Application of Dynamic Simulations for Assessment of Urban Wastewater Systems Operation

I. Pijáková* and J. Derco
Institute of Chemical and Environmental Engineering, Faculty of Chemical and Food Technology, Slovak University of Technology, Radlinského 9, 812 37 Bratislava, SK

doi: 10.15255/CABEQ.2014.2127
Original scientific paper
Received: October 10, 2014
Accepted: March 2, 2015

The paper presents the results of a study aimed at the use of simple mathematical models of a sewer network, wastewater treatment plant (WWTP) and receiving water to control the discharge of diluted wastewater from combined sewer overflow system in order to protect water resources.

The greatest burden on the receiving water usually occurs at the time of combined sewer system overflow, when diluted municipal wastewater is also discharged into the receiving water. Literature usually presents impact assessment results of either wastewater treatment plants or sewer system on the receiving water. In our work, we assess the impact of the integrated municipal wastewater system on the receiving water.

The models for the sewer system, wastewater treatment plant, and receiving water under consideration were developed. Mathematical modelling of the subsystems of urban wastewater system was carried out using simulator SIMBA 6. Simulations were performed using real experimental data. Information about the sewer system overflow during the year (total amount of overflow, pollutant load of COD during overflow) was obtained by using dynamic simulations. The simulation results aimed at the impact assessment of the sewer system overflow and WWTP on the receiving water quality showed that the values of the monitored parameters in the river could exceed several times the environmental quality standards for receiving water.

Key words
combined sewer overflows, impact on receiving water, modelling, receiving water, urban wastewater systems, wastewater treatment plant

Introduction

The construction and operation of municipal drainage systems has been historically driven by two objectives: (1) To maintain public hygiene, and (2) To prevent flooding. The importance of the pollution control aspect has grown over the years, and gradually treatment facilities have been introduced to preserve the aquatic ecosystem[1].

The urban wastewater system has a major impact on the receiving water quality. Combined sewer overflows (CSOs) are used to divert excess stormwater into a nearby recipient. In Europe, it is widely assumed that the frequency or total volume of overflow discharges is a good indicator of the pollution impact on receiving waters. Less frequent overflow will result in less adverse impact on receiving water quality. Reduction of overflow frequency leads at least to the reduction in aesthetic pollution[2]. On the other hand, wastewater treatment plants continuously discharge effluents which always contain certain pollutants (depending on the plant treatment efficiency).

The idea of understanding and potentially exploiting the integrated system is not new.

For example, Beck[3] discussed the idea of a 'water quality system', consisting of water distribution network, sewer system, treatment plant, and river[4].

Integrated urban wastewater assessment fits into the holistic approach suggested by the Water Framework Directive[5], which requires good ecological and chemical quality of surface and groundwater. Representing and understanding the urban wastewater system as a whole allows better, more cost-effective solutions to be engineered, because consideration of just the individual elements does not take into account the interactions between the various subsystems.

Implementation of an integrated model can be done in view of various goals. It can be used to test scenarios in order to evaluate future impact e.g. future housing or increase of drained impervious surfaces, operation strategies evaluation like influent

*Corresponding author: e-mail: ivana.pijakova@stuba.sk

load increase to the WWTP. Overall, problems with integrated model implementation are the heaviness of the model and the data availability[6].

This paper presents the implementation of an integrated model on a case study in Slovakia. The main aim was to apply simple mathematical models of a sewer network, WWTP and receiving water to control the discharged diluted wastewater from combined sewer overflow system in order to protect water resources.

Description of the case study

The case study data were taken from facilities located in western Slovakia; the wastewater from two small cities (Trenčianska Teplá, Trenčianske Teplice) and a village Dobrá is collected mainly by a combined sewer system and treated in a WWTP. The sewer system load was 7363 population equivalent, in 2011. There are combined sewer networks of overall length of 15 046.1 m in Trenčianska Teplá, and 23 596.5 m in Trenčianske Teplice. The sewer system of the village Dobrá comprises a gravitational sewer network, pumping station and discharge pipelines with a total length of 4422.1 m. The sewer system contains seven combined sewer overflows. The sewer system catchment area was unknown and thus calculated according to satellite view. The total catchment area of 126.9 ha was considered, comprising a small impervious area of 12 ha. The runoff coefficient was set to 0.3. The catchment area was divided into fifteen smaller sub-catchment areas drained by the sewer system. The scheme of the sewer system connected to the receiving water, which was implemented to Simba 6, is shown in Figure 1.

The wastewater treatment plant comprises mechanical and biological stages, and anaerobic sludge stabilization. The volume of the aeration reactor is 520 m^3 and total volume of the secondary clarifier is 850 m^3. The aeration tank is operated as oxic reactor with average dissolved oxygen concentration of 2.5 mg L^{-1}. The average dry weather inflow into the WWTP was 6 593 m^3 d^{-1}, in 2011. Temperature, pH, dissolved oxygen (DO) and inflow are measured on-line every hour, while total chemical oxygen demand (COD), biological oxygen demand (BOD_5) and ammonium nitrogen (NH_4-N) are analysed in the laboratory four times per month.

Teplička is the receiving water of the WWTP in Trenčianske Teplice. The average daily flow of the river (Q_{355}) was 110 L s^{-1} in 2011. Composition of the water is measured at two monitoring locations. Table 1 shows the average annual values. Originally designed cross-sections were used for characterization of the river profile.

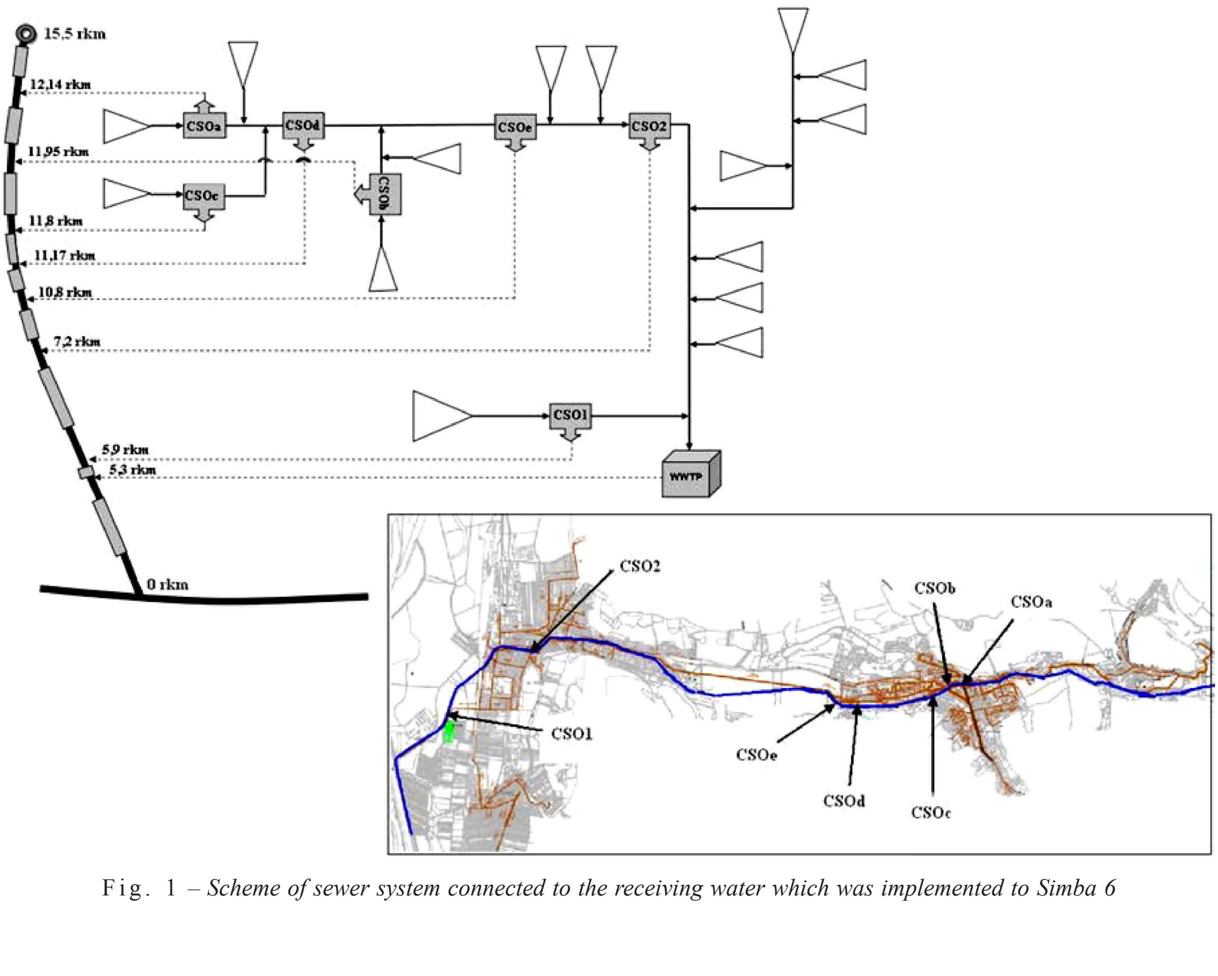

Fig. 1 – *Scheme of sewer system connected to the receiving water which was implemented to Simba 6*

Table 1 – *Characterization of receiving water*

	15.5 rkm	4.9 rkm
O_2 [mg L^{-1}]	10.9	11.4
pH [–]	8.4	8.4
T [°C]	9.3	10.5
BOD_5 [mg L^{-1}]	3.9	2.5
COD [mg L^{-1}]	8.8	9.6
NH_4-N [mg L^{-1}]	0.3	0.1
NO_3-N [mg L^{-1}]	1.6	1.3

Model building

Mathematical modelling of the subsystems of an urban wastewater system was carried out using simulator SIMBA 6 programme, which is a software package for modelling and simulating urban wastewater systems. It is based on the simulation system MATLAB-Simulink, and offers access to its features and versatility. Within SIMBA, there are a large number of models for various parts of wastewater systems. These can be used as building blocks for a representative model of the urban wastewater system to be investigated. A model structure and its complexity is determined by the goal of the study and the availability of data. Detailed information on catchments and river are often not available and therefore conceptual models (with fewer parameters to calibrate) appear more suitable to represent the subsystems.[6] For example, in the river or the sewer pipelines, water transport is modelled by a linear reservoirs cascade.

In this work, the rainfall – runoff model was used for modelling the system at different operating conditions and transport of pollution from sewer networks. Flow in the sewer system is modelled by the hydrodynamic diffusive-wave approximation of the Saint-Venant equations, which consist of the continuity (1) and the momentum (2) equations[7]:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$S_f = S_0 - \frac{\partial h}{\partial x} - \frac{1}{gA}\frac{\partial}{\partial x}\left[\frac{Q^2}{A}\right] - \frac{1}{gA}\frac{\partial Q}{\partial t} \tag{2}$$

where Q is flow rate [m^3 s^{-1}], t is time [s], A is cross-sectional area of channel segment [m^2], x is longitudinal distance [m], h is channel depth [m], S_0 is bottom slope [–], S_f is friction slope [–] and g is acceleration due to gravity [m s^{-2}].

Assumptions for St. Venant Equations[8]:

– one-dimensional flow

– hydrostatic pressure prevails and vertical accelerations are negligible

– small streamline curvature

– small bottom slope of the channel

– homogeneous and incompressible fluid

– Manning's equation is applied to describe the resistance effects[9]:

$$Q = \frac{1}{n} A R_h^{2/3} S_f^{1/2} \tag{3}$$

where n is Manning's roughness coefficient [$m^{-1/3}$ s], R_h is hydraulic radius ($R_h = A/P$) [m] and P is wet perimeter [m]. Manning's roughness coefficient is one of the energy loss coefficients describing the energy loss due to friction between water and riverbed in open streams. Manning's coefficient varies considerably and depends on many factors, such as surface roughness, vegetation, channel irregularity, etc.

The bottom of the riverbed was created artificially from concrete slabs and paving. The lateral sides of the riverbed were formed from paving and humus. Manning's coefficient values of these materials were taken from Schütze *et al.*[10]: n (concrete slabs) = 0.015 $m^{-1/3}$ s, n (paving) = 0.014 $m^{-1/3}$ s and n (humus) = 0.029 $m^{-1/3}$ s.

Activated Sludge Model No. 1 (ASM1) was used to describe the processes of removing organic and nitrogen pollutants in WWTP, which includes 8 biochemical processes and 13 components[11]. Basically, Monod type reaction kinetics is applied to describe the transformation of process components by the biochemical processes. Simple Water Quality Model (SWQM) was implemented for river quality. It includes 5 processes and 7 components[12]. The sub-models are connected by means of interface models, which transform the state variables of the one sub-model into the state variables of the following sub-model.

Results and discussion

Simulation program SIMBA 6.0[13] was used for dynamic simulations of municipal wastewater system. A mathematical model was developed for a selected municipal wastewater system. Simulations were carried out with a simplified model.

Different approaches for rainfall runoff calculation are applied for pervious and impervious areas. Evaporation is modelled using a double-sinoid approach, considering diurnal and annual variations. Rainfall runoff is modelled using a conventional approach with standard parameters. Surface runoff and runoff concentration is modelled by Nash cascades (cascades of conceptual linear reservoirs). Only one pollutant – COD is modelled, assuming constant distribution of flows and pollution over

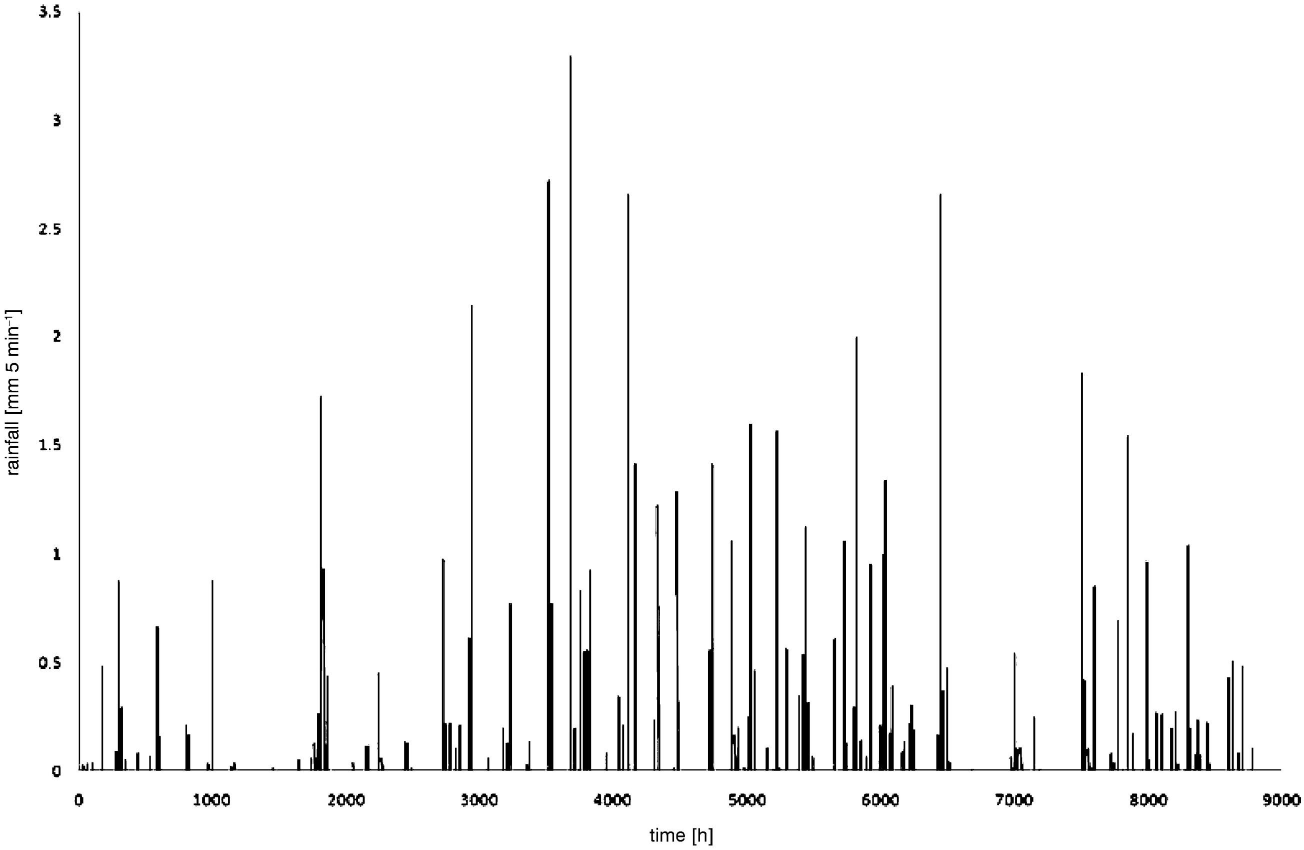

Fig. 2 – *Rainfall data [mm 5 min^{-1}] used in simulation*

day. Pollutant concentration was 100 mg L^{-1} in rainfall runoff. Maximal wet weather inflow to WWTP was considered 32 830.5 m^3 d^{-1}. Maximal wet weather inflow was 9 156 m^3 d^{-1} on biological stage of WWTP. The model was not calibrated due to the unavailability of some data for the sewer system modelling. Thus, rainfall-runoff parameter values recommended in the literature were used during simulation calculations, for the following parameters: rainfall runoff factor, wetting losses, total depression losses, percentage of area with no depression losses, percentage of effective area, saturation moisture. Sewer system overflow projection during the year was obtained from the simulation results. The average temperature of 10 °C was used for simulations. Precipitation in 2011 (Figure 2) was taken into account during the simulations. Average precipitation was 831.9 mm. The same rainfall intensity was considered in all variations of simulations. One hour of

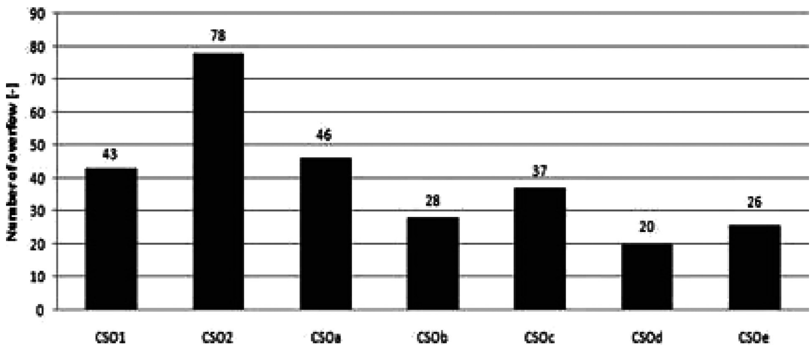

Fig. 3 – *Results of simulation – Number of overflows during year 2011*

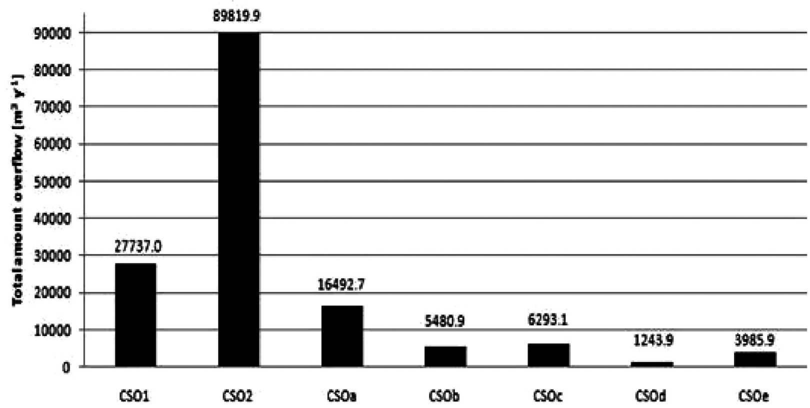

Fig. 4 – *Results of simulations – Total amount of overflow [m^3 y^{-1}] during year 2011*

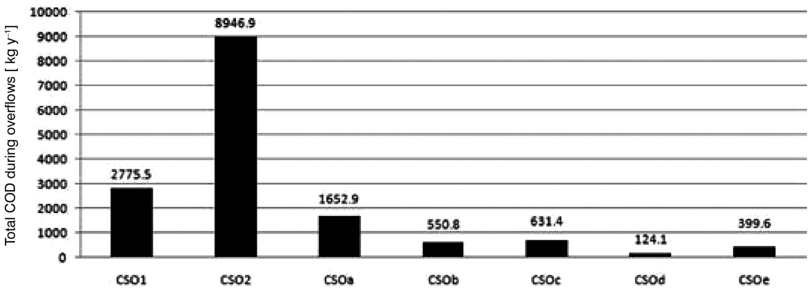

Fig. 5 – *Results of simulations – Pollutant load of COD during overflows [kg y⁻¹]*

rain on a particular day was considered, while the mixing ratio 1:4 was applied.

Figures 3–5, present the results of sewersystem overflow simulation. Active overflows from every CSO follow from the results. Total amount of overflow was 151 053.4 m^3, while the total pollutant load of COD from CSOs was 15 081.2 kg, in 2011. It is obvious that overflows represent a significant load of pollution for the river.

ASM1 was used for the mathematical modelling of the WWTP. This model includes the following processes: aerobic and anoxic growth of heterotrophs, aerobic growth of autotrophs, decay of heterotrophs and autotrophs, amonification of soluble organic nitrogen, hydrolysis of entrapped organics and entrapped organic nitrogen. Average wastewater inflow to the biological stage of the WWTP, without rainwater, was 6593 m^3 d^{-1}, in 2011. The diurnal variation of inflow was provided by the WWTP operator. The diurnal variation of composition was not available; therefore, it was generated by an algorithm incorporated in SIMBA 6. The calibration was performed in order to achieve minimum differences between the experimental and calculated pollution concentration values at WWTP effluent. In all simulation calculations, the respective pollution concentrations of discharged wastewater from WWTP were assumed to amount to COD = 19.9 mg L^{-1}, BOD_5 = 3.3 mg L^{-1} and NH_4-N = 3.1 mg L^{-1}. In general, the wastewater treatment plant complies with the WWTP effluent standards. The ammonium nitrogen limit was exceeded in the river after mixing with the effluent from the WWTP. Thus, the objective of our calculations was to find suitable effluent values to satisfy the Environmental Quality Standard (EQS) in the river.

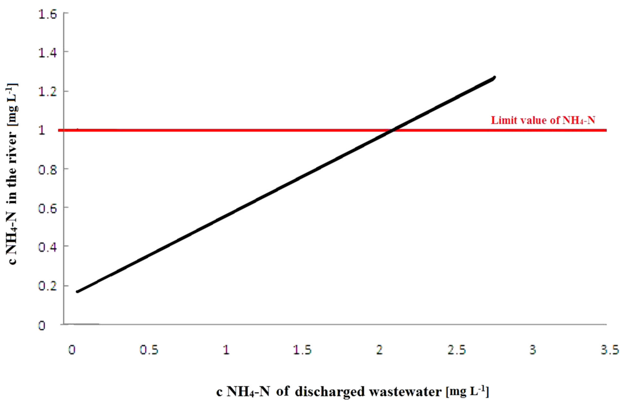

Fig. 6 – *Results of simulations – Impact of NH4-N of discharged wastewater from WWTP on receiving water quality*

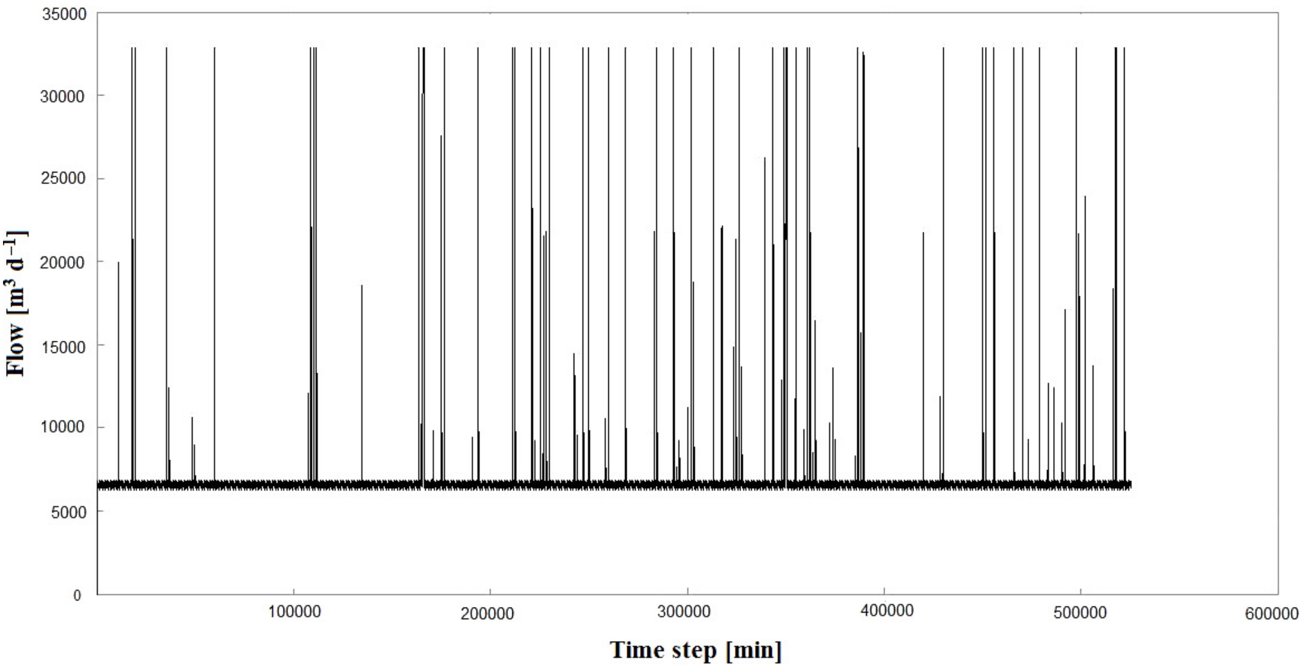

Fig. 7 – *Results of simulations – Inflow [m³ d⁻¹] to wastewater treatment plant*

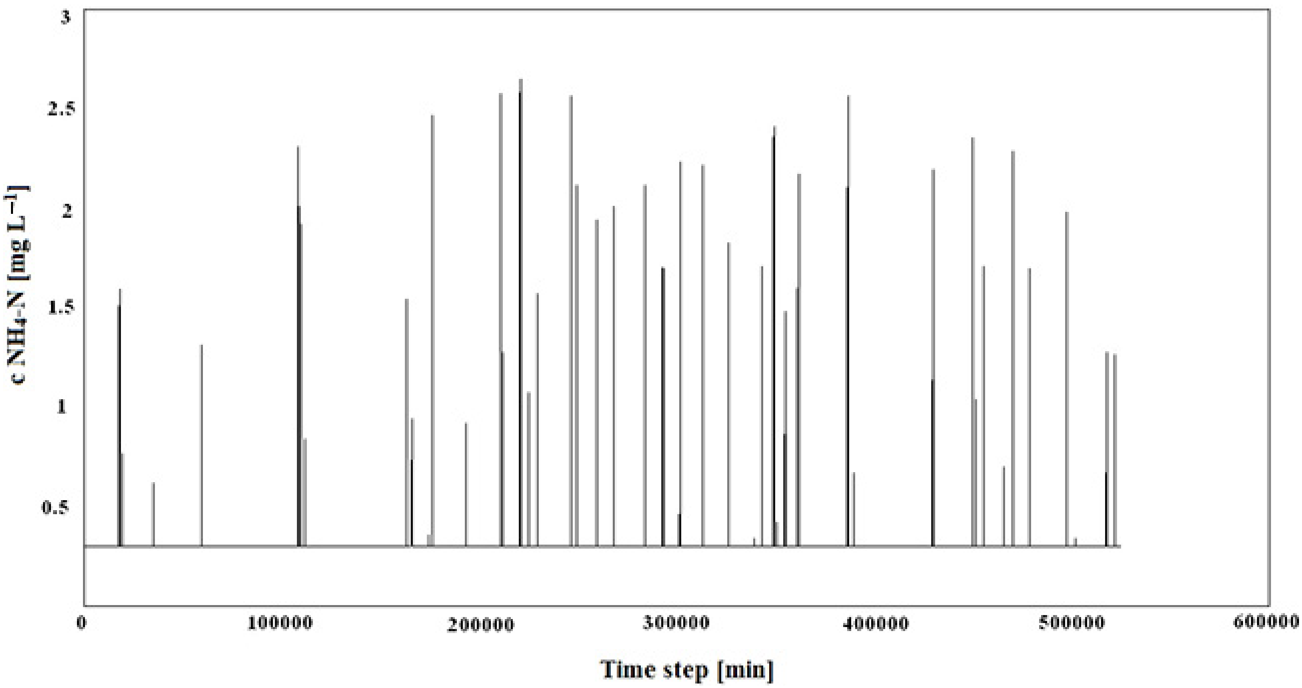

Fig. 8 – *Results of simulations – Concentration of ammonium nitrogen [mg L^{-1}] after discharge point CSO_d in the river*

Figure 6 shows the results of these simulations. If the value of ammonia nitrogen concentration in discharged wastewater equals 2 mg L^{-1}, the standard value is satisfied.

On the other hand, if NH_4-N concentration decreases to 0.1 g L^{-1} in the river before WWTP, the ammonia nitrogen from wastewater treatment plants only needs to reach 2.3 mg L^{-1} in order to meet the quality standard in the river for this indicator. It can be concluded that NH_4-N was influenced by WWTP performance. Dissolved oxygen and solid retention time in the aeration tank play important roles. The necessity to supply more oxygen into the system in order to meet NH_4-N concentration at the output results from our simulations.

The results of simulation with precipitation (Figure 7) show that the wastewater influent to

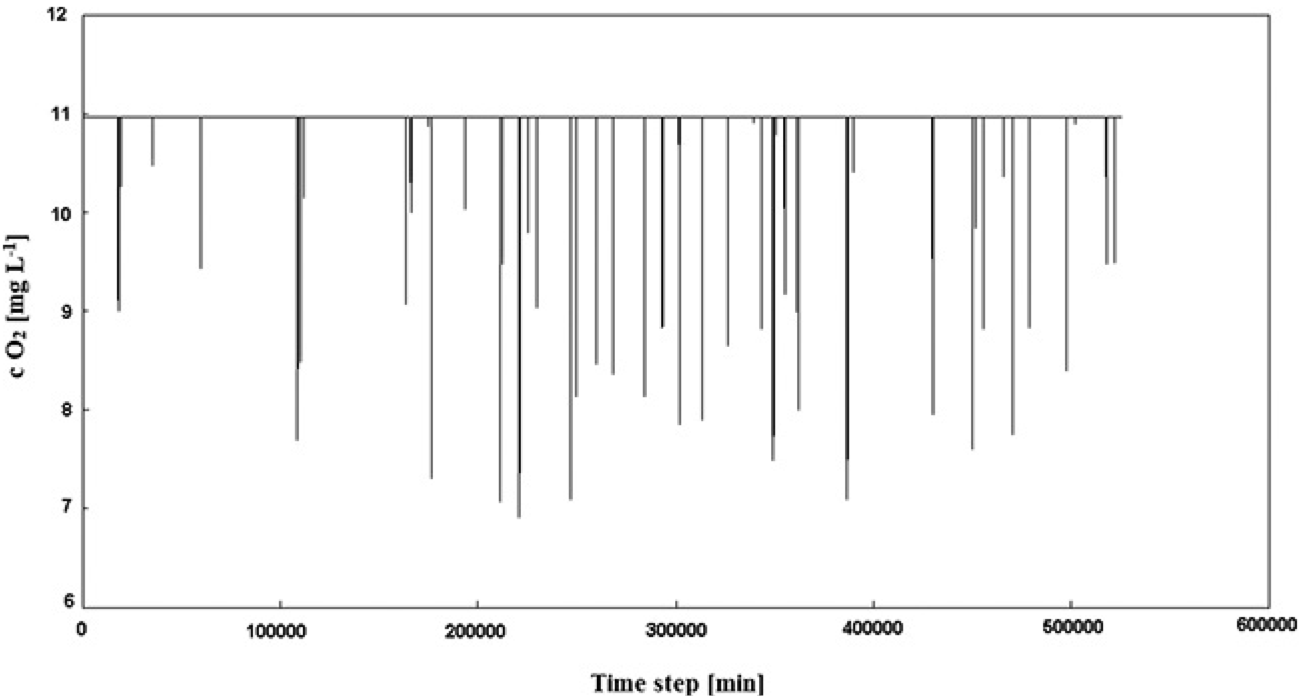

Fig. 9 – *Results of simulations – Concentration of oxygen [mg L^{-1}] after discharge point CSO_d in the river*

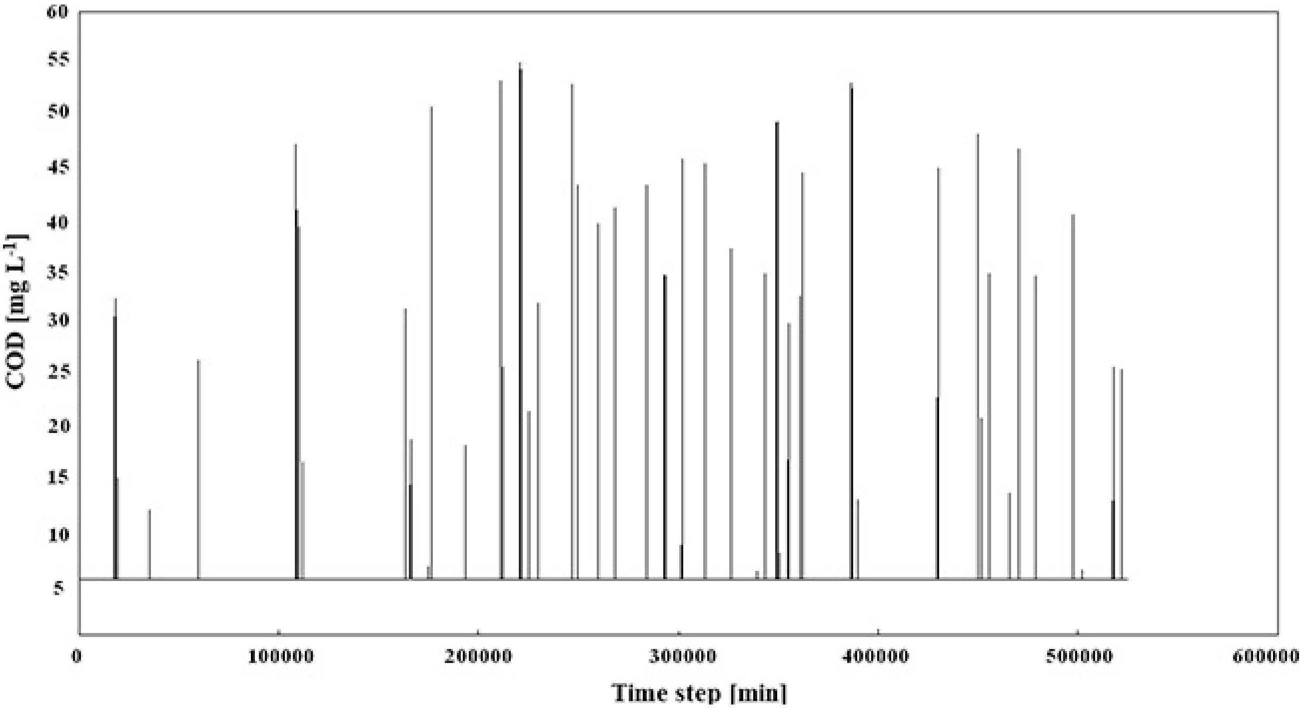

Fig. 10 – *Results of simulations – Pollutant load of COD [mg L⁻¹] after discharge point CSO_d in the river*

WWTP can be diluted 5 times during rainfall, and thus lower pollution removal efficiency from WWTP should be expected.

The investigation of the impact of sewer system overflows on receiving water quality was carried out. Oxygen, NH_4-N concentration and COD in the river were calculated before and after locations of CSOs during torrential rains. The status of water quality in the river at Q_{355} during rainfall events was investigated for mixing ratio of 1:4. Figures 8–10 show, for example, the flow rates in the river and pollution concentration after overflow CSO_d (11.17 river kilometre-rkm).

These results indicate that EQS in river are exceeded, which may actually cause an adverse impact on aquatic life in the river. The limit value of

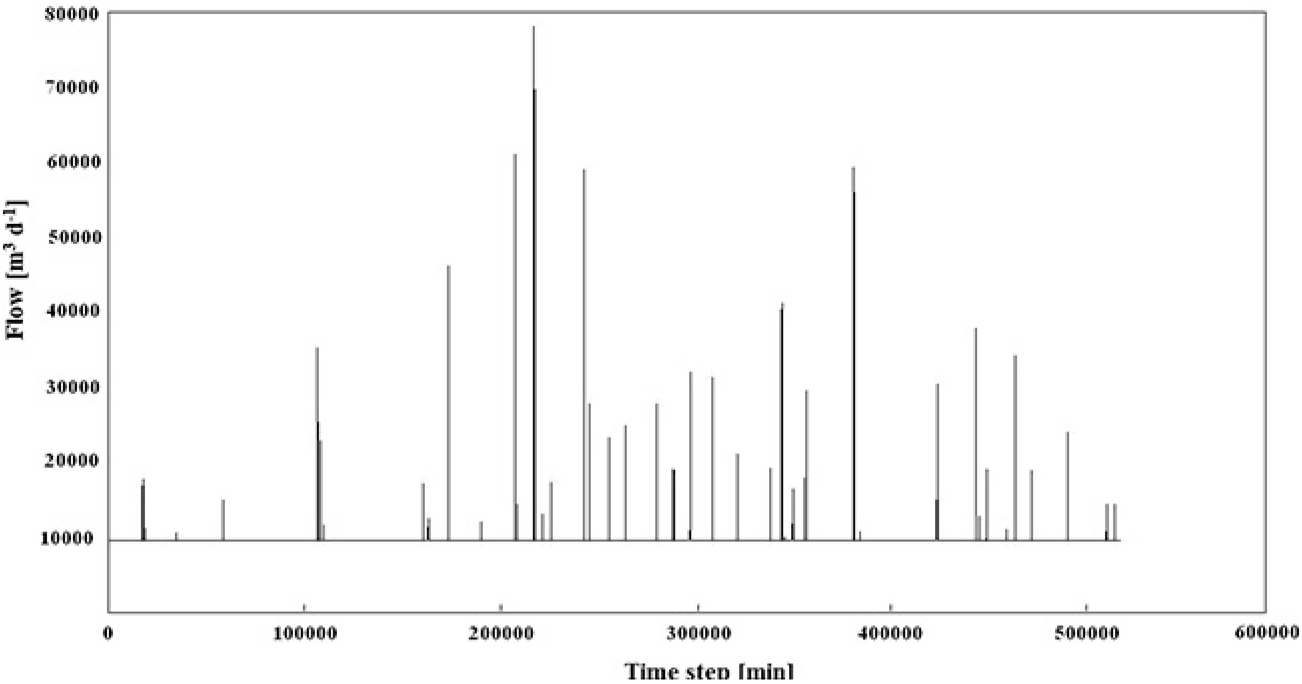

Fig. 11 – *Results of simulations – River flow [m^3 d^{-1}] after discharge point CSO_d*

COD in the river (35 mg L^{-1}) is exceeded around 27 times, and the limit value of NH_4-N (1 mg L^{-1}) is exceeded 41 times during the year. Maximum concentration of NH_4-N was 2.7 mg L^{-1} and maximum load COD was 53 mg L^{-1} in the river. The values of oxygen are in accordance with the EQS for the river.

Conclusion

The aim of this work was to use simple mathematical models of the sewer system, WWTP and receiving water to predict urban wastewater systems management in the aim of protecting water resources. Mathematical modelling of the subsystems of municipal wastewater systems using simulator SIMBA 6 was carried out.

The results suggest that all overflows discharging municipal wastewater and rainwater from every CSOs at mixing ratio of 1:4 were active. Total amount of overflow was 151 053.4 m^3 and the total pollutant load of COD was 15 081.2 kg from CSOs, during the year. The results of WWTP impact simulations on the receiving water during dry weather confirmed that, although the wastewater treatment plant met the effluent standards in terms of NH_4-N, the EQS for ammonium nitrogen in the river was not met. Thus, the required quality of discharged wastewater was investigated in order to meet the EQS values in the river. The results of dynamic simulations, including precipitations, showed that the wastewater influent to WWTP should be diluted 5 times, during rainfall events.

The results of simulation focused on the CSOs impact assessment on receiving water quality showed that the values of the monitored parameters in the river may exceed several times the river quality standard. The COD limit value was exceeded around 27 times in the river, and the limit NH_4-N value was exceeded 41 times during the year. Maximum NH_4-N concentration reached 2.7 mg L^{-1}, while the maximum load COD was 53 mg L^{-1} in the river after discharge point from CSO_d. Dissolved oxygen values comply with EQS. It may be concluded from the simulation results that increased mixing ratio, e.g. 1:8 is more appropriate in terms of EQS values.

ACKNOWLEDGEMENTS

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-0656–12. The authors are grateful for the support of the VEGA Grant 1/0859/14. Our thanks also go to Ifak e.V. Magdeburg for their support with program Simba.

References

1. *Rauch, W., Bertrand-Krajewski, J., Krebs, P., Mark, O., Schilling, W., Schutze, M., Vanrolleghem, P.*, Deterministic modelling of integrated urban drainage systems, Wat. Sci. Tech. **45** (2002) 81.
2. *Lau, J., Butler, D., Schütze, M.,* Is combined sewer overflow spill frequency/volume a good indicator of receiving water quality impact? Urban Water **4** (2002) 181. doi: http://dx.doi.org/10.1016/S1462–0758(02)00013–4
3. *Beck, M. B.*, Dynamic modelling and control applications in water quality maintenance, Wat. Res. **10** (1976) 575. doi: http://dx.doi.org/10.1016/0043–1354(76)90139–1
4. *Butler, D., Schütze, M.*, Integrating simulation models with a view to optimal control of urban wastewater systems, Environmental Modelling & Software **20** (2005) 415. doi: http://dx.doi.org/10.1016/j.envsoft.2004.02.003
5. CEC, Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Community (2000).
6. *Solvi, A. M., Benedetti, L., Vandenberghe, V., Gillé, S., Schosseler, P., Weidenhaupt, A., Vanrolleghem, P. A.,* Implementation of an integrated model for optimised urban wastewater management in view of better river water quality: A case study. Proceedings of IWA World Water Congress (2006).
7. *Ogurek, M., Schütze, M., Tschepetzki, R.*, Einführungsskript in die Simulation von Abwassersystemen. ifak e.V. Magdeburg, Barleben (2005).
8. *Havlik, V.*, Computational Hydraulic Modelling I. NATO-ASI on Hydroinformatics in Planning, Design, Operation and Rehabilitation of Sewer Systems. Harachov (1996).
9. *McGhee, T. J.,* Water Supply and Sewerage, 6th edn. McGrawHill, New York 1991.
10. *Schütze, M., Erbe, V., Krebs, P.,* Integrated modelling of urban wastewater systems. NATO advanced Reasearch Workshop, „Urban Water Management: Science, Technology and Service Delivery“, Bulgaria, October 2002, 16–20.
11. *Henze, M,, Gredy, C. P. L., Gujer, W., Marais, G. W. R., Matsuo, T.*, Activate Sludge Model No. 1., Scientific and Technical Report (1987), IAWPRC, ISSN 1010–707 X.
12. *Schütze, M.*, The Simple Water Quality Model (SWQM), internal report ifak e. V. Magdeburg (2009).
13. URL: http://www.ifak-system.com/products/simulation--software/wastewatersimulation/ simba-6.html (27.12.2014)