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Modelling of Combined Sewer Overflow Impacts on the Receiving Water Quality: Case Studies Hron and Drava

Marek Sokáč[1], Marta Jerković[2]

[1] *Department of Sanitary and Environmental Engineering, Faculty of Civil Engineering, Slovak University of Technology in Bratislava, Slovak republic*
[2] *Department for Hydrotechnics and Ecology, Faculty of Civil Engineering, Josip Juraj Strossmayer University of Osijek, Croatia*
E-mail: [1]*marek.sokac@stuba.sk (corresponding author),* [2]*mjerkovic@gfos.hr*

Abstract. Paper analyses the influences of combined sewer overflows (CSO's), on the receiving water quality, but generally deals also with various types of storm water management in urban areas. The first case study analyses the impacts of the continuous (wastewater treatment plant in the town Osijek) and discontinuous pollution sources (CSO's in the town Osijek) on the quality of the receiving water – the Drava river (Croatia). The second modelling case study was performed on the river Hron (Slovak republic). In this study, the impacts on the water quality from combined sewer overflows form the biggest town on Hron River – Banská Bystrica were studied, as well as four feasible alternatives of storm sewer management (different mixing ratio, different size of storm tanks) were analysed. For both case studies, the mathematical simulation model MIKE11 (Danish Hydraulic Institute, DHI) was used.

Keywords: water quality, modelling, receiving water, impact, discontinuous pollution, combined sewer overflow.

Conference topic: Water engineering.

Introduction

Mathematical models are a powerful and potent tool in water management planning. It can be used for comprehensive forecasting of the water quality and quantity development, but also to assess the impact of various measures in catchments or waterways.

Evaluation of the influence of the waste water on the receiving water can be done on various ways: beside the classical approach (volume, concentration limits, emission, imission standards or limits), are now coming into foreground biological methods, evaluation directly the influences on the aquatic life. Mostly used methods for evaluating the influence of waste water on the receiving water are still the imission and emission methods. Both methods have been known for a long time and are worked out in detail in literature and also in the legislation, where it is successfully used for evaluating the influence of the continuous outflow of waste waters – from the communal or industrial waste sewerage plants etc. But the question is how to evaluate the effects of discontinuous sources of pollution, for example of the combined sewer overflows (CSO's) on individual sewage networks?

Urban sewerage networks in both countries (Slovakia and Croatia, especially in bigger cities) were very often designed as sewerage networks of combined type, i.e. mixing of stormwater and wastewater is assumed. These systems suffer very often from absence of centralized or decentralized retention and detention elements, thus from hydraulic point of view, in case of storm events it is necessary to discharge a large part of the stormwater through combined sewer overflows (CSO's) directly to the receiving water. This approach, of course, lead to a deterioration of water quality in receiving water bodies.

The basic approach towards solving the effect which waste water has on the receiving water is based on the achieving of the required quality of the receiving water and preventing of discharging out the waste water in large amounts, according to what the receiving water is used for (fish protected water bodies, bathing, drinking water etc.). General approach is to achieve at least the "good" water quality status of the entire water body. It is necessary to follow water quality criteria for surface waters, in order to ensure required limits defined in the legislation, for example a minimal concentration of dissolved oxygen in the receiving water, the maximal concentration of harmful substances, e.g. ammonia nitrogen (NH_3-N) in reference to the pH and temperature of the water in the receiving water. Such requirements should be based on environmental limits, e.g. respect the values LC_x with prescribed frequency, where the x is the required safety level. LC_{50} means 50% death rate of fish with the stated pollutant concentration and exposition time).

Such regulation method could be called "imission" regulation method, and can be used also for non- continuous (discontinuous) pollution sources, like CSO's.

On the other hand, this method for evaluating the influence of waste water from CSO structures on the receiving water requires the use of the most up to date technology during design phase or for evaluating sewerage systems. In other words, for evaluating the effects on the receiving water the runoff models are required (which can include the quality module), then the surface water quality models and the last stage requires the simulation of processes in WWTP's.

This kind of a complex approach is not feasible for small pollution sources due to the amount of input information needed to evaluate the influence, taking into consideration the conditions in Slovak republic (but similar conditions are also in in other countries). The needed information either does not exist, or are not available in practice. Another problem is the price of the required models, inadequate or poor experience with modelling, problems with the calibration and verification of the models (verification of the basic model requires a large amount of field measurement data). It is apparent that proving the fulfilment or the inability to fulfil the required limits is possible only by direct continual measurements in the field or using mathematical models.

Modelling work

For the mathematical simulation of the water quality the model MIKE 11 (Danish Hydraulic Institute, DHI) was used. This model, developed by the Danish Hydraulic Institute, is a set of hydrodynamic one-dimensional model tools for detailed proposal and management of simple and also complex river and channel systems. Simulation results can be used in engineering, water management, water quality management and planning applications.

MIKE 11 consists of several modules for: hydrodynamics (basic module), hydrology, cohesive sediment transport, water quality and non-cohesive sediment transport. In both studies the basic hydrodynamic, the advection-dispersion transport and the water quality modules were used for simulation. Generally, a module structure of the model offers great flexibility: each of modules can be processed separately; data transfer among modules is automated; coupling of physical processes is easier; quick and simple application and development of new modules is possible.

Physical definition of the river beds was made by the graphic editor of the simulation software MIKE 11. As a basis, we used digital maps in DWG format, obtained from the river authorities, eventually from other sources (Mišík 1998), (Bara, Velísková 2012), (Bara *et al.* 2012). Into this map base we entered all the river bed direction points and also all the connection points in which the tributaries, pollution release, eventually other objects were defined.

Unfortunately, not sufficient information about the flow hydraulics (roughness coefficients) has been provided for the modelled river section, respectively for the kinetics of physical, chemical and biological processes in the river (dispersion coefficients, re-aeration or de-oxygenation coefficients etc.), required by the water quality module. Individual coefficients, affecting the process kinetics, were set up according the results of the steady state simulation. Results of these simulations, computed in the final section of the modelled river section, should correspond to the monitored water quality value.

Also, there were no direct measurements of pollution concentrations of the CSO effluent available, so we used data obtained during the survey in Slovakia (Sztruhár *et al.* 2002). These values are presented in Table 1.
For the water quality simulation, we used the level 5 of the standard model, which allows modelling of concentrations of dissolved oxygen (O_2), ammonia nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), biochemical oxygen demand (BOD_5) and phosphorus (P) in dissolved and particular form including a delayed oxygen consumption. This level of complexity comprises modelling of following processes:

1. The re-aeration;
2. The degradation of organic matter – instantaneous oxygen consumption;
3. Nitrification;
4. Denitrification

Table 1. Output concentration values of the modelled pollution parameters – outflow from CSO Osijek (Sztruhár *et al.* 2002)

Indicator	Unit	Value
Dissolved oxygen O2	mg.l-1	2
Water temperature	°C	25
Ammonia nitrogen (NH4-N)	mg.l-1	6.21
Nitrate nitrogen (N03-N)	mg.l-1	1.28
Dissolved phosphorus – P	mg.l-1	2.37
Particular phosphorus – P	mg.l-1	0.26
Biochemical oxygen demand – BOD5	mg.l-1	175

Case 1: Drava river (Croatia)

From the spatial point of view, we modelled the part of the Drava river from rkm 69.118 (downstream from the monitoring profile no. 29111 between the villages of Donji Miholjac and Podravski Podgajci) to the mouth of the Danube River (rkm 0,000). In this section of the Drava river, the river bed is diverting from state border with Hungary and flows through the territory of Croatia. The river Drava has in this section the character of meandering flow with lots of side branches, but no major tributaries.

Water quality models for rivers are usually used to resolve or predict adverse conditions on the river, which mainly occur at relatively low discharges. We consider the simulation for this case study with quasi-steady-state discharge near to the minimum discharge Q_{min} = 152 $m^3.s^{-1}$. This flow rate was defined as the upper boundary condition at 69.118 rkm profile. The lower boundary condition was defined as the constant level of the water level 79 m above sea level (the mouth of the river Drava and Danube in rkm 0,543).

As the aim of this work was the modelling of water quality, it was necessary to enter the concentrations of substances entering the modelled area as well. The assignment was necessary for each state variable, considered in the simulation water quality model.

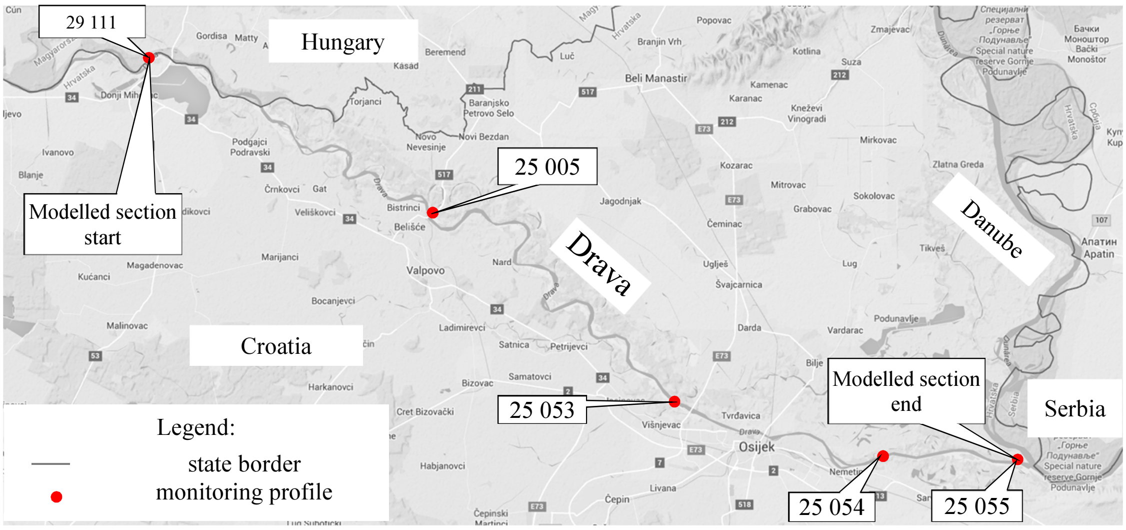

Fig. 1. Modelled river section with monitoring profiles

For steady state, we used the c_{90} values from the monitoring station Donji Miholjac (monitoring profile no. 29111, see Fig. 1), i.e. the values of the quality indicators corresponding to 90% quantile of not – exceeding probability (exceeding for oxygen, O_2) the substance concentration in the river.

In this scenario, we simulated the effect of wastewater, relieved through combined sewer overflows (CSO's) from the sewer network of the Osijek city. The city has a total of 8 CSO's flowing to the Drava river, for simplification reasons we concentrated the effluent into three points (see Fig. 2). For this scenario simulation, we used the data from the work (Krsnik 2011). In this diploma work is presented storm water discharges monitoring in the sewer network of the Osijek city, as well as statistical evaluation of rain gauge data from GMS Osijek station, based on historical rain gauge data series recorded in 1959–1991.

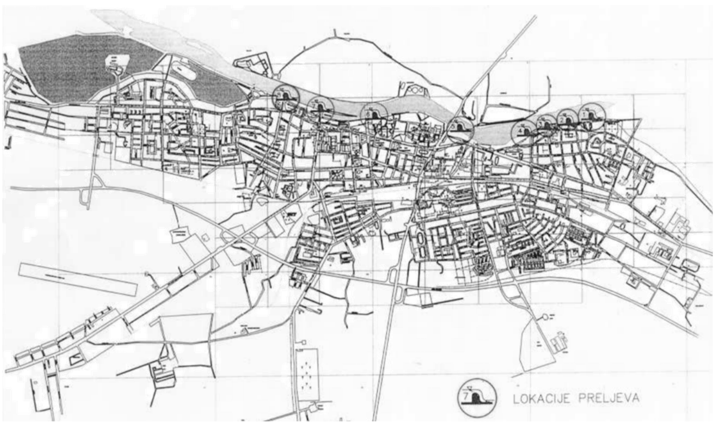

Fig. 2. Localisation od combined sewer overflows (CSO's) in the town Osijek (Krsnik 2011)

Considering the fact that the raw waste water flow from CSO's depends on the rainfall intensity, we simulated several options with different frequency and duration of the storm events. An overview of used storm return periods, intensities and durations are presented in Table 2.

Table 2. Used return periods, durations and rainfall intensities from station GMS Osijek (1959–1991), (Krsnik 2011)

Rainfall intensity (l.s-1ha-1)					
Return period / Rainfall duration	1 year	3 years	5 years	10 years	20 years
30 mins.	35	102	123	153	187
60 mins.	18	60	75	95	117
120 mins.	13	32	42	53	66
240 mins.	8	20	24	30	36

The total catchment area of the sewer system is 7.56 km^2, peak runoff coefficient we considered after (Krsnik 2011) with the value $\psi = 0.36$. The CSO effluent discharge time course was not simulated, the outfall duration was considered to be equivalent the storm duration. The CSO effluent discharge was considered also constant, for its determination we used simple intensity – area method.

Case 2: Hron river (Slovakia)

The first part of the project was modelling the stormwater runoff from the sewer system of the city Banská Bystrica in aim to simulate CSO waste water discharges from the CSO structures to the river Hron.

The primary intention of the model study was to use data from long- term rain monitoring for the time period of 28 years from the station Sliač. Such long- term simulation will require very long simulation time, what did not suit to our conditions and requirements. So instead a long – term modelling an alternative solution -statistical approach was used. We used block rainfalls with the periodicity of 0.033, 0.1, 0.2, 0.5, 1.0 and 5.0 with duration of 15, 30, 60 and 180 minutes.

Overall, we simulated on the catchment of the city 4 basic alternatives of the storm water management (according the SK legislation -please note, that the sequence numbers of alternatives are used for marking the IDF curves in consequent figures):

1. Dilution (mixing) ratio of the CSO 1:4 (minimum requirement according the SK legislation)
2. Dilution (mixing) ratio of the CSO 1:8 (maximum, which can be required according the SK legislation)
3. Storm tank with the volume necessary for accumulation of CSO volume with the frequency p = 0.5 (2 years return period)
4. Storm tank with the volume necessary for accumulation of CSO volume with the frequency p = 5 (return period 5 times in a year)

The second part of the case study was to create a mathematical model of the receiving water – river Hron to simulate the water quality and its changes due to the CSO overflows from the city of Banská Bystrica. The receiving water – river Hron was modelled in the space extent from the river kilometre 261.300 (Valkovňa profile), i.e. from the first monitored profile on the river to the estuary (km 0.000), which is practically the whole river length except for a short section near the spring (see Fig. 3).

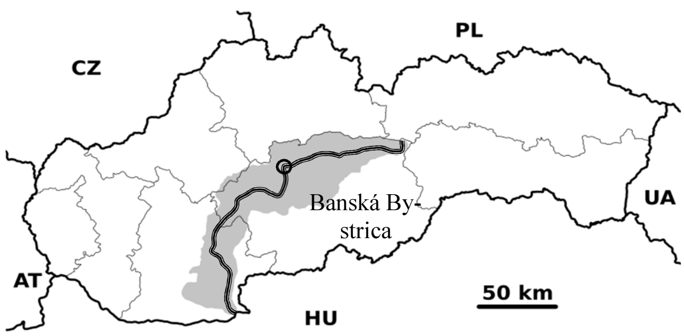

Fig. 3. Hron river, its river basin (grey colour) and the city of Banská Bystrica on the Slovakia outline map.

Simulations for two "basic" states of hydrologic situation at the river Hron were modelled -the long-term average flow (Q_a – for the river Hron, and also in all the tributaries) and flow, which are close to the minimal flows – for a 355-day flow Q355.

In the first alternative (average flow Q_a) the average pollution concentrations to simulate the water quality were used; in the second alternative (Q_{355}) the simulation was performed using the value c_{90} (90% distribution percentile of the most unfavourable concentration value). As input values, we use information gained from the annual water quality reports (SHMU 1999–2009).

The modelled flows and the quality of the waste waters discharged from CSO's were used as input to the model of the water quality in the river Hron. In first step, we evaluated only the alternative, where the discharged waste waters will be discharged into the average river flow (Q_a), but we deal also with the alternative that the discharged waste waters will be discharged into the 355-day flow (Q_{355}).

Discussion

Case 1: Drava river (Croatia)

In this scenario, discontinuous emission of the waste water to the Drava river has been simulated, which is very common in practice – hydraulic overflow of sewage from sewer systems during storm events through the CSO's. This is a relatively short, but the more intense hydraulic and pollution load of the recipient, depending on the intensity and duration of the storm event.

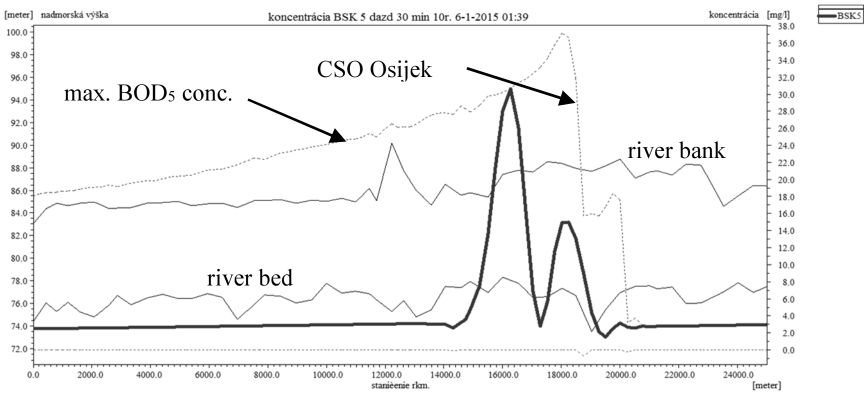

Fig. 4. Modelled BOD_5 concentrations in Drava river (rain duration 30 mins., return period 10 y.)

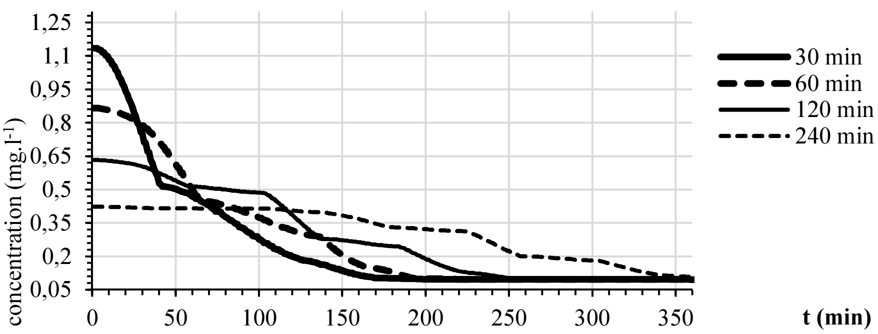

Fig. 5. IDF curve of ammonia nitrogen (NH_4 -N) concentrations in Drava river (return period 10 y., river km. 17.825)

All used storm events had different duration and different frequencies. simulation results are documented in the following figures: Fig. 4 documents the pollution – BOD_5 concentration longitudinal profile, using the 30-minute storm event with return period 10 years (p = 0.1). The figure shows only a section of the river Drava, downstream of the Osijek city, from rkm 24.0 to the estuary to the Danube (rkm. 0.0). As can be seen on the figure, short-term intense rain caused higher pollution concentration, but only with short-term duration, whereas the longer storm event causes smaller increase of the pollutants concentrations, but with longer effect time.

These different effects of specific pollutants on the receiving water quality can be expressed with IDF curves (Intensity – Duration – Frequency) (Sokáč 2010). To illustrate the simulation results an example is shown on Fig. 5 – IDF curves of the concentration and effect duration of ammonia nitrogen NH_4-N. All curves are simulation results using storm events with different duration and return period of 10 years.

Case 2: Hron river (Slovakia)

Simulation results of the water quality are shown in form of the IDF (Intensity – Duration - Frequency) curves for the basic water quality parameters – the dissolved oxygen concentration, also for BOD_5 and N-NH_4. IDF curves for various alternatives are displayed on Figures 1–3. These curves show the intensity of the negative effects and the duration of this exposition on the biocoenosis of the river.

As shown on the figures, the discharging of waste water represents a relatively short-term stress on the receiving water. It is necessary to mention that the catchment of Banská Bystrica is relatively specific – it has relatively big slopes and a large amount of CSO structures, which means that the large volumes of the waste water gets to the receiving water through the CSO structures very fast (very small retention capacity of the system, a total absence of accumulation structures in the system).

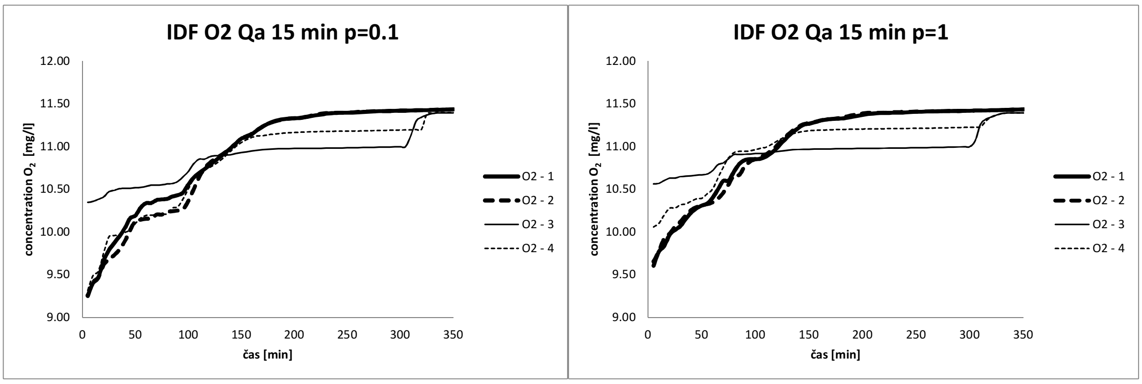

Fig. 6. IDF lines of the dissolved oxygen concentration (O_2) in the receiving water during a 15-minute rain event with a periodicity of occurrence p = 0,1 and 1,0 (the numbers in the legend represent the storm water management alternative)

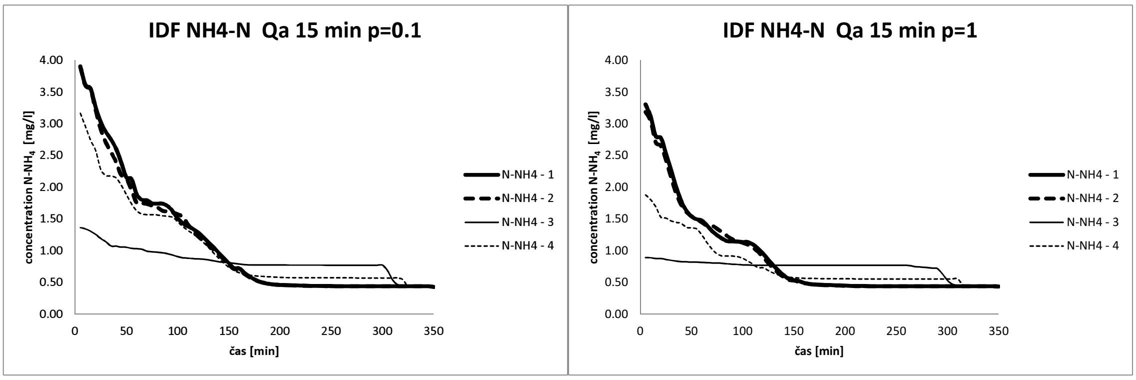

Fig. 7. IDF lines for the ammonium nitrogen (N- NH_4) concentration in the receiving water during a 15-minute rain event with a periodicity of occurrence p = 0,1 and 1,0 (the numbers in the legend represent the storm water management alternative)

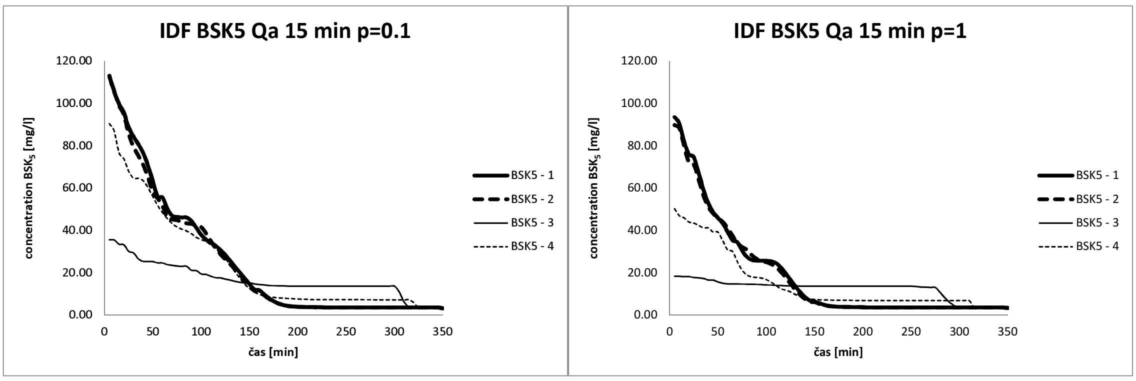

Fig. 8. IDF lines for the biochemical oxygen demand (BOD_5) concentration the in the receiving water during a 15-minute rain event with a periodicity of occurrence p = 0.1 and 1.0 (the numbers in the legend represent the storm water management alternative, BSK5 means BOD5)

When comparing individual methods of storm water management (see Fig. 6–8), the following facts can be stated:

1. The size of the mixing ratio for short-term intensive rain events practically doesn't have any effect on the quality of water in the receiving water,
2. The most effective method of structural regulation is, despite of many disagreements and problems, the construction of storm tanks.

Ad 1: the judged alternatives represent minimum and maximum requirements according to the current Slovak legislation. As can be seen on figures 1–3, during short-term rain events with a relatively low periodicity of occurrence, there isn't a big difference between these two alternatives concerning the quality of water in the receiving water. The difference is shown more during longer rain events or during heavy rains with lower periodicity. Also, when using a higher mixing ratio, the periodicity of occurrence of the CSO events (discharges of the raw waste water into the receiving water) decreases, which can in some cases have a significant importance.

Ad 2: this conclusion is not in any way surprising, these results were expected. Nevertheless, they are shown here, because they easily show the effect of storm tanks on the quality of water in the receiving water – the concentration of harmful substances in the receiving water in the described cases is three to four times lower (alt. 3) than alternatives without storm tanks.

For complex information, also the longitudinal profiles with oxygen and BOD_5 concentrations of the in the river Hron (Fig. 9 and 10) are presented.

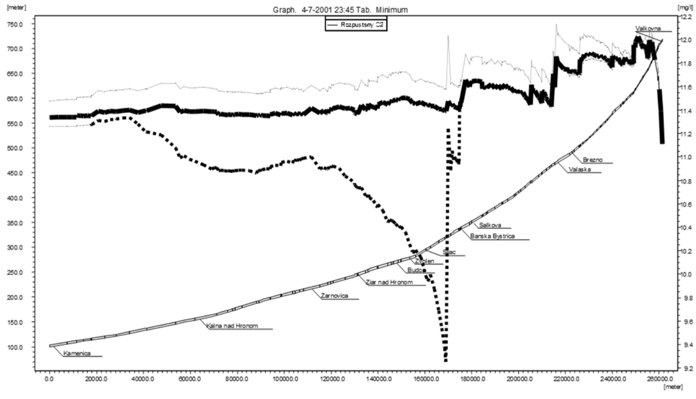

Fig. 9. Concentration of solved oxygen (O_2) in the receiving water (longitudinal profile) during a 15-minute rain with a periodicity of occurrence p = 0.1 and 1.0, alternative no. 1 (Legend: full line – continuous state, dotted lines – minimum or maximum concentration)

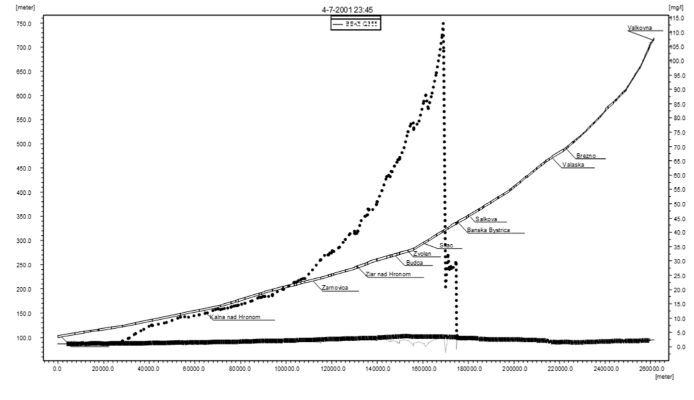

Fig. 10. Concentration of BOD_5 in the receiving water (longitudinal profile) during a 15-minute rain with an occurrence periodicity p = 0.1 and 1.0, alternative no. 1 (Legend: full line – continuous state, dotted line –maximum concentrations)

Conclusions

This paper presents two modelling studies, focused on stormwater runoff modelling from urbanized catchments through sewer system to the receiving water and analyses its effect on water quality in the receiving water.

Among other, the second case study (Hron river, Slovakia) analysed the possible strategies of stormwater management in urban catchments within the present legislative framework in Slovakia.

In both case studies, the pollution load on receiving water and its water quality deterioration takes relatively short time, so for the impact analysis the IDF (intensity – duration – frequency) curves are used, reflecting the short-term deterioration of water quality. The IDF curves are presented for all scenarios of urbanized catchment stormwater management.

Modelled short-term scenarios of water quality development show the vulnerability of the simulated section of the Drava river. Storm events on the urbanised catchment area causes short-term pollution loads on the Drava river, which have particularly unfavourable impacts on river biocoenosis. The simulation results of the second scenario refer to the need to resolve the stormwater management with methods of central or decentralized retention and detention to achieve decrease of the hydraulic and pollution loads of the receiving water.

The results of presented model study point out to the limitations of the current legislation approach, as well as the effectiveness of different stormwater management measures (scenarios) for urbanized catchments in terms of their impact on water quality on the receiving water.

Despite all the stated difficulties and problems, we think, that the imission method for evaluating the influence of waste water outflows from CSO is possible, the question of how we can apply it in practice and in the conditions, where the mathematical models are available, but there is a big lack of the necessary data.

When modelling the quality of water in the river Hron, we came to the conclusion that the pollution concentration in the river Hron isn't decreased only by the self-cleaning ability of the river, but also by the hydrology and the hydraulics of the stream, which is the dilution, mixing and dispersion. For example, after the CSO event, due to the lateral inflows (tributaries) of Hron, discharge in river doubles within a short river section (from profile Sliač to profile Žarnovica, approx. 60 km), due to this fact the concentration decreases to one half of the original concentration. This fact has a significant effect on the modelling of the concentration of dissolved oxygen – water with a large amount of oxygen flows from the tributaries to the river Hron (mountain areas, tributaries with big slope), which significantly improves the oxygen balance of the Hron river after the CSO event. This situation is relatively specific, even though it is possible to assume it on a large number of rivers and streams in Slovakia.

The results of the study described in this paper also show the effect of storm tanks in the sewage system of the urbanized catchment. The obtained result is that when a storm tank is included into a sewer system, the pollution concentration in the receiving water can be three to four times lower than in network schemes without storm tanks. Results of this modelling study also show that such modelling approach can be very useful for modelling of impacts on the water quality in receiving water and can be also very helpful in evaluation of various strategies and management practices focused on the receiving water quality improvement.

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Contribution

The first author – M. Sokáč declare involvement in conception and design of the work, result analysis and data interpretation in both studies as well as on data acquisition, model set-up, modelling the study case Hron (Slovakia). The second author – M. Jerković was involved in data acquisition, model set-up, modelling, result analysis and data interpretation in the case study Drava (Croatia).

Disclosure statement

The authors declare that they do not have any competing financial, professional, or personal interests from other parties.

References

Bara, M.;Velísková, Y. 2012. Analysis of water resources quality in upper part of Hron river, in *12th International Multidisciplinary Scientific Geoconference, SGEM 2012, Vol. III*, 17–23 June, Albena, Bulgaria, 561–568.

Bara, M.; Velísková, Y.; Takáčová, D. 2012. Evaluation of point-source pollution hazard in the upper Hron river basin, in *12th International Multidisciplinary Scientific Geoconference, SGEM 2012, Vol. III*, 17–23 June, Albena, Bulgaria, 655–662.

Krsnik, H., 2011. *Oborinske vode u kanalizacijskom sustavu odvodnje*: Diplomski rad (Diplomma work). GFV UNIZG Varaždin.

Mišík, M. 1998. *Examination of the geomorphologic and hydrodynamic parameters of river Hron. (in Slovak).* Bratislava: Water Research Institute.

SHMU. 1999–2009. *Surface water quality in Slovakia* [online], [cited 25 September 2009]. Available from Internet: www.shmu.sk

Sokáč, M. 2010. *The influence of discontinuous pollution sources on the receiving water bodies. (In Slovak).* Edition of scientific works of the Faculty of Civil Engineering ed. Bratislava: Slovak University of Technology.

Sztruhár, D.; Sokáč, M.; Holienčin, A.; Markovič, A. 2002. Comprehensive assessment of combined sewer overflows in Slovakia, *Urban Water* 4(3): 237–243, https://doi.org/10.1016/S1462-0758(02)00008-0