV: MAXIMUM RAINFALL AMOUNTS (H, MM) FORECASTED FOR THE YEAR 2050

t, min	$C = 1$	$C = 2$	$C = 3$	$C = 5$	$C = 10$	$C = 30$	$C = 50$
5	8.6	10.0	11.0	12.4	14.3	17.4	18.8
10	10.3	12.2	13.6	15.5	18.1	22.3	24.3
15	11.4	13.6	15.2	17.4	20.4	25.2	27.5
30	13.6	16.3	18.3	20.9	24.6	30.5	33.3
45	15.0	18.1	20.3	23.2	27.4	34.0	37.1
60	16.2	19.5	21.9	25.0	29.5	36.6	40.0
90	17.9	21.6	24.3	27.8	32.7	40.7	44.4
120	19.3	23.2	26.1	29.9	35.2	43.8	47.8
180	21.4	25.7	28.9	33.2	39.1	48.6	53.0
360	25.6	30.7	34.5	39.6	46.6	57.9	63.2
720	30.5	36.6	41.2	47.2	55.5	69.0	75.3
1080	33.8	40.6	45.6	52.3	61.5	76.5	83.4
1440	36.4	43.7	49.1	56.2	66.2	82.2	89.7
2160	40.3	48.4	54.4	62.3	73.3	91.1	99.4
2880	43.4	52.1	58.5	67.0	78.8	97.9	106.9
4320	48.1	57.7	64.8	74.2	87.3	108.5	118.4

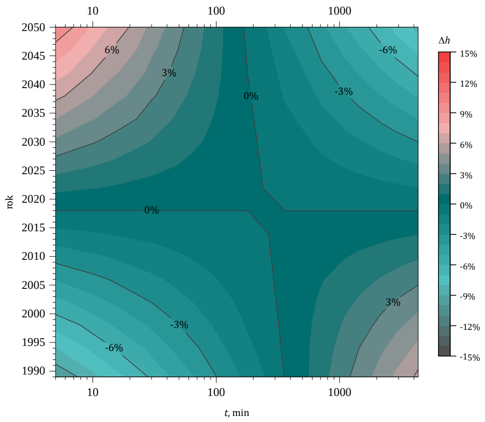

Fig. 4. Changes in precipitation amounts observed so far and forecasted until 2050 (Δh, %) with the occurrence frequency of $C = 1$ year in Wroclaw in years 1960–2018.

For rainfalls with a frequency of occurrence of $C = 1$ year, in the last three decades, i.e. in the years 1989–2018, an increase in the amount of precipitation with durations up to $t = 120$ min and a decrease for longer durations was observed. The largest increases, at the level of 6–10%, were recorded for the most intense rainfall, with durations up to $t = 15$ min. The biggest decreases, at the level of 3–6%, were recorded for rainfalls with a duration exceeding $t = 1080$ min. A further increase in the amount of short-term rainfalls and a decrease in the amount of longer rainfalls are forecasted. The largest increases, at the level above 9% by 2050, are forecasted for rainfalls with a duration of $t = 5$ min. In addition, increases of more than 6% in the same time horizon are forecasted for rainfalls with durations of $t = 10$ and $t = 15$ min. The reverse tendency is foreseen for rainfalls with a duration above $t = 120$ min. The biggest decreases, at the level above 6% by 2050, are forecasted for rainfalls with the duration of one day and longer.

VI. CONCLUSIONS

For rainfalls with a frequency of occurrence of $C = 1$, $C = 2$, $C = 3$ and $C = 5$ years, in the last three decades, i.e. in the years 1989–2018, an increase in the amount of precipitation with durations up to approximately dozens of minutes and a decrease for longer durations. The largest increases, at the level of 6–10%, were recorded for the most intense rainfall (with durations of $t = 5$ min). The biggest decreases, at the level up to 10%, were recorded for rainfalls with a duration exceeding $t = 1080$ min. A further increase in the amount of short-term rainfalls and a decrease in the amount of longer rainfalls are forecasted. The largest increases, at the level above 10% by 2050, are forecasted for rainfalls with a duration of $t = 5$ min. In addition, increases of more than 6% in the same time horizon are forecasted for rainfalls with durations of $t = 10$ and $t = 15$ min. The reverse tendency is foreseen for rainfalls with a duration above $t = 120$ min. The biggest decreases, at the level above 10% by 2050, are forecasted for rainfalls with the duration of one day and longer.

For rainfalls with a frequency of occurrence of $C = 10$, $C = 30$ and $C = 50$ years, in 1989–2018 an increase in rainfall amounts was observed, with durations up to approximately $t = 10$ min and a decrease for longer durations. The largest increases, at the level up to 15%, were recorded for the most intense rainfalls (with durations of $t = 5$ min). The biggest decreases, at the level of 9–13%, were recorded for rainfalls with a duration exceeding $t = 1080$ min. A further increase in the amount of short-term rainfalls and a decrease in the amount of longer rainfalls are forecasted. The largest increases, at the level of 7% by 2050, are forecasted for rainfalls with a duration of $t = 5$ min. The reverse tendency is foreseen for rain-falls with a duration above $t = 10$ min. The biggest decreases, at the level of 9–12% by 2050, are forecasted for rainfalls with the duration of one day and longer.

Formulated in work the prediction model of maximum rainfall amount allows the urban drainage systems designers to take into account, in the design process, the forecasted increase in intensity of short-term rainfall, and therefore meet the requirements of the standard PN-EN 752 regards the acceptable frequency of flooding occurrence from sewage systems – being currently designed, and having to safely operate in perspective of many decades.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

BK: design the study and analyzed the data and worked on the manuscript. KW: contributed the research and co-wrote the paper. All authors had approved the final version.

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