Dear Editor and Referees,

Thank you for the quality of your proofreading and comments; they have greatly improved the manuscript. The methodology and results were adjusted accordingly. Below, we address the points risen by the two anonymous reviewers and state how we would like to address them in a revised version of the manuscript. Our replies to the reviewers' comments are written in black and green and normal font to distinct them from the reviewers' comments.

We believe we have substantially addressed all of the outstanding comments and issues, and we look forward to your second review of the work.

On the behalf of all co-authors,

Yours sincerely,

Bartosz Szeląg

Reviewer #1

Thank you for carefully reading the manuscript and providing constructive suggestions and comments to improve the article. Our answers to question/comment are provided below.

Comment #1

Wording: a lot of terms not common in the literature are used throughout the manuscript, e.g., receiver should be replaced by receiving waters. What do you mean by episode? Is it an event or a period or the event duration? Please be more specific! Movement of air could be replaced by advection. The term forecast is not appropriate in this context. I would replace this term by prediction. There is a lot of confusion regarding the usage of overflow and discharge. You do not predict discharge, only the number of overflow events.

The authors fully agree with the comments made. The text has been amended and supplemented as suggested. Precipitation episodes in the manuscript mean independent precipitation events, which have been separated from long-term rainfall series. As a result, the first sentence in Section 4.1 was modified as follows:
„One of the basic conditions allowing for the completion of a synthetic precipitation generator is the separation of single independent rain events (episodes) in rainfall time series."

Comment #2

Independent validation: Even though the logit model seems to perform very well, it does not become clear how well the model works in my opinion. Is there any chance to add some comparisons with observations in the Figure 9 (at least averages as vertical lines)? Is it possible to perform a split sample test in order to analyze if the model chain provides reliable results for an independent period of time not involved into parameter estimation?
Transferability of the stochastic approach: as already mentioned, for me it remains unclear how the method could be transferred to other urban catchments. You argue that the catchment detention is physically meaningful. I agree in principle but I could imagine that a lot of other catchment characteristics might be relevant too. For instance, what is the impact of the network structure on the results? Even though the detention is tangible, its empirical deviation (Eq.

5 and 6) is rather empirical. Is there any chance to quantify this value with simplified hydrological calculations? This would support your argumentation regarding the transferability and the practical relevance. It might be worth to discuss the added value when compared to long-term simulation using hydrological (and hydrodynamic) models.

Thank you very much for your comments. The change in the order of the contents discussed in the manuscript has a positive influence on the clarity of the considerations. Moreover, a very helpful comment was made concerning the supplementation of the calculation results with simulations with the calibrated hydrodynamic model of the catchment. These calculations were performed and the results were found to be consistent with the results obtained by means of the probabilistic model, which confirms the universal character of the relation given in the paper. The comparison of curves describing the average rainfall intensity limiting the occurrence of storm overflow (Fig. 6) was also valuable from the point of view of model verification; the curves were obtained based on simulation results and measurement data.

Section 4 has been modified. The order of its sections has been changed and in the new layout it is as follows:
4. Methodology
4.1. Simulation of the annual number of storm overflow events using a hydrodynamic model
4.2. Logistic regression
4.3. Separation of the rain event and synthetic rainfall simulator
4.4. Simulator of annual rainfall series
A new Section 4.1 has been introduced in Section 4 entitled "Simulation of the annual number of storm overflow events using a hydrodynamic model". The content of it is as follows:
"One of the possible solutions allowing for the verification of empirical dependencies describing the operation of stormwater systems is the simulation of this operation with the use of a calibrated hydrodynamic model. It is an approach applied in engineering practice, which is confirmed by a number of works in this field (Bacchi et al., 2008; Andrés-Doménech et al., 2010). The simulations performed with a hydrodynamic model based on rainfall data allow the verification of the prediction capabilities of the probabilistic models designed to simulate the quantity and quality of stormwater, and the operation of separate objects located in the stormwater system (tanks, overflows).
Within the framework of the conducted analyses, a calibrated model of the catchment basin made in the SWMM (storm water management model) program was used to verify the annual number of storm overflows (Figure 1). The total area of the analysed catchment is 62 ha, while the area of partial catchments ranges from 0.12 ha to 2.10 ha. The number of stormwater junctions in the catchment area is 200, and the number of stormwater pipes is 72. The retention depth of the imperviousness surfaces of the catchment area is 2.5 mm and the retention depth of the pervious surfaces is 6.0 mm. The roughness coefficient of impervious areas is equal to 0.025 $m^{-1/3}\cdot s$, and that of pervious areas is 0.250 $m^{-1/3}\cdot s$. The roughness coefficient of the stormwater channels is equal to 0.018 $m^{-1/3}\cdot s$.
The results of the simulation with the hydrodynamic model were compared with the results of calculations made with the use of logit models for the data from the examined catchment from the period 2008-2017, which allowed the verification of the determined relation $p = f(x_1, x_2, x_3, ..., x_i)$. Simultaneously, using the measurement data from the period of 1961-2000, a simulation of the annual number of storm overflow events was performed, taking into account the precipitation genesis, which enabled the verification of the developed probabilistic model."

Section 5.1 has also been modified. Indeed, at present, the SENS and SPEC values form the basis for the assessment of the predictive capabilities of the logit model in the majority of studies. Graphical interpretation of the relationship between them is expressed by the AUC value. Therefore, we would like to thank you for your remark, because the curves in Figure 5 are a valuable addition to the results of the calculations and are easy to read when interpreting the results.
Section 5.1 title is now "Logit model and its verification". The following text is included in this section below the logit models description therein:
"The values of the SENS (sensitivity) and SPEC (specificity) coefficients are usually calculated to assess the predictive capability of the models. However, SENS = *f*(SPEC) may also be used for this purpose. In this case, the greater the area value (the maximum value is AUC = 1) between the SENS = SPEC and SENS = *f*(SPEC) curves is, the more accurate the model will be (Figure 5).

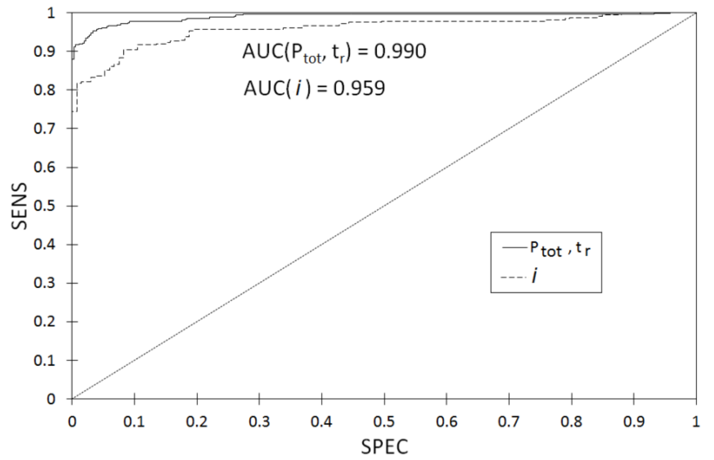

Figure 5: Relation SENS = f(SPEC) for the logit curves $p = f(i)$ and $p = f(P_{tot}, t_r)$

To verify the predictive capabilities of the logit models and their dependencies, a calibrated hydrodynamic model was used. The results of the simulation obtained with the hydrodynamic model for data from the period 2008-2017 were compared with the results of the calculations made with the use of the logit models $p = f(i)$ and $p = f(P_{tot}, t_r)$ (see Table 1).

Table 1: Comparison of the measurements of the annual number of overflow events with the calculations results obtained with hydrodynamic and logit models

Year	Z_a	Z_{SWMM}	$Z_{logit(P,t)}$	$Z_{logit(i)}$
2008	13	15	14	12
2009	15	16	16	14
2010	17	18	19	16
2011	19	20	19	17
2012	13*	21	20/14*	19/11*
2013	13*	22	20/13*	20/11*
2014	16*	29	28/16*	27/14*
2015	25	26	26	23
2016	26	22	21	24
2017	16	17	17	14

* – storm overflow events in the period 2012-2014 determined on the basis of the maximum filling of the diversion chamber (DC). Explanations of symbols are in the Appendix."

In order to assess the convergence of the results of calculations obtained with the use of the probabilistic model with the measurements, the ranges of variability of rain intensity were calculated, which determines the occurrence of storm overflow, taking into account the rainfall genesis. For comparison, Fig. 8b shows the results of calculations (made on the basis of measurement data) of the value of the i parameter that determines a storm overflow. Based on Fig. 8b it can be stated that the results of the calculations obtained with the use of the probabilistic model are satisfactory.

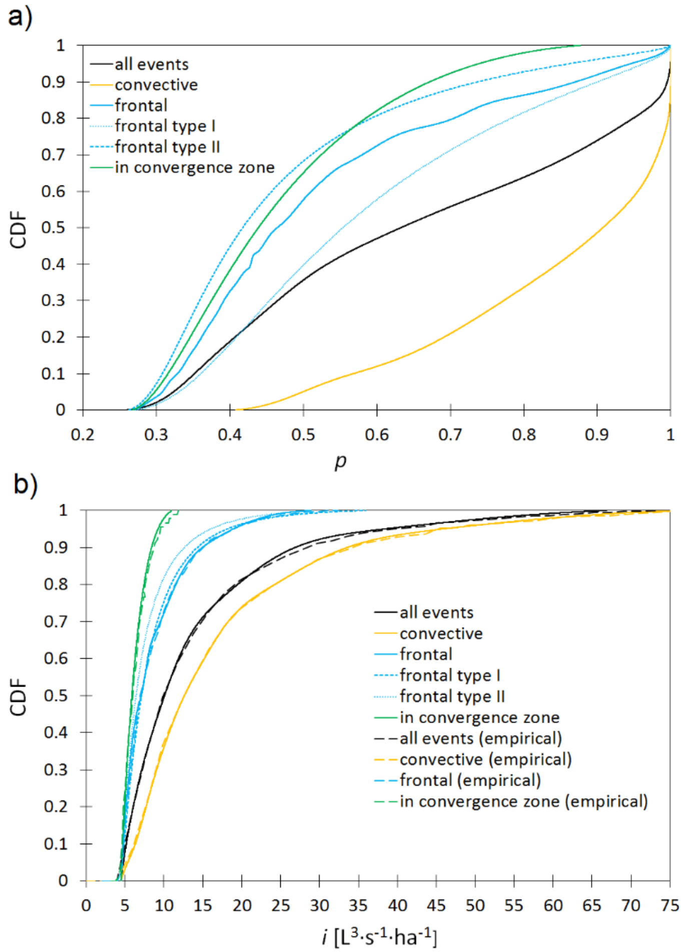

Figure 8: (a) Impact of rainfall genesis on: a) the probability of storm overflow, (b) rainfall intensity distribution determining storm overflow in a single episode.

Referring to Comment #2, the text in Section 5.1 (from P13L12 to P13L23) has also been modified:

"The above relations (3) and (4) are of local character and can be applied in principle only in relation to the analysed catchment area. With this in mind, an attempt was made to build a universal model by modifying these relations. Based on theoretical considerations of Thorndahl and Willems (2008), who investigated the relationships between the characteristics of catchment areas, including the limit retention that determines the volume of overflow, the following equations were determined:

$$0.566\,P_{\mathrm{tot}} - 0.004\,t_{\mathrm{r}} - 2.152 = 0\ /\cdot\frac{1}{0.566} = P_{\mathrm{tot}} - 0.007\,t_{\mathrm{r}} - 3.802 = 0 \quad (5)$$

$$P_{\mathrm{tot}} - 0.007\mathrm{t}_{\mathrm{r}} - 3.802 = P_{\mathrm{tot}} - 0.007t_{\mathrm{r}} - d_{\mathrm{av}} = 0 \quad (6)$$

$$0.312\,i - 1.257 = 0\ /\cdot\frac{1}{0.312} = i - 4.03 = 0 \quad (7)$$

$$i - 4.03 = i - d_{\mathrm{av}} = 0 \quad (8)$$

On the basis of these relationships, it can be concluded that the values of the intercept obtained in them are similar to the weighted average value of the catchment retention (d_{av}). The relative difference between the values of intercept and retention of the catchment area does not exceed 5 %. The simulation calculations of the annual number of overflow events in the tested catchment area confirm the above statement (Table 1). In addition, this fact is supported by the results obtained in Figure 5, which indicate that the results of the simulation of the annual number of overflow events using the hydrodynamic model are within the scope of a probabilistic solution. However, because the presented analyses were performed only for a single catchment, it is necessary to verify the obtained results using examples of other catchments with different physical and geographical characteristics."

Indeed, we agree with the Reviewer that the average retention of a catchment is a not simple parameter to determine. In view of the above, the authors envisage a continuation of the studies which will aim at linking the value of the intercept determined in equations (5) to (8) to the CN curves. However, this requires further analysis, which will continue at a later stage.

Comment #3

I would suggest revising the manuscript. Some things are too detailed (Section 3) or too general (e.g., the discussion on rainfall models that are not used here in Sect. 4.3; I would expect some methodology rather than an introduction to this topic). Sect. 5.2 should be sub-divided in order to increase readability.

Thank you very much for your comments. Of course, the introduction of subsequent sections will significantly improve the readability of the contents discussed in the manuscript.
The contents of Section 3, 4 and 5 have been modified. We consider Section 3 to be an important part of our work in terms of the goals we have set. The article discusses the problem of storm overflows in the urban catchment area, caused by rainfall of different origins. One of the elements of the proposed probabilistic model for modelling the number of storm overflow events is a generator of synthetic rainfall. In order to simulate this model, rainfall events with different genesis had to be taken into account. The conducted analyses allowed to determine the influence of the distribution of the average annual number of precipitation episodes with different genesis of precipitation on the variability of the number of storm overflow events. Therefore, in our opinion, it is important to familiarize the reader with the main processes and mechanisms occurring in the troposphere over central Europe, which are reflected in high precipitation. The presentation of this problem is presented in the introduction to Section 3 of the manuscript. The main characteristics of convective precipitation, frontal precipitation, and rainfall in convergence zone presented in this Section are the result of the exceptional variability of meteorological conditions in this part of the European continent and are therefore presented in a broader context. However, we agree with the Reviewer's comment that the considerations on this subject presented in Section 3 may be shortened and partly moved to the introductory Section of the article.
Therefore, the following changes have been made to the manuscript:
– the title of Section 3 has been changed as follows: "Rainfall data and analysis"
– the previous content presented in the text from P4L8 to P5L17 was modified in the following way and moved to Section 1 (after P3L7):
"Rainfall is universally classified into three types (Sumner, 1988; Smith, 1993): convective, cyclonic and orographic. The main distinguishing feature between convective precipitation in an air mass and frontal precipitation in mid-latitudes is its spatial extent and duration. The range of convective precipitation associated with local air circulation is much smaller than in the case of travelling extratropical cyclones with weather fronts. Convective precipitation induced by single thunderstorm cells, their complexes or squall lines is short-lived but is characterized by high average intensity (Kane et al., 1987) and causes flash floods (Gaume et al., 2009; Marchi et al., 2010; Bryndal, 2015). On the other hand, the lifespan of the mechanisms of creating cyclonic precipitation is much longer than that of convective precipitation – on the order of days rather than hours. Hence, the effect of this is long-term rainfall with a high depth (Frame et al., 2017) often cause regional floods (Barredo, 2007). The presented classification of precipitation types distinguished by Sumner (1988) due to the origin, developed for the British Isles and Western Europe, cannot be directly applied in practical hydrology in other regions of the continent, especially in its eastern and central parts due to exceptional variability of meteorological conditions occurring in the temperate zone of the warm transition climate – on the border of air masses coming from the Atlantic and continental masses from the east (Twardosz and Niedźwiedź, 2001; Niedźwiedź et al., 2009; Twardosz et al., 2011; Łupikasza, 2016). The analysis of maximum rainfall of different duration in Poland carried out at the end of the 1990s (Kupczyk and Suligowski, 1997, 2011), supplemented by an analysis of the synoptic situation (based on surface synoptic charts of Europe, published in the Daily Meteorological Bulletin of the Institute of Meteorology and Water Management – IMGW in Warsaw) and a calendar describing the types of atmospheric circulation together with air masses and air fronts (Niedźwiedź, 2019), led to the separation of three types of genetic precipitation: convective in air mass, frontal and generated in convergence zone."

– also Figure 2 (P6L1) has been removed from Section 3.

The main changes in Section 4 have been discussed earlier. In addition, the following introduction text from the existing Section 4.3 ("Synthetic precipitation generator"), i.e. contained from P10L17 to P10L23, has been moved to the introductory Section (P2L22):

"Multidimensional scaling methods and fractal geometry (Rupp et al., 2009; Licznar et al., 2015; Müller-Thomy and Haberlandt, 2015) are used to simulate rainfall series. An alternative solution is an approach based on the multidimensional distributions created based on theoretical distributions and copula functions (Vandenberghe et al., 2010; Vernieuwe et al., 2015). Despite numerous applications, these solutions are relatively complex and require expert knowledge. For the storm overflow simulation, hydrodynamic models are usually used, and less frequently, empirical models are used (Szeląg et al., 2018). Nevertheless, this approach to the simulation of the annual number of overflows is very local and, in many cases, requires the construction of a catchment model."

In view of the above changes, the text after P9L19 has also been modified as follows:

"Taking into account the computational algorithm described at the beginning of Section 4 (Methodology), based on the determined distributions of the theoretical rainfall characteristics describing the operation of a storm overflow, a model for the simulation of a synthetic rainfall series was adopted for further analysis. The simulations carried out for this purpose included the Monte Carlo method with modification of Iman-Conover (1982). This model provides the possibility simulating the independent variables based on the determined theoretical distributions. In this method, the variability of the considered variables is described by boundary (theoretical) distributions, and the basis for the evaluation of their correlation is the Spearman correlation coefficient. The conditions that must be met in order for the results obtained to be considered correct, are as follows.

– In the data obtained from simulation and measurements, the mean values $(\mu_1(x_1), \mu_2(x_2),...,\mu_i(x_i))_s$ and the standard deviations $(\sigma_1(x_1), \sigma_2(x_2),...,\sigma_i(x_i))_s$ of the variables (x_i) considered in j samples do not differ by more than 5 %.
– The theoretical distributions of x_i variables obtained from simulation should be consistent with those obtained from measurements; in order to meet this condition it is recommended to use the Kolmogorov-Smirnov (KS) test.
– The value of the correlation coefficient (R) between the individual dependent variables (x_i) obtained for the data from Monte Carlo (MC) simulation does not differ by more than 5 % from the value of R obtained for empirical data.

If the above mentioned conditions are met, the results of the simulation performed with the Iman-Conover (IC) method can be considered correct. If these conditions are not met, the sample size of the MC needs to be increased (Wu and Tsang, 2004). To limit the sample size and improve the efficiency of the Iman-Conover (IC) algorithm, a modification has been developed by using the Latin hybercube (LH) algorithm, which is part of the layered sampling methods aimed at improving the "uniformity" of the numbers generated from the boundary distributions.

Based on the determined boundary distributions of rainfall characteristics, the simulations of the synthetic rainfall series were performed with the use of the Monte Carlo (MC) method with Iman-Conover (IC) modifications and taking into account the Latin hybercube (LH) algorithm."

With reference to Section 5.2, the text of it was divided into the following three 4 Sections:

5.2. Identification of the empirical and theoretical distributions of the selected rainfall characteristics

Section 5.2 includes analyses related to the determination of statistical distributions of the following variables: rainfall depth (P_{tot}), rainfall duration (t_r), average rainfall intensity (i), and number of rain events in a year of varied genesis.

Section 5.2 in the manuscript contains the text from P13L24 to P17L5 (in original manuscript).

5.3. Impact of rainfall genesis on the probability of storm overflow occurrence

Section 5.3 presents the determined relationship between the genesis of rainfall and the probability of overflow event, as well as the ranges of variation of average rainfall intensity, taking into account the rainfall genesis, which determines the occurrence of storm overflow event.

Section 5.3 in the manuscript contains the text from P17L6 to P17L27 (in original manuscript).

5.4. Impact of rainfall genesis on the average rainfall intensity occurrence of a storm overflow

Section 5.4 presents the results of calculations of the impact of rainfall genesis on the rainfall intensity limit values determining the occurrence of storm overflow. Section 5.4 covers the text from P18L3 to P18L27.

5.5. Impact of rainfall genesis on the annual number of overflow events

Section 5.5 presents the annual number of overflow events caused by rainfall (convective, frontal, and in convergence zone). At the same time, a comparative analysis of the annual number of overflow events obtained with a simplified logit model (based on the average rainfall intensity) and the number of overflow events obtained with an accurate model (based on the total rainfall and its duration) is carried out in this Section.

Section 5.5 in the manuscript contains the text from P18L28 to P20L16 (in original manuscript).

The text in P18L30 has been modified as follows:

"The simulation calculations performed with the calibrated hydrodynamic model of the catchment area show that the results of the simulation of the annual number of storm overflow events (Figure 9d) caused by precipitation of different genesis are within the scope of the solution obtained with the probabilistic model. This finding confirms that the probabilistic model developed in the paper is an alternative solution to the hydrodynamic model. This fact is also confirmed by the annual number of overflow events caused by rainfall of different genesis obtained on the basis of measurements (Figure 9d). The conformity of the simulation results obtained with the probabilistic and hydrodynamic model may indicate that the values of the intercept determined in the relevant equations may correspond to the depth of the weighted average retention of the catchment area."

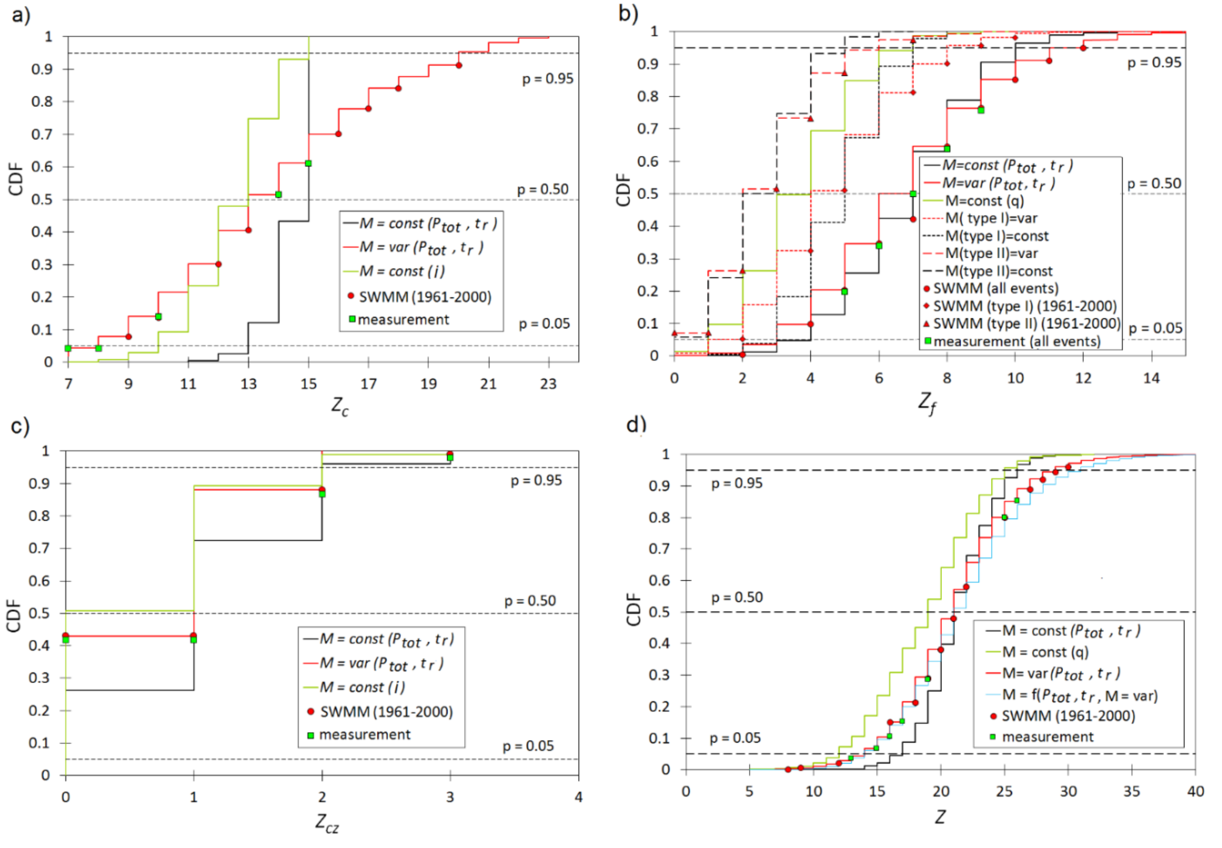

Figure 9: Distribution function (CDF) showing the annual number of storm overflow events (*Z*) caused by: (a) convective rainfall, (b) frontal rainfall, (c) rainfall in convergence zone*;* (d) Curve showing the probability of non-exceeding the annual number of overflows *(Z).* Explanations of the other symbols are in the Appendix.

Specific comments:
P2L5; National guidelines?

Indeed, the quoted guidelines are foreign. The paper also takes into account national Polish guidelines in the form of the Regulation of the Minister of the Environment of 18 November 2014 on the conditions to be met when discharging sewage into water or soil and on the substances particularly harmful to the aquatic environment.

P3L18; I would suggest adding some more details on the catchment area (e.g. dryweather flow).

The characteristics of the catchment area have been extended. In item P3L24 of the manuscript the following additional information has been added:
"The analysis of the measurement data (2008-2017) concerning the analysed catchment area showed that the antecedent period lasted 0.16–60 days, and storms occurred 27–47 times a year. The average annual air temperature during the period under consideration varied from 8.1 to 9.6 °C. In addition, the analysis of the measurement data of flows recorded with the MES1 flow meter showed that in the antecedent periods, the temporary stream of the stormwater was from 0.001 to 0.009 $m^3 \cdot s^{-1}$, which indicates the occurrence of infiltration in the stormwater system under study."

Figure 4: When I read the paper for the first time, my first idea was that you compare genesis of rainfall vs. not distinguishing the genesis as shown in Figure 4. In Figure 9, however, you mainly compare the average number of events vs. a modelled number of events (including the comparison genesis vs. generalization of events?)

Thank you kindly for your valuable remark.
Taking as a starting point the diagram of the algorithm in Fig. 4 (P8L8), two approaches to the simulation of the annual number of overflow events were analysed. In the first one the genesis of rainfall M = const(P_{tot}, t_{r}) or M = const(i) (Fig. 9) was omitted. In the second approach the developed rainfall generator (Fig. 5), described in Section 4.4 ("Simulator of synthetic annual rainfall series"), was used and the results obtained are shown in Fig. 9d in the form of M = var(P_{tot}, t_{r}) curve. The additional dependencies showed in Fig. 9a, 9b, 9c are a detailed description of the results of the simulation analyses and illustrate the annual number of overflow events caused by rainfall of various origins (convective, frontal, in convergence zone).
Taking into account the valuable suggestion of the Reviewer, the appendix contains a list of symbols used in the manuscript. Indeed, in the original version of the manuscript, this may lead to confusion. The corrected manuscript therefore contains the following table of symbols and abbreviations (Appendix):

Appendix 1. List of symbols and abbreviations

AUC	area under curve
CDF	cumulative distribution function of probability density
Chi	chi-square test
DC	diversion chamber
d_{av}	weighted mean of the retention depth of the catchment area
$f(x)$	probability density function
$F(x)_{\mathrm{c}}$	theoretical distribution to simulate rainfall characteristics due to convective rainfall
$F(x)_{\mathrm{f}}$	theoretical distribution to simulate rainfall characteristics due to frontal rainfall
$F(x)_{\mathrm{cz}}$	theoretical distribution to simulate rainfall characteristics due to rainfall in the convergence zone
$F(\zeta)_{\mathrm{c}}$	theoretical distribution to simulate the annual number of convective rainfall events
$F(\zeta)_{\mathrm{f}}$	theoretical distribution to simulate the annual number of frontal rainfall events

$F(\zeta)_{cz}$	theoretical distribution to simulate the annual number of rainfall events in the convergence zone
FORM	first-order reliability model
i	average rainfall intensity; 166.7 P_{tot} /t_r [$L \cdot s^{-1} \cdot ha^{-1}$]
IC	Iman-Conover method
K	number of samples modelled using the Monte Carlo method of annual rainfall series
KS	Kolmogorov-Smirnov test
LH	Latin-hypercube method
M	annual number of rainfall events
$M = const(i)$	calculation variant (annual number of overflow events), in which for simulation constant average annual number of rainfall events is used and to identify the overflow in a rainfall episode the following logit models were applied logit model $p = f(i)$
$M = const(P_{tot}, t_r)$	calculation variant (annual number of overflow events), in which for the simulation, the constant average annual number of rainfall events is used, and for identifying the overflow in a rainfall episode, the following logit models were applied: logit model $p = f(P_{tot}, t_r)$
$M = var(i)$	calculation variant (annual number of overflow events), in which the annual number of rainfall events caused by precipitation (convective, frontal, and in the convergence zone) is modelled, and for identification of overflow in a rainfall episode, the following logit models were applied: logit model $p = f(i)$
$M = var(P_{tot}, t_r)$	calculation variant (annual number of overflow events), in which the annual number of rainfall events caused by precipitation (convective, frontal, and in the convergence zone) is modelled, and for identification of overflow in a rainfall episode, the following logit models were applied: logit model $p = f(P_{tot}, t_r)$
M_c	annual number of convective rainfall events
M_f	annual number of frontal rainfall events
M_{cz}	annual number of rainfall events in the convergence zone
MC	Monte Carlo simulation
MES1, MES2	flowmeter measures
MLE	maximum likelihood estimation
N	number of samples in the Monte Carlo simulation
OV	storm overflow
p	probability of a storm overflow event
P_{tot}	total rainfall [mm]
t_r	rainfall duration [min]
R	Spearman's correlation coefficient
R_z^2	counting error
SENS	sensitivity
SPEC	specificity
STP	stormwater treatment plant
SWMM	Stormwater Management Model
Z	annual number of storm overflow events

Z_c	annual number of storm overflow events due to convective rainfall
Z_f	annual number of storm overflow events due to frontal rainfall
Z_{cz}	annual number of storm overflow events due to rainfall in the convergence zone
x_i	independent variables included in the logit model
α_i	values of estimated coefficients in the logit model
$\alpha, \beta, \gamma, \lambda, \mu, \sigma, \zeta$	empirical coefficients estimated in statistical distributions
$(\mu_1(x_1),..., \mu_i(x_i))_s$	mean value of variable x_i in the data set obtained from simulation using the Iman-Conover method
$(\sigma_1(x_1),..., \sigma_i(x_i))_s$	value of standard deviation of variable x_i in the data set obtained from simulation using the Iman-Conover method

P5L9; The discussion on an "increase in the roughness of the substrate" is awkward in my opinion and not correct. Is this discussion really needed here? I would suggest rephrasing this section in a way that makes the explanations more concise, given the topic of the paper.

Thank you for the valuable comment and signalling that one of the reasons given for the variability in the frequency, intensity and duration of rainfall associated with weather fronts in Central Europe was unclear and awkward. The discussion on this issue was omitted, as mentioned above (in response to Comment #3). The existing content presented from P4L8 to P5L17 was modified and moved to Section 1.

P17L4; This statement remains unclear to me. Please be more precise! Why do you abandon this approach? I found this explanation confusing. I thought that M was modelled or even assumed to be constant? How is this related to your argumentation?

Thank you very much for your remark. It turned out to be very useful in the improvement of substantive assessments resulting from simulations and thus in the improvement of the conclusions formulated. Indeed, the aim of the study was to compare the results of calculations of the annual number of storm overflows, taking into account the simplifications associated with omitting or including rainfall genesis in the analyses. Currently, in section 4.4 ("Simulator of annual synthetic rainfall series") the calculation variants considered in the paper are discussed. In the paper finally calculations for all considered simulation variants were made. The variant in which the changing number of rain events in the year $M = f(P_{\mathrm{tot}}, t_{\mathrm{r}}, M = var)$ was taken into account was also analysed. The results obtained for this case may have a great practical significance in the methodology of designing storm overflows. The results of the simulation showed that omitting the precipitation genesis and taking into account only the variability of the annual number of precipitation events, i.e. variant $M = f(P_{\mathrm{tot}}, t_{\mathrm{r}}, M = var)$, results in overestimation of the annual number of storm overflows. Thus, in engineering practice, it means that the height of the overflow edge (level) is inflated, which results in hydraulic overload (e.g. of a rainwater treatment plant).
In the corrected manuscript, items P17L4 and P17L5 were removed.

P18L31; I don't think that there is any exact model. Please rephrase

Thank you for your comments. The term "exact model" has been replaced by the term "model that takes into account the genesis of rainfall".

P2L19; Do you mean Thornsal and Willams (2008)?

The order of names has been changed: 'Willems and Thorndahl (2008) is now replaced by "Thorndahl and Willems (2008)'.

P11L3; What is IC? Iman-Conover?

Indeed, IC is the abbreviation for the Iman-Conover method.

P3L2; Consider dropping knowledge.

The word “knowledge” has been removed from the text.

Reviewer #2

We thank the reviewer for the effort and the time spend on this manuscript.
Thank you very much for putting forward very concrete proposals for improving it. The article after the correction was checked by a specialist in hydrology and mathematical modelling in urban drainage basins.

Below we present detailed responses to the following comments.

Comment #1
The authors have used some variables. It would be useful to add a table with the most important variables, their meaning and unit.

At the end of the paper (in Appendix) there is a table with a list of all used symbols and abbreviations.

Appendix 1. List of symbols and abbreviations

AUC	area under curve
CDF	cumulative distribution function of probability density
Chi	chi-square test
DC	diversion chamber
d_{av}	weighted mean of the retention depth of the catchment area
$f(x)$	probability density function
$F(x)_c$	theoretical distribution to simulate rainfall characteristics due to convective rainfall
$F(x)_f$	theoretical distribution to simulate rainfall characteristics due to frontal rainfall
$F(x)_{cz}$	theoretical distribution to simulate rainfall characteristics due to rainfall in the convergence zone
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$F(\zeta)_f$	theoretical distribution to simulate the annual number of frontal rainfall events
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M	annual number of rainfall events
$M = const(i)$	calculation variant (annual number of overflow events), in which for simulation constant average annual number of rainfall events is used and to identify the overflow in a rainfall episode the following logit models were applied logit model $p = f(i)$
$M = const(P_{tot}, t_r)$	calculation variant (annual number of overflow events), in which for the simulation, the constant average annual number of rainfall events is used, and for identifying the overflow in a rainfall episode, the following logit models were applied: logit model $p = f(P_{tot}, t_r)$
$M = var(i)$	calculation variant (annual number of overflow events), in which the annual number of rainfall events caused by precipitation (convective, frontal, and in the convergence zone)

	is modelled, and for identification of overflow in a rainfall episode, the following logit models were applied: logit model $p = f(i)$
$M = var(P_{\mathrm{tot}}, t_{\mathrm{r}})$	calculation variant (annual number of overflow events), in which the annual number of rainfall events caused by precipitation (convective, frontal, and in the convergence zone) is modelled, and for identification of overflow in a rainfall episode, the following logit models were applied: logit model $p = f(P_{\mathrm{tot}}, t_{\mathrm{r}})$
M_c	annual number of convective rainfall events
M_f	annual number of frontal rainfall events
M_{cz}	annual number of rainfall events in the convergence zone
MC	Monte Carlo simulation
MES1, MES2	flowmeter measures
MLE	maximum likelihood estimation
N	number of samples in the Monte Carlo simulation
OV	storm overflow
p	probability of a storm overflow event
P_{tot}	total rainfall [mm]
t_{r}	rainfall duration [min]
R	Spearman's correlation coefficient
R_z^2	counting error
SENS	sensitivity
SPEC	specificity
STP	stormwater treatment plant
SWMM	Stormwater Management Model
Z	annual number of storm overflow events
Z_c	annual number of storm overflow events due to convective rainfall
Z_f	annual number of storm overflow events due to frontal rainfall
Z_{cz}	annual number of storm overflow events due to rainfall in the convergence zone
x_i	independent variables included in the logit model
α_i	values of estimated coefficients in the logit model
$\alpha, \beta, \gamma, \lambda, \mu, \sigma, \zeta$	empirical coefficients estimated in statistical distributions
$(\mu_1(x_1),..., \mu_i(x_i))_s$	mean value of variable x_{i} in the data set obtained from simulation using the Iman-Conover method
$(\sigma_1(x_1),..., \sigma_i(x_i))_s$	value of standard deviation of variable x_{i} in the data set obtained from simulation using the Iman-Conover method

The following sentence (P10L28):
,,in the data obtained from simulation and measurements, the mean values $(\mu_1(x_1), \mu_2(x_2),...,\mu_i(x_i))_s$ and the standard deviations $(\sigma_1(x_1), \sigma_2(x_2),...,\sigma_i(x_i))_s$ of the variables (x_i) considered in j samples do not differ by more than 5 %"
has been modified as follows:
,, in the data obtained from simulation and measurements, the mean values $(\mu_1(x_1), \mu_2(x_2),...,\mu_i(x_i))_s$ and the standard deviations $(\sigma_1(x_1), \sigma_2(x_2),...,\sigma_i(x_i))_s$ of the variables (x_i) considered in j samples do not differ by more than 5 %."

Comment #2

In line 9-11 Ptot and tr are mentioned, but defined later in line 9-29. There it would be better to write q = Ptot / tr = 166.7 . . .

The reviewer knows q as specific discharge ore runoff rate, but not as rain intensity. In English parers for rain intensity stands often I or i (sometimes PI for precipitation intensity).

The following text (P9L11):
„In order to obtain the best possible matching of theoretical data (precipitation characteristics including P_{tot} and t_r values for precipitation of appropriate genesis) with empirical data, the following statistical distributions were considered …"
has been modified as follows:
„To obtain the best possible fit of the theoretical data to the empirical precipitation data (including: rainfall depth – P_{tot}, rainfall duration – t_r and average rainfall intensity – i, for precipitation of appropriate genesis), the following statistical distributions were considered …"

The designations in Figures 8 and 9 below have thus been changed:

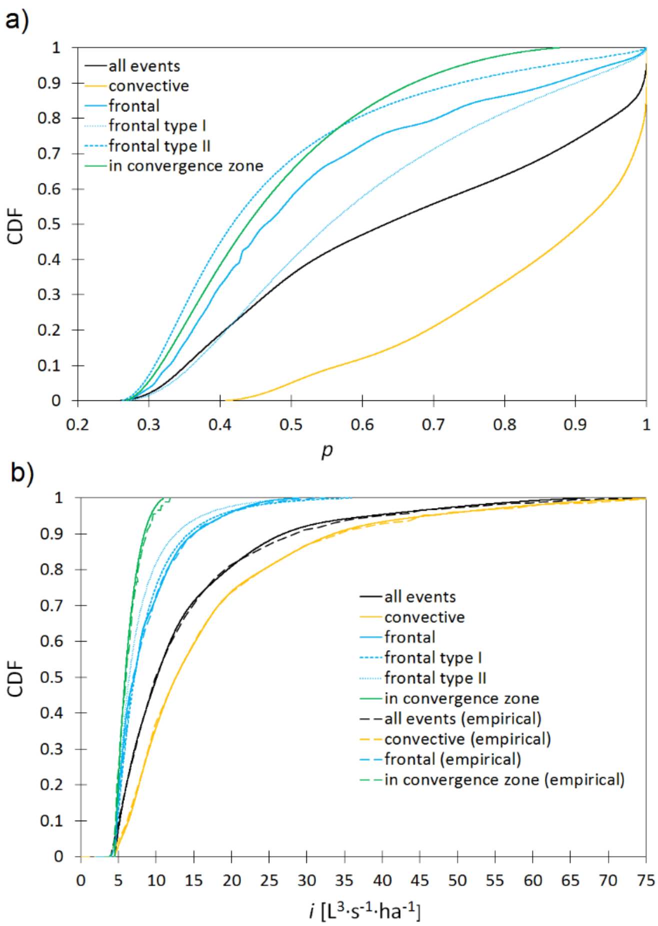

Figure 8: (a) Impact of rainfall genesis on: a) the probability of storm overflow, (b) rainfall intensity distribution determining storm overflow in a single episode.

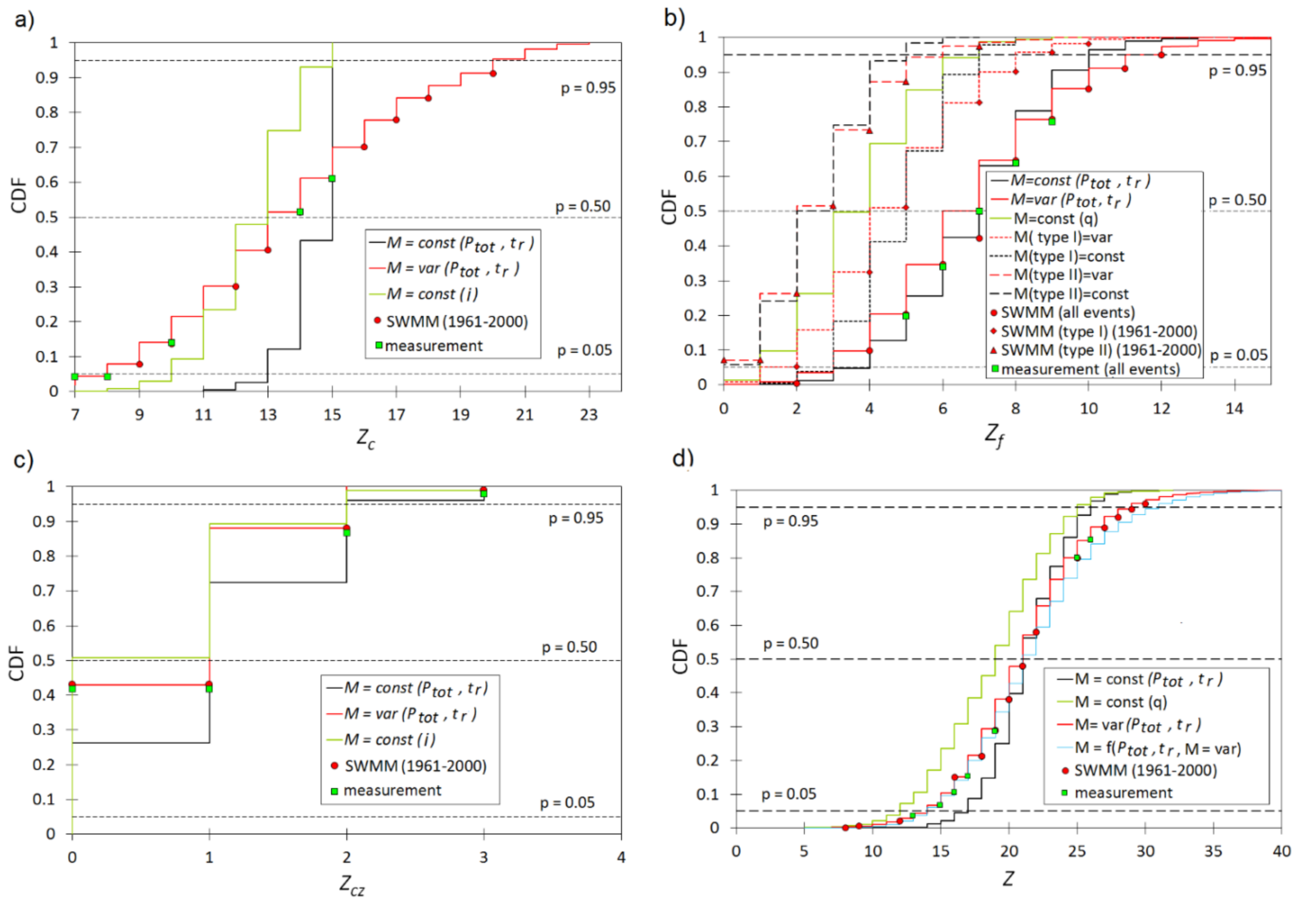

Figure 9: Distribution function (CDF) showing the annual number of storm overflow events (*Z*) caused by: (a) convective rainfall, (b) frontal rainfall, (c) rainfall in convergence zone; (d) Curve showing the probability of non-exceeding the annual number of overflows *(Z)*. Explanations of the other symbols are in the Appendix.

In view of the modification of the designations in Figures 8 and 9, further following corrections have been made:
- P13L27; text „(P_{tot}, t_r, q, M)" has been modified as follows: „(P_{tot}, t_r, i, M)"
- P18L18; text „q = 4.49–35.50 L s^{-1} ha^{-1}" has been modified as follows: „i = 4.49–35.50 L·s^{-1}·ha^{-1}"
- P18L22; text „it corresponds to q = 4.49–35.50 L·s^{-1}·ha^{-1}" has been modified as follows: „it corresponds to i = 4.49–35.50 L·s^{-1}·ha^{-1}"
- P18L27; text „q > 4.86 L s^{-1} ha^{-1}" has been modified as follows: „i > 4.86 L·s^{-1}·ha^{-1}"

Comment #3

In table 1 and figure 8 the terms "frontal, type I" and frontal, type II" are used, but they are defined first in line 18-2. Why do the authors not use the terms "cold front" and "warm front"? In table 1 the symbol M is used, but nowhere declared.

Table 1 (P14L3) is supplemented by additional explanatory notes: frontal type I – cold front, frontal type II – warm front (see answer to Comment #5).
In response #1 there are descriptions of symbols included in the work.

Comment #4

In line 7-25 CDF's "describe the probability of exceeding the flow number of storm overflow discharges." But in the paper CDF is used generally, as customary. On the contrary in picture 8b) CDF is the distribution of the rain intensity. Beside "exceeding" seems to be not correct, since CDF's represent the probability of undershooting!

Of course, we agree with the reviewer. We have corrected the use of the CDF term in the text.

Comment #5

Table 1: The sequential arrangement of the variables is not perfect. The order could be all P_{tot}, t_r , q, and M ore all annual values, convective frontal . ..

Table 1 has been modified (in accordance with the remark above) to the following form:

Variable	Distribution	Model parameters	*p* (KS)	*p* (Chi)
P_{tot} (all events)	Weibull	$\beta = 0.772$; $\gamma = 5.158$; $\mu = 3.00$	0.121	0.096
t_r (all events)	GEV	$\zeta = 0.466$; $\sigma = 129.355$; $\mu = 108$	0.096	0.071
i (all events)	log-normal	$\sigma = 1.932$; $\mu = 0.855$	0.112	0.096
M (all events)	Poisson	$\lambda = 32.80$	0.624	0.053
P_{tot} (convective)	Weibull	$\beta = 0.821$; $\gamma = 3.102$; $\mu = 3.00$	0.477	0.412
t_r (convective)	beta	$\alpha = 1.391$; $\beta = 1.173$; $c =5.5$; $d = 150$	0.268	0.173
i (convective)	log-normal	$\sigma = 2.557$; $\mu = 0.694$	0.238	0.211
M (convective)	Poisson	$\lambda = 14.33$	0.871	0.756
P_{tot} (frontal)	Weibull	$\beta = 0.968$; $\gamma = 6.054$; $\mu = 3.00$	0.353	0.314
t_r (frontal)	Weibull	$\beta = 1.201$; $\gamma = 164.99$; $\mu = 150$	0.639	0.589
i (frontal)	log-normal	$\sigma = 1.485$; $\mu = 0.644$	0.906	0.878
M (frontal)	Poisson	$\lambda = 15.95$	0.372	0.831
P_{tot} (frontal, type I)	Weibull	$\beta = 0.862$; $\gamma = 4.535$; $\mu = 3.00$	0.631	0.425
t_r (frontal, type I)	beta	$\alpha = 1.221$; $\beta = 1.372$; $c =150$; $d = 270$	0.200	0.145
i (frontal, type I)	log-normal	$\sigma = 1.701$; $\mu = 0.612$	0.104	0.085
P_{tot} (frontal, type II)	Weibull	$\beta = 1.065$; $\gamma = 7.222$; $\mu = 3.00$	0.397	0.342
t_r (frontal, type II)	beta	$\alpha = 0.829$; $\beta = 1.562$; $c = 266$; $d = 650$	0.270	0.226
i (frontal, type II)	log-normal	$\sigma = 1.289$; $\mu = 0.611$	0.059	0.056
P_{tot} (in convergence zone)	log-normal	$\sigma = 0.603$; $\mu = 3.00$	0.969	0.856
t_r (in convergence zone)	Weibull	$\beta = 0.802$; $\gamma = 276.138$; $\mu = 650$	0.947	0.879
i (in convergence zone)	log-normal	$\sigma = 1.296$; $\mu = 0.497$	0.942	0.923
M (in convergence zone)	Poisson	$\lambda = 2.55$	0.067	0.652

where: type I – cold front, type II – warm front.

Comment #6

Figures: Partly the units and symbols are missed. The caption of figures should be understandable and clear enough without reading the text. Figure 6 and 7: It would be favourable, if the both axes would have the same range. Not every reader is experienced in such analysis. One sentence or two sentences would be useful to explain, what the background of such pictures is. Instead of "Observed Value" (y-axis) it is recommended to write "Empirical Quantile".

The caption could be: “Comparison of empirical and theoretical quantiles concerning the number of rainfall episodes and distinguishing rainfall types”

In Figures 6 and 7 (P15L14-P16) the descriptions of X and Y axes have been modified in accordance with the drawings below.
The X axis is described as:
- theoretical quantile (P_{tot}),
- theoretical quantile (t_r),
- theoretical quantile (i),
- theoretical quantile (M),
The Y-axis is described as:
- empirical quantile (P_{tot}),
- empirical quantile (t_r),
- empirical quantile (i),
- empirical quantile (M)

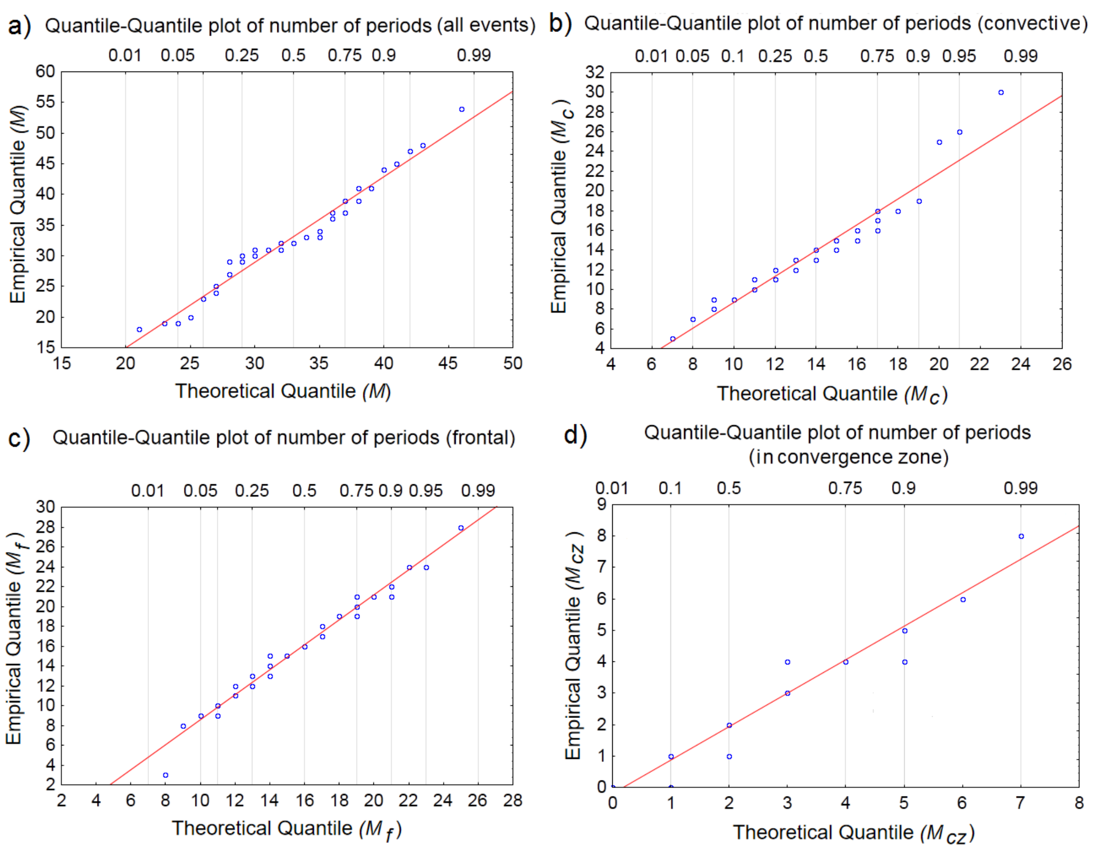

Figure 6: Comparison of empirical and theoretical quantiles concerning the number of rainfall episodes and distinguishing rainfall types: (a) all events (b) convective, (c) frontal, (d) in convergence zone.

The title of Figure 6 has been corrected according to the reviewer's remark.

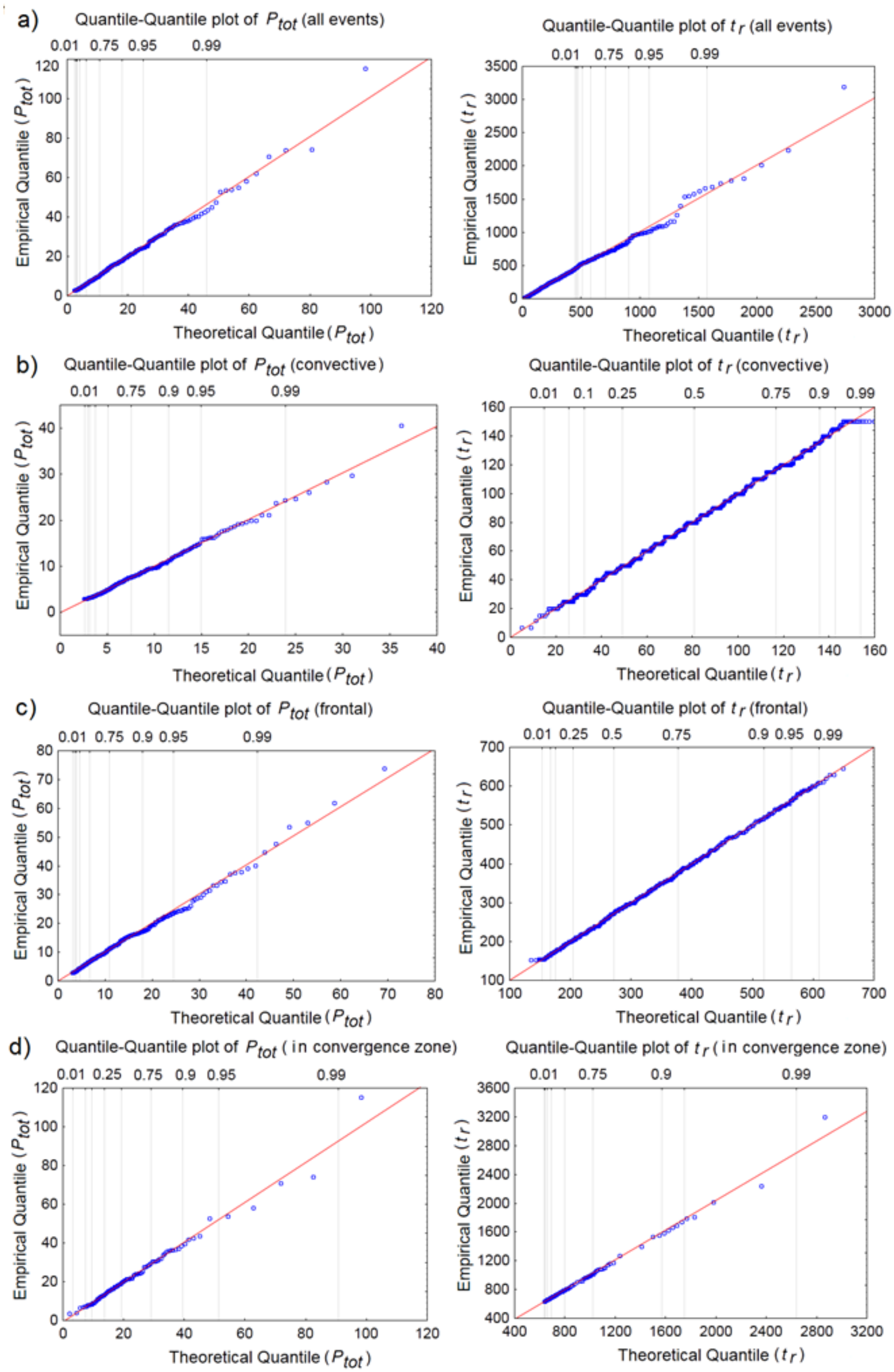

Figure 7: Comparison of empirical and theoretical quantiles concerning P_{tot} and t_r values for: (a) all events, (b) convective, (c) frontal, and (d) rainfall in convergence zone.

It is possible, but unreasonable, to perform Figure 6 in such a way as to maintain an identical range of variation in the annual number of rainfall events of different genesis. This is due to the large variation in the independent variable. Identically, this issue relates to the rainfall depth and its duration.

Comment #7

Figure 6: Is it right, that the sum of the highest values of b), c) and d) = 55 should be equal to the highest value of a)?

Thank you for your valuable insight. The maximum values for the number of rainfall events caused by convective, frontal, and rainfall in convergence zone were recorded for the same year. This means that the sum does not have to be 55, but it may be less, as was obtained in the case under consideration.

Comment #8

Figure 8 (a): p is the probability of overflow discharge. But for wich variable stands CDF here? The reviewer has not found any remarks. Therefore he don't understand in line 18-5 why "the percentiel value p = 0,50 is as high as 0,90"? It looks like that the CDF-value 0,50 is as high as 0,90? But what means CDF here?

Indeed, the markings introduced are misleading. The CDF value means the probability of non-exceedance the probability of stormwater overflow by a storm overflow in a rainfall episode. Thus, further modifications have been made to the manuscript:
- P18L5 now: „percentile value p= 0.50" after modification: „percentile value 0.50"
- P19L9 now: „for example, for p= 0.05" after modification: „for example, for the percentile value 0.05"
- P19L10 now: „for the percentile value p= 0.95" after modification: „for the percentile value 0.95"
- P20L4 now: „The influence of the theoretical distribution of the number of rainfall events per year on the values of 0.99 > p > 0.50 is confirmed by Szeląg et al. (2018)" after modification: „The influence of the theoretical distribution of the number of rainfall events per year on the values of percentiles 0.50–0.99 is confirmed by Szeląg et al. (2018)."

Comment #9

Line 1-15: The Model is innovative, formulate more clear, what the reasons are

The following manuscript text (P1L15): „This paper proposes an innovative probabilistic model to simulate the number of storm overflow discharges, which takes into atmospheric circulation and related rainfall in the research area (the city of Kielce located in the central part of Poland)."
has been modified to the following form:
„The paper presents a probabilistic model for simulating the annual number of storm overflows. In this model, an innovative solution is to use the logistic regression method to analyse the impact of rainfall genesis on the functioning of a storm overflow in the example of a catchment located in the city of Kielce (central Poland)."

In addition, the following manuscript text (P2L2): „They can be used to develop warning systems, in which information on the predicted rainfall genesis is a component of the assessment of the operation of the stormwater system and the facilities located on it."
has been expanded by the sentence:
„This approach is an original solution that has not yet been considered by other researchers. On the other hand, it represents an important simplification and an opportunity to reduce the amount of data to be measured."

Comment #10

Line 1-24 and 7-21: The generator should be mentioned as first element.

The text (P1L18) in the manuscript: „ The first element is the model of logistic regression, which can be used to model storm overflow discharge resulting from the occurrence of a single rainfall episode. The paper confirmed that storm overflow

discharge can be modeled on the basis of data on the total amount of rainfall and its duration. An alternative approach was also proposed, in which the possibility of forecasting overflow discharge only on the basis of the average rainfall intensity was demonstrated, which is a big simplification in simulation of the phenomenon under study in comparison with the works published so far in this scope. It is worth noting that the coefficients determined in logit models have a physical interpretation and these models have a universal character, which is why they can be easily adapted to other examined catchment areas. The second element of the model is a synthetic precipitation generator, in which the simulation of rainfall takes into account its genesis resulting from various processes and phenomena taking place in the troposphere. This approach makes it possible to take into account the stochastic nature of rainfall also in relation to the annual number of events"
has been modified as follows (P1L18):
,,The first element of the model is a synthetic precipitation generator, in which the simulation of rainfall takes into account its genesis resulting from various processes and phenomena occurring in the troposphere. This approach makes it possible to account for the stochastic nature of rainfall in relation to the annual number of events. The second element is the model of logistic regression, which can be used to model the storm overflow resulting from the occurrence of a single rainfall episode. The paper confirmed that storm overflow can be modelled based on data on the total rainfall and its duration. An alternative approach was also proposed, providing the possibility of predicting storm overflow only based on the average rainfall intensity. Substantial simplification in the simulation of the phenomenon under study was achieved compared with the works published in this area to date. It is worth noting that the coefficients determined in the logit models have a physical interpretation, and the universal character of these models, facilitates their easy adaptation to other examined catchment areas."

The text (P7L21) in the manuscript: ,,The first component is a logit model, which is used to simulate the occurrence of a storm overflow discharge. Another component are synthetic precipitation generators, which are realized in two variants. In the first variant it was assumed that the basis for the simulation of rainfall series is their genesis. In the second variant precipitation is forecasted regardless of its origin – in the annual cycle."
has also been modified as follows:
,,The first components are synthetic precipitation generators, which are realized in two variants. In the first variant it was assumed that the basis for the simulation of rainfall series is their genesis. In the second variant, precipitation is predicted regardless of its origin – in the annual cycle. Another component is a logit model, which is used to simulate the occurrence of a storm overflow. The third component of the model is a calculation block, in which the annual number of overflows is simulated for the generated rainfall series. On this basis, distribution functions (CDF) are determined that describe the probability of non-exceeding the number of storm overflows."

Comment #11

Line 2-14: write "such discharges". Mostly the words "overflow discharge" are used, but in some further cases only the word "discharge" (for example 8-4 and 18-29), while "overflow discharge" is meant. Please check such cases.

The vocabulary was modified in the paper. Expression ,,overflow discharge" has been replaced by ,,storm overflow", and the expression ,,annual number of overflow discharges" has been replaced by ,,annual number of overflows".

Comment #12

Line 5-22: write better "It concerns events with high intensity and short duration.

The following manuscript text (P5L22): ,,These data were taken into account in the conducted analyses, as the launch of a new device, the SEBA electronic rain gauge (tipping-bucket SEBA rain gauge), a few years later in the state measuring network, resulted in the recording of significantly lower precipitation levels (by several percent) high intensity and short-lived, compared to measurements recorded by a traditional pluviograph (Kotowski et al., 2011)"
has been modified as follows:
,,Only these data were taken into account in the conducted analyses, as the launch of a new device, the SEBA electronic rain gauge (tipping-bucket SEBA rain gauge), a few years later in the state measuring network resulted in the recording of significantly lower precipitation levels (by several percent). The data concerns events with high intensity and short duration (Kotowski et al., 2011)."

Comment #13

Lines 7-7 to 7-11: this paragraph seems to be a repeat.

Based on this Comment, the following manuscript text (P7L7 to P7L11): ,,Within the conducted analyses, an innovative probabilistic model was proposed for forecasting the number of storm overflow discharges (Figure 4). This model allows for the forecast of the annual number of discharges and the simulation of the number of events per year, taking into account the genesis of rainfall (convective in air mass, frontal, convergence zones precipitation), which is typical for countries located in central Europe and other regions of world. Although the paper focuses on the genesis of rainfall developed by Kupczyk and Suligowski (1997, 2011), the proposed approach is universal. The distribution of rainfall data may be based on local conditions determining the movement of air masses, which has a key impact on the dynamics of rainfall events. The time range of particular rainfall groups can then be determined on the basis of meteorological, synoptic and statistical analysis in the periods of high precipitation sums or precipitation intensity in a given area (Llasat, 2001; Rigo and Llasat, 2004; Millán et al., 2005; Langer and Reimer, 2007; Federico et al., 2008; Lazri et al., 2012; Berg and Haerter, 2013)."
has been modified as follows (P7L11):
,,An innovative probabilistic model is proposed for modelling the annual number of storm overflows (Figure 3). This model allows for the prediction of the annual number of overflows and the simulation of the number of events per year, taking into account the genesis of rainfall, which is typical for countries located in central Europe and other regions of the world. Although the paper focuses on the genesis of rainfall developed by Kupczyk and Suligowski (1997, 2011), the proposed approach is universal. The distribution of rainfall data may be based on local conditions determining the advection of air masses, which has a key impact on the dynamics of rainfall events. The time range of particular rainfall groups can then be determined based on meteorological, synoptic and statistical analysis in the periods of high precipitation totals or precipitation intensity in a given area (Llasat, 2001; Rigo and Llasat, 2004; Millán et al., 2005; Langer and Reimer, 2007; Federico et al., 2008; Lazri et al., 2012; Berg and Haerter, 2013)."

Comment #14

Lines 8-9 to 9-2: Both sentences sound similar.

The following sentences are indeed similar: ,,The paper presents the following stages of construction of a probabilistic model on the example of an urban catchment located in the area of Kielce city. In the following sections the individual steps of the above mentioned calculation algorithm of the probabilistic model (separation of rainfall events, creation of a logistic regression model, development of a rainfall generator) are discussed in detail (Figure 4).

Therefore, the text has been modified as follows (P8L9):
,,The paper presents a probabilistic model for simulating the annual number of storm overflows. In this model, an innovative solution is to use the logistic regression method to analyse the impact of rainfall genesis on the functioning of a storm overflow in the example of a catchment located in the city of Kielce (central Poland)."

Comment #15

Line 9-5: What is meant by "in the ranks of"

The following sentence (P9L5) has been modified: ,,One of the basic conditions allowing for the completion of a synthetic precipitation generator is the separation of single independent rain events in the ranks of rainfall"
as follows:
,,One of the basic conditions allowing for the completion of a synthetic precipitation generator is the separation of single independent rain events (episodes) in rainfall time series."

Comment #16

Lines 9-9 to 9-18: this paragraph seems to be a repeat.

In the first quoted sentence (P9L9) the reader was informed only about empirical distributions, determined on the basis of separated rain episodes. In the next paragraph of the text this information is detailed and the methodology of research is presented. Thus, although the sentences P9L9 and P9L18 are similar, both are of significant importance in the applied research methodology.

Comment #17

Line 9-24: "simulate objects" sounds strange, write better "simulate the influence of constructions on flow procsses"

The following sentence (P9L24): „It is also used to simulate objects located in rainwater drainage networks (storm overflows) (Szeląg et al., 2018)"
has been modified as follows:
„This model is also used to simulate the influence of constructions on flow processes (Szeląg et al., 2018)."

Comment #18

Line 10-14: The investigation period is 1961 to 2000 (page 5). Here the years 2012-2014 are discussed?

Description of the data used to construct the model (P10L11-15): „The second variant assumes simplification and considers a single independent variable, i.e. average rainfall intensity. To determine the logit model, the results of measurements of the operation of the investigated storm overflow have been used from the years 2009-2011, when 69 overflow of 188 precipitation events occurred, and from the years 2012-2014, when 42 overflow of 93 precipitation events occurred."
has been made more specific:
„In the urban catchment area, continuous flow measurements were carried out in the period 2008-2011 (69 storm overflows during 188 rainfall events were separated at that time), whereas in the years 2012-2014, only fillings in the diversion chamber were measured (42 overflows during 93 rainfall episodes were separated). The reason for this was the construction works carried out in the analysed catchment and a large amount of suspended solids limiting the operation of the measuring devices. Since 2015, MES1 and MES2 flow meters have been installed, which also allow the measurement of the volume of stormwater discharged by overflow. Thus, based on data from the period 2008-2014, a logit model was developed, while data from the period 2015-2017 were used to verify it."

Comment #19

Line 11-14: What is meant by "period separating subsequent rainfall events"?

The following sentence (P11L14): „Currently conducted research in the field of rainfall simulators based on multidimensional boundary distributions combined with the so-called dome functions take into account the distribution of rainfall in the rainfall episode (Vernieuwe et al., 2015), spatial diversity of rainfall (Dai et al., 2014), seasons (Khedun et. al., 2014) and the period separating subsequent rainfall events (Balistrocchi and Bacchi, 2011)."
has been modified as follows:
„A literature review (Vendenberge et al., 2008) shows that the seasons of the year were taken into account in models for predicting rainfall distribution based on copula functions."

Comment #20

Line 11-15 to 11-24: This part concerns not methods. Similar discussions are in the first parts of the paper.

The text from P11L15 to P11L24 and P10L17 to P10L24 is shortened and included in the introduction (P2L22) in the following form:

„Multidimensional scaling methods and fractal geometry (Rupp et al., 2009; Licznar et al., 2015; Müller-Thomy and Haberlandt, 2015) are used to simulate rainfall series. An alternative solution is an approach based on the multidimensional distributions created based on theoretical distributions and copula functions (Vandenberghe et al., 2010; Vernieuwe et al., 2015). Despite numerous applications, these solutions are relatively complex and require expert knowledge. For the storm overflow simulation, hydrodynamic models are usually used, and less frequently, empirical models are used (Szeląg et al., 2018). Nevertheless, this approach to the simulation of the annual number of overflows is very local and, in many cases, requires the construction of a catchment model."

Due to the above correction and Comment #5, the text after P9L19 was also modified:
"Taking into account the computational algorithm described at the beginning of Section 4 (Methodology), based on the determined distributions of the theoretical rainfall characteristics describing the operation of a storm overflow, a model for the simulation of a synthetic rainfall series was adopted for further analysis. The simulations carried out for this purpose included the Monte Carlo method with modification of Iman-Conover (1982). This model provides the possibility simulating the independent variables based on the determined theoretical distributions. In this method, the variability of the considered variables is described by boundary (theoretical) distributions, and the basis for the evaluation of their correlation is the Spearman correlation coefficient. The conditions that must be met in order for the results obtained to be considered correct, are as follows.

– In the data obtained from simulation and measurements, the mean values $(\mu_1(x_1), \mu_2(x_2),...,\mu_i(x_i))_s$ and the standard deviations $(\sigma_1(x_1), \sigma_2(x_2),...,\sigma_i(x_i))_s$ of the variables (x_i) considered in j samples do not differ by more than 5 %.
– The theoretical distributions of x_i variables obtained from simulation should be consistent with those obtained from measurements; in order to meet this condition it is recommended to use the Kolmogorov-Smirnov (KS) test.
– The value of the correlation coefficient (R) between the individual dependent variables (x_i) obtained for the data from Monte Carlo (MC) simulation does not differ by more than 5 % from the value of R obtained for empirical data."

Comment #21

Lines 12-8 to 12-11: This sentences are nearly a repeat of pages 7/8, but the steps are not denominated identical. Here 4 steps are listed, but the Section consists of the two parts 5.1 and 5.2 only.

Indeed, the text on page P12L8 to P12L11 is similar to this one on pages 7/8. The text (P12L8 to P12L11) lists in detail the stages that are discussed in the manuscript below.
To eliminate the similarity, the Section 5.2 has been divided into four following Sections:

5.2. Identification of the empirical and theoretical distributions of the selected rainfall characteristics
Section 5.2 includes analyses related to the determination of statistical distributions of the following variables: rainfall depth (P_{tot}), rainfall duration (t_{r}), average rainfall intensity (i), and number of rain events in a year of varied genesis.
Section 5.2 in the manuscript contains the text from P13L24 to P17L5.

5.3. Impact of rainfall genesis on the probability of storm overflow occurrence
Section 5.3 presents the determined relationship between the genesis of rainfall and the probability of overflow event, as well as the ranges of variation of average rainfall, taking into account the rainfall genesis, which determines the occurrence of storm overflow event.
Section 5.3 in the manuscript contains the text from P17L6 to P17L27.

5.4. Impact of rainfall genesis on the average rainfall intensity occurrence of a storm overflow
Section 5.4 presents the results of calculations of the impact of rainfall genesis on the rain intensity limit values that determine the occurrence of storm overflow. Section 5.4 includes the text from P18L3 to P18L27.

5.5. Impact of rainfall genesis on the annual number of overflow events
Section 5.5 presents the annual number of overflow events caused by rainfall (convective, frontal, and in convergence zone). In addition, a comparative analysis of the annual number of overflow events obtained with a simplified logit model (based on

the average rainfall intensity) and the number of overflow events obtained with an accurate model (based on the total amount of rainfall and its duration) is carried out in this Section.
Section 5.5 in the manuscript contains the text from P18L28 to P20L16 in the manuscript.

Comment #22
Line 13-19: The reviewer don't know what "values of free words" are? Possibly other readers will have the same problem.

The following sentence (P13L19 – P13L21): „On the basis of the relationships (eq. 5 and eq. 6) it can be concluded that the values of free words obtained in them are similar to the weighted average value of the catchment retention (d_{av}). The relative difference between the values of free words and retention of the catchment area does not exceed 5 % "
has been modified as follows:
„On the basis of these relationships, it can be concluded that the values of the intercept obtained in them are similar to the weighted average value of the catchment retention (d_{av}). The relative difference between the values of intercept and retention of the catchment area does not exceed 5 %."

Comment #23
Line 1-16: The text within the brackets should be formulated as sub-clause or as an additional sentence.

The manuscript text has been corrected (see Comment and Response #9).

Comment #24
Line 1-21: write "great" instead of "big"

The amended sentence is set out in answer to Comment #10.

Comment #25
Line 1-29: two times determine

The following sentence (P1L29): „On the basis of the obtained results, the range of variability of average rainfall intensity was determined, which determines the discharge by storm overflow, as well as the annual number of discharges resulting from the occurrence of rain of different genesis."
has been modified as follows:
„Based on the obtained results, the range of the variability of the average rainfall intensity, which determines the storm overflow, and the annual number of overflows resulting from the occurrence of rain of different genesis were defined."

Comment #26
Line 1-31: the results are suited for implementation

The following sentence (P1L31): „The obtained results enable their practical implementation in the assessment of storm overflows only on the basis of knowledge concerning the genetic type of rainfall."
has been modified as follows:
„The results are suited for the implementation in the assessment of storm overflows only based on the genetic type of rainfall."

Comment #27
Line 2-2: three times the word "of" in series.

The following sentence (P2L2): „They can be used to develop warning systems, in which information on the predicted rainfall genesis is a component of the assessment of the operation of the stormwater system and the facilities located on it."
has been modified as follows:

„The results may be used to develop warning systems in which information about the predicted rainfall genesis is an element of the assessment of the rainwater system and its facilities."

Comment #28
Line 2-29: what was not taken into account when rainfall generators were used to simulate

The following sentence (P2L29): ,,It seems puzzling why the fact that the time course and dynamics of rainfall are the result of complex movements of air masses (Serrano et al., 2009; Alhammoud et al., 2014; Dayan et al., 2015) was not taken into account when modelling rainfall generators to simulate storm overflows."
has been modified as follows:
,,It seems puzzling that the time course and the dynamics of the rainfall as the result of air masses advection (Serrano et al., 2009; Alhammoud et al., 2014; Dayan et al., 2015) were not taken into account when rainfall generators were used to simulate storm overflows."

Comment #29
Line 2-32: "concern simulations" sounds strange, write perhaps better "consider"
Line 3-1: "course of precipitation phenomena" sounds strange.

The following sentence (P2L32): ,, The models created concern simulations of meteorological conditions changing in time and determining the distribution of temperature, pressure and humidity, which affects the dynamics of air movement and, consequently, the course of precipitation phenomena."
has been modified as follows:
,,The models created consider simulations of meteorological conditions changing in time and determining the distribution of temperature, pressure and humidity, which affects the dynamics of air advection and, consequently, the patterns of precipitation phenomena."

Comment #30
Line 3-4: "forecasting the operation" sounds strange, write "basis for the control of systems"

The following sentence (P3L4): ,,This information may be the basis for forecasting the operation of the stormwater system and developing an early warning system against the risks of flash flood."
has been modified as follows:
,,This information may be the basis for control of the systems and the development of an early warning system against the risks of flash floods."

Comment #31
Line 3-11: Sometime it is written "model of the rainfall generator". The generator is a model, the word "model" seems to be unnessecary.

The following sentence (P3L11): „In the model of the rainfall generator the genesis of rainfall was taken into account, which allowed to determine the curves showing the influence of rainfall genesis on the occurrence of overflow discharge in a single rainfall episode."
has been modified as follows:
„In the rainfall generator, the genesis of rainfall is taken into account, which allows determining the curves that show the influence of rainfall genesis on the occurrence of storm overflow in a single rainfall episode."

Comment #32
Line 3-22: a space is missed

A space is inserted between the sentences (P3L22): "... (Szeląg et al., 2016). The length …."

Comment #33

Line 3-23: better “height difference”, cancel “of ordinates”

The following sentence (P3L23): „The maximum difference of ordinates in the catchment is 12.0 m and the average slope in the catchment is 7.1 %.”
has been modified as follows:
„The height difference in the catchment is 12.0 m and the average slope is 7.1 %.”

Comment #34

Line 4-10: “generated” better as “shaped”

The sentence (P4L10) has been removed.

Comment #35

Line 4-11: write “A third”, since before only two mechanism are announced
Line 4-11: write “which include both above mentioned components”

The sentence (P4L11) has been removed.

Comment #36

Line 4-16: write at the end “are” instead of “is”

The following sentence (P4L16): „Convective precipitation induced by single thunderstorm cells, their complexes or squall lines is short-lived but is characterized by high average intensity (Kane et al., 1987) and causes flash floods (Gaume et al., 2009; Marchi et al., 2010; Bryndal, 2015)” has not been modified.

Comment #37

Line 5-2 and 5-13: line break (new paragraph)

We agree with the Reviewer's #1 comment that the considerations on this subject presented in Section 3 may be shortened and partly moved to the introductory Section of the article.
Therefore, the following changes have been made to the manuscript:
– the title of Section 3 (P4L7) has been changed as follows: “Rainfall data and analysis”
– the previous content presented in the text from P4L8 to P5L17 was modified in the following way and moved to Section 1 (after P3L7):
“Rainfall is universally classified into three types (Sumner, 1988; Smith, 1993): convective, cyclonic and orographic. The main distinguishing feature between convective precipitation in an air mass and frontal precipitation in mid-latitudes is its spatial extent and duration. The range of convective precipitation associated with local air circulation is much smaller than in the case of travelling extratropical cyclones with weather fronts. Convective precipitation induced by single thunderstorm cells, their complexes or squall lines is short-lived but is characterized by high average intensity (Kane et al., 1987) and causes flash floods (Gaume et al., 2009; Marchi et al., 2010; Bryndal, 2015). On the other hand, the lifespan of the mechanisms of creating cyclonic precipitation is much longer than that of convective precipitation – on the order of days rather than hours. Hence, the effect of this is long-term rainfall with a high depth (Frame et al., 2017) often cause regional floods (Barredo, 2007). The presented classification of precipitation types distinguished by Sumner (1988) due to the origin, developed for the British Isles and Western Europe, cannot be directly applied in practical hydrology in other regions of the continent, especially in its eastern and central parts due to exceptional variability of meteorological conditions occurring in the temperate zone of the warm transition climate – on the border of air masses coming from the Atlantic and continental masses from the east (Twardosz and Niedźwiedź, 2001; Niedźwiedź et al., 2009; Twardosz et al., 2011; Łupikasza, 2016). The analysis of maximum rainfall of different duration in Poland carried out at the end of the 1990s (Kupczyk and Suligowski, 1997, 2011), supplemented by an analysis of the synoptic situation (based on surface synoptic charts of Europe, published in the Daily Meteorological Bulletin

of the Institute of Meteorology and Water Management – IMGW in Warsaw) and a calendar describing the types of atmospheric circulation together with air masses and air fronts (Niedźwiedź, 2019), led to the separation of three types of genetic precipitation: convective in air mass, frontal and generated in convergence zone."

Comment #38
Line 5-17: "convergence zone" is not a type of precipitation, write better "generated in convergence zones"

The amended text is presented at the end of the answer to Comment #37.

Comment #39
Line 5-19: write "only these data were"

Fragment of the sentence (P5L19): ,,These data were taken into account in the conducted analyses,…."
has been modified as follows:
,,Only these data were taken into account in the conducted analyses,…."

Comment #40
Line 5-33: "variable" instead of "varied"

The following sentence (P5L33): ,,The second type (frontal rainfall) forms a group of precipitation in Kielce, in which the duration is very varied and ranges from 2.5 h to 10.5 h."
has been modified as follows:
,,The second type (frontal rainfall) forms a group of precipitation in Kielce, in which the duration is very variable and ranges from 2.5 h to 10.5 h."

Comment #41
Line 6-12: "precipitation emitted" sounds strange.

The following sentence (P6L12): ,,Transformation of air masses over the western part of the continent, lower speeds of movement of frontal zones, as well as weakening of the dynamics of processes in the front zone cause that precipitation in Kielce differ in intensity and duration in relation to precipitation emitted by Sumner (1988) as cyclonic."
has been modified as follows:
,,The transformation of the air masses over the western part of the continent, the lower speeds of the air advection and the weakening of the dynamics of processes in the front zone cause precipitation in Kielce to differ in intensity and duration in relation to precipitation defined by Sumner (1988) as cyclonic."

Comment #42
Line 7-25: overflow discharges per year

The following sentence (P7L25): ,,On this basis, distribution functions (CDF) are determined that describe the probability (Z) of exceeding the number of storm overflow discharges."
has been modified as follows:
,,On this basis, distribution functions (CDF) are determined that describe the probability of non-exceeding the number of storm overflows."

Comment #43

Line 10-10: Write “. is a simplification. It considers only a single”

The following sentence (P10L10): „The second variant assumes simplification and considers a single independent variable, i.e. average rainfall intensity.”
has been modified as follows:
„The second variant is a simplification. This variant considers only a single independent variable, i.e., average rainfall intensity.”

Comment #44

Line 10-18: set methods before the brackets.

The above remark has already been taken up in answer to Comment 20 and the quotes have been moved to the end of the sentence.

Comment #45

Line 10-30: write better “should be consistent”

The following sentence (P10L30): „…theoretical distributions of x_i variables obtained from simulation are consistent with those obtained from measurements; in order to meet this condition it is recommended to use the Kolmogorov-Smirnov test…”
has been modified as follows:
„… theoretical distributions of x_i variables obtained from simulation should be consistent with those obtained from measurements; in order to meet this condition it is recommended to use the Kolmogorov-Smirnov (KS) test.…”

Comment #46

Line 13-16: write “are valid” instead of “take place”

The following sentence (P13L16): „Based on theoretical considerations conducted by Thorndahl and Willems (2008), who provided a generalised model for forecasting the volume of wastewater discharge via a storm overflow, it can be concluded that in this case the following relations take place:”
has been modified as follows:
„Based on theoretical considerations of Thorndahl and Willems (2008), who investigated the relationships between the characteristics of catchment areas, including the limit retention that determines the volume of overflow, the following equations were determined:”

Comment #47

Line 13-19: write “of this relationship” and cancel the “(eq. 5 and eq. 6)”

The corrected sentence is in answer to Comment 22.

Comment #48

Line 15-8: expressed better by

The following sentence (P15L8): „Also, the variation in rainfall duration in episodes resulting from rainfall of different genesis in most cases is described by the Weibull distribution and only in the case of data measured over an annual cycle is it expressed by the GEV distribution (eq. 9).”
has been modified as follows:
„In addition, the variation in rainfall duration of the episodes resulting from rainfall of different genesis is described, in most cases, by the Weibull distribution and only in the case of the data measured over an annual cycle is it expressed better by the GEV distribution (eq. 11).”

Comment #49

Line 18-3: Write "distinguished" instead of "made".

The following sentence (P18L3): „Within the framework of the conducted analyses, the division of frontal rainfall events of the duration not longer than 4.5 h (related to the cold front – type I) and exceeding the given value (due to the displacement of the warm front – type II) was additionally made."
has been modified as follows:
„Within the framework of the conducted analyses, the division of frontal rainfall events of the duration not longer than 4.5 h (related to the cold front – frontal type I) and exceeding the given value (due to the displacement of the warm front – frontal type II) was additionally distinguished."

Comment #50

Line 18-6: line break (new paragraph).

Section 5.2 and its division is discussed in answer to Comment #21.

Comment #51

Following words seems to be unnessecary: Line 1-20: was demonstrated; Line 1-31/32: knowledge concerning; Line 2-10: collecting; Line 2-19: in the work; Line 2-22: of simulation; Line 2-27: in its modeling; Line 3-26: the work; Line 4-6: article; Line 4-17: in many areas; Line 5-3: of the phenomenon; Line 9-6: in the paper; Line 10-10: in the analysis performer; Line 11-13: in the rainfall episode; Line 13-1: using the model.

All words indicated by the reviewer have been deleted.

Application of logistic regression to simulate the influence of rainfall genesis on storm overflow operations: a probabilistic approach

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Abstract. One of the key parameters constituting the basis for the operational assessment ~~of the operation~~ of stormwater systems is the annual number of storm overflows. Since uncontrolled overflows ~~overflow discharges~~ are a source of pollution washed away from the surface of the catchment area, which leads to ~~an imbalance in the~~ imbalanced receiving waters ~~receivers~~, there is a need for their prognosis and potential reduction. The paper presents a probabilistic model for simulating the annual number of storm overflows. In this model, an innovative solution is to use the logistic regression method to analyse the impact of rainfall genesis on the functioning of a storm overflow in the example of a catchment located in the city of Kielce (central Poland).

~~This paper proposes an innovative probabilistic model to simulate the number of storm overflow discharges, which takes into account atmospheric circulation and related rainfall in the research area (the city of Kielce located in the central part of Poland).~~ The developed model consists of two independent elements. ~~The first element is the model of logistic regression, which can be used to model storm overflow discharge resulting from the occurrence of a single rainfall episode. The paper confirmed that storm overflow discharge can be modeled on the basis of data on the total amount of rainfall and its duration. An alternative approach was also proposed, in which the possibility of forecasting overflow discharge only on the basis of the average rainfall intensity was demonstrated, which is a big simplification in simulation of the phenomenon under study in comparison with the works published so far in this scope. It is worth noting that the coefficients determined in logit models have a physical interpretation and these models have a universal character, which is why they can be easily adapted to other examined catchment areas. The second element of the model is a synthetic precipitation generator, in which the simulation of rainfall takes into account its genesis resulting from various processes and phenomena taking place in the troposphere. This approach makes it possible to take into account the stochastic nature of rainfall also in relation to the annual number of events.~~ The first element of the model is a synthetic precipitation generator, in which the simulation of rainfall takes into account its genesis resulting from various processes and phenomena occurring in the troposphere. This approach makes it possible to account for the stochastic nature of rainfall in relation to the annual number of events. The second element is the model of logistic regression, which can be used to model the storm overflow resulting from the occurrence of a single rainfall episode. The

paper confirmed that storm overflow can be modelled based on data on the total rainfall and its duration. An alternative approach was also proposed, providing the possibility of predicting storm overflow only based on the average rainfall intensity. Substantial simplification in the simulation of the phenomenon under study was achieved compared with the works published in this area to date. It is worth noting that the coefficients determined in the logit models have a physical interpretation, and the universal character of these models, facilitates their easy adaptation to other examined catchment areas.

~~Calculations~~ The calculations made in the paper ~~on~~ using the example of the examined catchment allowed ~~to assess~~ an assessment of the influence of rainfall characteristics (depth, intensity, duration) of different genesis on the probability of storm overflow ~~discharge~~. ~~On the basis of the obtained results, the range of variability of average rainfall intensity was determined, which determines the discharge by storm overflow, as well as the annual number of discharges resulting from the occurrence of rain of different genesis. The obtained results enable their practical implementation in the assessment of storm overflows only on the basis of knowledge concerning the genetic type of rainfall. They can be used to develop warning systems, in which information on the predicted rainfall genesis is a component of the assessment of the operation of the sewage system and the facilities located on it.~~ Based on the obtained results, the range of the variability of the average rainfall intensity, which determines the storm overflow, and the annual number of overflows resulting from the occurrence of rain of different genesis were defined. The results are suited for the implementation in the assessment of storm overflows only based on the genetic type of rainfall. The results may be used to develop warning systems in which information about the predicted rainfall genesis is an element of the assessment of the rainwater system and its facilities. This approach is an original solution that has not yet been considered by other researchers. On the other hand, it represents an important simplification and an opportunity to reduce the amount of data to be measured.

1 Introduction

One of the important criteria for assessing the operation of stormwater systems is the annual number of storm overflows, ~~overflow discharges,~~ which is confirmed by ~~national and~~ foreign guidelines (US EPA, 1995; Zabel et al., 2001; ÖWAV, 2003). The physics of the phenomenon is complex and depends on the dynamics of rainfall, ~~it's~~ the changes in rainfall over time and the characteristics of urban catchment areas with storm overflows. Currently, the annual number of overflows ~~overflow discharges~~ in the catchment areas can be assessed ~~on the basis of~~ based on long-term observations of their operation (Price, 2008; Andrés-Doménech et al., 2010; Gemerith et al., 2011), but it is a costly solution due to the need for the continuous monitoring of flows. An alternative approach is to build a hydrodynamic model of the catchment, which requires ~~collecting~~ detailed data ~~on~~ about the basin, precipitation from a long~~-term~~ period (30 years according to DWA A–118) and flows ~~in order~~ to calibrate the model from a period ~~not shorter than~~ of at least two years (Szeląg et al., 2016). Using the model of the catchment built ~~on the basis of~~ based on long-term rainfall measurements, it is possible to perform the so-called continuous simulation, which will allow ~~to estimate~~ an estimation of the annual number of storm overflows ~~overflow discharges.~~ Such a solution may be a source of reliable estimation of the number of overflows, ~~overflow discharges,~~ although its technical implementation is complex and the results obtained (numerical simulations of the catchment model) are not always satisfactory (Romanowicz and Beven, 2006; Beven and Binley, 2014).

Considering the above, the article uses probabilistic models to predict ~~forecast~~ the annual number of overflows ~~overflow discharges~~, which take into account the stochastic nature of rainfall and the complex nature of runoff in urban catchment areas. This problem was discussed ~~in the work~~ by ~~Willems and Thorndahl~~ Thorndahl and Willems (2008), who used the FORM (first-order reliability model) method to simulate the storm overflow ~~discharge~~ event; its application in engineering practice is limited due to the complexity of its implementation ~~process~~. In subsequent works ~~dealing with~~ addressing this problem, rainfall generators and episode of ~~discharge~~ storm overflow ~~simulation~~ models (Grum and Aalderink, 1999) were used to simulate ~~forecast~~ the annual number of overflows ~~overflow discharges~~. Multidimensional scaling methods and fractal geometry (Rupp et al., 2009; Licznar et al., 2015; Müller-Thomy and Haberlandt, 2015) are used to simulate rainfall series. An alternative solution is an approach based on the multidimensional distributions created based on theoretical distributions and copula functions (Vandenberghe et al., 2010; Vernieuwe et al., 2015). Despite numerous applications, these solutions are relatively complex and require expert knowledge. For the storm overflow simulation, hydrodynamic models are usually used, and less frequently, empirical models are used (Szeląg et al., 2018). Nevertheless, this approach to the simulation of the annual number of overflows is very local and, in many cases, requires the construction of a catchment model. Szeląg et al. (2018) presented a model of simulation of storm overflow ~~discharge~~ (single rainfall episode) determined by the logistic regression method. A significant disadvantage of the above mentioned solutions is the fact that in the probabilistic models, simplified rainfall generators were used and the variability of precipitation characteristics was taken into account in relation to only one episode of overflow ~~discharge~~. At the same time, the issue of precipitation genesis was not addressed at all. Therefore, the question arises whether the information on the nature of precipitation (e.g., season of the year, precipitation genesis) could not find practical use in its modelling. It seems puzzling ~~why the fact~~ that the time course and the dynamics of the rainfall as the result of air masses advection ~~complex movements of air masses~~ (Serrano et al., 2009; Alhammoud et al., 2014; Dayan et al., 2015) were not taken into account when ~~modelling~~ rainfall generators were used to simulate storm overflows. The problem of the modelling of complex atmospheric phenomena is the subject of many works (Madsen et al., 1995; Paquet et al., 2006; Vi~~n~~cente-Serrano et al., 2009; Garavaglia et al., 2010; Abushandi and Merkel, 2011). The models created consider ~~concern~~ simulations of meteorological conditions changing in time and determining the distribution of temperature, pressure and humidity, which affects the dynamics of air advection ~~movement~~ and, consequently, the patterns ~~the course~~ of precipitation phenomena. According to the literature ~~knowledge~~, the information concerning the genesis of precipitation allows for preliminary assessment (quantitative and qualitative) of ~~it's~~ the course and estimation of the average rainfall intensity (Suligowski, 2004). This information may be the basis for control of the systems ~~forecasting the operation of the stormwater system~~ and ~~developing~~ the development of an early warning system against the risks of flash floods. This problem has not been considered so far and, at the same time, it seems possible ~~to model~~ that modelling the functioning of the stormwater system and the facilities located ~~on~~ in it ~~only on the basis~~ based only on forecasts and identification of the rainfall genesis could be accomplished.

Rainfall is universally classified into three types (Sumner, 1988; Smith, 1993): convective, cyclonic and orographic. The main distinguishing feature between convective precipitation in an air mass and frontal precipitation in mid-latitudes is its spatial extent and duration. The range of convective precipitation associated with local air circulation is much smaller than in the case of travelling extratropical cyclones with weather fronts. Convective precipitation induced by single thunderstorm cells, their complexes or squall lines is short-lived but is characterized by high average intensity (Kane et al., 1987) and causes flash floods (Gaume et al., 2009; Marchi et al., 2010; Bryndal, 2015). On the other hand, the lifespan of the mechanisms of creating cyclonic precipitation is much longer than that of convective precipitation – on the order of days rather than hours. Hence, the effect of this is long-term rainfall with a high depth (Frame et al., 2017) often cause regional floods (Barredo, 2007).

The presented classification of precipitation types distinguished by Sumner (1988) due to the origin, developed for the British Isles and Western Europe, cannot be directly applied in practical hydrology in other regions of the continent, especially in its eastern and central parts due to exceptional variability of meteorological conditions occurring in the temperate zone of the warm transition climate – on the border of air masses coming from the Atlantic and continental masses from the east (Twardosz and Niedźwiedź, 2001; Niedźwiedź et al., 2009; Twardosz et al., 2011; Łupikasza, 2016). The analysis of maximum rainfall of different duration in Poland carried out at the end of the 1990s (Kupczyk and Suligowski, 1997, 2011), supplemented by an analysis of the synoptic situation (based on surface synoptic charts of Europe, published in the Daily Meteorological Bulletin of the Institute of Meteorology and Water Management – IMGW in Warsaw) and a calendar describing the types of atmospheric circulation together with air masses and air fronts (Niedźwiedź, 2019), led to the separation of three types of genetic precipitation: convective in air mass, frontal and generated in convergence zone.

Taking into account the above considerations, an innovative probabilistic model for calculating the number of storm overflows ~~overflow discharges~~ is proposed in the paper. This model is composed of two independent elements: a synthetic rainfall generator and a model for predicting ~~forecasting~~ storm overflows ~~overflow discharges~~. The identification of overflows ~~discharges~~ takes place only ~~on the basis of~~ based on information ~~on~~ about average rainfall intensity. In the ~~model of the~~ rainfall generator, the genesis of rainfall ~~was~~ is taken into account, which ~~allowed to determine~~ allows determining the curves that show the influence of rainfall genesis on the occurrence of storm overflow ~~discharge~~ in a single rainfall episode. ~~On the basis of~~ Based on the performed analyses, the ranges of variability of the average rainfall intensity assigned to rainfall of different genesis, for which storm overflow ~~discharge~~ may occur in the examined city catchment, were determined. ~~Calculation~~ The calculation experiments carried out in the study ~~allowed to determine~~ facilitated the determination of the influence of the distribution of the annual number of rainfall episodes of different genesis on the variability of the number of storm overflows ~~overflow discharges~~.

2 Object of study

The object of analysis was a 62 ha urban catchment located in the south-eastern part of Kielce (Figure 1). The city covers an area of 109 km^2 and is located in Świętokrzyskie Voivodeship. The average population of the area in question is 21.4 people ha^{-1}. Impervious areas, including pavements, roads, parking lots, roofs and school playgrounds, constitute 47.2 %. On the other hand, pervious areas, i.e., lawns, including green areas, occupy 52.8 %. On this basis, it was established that the weighted average value of the catchment retention is d_{av}= 3.81mm (Szeląg et al., 2016). The length of the main canal is 1.6 km, and its diameter changes between 0.60–1.25 m. ~~The maximum difference of ordinates in the catchment is 12.0 m and the average slope in the catchment is 7.1 %.~~ The height difference in the catchment is 12.0 m and the average slope is 7.1 %. The analysis of the measurement data (2008-2017) concerning the analysed catchment area showed that the antecedent period lasted 0.16–60 days, and storms occurred 27–47 times a year. The average annual air temperature during the period under consideration varied from 8.1 to 9.6 °C. In addition, the analysis of the measurement data of flows recorded with the MES1 flow meter showed that in the antecedent periods, the temporary stream of the stormwater was from 0.001 to 0.009 $m^3 \cdot s^{-1}$, which indicates the occurrence of infiltration in the stormwater system under study.

Stormwater from the catchment is discharged to the Silnica River. Detailed information about the catchment can be found in ~~the work~~ Dąbkowski et al. (2010). The stormwater from the catchment is drained via channel S1 into the diversion chamber ~~distribution~~ (DC). If the chamber ~~filling~~ level is less than h = 0.42 m, the stormwater is discharged into the stormwater ~~sewage~~ treatment plant (STP). If ~~it~~ the chamber level is filled above h, the stormwater is discharged by a storm overflow (OV) into the S2 canal, from where it flows into the Silnica River.

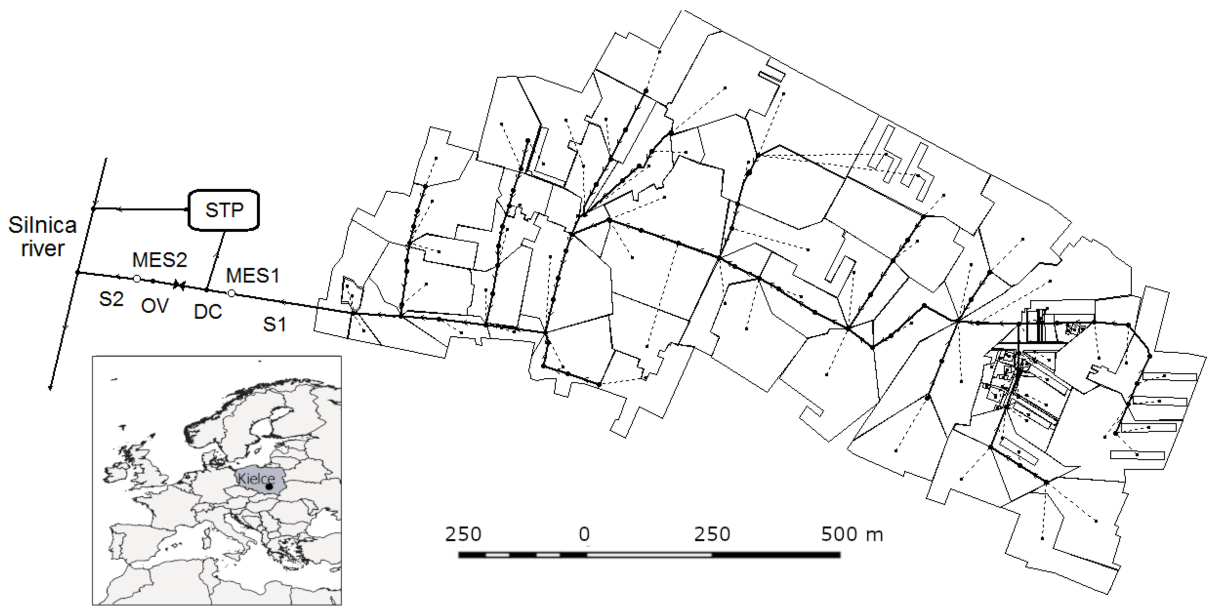


Figure 1: Diagram of the analysed urban catchment.

In the years 2009-2011, the amount of stormwater outflowing the catchment area was measured with the use of the MES1 flow meter located in the canal (S1) at a distance of 3.0 m from the inlet to the DC chamber. On the other hand, since 2015 in the inlet (S1) and discharge (S2) channels, MES1 and MES2 flowmeters measuring the values of filling and flows have been installed. A detailed description of the installed measuring equipment can be found in Szeląg ~~article~~ (2016).

~~3 Rainfall – genesis, number of rain events~~

~~Precipitation series covering all events, regardless of their duration, cannot be considered statistically homogeneous. Precipitation reflects the different processes taking place in the troposphere. Therefore, it seems justified to divide the whole set of precipitation events and to compare data in groups of identical genesis. Precipitation is shaped by two different precipitation mechanisms: convective and stratiform (Houze, 2014). The third rainfall mechanism, which may have the above mentioned components, is related to the orographic lifting of air masses over mountains or hills (Smith, 1993). Thus, rainfall is universally classified into three types (Sumner, 1988): convective, cyclonic and orographic. The main distinguishing feature between convective precipitation in air mass and frontal precipitation in mid-latitudes is its spatial extent and duration. The range of convective precipitation associated with local air circulation is much smaller than in the case of travelling extratropical cyclones with weather fronts. Convective precipitation induced by single thunderstorm cells, their complexes or squall lines is short-lived, but is characterized by high average intensity (Kane et al., 1987) and causes flash floods in many areas (Gaume et al., 2009; Marchi et al., 2010; Bryndal, 2015). On the other hand, the lifespan of the mechanisms of creating cyclonic precipitation is much longer than that of convective precipitation – in the order of days rather than hours. Hence, the effect of this is long-term rainfall with a high total sum (Frame et al., 2017), often causing regional floods (Barredo, 2007). The presented classification of precipitation types distinguished by Sumner (1988) due to the origin of the phenomenon, developed for the British Isles and Western Europe, cannot be directly applied in practical hydrology in other regions of the continent, especially in its eastern and central parts. This is the result of exceptional variability of meteorological conditions occurring in the temperate zone of warm transition climate – on the borderline of air masses coming from the Atlantic and continental masses from the east (Twardosz and Niedźwiedź, 2001; Niedźwiedź et al., 2009; Twardosz et al., 2011; Łupikasza, 2016). The transformation of air masses over the western part of the continent, lower velocities of the movement of atmospheric fronts due to an increase in the roughness of the substrate and the height of the friction layer, as well as a weakening of the dynamics of processes in their zone cause that the precipitation associated with them in central Europe differs in frequency, intensity and duration in relation to the precipitation separated by Summer (1988) as cyclonic. In addition, in the summer, low-pressure systems in central Europe, bringing precipitation of high altitude are also genetically associated with the Mediterranean and Black Seas (Łupikasza, 2016). Analysis of maximum rainfall of different duration in Poland carried out at the end of the 1990s (Kupczyk and Suligowski, 1997, 2011), supplemented by the analysis of synoptic situation (on the base of surface synoptic charts of Europe, published in Daily Meteorological Bulletin of the Institute of Meteorology and Water Management – IMGW in Warsaw) and a calendar describing the types of atmospheric circulation together with air masses and air fronts (Niedźwiedź, 2019), led to the separation of three types of genetic precipitation: convective in air mass, frontal and convergence zones.~~

3 Rainfall data and analysis

The source material for the study presented was data from May – October 1961-2000 obtained from the records of a traditional float pluviograph (precipitation depth, duration, and mean intensity) installed at the IMGW meteorological station in Kielce. Only these ~~These~~ data were taken into account in the conducted analyses, as the launch of a new device, the SEBA electronic rain gauge (tipping-bucket SEBA rain gauge), a few years later in the state measuring network resulted in the recording of significantly lower precipitation levels (by several percent). ~~, high intensity and short-lived, compared to measurements recorded by a traditional pluviograph~~ The data concerns events with high intensity and short duration (Kotowski et al., 2011). In the period 1961-2000 there were 1312 precipitation events in Kielce with a depth ~~height~~ above 3 mm, ~~which gives~~ with an average of 32.8 episodes per year. The greatest number of rainfall episodes (54) was observed in 1974 ~~(Figure 2)~~. In Kielce, precipitation classified as the first genetic type (convective in an air mass) lasts up to 150 min. ~~minutes. They are~~ This precipitation is caused by single convective cells with intensive ascending and descending currents, or by complexes of cells forming systems in the form of bands (squall line). The average annual number of these precipitation events in Kielce is 14.3 (1961-2000), ~~although at the end of the 1990s their frequency increased significantly (30 episodes in 2000, 26 in 1996) (Figure 2)~~. These precipitation events are characterized by a low depth (Figure 2a) ~~(Figure 3a)~~ but rapidly increase with the increase in duration (max. 40.5 mm in 137 min). Due to the short duration of all rainfall episodes (from 5 min to 2.5 h), ~~they~~ these events have a high intensity (median 7.97 L s^{-1} ha^{-1}; max. 97.8 L s^{-1} ha^{-1}) (Figure 2b) ~~(Figure 3b)~~. The second type (frontal rainfall) forms a group of precipitation in Kielce, in which the duration is very variable ~~varied~~ and ranges from 2.5 h to 10.5 h. These are the most frequent precipitation events in Kielce (average 16 events per year~~, Figure 2~~). ~~They~~ These precipitation events are associated with the movement of weather ~~atmospheric~~ fronts, while the fast cold front together with dynamic processes in its zone leads to a high intensity of precipitation lasting 2.5–5.5 h (max. 53.8 L s^{-1} ha^{-1}). On the other hand, the 3 processes in the zone affected by the warm front usually generate higher precipitation levels, but due to their duration (5.5–10.5 h), ~~even twice~~ two-fold lower precipitation intensity (max. up to 10.8 L s^{-1} ha^{-1}). The transformation of the air masses over the western part of the continent, the lower speeds of the air advection ~~as well as~~ and the weakening of the dynamics of processes in the front zone cause ~~that~~ precipitation in Kielce to differ in intensity and duration in relation to precipitation defined ~~emitted~~ by Sumner (1988) as cyclonic.

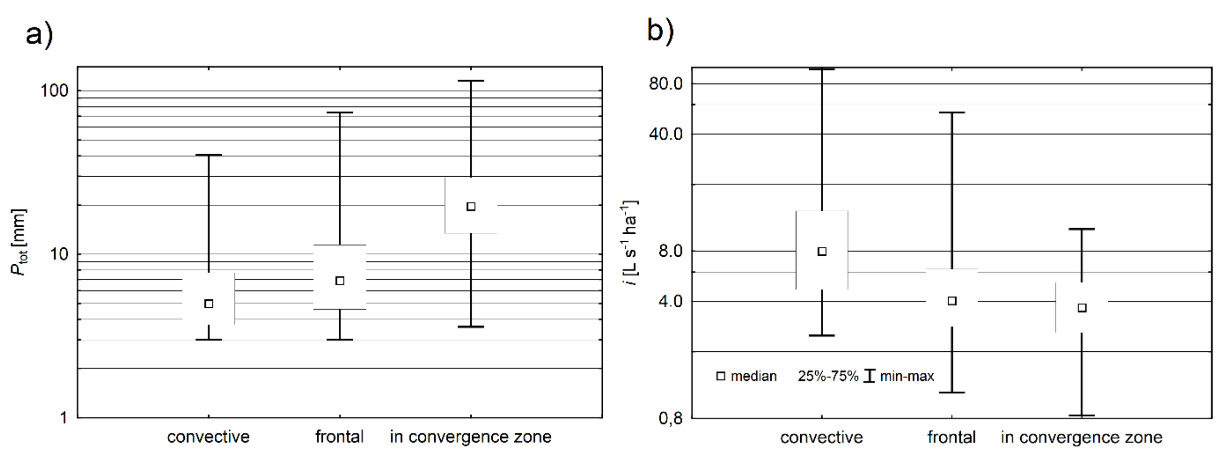


Figure 2 ~~Figure 3~~: Positional statistics of rainfall depth (a) and rainfall intensity (b) in genetic types.

On the other hand, the precipitation associated with convergence zone occurs in Kielce on average 2.3 times a year ~~(Figure 2)~~. ~~They~~ These events are the result of the passage of deep low pressure centres ~~deep centers of low atmospheric pressure~~ or a series of low pressures with two clearly marked frontal areas. The high dynamics and magnitude of processes operating within them cause ~~that~~ a long-term continuous precipitation (> 10.5 h) that is recorded near the ground surface, with a clearly increasing sum (Figure 2a ~~Figure 3a~~) and ~~variable~~ variability (weakening of intensity after passing a warm front, increase of intensity on a cold front), although with a low mean intensity (Figure 2b ~~Figure 3b~~).

4 Methodology

~~Within the conducted analyses, an innovative probabilistic model was proposed for forecasting the number of storm overflow discharges (Figure 4).~~ An innovative probabilistic model is proposed for modelling the annual number of storm overflows (Figure 3).

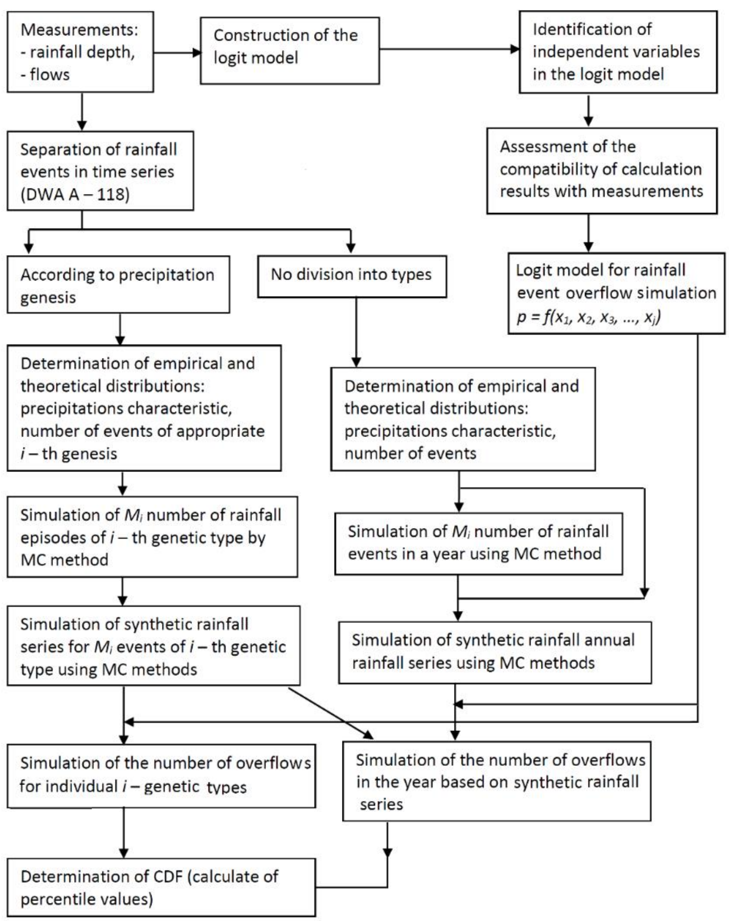


Figure 3 ~~Figure 4~~: Calculation diagram of the algorithm of building a probabilistic model for modelling the annual number of storm overflows ~~forecasting the number of discharges~~.

This model allows for the prediction ~~forecast~~ of the annual number of ~~discharges~~ overflows and the simulation of the number of events per year, taking into account the genesis of rainfall ~~(convective in air mass, frontal, convergence zones precipitation)~~, which is typical for countries located in central Europe and other regions of the world. Although the paper focuses on the genesis of rainfall developed by Kupczyk and Suligowski (1997, 2011), the proposed approach is universal. The distribution of rainfall data may be based on local conditions determining the advection ~~movement~~ of air masses, which has a key impact on the dynamics of rainfall events. The time range of particular rainfall groups can then be determined ~~on the basis of~~ based on meteorological, synoptic and statistical analysis in the periods of high precipitation totals or precipitation intensity in a given area (Llasat, 2001; Rigo and Llasat, 2004; Millán et al., 2005; Langer and Reimer, 2007; Federico et al., 2008; Lazri et al., 2012; Berg and Haerter, 2013). The classification of precipitation proposed by Sumner (1988) for Western Europe can also be used in such analyses. A literature review (Vendenberge et al., 2008) shows that the seasons of the year were taken into account in models for predicting ~~forecasting~~ rainfall distribution based on copula ~~dome~~ functions. ~~Aspects~~ The aspects related to the genesis of rainfall have so far not been included in probabilistic models for the operational analysis of stormwater systems operation. The model proposed in the present study consists of three components. The first components are synthetic precipitation generators, which are realized in two variants. In the first variant it was assumed that the basis for the simulation of rainfall series is their genesis. In the second variant, precipitation is predicted regardless of its origin – in the annual cycle. Another component is a logit model, which is used to simulate the occurrence of a storm overflow. ~~The first component is a logit model, which is used to simulate the occurrence of a storm overflow discharge. Another component are synthetic precipitation generators, which are realized in two variants. In the first variant it was assumed that the basis for the simulation of rainfall series is their genesis. In the second variant precipitation is forecasted regardless of its origin – in the annual cycle.~~ The third component of the model is a calculation block, in which the annual number of overflows ~~overflow discharges~~ is simulated for the generated rainfall series. On this basis, distribution functions (CDF) are determined that describe the probability ~~(Z)~~ of non-exceeding the number of storm overflows ~~overflow~~ ~~discharges~~. The proposed algorithm includes the following steps:

a) separation of precipitation events in rainfall measurement series,

b) identification of independent variables (x_i) in a logit model at the accepted confidence level and estimation of empirical coefficients,

c) determination of empirical distributions and theoretical rainfall characteristics of the different types of genetic precipitation (convective in air mass, frontal, and in convergence zone),

d) simulation ~~by means of the Monte Carlo method~~ of the number of precipitation events by means of the Monte Carlo method; ~~as an alternative, an approach~~ or based on a fixed average number of rain episodes ~~can be used~~,

e) Monte Carlo simulation of rainfall characteristics for the number of rain events generated,

f) determination of the number of storm overflows ~~overflow discharges~~ for the generated rainfall series:

– per year,

– in different genetic types.

In the following sections the individual steps of the above mentioned calculation algorithm of the probabilistic model (separation of rainfall events, creation of a logistic regression model, development of a rainfall generator) are discussed in detail (Figure 4).

4.1 Simulation of the annual number of storm overflow events using a hydrodynamic model

One of the possible solutions allowing for the verification of empirical dependencies describing the operation of stormwater systems is the simulation of this operation with the use of a calibrated hydrodynamic model. It is an approach applied in engineering practice, which is confirmed by a number of works in this field (Bacchi et al., 2008; Andrés-Doménech et al., 2010). The simulations performed with a hydrodynamic model based on rainfall data allow the verification of the prediction capabilities of the probabilistic models designed to simulate the quantity and quality of stormwater, and the operation of separate objects located in the stormwater system (tanks, overflows).

Within the framework of the conducted analyses, a calibrated model of the catchment basin made in the SWMM (storm water management model) program was used to verify the annual number of storm overflows (Figure 1). The total area of the analysed catchment is 62 ha, while the area of partial catchments ranges from 0.12 ha to 2.10 ha. The number of stormwater junctions in the catchment area is 200, and the number of stormwater pipes is 72. The retention depth of the imperviousness surfaces of the catchment area is 2.5 mm and the retention depth of the pervious surfaces is 6.0 mm. The roughness coefficient of impervious areas is equal to 0.025 $m^{-1/3}\cdot s$, and that of pervious areas is 0.250 $m^{-1/3}\cdot s$. The roughness coefficient of the stormwater channels is equal to 0.018 $m^{-1/3}\cdot s$.

The results of the simulation with the hydrodynamic model were compared with the results of calculations made with the use of logit models for the data from the examined catchment from the period 2008-2017, which allowed the verification of the determined relation $p = f(x_1, x_2, x_3, ..., x_i)$. Simultaneously, using the measurement data from the period of 1961-2000, a simulation of the annual number of storm overflow events was performed, taking into account the precipitation genesis, which enabled the verification of the developed probabilistic model.

4.2 Logistics regression

The logistic regression model is also called the binomial logit model and is usually used to simulate binary data. Therefore, this model is commonly used for probability modelling. The logit model is often used to simulate forecast phenomena and processes in medicine, social sciences and psychology (Bagley et al., 2001). This model is also successfully used to model processes in ecology, water engineering, geotechnics (Hayer et al., 2013, Inglemo et al., 2011) and wastewater treatment (Bayo et al., 2006; Szeląg et al., 2019). This model is also used to simulate the influence of constructions on flow processes It is also used to simulate objects located in rainwater drainage networks (storm overflows) (Szeląg et al., 2018). The logit model takes the following form:

$$p = \frac{\exp(X)}{1+\exp(X)} = \frac{\exp(\sum_{i=1}^{j} \alpha_i \cdot x_i + \alpha_0)}{1+\exp(\sum_{i=1}^{j} \alpha_i \cdot x_i + \alpha_0)} \quad (1)$$

where the following are defined: p [–] – probability of occurrence of storm overflow in a single rainfall episode, α_i – empirical coefficients estimated with the method of Mmaximum Llikelihood Eestimation (MLE), x_i – independent variables, which in this paper include: rainfall depth (P_{tot} [mm]), rainfall duration (t_r [min]), and average intensity of rainfall event (i [L s^{-1} ha^{-1}]) ($q = 166.7\ P_{tot}\ t_r^{-1}$ [L s^{-1} ha^{-1}]).

The calculations assume that a storm overflow occurs discharge takes place when p is not less than 0.50, which corresponds to the following condition:

$$\sum_{i=1}^{j} \alpha_i \cdot x_i + \alpha_0 = 0 \quad (2)$$

To evaluate the predictive capacity of the logit model, the following measures were used to match the calculation results to the measurements: sensitivity – SENS (determines the correctness of data classification in the set of data, including events when a storm overflow discharge occurred), specificity – SPEC (determines the correctness of data classification in the set of data constituting cases when no storm overflow discharge occurred) and counting error – R_z^2 (determines the correctness of identification of the simulation of events: storm overflow discharge occurred/did not occur no occured). These measures are discussed in detail in McFadden's paper (1963).

Two variants of the logit model were considered in the analyses performed. In the first of them variant, the height of rainfall depth and its duration were assumed to be independent variables, as described in Szeląg et al. (2018). The second variant is a simplification. This variant considers only a single independent variable, i.e., average rainfall intensity. In the urban catchment area, continuous flow measurements were carried out in the period 2008-2011 (69 storm overflows during 188 rainfall events were separated at that time), whereas in the years 2012-2014, only fillings in the diversion chamber were measured (42 overflows during 93 rainfall episodes were separated). The reason for this was the construction works carried out in the analysed catchment and a large amount of suspended solids limiting the operation of the measuring devices. Since 2015, MES1 and MES2 flow meters have been installed, which also allow the measurement of the volume of stormwater discharged by overflow. Thus, based on data from the period 2008-2014, a logit model was developed, while data from the period 2015-2017 were used to verify it. The second variant assumes simplification and considers a single independent variable, i.e. average rainfall intensity. To determine the logit model, the results of measurements of the operation of the investigated storm overflow have been used from the years 2008-2011, when 69 discharges of 188 precipitation events occurred, and from the years 2012-2014, when 42 discharges of 93 precipitation events occurred.

4.1 Separation of rain events

4.3 Separation of the rain event and synthetic rainfall simulator

One of the basic conditions allowing for the completion of a synthetic precipitation generator is the separation of single independent rain events in the ranks of rainfalls (episodes) in rainfall time series. For this purpose, the guidelines DWA A–118 (2006) were used, in which the basis for precipitation separation is a minimum antecedent period of 4 h. As a precipitation event, in the paper such a precipitation episode has been assumed for which the rainfall depth is not less than 3.0 mm (Fu and Kapelan, 2013; Fu et al., 2014).

On the basis of Based on the precipitation observed in the period 1961-2000, independent precipitation events were separated, for which statistical distributions were determined. In order to obtain the best possible matching of theoretical data (precipitation characteristics including P_{tot} and t_r values for precipitation of appropriate genesis) with empirical data, To obtain the best possible fit of the theoretical data to the empirical precipitation data (including: rainfall depth – P_{tot}, rainfall duration – t_r and average rainfall intensity – i, for precipitation of appropriate genesis), the following statistical distributions were considered (Adams and Papa, 2000; Bacchi et al., 2008; Domenech et al., 2010): Weibull, chi-square, exponential, GEV, Gumbel, gamma, Johnson, log-normal, Pareto and beta. Kolmogorov-Smirnov and chi-square tests were used to assess the conformity of the empirical and theoretical distributions. Empirical The empirical distributions were also determined, and the theoretical distributions were adjusted to the data describing the number of precipitation events in the year and the number of episodes resulting from convective precipitation, frontal rainfall (warm and cold fronts), and rainfall in convergence zone. Within the theoretical distributions, Poisson's, geometric, Bernoulli's and binomial distributions were considered. Kolmogorov-Smirnov tests were used to assess the conformity of empirical and theoretical distributions.

Taking into account the computational algorithm described at the beginning of Section 4 (Methodology), based on the determined distributions of the theoretical rainfall characteristics describing the operation of a storm overflow, a model for the simulation of a synthetic rainfall series was adopted for further analysis. The simulations carried out for this purpose included the Monte Carlo method with modification of Iman-Conover (1982). This model provides the possibility simulating the independent variables based on the determined theoretical distributions. Simulating continuous series of rainfall is a complex task that requires the implementation of complex numerical algorithms. For this purpose, multi-dimensional scaling, fractal geometry (Rupp et al., 2009; Licznar et al., 2015; Müller-Thomy and Haberlandt 2015) methods are currently used in many cases. Alternative approaches are models based on the creation of multidimensional distributions using dome functions (Vandenberghe et al., 2010; Vernieuwe et al., 2015). Despite numerous applications, as indicated by the number of works in this field (Zhang and Singh, 2019), the above approach is not simple and in some cases requires searching for many different combinations of theoretical distributions and an appropriate combining function (Clayton, Frank, Gumbel, etc.) in order to obtain a generator with satisfactory predictive capabilities. Much less complex is the application of the Monte Carlo method with modification of Iman-Conover (1982) allowing to simulate variables that are dependent. In this method, the variability of the considered variables is described by boundary (theoretical) distributions, and the basis for the evaluation of their correlation is the Spearman correlation coefficient. The conditions~~, which~~ that must be met in order for the results obtained to be considered correct, are as follows~~:~~.

– ~~in~~ In the data obtained from simulation and measurements, the mean values ~~$(\mu_1, \mu_2,...,\mu_i)_s$~~ $(\mu_1(x_1), \mu_2(x_2),...,\mu_i(x_i))_s$ and the standard deviations ~~$(\sigma_1, \sigma_2,...,\sigma_i)_s$~~ $(\sigma_1(x_1), \sigma_2(x_2),...,\sigma_i(x_i))_s$ of the variables (x_i) considered in j samples do not differ by more than 5 %.

– The theoretical distributions of x_i variables obtained from simulation should be ~~are~~ consistent with those obtained from measurements; in order to meet this condition it is recommended to use the Kolmogorov-Smirnov (KS) test.

– The value of the correlation coefficient (R) between the individual dependent variables (x_i) obtained for the data from Monte Carlo (MC) simulation does not differ by more than 5 % from the value of R obtained for empirical data.

If the above mentioned conditions are met, the results of the simulation performed with the Iman-Conover (IC) method can be considered correct. If ~~this is not the case~~ these conditions are not met, the sample size of the MC needs to be increased (Wu and Tsang, 2004). ~~In order to~~ To limit the sample size and improve the efficiency of the Iman-Conover (IC) algorithm, a modification has been developed by using the ~~Latin Hybercube~~ Latin hybercube (LH) algorithm, which is part of the layered sampling methods aimed at improving the "uniformity" of the numbers generated from the boundary distributions.

~~On the basis of~~ Based on the determined boundary distributions of rainfall characteristics, the simulations of the synthetic rainfall series were performed with the use of the Monte Carlo (MC) method with Iman-Conover (IC) modifications and taking into account the ~~Latin Hybercube~~ Latin hybercube (LH) algorithm.

4.4 Simulator of annual synthetic rainfall series

~~Currently conducted research in the field of rainfall simulators based on multidimensional boundary distributions combined with the so-called dome functions take into account the distribution of rainfall in the rainfall episode (Vernieuwe et al., 2015), spatial diversity of rainfall (Dai et al., 2014), seasons (Khedun et. al., 2014) and the period separating subsequent rainfall events (Balistrocchi and Bacchi, 2011). The studies conducted in this way are very important from the point of view of the most accurate mapping of stormwater outflow from urban and agricultural catchments in terms of rainwater management and facility design. At present, however, a significant problem is simulation of continuous precipitation values, and a simpler task, which is being considered in practice, seems to be the identification of rainfall genesis, i.e. whether rainfall is the result of convective processes taking place in the air mass, processes in the zone of moving atmospheric fronts or is connected with extensive convergence zones. In many cases, this information may constitute a valuable source of knowledge, which enables the identification of rainfall characteristics (Suligowski, 2004), which may be useful at the stage of operation of the underground infrastructure systems and river basins. Taking into account the above considerations, an innovative precipitation simulator was developed (Figure 5), in which the genesis of rainfall plays a key role.~~

The paper presents two approaches to the simulation of rainfall series. In the first approach to the simulation, the average annual number of precipitation events (convective rainfall in air mass, frontal rainfall and rainfall in convergence zone was assumed (Figure 4). In the second approach, it was assumed that the number of rainfall events of the appropriate genetic type is stochastic.

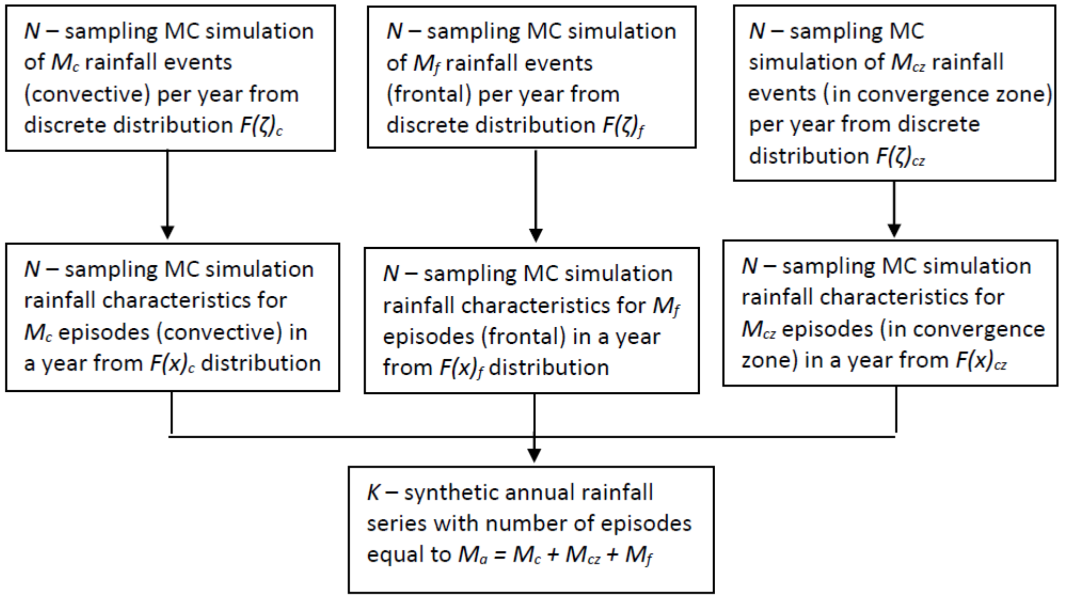


Figure 4: ~~Figure 5~~ Algorithm of the simulation of annual rainfall series, taking into account the generation of rainfall. *N* – number of modelled samples for *M* rainfall episodes (N= 500); *K* – number of samples of rainfall characteristics modelled with IC + LH method (*K* = 1000); Explanations of the other symbols are in the Appendix.

Within the framework of the conducted analyses, an attempt was made to establish simplifications related to the omission of the impact of rainfall genesis on the annual number of storm overflows. Based on the calculation algorithm (Figures 3, 4) and the proposed rainfall generator, several simulation variants were considered. In the simplest case, all rainfall events were considered regardless of their genesis. Thus, the average number of rain events per year – $M=const(x_i)$ – was assumed. In the next case rainfall of different genesis (convective, frontal, and in convergence zone) was taken into account. This approach reflects the different dynamics of rainfall and the changing number of rainfall episodes in the year - $M=var(x_i)$. In addition, an attempt was made to analyse the intermediate variants. The differentiated number of rainfall events in the year was taken into account, but the genesis – $M=f(x_i, M=var)$ – was omitted.

5 Results

Following the above mentioned methodology concerning the structure of the individual elements of the probabilistic model (Figure 3 ~~Figure 4~~), calculations were made. ~~They~~ The calculations consisted ~~in~~ of the determination of the logit model, the identification of empirical distributions and theoretical rainfall characteristics, the simulation of synthetic rainfall series with the inclusion of rainfall genesis and the modelling ~~forecast~~ of the annual number of overflows ~~overflow discharges~~.

5.1 Logit model and verification

Based on the results of the measurements of storm overflow (OV) and rainfall described in detail in the sections above and in the works of Szelag et al. (2013, 2018), independent rain events were separated, on the basis of which the logit model was determined. In the case of independent variables such as P_{tot} and t_r, the logit model takes the form (Szeląg et al., 2018):

$$p = \frac{\exp(0.566 \cdot P_{tot} - 0.004 \cdot t_r - 2.152)}{1 + \exp(0.566 \cdot P_{tot} - 0.004 \cdot t_r - 2.152)} \quad (3)$$

It The logit model is characterized by satisfactory predictive abilities because the value of SPEC= 96.90 % (out of 106 overflows overflow discharges in 103 episodes the model correctly identified the event), SENS= 98.20 % (out of 165 events, the 162 overflows overflow discharges were correctly classified using the model) and R_z^2= 97.78 % (out of 271 observed episodes, in 265 events the calculation results were consistent with the measurements).

If only the average rainfall intensity (i) (q) was included in the analyses, a logit model of the form was obtained:

$$p = \frac{\exp(0.312 \cdot q - 1.257)}{1 + \exp(0.312 \cdot q - 1.257)} \quad (4)$$

$$p = \frac{\exp(0.312 \cdot i - 1.257)}{1 + \exp(0.312 \cdot i - 1.257)} \quad (4)$$

An interesting result of the research is the fact that it is possible to simulate storm overflows with satisfactory accuracy only on the basis of rainfall intensity (i). This fact is important from the perspective of constructing models for modelling rainfall. The result obtained in the study indicates the possibility of significant simplification of the construction of the probabilistic model for the simulation of the annual number of overflows. This model is also characterized by satisfactory predictive abilities, because the value of SPEC= 84.90 % (out of 106 overflows overflow discharges, in 90 episodes the model correctly identified the event), SENS= 90.20 % (out of 165 events, the 148 overflows were correctly classified using the model) and R_z^2= 87.82 % (out of 271 observed episodes, in 229 events, the calculation results were consistent with the measurements). An interesting result of the research is the fact that it is possible to simulate discharges with satisfactory accuracy only on the basis of rainfall intensity (q). This fact is important from the point of view of the construction of models for modelling rainfall. The result obtained in the study indicates the possibility of significant simplification of the construction of the probabilistic model for the simulation of the number of discharges.

The values of the SENS (sensitivity) and SPEC (specificity) coefficients are usually calculated to assess the predictive capability of the models. However, SENS = f(SPEC) may also be used for this purpose. In this case, the greater the area value (the maximum value is AUC = 1) between the SENS = SPEC and SENS = f(SPEC) curves is, the more accurate the model will be (Figure 5). To verify the predictive capabilities of the logit models and their dependencies, a calibrated hydrodynamic model was used. The results of the simulation obtained with the hydrodynamic model for data from the period 2008-2017 were compared with the results of the calculations made with the use of the logit models $p = f(i)$ and $p = f((P_{tot}, t_r)$ (see Table 1).

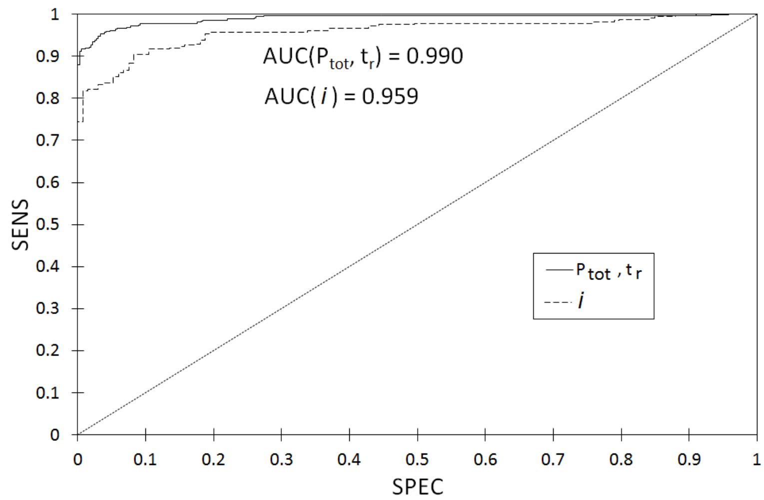


Figure 5: Relation SENS = *f*(SPEC) for the logit curves *p* = *f*(*i*) and *p* = *f*(P_{tot}, t_r)

Table 1: Comparison of the measurements of the annual number of overflow events with the calculations results obtained with hydrodynamic and logit models

Year	Z_a	Z_{SWMM}	$Z_{logit(P,t)}$	$Z_{logit(i)}$
2008	13	15	14	12
2009	15	16	16	14
2010	17	18	19	16
2011	19	20	19	17
2012	13*	21	20/14*	19/11*
2013	13*	22	20/13*	20/11*
2014	16*	29	28/16*	27/14*
2015	25	26	26	23
2016	26	22	21	24
2017	16	17	17	14

* – storm overflow events in the period 2012-2014 determined on the basis of the maximum filling of the diversion chamber (DC). Explanations of symbols are in the Appendix.

The above relations (3) and (4) are of local character and ~~it seems that they~~ can be applied in principle only in relation to the analysed ~~for the investigated research~~ catchment area. With this in mind, an attempt was made to build a universal model by modifying these relations. ~~Considering the above and the need to build universal models, the models formulated above have been transformed.~~ Based on theoretical considerations ~~conducted by~~ of Thorndahl and Willems (2008), ~~who provided a generalised model for forecasting the volume of wastewater discharge via a storm overflow, it can be concluded that in this~~

case the following relations take place who investigated the relationships between the characteristics of catchment areas, including the limit retention that determines the volume of overflow, the following equations were determined:

$$P_{\mathrm{tot}} - 0.007 \cdot t_r = 3.802 \approx d_{\mathrm{av}} \quad (5)$$

$$q = 4.030 \approx d_{\mathrm{av}} \quad (6)$$

$$0.566\, P_{\mathrm{tot}} - 0.004\, t_{\mathrm{r}} - 2.152 = 0 \,/\cdot \frac{1}{0.566} = P_{\mathrm{tot}} - 0.007\, t_{\mathrm{r}} - 3.802 = 0 \quad (5)$$

$$P_{\mathrm{tot}} - 0.007\mathrm{t_r} - 3.802 = P_{\mathrm{tot}} - 0.007 t_{\mathrm{r}} - d_{\mathrm{av}} = 0 \quad (6)$$

$$0.312\, i - 1.257 = 0 \,/\cdot \frac{1}{0.312} = i - 4.03 = 0 \quad (7)$$

$$i - 4.03 = i - d_{\mathrm{av}} = 0 \quad (8)$$

On the basis of the relationships (eq. 5 and eq. 6) it can be concluded that the values of free words obtained in them are similar to the weighted average value of the catchment retention (d_{av}). The relative difference between the values of free words and retention of the catchment area does not exceed 5 %. The result obtained may have a significant practical meaning, as it gives the possibility of transferring the dependencies obtained above to other drainage basins. Nevertheless, in order to confirm this, further detailed analyses on other objects concerning measurements and calculation experiments are necessary.

On the basis of these relationships, it can be concluded that the values of the intercept obtained in them are similar to the weighted average value of the catchment retention (d_{av}). The relative difference between the values of intercept and retention of the catchment area does not exceed 5 %. The simulation calculations of the annual number of overflow events in the tested catchment area confirm the above statement (Table 1). In addition, this fact is supported by the results obtained in Figure 5, which indicate that the results of the simulation of the annual number of overflow events using the hydrodynamic model are within the scope of a probabilistic solution. However, because the presented analyses were performed only for a single catchment, it is necessary to verify the obtained results using examples of other catchments with different physical and geographical characteristics.

5.2 Identification of the empirical and theoretical distributions of the selected rainfall characteristics

Table 2 Table 1 presents the results of the Kolmogorov-Smirnov (KS) and chi-square (Chi) tests of fitting matching the empirical distributions to theoretical distributions for the rainfall characteristics (P_{tot}, t_r, q, M) (P_{tot}, t_r, i, M) depending on the genesis of precipitation and shows the determined parameters coefficients in equations describing theoretical distributions.

Table 2 Table 1: Results of KS and Chi tests and parameters coefficients of theoretical models for considered random variables (P_{tot}, t_r, i, M) (P_{tot}, t_r, q, M) depending on rainfall genesis.

Variable	Distribution	Model parameters	p (KS)	p (Chi)
t_r (year)	GEV	$\zeta = 0.466$; $\sigma = 129.355$; $\mu = 108$	0.096	0.071
P_{tot} (year)	Weibull	$\beta = 0.772$; $\gamma = 5.158$; $\mu = 3.00$	0.121	0.096

~~t_r (convective)~~	~~beta~~	~~α = 1.391; β = 1.173; c =5.5; d = 150~~	~~0.268~~	~~0.173~~
~~P_{tot} (convective)~~	~~Weibull~~	~~β = 0.821; γ = 3.102; μ = 3.00~~	~~0.477~~	~~0.412~~
~~t_r (frontal)~~	~~Weibull~~	~~β = 1.201; γ = 164.99; μ = 150~~	~~0.639~~	~~0.589~~
~~P_{tot} (frontal)~~	~~Weibull~~	~~β = 0.968; γ = 6.054; μ = 3.00~~	~~0.353~~	~~0.314~~
~~P_{tot} (frontal, type I)~~	~~Weibull~~	~~β = 0.862; γ = 4.535; μ = 3.00~~	~~0.631~~	~~0.425~~
~~t_r (frontal, type I)~~	~~beta~~	~~α = 1.221; β = 1.372; c =150; d = 270~~	~~0.200~~	~~0.145~~
~~P_{tot} (frontal, type II)~~	~~Weibull~~	~~β = 1.065; γ = 7.222; μ = 3.00~~	~~0.397~~	~~0.342~~
~~t_r (frontal, type II)~~	~~beta~~	~~α = 0.829; β = 1.562; c = 266; d = 650~~	~~0.270~~	~~0.226~~
~~t_r (convergence zone)~~	~~Weibull~~	~~β = 0.802; γ = 276.138; μ = 650~~	~~0.947~~	~~0.879~~
~~P_{tot} (convergence zone)~~	~~log-normal~~	~~σ = 0.603; μ = 3.00~~	~~0.969~~	~~0.856~~
~~q (year)~~	~~log-normal~~	~~σ = 1.932; μ = 0.855~~	~~0.112~~	~~0.096~~
~~q (convective)~~	~~log-normal~~	~~σ = 2.557; μ = 0.694~~	~~0.238~~	~~0.211~~
~~q (frontal)~~	~~log-normal~~	~~σ = 1.485; μ = 0.644~~	~~0.906~~	~~0.878~~
~~q (frontal, type I)~~	~~log-normal~~	~~σ = 1.701; μ = 0.612~~	~~0.104~~	~~0.085~~
~~q (frontal, type II)~~	~~log-normal~~	~~σ = 1.289; μ = 0.611~~	~~0.059~~	~~0.056~~
~~q (convergence zone)~~	~~log-normal~~	~~σ = 1.296; μ = 0.497~~	~~0.942~~	~~0.923~~
~~M (year)~~	~~Poisson~~	~~λ = 32.80~~	~~0.624~~	~~0.053~~
~~M (convective)~~	~~Poisson~~	~~λ = 14.33~~	~~0.871~~	~~0.756~~
~~M (frontal)~~	~~Poisson~~	~~λ = 15.95~~	~~0.372~~	~~0.831~~
~~M (convergence zone)~~	~~Poisson~~	~~λ = 2.55~~	~~0.067~~	~~0.652~~

Variable	Distribution	Model parameters	p (KS)	p (Chi)
P_{tot} (all events)	Weibull	β = 0.772; γ = 5.158; μ = 3.00	0.121	0.096
t_r (all events)	GEV	ζ = 0.466; σ = 129.355; μ = 108	0.096	0.071
i (all events)	log-normal	σ = 1.932; μ = 0.855	0.112	0.096
M (all events)	Poisson	λ = 32.80	0.624	0.053
P_{tot} (convective)	Weibull	β = 0.821; γ = 3.102; μ = 3.00	0.477	0.412
t_r (convective)	beta	α = 1.391; β = 1.173; c =5.5; d = 150	0.268	0.173
i (convective)	log-normal	σ = 2.557; μ = 0.694	0.238	0.211
M (convective)	Poisson	λ = 14.33	0.871	0.756
P_{tot} (frontal)	Weibull	β = 0.968; γ = 6.054; μ = 3.00	0.353	0.314
t_r (frontal)	Weibull	β = 1.201; γ = 164.99; μ = 150	0.639	0.589
i (frontal)	log-normal	σ = 1.485; μ = 0.644	0.906	0.878
M (frontal)	Poisson	λ = 15.95	0.372	0.831
P_{tot} (frontal, type I)	Weibull	β = 0.862; γ = 4.535; μ = 3.00	0.631	0.425
t_r (frontal, type I)	beta	α = 1.221; β = 1.372; c =150; d = 270	0.200	0.145
i (frontal, type I)	log-normal	σ = 1.701; μ = 0.612	0.104	0.085
P_{tot} (frontal, type II)	Weibull	β = 1.065; γ = 7.222; μ = 3.00	0.397	0.342
t_r (frontal, type II)	beta	α = 0.829; β = 1.562; c = 266; d = 650	0.270	0.226
i (frontal, type II)	log-normal	σ = 1.289; μ = 0.611	0.059	0.056

P_{tot} (in convergence zone)	log-normal	σ = 0.603; μ = 3.00	0.969	0.856
t_r (in convergence zone)	Weibull	β = 0.802; γ = 276.138; μ = 650	0.947	0.879
i (in convergence zone)	log-normal	σ = 1.296; μ = 0.497	0.942	0.923
M (in convergence zone)	Poisson	λ = 2.55	0.067	0.652

where: type I – cold front, type II – warm front.

~~On the basis of~~ Based on the data in Table 2 ~~Table 1~~ it appears that the empirical distributions can be expressed by means of the following theoretical distributions:

Weibull:

$$f(x) = \frac{\beta}{\gamma} \cdot \left(\frac{x-\mu}{\gamma}\right)^{\beta-1} \cdot \mathrm{e}^{-\left(\frac{x-\mu}{\gamma}\right)^{\beta}} \qquad (9)$$

log-normal:

$$f(x) = \frac{1}{x \cdot \sigma \cdot \sqrt{2 \cdot \pi}} \cdot \mathrm{e}^{\frac{(\ln(x)-\mu)^2}{2 \cdot \sigma^2}} \qquad (10)$$

generalized maximum value (GEV):

$$f(x) = \frac{1}{\sigma} \cdot (1 + \xi \cdot (x-\mu)/\sigma)^{\frac{-1}{\xi-1}} \cdot \mathrm{e}^{\left[-1 \cdot (1+\xi \cdot (x-\mu)/\sigma)^{\frac{-1}{\xi}}\right]} \qquad (11)$$

beta:

$$f(x) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha) \cdot \Gamma(\beta)} \cdot \frac{(x-c)^{\alpha-1} \cdot (x-d)^{\beta-1}}{(d-c)^{\alpha+\beta-1}} \qquad (12)$$

Poisson:

$$f(x) = \frac{\mathrm{e}^{-\lambda} \cdot \lambda^x}{x!} \qquad (13)$$

where the following are defined: $\beta, \gamma, \lambda, \mu, \sigma, \xi$ – parameters of distributions determined by the maximum likelihood estimation (MLE) method.

The calculations performed ~~(Table 1)~~ (Table 2) showed that in most cases the Weibull distribution in the form (eq. 9) ~~(eq. 7)~~ is the best suited to the empirical data describing the variability of the total depth of rainfall (P_{tot}) in a rainfall episode. ~~Also~~ In addition, the variation in rainfall duration ~~in~~ of the episodes resulting from rainfall of different genesis ~~in most cases~~ is described, in most cases, by the Weibull distribution and only in the case of the data measured over an annual cycle is it expressed better by the GEV distribution (eq. 11) ~~(eq. 9)~~. The values of the rainfall intensities of different genesis are, in most cases, described by log-normal distributions (eq. 10) ~~(eq. 8)~~, whereas in the case of the rain intensity caused by frontal precipitation, its dynamics ~~is~~ are described by a generalized distribution of extreme values. Satisfactory adjustment of the calculation results to the measurements of the tested variables of a continuous nature is confirmed by the curves shown in Figures 6–7.

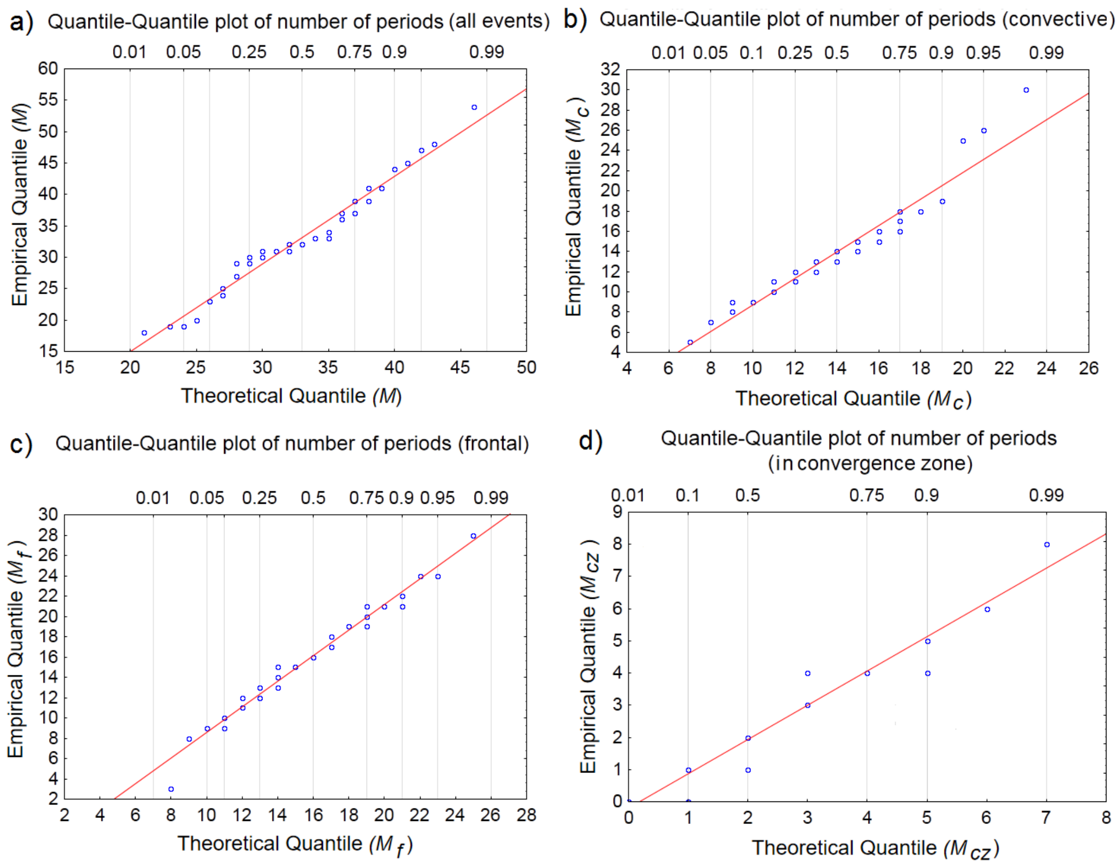


Figure 6: Comparison of empirical and theoretical quantiles concerning the number of rainfall episodes and distinguishing rainfall types: (a) all events (b) convective, (c) frontal, (d) in convergence zone.

~~**Figure 6: Comparison of quantiles of empirical distributions and theoretical number of precipitation episodes per year for the rainfall type: (a) all events, (b) convective, (c) frontal, (d) convergence zone.**~~

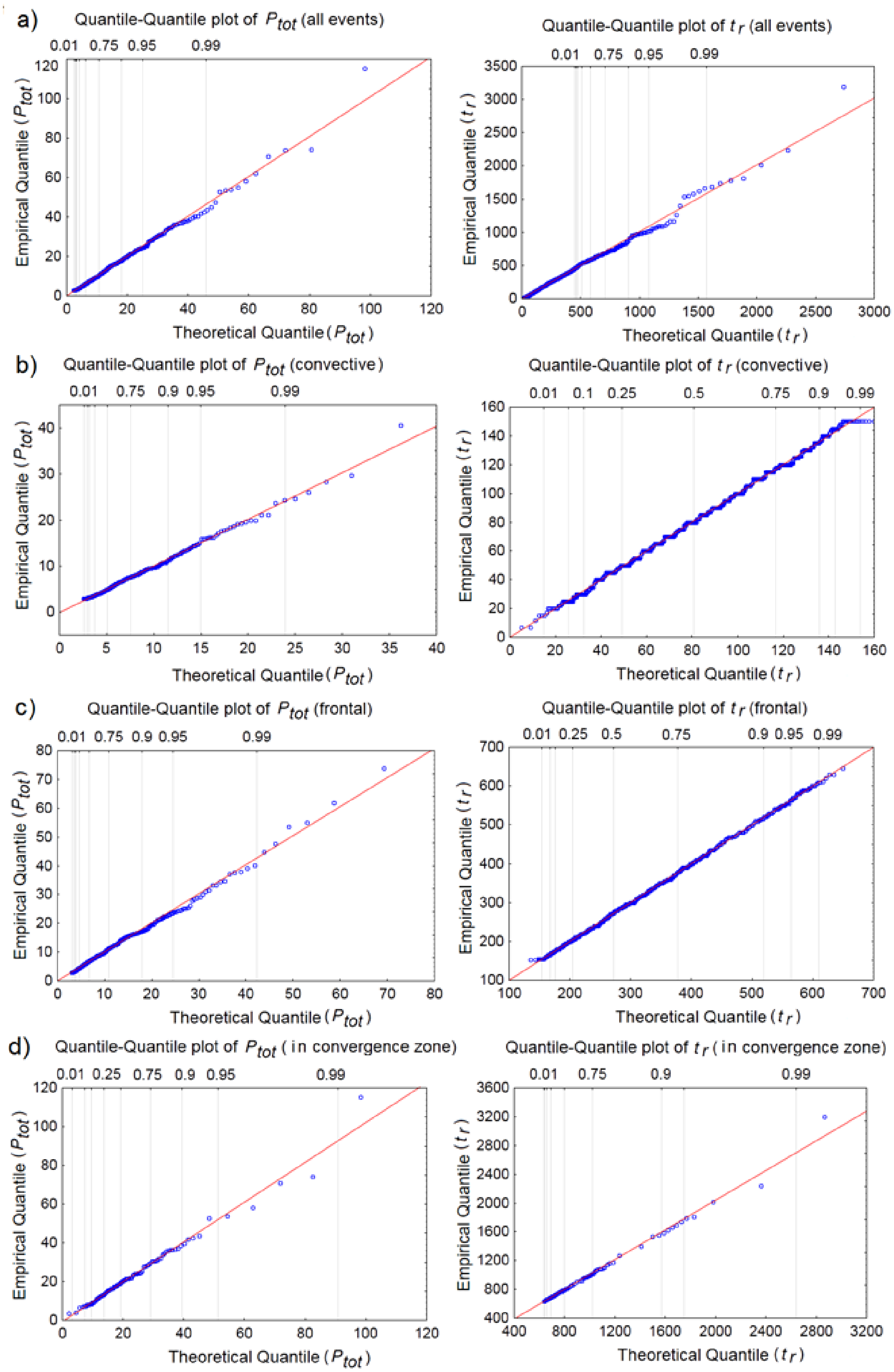


Figure 7: Comparison of empirical and theoretical quantiles concerning P_{tot} and t_r values for: (a) all events, (b) convective, (c) frontal, and (d) rainfall in convergence zone.

Figure 7: Comparison of quantiles of empirical and theoretical distributions of P_{tot} and t_r values for: (a) all events, (b) convective, (c) frontal, and (d) convergence zone rainfall.

The curves in Figure 6 and Figure 7, illustrating the fitting of the quantile values obtained from the measurements and based on the specific theoretical distributions in most of the cases considered, show a high agreement of the data in relation to the number of rainfall events per year ($M_{c,f,cz}$), precipitation altitude and duration (P_{tot}, t_r). For the distribution describing the annual number of events, the values of the minimal quantiles are overstated by 5, while the maximal values are understated by 7. As a result, this distribution may affect the results of the determined number of storm overflows.

In the case of discrete variables, the number of rainfall events in a year of different genetic type is described by Poisson's distribution (eq. 11) with satisfactory accuracy. Only for the variability of episodes recorded in the annual cycle, significant differences in the results of measurements and calculations were found. Therefore, by the simulation of the annual number of overflow discharges, the variant in which the variability of the number of precipitation episodes in the year is included, was abandoned.

5.3. Impact of rainfall genesis on the probability of storm overflow occurrence

Based on the models determined for the modelling forecast of storm overflow discharge and the determined theoretical rainfall distributions, the impact of rainfall genesis on the occurrence of a single storm overflow discharge was calculated determined in the first place. Taking into account the different predictive abilities of the logit models obtained, the analyses were limited to calculations with a model that best represented the existing state. The results of the simulations are shown in Figure 8.

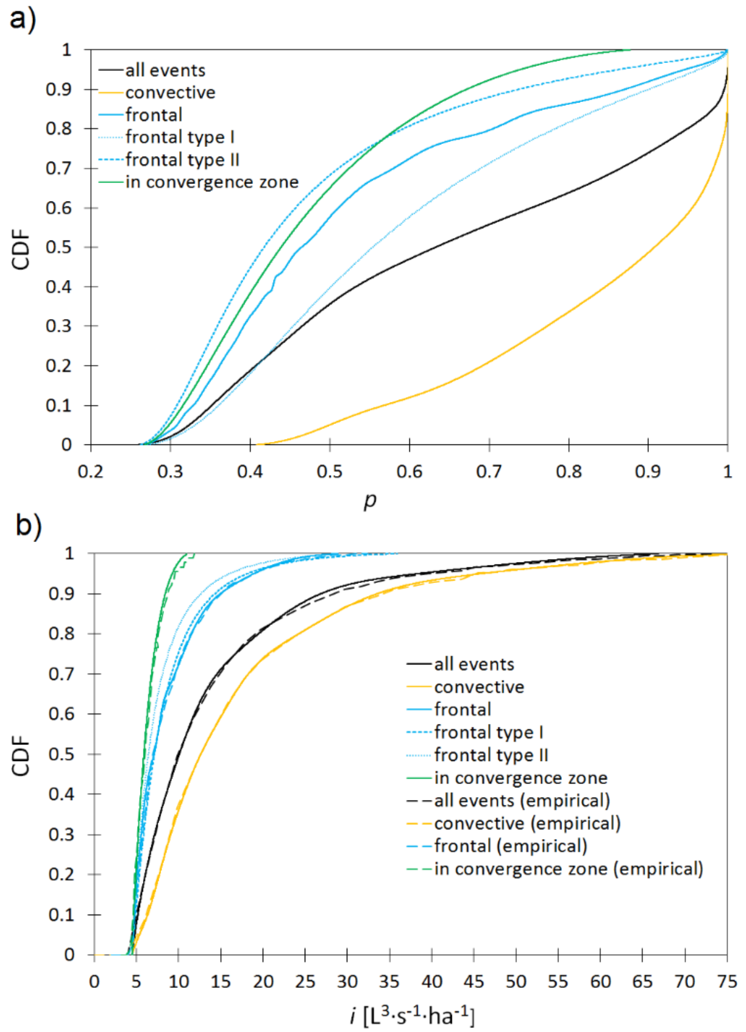


Figure 8: (a) Impact of rainfall genesis on: a) the probability of storm overflow ~~discharge~~, (b) rainfall intensity distribution determining storm overflow in a single episode.

Within the framework of the conducted analyses, the division of frontal rainfall events of the duration not longer than 4.5 h (related to the cold front – frontal type I) and exceeding the given value (due to the displacement of the warm front – frontal type II) was additionally distinguished ~~made~~. Based on the curves shown in Figure 8a, it can be concluded that the greater probability of storm overflow ~~discharge~~ was obtained for events caused by convective rainfall episodes. For precipitation of this genesis, the minimum probability of storm overflow ~~discharge~~ is not less than 0.40 and the percentile value 0.50 ~~percentile value $p = 0.50$~~ is as high as 0.90. In order to verify the obtained relationship using a probabilistic model, empirical curves plotted based on the measurement data (Figure 8b). Curves obtained on the basis of measurements and simulations show high compliance, which confirms the usefulness of the determined model.

5.4. Impact of rainfall genesis on the average rainfall intensity occurrence of a storm overflow

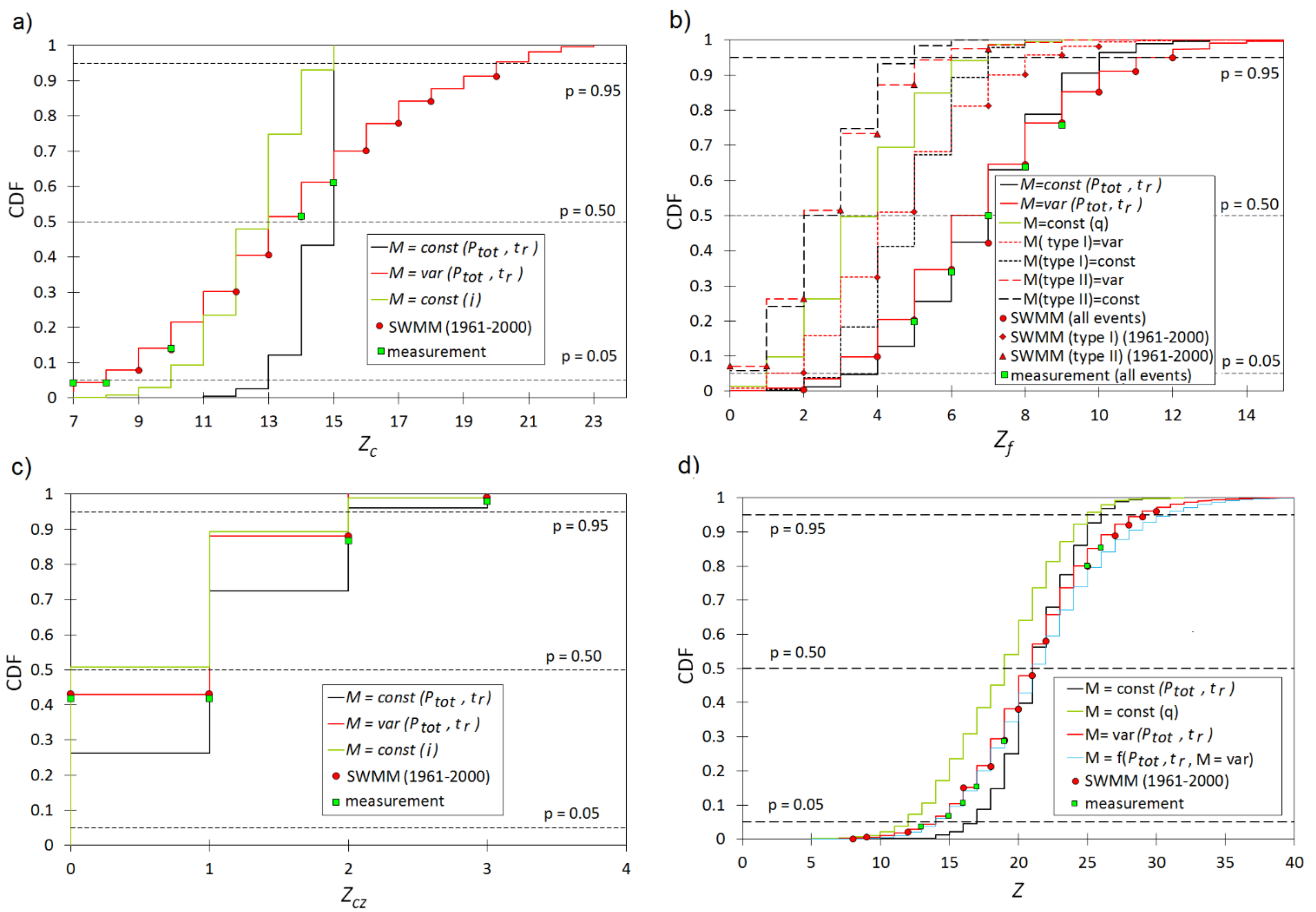
Based on the results of the calculations obtained above, the ranges of the variability of the average rainfall intensity (i) were determined depending on the genesis conditioning the occurrence of a storm overflow (Figure 8). ~~This confirms that most convective rainfall leads to storm overflow discharge, and the value q is in the range of 4.49–75.00 L s^{-1} ha^{-1} (Figure 8b).~~ Based on the determined curves, it can be stated that among the analysed rainfall, the highest range of variability of values i = 4.49–75.00 L s^{-1} ha^{-1} was obtained for convective rainfall (Figure 8b). From the point of view of modelling and forecasting, ~~it~~ this result seems to be interesting because the information about the genesis of precipitation (it is now generally available information) ~~allows to assess~~ enables assessing, to some extent, the conditions of the functioning stormwater systems ~~functioning~~. ~~On the basis of~~ Based on the analysis of the variability of curves from Figure 8a and 8b, it can be stated that the lowest probability of storm overflow ~~discharge~~ is obtained in the case of rainfall in the convergence zone ~~q = 4.49–10.94 L s^{-1} ha^{-1}~~ i = 4.49–10.94 L s^{-1} ha^{-1} and rainfall in the warm front zone (with a duration longer than 4.5 h), for which ~~q = 4.49–28.50 L s^{-1} ha^{-1}~~ i = 4.49–28.50 L s^{-1} ha^{-1}. In the analysed case, it was ~~obtained~~ determined that for p = 0–0.57 in the examined catchment the lowest probability value is obtained for episodes caused by precipitation in the warm front zone ($t_r \geq 4.5$ h), while for higher p values, the lowest probability of overflow ~~discharge~~ occurrence is obtained as a result of rainfall in the convergence zone ~~of convergence zones rainfall~~ (Figure 8a). This fact can be justified by the physics of the studied phenomenon. In the case of rainfall in convergence zone ~~convergence zone rainfall~~ a lasting relatively long time, the average rainfall intensity is lower than in the case of frontal rainfall with a rainfall duration longer than 4.5 h.

Dependencies requiring commentary were also obtained for frontal precipitation ($t_r \geq 2.5$ h), for which ~~q = 4.49–35.50~~ i = 4.49–35.50 L s^{-1} ha^{-1}. The conducted analyses showed that with the increase ~~of~~ in p values, the difference in absolute values of the probability of storm overflow ~~discharge~~ caused by precipitation being the effect of the cold (t_r = 2.5–4.5 h) and warm ($t_r \geq 4.5$ h) front increases (Figures 8a, 8b). The difference between individual values of p (p_I–p_{II}) between individual curves increases ~~up~~ to 0.20 for p = 0.60 and then decreases. It is worth noting that this difference (its maximum value) includes episodes in the case of frontal precipitation caused by a cold and warm front (it corresponds to ~~q = 4.49–35.50~~ i = 4.49–35.50 L s^{-1} ha^{-1}), when storm overflows ~~discharge occur~~ take place, i.e., when $p > 0.50$. The attention is drawn to the fact that the variability of the curve describing the probability of storm overflow ~~discharge~~ by the effect of frontal rainfall, for which $t_r \leq$ 4.5 h, shows in the range of p = 0–0.55 a similar variability to the curve obtained for rainfall data regardless of their genesis. For $p > 0.55$, a greater probability of storm overflowing ~~discharging~~ due to all rainfall events than precipitation lasting t_r = 2.5–4.5 h was found. The curves determined in Figure 8b may indicate lower values of i ~~lower values of q~~ for rainfall episodes t_r = 2.5–4.5 h than when ~~$q > 4.86$~~ $i > 4.86$ L s^{-1} ha^{-1} which corresponds to all rainfall.

5.5 Impact of rainfall genesis on the annual number of overflow events

~~Simulation~~ The simulation calculations performed with the use of the logit model described by ~~equation~~ eq. (3) showed that the annual number of overflows ~~overflow discharges~~ resulting from convective rainfall, frontal rainfall, and rainfall in convergence zone ~~convergence zones precipitation~~ is lower in the case of using the simplified model taking into account only the i value ~~q value~~ (Figure 9). These results are confirmed by the value of average retention in logit models, i.e., when ~~$d = 3.80$~~ $d_{av} = 3.80$ mm (in ~~exact model~~ the model that takes into account the genesis of rainfall) and ~~$d = 4.32$ mm~~ $d_{av} = 4.32$ mm (in the simplified model with lower predictive capabilities).

~~On the basis of~~ Based on the calculations, it was found that the inclusion in the simulation of the annual number of storm overflows ~~overflow discharges of the~~ with a stochastic character of rain events has a significant impact on the results of the analyses. The analyses showed that in the case of precipitation caused by convection in air mass and frontal rainfall, the annual number of overflows ~~overflow discharges~~ (percentile value 0.50 ~~value $p = 0.50$~~) is lower when the number of episodes is described by Poisson's distribution.



~~**Figure 9: (a) Distribution function (CDF) showing the annual number of discharges due to convective rainfall; (b) Distribution function (CDF) showing the annual number of discharges due to frontal rainfall; (c) Distribution function (CDF) showing the annual number of discharges due to convergence zones precipitation; (d) Curve showing the probability of exceeding the annual number of discharges.**~~

Figure 9: Distribution function (CDF) showing the annual number of storm overflow events (Z) caused by: (a) convective rainfall, (b) frontal rainfall, (c) rainfall in convergence zone; (d) Curve showing the probability of non-exceeding the annual number of overflows (Z). Explanations of the other symbols are in the Appendix.

The calculations show that in the case of storm overflows ~~overflow discharges~~ resulting from convective precipitation, the stochastic nature of the precipitation has a significant impact on the values of the lower and upper percentiles (Figure 9a). For example, for the percentile value 0.05 ~~$p = 0.05$~~, the difference in the annual number of overflows ~~overflow discharges~~ obtained with the assumption of M = var is 5 times greater than the solution when the average number of precipitation events per year was assumed. For the percentile value 0.95 ~~percentile value $p = 0.95$~~, the difference in the annual number of overflows ~~overflow discharges~~ between the considered solutions is 4. In the case of storm overflows ~~overflow discharges~~ resulting from frontal rainfall (Figure 9b), the difference in the annual number of overflows ~~overflow discharges~~ obtained for the variants when M = const and M = var is much smaller than for convective rainfall (Figure 9a). This difference may be due to a significant variation in the number of convective and frontal rainfall events over an annual cycle and the variation in rainfall intensity in both cases. ~~Analysing~~ By analysing the results of the simulation, it can be concluded that when the number of precipitation episodes (convective, frontal, and in convergence zone) is determined by Poisson's distribution, the calculated annual number of overflows ~~overflow discharges~~ for $p < 0.50$ is smaller than when M = const (Figure 9). On the other hand, for $p > 0.50$, the inverse relation is maintained. The influence of the theoretical distribution of the number of rainfall events per year on the values of percentiles 0.50–0.99 ~~of $0.99 > p > 0.50$~~ is confirmed by Szeląg et al. (2018). ~~On the basis of~~ Based on the implemented simulations ~~made~~ and designed curves, ~~designed~~ it can be established that the average annual number of overflows ~~overflow discharges~~ resulting from convective rainfall is 15 (Figure 9a), and in the case of frontal rainfall and rainfall in convergence zone it is much smaller and equals 7 and 1, ~~respectively,~~ assuming that M = const (Figures 9b, 9c). In the case of storm overflows ~~overflow discharges~~ caused by frontal overflow, it was found ~~on the basis of~~ based on the determined curves that out of 7 overflows, ~~overflow discharges~~ as many as 5 ~~of them~~ are caused by rainfall connected with a cold front (type I), for which the duration of rainfall does not exceed t_r= 4.5 h (Figure 9b). Very interesting results were obtained in the calculation variant, in which the number of rain events in a year was taken into account, regardless of their genesis. The average annual number of storm overflows for $p > 0.5$ is then greater than the number of overflows taking into account the rainfall genesis (Figure 9d). In conclusion, the omission of rainfall genesis in the calculations may result in the overestimation of the average annual number of storm overflows. This overestimation affects the designed storm overflow height and the functioning of facilities located in the sewage network, e.g., stormwater treatment plants.

The innovative synthetic precipitation generator proposed in the paper ~~allows to quantify~~ enable the quantification of the impact of rainfall genesis on the annual number of storm overflows ~~overflow discharges~~ (Figure 9d), which until now, has not been included in the models developed by other authors. This approach can be transferred to other facilities located in stormwater systems and used to assess the effectiveness of stormwater drainage systems. Ultimately, the results obtained ~~in this way~~ with this approach may be the basis for the construction of an expert system for early warning ~~of~~ about torrential phenomena caused by heavy rainfall. ~~The~~ Another advantage of the developed probabilistic model is ~~also~~ the possibility it provides to perform simulations of a long-term nature (multiannual), and thus, to assess the impact of the distribution of individual precipitation types ~~of precipitation~~ on the annual number of storm overflows ~~overflow discharges~~ and its variability.

The simulation calculations performed with the calibrated hydrodynamic model of the catchment area show that the results of the simulation of the annual number of storm overflow events (Figure 9d) caused by precipitation of different genesis are within the scope of the solution obtained with the probabilistic model. This finding confirms that the probabilistic model developed in the paper is an alternative solution to the hydrodynamic model. This fact is also confirmed by the annual number of overflow events caused by rainfall of different genesis obtained on the basis of measurements (Figure 9d). The conformity of the simulation results obtained with the probabilistic and hydrodynamic model may indicate that the values of the intercept determined in the relevant equations may correspond to the depth of the weighted average retention of the catchment area.

6 Conclusions

The calculations performed showed that the measurements of average rainfall intensity can be used to simulate (using a logit model) the storm overflow occurrence ~~discharge~~ in a single rain episode. The simulation results obtained do not differ significantly from the calculations made ~~on the basis of~~ based on the rainfall depth and duration. In both models, it was shown that the numerical value of the ~~free word~~ intercept in the model equations does not differ by more than 10 % from the depth ~~height~~ of the weighted average retention of the catchment area. This fact has a significant practical meaning because it ~~gives~~ provides the possibility of using ~~to transfer~~ the results obtained in ~~to~~ other urban ~~municipal~~ catchments. However, in order to confirm this, further analyses on catchment areas with different physical and geographical characteristics are advisable.

The computational experiments carried out in the study allowed an assessment of ~~to~~ ~~assess~~ the influence of the rainfall genesis (convective in air mass, frontal ~~– cold and warm~~, and in convergence zone ~~precipitation~~) on the occurrence of storm overflow ~~discharge~~. Moreover, the ranges of the variability of the average rainfall intensity were determined, for which storm overflows ~~overflow discharges~~ were found. The information obtained may be used in engineering practice because on ~~its~~ this basis, it is possible to determine whether a storm overflow ~~discharge~~ will take place.

The identification ~~Identification~~ of the operational state ~~of operation~~ of the stormwater system (in this case, storm overflow ~~discharge~~) ~~on the basis of the~~ based on forecasting ~~identification of~~ the weather ~~rain~~ front may be of ~~have a significant~~ practical significance. ~~It~~ This identification of the operational state provides an opportunity to develop an early warning system against the occurrence of emergencies (spill of stormwater to the surface, hydraulic overload of pipes, overfilling of tanks) in stormwater systems.

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Appendix 1. List of symbols and abbreviations

AUC	area under curve
CDF	cumulative distribution function of probability density
Chi	chi-square test
DC	diversion chamber
d_{av}	weighted mean of the retention depth of the catchment area
$f(x)$	probability density function
$F(x)_c$	theoretical distribution to simulate rainfall characteristics due to convective rainfall
$F(x)_f$	theoretical distribution to simulate rainfall characteristics due to frontal rainfall
$F(x)_{cz}$	theoretical distribution to simulate rainfall characteristics due to rainfall in the convergence zone
$F(\zeta)_c$	theoretical distribution to simulate the annual number of convective rainfall events
$F(\zeta)_f$	theoretical distribution to simulate the annual number of frontal rainfall events
$F(\zeta)_{cz}$	theoretical distribution to simulate the annual number of rainfall events in the convergence zone
FORM	first-order reliability model
i	average rainfall intensity; 166.7 P_{tot} /t_r [$L \cdot s^{-1}$ ha^{-1}]
IC	Iman-Conover method
K	number of samples modelled using the Monte Carlo method of annual rainfall series
KS	Kolmogorov-Smirnov test
LH	Latin-hypercube method
M	annual number of rainfall events
$M = const(i)$	calculation variant (annual number of overflow events), in which for simulation constant average annual number of rainfall events is used and to identify the overflow in a rainfall episode the following logit models were applied logit model $p = f(i)$
$M = const(P_{tot}, t_r)$	calculation variant (annual number of overflow events), in which for the simulation, the constant average annual number of rainfall events is used, and for identifying the

	overflow in a rainfall episode, the following logit models were applied: logit model $p = f(P_{tot}, t_r)$
$M = var(i)$	calculation variant (annual number of overflow events), in which the annual number of rainfall events caused by precipitation (convective, frontal, and in the convergence zone) is modelled, and for identification of overflow in a rainfall episode, the following logit models were applied: logit model $p = f(i)$
$M = var(P_{tot}, t_r)$	calculation variant (annual number of overflow events), in which the annual number of rainfall events caused by precipitation (convective, frontal, and in the convergence zone) is modelled, and for identification of overflow in a rainfall episode, the following logit models were applied: logit model $p = f(P_{tot}, t_r)$
M_c	annual number of convective rainfall events
M_f	annual number of frontal rainfall events
M_{cz}	annual number of rainfall events in the convergence zone
MC	Monte Carlo simulation
MES1, MES2	flowmeter measures
MLE	maximum likelihood estimation
N	number of samples in the Monte Carlo simulation
OV	storm overflow
p	probability of a storm overflow event
P_{tot}	total rainfall [mm]
t_r	rainfall duration [min]
R	Spearman's correlation coefficient
R_z^2	counting error
SENS	sensitivity
SPEC	specificity
STP	stormwater treatment plant
SWMM	Stormwater Management Model
Z	annual number of storm overflow events
Z_c	annual number of storm overflow events due to convective rainfall
Z_f	annual number of storm overflow events due to frontal rainfall
Z_{cz}	annual number of storm overflow events due to rainfall in the convergence zone
x_i	independent variables included in the logit model
α_i	values of estimated coefficients in the logit model
$\alpha, \beta, \gamma, \lambda, \mu, \sigma, \zeta$	empirical coefficients estimated in statistical distributions
$(\mu_1(x_1),..., \mu_i(x_i))_s$	mean value of variable x_i in the data set obtained from simulation using the Iman-Conover method
$(\sigma_1(x_1),..., \sigma_i(x_i))_s$	value of standard deviation of variable x_i in the data set obtained from simulation using the Iman-Conover method