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Original Research Article

ESTIMATION OF THE HYDRAULIC WIDTH OF THE SUBCATCHMENT DEPENDING ON THE DEGREE OF DETAIL OF THE DRAINAGE SYSTEM MODEL

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Abstract

The article presents the current state of knowledge in the field of estimating preliminary values of storm water subcatchment calibration parameters in the case of using the Storm Water Management Model (SWMM) for building a model of storm water drainage system. The key issue is estimating the runoff width in the case of reducing the network structure and storm water catchments due to the shortening of calculation time and simplification of the model calibration process. Correction of one of the recommended literature methods has been proposed. The assessment was based on the real catchment model with single and multi-family housing. It was found possible to apply the proposed method in the case of reducing systems connected in series.

Keywords: drainage, modelling, runoff, storm water, SWMM

1. INTRODUCTION

The implementation and use of calibrated theoretical models of rainwater drainage systems is a necessity primarily from a technical point of view (system expansion analysis, the possibility of connecting additional catchments,

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trenchless renovation). Without a simulation model, the assessment of the effects of modernization requires continuous monitoring of the drainage system parameters, both before and after implementation [10].

Ideally, stormwater drainage systems should be designed and analyzed using a catchment model that fully recreates all drainage generation and stormwater transport processes [2]. However, this requires catchment modeling systems that cover all potential and feasible processes that affect the system's response to different atmospheric conditions. In practice, this is not possible because:

- the formation and transfer of surface runoff is complicated and involves many processes whose full mathematical description may be too complicated;
- even if the process in the subcatchment can be briefly and completely described, the number of calculations and, consequently, the duration of their implementation may be unacceptable;
- the data that is available to define variables for the model is limited in both spatial and temporal dimensions.

Depending on the purpose of building the model, results are often only needed for a small subset of modeled units or locations, which makes the use of very detailed models superfluous [6]. For more sophisticated models, it is often necessary to reduce the computation time for individual sub-models to maintain the overall complexity of the integrated model at an acceptable level while maintaining high model accuracy. Three basic categories of solutions are used:

- reduction of modeled network structure;
- simplification of basic calculations;
- conceptualization - system schematization.

After identifying the baseline parameters and building the model, most simplified modeling methods require calibration. The parameters for calibration may depend on the modeling approach used [7] - they include simple scalars, such as the percent of impervious area, outflow concentration time or maximum conduit capacity. A typical approach to model calibration can be described as a "trial and error" method in which control parameter values are systematically modified to obtain a correlation between monitored parameters and simulated parameters describing the catchment response [9].

The most extensive list of parameters potentially used for model calibration includes 11 parameters [14] or 8 parameters [4]. Due to the inconvenient calibration based on all parameters, calibration is usually chosen using a limited number of calibration parameters. The assessment can be based on one of the following methods [4]:

- single parameter calibration based on average impervious surface - in the literature this is usually the most sensitive parameter.

- two-parameter calibration - in case of too low convergence of simulation results with the results of field measurements; the average catchment width is indicated as an additional parameter (the second calibration parameter in terms of sensitivity);
- two-parameter calibration - in case of too low convergence of simulation results with the results of field measurements - optional; the maximum infiltration in the Horton equation is indicated as an additional parameter.

In the case of sensitivity analysis of calibration parameters of the model covering industrial areas [13], three categories were indicated: very sensitive (percentage change in maximum outflow Qmax% = 40-60%), sensitive (Qmax% = 20-40%) and low (Qmax% < 20). For industrial areas, the roughness coefficient of impervious surfaces turned out to be a very sensitive parameter. The catchment hydraulic width and average catchment slope were indicated as sensitive parameters.

2. MATERIALS AND METHODOLOGY

The hydraulic width of the catchment area W is the ratio of the reduced catchment area to the calculated length of runoff from the catchment. This is a parameter that affects the size of the drain. The higher the W value, the larger the outflow from the catchment area. According to Rossman [11], the hydraulic width of the catchment W is determined from formula (2.1).

$$W = F_i / L_K \tag{2.1}$$

Review of other methods carried out by Nowakowska et al. [8] allowed to indicate other methods of estimating the hydraulic width, depending on the complexity of the catchment shape. The methods used are described in the formulas 2.2 [1], 2.3 [8], 2.4 [3], 2.6 [8], 2.7 [8] i 2.8 [12].

$$W = (F_i)^{1/2} \tag{2.2}$$

$$W = 1.5 \cdot L_K \tag{2.3}$$

Formula 2.4 [3] is used in the case of asymmetrical catchments by taking into account the so-called skew factor S_K , described by formula 2.5 [3, 11].

$$W = (2 - S_K) \cdot L_K \tag{2.4}$$

$$S_K = \frac{A_2 - A_1}{A_{tot}} \tag{2.5}$$

$$W = \{1.4; 1.5; 1.6\} \cdot (F_i)^{1/2} \tag{2.6}$$

$$W = \{1.6; 1.8; 2.0\} \cdot (F_{ii})^{1/2} \tag{2.7}$$

$$W = (F_{ii})/\{50; 75; 100\} \tag{2.8}$$

where:
W is the width of the overland flow path [m];
S_K is the skew factor;
F_i - catchment area [ha];
F_i - impervious catchment area [ha];
L_K [m] is the overland flow path.
A_1 is the portion of area on one side of the overland flow path;
A_2 is the portion of area on the other side;
A_{tot} is the total area.

As a result of simplifications applied at the stage of model construction, the partial catchment can include both surface runoff and flow in small-diameter channels [5]. As a result, the calculated length of the runoff path is greater than that resulting from the double distance between the outlets or the length adopted by another method. The more channels are omitted in the model, the calculated trailing path length must be increased to compensate for the impact of the introduced simplifications.

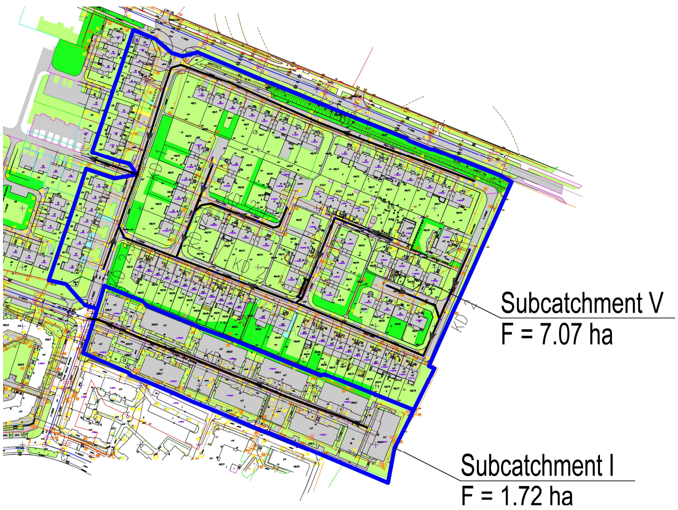

Fig. 1. Diagram of rainwater catchments I and V - modeled network structure reduced

The analysis covered subcatchment of housing estates in single-family and multi-family houses, located in the north-eastern part of Gorzów Wielkopolski. Two rain catchments were selected, differing in the degree of complexity of the simplified catchment and the type of buildings. The larger subcatchment designated as the catchment V, with an area of F = 7.07 ha. It is built-up with single-family houses, usually in terraced form (Figure 1).
The smaller catchment is designated as the catchment I. The area of the catchment is approximately 1.72 ha. 10 multi-family buildings were located in the analyzed area (Figure 1).
The detailed model of catchments I and V is based on partial catchments taking into account all connections to the drainage network. The V catchment was divided into 42 partial catchments (Figure 2). The catchment area I was divided into 6 partial catchments (Figure 3).

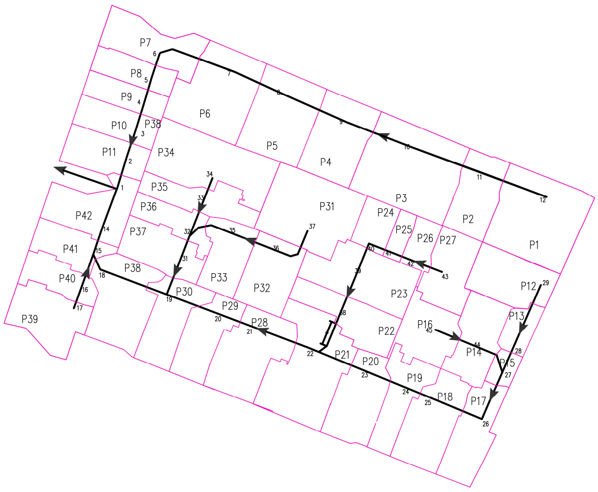

Fig. 2. Diagram of the V catchment - modeled detailed network structure

The total value of the impervious area for the V catchment area is 3.20 ha. The total value of the impervious area for partial sub-basins I is 1.16 ha.

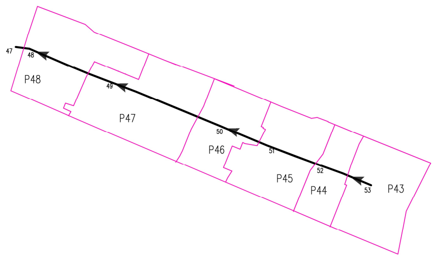

Fig. 3. Diagram of the V catchment - modeled detailed network structure

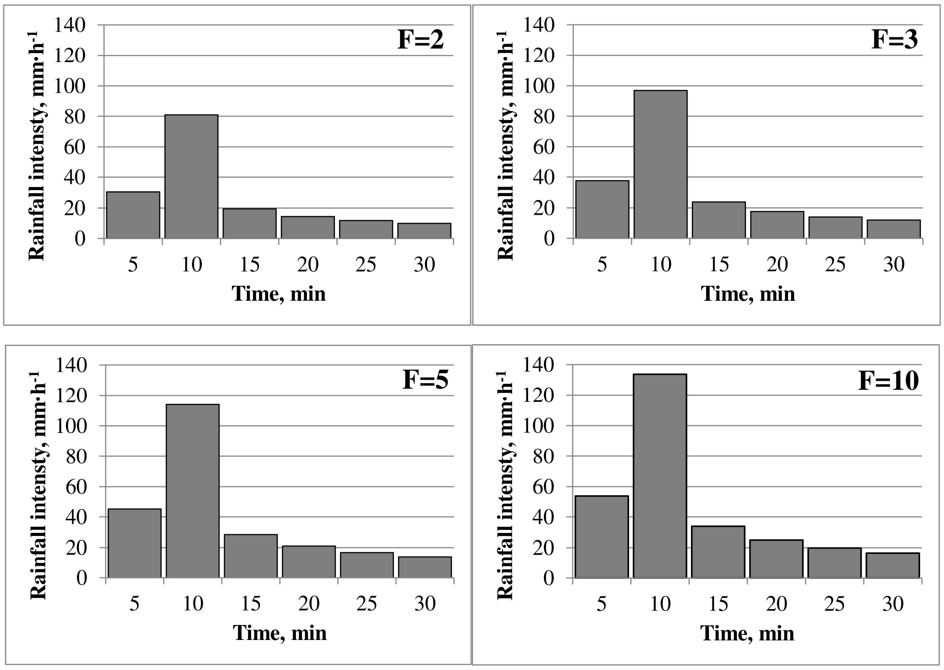

Fig. 4. Characteristics of model rainfalls (F – rainfall frequency)

An analysis of the simulation results was carried out based on the following assumptions:

- calculations were made for two levels of detail:
  - the network of channels reconstructed in detail (with the exception of connections) along with the division into appropriately detailed rain basins;
  - simplified network of channels (drainage channel from the catchment) connected to a single (replacement) rainwater catchment;
- the equivalent hydraulic width of the simplified catchment was estimated based on formula 2.1, and the calculated length of the runoff route for the catchment with a detailed channel system was adopted as the longest section from the initial well to the outlet;
- calculation variants were implemented taking into account Euler type II model precipitation (duration t = 30 min - proportional to the flow time of the main collector) on the basis of the Bogdanowicz-Stachý model [5];
- the simulation was carried out for four rainfall frequencies (figure 4): 2 (calculated rain according to PN-EN 752 [5]), 3 (for verification of damming up according to DWA-A118 [5]), 5 and 10 years (considering the impact of climate change over the longer term);

- a dynamic wave model was used with a time step of 15 seconds and a routing step of 1 second;
- total emptying of the channel network was assumed at the start of the simulation.

3. RESULTS AND DISCUSSION

The results in graphical form are presented in Figures 5 to 8 for the drainage basin I and in Figures 9 to 12 for the drainage basin V. The data presented is limited to a full two hours in which the majority of the runoff occurs via the drainage system. Other results presented in the following parts of the article include a full calculation day.
Since it was assumed that the channel network was completely drained of earlier outflows and no significant incidental water inflows, it was not necessary to carry out an extended calculation period before recording the results. As a result, the calculations take several to several seconds.

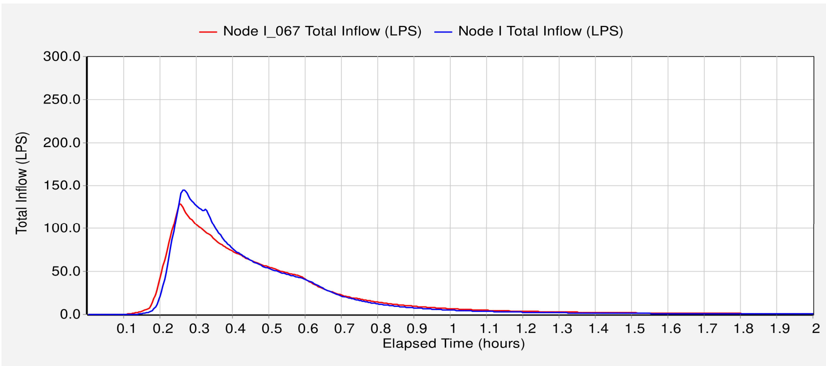

Fig. 5. Runoff flow rate at outfalls I and I_067 – rainfall F=2 years

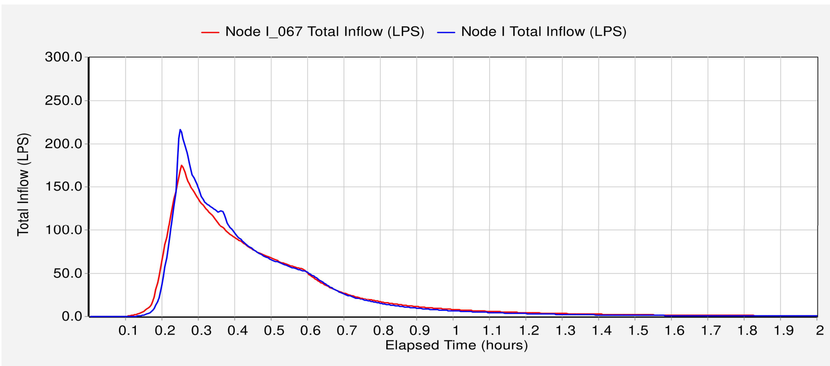

Fig. 6. Runoff flow rate at outfalls I and I_067 – rainfall F=3 years

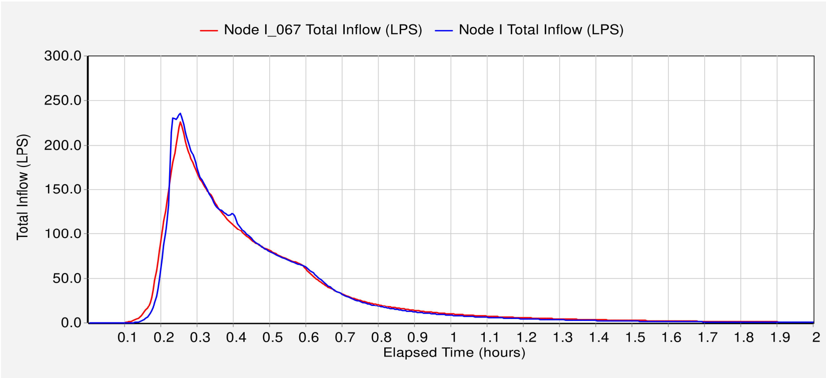

Fig. 7. Runoff flow rate at outfalls I and I_067 – rainfall F=5 years

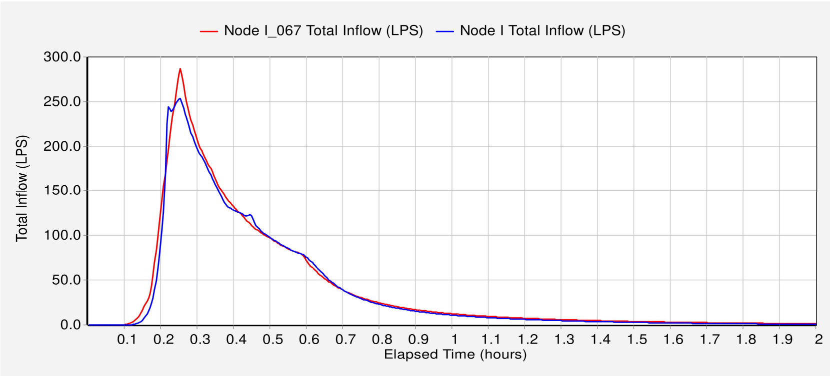

Fig. 8. Runoff flow rate at outfalls I and I_067 – rainfall F=10 years

Analysis of the results obtained for the catchment I allows us to conclude that in the case of reduction of the modeled network structure by omitting the serially connected channel system, the application of the proposed method for determining the equivalent width is acceptable. The results obtained in the case of reduction of the network structure are understated in relation to the detailed model, especially in the case of a rainfall frequency of 3 years. Only at a frequency of 10 years are the results of the simplified model overstated.

Analysis of the results obtained for the V catchment allows for the conclusion that in the case of reduction of the modeled network structure by omitting the extended series and parallel connected channel system, the application of the proposed method for determining the equivalent width is not acceptable. The results obtained in the case of network structure reduction are understated in relation to the detailed model, especially in the case of a rainfall frequency of 2 years. Only at a frequency of 10 years are the results of the simplified model overstated.

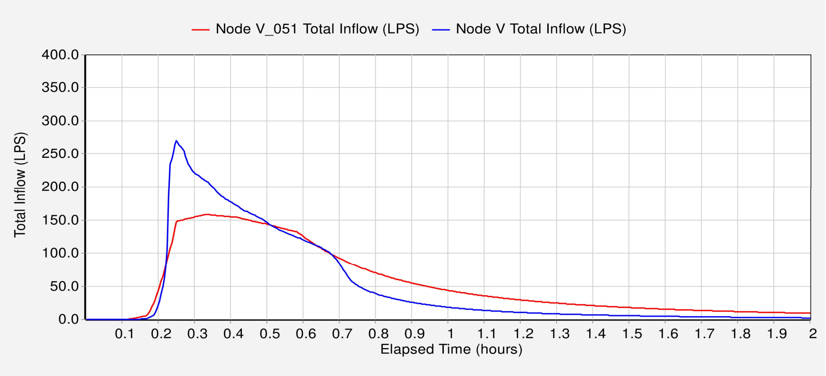

Fig. 9. Runoff flow rate at outfalls V and V_051 – rainfall F=2 years

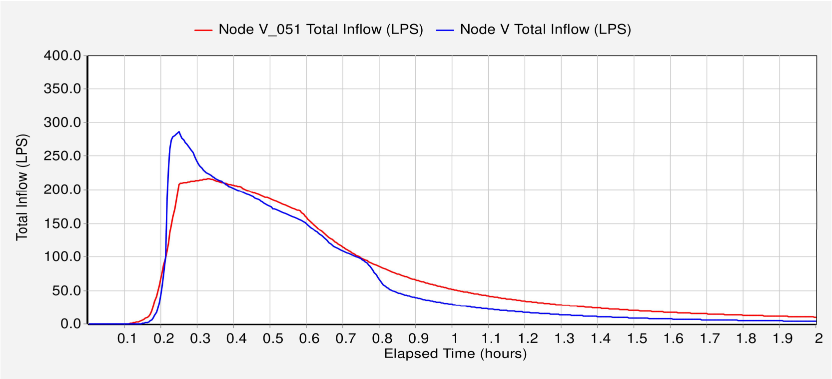

Fig. 10. Runoff flow rate at outfalls V and V_051 – rainfall F=3 years

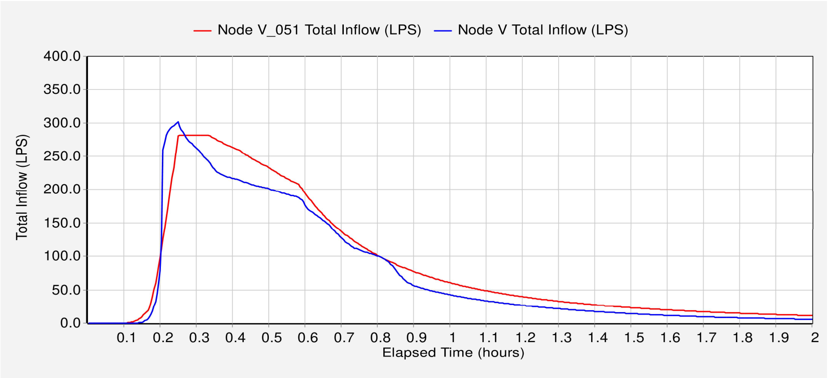

Fig. 11. Runoff flow rate at outfalls V and V_051 – rainfall F=5 years

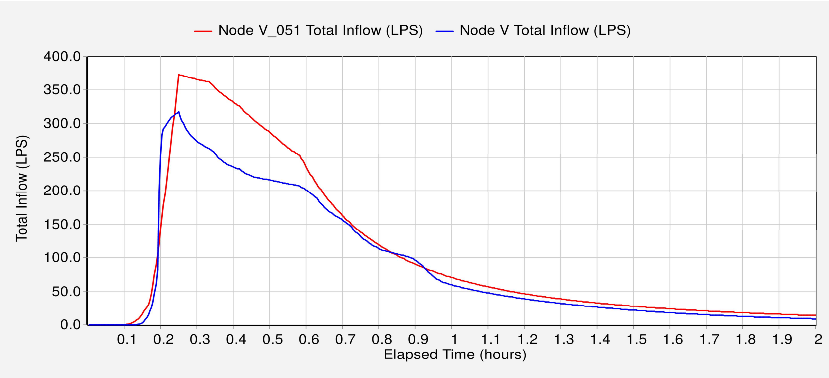

Fig. 12. Runoff flow rate at outfalls V and V_051 – rainfall F=10 years

The hydraulic width is a calibration parameter with a significant impact on the ability to obtain the correct adjustment of the simulation model to real conditions, and the limits in which it is possible to correct are significant because estimated for ± 30% [14].

The results easy to interpret in graphic form also confirm the numerical values listed in Table 1. For catchment I, the peak flow rate does not show differences greater than 20% in the least favorable conditions for precipitation with a frequency of F = 3 years. In the case of the V catchment, the differences may exceed even 40%. The explanation turns out to be simple after taking into account significant differences in the total drainage from the catchment area. In the catchment area V a significant share of channels with a diameter of 200 mm is observed. This solution does not comply with the guidelines for design, both contemporary and used during the implementation of the investment. With heavy rainfall, some runoff floods the catchment area locally and remains in uneven terrain. As a result, some storm water will never go to the drainage system, flooding green areas and threatening the flooding of the lowest properties.

The method used to estimate the replacement runoff width becomes uncertain not only because of the extensive drainage system subject to reduction, but also in the conditions of hydraulic overloading of the channel network.

This phenomenon is confirmed by the results obtained in the case of catchment I for precipitation with an incidence of 10 years. Here, too, the reduction in the maximum outflow intensity is associated with a significant over 5% loss in the volume of the storm water outflow. Limited capacity of reduced channels in the case of the simplified catchment causes the delay of outflow.

Table 1. Error in estimating the maximum flow and total outflow compared to the detailed model

Rainfall frequency [years]	Catchment	Relative error [%]	
		Flow rate	Outflow total
F=2	I	11.1	1.4
	V	41.8	22.6
F=3	I	19.1	1.1
	V	25.3	25.9
F=5	I	4.3	2.2
	V	7.6	30.3
F=10	I	13.0	5.5
	V	16.0	35.4

4. CONCLUSION

Optimization of calculation time, as mentioned above, is most often done by reducing the network structure, which necessitates replacing several or several rainwater catchments with one replacement catchment. This causes significant problems with determining the starting calibration parameters of such a catchment area, among others the so-called runoff width. The proposed solution, consisting in the application of the modified simplest method described by Rossman [11], only partly allows to solve the problem. It is permissible to reduce the structure of unbranched networks except for building connections and street inlet connections. In the case of branched systems, the value obtained, especially for the incidence of rainfall frequency F = 2 and 3 years, may disturb or even prevent the calibration of the model.

Based on the results obtained, the following recommendations can be made:

- due to the lack of a universal method for determining the replacement runoff width of a subcachment, reduction of the catchment together with the channel system should be limited to sections connected in series;
- particular attention should be paid to subsystems where there is a risk of hydraulic overloading of the channel network. First, the signal may be the presence of rainwater channels with a diameter less than 250 mm.

The issue requires further work, enabling the development of a universal method for estimating the initial values of the runoff width, which can be applied in the case of reducing branched systems.

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