



Relationship Between Rainfall Duration and Sewer System Performance Measures Within the Context of Uncertainty

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Abstract

Urbanization and climate change have resulted in an increase in catchment runoff, often exceeding the designed capacity of sewer systems. The decision to modernize a sewer system should be based on appropriate criteria. In engineering practice, the above is commonly achieved using a hydrodynamic model of the catchment and the simulation of various rainfall events. The article presents a methodology to analyze the effect of rainfall characteristics parametrized with intensity-duration-frequency (IDF) curves in regard to performance measures of sewerage networks (flood volume per unit impervious surface and share of overflowed manholes in the sewerage network) accounting for the model uncertainty determined via the generalized likelihood uncertainty estimation (GLUE) method. An urban catchment was modeled with the Storm Water Management Model (SWMM). Analyses showed that the model uncertainty exerts a large impact on certain measures of sewerage network operation. Therefore, these measures should be analyzed in similar studies. This is very important at the stage of decision making in regard to the modernization and sustainable development of catchments. It was found that among the model parameters, the Manning roughness coefficient of sewer channels yields a key impact on the specific flood volume, while the area of impervious surfaces yields the greatest impact on the share of overflowed manholes.

Keywords SWMM · Flooding · IDF · GLUE · Stormwater sewer system performance

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1 Introduction

Increasing urbanization and climate change have increased the diversion volume of stormwater from catchments, which has affected the water quality of receiving bodies (river, lake or sea) and has resulted in more frequent sewer floods (Fletcher et al. 2013; Karimlou et al. 2020). The above has also deteriorated the functionality of sewer systems. The European standard for drainage PN-EN-752 (2017) depends on the land use and accepts the number of floods at a given rainfall frequency (C). If a sewer system is to be modernized, it has been recommended to perform numerical modeling to formulate optimal decisions (Kolsky and Butler 2002; dos Santos Amorim et al. 2020). This may be accomplished via numerous computer programs (e.g., MIKE and XPSWMM) implementing rainfall-runoff models of urban catchments (Kwak et al. 2016; Yang et al. 2020). One of the most widely applied (Rossman 2010) models is the Storm Water Management Model (SWMM). The development of a numerical model of a given urban catchment requires data on its spatial and drainage characteristics. To represent sewer flooding, in addition to the properties of network channels, factors shaping surface runoff and sewer chamber conditions might also be important. These issues play a major role in the correct determination of flow dynamics and therefore in satisfactory model calibration. Acquisition of a good representation of catchment runoff, combined with all important processes for the design of a sewer system, is a complex task and requires appropriate computational methods (Bellos and Tsakiris 2016; Recanatessi and Petroselli 2020). In the SWMM, a sewer flood is only represented in terms of the volume of sewage overflowing from sewer manholes during an analyzed event. Due to the simplicity of the approach, it has been widely applied in practice (Fraga et al. 2016; Jato-Espino et al. 2019). It is possible to model flooding areas (Leandro and Martins 2016) by integrating the SWMM with a digital terrain model (DTM); with the SWMM, the flooding of streets (defined as open channels) connected to nodes of the sewer system (Rossman 2010; Yang et al. 2020) can be analyzed. It is also possible to define flooding areas, such as a reservoir, with a volume curve determined via the DTM. As such, the flooding extent could be considered, but this could also lead to much more complicated solutions requiring the definition of the link between the reservoir and sewer manholes (with weirs or orifices), which could cause numerical difficulties.

Considering the complexity of the modeling of sewage spills from sewer systems, it is necessary to determine the threshold operating conditions of the systems to be modernized (in regard to the effect of climate change, urbanization, and pipe aging), and engineering methods for the assessment of the performance of sewer systems have been proposed (Siekmann and Pinnekamp 2011). This approach defines the relevant threshold conditions (e.g., the unit volume of a sewer flood with respect to the impervious surfaces and the share of manholes experiencing overflow), the exceedance of which indicates the need for modernization (e.g., the construction of retention tanks or devices for the regulation of stormwater flow) of existing sewer systems to reduce the frequency of sewer floods and manhole overflows. Assessment of the operational performance of a sewer network requires the identification of rainfall conditions. For this purpose, long rainfall time series (~30 years) could be adopted (Schmitt and Thomas 2000). In their absence, estimated rainfall characteristics could be considered. In this case, models of the maximum rainfall, in the form of so-called intensity-duration-frequency (IDF) curves, have been commonly applied. They describe the theoretical relationship between the rainfall duration (t_r), its frequency (C) and the maximum depth of rainfall (P_{max}), assuming an average and uniform rainfall intensity (i). The results of numerous researchers (Schmitt and Thomas 2000; Kotowski et al. 2014)

have indicated that the most adverse conditions for a sewer system occur when the rainfall duration is exactly twice as long as the time of sewage flow through the sewer system, and the performance of the sewer network should be analyzed under these conditions. The variability in the rainfall temporal distribution during an event should be determined, considering local conditions and modeler knowledge, as reported by Huff (1990) and Licznar et al. (2017). Due to the diverse layout of sewer systems and the spatial variability in land use across catchments, the assessment of the operational performance of a sewer system has usually been performed considering different rainfall durations (Bruni et al. 2015). The calculations conducted by Siekmann and Pinnekamp (2011) demonstrated that the aforementioned measures of sewage network operation could be adopted in decisions on system modernization. The same conclusions were drawn by Kotowski et al. (2014) for the sewer system in Wrocław. The simulation results obtained by the abovementioned researchers also revealed the need to modify the rainfall frequency for the assessment of the sewer network performance. Other studies, e.g., Siekmann and Pinnekamp (2011) and Kotowski et al. (2014), have indicated the importance of reliable model calibration to decide on sewer modernization. Due to model simplifications, regarding the data on the physical and geographical characteristics of a given catchment area, i.e., the accuracy of rainfall measurements and their spatial distribution in the catchment area, there might be problems with the identification of the model parameter importance (Zhang and Li 2015). It has often been observed that there are many possible solutions of parameter value configurations yielding satisfactory results in terms of the goodness-of-fit against measured values. In this case, the parameter importance identification problem may be formulated in a probabilistic manner, where the parameters are considered random variables, and the variability explains the model uncertainty (Dotto et al. 2012). The aforementioned problem in the modeling of urbanized catchments was examined by Sordo-Ward et al. (2016). The simulation results obtained by numerous researchers (Fu et al. 2011; Fraga et al. 2016) in regard to a single sewer manhole, sections and elements of sewer drainage have demonstrated that the uncertainty exerts a large impact on the predicted volume of sewage discharge and its variability over time. Despite this finding, Siekmann and Pinnekamp (2011) and Kotowski et al. (2014) did not consider the hydrodynamic model uncertainty of the whole network in their studies. This has created a research gap, which the authors want to fill within the current elaboration.

In light of the results obtained by Siekmann and Pinnekamp (2011) and Kotowski et al. (2014), the above uncertainty must be considered, which may exert a large impact on the determination of the performance measures of sewer systems and thus on modernization decisions. It might also be very important to obtain the optimal solution for the improvement of system operation. Considering the above issues, this paper presents a modification of the method to analyze the operation performance of sewer networks proposed by Siekmann and Pinnekamp (2011). The main novelty of the proposed approach is the considered effect of the uncertainty of the stormwater system model on the relationship between the rainfall duration (the depth of rainfall determined on the basis of IDF curves) and the sewage flood volume in relation to the impervious area, the percentage of overflowed manholes and the volume of spilled sewage per overflowed manhole and impervious area unit. The model uncertainty resulting from the differentiated influences of the physical parameters of the modeled system as well as the geophysical properties of the catchment were analyzed via the dynamic simulation method. This approach has not been applied thus far in relation to the entire stormwater drainage network. Moreover, the influence of the uncertainty of the catchment model on the operating parameters of the stormwater network, as defined by Siekmann and Pinnekamp (2011), which could contribute to the improvement of the accuracy of decisions regarding

the sustainable development of a catchment area, has not been analyzed until now. An urban catchment model constructed in the SWMM program was adopted in the calculations. The uncertainty analysis was performed via the generalized likelihood uncertainty estimation (GLUE) method. As a notable part of the calculations, the dependency of the identified SWMM parameters on the performance measures of sewer system operation was determined, which is important from the point of view of parameter identification and credibility of the simulation results.

2 Study Area

The analyzed study area was previously investigated in terms of the quantity and design of sewer retention reservoirs (Kiczko et al. 2018). The Si9 channel catchment with an area of 62 ha is located in the central-eastern part of the city of Kielce (Fig. 1) in the southern part of Poland. The average population density of the city is 19.5 people/km², and in the study area, the average population density is 21.4 people/km². The area of the analyzed catchment is covered with housing estates, public buildings, and main and side streets. Six classes of land use with respect to runoff were distinguished: building roofs (14.3%), sidewalks (8.4%), roads (17.7%), parking lots (11.2%), green areas (47.2%) and school playgrounds (1.3%). The density of roads is 108 m·ha⁻¹. The highest point of the catchment is 271.20 m above sea level, and the lowest point occurs at 260 m above sea level, which indicates that the average slope of the area is 7.1%. The length of the main collector sewer is 1569 m with a diameter ranging from 600 mm in the upper part to 1250 mm downstream.

The catchment collects stormwater from 17 side channels (300–1000 mm), and the total length of the network is 5583 m (Kiczko et al. 2018). The slope of the sewers ranges from 0.04% to 3.90%, while that of the side channels reaches 2.61%.

Stormwater outflows from the catchment area through sewer S1 into a diversion chamber (DC). At a level below 0.42 m, stormwater flows into a stormwater treatment plant. When the DC level exceeds 0.42 m, stormwater flows overflow (OV) into the S2 sewer, where it flows into the receiving body (Silnica River). At a distance of approximately 3



Fig. 1 Structure of stormwater drainage in the analyzed catchment of Kielce

meters from the inlet of the S1 channel to the DC, an MES1 flow meter is installed, which measures the flow rate during intense rainfall events at 1-min intervals. The recorded flow during dry periods ranged from 1 to 9 dm³·s⁻¹, which suggests infiltration.

At a distance of 2.5 km from the catchment border, a meteorological station occurs where continuous rainfall measurements have been recorded since 2008 at a resolution of 1 min during rainfall events. Via identification of independent rainfall events in the measured time series, it was found that the annual number of rainfall events ranges from 36–58, the rainfall duration ranges from 20–2366 min, and the rainfall depth ranges from 3.0–45.2 mm. The annual rainfall depth ranged from 537 to 757 mm, and the number of rainfall days ranged from 155–266. The annual air temperature was 8.1–9.6°C, and the number of snowfall days was 36–84.

3 Methodology

In the present study, a method to analyze the functional performance of the above stormwater sewer system considering the uncertainty of its hydrodynamic model is proposed (Fig. 2). In regard to the criteria of the sewer system, the following sewer performance indexes were adopted (Siekmann and Pinnekamp 2011):

- specific flood volume, i.e., the flood volume per unit area of impervious surface:

$$\lambda_1 = \frac{\sum_{i=1}^k V_{t(i)}}{A_{imp}} \quad (1)$$

where A_{imp} is the area of the impervious surface (ha) and $V_{t(i)}$ is the flood volume stemming from the i -th sewer manhole (for $i=1,2,3,\dots,k$) (m³).

- degree of flooding, i.e., share of overflowed sewer manholes:

$$\lambda_2 = \frac{\theta_t}{K_{max}} \quad (2)$$

where θ_t is the number of overflowed manholes and K_{max} is the total number of sewer manholes.

Values of these performance indexes, which indicate the need to modernize the sewer system, were reported in the literature (Siekmann and Pinnekamp 2011) as follows: $\lambda_1 > 20$ m³·ha⁻¹ or $\lambda_2 > 0.5$. As these two indexes are independent and express separate aspects of the sewer system performance, in the present study, a joint measure is proposed:

$$\lambda_3 = \frac{\lambda_1}{\theta_t} \quad (3)$$

In the proposed approach, the sewer system performance is assessed on the basis of the maximum rainfall model at a given frequency (C) with IDF curves.

In regard to the shape of the modeled hyetograph of a single event, the Euler II distribution function was adopted (Fig. S1 Support Information). The catchment was represented using the numerical model of the SWMM, whose uncertainty was analyzed on the basis of the GLUE methodology (Ratto et al. 1998). Additionally, an analysis of the dependency between the identified model parameters and performance indexes λ_1 , λ_2 and λ_3 was

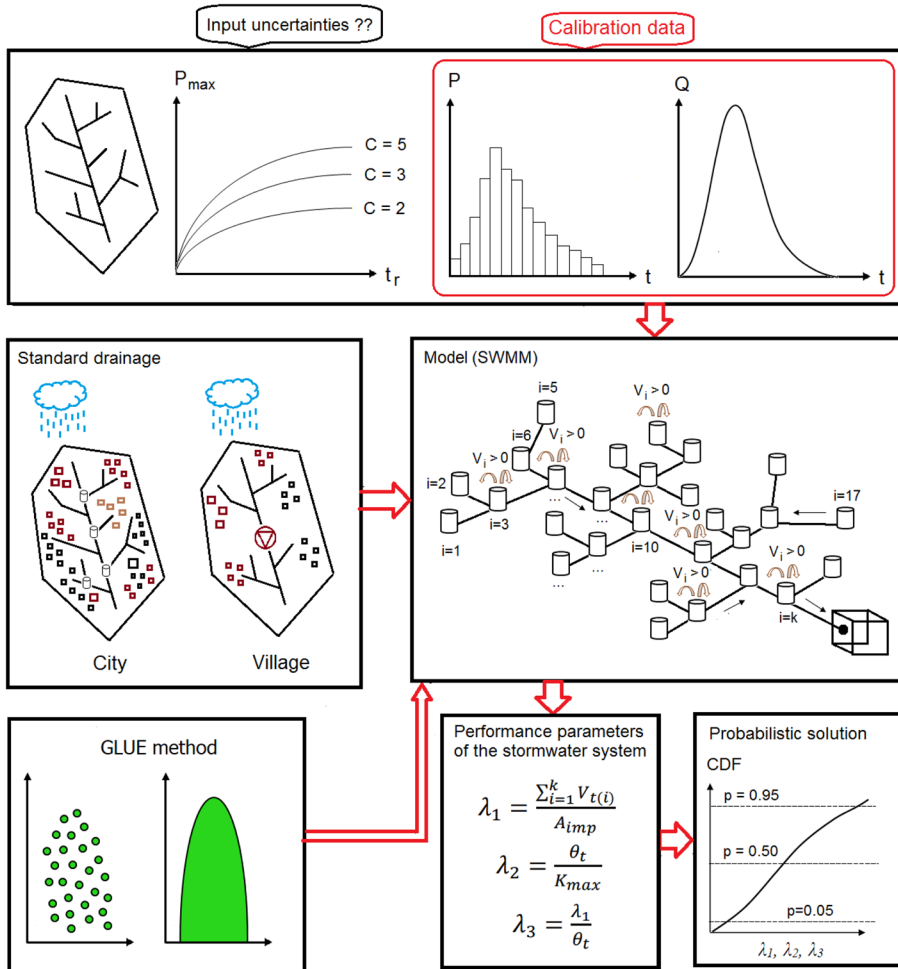


Fig. 2 Computational scheme for the sewer system performance

included (Fig. 2). The outcome of probabilistic model identification is a multidimensional empirical distribution of the parameters $F(x_j)$, where j denotes the number of parameters obtained using observations of real rainfall events (the GLUE method). The procedure to obtain $F(x_j)$ is given in the Uncertainty Analysis section. With the use of the SWMM, independent models (simulation of the stormwater network for rainfall data equal to $P_{max}(C)$ and t_r) were established based on the hyetographs determined with IDF curves (Fig. 2). Simulations were performed using the identified parameter $[x_1 x_2 x_3 \dots x_j]$ distribution $F(x_j)$. The performance indexes (λ_1, λ_2 , and λ_3) were expressed in the form of cumulative distribution functions (CDFs) computed with Eqs. (1), (2) and (3). The presented methodology is general and could be applied to other urban catchments. The SWMM model is presently developed as an open-source project, and the GLUE method with appropriate algorithms has been given in numerous studies (Ratto et al. 1998). The presented approach provides a tool to analyze the relationship between the rainfall duration (in terms of IDF

curves) and sewer system performance measures, accounting for uncertainty, which has not been investigated before.

3.1 Design of Rainfall for Stormwater Flood Modeling

In engineering practice, when long-term rainfall observations are missing, continuous simulations have been performed with IDF curves (Burak et al. 2020). This facilitates the design of stormwater networks and their facilities. IDF curves describe the relationship between the rainfall duration (t_r) and the frequency of occurrence (C), which is expressed by the following equation:

$$J = f(t_r, C, \omega) \quad (4)$$

where t_r is the rainfall duration, C is the rainfall frequency, ω is a regional parameter, and J is the average rainfall intensity defined as $J = 166.7 \cdot P_{max}$.

Due to the varied local conditions, i.e., air mass movement, meteorological conditions, climate changes, and terrain, the relationship described in Eq. (4) takes various forms, as reported by Bogdanowicz and Stachy (1998). Currently, the maximum depth of rainfall (P_{max}) caused by rainfall duration t_r at its frequency of occurrence (C) can be determined for Polish basins using the Bogdanowicz and Stachy (1998) equation:

$$P_{max} = 1.42 \cdot t_r^{0.33} + \omega(R, t_r) \cdot (-C^{-1})^{0.584} \quad (5)$$

where t_r is the rainfall duration (min) and $\omega(R, t_r)$ is a local empirical function. In terms of the area of the Świętokrzyskie Voivodeship, Eq. (5) exhibits the following form at $t_r < 120$ min:

$$\omega(R, t_r) = 4.693 \cdot \ln(t_r - 1) - 1.249 \quad (6)$$

In this approach, the rainfall duration depends on the time necessary for stormwater to flow through the sewer system. However, the necessary time length is difficult to estimate, and calculations are usually performed considering different durations (t_r).

In accordance with DWA A-118 (2006), the rainfall duration should not be shorter than two times the stormwater flow duration and the frequency of rainfall $C=3$. The stormwater flow duration for the analyzed basin was determined using the hydraulic model, at 20 min (Kiczko et al. 2018). In the performed studies to analyze the effect of the catchment model uncertainty on the performance indexes of the stormwater system, frequencies of $C=2$ and $C=5$ and durations t_r ranging from 30–120 min were also considered.

3.2 Hydrodynamic Catchment Model

The catchment in the present study is modeled using the SWMM. The model consists of 92 subcatchments with an area ranging from 0.12–2.10 ha, $K_{max} = 82$ manholes and 72 conduits. The performed calibration showed that the Manning roughness coefficient value of the sewer channels is equal to $n_n = 0.018 \text{ m}^{-1/3} \cdot \text{s}$, while the Manning roughness coefficient and depth of the depression storage of the impervious areas, i.e., the retention depths of the impervious areas, are $n_{imp} = 0.025 \text{ m}^{-1/3} \cdot \text{s}$ and $D_{imp} = 2.50 \text{ mm}$, respectively. The width of the runoff path in the subcatchments was determined as $W = \alpha \cdot A^{0.50}$ (Kiczko et al. 2018).

In the SWMM model, regarding sewer floods, the commonly used option of flooding was adopted at each sewer node. On the one hand, a more sophisticated solution was hard to implement due to the poor DTM of the catchment area. On the other hand, the flood volumes were sufficient to calculate the proposed performance measures. The SWMM enabled us to obtain a spilling hydrograph for each i -th sewer manhole: $Q(t)_F$. The flood volume for each manhole was calculated as $V_{i(k)} = \int Q(t)_F dt$, and the total volume was determined as $V_T = \sum_{i=1}^k \int Q(t)_F dt$.

3.3 Uncertainty Estimation

The model uncertainty was estimated using the Bayesian framework of the GLUE method (Ratto et al. 1998). It is based on the probabilistic formulation of the parameter identification problem. In this approach, the concept of a single optimal parameter set is rejected, and the parameters are considered random variables whose distribution has to be determined via parameter identification. The randomness of the parameters explains the model uncertainty. In the present study, the parameters were identified on the basis of Bayesian estimation (Dotto et al. 2012):

$$P(Q/\theta) = \frac{L(Q/\theta)P(\theta)}{\int L(Q/\theta)P(\theta)d\theta} \quad (7)$$

where $P(\theta)$ is the a priori parameter distribution (here, a uniform distribution was applied), and $L(Q/\theta)$ is the likelihood function used to calculate the weights of Monte Carlo sampling, which depends on the model fit to the observed basin discharges Q and $P(Q/\theta)$, resulting in the a posteriori distribution of model parameters θ . In regard to the likelihood function, the following equation was used (Dotto et al. 2012):

$$L(Q/\theta) = \exp\left(-\frac{\sum_{i=1}^N (Q_s - \hat{Q}_i)^2}{\kappa \cdot \sigma^2}\right) \quad (8)$$

where Q_s and \hat{Q}_s are the s -th values in the time series of the observed and computed discharges, respectively, and κ is a scaling factor for the variance σ^2 in the model residuals, which is applied to adjust the width of the confidence intervals. In the study of Kiczko et al. (2018), the value of κ was determined, ensuring that 95% of the observed discharge points are enclosed by the 95% confidence interval of the model output.

The parameter ranges listed below are determined on the basis of numerical experiments (Kiczko et al. 2018) and are consistent with the values reported by other authors (Zhang and Li 2015; Fraga et al. 2016; Rai et al. 2017; Gong et al. 2018):

- Coefficient of the flow path width α : 2.7–4.7 (–).
- Depth of depression storage of the impervious areas D_{imp} : 0.8–4.8 (mm).
- Depth of depression storage of the pervious areas D_{imp} : 0.8–6.8 (mm).
- Manning roughness coefficient of the impervious areas n_{imp} : 0.01–0.022 ($m^{-1/3} \cdot s$).
- Manning roughness coefficient of the pervious areas n_{perv} : 0.16–0.2 ($m^{-1/3} \cdot s$).
- Manning roughness coefficient of the sewer channels n_n : 0.01–0.048 ($m^{-1/3} \cdot s$).
- Correction coefficient of the subcatchments slope γ : 0.7–1.275 (–).
- Correction coefficient of the percentage of the impervious areas β : 0.8–1.375 (–).

In the GLUE methodology, Eq. (7), (8) is solved using Monte Carlo sampling. In the first step, a sample of the parameters was generated using an assumed a priori distribution, with a size of $m=5000$. Likelihood measures and a posteriori distributions were computed using simulations performed based on the observed hyetographs and catchment outflow hydrographs (Q) for the following rain events: 24 July 2011 and 15 September 2010. Verification was performed based on the 30 May 2010 and 30 July 2010 events. Detailed information on the obtained fit can be found in Kiczko et al. (2018). The obtained likelihood measures, along with the a priori parameter distributions, were employed in simulations to generate hyetographs $P_{max}=f(t_r, C)$. Performance measures were calculated with Eqs. (1), (2), and (3).

3.4 Sensitivity Analysis

With the simulations of the sewer system performance for k combinations of the model parameters (listing in chapter 3.3), the performance indexes (λ_1 , λ_2 and λ_3) were computed with Eqs. (1), (2), and (3), respectively. On this basis, empirical relationships were established:

$$\lambda = f(x_j) \quad (9)$$

This allowed us to assess the effect of the model parameters on the performance indexes.

4 Results

4.1 Sensitivity Analysis

With the use of the proposed methodology, empirical relationships were established with Eq. (1). Figure 3 show box plots of the calculated performance measures as a function of the model parameter values. The variability in the model parameters originates from the adopted uniform distribution used in Monte Carlo sampling. The rectangular box in Fig. 3 encloses the 0.25–0.75 quartiles, and the whiskers extend to the extreme values of a performance measure within a given parameter range. Figure 3 suggest that the Manning roughness coefficient of sewer channels (n_n) imposes the greatest effect on the specific flood volume (λ_1 , λ_3). An increase in n_n from 0.01 to 0.025 $\text{m}^{-1/3}\cdot\text{s}^{-1}$ leads to an increase in λ_1 from 38 to 82 $\text{m}^3\cdot\text{ha}^{-1}$ (an increase of 116%; mean value) and in λ_3 from 0.50 to 1.20 $\text{m}^3\cdot\text{ha}^{-1}\cdot\text{Nd}^{-1}$ (an increase of 140%).

The physical and geographical characteristics of the catchment exert a relatively small impact on the discharge of sewage. This is confirmed by the relationships obtained for the specific flood volume (λ_1 , λ_3) and the correction coefficient of the percentage of impervious areas (β), the Manning roughness coefficient of the impervious areas (n_{imp}) and the depth of storage depression of the impervious areas (D_{imp}). An increase in β from 0.8 to 1.3 increases λ_1 and λ_3 from 52 to 72 $\text{m}^3\cdot\text{ha}^{-1}$ (an increase of 38%; mean value) and increases λ_3 from 0.79 to 0.97 $\text{m}^3\cdot\text{ha}^{-1}\cdot\text{Nd}^{-1}$ (an increase of 23%). Moreover, an increase in n_{imp} from 0.012 to 0.018 $\text{m}^{-1/3}\cdot\text{s}$ decreases λ_1 from 70 to 58 $\text{m}^3\cdot\text{ha}^{-1}$ (a reduction of 18%) and decreases λ_3 from 1.2 to 0.83 $\text{m}^3\cdot\text{ha}^{-1}\cdot\text{Nd}^{-1}$ (a reduction of 31%). Based on the curves (Fig. 3), it was found that an increase in the values of n_{imp} and D_{imp} results in a decrease in the specific flood volume (λ_1 and λ_3 , respectively).

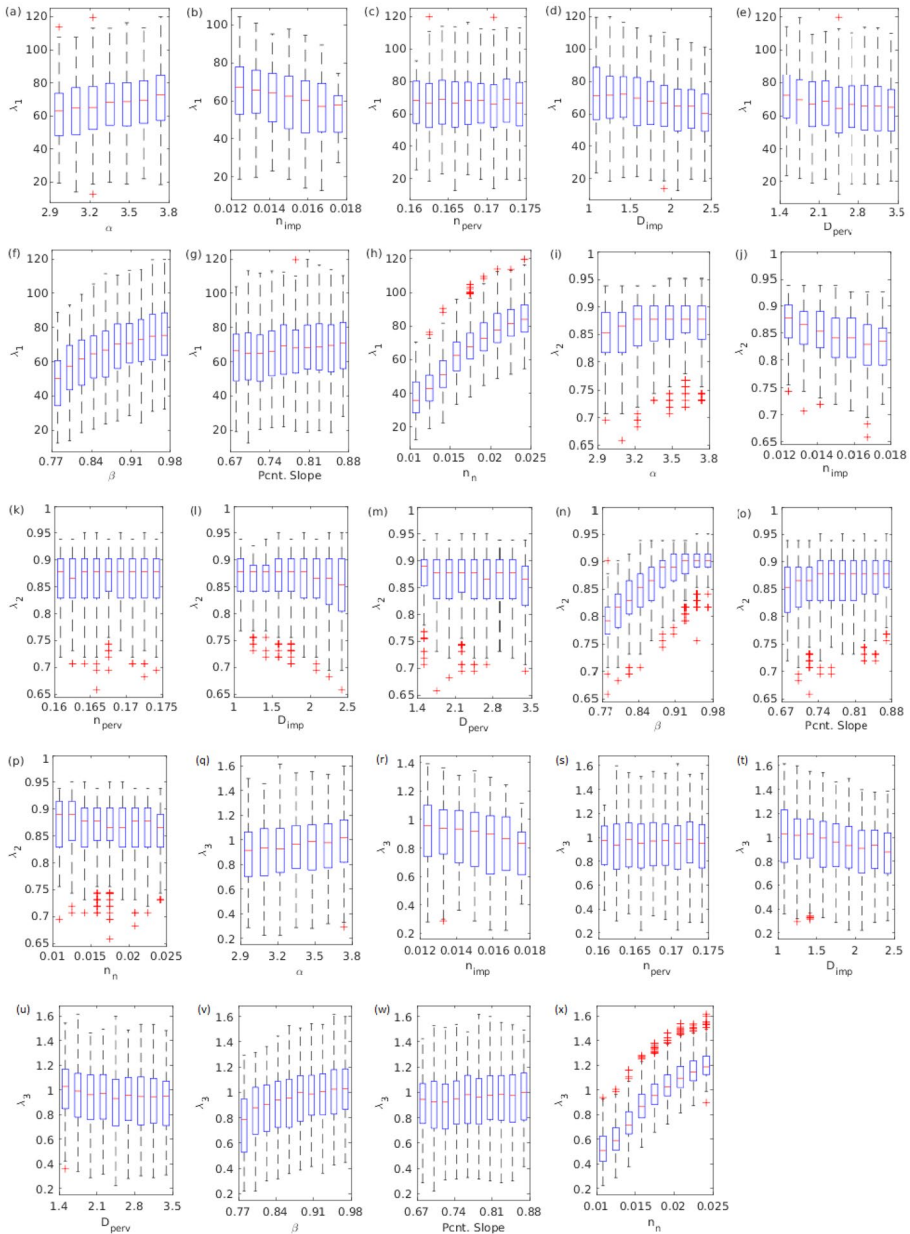


Fig. 3 Relationships of (a) $\lambda_1=f(\alpha)$, (b) $\lambda_1=f(n_{imp})$, (c) $\lambda_1=f(n_{perv})$, (d) $\lambda_1=f(D_{imp})$, (e) $\lambda_1=f(D_{perv})$, (f) $\lambda_1=f(\beta)$, (g) $\lambda_1=f(\gamma)$, (h) $\lambda_1=f(n_n)$, (i) $\lambda_2=f(\alpha)$, (j) $\lambda_2=f(n_{imp})$, (k) $\lambda_2=f(n_{perv})$, (l) $\lambda_2=f(D_{imp})$, (m) $\lambda_2=f(D_{perv})$, (n) $\lambda_2=f(\beta)$, (o) $\lambda_2=f(\gamma)$, (p) $\lambda_2=f(n_n)$, (q) $\lambda_3=f(\alpha)$, (r) $\lambda_3=f(n_{imp})$, (s) $\lambda_3=f(n_{perv})$, (t) $\lambda_3=f(D_{imp})$, (u) $\lambda_3=f(D_{perv})$, (v) $\lambda_3=f(\beta)$, (w) $\lambda_3=f(\gamma)$, (x) $\lambda_3=f(n_n)$

In regard to the correction coefficient of the flow path width (α) and the Manning roughness coefficient of the impervious areas (n_{imp}), it was found that their increase led to an increase in the specific flood volume. On the basis of the obtained data (Fig. 3), it was

found that the physical and geographical characteristics of the catchment exert the greatest impact on the value of λ_2 . The correction coefficient of the percentage of impervious areas (β) imposed the largest effect on the degree of flooding (Fig. 3). The Manning roughness coefficient of the impervious surfaces and the correcting coefficient of the flow path width exerted a less notable impact on λ_2 . An increase in β from 0.77 to 0.98 increased λ_2 from 0.79 to 0.91 (Fig. 3n), increased n_{imp} from 0.012 to 0.018 $m^{-1/3}\cdot s$ and decreased λ_2 from 0.87 to 0.83 (Fig. 3j). An increase in α from 2.9 to 3.8 resulted in an increase in λ_2 from 0.85 to 0.88 (Fig. 3i).

4.2 Uncertainty Effect of the Indexes on the Sewer System Performance

With the use of the a priori parameter sample with the likelihood measures calculated based on real rainfall events, simulations of the total flood volume V_f and number of overflowed manholes K were performed. Inflow hyetographs were generated considering rainfall durations of $t_r=30-120$ min at frequencies of $C=2, 3,$ and 5 . The obtained CDFs for $\lambda_1, \lambda_2,$ and λ_3 show the probability of exceeding given values of the sewer performance indexes.

Example results of λ_1 and λ_2 at $C=2$ for rainfall durations of $t_r=30$ min, $t_r=85$ min and $t_r=105$ min are shown in Fig. 4. The remaining results are included in the SI (Supporting Information). Figure 4 shows that the model uncertainty imposes a great effect on the obtained values of sewer performance indexes λ_1 and λ_2 . This is further confirmed by the large span of their values in the CDFs for a given rainfall duration time. The values (0.50 percentile) of λ_1 and number of overflowed manholes (K) at

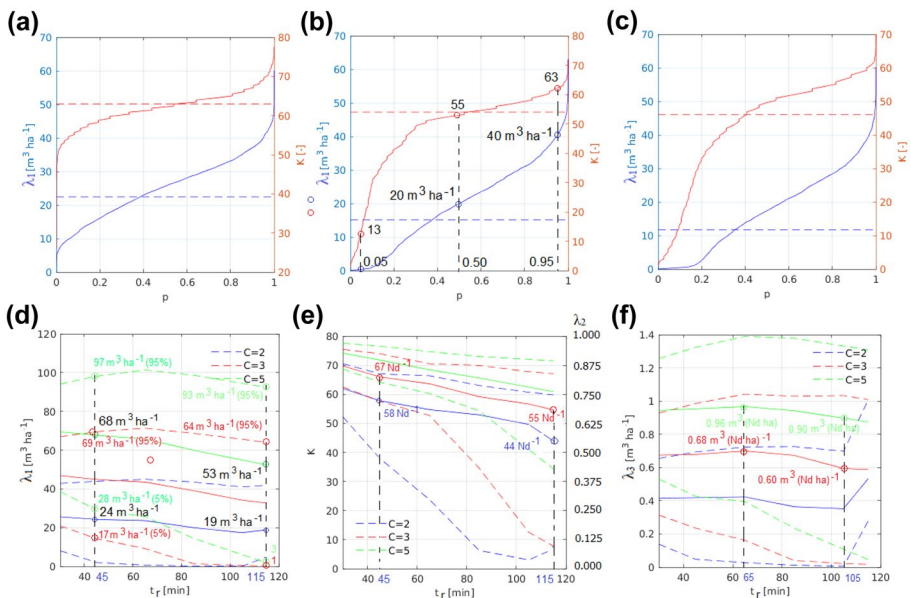


Fig. 4 CDFs representing the model uncertainty of sewer performance indexes λ_1 and $\lambda_2 = f(K)$ for $C=2$ and $t_r=30$ min (a), $t_r=85$ min (b) and $t_r=105$ min (where p is the CDF); rainfall duration t_r and frequency C effects on the sewer performance measures: λ_1 (d), λ_2 (e), λ_3 (f) accounting for the model uncertainty

$t_r = 30$ min equal $\lambda_1 = 27 \text{ m}^3 \cdot \text{ha}^{-1}$ and $K = 63$, respectively, and those at $t_r = 105$ min equal $\lambda_1 = 18 \text{ m}^3 \cdot \text{ha}^{-1}$ and $K = 51$, respectively.

Moreover, at $t_r = 85$ min, the values λ_1 under the corresponding percentiles, $p = 0.05$, 0.50 and 0.95 , are 1 , 20 and $40 \text{ m}^3 \cdot \text{ha}^{-1}$, respectively. The corresponding results for λ_2 are 13 , 55 and 63 overflowed manholes, respectively.

Figure 4 shows an inappropriate operational performance of the analyzed sewer system, based on the values of λ_1 , λ_2 and λ_3 . At $C = 2, 3$, and 5 , it is found that the values of performance indexes λ_1 and λ_2 (within the confidence interval), for most of the analyzed values of t_r , exceed the thresholds ($\lambda_1 = 20$ and $\lambda_2 = 0.50 \text{ m}^3 \cdot \text{ha}^{-1}$, respectively) at which modernization of the sewer system should be considered. An increase in t_r from 45 to 115 min ($C = 2$) leads to a decrease in the specific flood volume (λ_1) from 24 to $19 \text{ m}^3 \cdot \text{ha}^{-1}$ (a reduction of 20%), while for the same values of t_r ($C = 5$), the flood volume decreases from 68 to $53 \text{ m}^3 \cdot \text{ha}^{-1}$ (Fig. 4d). At $C = 3$ and $C = 5$, with increasing t_r , the width of the confidence intervals of λ_1 notably increases. In the case of frequency $C = 2$, the variation in λ_1 remains approximately constant for all rainfall durations. For example, at $t_r = 45$ min and $C = 3$, 5 values of λ_1 within the 95% confidence interval range from 17 – 69 and 28 – $97 \text{ m}^3 \cdot \text{ha}^{-1}$, while at $t_r = 115$ min, they are equal to 1 – 64 and 3 – $93 \text{ m}^3 \cdot \text{ha}^{-1}$, respectively (Fig. 4d).

The results for the λ_2 index with respect to the rainfall duration revealed a similar dependency to that in the case of λ_1 . Increasing the rainfall duration at $C = 2, 3$, and 5 led to a decrease in λ_2 , which indicates a decrease in the number of overflowed manholes in the stormwater network (Fig. 4e). For example, an increase in the value of $t_r = 45$ min to $t_r = 115$ min ($C = 2, 3$) resulted in a decrease in the number of overflowed manholes from 58 to 44 (a reduction of 17%) at $C = 2$ and from 67 to 55 (by 18%) at $C = 3$. In contrast to the λ_1 index, λ_2 exhibited a different variability in its 95% confidence intervals. The widest confidence intervals for λ_2 were obtained at $C = 2$, and the smallest variation in the output was obtained at $C = 5$. In addition, at $C = 2, 3$, and 5 , the uncertainty of λ_2 increased with the rainfall duration.

In the case of joint index λ_3 , its median at $C = 2, 3$, and 5 for rainfall durations in the range of $t_r = 45$ – 65 min remained constant (the difference in the extreme values did not exceed 5%). A further increase in the value of t_r at $C = 3, 5$ led to a decrease in the specific flood volume (λ_3) for the considered rainfall duration range (Fig. 4f). For example, extending the rainfall duration from $t_r = 65$ min to $t_r = 105$ min ($C = 3, 5$) resulted in a reduction in the λ_3 value from 0.68 to $0.60 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{Nd}^{-1}$ (a reduction of 12%) and from 0.96 to $0.90 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{Nd}^{-1}$ i.e., a reduction of 5% . Different dependences for $\lambda_3 = f(t_r)$ were observed at $C = 2$ because at $t_r = 105$ – 115 min, the value of this index increased.

5 Conclusions and Discussion

Due to the complexity of the flooding process in regard to the sewer system, its dynamics are usually modeled for single manholes (Fu et al. 2011; Thorndahl 2009) or certain drainage sections (Fraga et al. 2016). Hydrodynamic models are typically affected by uncertainty, which should be reflected in the analyses of their results. The performed calculations confirmed that the Manning roughness coefficient of the sewer channels, among all analyzed parameters (listed in chapter 3.3), imposes the greatest effect on the specific flood volume, as previously reported by Fu et al. (2011) and Fraga et al. (2016). Additionally, the geophysical properties of the catchment (β and n_{imp}) were found to be important for the total flood volume (Brown et al. 2007; Fu et al. 2011; Fraga et al. 2016). Moreover, it should be noted that the model uncertainty was analyzed for the first time in terms of the degree or number of overflowed manholes. The model parameter of the impervious areas exerted the greatest impact on λ_2 . Knowledge of the dependence of the

number of overflowed manholes and model parameters could help improve predictions of the sewer system performance by focusing on relevant model parameters. Parameter λ_3 facilitates the joint assessment of the operation of the sewer system in terms of flooding of the impervious surfaces in relation to a single overflowed manhole. This provides information on the flood volume in relation to the active runoff area and thus enables analysis of the phenomenon considering local conditions. Combining the λ_1 and λ_2 indexes may allow for the assessment of the scope of works at the modernization stage and determination of the optimal solution, as an extension of the Siekmann and Pinnekamp (2011) methodology. However, this requires detailed analyses of catchments with different physical and geographical characteristics.

The obtained values of the sewer performance indexes, compared to those reported by other authors (Fu et al. 2011; Fraga et al. 2016), confirm the great importance of uncertainty in calculations of the sewer flood volume. It is verified that the longer the rainfall duration is, the higher the simulation uncertainty $\lambda_1, \lambda_2, \lambda_3 = f(t_r, C)$. This is an important aspect when designing and modernizing sewer networks and has not been analyzed so far. Siekmann and Pinnekamp (2011) and Kotowski et al. (2014), similar to Fu et al. (2011) (who analyzed this problem from a sustainable development perspective), neglected uncertainty, which, according to the obtained results, may affect modeling outcomes. The results allow the design of sustainable solutions for the catchment (at the catchment scale, e.g., green roofs, rain gardens, and infiltration trenches, or in the sewer network, reservoirs or flow regulators) considering the probability of exceeding λ_1, λ_2 and λ_3 . This improves the previous methodology neglecting uncertainty. The design assignments regarding sewer systems, which account for the probability of exceeding a given value of the performance indexes (λ_1, λ_2 and λ_3), enable the assessment of the risk of obtaining the assumed hydraulic effects (reduction in the values of λ_1, λ_2 and λ_3), which is not a common practice even for particular elements of sewage networks (Fletcher et al. 2013). Within this elaboration, for the first time, many parameters and stormwater network devices comprehensively treated as a whole system have been examined in detail. The lower the exceedance probability, the higher the risk that the adopted solutions (failure to formulate appropriate decisions at the modernization stage) may result in further problems with continued operation of the sewer network. In terms of high values of the exceedance probability (as percentiles, e.g., 95%), which are the basis for modernization design, the calculated values of λ_1, λ_2 and λ_3 are much higher than those under the considered percentiles, e.g., 5%. Hence, the adopted solutions, e.g., 95%, are more expansive and certainly cover a wide range (within the catchment area and sewer network), and they better guarantee the required hydraulic effects than those adopted at low values of the exceedance probability. Because of the novelty of the proposed approach bridging the scientific gap identified in the Introduction section and the lack of studies on comprehensive system performance measures considering the model uncertainty, further analyses are advisable for urban catchments with different physical and geographical characteristics of their stormwater networks.

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Declarations

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to Participate Not applicable.

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