

1           **Simulation of the number of storm overflows considering changes in precipitation**  
2           **dynamics and the urbanisation of the catchment area: a probabilistic approach**

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28 **Abstract**

29 This paper presents a probabilistic methodology that allows the study of the interactions  
30 between changes in rainfall dynamics and impervious areas in urban catchment on a long- and  
31 short-term basis. The proposed probabilistic model predict future storm overflows while  
32 taking into account the dynamics of changes in impervious areas and rainfall. In this model, a  
33 logistic regression method was used to simulate overflow resulting from precipitation events  
34 based on average rainfall intensity and impervious area. The adopted approach is universal (as  
35 it can be used in other urban catchments) and is a significant simplification of classic  
36 solutions; a hydrodynamic model is used to analyse the operation of the overflow. For the  
37 rainfall simulations, a rainfall generator based on the Monte Carlo method was used. In this  
38 method, a modification that allows the simulation of changes taking place in rainfall  
39 dynamics, including the effects of climate change, was introduced. This method provides the  
40 opportunity to expand and modify probabilistic models in which outflow from the catchment  
41 is modelled to predict the functioning of reservoirs and to design sewer networks that have the  
42 ability to deal with future rainfall dynamics, including moderate, strong, and violent  
43 downpours according to the Sumner scale.

44 To verify the simulation results with a probabilistic model, an innovative concept using a  
45 hydrodynamic model was considered. This verification considers the changes in the  
46 impervious area in the period covered by the simulations and is limited using standard  
47 calculation procedures.

48 In practice, the model presented in this work creates opportunities for defining the concept of  
49 sustainable development in urban catchments while taking into account the factors mentioned  
50 above. From the perspective of landscaping, this is important because it creates the  
51 opportunity to limit the impacts of climate change and area urbanization on the receiving  
52 waters.

53

54 **Keywords:** logistic regression, storm overflow, probabilistic model, urbanization, rainfall  
55 dynamics, sustainability.

56

## 57 **1. Introduction**

58 Storm overflows constitute important objects in sewage networks. Based on the main  
59 conditions of overflows, including the discharge volume, maximum flow, pollution load and  
60 the yearly number of storm overflows, it can be determined whether a studied sewage system  
61 operates correctly or requires modernization (Fortier and Malhot, 2015; Tavakol-Davani et  
62 al., 2016; Jean et al., 2018). In this case, it is necessary to compare the resulting (determined  
63 by measurements) number of storm overflows with their number specified in legal acts and  
64 industrial documents. The precise determination of the number of storm overflows and their  
65 variation serves an important function since it can be one of the factors upon which the  
66 selection of an optimal pattern for the modernisation of a sewage network is based (DWA-M  
67 180E). In numerous cases, modernisation of stormwater management systems is associated  
68 with high expenses. It is therefore necessary to optimise the selection of adopted solutions  
69 that are already at the design stage of sewage network conversions to achieve the pursued  
70 ecological effect (McGrane, 2016; Liu et al., 2017; Zhang et al., 2018).

71 Assessments of the impacts of adopted sewage network solutions on changes in the number of  
72 overflows and the operating conditions of storm overflows are performed using  
73 hydrodynamic models (Kleidorfer et al., 2009; McGrane, 2016). Models constitute a useful  
74 tool when analysing the operations of sewage networks, but their construction requires a  
75 database containing the characteristics of the catchment area and the drainage network as well  
76 as measurements of precipitation and flows (with a high temporal resolution). Despite this,  
77 these models have a local nature; the cost of their preparation is high, and the results of model  
78 simulations do not always correspond to measured data (Elliott and Trowsdale, 2007;  
79 Thorndahl and Willems, 2008; Jean et al., 2019). However, access to universal tools that can  
80 be used for urban catchment areas with diverse physical-geographical characteristics without  
81 the need for model calibration is currently limited. This represents a current problem since

82 there is a high demand for tools that enable quick analyses of the actions of stormwater  
83 drainage systems during the concept formulation stage spatial development in urban areas.  
84 Because of this, attempts have been made to construct models that simulate the operations of  
85 sewage networks (storm overflows and sewer overflows) and could be used for various  
86 catchment areas. Such analyses are presented by Szeląg et al. (2018), who suggest a universal  
87 model for simulating the operations of storm overflows. However, these results have not been  
88 confirmed by the performance of continuous simulations. Interesting analyses were presented  
89 by Thorndahl and Willems (2008) and Grum and Aalderink (1999), who developed empirical  
90 models for predicting storm overflow, along with Espino et al. (2018), who presented the  
91 possibility of applying logistic regression to sewer overflow simulations. Nonetheless, the  
92 determined relationships presented by these and other researchers (Kleidorfer et al., 2009;  
93 Gironás et al., 2010; Fu and Kapelan, 2013) had local nature; therefore, it was not possible to  
94 apply them to other catchment areas.

95 To enable the assessment of storm overflow operations, it is necessary to perform continuous  
96 simulations, which require multiannual precipitation data. However, studies performed by  
97 numerous teams of scientists indicate that the dynamics of precipitation (frequency,  
98 magnitude, intensity) varies as a result of climate change (Wu et al., 2013). This is why, at the  
99 stage of sewage network simulations, it seems appropriate to present the impacts of changes  
100 in rainfall dynamics on the operations of sewage networks over consecutive years. This is  
101 very important, as it allows the optimal selection of a sustainable development concept for a  
102 given catchment area (Huong and Pathirana, 2013; Kirshen et al., 2014). However, the  
103 construction of a model for simulating rainfall variations caused by climate change is a  
104 complicated task that requires the implementation of complex numerical algorithms (Boyle,  
105 1998; Sharma et al., 2007). In engineering considerations, this task is difficult to perform;  
106 therefore, the need arises for the development of a simplified methodology. Precipitation data

107 acquired by means of climatic models (CGM, LGM, etc.) constitute input information  
108 necessary for continuous simulations (Gironás et al., 2010; Arnell, 2011; Arnbjerg-Nielsen et  
109 al., 2013). The produced results of the simulations are significant from a practical point of  
110 view in terms of the modernisation of sewage networks with the consideration of climate  
111 change. However, in the abovementioned approach, some authors (Adams and Papa, 2000;  
112 Kleidorfer et al., 2009) usually apply limited considerations of changes in impervious areas.  
113 Additionally, in numerous analyses, the dynamics of changes in the impervious of a  
114 catchment in the long term is considered within a limited scope.

115 Due to the above, it is appropriate to develop a computational methodology that allows the  
116 simultaneous analyses of the impacts of changes in rainfall dynamics (in the long and short  
117 term) and the dynamics of urbanisation, and the yielded results should be characterised by  
118 strong compliance with theoretical data. In terms of land development plans for cities, it  
119 seems desirable to make an attempt aimed at the development of an optimal concept for the  
120 urbanisation of catchment areas in a manner in which negative impacts on the receiving  
121 waters are as limited as possible while considering the nature of rainfall, i.e., to minimise the  
122 number of storm overflows affecting the heavy pollution of receiving waters. This paper  
123 presents a concept of the construction of a probabilistic model for simulating the number of  
124 storm overflows (in a short- and long-term approach) while not only incorporating the  
125 dynamics of changes in rainfall intensity in the consecutive years covered by the simulations  
126 but also allowing an analysis of this phenomenon considering the progressing urbanisation of  
127 the catchment area. This paper also presents a research methodology allowing optimisation of  
128 the concept of sustainable development of a catchment area, involving the limitation of the  
129 number of storm overflows and taking into account the variable dynamics of rainfall. This  
130 study presents two parallel approaches, i.e., simulation of the number of storm overflows  
131 determined by a mathematical model (considering changes in rainfall dynamics in a

132 multiannual approach and changes in the impervious area of the catchment) and the  
133 comparisons among these simulations and calculations using a calibrated hydrodynamic  
134 model.

135

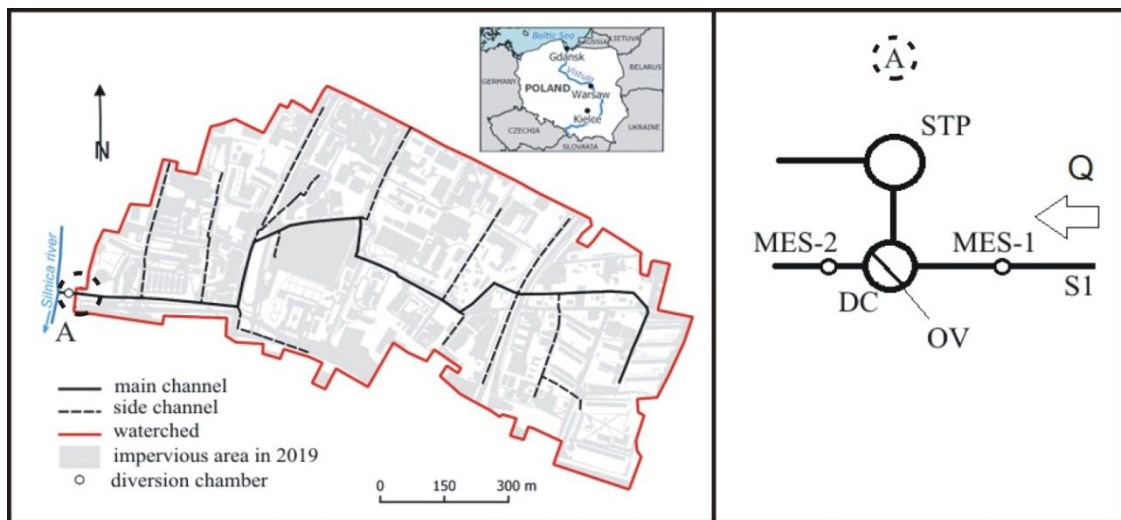
## 136 **2. Study area**

137 The research area comprises an urban catchment area covering 62 ha located in the south-  
138 eastern part of Kielce city (Fig. 1). The city is located in the southern part of Poland and is the  
139 capital of Świętokrzyskie Province. It occupies an area of 109 km<sup>2</sup>. The average population  
140 density is 17.9 people·ha<sup>-1</sup>. The highest point in the catchment area is at an elevation of  
141 271.20 m a.s.l., and the lowest point is at 260.00 m a.s.l. The average slope of the land in the  
142 catchment area is 7.1%. Within the catchment area, there are housing estates, public utility  
143 buildings and a network of roads with a density of 108 m·ha<sup>-1</sup>. Over the last 10 years (2009-  
144 2019), there was visible intensification of urbanisation processes in the studied catchment  
145 area, which caused an increase in the share of impervious areas (Imp) from 33% to 55% (in  
146 the period 2009-2011, the impervious areas changed from Imp = 33% to Imp = 38%, while in  
147 2014 it reached the value of Imp = 41% – Appendix A). The roofs of buildings currently  
148 occupy 16.5% of the whole catchment area, and 17.7% of the whole area is covered by roads,  
149 12.2% by parking areas and 8.6% by pavement. The remaining portion of the catchment area  
150 (45%) is covered by urban greenery.

151 This paper analyses a separate storm sewer system. Only treated stormwater is delivered by  
152 the S1 storm sewer to the Silnica River. The main canal, with a diameter of  $\phi$  600-1250 mm,  
153 has a length of 1569 m, and its gradient ranges from 0.04% to 3.90%. This sewer collects  
154 stormwater from approximately a side sewers ( $\phi$  300-1000 mm) (Fig. 1), the slope of which  
155 do not exceed 2.61%. The total length of the drainage network is 11,375 m. The volume of  
156 the sewers and drainage manholes is 2032 m<sup>3</sup>. Stormwater from the catchment area is



157 discharged via the S1 sewer to a stormwater treatment plant (STP) by means of a flow divider  
 158 (DC). When the level of stormwater in the DC is lower than  $h_{\min} = 0.42$  m, their entirety flows  
 159 to the STP. In contrast, when the level of stormwater exceeds the value of  $h_{\min}$ , a storm  
 160 overflow (OV) occurs, and a portion of the stormwater is delivered directly (without  
 161 treatment) to the the Silnica River.



162  
 163 **Fig. 1.** Study area.

164  
 165 In the analysed urban catchment area, continuous measurements of flows and filling levels  
 166 were performed in the years 2009-2011 by means of an MES-1 flow metre installed in the S1  
 167 sewer at a distance of 3.0 m from the DC. The flow metre measures the flow and filling level  
 168 with a resolution of 1 minute. The probe of the flow metre measures the level (by measuring  
 169 the water level pressure) and average flow rate of stormwater (via the Doppler effect), which,  
 170 with the specific shape and dimensions of the canal, allow the calculation (by means of a  
 171 built-in microprocessor) of the volumetric flow rate of the stormwater. Moreover, in 2015,  
 172 another MES-2-type flow metre was installed in the sewer downstream of the storm overflow.  
 173 An analysis of the collected measurement data (from 2008-2017) demonstrated that the  
 174 annual rainfall depth varied within a range of 537-757 mm, and the number of rainy days  
 175 ranged from 155 to 266. The length of the dry period was 0.16-60 days. Moreover, it was

176 concluded that storms occurred 27-47 times a year. The average annual air temperature in the  
 177 studied period was 8.1-9.6 °C, and the number of days with snowfall ranged from 36 to 84. At  
 178 the same time, an analysis of the flow measurement data recorded by means of the MES-1  
 179 flow metre demonstrated that the momentary flow rate of stormwater in dry periods ranged  
 180 from 1 to 9 L·s<sup>-1</sup>, which indicated the occurrence of infiltration in the studied sewer network.

181

### 182 3. Methodology of research

#### 183 3.1. The model of overflow operations, taking into account climate changes and 184 urbanisation of the catchment area

185 The impact of the intensity of rainfall and the progressing urbanisation of the catchment area  
 186 in  $t$  consecutive years on the occurrence of storm overflows can be described by the following  
 187 relationships:

$$188 [P_1, P_2, P_3, \dots, P_i, t_r]_{1,t=1}, [P_1, P_2, P_3, \dots, P_i, t_r]_{2,t=1}, [P_1, P_2, P_3, \dots, P_i, t_r]_{m,t=1}, \dots, [P_1, P_2, P_3, \dots, P_i, t_r]_{j,t=k} \quad (1)$$

$$189 [0, Q_1, Q_2, \dots, Q_i]_{1,t=1}, [0, Q_1, Q_2, \dots, Q_i]_{2,t=1}, [0, Q_1, Q_2, \dots, Q_i]_{m,t=1} \dots, [0, Q_1, Q_2, \dots, Q_i]_{j,t=k} \quad (2)$$

$$190 T = \begin{cases} 0 & \text{when } h(Q_i)_j < h_g \\ 1 & \text{when } h(Q_i)_j > h_g \end{cases} \quad (3)$$

191 which results in:

$$192 T_{1,t=1}, T_{2,t=1}, T_{3,t=1}, \dots, T_{j,k} \quad (4)$$

$$193 \text{Imp}_1, \text{Imp}_2, \text{Imp}_3, \dots, \text{Imp}_{t=k} \quad (5)$$

194 Therefore, every rainfall event that corresponds to an operating overflow state can be  
 195 described by the following vector:

$$196 [T]_{j,k} = [P_1, P_2, P_3, \dots, P_i, t_r, \text{Imp}_k] \quad (6)$$

197 where

198  $P_1, P_2, P_3, \dots, P_i, t_r$  – the rainfall characteristics of a single  $j$ -th precipitation event ( $P$   
 199 represents rainfall depth or rainfall intensity and  $t_r$  represents rainfall duration),  $\text{Imp}$  – the  
 200 impervious area of the catchment,  $j$  – the number of rainfall events in a year ( $i = 1, 2,$



201 3,..., j),  $t$  – the time period covered by the calculations ( $t = 1, 2, 3, \dots, k$ ),  $h(Q_i)_j$  – the  
 202 filling level at the storm overflow, and  $h_g$  indicates the height of the edge of the storm  
 203 overflow.

204

205 For a task set in this manner, the storm overflow is interpreted as a binary variable as  
 206 presented in equation (3). This is why, based on the data, including measurements of  
 207 precipitation characteristics in independent precipitation events and the operations of the  
 208 overflow, it is possible to develop a classification model to simulate the operation of the  
 209 overflow. In a multiannual approach, the impact of climate change and its trend in a time  
 210 series can be identified in the proposed model based on variations in the values of estimated  
 211 parameters,  $\theta_n$ , in theoretical distributions,  $f(P_i)$ , describing rainfall characteristics in the  
 212 following form:

$$213 \theta_n = f(t = k) \quad (7)$$

214 where

215  $f(t)$  – an empirical model to determine the values of parameters in the theoretical  
 216 distribution for the consecutive  $t$  years covered by the calculations,  $n$  – the number of  
 217 parameters determined in the theoretical distribution.

218

219 On this basis, it can be stated that the values of precipitation characteristics in the consecutive  
 220  $t$  years in a time series are as follows:

$$221 [P_1, P_2, P_3, \dots, P_i, t_r, \theta_{1,n}]_{1,2,3,\dots,j,t=1}, [P_1, P_2, P_3, \dots, P_i, t_r, \theta_{2,n}]_{1,2,3,\dots,j,t=2}, [P_1, P_2, P_3, \dots, P_i, t_r, \theta_{2,n}]_{1,2,3,\dots,j,t=k} \quad (8)$$

222 In contrast, the events for which the function of an overflow can be described in a single  
 223 episode are defined by the relationship:

$$224 [T]_{j,k} = [P_1, P_2, P_3, \dots, P_i, t_r, \theta_{n,k}, Imp_k] \quad (9)$$

225 where

226  $\theta_{n,t}$  – the numerical values of n parameters in a theoretical distribution, describing  
227 precipitation characteristics for the k, z, or t years covered by the calculations.

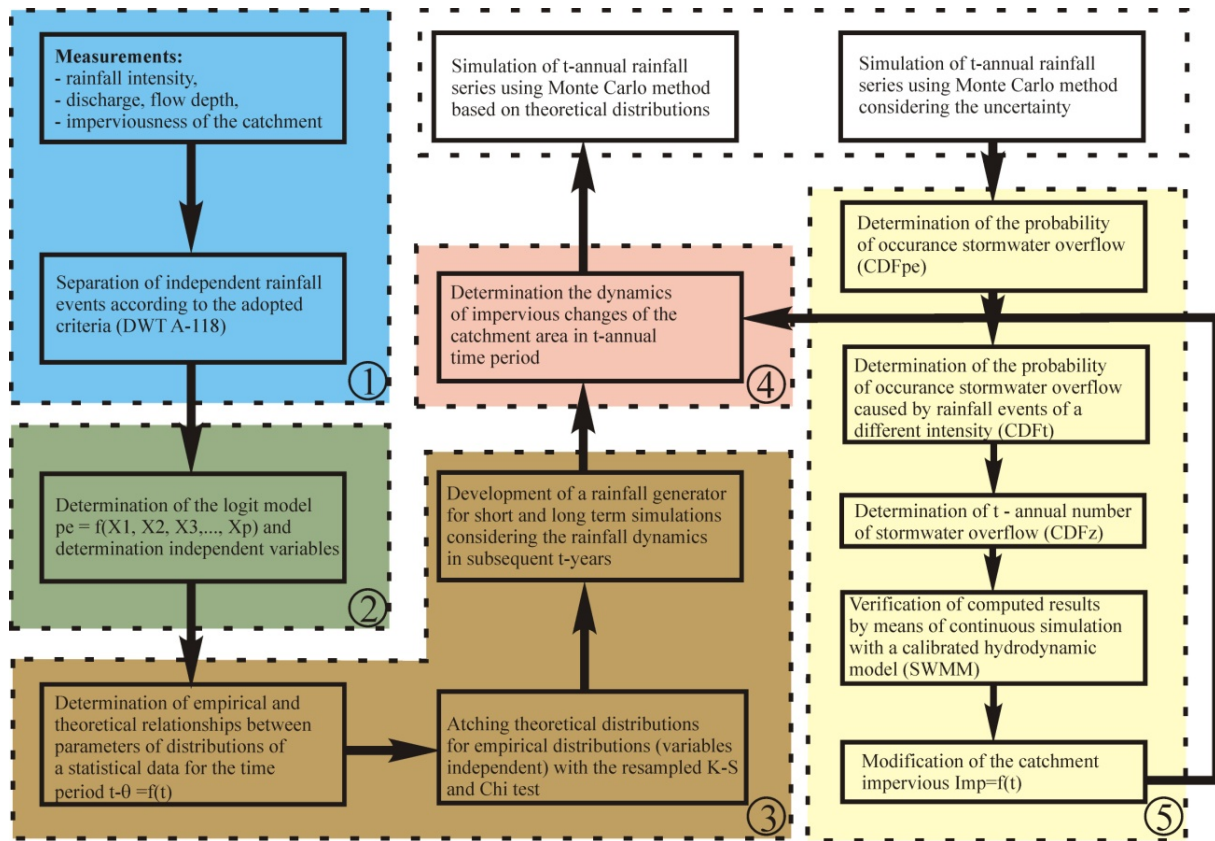
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229 The relationships presented above constitute a basis for calculating the number of storm  
230 overflows in short-term (e.g., a single episode) or long-term approaches (1, 2, or 5 years),  
231 which can take into account both changes in the impervious area of the catchment (Imp) and  
232 changes in the rainfall dynamics that result from climate changes.

233

### 234 **3.2. An algorithm for the construction of a probabilistic model for analysing the** 235 **operation of a storm overflow**

236 A probabilistic storm overflow model designed to simulate the number of storm overflows in  
237 both short- and long-term approaches was developed as part of the performed analyses. In  
238 contrast to the models developed by other researchers (Fortier and Maihot, 2015; Jean et al.,  
239 2018), the suggested approach will take into account the dynamics of urbanisation processes  
240 and changes in precipitation at the same time. Therefore, the suggested solution enables an  
241 analysis of the interaction between an increase in rainfall intensity and an increase in the  
242 impervious area of the catchment in a multiannual approach. The developed methodology  
243 also enables an assessment of the impacts of the uncertainty associated with the identification  
244 of rainfall dynamics in short- and long-term approaches on storm overflow operations. The  
245 computational algorithm used to construct a probabilistic model is presented in Fig. 2.



246  
247

248 **Fig. 2.** An algorithm used for the construction of a probabilistic model designed to analyse storm  
 249 overflow operations:  $CDF_{pe}$  – empirical distribution function describing the probability of exceeding  
 250 the occurrence probability of a storm overflow,  $CDF_I$  – empirical distribution function describing the  
 251 probability of exceeding the occurrence probability of a given number of storm overflow in the  
 252 designated year, caused by precipitation with a varying average intensity ( $i$ ), and  $CDF_Z$  – a distribution  
 253 function describing the probability of exceeding the number of storm overflows expected in a period  
 254 of  $t$  years.

255

256 The probabilistic model presented in Fig. 2 consists of 5 independent components. Within  
 257 them, the following modules are determined: prediction of a storm overflow occurring in a  
 258 single precipitation episode, rainfall depths and changes in their dynamics, urbanisation in a  
 259 long-term approach and analyses of the produced results. The first component (1) includes the  
 260 gathering of measured data (intensity of rainfall, flow, filling level, and the impervious

261 surface of the catchment area). This component serves as a basis for determining a logit  
262 model designed to simulate the occurrence of a storm overflow. The second model component  
263 model (2) is a synthetic precipitation generator, in which empirical distributions are  
264 determined based on the obtained precipitation data and are matched to theoretical  
265 distributions. In this component, it is assumed that the values of the parameters in the  
266 theoretical distributions exhibit trends that are functions of time; these trends result from  
267 changes in precipitation dynamics, which can be caused by climate changes (Bates et al.,  
268 2008). This aspect is described in detail in the following part of the paper. The studies  
269 included an uncertainty analysis of the identified parameter values of the theoretical rainfall  
270 distributions. The third component of the model (3) involves a rainfall simulator based on the  
271 Monte Carlo method. The rainfall simulator takes into account the possibility of modelling  
272 synthetic precipitation series with changes in precipitation dynamics. The next component (4)  
273 includes a module in which rainfall events in consecutive years  $[P_1, P_2, \dots, P_i]_{k=1,2,\dots,t}$  are  
274 assigned impervious area of the catchment. The suggested solution allows the coefficients to  
275 have constant values or to be variable as a function of time for the consecutive years covered  
276 by the calculations. The final model component (5) constitutes an element in which  
277 simulations are performed involving the number of overflows. The impact of the  
278 abovementioned factors on the functioning of a storm overflow is analysed based on the  
279 produced results. To verify the predictive power of the suggested probabilistic model,  
280 continuous simulations are performed based on precipitation data using a calibrated  
281 hydrodynamic model.

282

### 283 **3.3. Distinguishment of precipitation events and their classification**

284 The precipitation data were acquired from the records of a traditional float pluviograph  
285 located in a meteorological station in Kielce city; records from May-October 1961-2005 were

286 collected. Individual precipitation events were distinguished based on the guidelines of DWA-  
287 A 118E (2006). The adopted criteria were 4 h as the minimum dry period length and a  
288 minimum precipitation level of 3.0 mm (Fu and Kapelan, 2013; Fu et al., 2014). As a result,  
289 1484 precipitation events were identified in the 1961-2005 period, which means an average of  
290 33 episodes per year. Most of the events involved frontal precipitation (Szeląg et al., 2020).  
291 The analysed precipitation events were grouped based on their average intensities. To this  
292 end, Sumner's classification (Sumner, 1988) was used as it is the most popular classification  
293 method among meteorologists. The precipitation events were grouped into the following  
294 categories (WMO, 2012): moderate rain shower (between 2.5 and 10 mm·h<sup>-1</sup>; 416-1667 L·s<sup>-1</sup>·  
295 ha<sup>-1</sup>), heavy shower (between 10 and 50 mm·h<sup>-1</sup>; 1667-8335 L·s<sup>-1</sup>·ha<sup>-1</sup>) and violent shower  
296 (greater than or equal to 50 mm·h<sup>-1</sup>; >8335 L·s<sup>-1</sup>·ha<sup>-1</sup>). In 1961-2005 in Kielce city, 768, 601,  
297 98 and 17 episodes of light rains, moderate rains, heavy rains and violent rains were  
298 identified, respectively.

299

### 300 3.4. Logistic regression

301 Logistic regression, also called the binomial logit model, constitutes a classification model  
302 comprising the methods of supervised learning. This model is used to analyse output and  
303 input data of a continuous and binary nature (zero – one). The logit model has been found to  
304 be useful in many fields of science, from economy, medicine, microbiology, ecology, and  
305 biotechnology to the modelling of objects in drainage networks (Salman and Salem, 2012;  
306 Khudhair et al. 2019). The logit model is described by the following equation:

$$307 \quad p_e = \frac{\exp(\alpha_0 + \alpha_1 \cdot x_1 + \alpha_2 \cdot x_2 + \alpha_3 \cdot x_3 \dots + \alpha_q \cdot x_q)}{1 + \exp(\alpha_0 + \alpha_1 \cdot x_1 + \alpha_2 \cdot x_2 + \alpha_3 \cdot x_3 \dots + \alpha_q \cdot x_q)} \quad (10)$$

308 where

309  $p_e$  – the probability of the occurrence of a storm overflow in a precipitation event,  $\alpha_0$   
310 indicates constant term;  $\alpha_1, \alpha_2, \dots, \alpha_q$  – empirical coefficients that are determined using



311 the method of maximum likelihood estimation, and  $x_q$  – independent variables including  
312 rainfall characteristics and the impervious area of the catchment.

313  
314 Equation (10) was used to assess the operation of a storm overflow in a precipitation event.  
315 Therefore, a threshold value  $p_e$  was established, which, when exceeded, defines the  
316 occurrence of an storm overflow. Based on a review of the literature (Szeląg et al., 2020), it  
317 was assumed that a storm overflow occurred for values of  $p \geq 0.5$ , which can be presented as:

$$318 \quad \alpha_0 + \alpha_1 \cdot x_1 + \alpha_2 \cdot x_2 + \alpha_3 \cdot x_3 \dots + \alpha_q \cdot x_q > 0 \quad (11)$$

319 In an opposite case, i.e., when  $p < 0.5$ , it was assumed that there was no storm overflow. The  
320 assessment of the predictive power of the logistic regression model used the following  
321 indicators: sensitivity, denoted by SENS (determines the correctness of the classification of  
322 data in a set containing events involving the occurrence of an storm overflow); specificity,  
323 denoted by SPEC (determines the correctness of the classification of data in a set constituting  
324 cases in which there was no overflow); and calculation error, denoted by  $R_z^2$  (determines the  
325 correctness of the identification of event simulations – overflow/no overflow).

326 The logit model was developed based on the results of the rainfall and flow measurements  
327 performed in the catchment area in the years 2009-2011 (188 precipitation episodes and 69  
328 overflow events were observed) and 2012-2015 (261 and 140 precipitation and overflow  
329 events, respectively). Validation of the logit model used 12 independent precipitation events  
330 with available measurements of the operation of the storm overflows. To verify the resulting  
331 logit model, continuous calculations were performed by means of a calibrated SWMM model  
332 based on precipitation in the years 2008-2018. On this basis, the number of storm overflows  
333 was determined for consecutive years and compared to the results of the measurements.

334

### 335 **3.5. Selection of theoretical distributions for the description of precipitation** 336 **characteristics**

337 Based on the results of the rainfall measurements from 1961-2005, this paper identifies  
338 precipitation events in consecutive 30-year periods of the multiannual time interval: 1961-  
339 1990, 1962-1991, ..., 1976-2005. The following (two-parameter) theoretical distributions  
340 were matched with the empirical data (precipitation characteristics determining storm  
341 overflow operations): Gumbel, Weibull, Frechet, gamma and log-normal (Adams and Papa,  
342 2000). The assessment of the compliance of the empirical and theoretical distributions were  
343 performed using the bootstrap version of Kolmogorov-Smirnov (K-S) test and  $\chi^2$  test. The  
344 whole procedure of Monte Carlo simulation in goodness of fit testing can be found in the  
345 literature (Savapandit and Gogoi, 2015). Proposed number of resampled data is 40 times  
346 bigger than number of samples in original data (Wang et al., 2011). There are two types of  
347 bootstrap estimation like parametric and nonparametric. The first is more popular in context  
348 of goodness of fit testing, in which sample are draw from theoretical distribution with  
349 parameters estimated based on original data. In the second one, the samples are draw from  
350 original data. The main reason of using resampled version of K-S test was fact that the  
351 distribution parameters were estimated form data. The issue with classical Kolmogorov-  
352 Smirnov goodness of fit test in such situations widely discussed in the literature (Stephens,  
353 1974; D'Agostino, 2017). 5000 samples were taken for the simulation and a non-parametric  
354 approach was used (Savapandit and Gogoi, 2015). The assessment of the compliance of the  
355 empirical and theoretical distributions was based on the calculated p-values and critical test  
356 values (D) (Fu et al., 2014). In a case in which the calculated values of p were lower than the  
357 p-value at the declared significance level (0.05), there was a basis to reject the hypothesis  
358 claiming that the analysed theoretical distribution did not comply with the empirical  
359 distribution.



360

### 361 3.6. Analysis of changes in precipitation dynamics in a long-term approach

362 The calculated changes in rainfall dynamics were based on a trend analysis (Ganguli and  
363 Coulibaly, 2019) in which a multiannual time interval of 30 years was adopted as a reference  
364 unit (DWA-A 118E, 2006). A time series including a period longer than the multiannual time  
365 interval, in which the measurements begin in year  $X_0$ , can be described by the following  
366 relationship:

$$367 \quad X_0 + k_1, X_0 + k_2, X_0 + k_3, X_0 + k_4, X_0 + k_5, X_0 + k_6, \dots, X_0 + (t - 2), X_0 + (t - 1), X_0 + (t = k) \quad (12)$$

368 where in each subsequent ( $X_0 + k$ ) year, there was an average of  $j$  precipitation events.

369 The analyses of changes in rainfall dynamics in the multiannual time interval adopted a  
370 reference period (time series) including data from within the range of  $X_0 + (t = k)$  to  $X_0 + (t =$   
371  $k) - 30$ , containing  $30 \cdot j$  precipitation events constituting vectors  $[P_1, P_2, \dots, P_i]$ . To analyse the  
372 variation in precipitation characteristics in the investigated period, an empirical distribution  
373  $f(P_i)_{X_0+(t=k)}$  was determined and was paired with the corresponding theoretical distribution  
374  $f(P_i)_{X_0}^{\text{th}}_{(t=k)}$ , with the determination of the parameters represented as  $\theta_{X_0+(t=k),1,2,\dots,n}$ .  
375 Subsequently, because the analysed period  $t$  was longer than 30 years, another data series was  
376 determined for the period between the years  $X_0 + (t-1)$  and  $X_0 + (t-1) - 30$ . Based on the  
377 acquired data, the empirical distribution was determined, followed by the selection of the  
378 theoretical distribution  $f(P_i)_{X_0}^{\text{th}}_{+(t-1)}$  and the calculation of the numerical values of the  
379 coefficients

380  $\theta_{X_0+(t-1),1,2,\dots,n}$ . Subsequently, a time series was determined, including data from the  
381 multiannual time interval from  $X_0 + (t-2)$  to  $X_0 + (t-2) - 30$ , and theoretical distributions  
382  $f(P_i)_{X_0}^{\text{th}}_{+(t-2)}$  were established for the resulting data along with the determination of the values  
383 of  $\theta_{X_0+(t-2),1,2,\dots,n}$ . These models were used to simulate rainfall in the consecutive years covered  
384 by the analyses. This is why, to determine the uncertainty of the model predictions, the values



385 of the standard deviations ( $\sigma$ ) of the estimated parameters  $\alpha_f$  were determined in the  
386 theoretical models  $\theta_{X0^{th}+(t-k),1,2,\dots,n} = f(\alpha_f, k)$ . The adopted approach allows the identification of  
387 distribution parameters and therefore an analysis of changes in precipitation dynamics  
388 (Każmierczak and Kotowski, 2015). By distinguishing 30-year periods within the 50-year  
389 precipitation series, these authors suggested the nonlinear variance of the statistical  
390 distribution parameters in the analysed timeframe for Wrocław (Poland). Their results were  
391 also confirmed by the calculations of Sarhadi and Soulis (2017), who created IDF (intensity-  
392 duration-frequency) curves for part of the North American continent, taking into account  
393 varying rainfall dynamics. Nonetheless, the relationships identified in this manner were used  
394 in a limited capacity to simulate multiannual rainfall series by means of synthetic  
395 precipitation generators. Changes in rainfall dynamics in the years 1961-2005 were analysed  
396 following the methodology described above.

397

### 398 **3.7. Simulator of synthetic rainfall series**

399 The modelling of synthetic rainfall series commonly uses multidimensional probability  
400 density distributions generated on the basis of copula functions linking the adopted marginal  
401 distributions or modified Monte Carlo generators (e.g., Iman-Conover). If the independent  
402 variables ( $x_p$ ) included in a multidimensional distribution are independent (i.e., their  
403 correlations can be omitted), then there is no need to implement linking functions. In this  
404 case, each of the variables considered by the model can be modelled independently based on  
405 the established theoretical distribution  $F(P_i)^{th}$  of the Monte Carlo random number generator.  
406 The abovementioned solutions are useful when simulating synthetic rainfall series in a  
407 situation in which the dynamics of the changes in the rainfall series over a period covered by  
408 the calculations do not change, i.e., when  $\theta_n$  is constant. Based on the theoretical distribution  
409 function  $F^{-1}(P_i)$ , it is then possible to predict the  $t$ -year rainfall series. However, when the



410 precipitation dynamics change in the period covered by the simulations and the  $\theta_n$  values in  
 411 theoretical distributions are different, the need arises to perform analyses on the precipitation  
 412 dynamics. In this case, the calculations of the  $t$ -year synthetic rainfall series by means of the  
 413 Monte Carlo method can be performed for consecutive years based on  $k$  combinations of  
 414 theoretical distributions:

$$415 \quad G(k = 1, 2, 3, \dots, t) = \begin{cases} \text{when } k = 1 \text{ year, } [P_i]_j = f(\theta_{X_0+(t-1),1,2,\dots,n}) \\ \text{when } k = 2 \text{ year, } [P_i]_j = f(\theta_{X_0+(t-2),1,2,\dots,n}) \\ \text{when } k = 3 \text{ year, } [P_i]_j = f(\theta_{X_0+(t-3),1,2,\dots,n}) \\ \dots \\ \text{when } k = t \text{ years, } [P_i]_j = f(\theta_{X_0+(t-k),1,2,\dots,n}) \end{cases} \quad (13)$$

416 assuming that

$$417 \quad j(k = 1, 2, 3, \dots, t) = \text{const and } \theta_{X_0+(t-k),1,2,\dots,n}^{\text{th}} = f(\alpha_f, k) \quad (14)$$

418 where

419  $j, k, P_i, X_0, n,$  and  $\alpha_f$  are denoted according to the symbols in formulas (1-12).

420

421 Based on the results of Suligowski (2004), who showed for selected Polish cities that the  
 422 variability of the average rainfall intensity in a rainfall event ( $i$ ) over a multi-year period can  
 423 be described by a log-normal (two-parameter) distribution and assuming that its parameters  
 424 ( $\mu, \sigma$ ) can be expressed as a polynomial function depending on time ( $t$ ), the following system  
 425 of equations for modeling rainfall series was obtained:

$$426 \quad \begin{cases} F(x) = \frac{1}{2} + \frac{1}{2} \cdot \text{erf} \left( \frac{\ln(x-\mu)}{\sigma \cdot \sqrt{2}} \right) \\ x \in \langle 0; 1 \rangle \\ \mu = a_1 \cdot t^2 + a_2 \cdot t + a_0 \\ \sigma = b_1 \cdot t^2 + b_2 \cdot t + b_0 \\ \text{for: } t = 0, 1, 2, 3, \dots, k \end{cases} \quad (15)$$

427 where

428  $F(x)$  – cumulative log-normal distribution,  $x$  – values of pseudo-random numbers  
 429 modeled from theoretical distributions,  $\mu$  i  $\sigma$  – parameters of the theoretical distribution,  
 430  $a_1, a_2, a_0, b_1, b_2, b_0$  – coefficients of the selected models for modelling  $\mu, \sigma$ . Assuming

431 the values of  $t$ , the parameters of the distribution  $F(x)$  for the following years are  
432 calculated and precipitation simulations are performed.

433  
434 The values of the parameters  $a_1$ ,  $a_2$ ,  $a_0$ ,  $b_1$ ,  $b_2$ ,  $b_0$  in Eq.15 were estimated using the least  
435 squares method, while the Akaike Information Criterion (AIC) was applied for the assessment  
436 of the models  $\mu = f(t)$  and  $\sigma = f(t)$ . The results of calculations of  $\mu$  and  $\sigma$  polynomial  
437 parameters are given in Appendix B.

438 The computational algorithm for simulating the  $t$ -year rainfall series as described above was  
439 used in the paper to model the number of storm overflows. The simulation of synthetic  
440 rainfall series for consecutive years involved the  $N$ -sampling of  $M$  precipitation events in a  
441 year, resulting from the established theoretical distributions. Due to the strong correlation  
442 between the precipitation intensity ( $i$ ) values in consecutive periods  $t$  (as indicated in the  
443 paper of Kupczyk and Suligowski, 1997 – Appendix C), the Iman-Conover (I-C) method was  
444 used in the simulations of multiannual synthetic rainfall series. In this method, the assessment  
445 of the correlations among  $z$  variables is based on the value of Spearman's correlation. The  
446 results of the application of the I-C method are discussed in detail in the paper by Iman and  
447 Conover (1982), and these results are also cited in the Appendix D. This method is useful  
448 when simulating numerous independent variables (even exceeding 10) that are correlated with  
449 each other in a model. A good example of this includes complex technical facilities such as  
450 wastewater treatment plants, power plants, industrial plants, elements of machines such as gas  
451 turbines, and processes (Bixio et al., 2002; Talebizadeh et al., 2014; Forrester and Keane,  
452 2017; Maronati and Petrovic, 2019). To limit the number of samples, the Monte Carlo  
453 simulations used the Latin Hypercube method (LH).

454 To take into account the uncertainty of the identified parameters of the theoretical  
455 distributions, it was initially necessary to perform  $P$  simulations (500 samples were used in  
456 the paper) of theoretical distribution parameters  $N(\mu_s, \sigma_s)$ . On their basis, calculations of  $N$

457 samples for M precipitation events were performed from distributions describing the  
 458 precipitation characteristics of a given event. The obtained results were entered into equation  
 459 (10), and the probability of storm overflow with the annual number of storm overflow was  
 460 calculated by establishing the empirical distribution functions ( $CDF_{pe}$ ,  $CDF_Z$ ). Moreover, a  
 461 95% confidence interval was determined for the established empirical percentiles. A detailed  
 462 description of the method used to analyse uncertainty is presented in the paper by Grum and  
 463 Aalderink (1999).

464

### 465 **3.8. A catchment area urbanisation process within a time horizon**

466 The description of long-term changes in the land development of a catchment area, which are  
 467 a direct cause of increases in land imperviousness, used an original model in the following  
 468 form:

$$469 \quad \text{Imp}(t) = \begin{cases} \text{Imp}_0 + (\text{Imp}_m - \text{Imp}_0) \cdot \left(\frac{t}{t_{cr}}\right)^a & \text{for } t_{cr} \geq t \geq 0 \\ \text{Imp}_e + (\text{Imp}_m - \text{Imp}_e) \cdot \left(\frac{t_{sust} - (t - t_{cr})}{t_{sust}}\right)^b & \text{for } t_{cr} + t_{sust} \geq t \geq t_{cr} \end{cases} \quad (16)$$

470 where

471  $t_{cr}$  – the period of an increase in the impervious area of the catchment;  $t_{sust}$  – the period of  
 472 optimal shaping of the impervious area of the catchment;  $\text{Imp}_0$  – the initial impervious  
 473 area of the catchment;  $\text{Imp}_m$  – the maximum impervious area of the catchment;  $\text{Imp}_e$  –  
 474 the impervious area of the catchment after a period of  $t_{cr} + t_{sust}$ , and a, b – empirical  
 475 coefficients describing the dynamics of urbanisation in the catchment area.

476

477 The developed model provides high flexibility when studying the relationships among the  
 478 phase of an increase in the impervious area of the catchment (this is allowed by the  
 479 coefficients a and b) and actions aimed at compensating for the insufficient retention volume  
 480 of the catchment area within a specified timeframe. This allows the deliberate and rational



481 management of the catchment area in compliance with the principles of sustainable  
482 development and a bio-circular economy.

483 The performed analyses of the functioning of a storm overflow took into account the impact  
484 of the dynamics of changes in the impervious area of the catchment within the given period  
485 ( $t_{cr} + t_{sust}$ ) on the number of storm overflows. In the performed calculations, the values of  $t_{cr}$   
486 and  $t_{sust}$  changed over a period of 1-5 years, and the timeframe of the simulations ( $t_{cr} + t_{sust}$ )  
487 did not exceed 10 years.

488

### 489 **3.9. Verification of the probabilistic model – continuous simulations using**

#### 490 **a hydrodynamic model**

491 A hydrodynamic model of an urban catchment area developed in SWMM 5.1 software was  
492 used to verify the probabilistic model of storm overflow operations. To this end, continuous  
493 simulations were performed based on 30-year rainfall series for consecutive computational  
494 scenarios.

495 The hydrodynamic model studied in the paper consists of 92 partial catchment areas, 200  
496 manholes and 72 sewers. The sizes of the partial catchment areas vary from 0.12 ha to 2.10  
497 ha. As result of the calibration procedure, it was determined that the value of Manning's  
498 roughness coefficient of the sewer was  $n_{sew} = 0.018 \text{ m}^{-1/3}\cdot\text{s}$ , the Manning roughness  
499 coefficient and retention of impervious areas were  $n_{imp} = 0.025 \text{ m}^{-1/3}\cdot\text{s}$  and  $d_{imp} = 2.50 \text{ mm}$ ,  
500 and the runoff path width was calculated as  $W = \alpha \cdot A^{0.50}$  where  $\alpha = 1.35$ . The results of the  
501 simulation (Szeląg et al., 2016) demonstrated that, for the abovementioned combinations of  
502 coefficients, the developed model is characterised by satisfactory predictability.

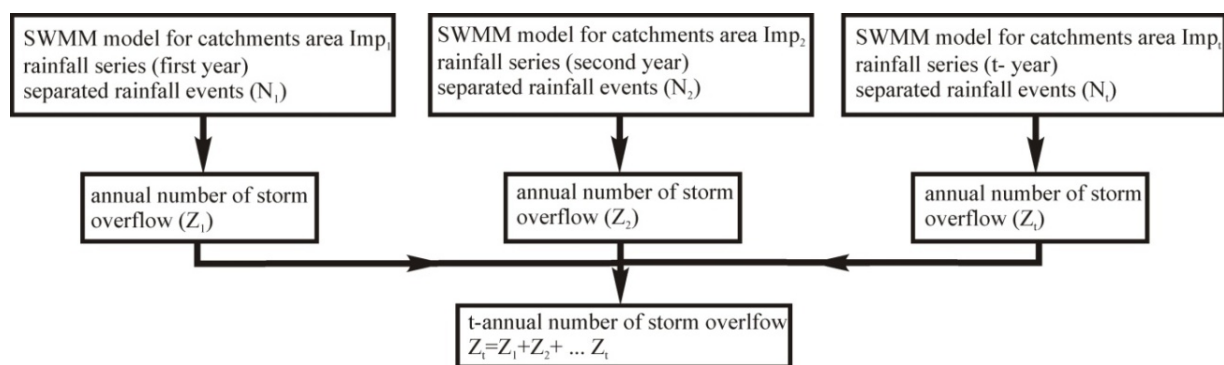
503 Two independent computational approaches were used during the verification of the  
504 probabilistic model. The first approach included a multiannual time interval (30 years)  
505 established based on equation (12), and the model performed continuous simulations of the



506 number of storm overflows for various impervious area of the catchment ( $Imp = 0.3-0.5$ ). In  
 507 the abovementioned solution, 30-year precipitation series were identified within the time  
 508 series, i.e., 1961-1990, 1962-1991, 1963-1992, etc., which, in the following step, were entered  
 509 into the SWMM model to simulate the annual number of storm overflows.

510 In the second approach, calculations of the multiannual number of storm overflows were  
 511 performed while taking into account the changes in imperviousness over the consecutive  
 512 years. In this case, it was necessary to simultaneously prepare numerous models of the  
 513 catchment area, in which different values of the impervious area of the catchment, assigned to  
 514 the consecutive years covered by the calculations, were defined based on equation (12). A  
 515 layout of the construction of a model for continuous simulations in which the characteristics  
 516 of the catchment area change in a dynamic system over consecutive years is presented in Fig.

517 3.



518  
 519 **Fig. 3.** Scheme of the construction of a hydrodynamic model used to simulate the number of storm  
 520 overflows in a period of  $t$  years.

521  
 522 Based on the suggested computational algorithm (Fig. 3), calculations of the number of storm  
 523 overflows were performed for a period of  $t = 10$  years.

524

## 525 4. Results and discussion

### 526 4.1. The logistic regression model

527 Based on precipitation data and changes in the impervious area of the catchment, the  
528 following logit model was developed:

$$529 \quad p_e = \frac{\exp(0.352 i + 3.928 \text{ Imp} - 5.298)}{1 + \exp(0.352 i + 3.928 \text{ Imp} - 5.298)} \quad (17)$$

530 where

531  $p_e$  – the probability of the occurrence of a storm overflow, Imp – the impervious area of  
532 the catchment, and  $i$  – the average rainfall intensity ( $\text{L} \cdot \text{s}^{-1} \cdot \text{ha}^{-1}$ ).

533

534 The established logit model is characterised by high accuracy of measurement data. This is  
535 indicated by the following values: SPEC = 87.22% (out of 209 storm overflows, 182  
536 precipitation episodes were identified properly), SENS = 87.87% (out of 240 precipitation  
537 episodes, 211 events were classified properly), and  $R_z^2 = 87.55\%$  (out of 449 events, the  
538 operation of the storm overflow was identified properly in 393). Validation of the resulting  
539 logit model was also performed. This was done using 12 independent precipitation events.

540 The completed calculations indicate that out of 7 storm overflows, the logit model properly  
541 predicted 6 events; for 5 measured precipitation events, in the absence of an overflow event,  
542 the results of the calculations using the logit model were similar for all episodes. To verify the  
543 logit model, continuous simulations of the annual number of storm overflows ( $Z_{\text{SWMM}}$ ) were  
544 performed by means of a calibrated hydrodynamic model of the catchment area. The results of  
545 calculations are presented in tab. 1.

546

547 **Tab. 1.** Results of the verification of the logit model

Year	Imp	N	$Z_{\text{mes}}$	$Z_{\text{logit}}$	$Z_{\text{SWMM}}$
2008	33	43	15	12	16
2009	33	47	16	17	16

2010	35	47	18	15	19
2011	38	51	20	21	20
2012	38.3	36	-	16	15
2013	38.6	41	-	17	15
2014	39	44	-	22	23
2015	40	58	24	21	24
2016	41.3	44	20	22	20
2017	45	38	20	18	20
2018	50	42	20	22	20

548  $Z_{mes}$  – actual number of storm overflows,  $Z_{logit}$  – number of overflows determined by the logit model,  $Z_{SWMM}$  –  
549 number of storm overflows resulting from continuous simulations.

550

551 Based on the data included in the table, it can be concluded that the annual numbers of storm  
552 overflows determined by means of the logit model and those based on the continuous  
553 simulations are highly compliant. The maximum difference in the annual number of storm  
554 overflows between the results from the SWMM model and those from the logit model equals  
555 3. An identical maximum difference was achieved between the measurements and the results  
556 of the logit model. As indicated above, the established logistic regression model can be  
557 applied to further analyses.

558 To allow the interpretation of the individual terms in equation (17), they were written in a  
559 simplified form:

$$560 \quad 0.395 i + 3.928 \text{ Imp} - 5.498 \geq 0 \quad (18)$$

561 By normalising equation (18) (Thorndahl and Willems, 2008, Szeląg et al., 2020), assuming  
562 that, in the analysed period,  $\text{Imp} \approx 0.40$ , the following relationship was produced:

$$563 \quad i + \frac{3.928}{0.395} \cdot 0.40 - \frac{5.498}{0.395} = i + 3.98 - 13.92 \geq 0 \quad (19)$$

564 which finally resulted in:

$$565 \quad i - 9.94 \geq 0 \quad (20)$$

566 In equation (20), the value of the constant term (i.e., 9.94) is similar to the value of the  
567 average rainfall intensity ( $i_0 = 10.82 \text{ L} \cdot \text{s}^{-1} \cdot \text{ha}^{-1}$ ) that determines the occurrence of a storm  
568 overflow event in the analysed catchment area (Szeląg et al., 2019). According to the



569 literature (Thorndahl and Willems, 2008), it can be assumed that the value  $i_0$  is a function of  
 570 the physical-geographical characteristics of the catchment area; however, this aspect has not  
 571 yet been studied in catchment areas with various characteristics, and it thus requires further  
 572 detailed analyses. This is important from the point of view of the construction of a universal  
 573 model for predicting the occurrence of a storm overflow event. Attention should also be paid  
 574 to the fact that the suggested approach, when compared to the traditional approach ( $P_t$ ,  $t_T$ )  
 575 discussed in numerous papers (Grum and Aalderink, 1999; Thorndahl and Willems, 2008;  
 576 Szeląg et al., 2019), constitutes a significant simplification at the construction stage of the  
 577 model and simulations, which constitutes its major advantage.

578

#### 579 4.2. Establishing the theoretical distributions of independent variables

580 Based on the distinguished precipitation events, empirical distributions of the rainfall intensity  
 581 values were determined for the consecutive periods of the multiannual time interval (30 years)  
 582 in the resulting time series. Subsequently, theoretical distributions were matched with the  
 583 resulting empirical distributions. Tab. 2 presents the critical test probability values of the  
 584 resampled Kolmogorov–Smirnov (K-S) and  $\chi^2$  tests, which resulted in the best match with the  
 585 empirical data. The results of the K-S and  $\chi^2$  test calculations for the remaining statistical  
 586 distributions are presented in the Appendix E.

587

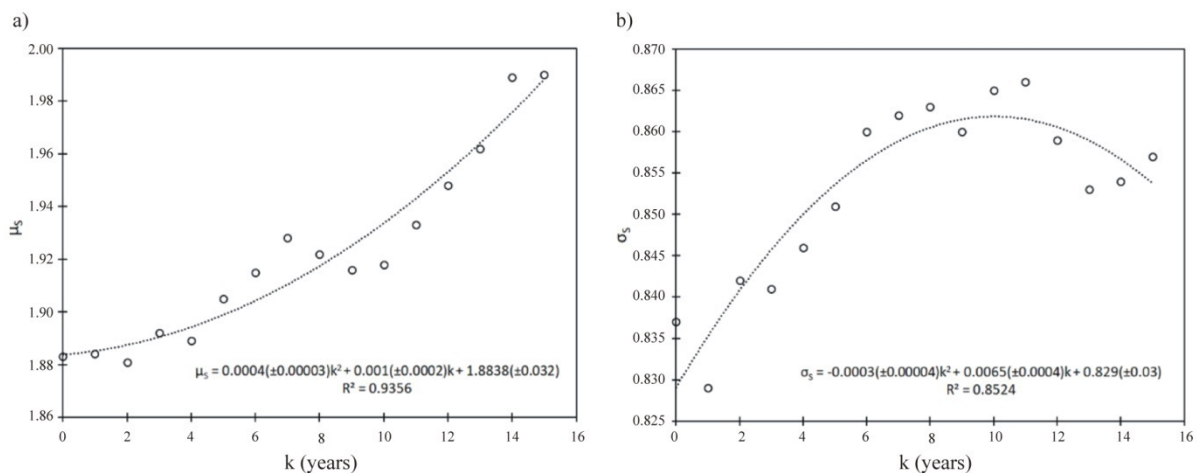
588 **Tab. 2.** Results of K-S\* and  $\chi^2$  test calculations and the values of the matching parameters ( $\mu$ ,  $\sigma$ ) in the  
 589 theoretical distributions

Multiannual time interval	Distribution	p(K-S)	p( $\chi^2$ )	Parameter (average value)		Standard deviation	
		p-value	p-value	$\mu_s$	$\sigma_s$	$\sigma_{\mu s}$	$\sigma_{\sigma s}$
1961-2005	lognorm	0.310	0.251	1.966	0.856	0.009	0.017
1961-1990	lognorm	0.210	0.187	1.883	0.837	0.034	0.010
1962-1991	lognorm	0.203	0.195	1.884	0.829	0.017	0.012
1963-1992	lognorm	0.105	0.092	1.881	0.842	0.020	0.017
1964-1993	lognorm	0.119	0.121	1.892	0.841	0.039	0.009
1965-1994	lognorm	0.237	0.221	1.881	0.845	0.023	0.008

1966-1995	lognorm	0.275	0.224	1.905	0.851	0.029	0.018
1967-1996	lognorm	0.303	0.258	1.915	0.860	0.027	0.005
1968-1997	lognorm	0.208	0.210	1.928	0.862	0.028	0.014
1969-1998	lognorm	0.141	0.121	1.922	0.863	0.027	0.016
1970-1999	lognorm	0.247	0.214	1.916	0.861	0.023	0.010
1971-2000	lognorm	0.142	0.123	1.918	0.865	0.019	0.012
1972-2001	lognorm	0.331	0.257	1.933	0.866	0.023	0.018
1973-2002	lognorm	0.311	0.287	1.948	0.859	0.025	0.012
1974-2003	lognorm	0.132	0.116	1.963	0.853	0.020	0.009
1975-2004	lognorm	0.398	0.321	1.989	0.856	0.029	0.018
1976-2005	lognorm	0.100	0.109	1.991	0.857	0.020	0.015

590  $\mu_s, \sigma_{\mu_s}$  – average value and standard deviation of the  $\mu$  values, resulting in a normal distribution in the form of  
591  $N(\mu_s, \sigma_{\mu_s})$  for simulating the uncertainty of parameter  $\mu_s$  of the theoretical distribution; and  
592  $\sigma_s, \sigma_{\sigma_s}$  – average value and standard deviation of the  $\sigma$  values, resulting in a normal distribution in the form of  
593  $N(\sigma_s, \sigma_{\sigma_s})$  for simulating the uncertainty of parameter  $\sigma_s$  of the theoretical distribution.

594  
595 An analysis of the data in Tab. 2 indicates that the empirical data are best matched by the log-  
596 normal distribution, and the standard deviation values in relation to the established values of  
597 parameters  $\mu_s$  and  $\sigma_s$  do not exceed 2.2% (the maximum error in the data from 1964-1993). In  
598 the case of parameter  $\sigma$ , it was concluded that the parameter reaches its maximum value in the  
599 period from 1969 to 1998 and then falls. The resulting relationships are presented in Figs. 4a  
600 and 4b.



601  
602 **Fig. 4.** Variability of the values of parameter  $\mu$  **(a)** and parameter  $\sigma$  **(b)**, measured and interpolated for  
603 the consecutive periods of the multiannual time interval.

604

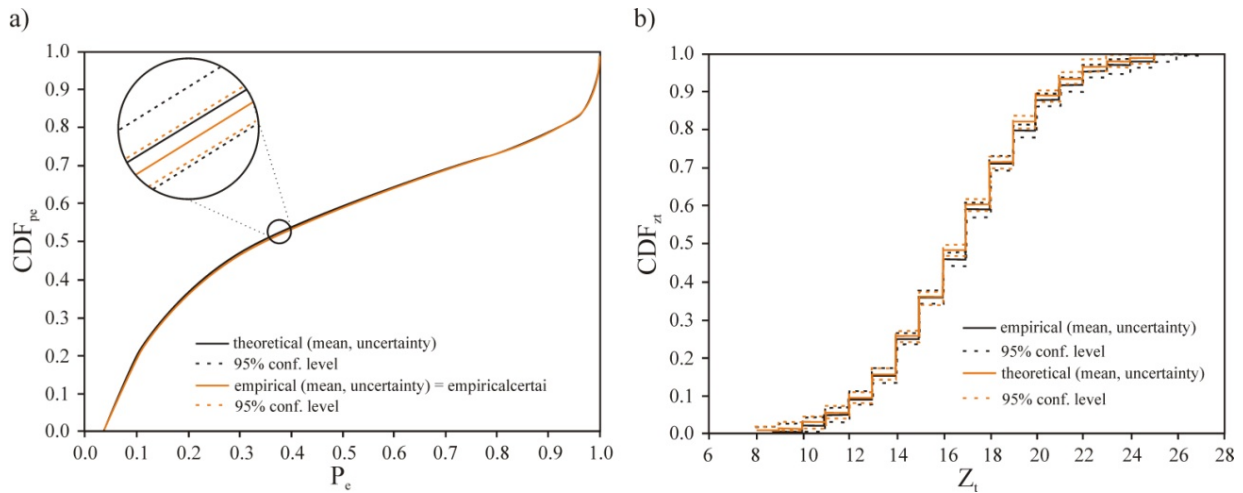
605 When analysing the shape of the curves (measurements and interpolation), it can be  
606 concluded that the adopted second-degree polynomials reflect the changes in the  $\mu_s$  and  $\sigma_s$   
607 coefficients in the log-normal distributions with a satisfying accuracy. The resulting  
608 relationships can constitute a basis for determining the values of  $\mu_s$  and  $\sigma_s$  in consecutive  
609 years. The presented approach is confirmed by the literature (Każmierczak and Kotowski,  
610 2015), and it is used in computational experiments involving changes in precipitation  
611 dynamics in a multiannual approach. In the following sections, calculations of the probability  
612 of a storm overflow in a given year (including multiannual calculations) and the number of  
613 storm overflows were conducted using the empirical values of  $\mu$  and  $\sigma$  derived from the  
614 theoretical distributions (tab. 2).

615

#### 616 **4.3. Impact of the uncertainty of the parameters of the statistical distributions** 617 **of precipitation on calculation results involving the operations of storm overflows**

618 The performed calculations included an analysis of the impact of the uncertainty of the  
619 identification of the parameters of statistical distributions (tab. 2) on the probability of the  
620 occurrence of an overflow event and on the simulated annual number of overflows. The first  
621 scenario involved modelling the impact of the uncertainty of the estimation of the parameters  
622 in distributions describing the average intensity of rainfall (tab. 2). In the second scenario, the  
623 values of the parameters in the theoretical distributions were calculated using regression  
624 models. The uncertainty of the parameters identified in the statistical distributions was  
625 modelled based on the calculated average values of the parameters and the calculated standard  
626 deviations. The results of the calculations of the empirical distribution functions ( $CDF_{pe}$ ,  
627  $CDF_{Zt}$ ) based on the theoretical distribution (1975-1994) and  $Imp = 0.50$ , taking into account  
628 the uncertainty (average value), with indicated 95% intervals, are presented in Fig. 5.





629

630 **Fig. 5.** Empirical distribution functions calculated while taking into account the uncertainty of the  
 631 estimation of the theoretical distribution parameters, describing the probability of exceeding: a) the  
 632 probability of the occurrence of an storm overflows ( $p_e$ ); b) the annual number of storm overflows ( $Z_t$ ).

633

634 The resulting distribution functions were compared to the simulation results for the case that  
 635 omitted the uncertainty of estimated parameters in the statistical distributions of rainfall  
 636 characteristics.

637 Based on the resulting curves (Figs. 5a and 5b), it was concluded that the uncertainty of the  
 638 estimation of the parameters in the statistical distributions of rainfall had a minor impact on  
 639 the results when calculating the probability of the occurrence of a storm overflows-event and  
 640 the annual number of storm overflows. This was confirmed by the established ranges of 95%  
 641 confidence intervals in relation to the modelled variables, i.e.,  $p_e$  and  $Z_t$ . Based on the  
 642 resulting curves (Fig. 5a) for the period of 1961-1990, it was concluded that the values of  $p_e$   
 643 that were determined based on the parameters of the theoretical distributions of precipitation  
 644 by means of the relationships  $\mu_s = f(t)$  and  $\sigma_s = f(t)$  are higher than those obtained in the results  
 645 of the calculations that were based on the empirical parameters (tab. 2, columns 7 and 8). This  
 646 is reflected by the calculated distribution functions representing the yearly number of storm  
 647 overflows (Fig. 5b). For the assumed number of storm overflows  $n$  each year ( $Z_t$ ), the

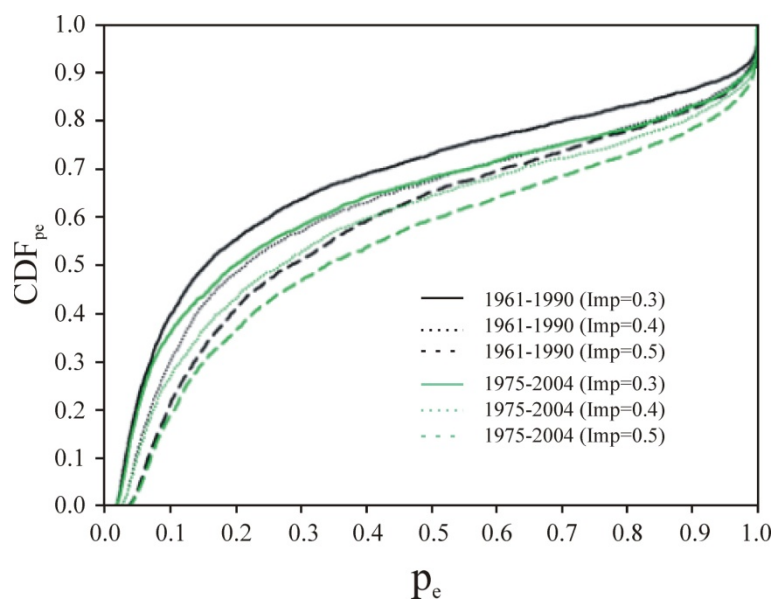
648 resulting percentile values were higher for the case in which the distribution parameter values  
649 were estimated based on the relationships  $\mu_s = f(t)$  and  $\sigma_s = f(t)$ . An analysis of the established  
650 95% confidence intervals demonstrated that, in the scenario in which the parameters of the  
651 statistical distributions of rainfall were estimated based on the relationships  $\mu_s = f(t)$  and  $\sigma_s =$   
652  $f(t)$ , the resulting parameters were lower than the values of the empirical parameters (tab. 2).  
653 Referring to the remaining rainfall distributions (periods: 1962-1991 to 1976-2005), it was  
654 proven that the values of  $p_e$  (percentile 0.50) calculated based on the empirical data and based  
655 on the relationships  $\mu_s = f(t)$  and  $\sigma_s = f(t)$  differed by a maximum of 3%. Therefore, it can be  
656 concluded that the uncertainty of parameter estimations in the statistical distributions had little  
657 impact on the values of  $p_e$  and  $Z_t$ . At the same time, this confirms the credibility of the  
658 produced results of the calculations of variables covered by the simulations.

659

#### 660 **4.4. The impact of changes in precipitation dynamics and urbanisation on the operation** 661 **of a storm overflow**

662 The impacts of the imperviousness of the catchment area and rainfall dynamics were analysed  
663 based on the established logit model and the theoretical distributions (a simulation of a single  
664 value of rainfall intensity was performed 2500 times using the LH method) of average rainfall  
665 intensity in the consecutive periods of the multiannual time interval (tab. 3). For example, the  
666 theoretical distributions of rainfall selected for the analyses originated from the periods from  
667 1961 to 1990 and from 1975 to 2004 (parameters were calculated from the statistical  
668 distributions based on the data from tab. 2). By means fitting the theoretical distributions of  
669 rainfall intensity, a simulation was performed using the LH method, and the probability of the  
670 occurrence of storm overflow was determined for the adopted impervious area of the  
671 catchment  $\text{Imp} = 0.3-0.5$ . The resulting  $\text{CDF}_{p_e}$  curves are presented in Fig. 6.





672  
 673 **Fig. 6.** The impacts of changes in precipitation dynamics in the consecutive periods of the multiannual  
 674 time interval and of the impervious area of the catchment on the probability of the occurrence of a  
 675 storm overflow event ( $p_e$ ).

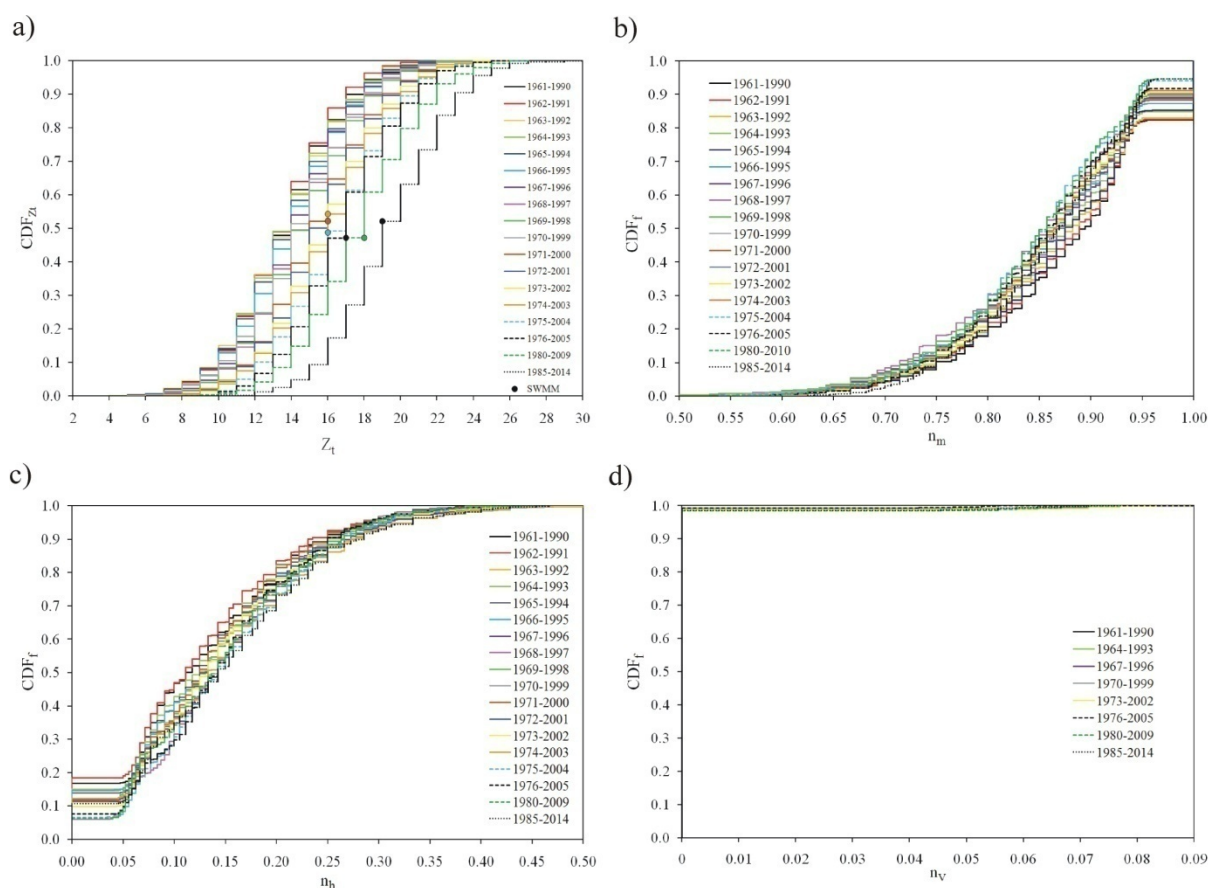
676  
 677 Based on an analysis of the shape of the curves (Fig. 6), it was concluded that both the  
 678 urbanisation of the catchment area and the dynamics of rainfall had significant impacts on the  
 679 probability of the occurrence of a storm overflow event ( $p_e$ ). For example, the values of the  
 680 0.5 percentile, determined based on the theoretical distribution, for the periods from 1961 to  
 681 1990 and from 1975 to 2004 at  $\text{Imp} = 0.30$  are 0.150 and 0.194, respectively. The results  
 682 yielded in this manner confirm the impact of changes in rainfall dynamics in a multiannual  
 683 approach on  $p_e$ , and these results are confirmed by the analyses of Bendel et al. (2013). By  
 684 applying the results of the precipitation forecasts of a 30-year period, the researchers indicated  
 685 an increase in the occurrence frequency of storm overflows based on calculations using a  
 686 hydrodynamic model of the studied catchment area. Moreover, an analysis of the  
 687 abovementioned curves indicates that, for theoretical distributions determined based on  
 688 precipitation data from the period from 1961 to 1990, an increase in the imperviousness of the  
 689 catchment area from  $\text{Imp} = 0.30$  to  $\text{Imp} = 0.50$  leads to an increase in the probability

690 (Arnbjerg-Nielsen et al., 2013) of an storm overflow event from  $p_e = 0.150$  to  $p_e = 0.271$ . The  
691 results of calculations demonstrate that both the urbanisation of the catchment area and the  
692 dynamics of changes in rainfall in a multiannual approach have a considerable impact on the  
693 operation of a storm overflow, with a strong interaction occurring between them (Wu et al.,  
694 2013). This is reflected by the value of the 0.5 percentile derived from the theoretical  
695 distributions for the period from 1961 to 1990 and  $Imp = 0.50$ , as well as the value derived  
696 from the theoretical distributions for the period from 1975 to 2004 and  $Imp = 0.40$ ; these  
697 values are almost identical and are equal to 0.268 and 0.265, respectively.

698

#### 699 **4.5. The impact of the dynamics of changes in precipitation on the annual number of** 700 **storm overflows with respect to the classification of precipitation**

701 Calculations of the annual number of storm overflows were performed based on the  
702 established theoretical distributions (a simulation of 33 precipitation events in a given year  
703 was performed 2500 times by means of the LH method) for the consecutive periods of the  
704 multiannual time interval (tab. 2) and by the developed logit model for the value  $Imp = 0.45$ .  
705 At the same time, continuous simulations were performed by means of a calibrated  
706 hydrodynamic model of the catchment area for the respective 30-year rainfall periods. The  
707 results of the performed analyses are presented in Fig. 7.



708  
 709 **Fig. 7.** The impact of the dynamics of changes in precipitation in the consecutive periods of  
 710 a multiannual time interval on **a)** the annual number of storm overflows; **b-d)** the probability of the  
 711 occurrence of a storm overflow in a given year caused by a moderate (b), heavy (c) or violent  
 712 downpour (d).

713  
 714 Based on the resulting curves, it can be concluded that changes in precipitation dynamics in  
 715 the consecutive periods of the multiannual time interval from 1961 to 1975 had significant  
 716 impacts on the annual number of storm overflows. The shape of the resulting curves indicates  
 717 an increase in the calculated number of storm overflows based on the theoretical distributions  
 718 derived from the precipitation data from the consecutive periods of the multiannual time  
 719 interval (starting from 1961). This is confirmed by the values of the resulting 0.5 percentiles.  
 720 For example, the annual number of storm overflows for the data from the period from 1961 to  
 721 1990 was 13, while the value determined for the period from 1976 to 2005 equalled 16. The



722 resulting pattern can also be observed in the values of the remaining percentiles. For example,  
723 for the 0.05 and 0.95 percentiles, the annual numbers of storm overflows determined for the  
724 period from 1961 to 1990 amounted to 9 and 18, and those for the period from 1976 to 2005  
725 amounted to 12 and 22, respectively. The results of the simulations indicate the impacts of  
726 climate change on the operation of sewage networks, including on the objects existing within  
727 the sewage networks, such as storm overflows. These results are confirmed by the analyses  
728 performed by Bendel et al. (2013), who, by using a calibrated model of the studied catchment  
729 area and predicting rainfalls by means of the NiedSim-Klima model, demonstrated an  
730 increase in the number of storm overflows in an urbanised catchment area in Baden-  
731 Württemberg. These results are also confirmed by the analyses performed by Tavakol-Davani  
732 et al. (2016), who, by performing simulations using a calibrated model for the catchment area  
733 of Toledo (Canada) based on multiannual precipitation forecasts, demonstrated a 15% impact  
734 of the annual number of overflows over a 30-year period. A similar increase in the number of  
735 storm overflows for a 30-year period was also confirmed by Abdellatif et al. (2015), who  
736 performed similar simulations for the catchment area of Crewe in northern England. It should  
737 be noted that the results of continuous simulations using a calibrated model of the studied  
738 catchment area fall within the range of probabilistic solutions, which indicates the  
739 applicability of the model to predicting the annual number of storm overflows.

740 The probability of the occurrence of an storm overflow in a given year caused by rainfall with  
741 a varying intensity was analysed to supplement the abovementioned results and investigate  
742 the impact of the dynamic process of rainfall changes on the operation of a storm overflow.  
743 The results of the calculations are presented in Figs. 7b-d. On the basis of these results, it was  
744 concluded that storm overflows in consecutive years occurred as a result of various types of  
745 precipitation: moderate, heavy and violent. Moreover, the resulting curves indicate that a  
746 change in rainfall dynamics in the consecutive years of the 1961-1975 period led to a decrease



747 in the probability of the occurrence of an storm overflow caused by a moderate downpour  
748 (Fig. 7b), as confirmed by the values of the calculated percentiles. In contrast, the probability  
749 of the occurrence of a storm overflow caused by a violent or heavy downpour increased  
750 correspondingly. To date, this aspect has not been addressed by researchers involved in the  
751 modelling of storm overflows. Based on the results of continuous measurements of  
752 precipitation and a calibrated hydrodynamic model for Innsbruck city, Jean et al. (2019)  
753 analysed the possibility of determining precipitation characteristics for the design of an  
754 overflow. However, to a limited extent, these authors took into consideration aspects related  
755 to the identification of rainfall, which could have affected the final results of the calculations  
756 and problems with the interpretation of the resulting relationships.

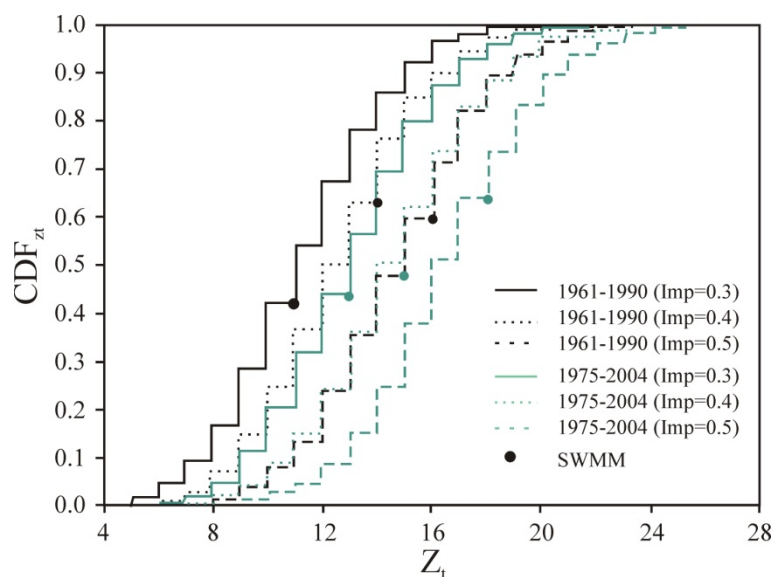
757 The results yielded in this paper can be used to identify the occurrence of a storm overflow  
758 based solely on precipitation intensity, depending on changes in rainfall dynamics during the  
759 multiannual time interval. However, one should aim to generalise the produced results;  
760 therefore, these analyses should cover broader areas (Guo and Urbonas, 2002; De Paola and  
761 Ranucci, 2012).

762

#### 763 **4.6. The impact of urbanisation and changes in precipitation dynamics on the annual** 764 **number of storm overflows**

765 By proceeding in accordance with the developed computational algorithm, based on the logit  
766 model (equation 17) and the established parameters of the theoretical distributions for the  
767 years 1961-1990 and 1975-2004, the annual numbers of storm overflows ( $Z_t$ ) were  
768 determined for the adopted values of  $Imp = 0.3-0.5$  (Fig. 8). The calculations used synthetic  
769 precipitation series (2500 samples), assuming 33 episodes per year. To assess the  
770 predictability of the model, continuous simulations were performed on the basis of the  
771 adopted time series.





772

773 **Fig. 8.** The impacts of changes in precipitation dynamics in the periods from 1961 to 1990 and 1975 to  
 774 2004 and of the impervious area of the catchment (Imp) on the annual number of storm overflows ( $Z_t$ ).

775

776 The resulting curves (Fig. 8) confirm the relationship shown in Fig. 6 and present the impact  
 777 of changes in rainfall dynamics in the analysed periods of the multiannual time interval. An  
 778 analysis of the shape of the curves of Fig. 8 indicates the significant impact of the  
 779 imperviousness of the catchment area on the annual number of storm overflows. For both the  
 780  $CDF_{Z_t}$  curve derived from precipitation data from the period from 1961 to 1990 and that from  
 781 1975 to 2004, an increase in the imperviousness of the catchment area of  $\Delta Imp = 0.1$  (from  
 782  $Imp = 0.3$  to  $Imp = 0.4$ ) led to an increase in the annual number of storm overflows by 1 for  
 783 the 0.5 percentile (from 11 to 12 in the period from 1961 to 1991 and from 13 to 14 in the  
 784 years 1975-2004). Similar relationships were also derived for the 0.95 percentile. These  
 785 results are confirmed by the calculations performed by other authors (Kirshen et al., 2014;  
 786 Fortier and Maihlot, 2015; Tavakol-Davani et al., 2016) by means of calibrated hydrodynamic  
 787 models of urban catchment areas. These authors observed that the impacts of changes in  
 788 precipitation dynamics relative to the multiannual time interval led to an increase in the  
 789 number of storm overflows of no less than 10%. Analogical conclusions were drawn by

790 Szeląg et al. (2019), who, like the abovementioned researchers, focused solely on the impact  
791 of changes in the impervious area of a catchment on the number of storm overflows; the  
792 aspect related to rainfall dynamics over time was neglected.

793 From a practical point of view and regarding the usefulness of the proposed model, it is  
794 important that the results of continuous simulations using the hydrodynamic model for the  
795 period from 1962 to 1991 and the period from 1975 to 2004 fall within the scope of the  
796 probabilistic solution, which confirms the correctness of the approach proposed in the paper.  
797 Moreover, the values of the 0.5 percentiles derived from the SWMM model and the proposed  
798 probabilistic model are highly compliant, which confirms the credibility of the produced  
799 calculation results.

800

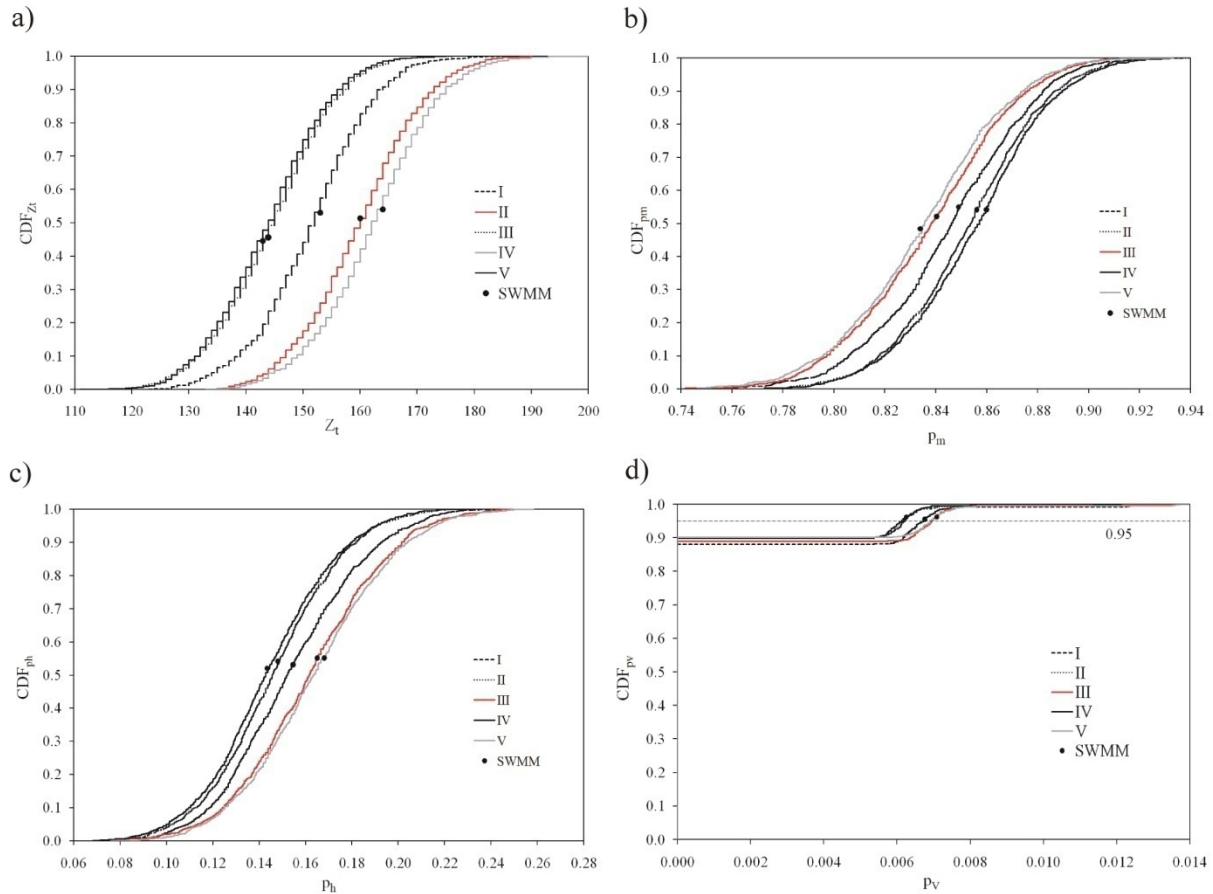
#### 801 **4.7. The impact of urbanisation dynamics on the multiannual number of storm** 802 **overflows**

803 The performed analyses included consideration of the impact of urbanisation dynamics in the  
804 studied urban catchment area in the period covered by the studies, which corresponded to  $t_{cr} =$   
805 10 years. Using the developed logit model, the theoretical distribution of precipitation  
806 intensity values (1961-2004), and the model for predicting the imperviousness of the  
807 catchment area (equation 17), while assuming that  $Imp_0 = 0.33$  and  $Imp_m = 0.55$ , simulations  
808 of the precipitation characteristics ( $i$ ) of the events were performed by means of the LH  
809 method (2500 samples). The following computational scenarios were analysed to assess the  
810 impacts of urbanisation dynamics on the number of storm overflows: I ( $a = 1.00$ ), II ( $a =$   
811  $0.40$ ), III ( $a = 2.40$ ), IV ( $a = 0.25$ ) and V ( $a = 2.80$ ). The calculations served as a basis for  
812 determining the multiannual number of storm overflows ( $Z_t$ ) and the probability of an storm  
813 overflows caused by downpours of the following intensities: moderate ( $n_m$ ), heavy ( $n_h$ ) and



814 violent ( $n_v$ ). The simulation results yielded for the abovementioned assumptions are presented  
 815 in Fig. 9a-c.

816



817

818 **Fig. 9.** Selected characteristics of storm overflows for scenarios I, II, III and IV of the dynamics of  
 819 changes in the impervious area: (a) the probability of exceeding a 10-year number of storm overflows  
 820 ( $Z_t$ ); (b-d) the probability of the occurrence of a storm overflow ( $t = 10$  years) caused by a moderate  
 821 (b), heavy (c) or violent downpour (d).

822

823 The shape of the curves in Fig. 9a unambiguously indicates that the lowest resulting number  
 824 of storm overflows ( $Z_t = 140$ ) corresponds to the value  $a = 2.8$  (scenario V). For the parameter  
 825 value  $a = 1.0$  (scenario I), the calculated number of storm overflows is  $Z_t = 152$  and is larger  
 826 by 12 than the number of storm overflows obtained in scenario V ( $a = 2.8$ ). The largest  
 827 resulting number of storm overflows (percentile 0.50), which equals  $Z_t = 162$ , corresponds to

828 the urbanisation dynamics in which the value of coefficient  $a$  is the lowest ( $a = 0.25$ ; scenario  
829 IV).

830 From the point of view of the number of storm overflows ( $t = 10$  years), the concept of  
831 urbanisation according to scenario V ( $a = 2.8$ ) seems optimal. This results in the smallest  
832 number of storm overflows (percentile 0.5). The considerable impact of the urbanisation of  
833 urban catchment areas on the increase in the number of storm overflows and their volume in a  
834 multiannual approach is confirmed in the paper by Shuster et al. (2005). These results remain  
835 in compliance with the papers of Pennino et al. (2016). By analysing three catchment areas in  
836 the Mid-Atlantic of the USA, the authors demonstrated the impacts of changes in the  
837 imperviousness of the studied catchment areas (including solutions related to LID) on the  
838 operations of storm overflows. The resulting relationships were also confirmed by the  
839 calculations of Todeschini (2016), which were performed by means of a calibrated  
840 hydrodynamic model using the example of a small catchment area in northern Italy. In that  
841 case, the analysis of the impact of urbanisation dynamics in the catchment area in a  
842 multiannual approach was performed within a limited scope, which, as demonstrated by the  
843 present paper, is of major significance for the operation of an overflow (the number of  
844 overflows). In relation to the spatial development plans of urban areas, the aspect analysed in  
845 the paper is extremely important, as it provides the ability to plan the development and take  
846 actions that allow the compensation of the disadvantageous impact of the catchment area  
847 imperviousness on the quality of water in streams. This requires extending the proposed  
848 methodology and taking into account both the volume and the pollution load in simulations.

849 The probability of the occurrence of a storm overflow in a period of  $t = 10$  years caused by  
850 moderate ( $p_m$ ), heavy ( $p_h$ ) or violent ( $p_s$ ) downpours (Fig. 9b-d) was determined to increase  
851 the level of detail of the abovementioned analyses. On the basis of the resulting curves, it was  
852 concluded that, when  $a = 2.80$  (scenario V), the resulting values of the probability of the

853 occurrence of a storm overflow caused by heavy and violent downpours were higher (Fig. 9c-  
854 d). Under the operating conditions of the network, this indicates an increase in the number of  
855 storm overflows, which also results in an increase of the pollution load introduced into the  
856 receiving waters. In terms of the probability of a storm overflow caused by moderate  
857 downpours, it was concluded that, among all considered scenarios (I-V), the lowest values of  
858  $p_m$  were observed in scenarios III and V. A comparison of the calculation results (0.5  
859 percentile) of the number of storm overflows determined by means of the developed  
860 mathematical model with the results of the continuous simulations (using the hydrodynamic  
861 model) resulted in their high similarity. This confirms the compliance of the relationships  
862 between the dynamics of changes in the imperviousness of the catchment area in a long-term  
863 approach, established through probabilistic and hydrodynamic models.

864

#### 865 **4.8. The impact of changes in rainfall dynamics and urbanisation on the multiannual** 866 **number of overflows – sustainable development of the catchment area**

867 The impact of changes in precipitation dynamics in consecutive years, as well as of the  
868 imperviousness of the catchment area (Imp), on the multiannual number of storm overflows is  
869 analysed below. Based on the parameters ( $\mu$ ,  $\sigma$ ) determined in the theoretical distributions  
870 (tab. 2), simulations of rainfall series were performed by means of the I-C method with a LH  
871 modification. Considering the long period covered by the calculations and the fact that the  
872 variables used in the simulations are dependent, 2,500,000 samplings were performed for the  
873 10-year rainfall series originating from the periods from 1990 to 1999 and from 1996 to 2005.  
874 During an intense increase in the imperviousness of the catchment area (Imp of 15%), a  
875 period of  $t_{cr} = 5$  years was assumed. The reduction in the impervious area ( $t_{sust}$ ) was also  
876 assumed to be 5 years. Tab. 3 presents values a and b for the modelled imperviousness  
877 scenarios, calculated using equation (17).



878

879 **Tab. 3.** List of the values of coefficients (a, b) in an empirical model describing  $\text{Imp} = f(t)$  in equation  
 880 (17).

Coefficient	Variant								
	I	II	III	IV	V	VI	VII	VIII	IX
a	1.0	0.4	2.4	1.0	1.0	0.4	0.4	2.4	2.4
b	1.0	0.4	2.4	0.4	2.4	1.0	2.4	1.0	0.4

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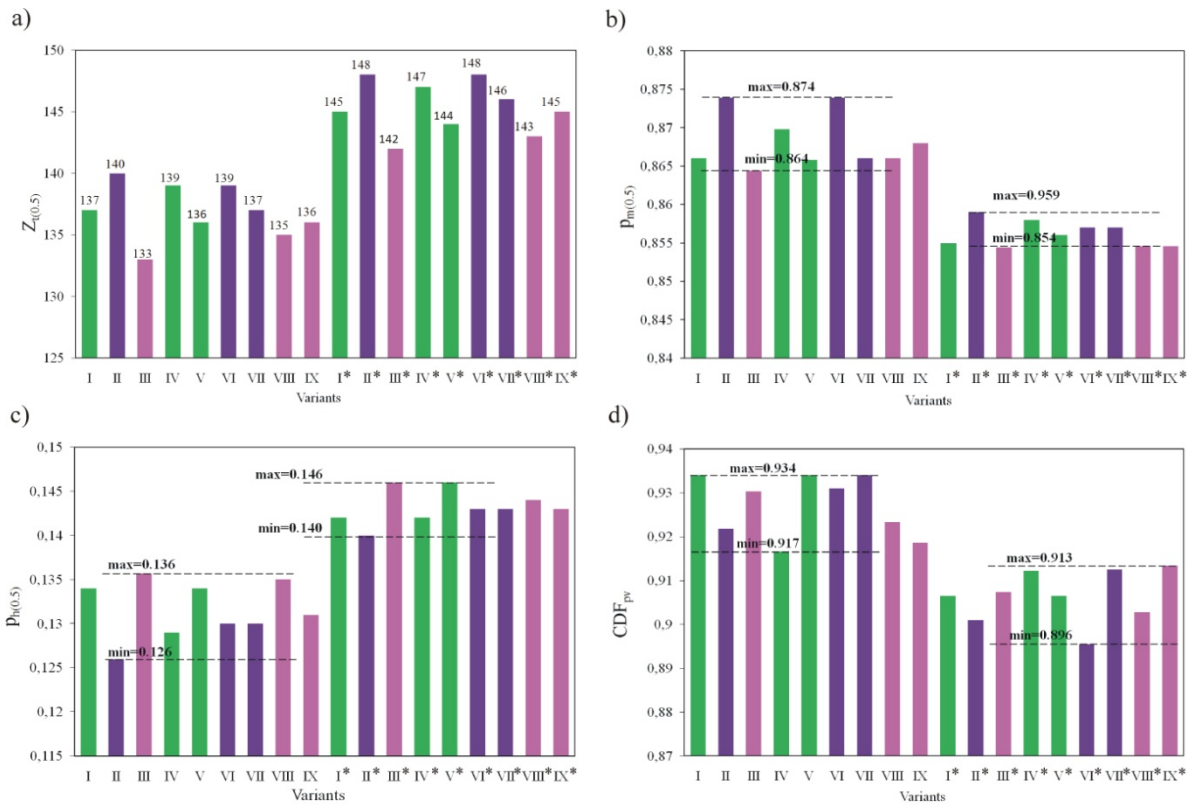
882 The calculations assumed an initial impervious area of the catchment of  $\text{Imp}_0 = 0.40$  and a  
 883 maximum impervious area of the catchment of  $\text{Imp}_m = 0.55$ ; the impervious area of the  
 884 catchment after the period of  $t_{cr} + t_{sust}$  was assumed to be  $\text{Imp}_e = 0.47$ . Simulations of the  
 885 operations of storm overflows were performed for the abovementioned assumptions in search  
 886 of an optimal scenario of changes in the imperviousness of the analysed catchment area. The  
 887 following were also determined on the same basis: the impact of changes in rainfall dynamics  
 888 in a multiannual approach and that of the imperviousness of the catchment area on the  
 889 multiannual number of storm overflows and the probability of the occurrence of a storm  
 890 overflow caused by moderate ( $p_m$ ), heavy ( $p_h$ ) and violent downpours ( $p_v$ ). The calculation  
 891 results, i.e., the empirical distribution functions reflecting the probability of exceeding the 10-  
 892 year number of storm overflows and the probability of exceeding the occurrence probability  
 893 of a storm overflow resulting from moderate, heavy and violent downpours in scenarios I–IX  
 894 for the precipitation periods from 1990 to 1999 and from 1996 to 2005 are presented in  
 895 Appendixes F and G. A comparison between the respective values (0.5 percentile) of  $Z_{t(0.5)}$   
 896 and  $p_{m(0.5)}$  or  $p_{h(0.5)}$  for the applied precipitation periods and imperviousness scenarios I–IX is  
 897 presented in Fig. 10. The yielded results are compared to the simulations that used the  
 898 hydrodynamic model. Due to the course of the empirical distribution function (Figs. 7d, 9b)  
 899 for violent downpours (compared to those for moderate and heavy downpours), the minimum



900 probability of exceeding the probability of a storm overflow ( $p_v$ ) was presented for the  
901 scenarios covered by the calculations.

902 Based on the resulting curves, it was concluded that the number of storm overflows  
903 (percentile) derived from the probabilistic model is larger by maximum 2 storm overflows  
904 than that determined using the hydrodynamic model for the analysed scenarios (tab. 3). The  
905 resulting model confirms the high compliance of the calculation results obtained using the  
906 probabilistic model suggested in the manuscript in terms of a simultaneous simulation of the  
907 dynamics of changes in rainfall and the imperviousness of the catchment area.

908 Based on the performed analyses, it can be concluded that the smallest numbers of storm  
909 overflows derived from the theoretical distributions for the period from 1990 to 1999 were  
910 observed in scenarios III ( $Z_{t(0.5)} = 133$ ), and the largest value was observed in scenario II  
911 ( $Z_{t(0.5)} = 140$ ). For the period from 1996 to 2005 (similarly to the preceding period), the  
912 largest number of storm overflows was observed in scenario II and VI ( $Z_{t(0.5)} = 148$ ) and the  
913 smallest in scenario III ( $Z_{t(0.5)} = 142$ ). For linear increases in  $Imp$  in the period  $t_{cr}$  and rainfall  
914 in the period from 1990 to 1999, the smallest number of storm overflows ( $Z_{t(0.5)} = 136$ ) was  
915 observed in scenario V ( $b = 2.40$ ) and the largest in scenario IV ( $Z_{t(0.5)}=139$ ). The largest  
916 number of storm overflows in each of the consecutive computational scenarios, i.e., II, VI and  
917 VII ( $a = 0.40$ ), as well as III, VIII and IX ( $a = 2.40$ ), in both periods (1990-1999 and 1996-  
918 2005) were observed for  $b = 0.4$  (Fig. 10a).



919

920 **Fig. 10.** Selected characteristics of storm overflows for imperviousness scenarios I – IX based on  
 921 precipitation data in the periods from 1990 to 1999 and from 1996 to 2005 (marked with an asterisk):  
 922 **a)** the number of storm overflows  $Z_{t(0.5)}$  (per values); **b)** minimum probability of exceeding the  
 923 probability of the occurrence of a storm overflow caused by violent downpours  $p_v$  (percentile 0.50);  
 924 **c)** the probability of the occurrence of a storm overflow caused by moderate downpours  $p_m(0.5)$   
 925 (percentile 0.50); and **d)** the probability of the occurrence of a storm overflow caused by heavy  
 926 downpours  $p_h(0.5)$  (percentile 0.50).

927

928 When assuming nonlinear dynamics of  $\text{Imp} = f(t)$  in period  $t_{cr}$  ( $a = 2.40$  and  $b = 0.40$ ), the  
 929 resulting number of overflows or period  $t_{sust}$  (equation 14) was larger by 1 overflows than that  
 930 of scenario VIII when  $b = 1.0$ . For scenario III, when  $a = b = 2.40$ , and for precipitation  
 931 distributions for the period from 1990 to 1999, it was observed that the number of overflows  
 932  $Z_t = 133$  was smaller by 4 overflows than that of scenario VII ( $a = 2.4$  and  $b = 1.0$ ) ( $Z_{t(0.5)} =$   
 933  $137$ ). In scenario II and in the precipitation distribution for the period from 1990 to 1999, the  
 934 number of overflows ( $Z_{t(0.5)} = 140$ ) was larger by 4 overflows compared to that of scenario IX.

935 Figs. 10b-d demonstrate that a change in precipitation dynamics (moderate, heavy and violent  
936 downpours) had a significant impact on the probability of the occurrence of a storm overflow.  
937 The resulting values of  $p_{m(0.5)}$  for the analysed scenarios, determined based on the theoretical  
938 distributions of precipitation in the period from 1990 to 1999, were lower than their  
939 counterparts from the 1996-2005 period. An identical relationship was observed with respect  
940 to the minimum probability of the occurrence of an storm overflow in a 10-year period for  
941 violent downpours (Fig. 10d). The values of the probability of an storm overflow caused by  
942 heavy downpours in the period from 1990 to 1999 were higher than their counterparts from  
943 the 1996-2005 period (Fig. 10c). In terms of the operation of a storm overflow, this means  
944 that it may be necessary to modify the position of the height of the overflow edges to limit the  
945 number of storm overflow events caused by precipitation with an average intensity of  $i = 10-$   
946  $50 \text{ mm} \cdot \text{h}^{-1}$ .

947 The interaction between the dynamics of changes in rainfall and the impervious area is of  
948 primary importance for the resulting number of storm overflows (10 years). For example, for  
949 the theoretical precipitation distributions in the period from 1990 to 1999 and for scenario II  
950 (tab. 3), the resulting number of storm overflows ( $Z_{t(0.5)} = 140$ ) was only 2 less than for the  
951 precipitation distributions for the period from 1996 to 2005 and scenario III. The dynamics of  
952 rainfall changes (caused by climate changes) presented using a long-term approach indicate  
953 an increase in the number of storm overflows. This is also confirmed by the simulation results  
954 obtained using hydrodynamic models (for a 30-year period) for urban catchment areas  
955 (Kleidorfer et al., 2014). The exclusion of the dynamics of changes in precipitation from the  
956 modelling process can result in the underestimation of the calculated number of storm  
957 overflows and, as a consequence, in the erroneous determination of the position of the edge of  
958 the overflow. The produced results unambiguously confirm the significant impacts of changes  
959 in precipitation dynamics and urbanisation on the functioning of storm overflows. This aspect

960 was analysed in detail in the paper by Wu et al. (2013). The authors presented the impacts of  
961 climate change and the impervious area of the catchment area on the runoff from the  
962 catchment to the receiving waters. The relationships demonstrated by these authors were  
963 confirmed by the work of other researchers who analysed catchment areas in the USA  
964 (Kirshen et al., 2014; Tavakol-Davani et al., 2016), Sweden (Semadeni-Davies et al., 2008)  
965 and Canada (Fortier and Mailhot, 2015; Jean et al., 2018).

966 The high compliance of the calculation results obtained using the probabilistic and  
967 hydrodynamic models indicates that the developed model constitutes a useful supporting tool  
968 when planning the directions of changes in the development of a catchment area (in a  
969 multiannual approach) in terms of reducing the number of storm overflows and therefore  
970 protecting water in streams. Due to the use of a simplified approach compared to that  
971 presented in previous papers (Kleidorfer et al., 2009; Thorndahl and Willems, 2008; Jean et  
972 al. 2019), the approach used in this paper can be applied to analyses in everyday engineering  
973 practice as an alternative to complicated hydrodynamic models requiring a large amount of  
974 data. Moreover, the developed rainfall generator allows modelling of the dynamics of its  
975 changes in a long-term approach, which, compared to the currently used models (Gironás et  
976 al., 2010; Arnell, 2011; Arnbjerg-Nielsen et al., 2013), constitutes a considerable  
977 simplification. The suggested computational methodology can be useful when constructing  
978 precipitation models by means of multidimensional density distributions used at the design  
979 stages of both the sewage system and the objects located above it.

980

## 981 **5. Summary and conclusions**

982 Currently, the modelling of objects (storm overflows, reservoirs, etc.) located in drainage  
983 networks, while taking into account the dynamics of precipitation and urbanisation in short-  
984 and long-term approaches, constitutes a topical issue. The calculations performed in this paper



985 indicated that a logistic regression model can be used for predicting the operation of a storm  
986 overflow during a precipitation event. The action of an overflow can be modelled based on  
987 the average rainfall intensity and the impervious area of the catchment; this constitutes a  
988 simplification compared to the work of other authors. The logistic regression model has been  
989 verified for different catchment area imperviousness values by means of simulations using a  
990 hydrodynamic model. The produced calculation results confirmed that the approach used in  
991 this paper has a universal nature and can be used for catchment areas with diverse physical-  
992 geographical characteristics.

993 The paper proves that modifications to the forms of empirical models used for predicting the  
994 parameters of statistical distributions depending on the time, as included in the Monte Carlo  
995 method, allows the modelling of changes in rainfall dynamics, which translates into the  
996 modelling of the number of storm overflows. The performed simulations demonstrated that  
997 the methodology suggested in the paper could be applied to simulations of short- and long-  
998 term rainfall series considering the changes in their dynamics. The suggested computational  
999 methodology has a universal nature and enables its implementation when modelling the  
1000 operations of sewage networks and objects located above them while considering changes in  
1001 precipitation dynamics.

1002 It was also concluded that the proposed probabilistic model allows the assessment of the  
1003 impacts of changes in land development and the dynamics of changes in rainfall intensity in  
1004 consecutive years on the occurrence of an overflow in a precipitation event and in a  
1005 multiannual aspect. The resulting model allows optimisation of the selection of the concept of  
1006 sustainable development for a catchment area, considering, on the one hand, changes in  
1007 rainfall dynamics and, on the other hand, the impervious area of the catchment, which so far  
1008 has not been studied in detail by other authors. The results produced in this manner confirmed  
1009 that the proposed model constitutes a useful tool for analysing the operation of a storm

1010 overflow (and for predicting the occurrence of a storm overflow) and provides the ability to  
1011 test various scenarios involving the development of catchment areas, even at their conceptual  
1012 stages.

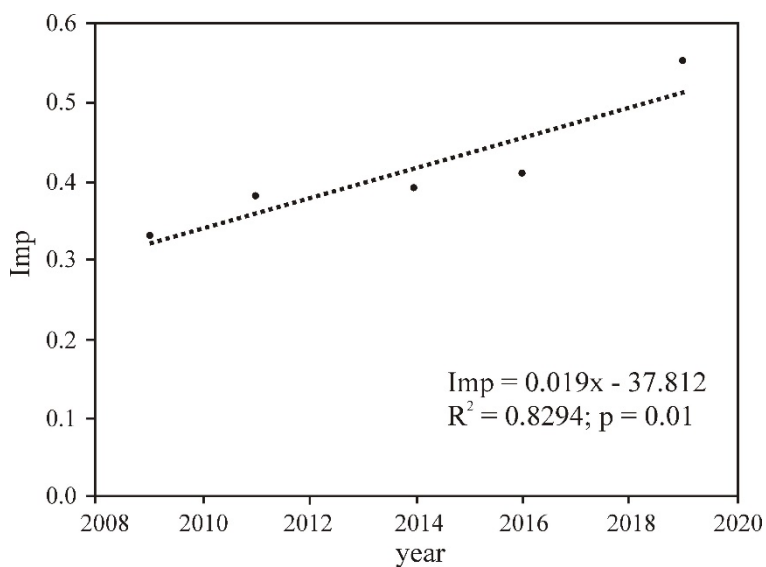
1013 The performed simulations proved that the dynamics of land development have strong  
1014 impacts on the number of overflows and their changes in the following years. The smallest  
1015 number of overflows in a multiannual aspect was achieved for scenarios in which the  
1016 urbanisation process in the initial period covered by the simulations proceeded slowly. In  
1017 contrast, in a scenario in which significant changes take place during the initial period of  
1018 urbanisation, the simulation resulted in the largest number of storm overflows.

1019 The yielded results confirmed the impacts of changes in precipitation dynamics in consecutive  
1020 years on the probability of the occurrence of a storm overflow, which decreased for moderate  
1021 precipitation. In contrast, a considerable increase was recorded in the case of storm overflows  
1022 caused by heavy and violent downpours. Therefore, there is a need for further analyses  
1023 intended to expand the model described in the present paper by the consideration of other  
1024 variables (e.g., the height of the storm overflow), which will allow a dynamic modification of  
1025 the operating conditions of the studied storm overflow in a multiannual time interval.

1026

1027 **Appendix**

1028 **Appendix A.** Change of the impervious area of the catchment in the years 2009-2019.



1029

1030

1031 **Appendix B.** Results of computations of  $\mu$  and  $\sigma$  of polynomials.

Degree of a polynomial	$\mu$			$\sigma$		
	RMSE	AIC	R <sup>2</sup>	RMSE	AIC	R <sup>2</sup>
1	0.012187	-21.1118	0.8886	0.008	-28.37	0.5374
2	0.001172	-22.5467	0.9356	0.005	-33.66	0.8574
3	0.010740	-19.1734	0.9498	0.008	-23.16	0.8691

1032

1033 **Appendix C.** The values of the Spearman's correlation coefficients between the values of average  
 1034 rainfall intensity in precipitation events ( $i$ ) in the consecutive years of a multiannual time interval.

	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
1961	1.00	0.82	0.84	0.76	0.70	0.63	0.51	0.41	0.30	0.21	-0.03	-0.11	-0.20	-0.26	-0.34	-0.41
1962		1.00	0.82	0.81	0.78	0.71	0.59	0.49	0.37	0.29	0.04	-0.05	-0.14	-0.19	-0.28	-0.34
1963			1.00	0.82	0.82	0.79	0.67	0.57	0.45	0.37	0.11	0.03	-0.06	-0.12	-0.21	-0.27
1964				1.00	0.84	0.81	0.75	0.64	0.53	0.45	0.18	0.10	0.00	-0.05	-0.14	-0.20
1965					1.00	0.83	0.81	0.71	0.59	0.51	0.23	0.15	0.05	0.00	-0.09	-0.16
1966						1.00	0.78	0.78	0.67	0.58	0.30	0.22	0.12	0.06	-0.02	-0.09
1967							1.00	0.80	0.79	0.70	0.41	0.32	0.23	0.17	0.08	0.02
1968								1.00	0.79	0.80	0.51	0.42	0.33	0.27	0.18	0.12
1969									1.00	0.81	0.61	0.52	0.43	0.37	0.28	0.21
1970										1.00	0.69	0.60	0.50	0.44	0.35	0.29
1971											1.00	0.82	0.82	0.75	0.65	0.57
1972												1.00	0.80	0.81	0.73	0.66
1973													1.00	0.82	0.80	0.76
1974														1.00	0.81	0.81
1975															1.00	0.81
1976																1.00

1035



1036 **Appendix D.** The Iman-Conover (IC) method.

1037 The following conditions must be fulfilled to confirm the correctness of the results produced  
1038 by the Iman-Conover method:

- 1039 ○ in data resulting from simulations and measurements, the average value and  
1040 standard deviations for the investigated dependent variables in samples cannot  
1041 differ by more than 5%,
- 1042 ○ the theoretical distributions of dependent variables resulting from the simulations  
1043 must comply with those resulting from the measurements; to fulfil this condition,  
1044 it is recommended to perform the Kolmogorov-Smirnov test, and
- 1045 ○ the value of the Spearman's correlation coefficient ( $R$ ) between dependent  
1046 variables ( $x_i$ ) corresponding to the data from simulations cannot differ by more  
1047 than 5% from the  $R$  value derived from the empirical data.

1048

1049 When the abovementioned conditions are fulfilled, the results of the calculations performed  
1050 by means of the IC method may be deemed correct. In contrast, when one of the  
1051 abovementioned conditions is not fulfilled, it is necessary to increase the sample size.

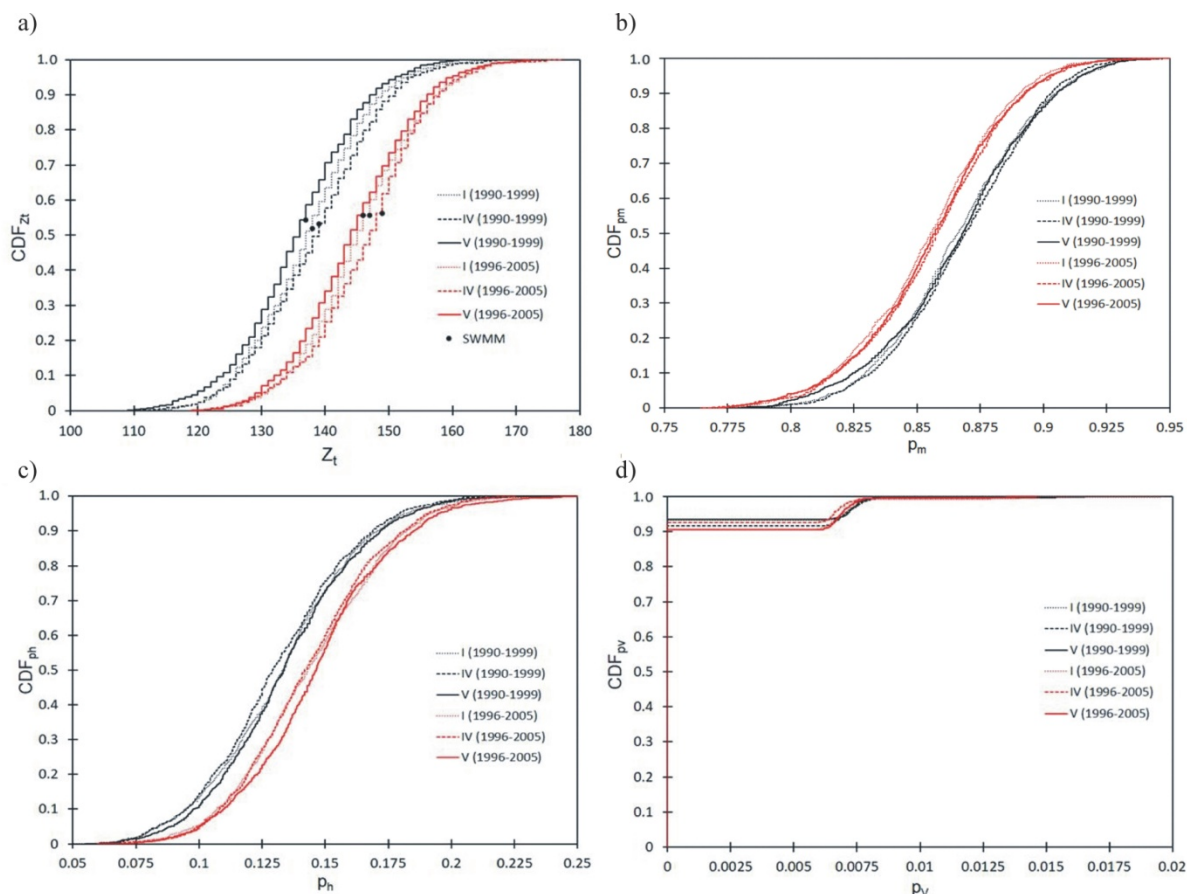
1052

1053 **Appendix E.** Results of the calculations of test probability values  $p$  for selected statistical distributions  
 1054 (Gumbel, Weibull, Frechet, Gamma).

Period	p-test							
	Gumbel		Weibull		Frechet		Gamma	
	K-S	$\chi^2$	K-S	$\chi^2$	K-S	$\chi^2$	K-S	$\chi^2$
1961-1990	0.0048	0.0030	0.0216	0.0210	0.0074	0.0068	0.0185	0.0141
1962-1991	0.0050	0.0021	0.0224	0.0212	0.0065	0.0064	0.0170	0.0123
1963-1992	0.0048	0.0042	0.0234	0.0273	0.0066	0.0053	0.0177	0.0115
1964-1993	0.0059	0.0023	0.0236	0.0214	0.0056	0.0051	0.0195	0.0128
1965-1994	0.0050	0.0034	0.0238	0.0236	0.0055	0.0044	0.0238	0.0211
1966-1995	0.0057	0.0035	0.0222	0.0222	0.0047	0.0042	0.0202	0.0149
1967-1996	0.0041	0.0023	0.0230	0.0243	0.0038	0.0028	0.0194	0.0111
1968-1997	0.0043	0.0022	0.0234	0.0247	0.0037	0.0033	0.0201	0.0148
1969-1998	0.0042	0.0031	0.0234	0.0227	0.0037	0.0031	0.0185	0.0110
1970-1999	0.0029	0.0025	0.0225	0.0221	0.0047	0.0032	0.0177	0.0138
1971-2000	0.0041	0.0027	0.0226	0.0224	0.0038	0.0029	0.0141	0.0129
1972-2001	0.0031	0.0023	0.0241	0.0213	0.0037	0.0028	0.0184	0.0168
1973-2002	0.0047	0.0041	0.0208	0.0249	0.0037	0.0031	0.0220	0.0177
1974-2003	0.0050	0.0032	0.0257	0.0258	0.0046	0.0039	0.0255	0.0211
1975-2004	0.0040	0.0023	0.0265	0.0257	0.0038	0.0042	0.0232	0.0209
1976-2005	0.0058	0.0031	0.0257	0.0253	0.0028	0.0032	0.0197	0.0168

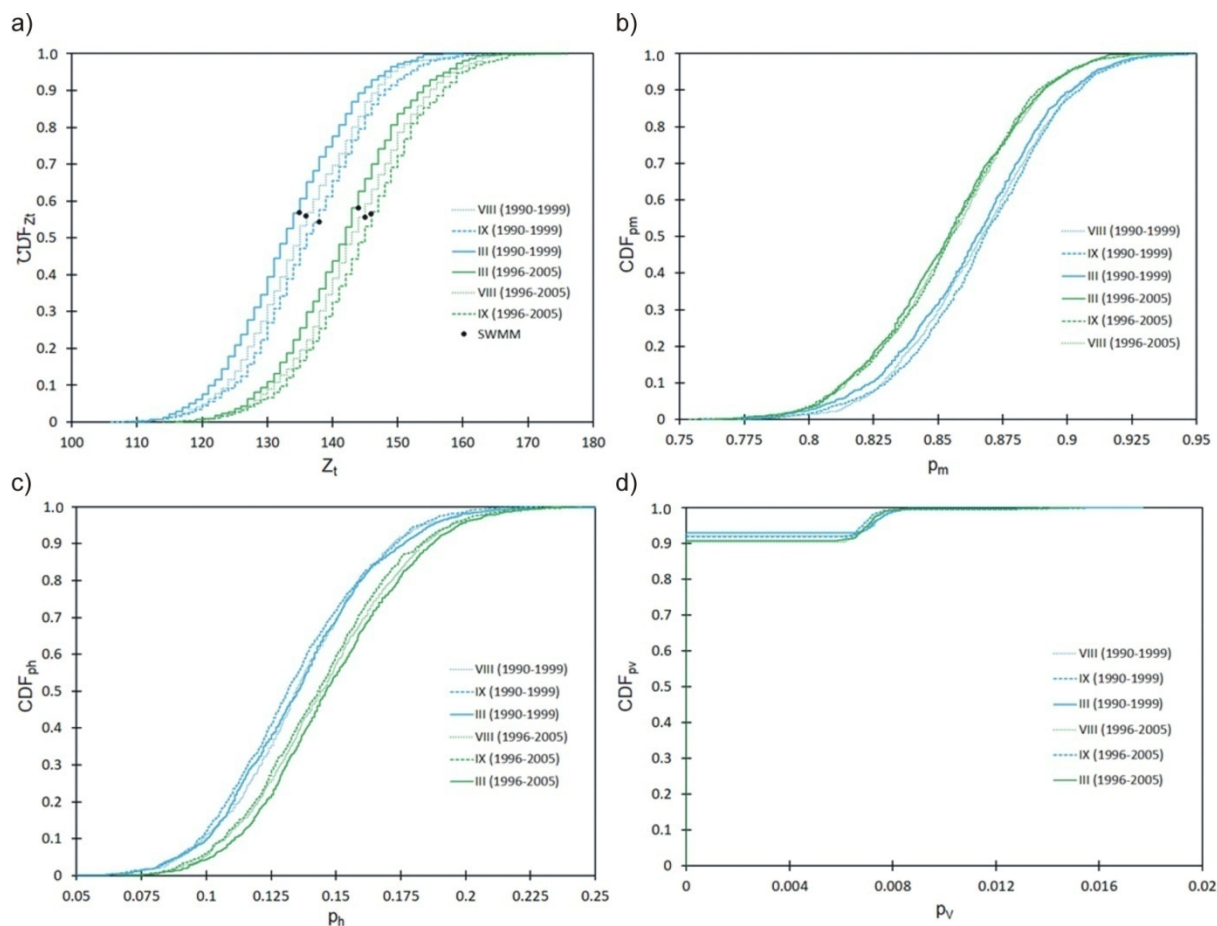
1055

1056 **Appendix F.** Multiannual ( $t = 10$  years) characteristics of overflows for imperviousness scenarios I,
   
1057 IV and V, based on the theoretical distributions of precipitation in the periods from 1990 to 1999 and
   
1058 from 1996 to 2005: **a)** the number of overflows; **b-d)** the probability of the occurrence of a overflow
   
1059 caused by a moderate (b), heavy (c) or violent (d) downpour.



1060  
1061

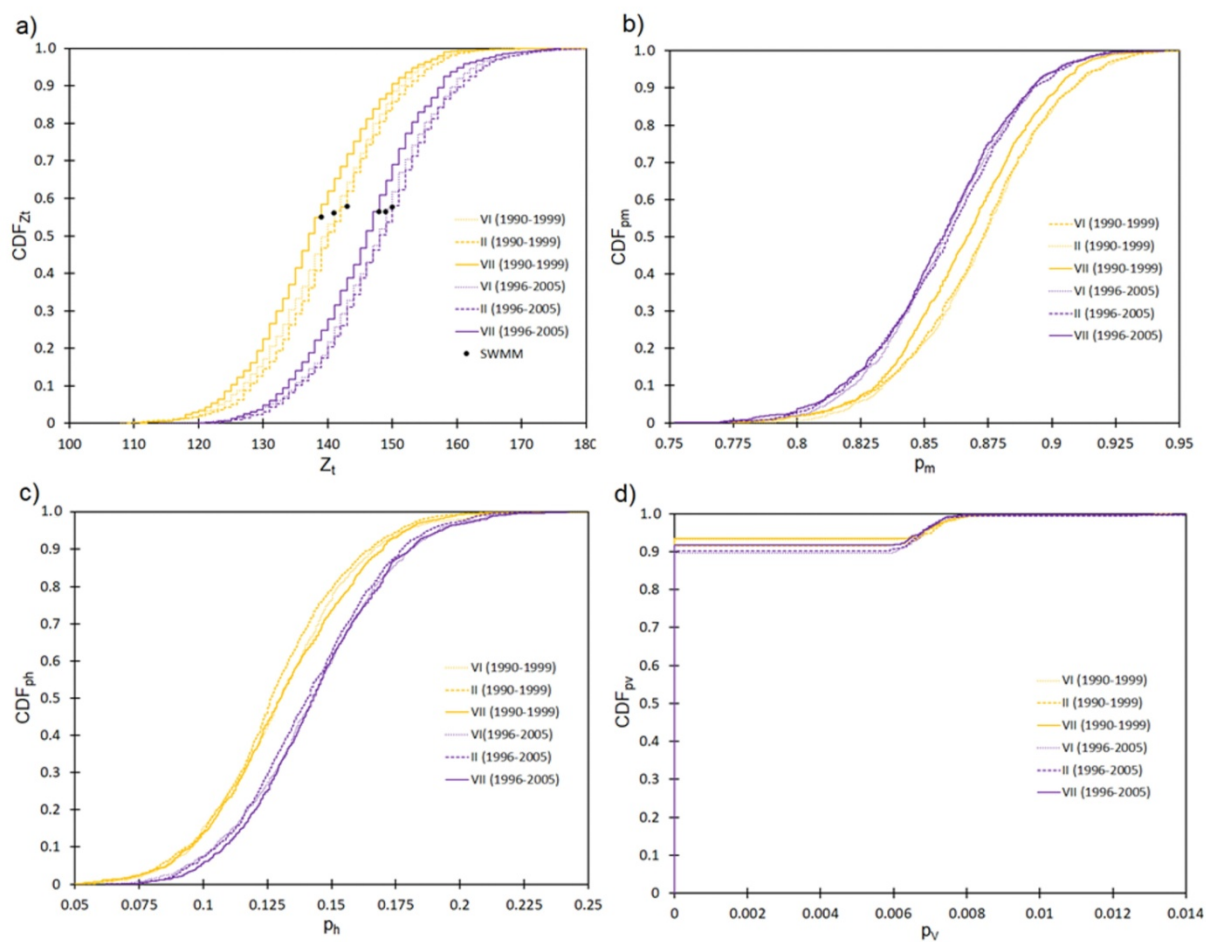
1062 **Appendix G.** Multiannual ( $t = 10$  years) characteristics of overflows for imperviousness scenarios III,  
 1063 VIII and IX, based on the theoretical distributions of precipitation in the periods from 1990 to 1999  
 1064 and from 1996 to 2005: **a)** the number of overflows; **b-d)** the probability of the occurrence of a  
 1065 overflow caused by a moderate (b), heavy (c) or violent (d) downpour.



1066

1067

1068 **Appendix H.** Multiannual ( $t = 10$  years) characteristics of overflows for imperviousness scenarios II,  
 1069 VI and VII, based on the theoretical distributions of precipitation in the periods from 1990 to 1999 and  
 1070 from 1996 to 2005: **a)** the number of overflows; **b-d)** the probability of the occurrence of a overflow  
 1071 caused by a moderate (b), heavy (c) or violent (d) downpour.



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