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Dynamic modeling of flow in combined sewer network using the mouse model

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ABSTRACT

Dynamical modeling in water supply and treatment and wastewater treatment helps to understand the flow in the networks. Therefore, it is important to incorporate dynamic modeling into the design and assessment processes and operation for the future of urban drainage systems.

The aim of this paper was using a mathematical model to analyze the functionality of combined sewer networks during a precipitation event on 13 October 2020. The analysis was performed based on the results from the assessment of the hydraulic capacity of the sewer network using the MOUSE model in the MIKE URBAN software. This study results that the evaluated sewer network does not fulfill his purpose during heavy rainfall events.

KEYWORDS

dynamic modeling, hydraulic capacity, storm-water

1. INTRODUCTION

Mathematical models of drainage systems are increasingly used in the planning and design of sewer networks, green solutions to reduce rainfall into sewers, and the possibility of urban floods. The Swedish study of Broekhuizen et al. [1] deals with the optimal use and comparison of these models and with the analysis of individual models Modeling Of Urban SEwer systems (MOUSE), Storm-Water Management Model (SWMM), and Mike SHE code) and their differences in surface runoff simulations from green areas. The models were evaluated based on simulations with 11 different soil types and 6 different soil depths. The results of individual models differ due to different mathematical descriptions of models. The study's conclusion is that differences in the results can significantly affect the design and assessment processes.

Before modeling, it is necessary to determine the goal and the subject. It is important because of the modification of the following phases. After setting the goals, the separate preparation of the modeled system is started, namely the preparation and inventory of the input data. The preparatory phase involves collecting and inventory data that enters the mathematical model. When modeling sewerage networks, the input data mainly include data on rain events, catchment characteristics, characteristics of sewerage networks, total volume of overflow, number of Combined Sewer Overflows (CSOs) and retention basins, data on pumping stations, and data on receiving water bodies [2].

Part of the preparatory phase is the actions associated with the definition of the sewerage network and the basin, the subsequent selection of the model of the rain. The reliability of the mathematical model depends on the mathematical formulations of physical phenomena; the assumed physical parameters of the network and the basin, the accuracy of the input data, and the definition of the initial state of the system. Therefore, the basic condition for a correct model is calibration and verification [2, 3].

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Modeling uncertainties stem from input data errors and inaccuracies that may arise from simplification. Analytical numeric analyzes are used to determine them. These include sensitivity analysis, mean value analysis, point estimation, Monte Carlo simulation and Mellin transformation [4]. Sensitivity analysis is an important part of modeling. It considers the dependencies between input and output data. It helps to better understand the basic behavior of the system. It aims to examine the changes in output data that are caused by changes in the input characteristics of the model [5]. Examples of the use of uncertainty analysis used in the solution of drainage systems modeling include many studies, e.g., Alhumaid et al. [6], Baek et al. [7], Babaei et al. [8] and many others [6–8].

Only the calibrated simulations and verified models provide reliable results. Calibration determines the most suitable model parameters. The calibration parameters of sewer systems are mainly considered parameters e.g., the slope and length of the sub-catchment, the proportion of permeable and impermeable areas, and the roughness (Manning's roughness coefficient) of surfaces the runoff coefficient [9]. Verification demonstrates the accuracy of the parameters obtained during calibration and confirms the agreement between the calculated and observed quantities [10]. Verification can also be defined as a demonstration of the model by calibrated amounts, which correctly represent the reality of the system. It aims to prove that the physical quantities of the drainage system have been perfectly incorporated into the model [11].

The aim of the paper is to assess the hydraulic capacity of part of the sewer network of the city of Trnava and to identify problem sections.

2. MATERIALS AND METHODS

2.1. Boundary conditions

Stanko et al. [12] defined the boundary conditions of the sewer network model as input values, data types, and calculation models that have a direct impact on the assessment results. Boundary conditions specify the boundaries within which the calculation takes place and determine the exact calculation method.

Boundary conditions are categorized into three groups in the mathematical model of sewer networks. The first group consists of boundary conditions formed by the input data. This category includes data describing elevation and topographic data of the sewer network, e.g., terrain dimensions, manhole bottoms, manhole position, area topology and diameters, shapes, and material of sewers. The second group of boundary conditions is determined by choice of the model itself. The choice of model affects the intent to use the results and the accuracy of the results. The third group of boundary conditions is included in creating load cases, and it is the design rain. Rusnák et al. [11] focused on assessing the impact of different boundary conditions same category. The study compared the impact of different design rains on the results of sewer network simulations in Vráble.

In the presented article, the boundary conditions are the input data characterizing the urban catchment (elevations of the individual object, the elevation of manhole bottoms, the elevation of manhole covers, the slope of the area, the slope of the pipe network, CSO geometry and elevations, pipe diameters, pipe shape, roughness, runoff coefficient, and imperviousness), data, which are representing the dry weather flow (specific sewage water production, course of production unevenness curve, point inflows), and data describing the load condition (design rainfall characteristics).

2.2. Study area

The subject of assessment and modeling was a unified sewerage network in the eastern part of the city of Trnava, specifically the sewer collector A. The catchment is located on the eastern bank of the river Trnávka, which is the receiving water body for the network – WasteWater Treatment Plant (WWTP) and all CSOs the city of Trnava is located in western Slovakia, 50 km northeast of Bratislava.

Urban catchment collector A is spread over four urban and 23 urban districts. Eleven collectors, whose total length is 64,076 m, open into collector A. The historical center in the central part of the urban area is drained by sewer collectors I, II, III, V, collectors D, C drain wastewater from the north-eastern part of the urban area. At the end of the section, just before CSO1D, collector C opens into collector D. They are connected to collector A via the drain from CSO (collector I). The eastern part of the area of interest is drained by collectors A9a, AN2, AN, which are also connected to collector A. In the southern part of the area, street collectors AM and AI are fed to collector A. There are 9 CSOs on the modeled network, and they are designed with a mixing ratio of 1:4.

The sewage network of Trnava also discharges sewage from the surrounding municipalities of Dolná Krupá and Špačince, which belong to the Blava river basin and the municipalities of Boleráz, Šelpice, and Bohdanovce and Trnavou in the Trnávka River basin.

The given research area was chosen because it has significant problems with sewer overloading in some parts. The city is growing, and urbanization significantly impacts the sewer network operation. The studied part of the sewerage was built at the beginning of the second half of the 20th century. Therefore, the pipe network was designed according to the old standards and lower flow.

3. RESULTS AND DISCUSSION

3.1. Determination of the boundary conditions

As it is mentioned above, the first category of boundary conditions is the model input data. The characteristics of the sewer system were provided by the sewer network operating company, Trnava Water Supply Company (TAVOS, a.s.) in the form of plot documentation, Geographic Information

System (GIS) data, and maps of the study area. From these documents, it was possible to determine the basic characteristics of the area and dry weather flow in addition to the structure of the sewer network.

A map of surface impermeability was created based on map data and a field inspection. The determination of runoff coefficients created the impermeability map according to the STN 75 6101 standard [13] using sample sub – catchments. Table 1 shows the study area classification and determination of runoff coefficients and impermeability.

Dry Weather Flow (DWF) conditions were determined according to the number of connected inhabitants and assuming that the specific production of wastewater is in the range of 130 90 l person^{-1} day^{-1} and the uneven outflow of sewage during the day was characterized as a cyclical boundary condition using the time redistribution of daily flow according to Urcikán and Rusnák [2] for housing estates and medium-sized cities. The surrounding municipalities belonging to the Trnávka and Blava River basins are also connected to the sewer network of the study area. Inlet pressure sewer pipes from municipalities are connected at three different points (manholes) to the sewer network. The total inflow from the municipalities is 101.42 l s^{-1}.

A sewer network model was plotted in the MIKE URBAN software based on this data. MIKE URBAN software works with the MOUSE hydrodynamic model, representing the second category of boundary conditions.

The third category of boundary conditions is the design rainfall, representing also the basic unit of the load condition. Many authors [14–17] took the research of design rains. Design rainfalls form the basis of a building block of hydrological models and surface runoff models. In the conditions of the Slovak Republic, reduced block rainfall was the most often was used. It represents a rainfall with constant intensity for the entire duration of the precipitation event. However, it is more advantageous to use design rainfalls based on real precipitation events in dynamic modeling. An actual precipitation event was used as a design rainfall in this paper for modeling purposes, which was

Table 1. Average runoff coefficient and impermeability of sample sub-catchments

No.	Type of development	Ψ_s (-)	I (%)
1	Family houses**	0.51–0.57	35–45
2	Housing estate (multi-story apartment houses)	0.57	45
3	Parks, cemeteries, green areas	0.36	10
4	Industrial areas	0.78–0.72	80–70
5	Business zone	0.78–0.66	80–60
6	Historical center (multifunctional houses, apartment houses, …)	0.84	90
7	Mixed zone (multifunctional houses, apartment houses, city walls with adjacent greenery)	0.6	50

**according to building density: medium dense building, rural type of building, Ψ_s (-) is the runoff coefficient, I (%) is the impermeability.

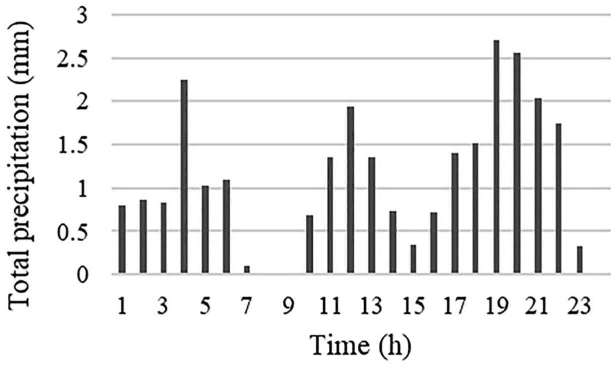

Fig. 1. Rainfall event from October 13, 2020

measured at the rain gauge station in Trnava on October 13, 2020. Slovak Hydro-meteorological Institute provided the rainfall data. This precipitation event was chosen because it represents the extreme values of total precipitation per day in 2020. Figure 1 shows the course of the precipitation from October 13, 2020.

3.2. Simulation results

All boundary conditions were entered after creating a mathematical model in the MIKE URBAN software, which works with the MOUSE model. A load condition corresponding to the DWF and Storm-Water Flow (SWF) conditions in the rainfall event of 10/13/2020 was created. The intensity of the rainfall event is evenly distributed over time. The precipitation event lasts 13 h and 15 min, while the maximum hourly total precipitation is 2.71 mm (18:00–19:00). The course of the precipitation event is shown in Fig. 2. In the intervals between 7:00–10:00 and 23:00–24:00, the total precipitation equals 0. At 18:56:36, the maximum flow in the network occurs. In the section before CSO1AN, its value is 572 l s^{-1}; for CSO1II it reaches up to 536 l s^{-1}. The total state of maximum flows is given in Table 2. The table also presents the flow rates on the given sections, the flood ratio, the water depth in the pipeline, the filling ratio, and the pressure conditions.

The time variability of flows in the sections in front of the CSO chambers is shown in Fig. 2. The left vertical axis shows the magnitude of the instantaneous flow over time, and the right vertical axis the rainfall intensity and the course of the rainfall event.

The maximum flow at collector D is 476 l s^{-1}. At the DN sewer, the maximum flow reached a value of up to 148 l s^{-1}. The maximum discharges on the collector discharging wastewater from the historical center are as follows: before CSO1I on sewer I there is 162 l s^{-1}, before CSO1II on sewer II there is 511 l s^{-1} and before CSO3AIII on collector A is 536 l s^{-1}. On sewer III the maximum flow for CSO3AIII is 345 l s^{-1}, on sewer AN (after the confluence of AN1 and AN2), the flow is 446 l s^{-1}, on the section before CSO1AN, there is 52 l s^{-1}, and before CSO1A2 312 l s^{-1}. The discharges at collector A reached the following maximum values: before CSO1AN 572 l s^{-1}, before CSO1A2 368 l s^{-1}.

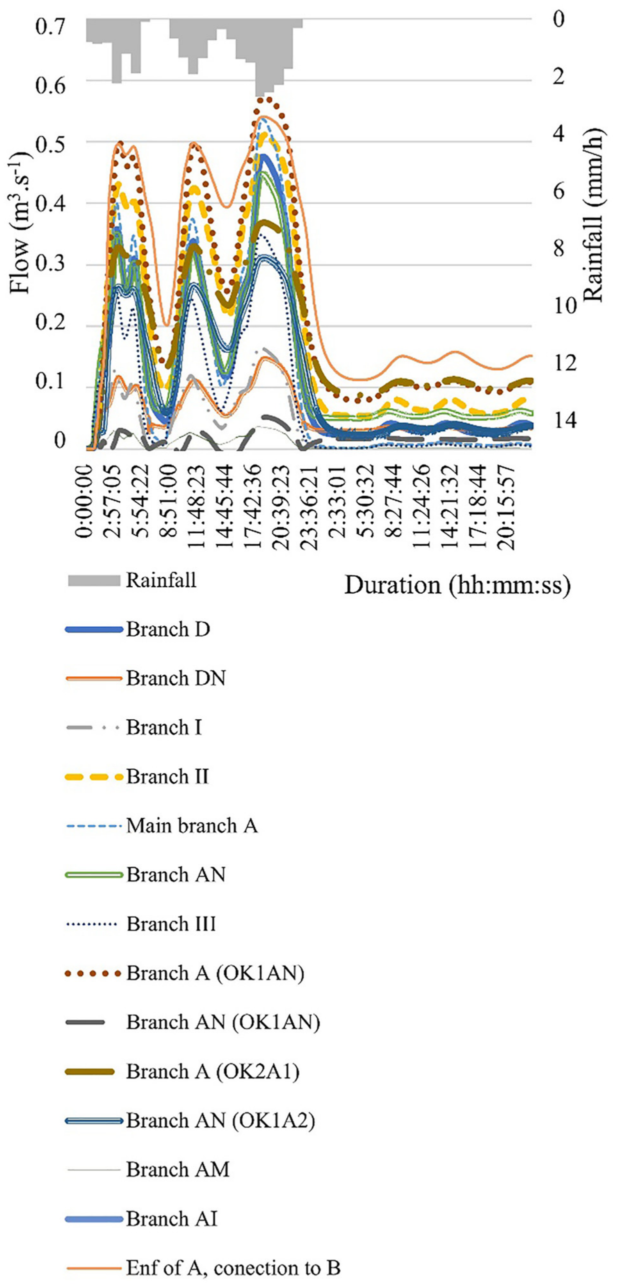

Fig. 2. Simulation results: waste-water flow in sections before CSOs

The maximum flow at the AM sewer collector is 35 l s^{-1}, and at the AI drain is 32 l s^{-1}. In front of the connection point to collector B, the maximum flow at collector A is 541 l s^{-1}.

After evaluating the simulation, it was found that the sewer network in question, when loaded by the rainfall event of October 13, 2020, has three flooded nodes and five flooded sections. The sections in question have a diameter of DN 300 with a length of 86 m and DN 600 with 100 m. Pressure-flow occurs in 73 sections of the sewer network. Figure 3 shows congested sections of the network.

3.3. Discussion

Mathematical modeling in water supply and treatment and wastewater treatment helps to understand the flow not only in pipelines but also in objects. Hrudka et al. [18] used dynamic flow modeling in a secondary sedimentation reservoir to simulate the sludge sedimentation. Based on the simulation results, it is possible to suggest a better object configuration. Šutúš et al. [19] also considered the assessment of the CSO chamber through modeling. The study of the hydrostatic model and its boundary conditions was dealt with by Rusnák et al. [11].

Table 2. Maximum flows in the sections in front of the CSO chambers

Collector	Diameter (m)	Flow ($m^3 s^{-1}$)	Flow velocity ($m s^{-1}$)	Water depth (m)	Pipe filling (-)
D	2400/1520	0.476	0.322	0.736	0.484
I	1300/900	0.162	0.422	0.351	0.390
A	1600/1010	0.536	0.885	0.598	0.592
II	1300/1500	0.511	0.850	0.598	0.399
III	1300/1500	0.345	0.691	0.489	0.326
A	1600	0.187	0.387	0.489	0.305
AN	2600/1950	0.446	0.423	0.544	0.279
A	900/1350	0.572	1.294	0.700	0.518
AN	1	0.052	0.098	0.700	0.700
A	900/1650	0.368	1.249	0.497	0.368
AN	1	0.312	0.827	0.497	0.497
AM	1	0.035	0.293	0.251	0.251
AI	1	0.032	0.400	0.177	0.177
END A	1300/900	0.541	1.403	0.313	0.347

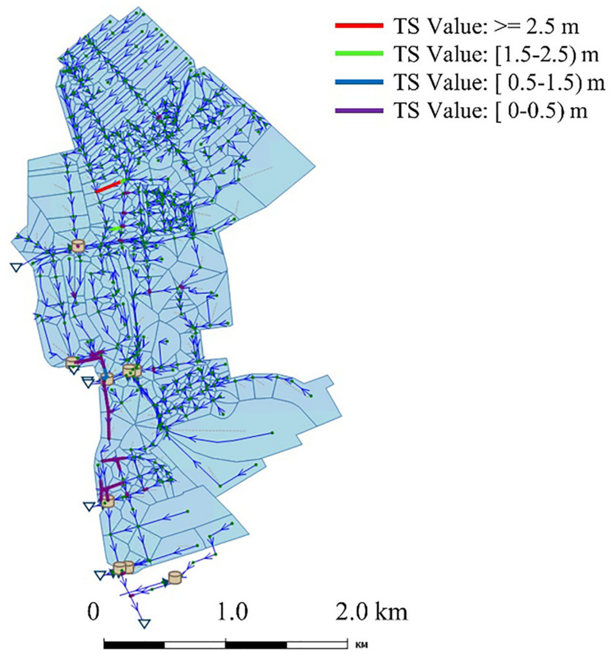

Fig. 3. Overloaded sections

Hydrostatic models can model only the static state of the network and the percentage of the overflow of the sewer network at maximum flow. Therefore, it is important to incorporate dynamic modeling into the design and assessment processes and operation for the future of urban drainage systems. In order to be able to react operatively to the possible impacts of climate change on specific sections and thus prevent pluvial floods in our cities. The future of urban drainage needs to adapt to the changes resulting from the new conditions created by climate change.

4. CONCLUSION

The presented paper focuses on using a mathematical model to analyze the functionality of combined sewer networks during a precipitation event on 13 October 2020. The analysis was performed based on the results from the assessment of the hydraulic capacity of the sewer network using the MOUSE model in the MIKE URBAN software. The mathematical model of the sewer network was created according to the data based on the processing of detailed map and GIS data and field inspection of the area of interest. A load case was created within the analysis, which simulated the DWF as a cyclic boundary condition and as a design rainfall event a real precipitation event measured at a rain gauge station in the city. Finally, the results of hydraulic capacity analysis for the load case were evaluated: it was found that the sewer network in question, when loaded by the rainfall event of October 13, 2020, has three flooded nodes and five flooded sections. The sections in question have a diameter of DN 300 with a length of 86 m and DN 600 with 100 m. Pressure-flow occurs in 73 sections of the sewer network.

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REFERENCES

[1] I. Broekhuizen, T. M. Muthanna, G. Leonhardt, and M. Viklander, "Urban drainage models for green areas: Structural differences and their effects on simulated runoff," *J. Hydrol. X*, vol. 5, 2019, Paper no. 100044.

[2] P. Urcikán and D. Rusnák, *Waste Water Collection and Treatment, Sewer Networks 1, Design of Sewer Systems* (in Slovak). Slovak Technical University in Bratislava, 2004.

[3] M. Sokáč, D. Sztruhár, P. Sinčák, and M. Bundzel, *Use of Hydroinformatics Tools in Urban Hydrology* (in Slovak). Institute of Scientific and Technical Information for Agriculture Nitra, Bratislava, 1999.

[4] C. Zoppou, "Review of storm-water models," Technical Report 52/99, CSIRO Land and Water, Canberra, 1999.

[5] M. Mair, R. Sitzenfrei, M. Kleidorfer, M. Möderl, and W. Rauch, "GIS-based applications of sensitivity analysis," *Water Sci. Technol.*, vol. 65, no. 7, pp. 1215–1222, 2012.

[6] M. Alhumaid, A. R. Ghumman, H. Haider, I. S. Al-Salamah, and Y. M. Ghazaw, "Sustainable evaluation framework of urban stormwater drainage options for arid environments using hydraulic modeling and multicriteria decision-making," *Water*, vol. 10, no. 5, pp. 1–21, 2018.

[7] S. S. Baek, M. Ligaray, J. Pyo, J. P. Park, J. H. Kang, Y. Pachepsky, J. A. Chun, and K. H. Cho, "A novel water quality modul of the SWMM model for assessing Low Impact Development (LID) in urban watersheds," *J. Hydrol.*, vol. 586, 2020, Paper no. 124886.

[8] S. Babei, R. Ghazavi, and M. Erfanian, "Urban flood simulation and prioritization of critical urban sub-catchments using SWMM model and PROMETHEE II approach," *Phys. Chem. Earth, Parts A/B/C*, vol. 105, pp. 3–11, 2018.

[9] I. Mrnčo, P. Blštak, P. Hudec, T. Gibala, and T. E. Michaeli, "Creation and calibration of rainfall – Runoff model for the needs of flood warning system," *Folia Geographica.* vol. 56, no. 1, pp. 101–112, 2014.

[10] D. Butler and J. W. Davies, *Urban Drainage*, 3rd ed., Taylor and Francis, 2010.

[11] D. Rusnák, Š. Stanko, and I. Škultétyová, "Rain model – Boundary condition in sewer network appraisal," *Pollack Period.*, vol. 11, no. 2, pp. 105–112, 2016.

[12] Š. Stanko, D. Rusnák, I. Škultétyová, M. Holubec, and K. Galbová, "Impact of topology and map precision on designed flow in rain sewers," *MM Sci. J.*, vol. 2017, pp. 1806–1809, 2017.

[13] *STN 75 6101*, Gravity sewerage systems outside buildings, Slovak Technical Standard, Bratislava, 2016.

[14] I. H. Elsebaie, "Developing rainfall intensity–duration–frequency relationship for two regions in Saudi Arabia," *J. King Saud Univ. Eng. Sci.*, vol. 24, no. 2, pp. 131–140, 2012.

[15] F. A. Huff, "Time distribution of rainfall in heavy storms," *Water Resour. Res.*, vol. 3, no. 4, pp. 1007–1019, 1967.

[16] E. A. H. El-Sayed, "Development of synthetic rainfall distribution curves for Sinai area," *Ain Shams Eng. J.*, vol. 9, no. 4, pp. 1949–1957, 2019.

[17] D. Rusnák, Š. Stanko, and M. Trošanová, "Design rainfall analysis tool for urbanized areas in Slovak Republic", *Pollack Period.*, vol. 12, no. 2, pp. 117–128, 2017.

[18] J. Hrudka, Š. Stanko, and M. Holubec, "Analysis of flow and sedimentation processes in secondary sedimentation tank", *Pollack Period.*, vol. 12, no. 2, pp. 79–89, 2017.

[19] M. Šutúš, J. Hrudka, G. Rózsa, I. Škultétyová, and Š. Stanko, "Hydrodynamic assessment of combined sewerage overflow chamber in Banská Bystrica," *Pollack Period.*, vol. 16, no. 2, pp. 50–55, 2021.