Analysis of the effects of a wastewater treatment plant failure on the Drava river water quality

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ANALYSIS OF THE EFFECTS OF A WASTEWATER TREATMENT PLANT FAILURE ON THE DRAVA RIVER WATER QUALITY

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Abstract: 1D model of the Drava River, between 00 + 543 rkm and 69 +118 rkm, was created by the MIKE 11 river-modeling tool. The aim of this model was to analyze the river water quality (WQ). Compared to the real Drava River section, the model was simplified to exclude any tributaries for the purpose of the water quality analysis. The inflow boundary was specified upstream, in addition to the WQ parameters (dissolved oxygen (DO), temperature, ammonia nitrogen, nitrate nitrogen, total phosphorus and orthophosphate, and five-day biochemical oxygen demand (BOD_5)). The water level and open boundary conditions were specified at the downstream end of section. The WQ parameters, mentioned earlier, were also defined at the Belišće wastewater treatment plant (WWTP) (54 + 373 rkm) and at the wastewater outlet near Osijek (14 + 580 rkm). The model was then used to simulate the effect on the WQ of the Drava River in a hypothetical extreme scenario: the 2-day failure of the Belišće WWTP. It was assumed that during this time untreated wastewater would be discharged into the river. After running the simulation, the resulting concentrations of DO, BOD_5, and ammonia nitrogen were analyzed. The results showed that, according to the concentration values of the untreated wastewater, the concentrations of BOD_5 and ammonia nitrogen rapidly increased and the DO concentrations rapidly decreased with the initiation of the WWTP failure. Immediately after the WWTP was repaired, the parameters returned to their pre-failure values. The resulting analysis of the effects of this scenario highlighted the self-purification ability of the Drava River.

Keywords: 1D river-modeling software MIKE 11; the Drava River; WQ parameters; self-purification process

ANALIZA UTJECAJA KVARA UREĐAJA ZA PROČIŠĆAVANJE NA KVALITETU VODE RIJEKE DRAVE

Sažetak: U programskom paketu MIKE 11 izrađen je jednodimenzionalni model rijeke Drave na dionici od 00+543 rkm do 69+118 rkm radi analize kakvoće vode rijeke Drave. Izrađena je pojednostavljena verzija promatrane dionice rijeke Drave bez pritoka. Za uzvodni rubni uvjet uneseni su protok i parametri kakvoće vode (otopljeni kisik, temperatura, amonijak, nitrati, otopljeni i partikularni fosfor te petodnevna biološka potrošnja kisika BPK_5), na nizvodnom presjeku definiran je vodostaj, dok je uvjet vezan za kakvoću vode ostao otvoren. Kao dio ulaznih podataka, također su određene koncentracije spomenutih parametara kakvoće vode na uređaju za pročišćavanje Belišće (54+373 rkm) i onih na položaju direktnog ispusta otpadne vode kod Osijeka (14+580 rkm). Modeliran je scenarij koji predstavlja ekstremnu situaciju: kvar na uređaju za pročišćavanje Belišće i njegov prestanak rada u trajanju od dva dana. Pretpostavljeno je da se tijekom tog razdoblja u rijeku Dravu ispušta nepročišćena voda s uređaja. Nakon modeliranja analizirane su dobivene koncentracije otopljenog kisika O_2, BPK_5, i amonijaka NH_3. Tijekom kvara, koncentracije BPK_5 i amonijaka naglo su se povećale, a otopljenog kisika smanjile u skladu s vrijednostima parametara nepročišćene vode, ali odmah po popravku uređaja dolazi do vraćanja parametara na prvotnu kakvoću vode rijeke Drave. Scenarij je ukazao na sposobnost samopročišćavanja rijeke Drave.

Ključne riječi: programski paket MIKE 11; rijeka Drava; parametri kakvoće vode; proces samopročišćavanja vode

1 INTRODUCTION

Rivers are an extremely valuable source of biological diversity and are a water management resource. These facts make them highly endangered by human activities and climate change impacts. The construction of wastewater treatment plants has significantly improved the quality of water bodies in Europe and, lately, Croatia. Many years of investment in the sewage system, combined with development of wastewater treatment technology, Europe's open waters have become much cleaner in recent decades. According to the European Environmental Agency, concentrations of biochemical oxygen demand (BOD) and total ammonium have decreased in European rivers from 1992 to 2012, mainly due to the general improvement in wastewater treatment [1]; however, each river has a self-purification capacity which contributes to the cleaning process to some extent. In actuality, the self-purification system and water quality formation is labile and easily transforms when environmental conditions change [2]. The role of self-purification increases with the deterioration of the natural water quality and the increased anthropogenic load on water bodies and streams. The self-purification of aquatic ecosystems and water quality formation is controlled by many factors [2].

There are a number of published investigations which prove that some substances present in wastewater can even contribute to the self-cleaning capacity of the river [3].

Hydrotechnical structures can also affect the environmental conditions of river ecosystems, including the self-purification capacity. For example, dam construction and operation has various impacts on the water quality and water self-purification capacity of different river segments in different periods [4].

The proposed research is related to the problems caused by the failure to treat wastewater and its impact on river water quality. Two aspects of the problem can be analyzed: the temporal impact of higher concentrations of dissolved oxygen, five-day biochemical oxygen demand, and ammonia nitrogen appeared to be due to the outflow of untreated wastewater and the spatial distribution and degradation of specific parameters along the river. The latter was obtained by mathematical modeling of the Drava River, performed by Sokáč et al (2015).The results of this short-term pollution simulation prove the strong influence of river hydrodynamics [5].

2 STUDY AREA

The Drava River, situated in southern Central Europe, originates in the Southern Alps in Italy and flows eastward through the Austrian state of Carinthia, Slovenia, and Croatia, where it partially forms a natural border between Croatia and Hungary. Approximately 20 km downstream of Osijek, it then joins the Danube River close to Aljmaš [6].

The 749-km-long Drava River has a catchment area of approximately 42 238 km^2. The river drops by approximately 1093 meters in elevation between its source at 1175 meters to its mouth at 82 meters. It has a glacial-nival flow regime, with the lowest flow in January and February and the highest in May and June [7].

The average discharge of the Drava River is 315 m^3/s where it enters Croatia, 530 m^3/s after the mouth of Drava's largest tributary (the river Mura), and approximately 580 m^3/s at Drava's mouth, which opens into the Danube River.

From a spatial point of view, modeling was conducted on the Drava River section between 69 + 118 and 00 + 543 rkm. In this section, the Drava flows through a number of cities such as Donji Miholjac, Bistrinci, Osijek, and Nemetin, where gauging stations for monitoring the water level and water quality of the river are also situated. The characteristic discharges recorded by the Donji Miholjac gauging station were Q_{min} = 152 m^3/s, Q_{av} = 535 m^3/s, and Q_{max} = 2288 m^3/s (1950 - 2013). Besides the wastewater treatment plant in Belišće, which is the main focus of this article (54 - 373 rkm), the other wastewater treatment plant in this Drava River section is located near Donji Miholjac. The wastewater discharge of the Osijek sewage system flows into the Drava River, downstream of the town, without any treatment. The locations of the gauging and water quality monitoring stations are presented in Figure 1.

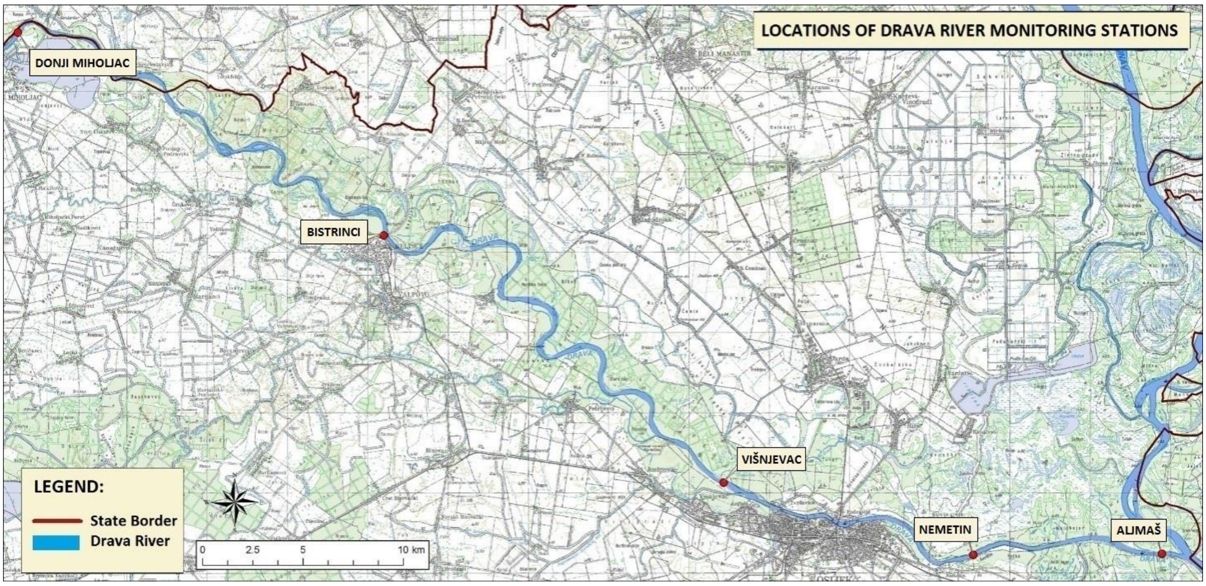
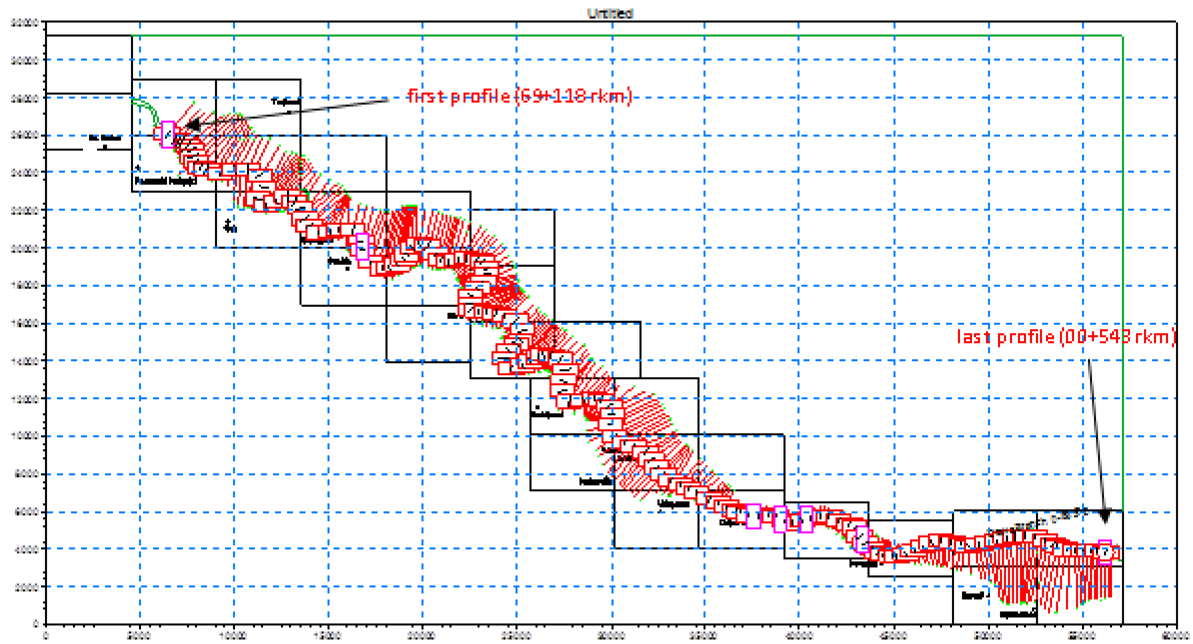


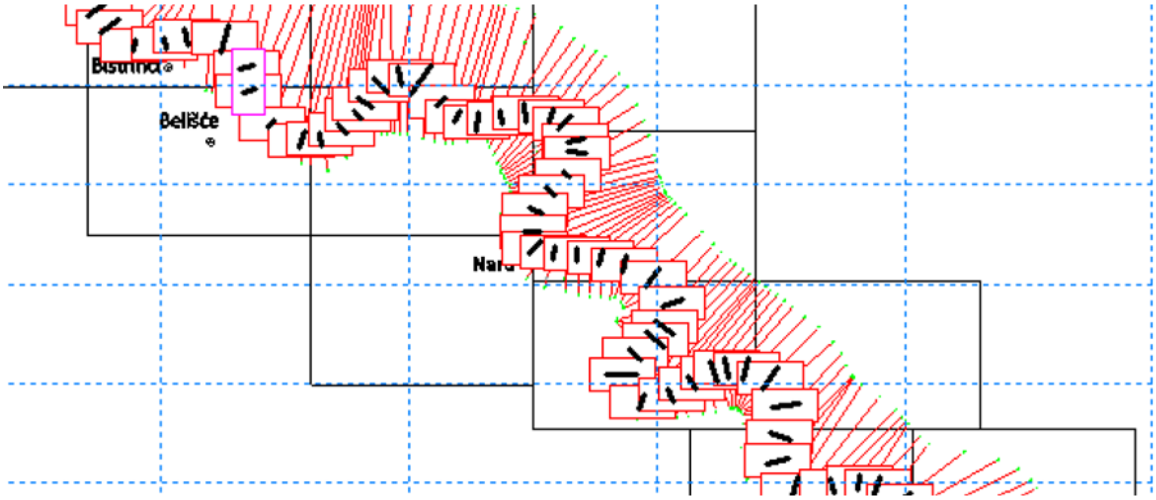
Figure 1 Locations of the gauging and water quality monitoring stations of the analyzed Drava River section

3 INITIAL AND BOUNDARY CONDITIONS

The definition of the riverbed was made by the graphic editor of the MIKE 11 modeling software. Digital maps, in DWG format, were used as a basis for entering all the riverbed direction points and pollution points. Cross-sectional profiles were defined approximately every 400 m using a local coordinate system (width and depth) (Figure 2). It was also necessary to enter the absolute elevation and river chainage (river kilometer, rkm) of each particular cross-section.



a)



b)

Figure 2 Ground plan of the modeled reach of the Drava River, with the locations of the defined cross-sections in the MIKE 11 software package (a) and Detail of the modeled reach of the Drava River with the locations of the defined cross-sections in the MIKE 11 software package (b)

River water quality models are usually used to resolve or predict adverse river conditions, which mainly occur at relatively low discharges. Therefore, for the quasi-steady state flow of minimum discharge, 152 m^3/s was considered (Donji Miholjac gauging station, 1950 - 2013). This flow-rate was defined as the upper boundary condition, at the 69 + 118 rkm profile. The lower boundary condition was defined as the constant water level of 79.00 m a.s.l., at the 00 + 543 rkm profile.

Since the aim of this work was to model the water quality, it was necessary to specify the concentrations of substances entering the modeled area as well. At the upper boundary profile, input water quality parameters were entered as C90 values, measured by the Donji Miholjac monitoring station (Figure 1), i.e. the values of the quality indicators corresponding to the 90% quantile of not exceeding probability (exceeding for oxygen, O_2) of the monitored substance concentrations in the river. The MIKE 11 software offers the possibility to choose between six model levels for water quality modeling, corresponding to different sets of state variables for the water quality and/or different descriptions of the transformation of the state variables in the river [8]. Model level 4 was used for this simulation, which allowed for the modeling of the concentrations of dissolved oxygen (O_2), ammonia nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), five day biochemical oxygen demand (BOD_5), and optional phosphorus (P) in dissolved and particular form. The values of the inserted water quality parameters are presented in Table 1.

Table 1 Water quality parameters defined as a part of the upstream boundary condition (Donji Miholjac monitoring station)

INDICATOR	UNIT	VALUE
Dissolved oxygen, O_2	mg/l	8.28
Temperature, T	°C	22.7
Ammonia nitrogen, NH_3-N	mg/l	0.29
Nitrate nitrogen, NO_3-N	mg/l	2.89
Total phosphorus, P	mg/l	0.17
Orthophosphate, P	mg/l	0.02
BOD_5	mg/l	5.57

From the water quality point of view, the downstream boundary condition, also defined at 00 + 543 rkm, has been formulated in the form of an open boundary condition, which is in fact entering the simulation without specific values, but maintains the overall balance of the contamination.

Finally, as a last initial condition, the outlet of the Osijek sewage system was defined at 14 + 580 rkm, with a discharge of 0.144 m^3/s, and the water quality parameters are shown in Table 2. Due to the lack of accurate information about the flow and water quality, the data used in the water quality modeling was provided empirically, based on the number of inhabitants and their average pollution load [9,10].

Table 2 Water quality parameters defined at the outlet downstream from Osijek

INDICATOR	UNIT	VALUE
Dissolved oxygen, O_2	mg/l	2
Temperature, T	°C	25
Ammonia nitrogen, NH_3-N	mg/l	15
Nitrate nitrogen, $N0_3$-N	mg/l	50
Total phosphorus, P	mg/l	27
Orthophosphate, P	mg/l	3
BOD_5	mg/l	719

4 CALIBRATION AND VERIFICATION

Model calibration is a process of adjusting the results of the model to match measured field conditions within some acceptable criteria. As mentioned previously, instead of defining the water quality parameters as part of the downstream boundary condition, the boundary was left open. After running the initial simulation, the resulting water quality parameters at the downstream end (dissolved oxygen (O_2) and BOD_5) were compared to the results measured at the Nemetin water quality monitoring station. The modeled results deviated from monitored results. In order to make the model simulate river behavior as accurately as possible, oxygen processes and degradation were altered until satisfactory results were obtained.

Table 3 Water quality parameters at 00 + 543 rkm, before and after calibration

INDICATOR	UNIT	BEFORE CALIBRATION	MONITORED VALUE	AFTER CALIBRATION
Dissolved oxygen O_2	mg/l	4.5	7.11	6.0
BOD_5	mg/l	1.8	7.26	2.5

Table 3 represents the values of the calibrated water quality parameters. The calibration of dissolved oxygen was successful, with only a 15 % deviation from the monitored value. Conversely, the calibrated BOD_5 values still deviated significantly from the monitored ones, most likely due to the rather simplified river model. By approximately 70 km along the modeled river section, only two pollution points (effluent of the Belišće WWTP and the direct sewage system outlet downstream of Osijek) and the upstream boundary condition were defined in the MIKE 11 software. In reality, there are more point and non-point sources of pollution along the modeled river section that contribute to higher values of biological oxygen demand.

Figure 3 presents the behavior of the modeled water quality parameters after calibration across the longitudinal profile. The water temperature maintains its value throughout the longitudinal profile, with a downstream value of approximately 22.7 °C. The concentration of dissolved oxygen at the downstream end is 6.0 mg/l. The five-day biological oxygen demand rises when treated wastewater from the Belišće WWTP is released into the river (circle) and at the untreated wastewater outlet, downstream of Osijek (rectangle). By the end of the analyzed river section, it had dropped to a value of 2.5 mg/l. The nitrate nitrogen values and ammonia nitrogen downstream values were 0.5 mg/l and 0.01 mg/l, respectively. The calibration of these parameters was not conducted, therefore their values dropped towards zero (open boundary condition).

Figure 3 Time series window showing the longitudinal profile of the modeled reach, with concentration values of the modeled water quality parameters after calibration

The main challenges in airborne study of the Mostar site are the low-altitude required for airborne operations and data acquisition over a heavily urbanized area. Operating in a congested area, with overhead infrastructure (e.g., power-lines) in a relatively narrow mountainous valley, requires careful mission planning and safety considerations to minimize any potential risk on the ground [9].

5 MODELED SCENARIO

The modeled scenario included the hypothetical failure of the Belišće WWTP (54 + 373 rkm), which would result in the discharge of untreated sewage wastewater directly into the Drava River. The WWTP was assumed to be out of order for two days (48 h). During that time, untreated wastewater, with a discharge of 0.097 m3/s, would have the water quality parameter values presented in Table 4. It was also assumed that for the time of the failure there would be no episodes of heavy precipitation, and that there would be no effects of the Danube River backwater included.

Table 4 Water quality parameters for treated and untreated wastewater at the Belišće wastewater treatment plant [11]

INDICATOR	UNIT	CONCENTRATIONS OF PARAMETERS IN TREATED WATER	CONCENTRATIONS OF PARAMETERS IN UNTREATED WATER
Dissolved oxygen, O_2	mg/l	1.95	1.95
Temperature, T	°C	26.01	26.01
Ammonia nitrogen, NH_3-N	mg/l	15	30
Nitrate nitrogen, $N0_3$-N	mg/l	7	24
Total phosphorus, P	mg/l	3.7	8
Orthophosphate, P	mg/l	0.6	1.11
BOD_5	mg/l	393.2	1867.4

Figure 4 presents a schematic of the analyzed Drava River section. Numbers 1, 2, 3, and 4 represent cross-sections of the boundary conditions (1 and 4) and pollution sources (2 and 3) defined for the chosen modeling scenario:

1 ~ Upstream boundary condition → discharge and water quality parameters defined at 69 + 118 rkm

2 ~ Discharge and water quality parameters of the untreated sewage wastewater from the Belišće WWTP (54 + 373 rkm)

3 ~ Osijek sewage wastewater outlet (downstream of Osijek) (14 + 580 rkm)

4 ~ Downstream boundary condition → water level and open boundary condition defined at 00 + 543 rkm

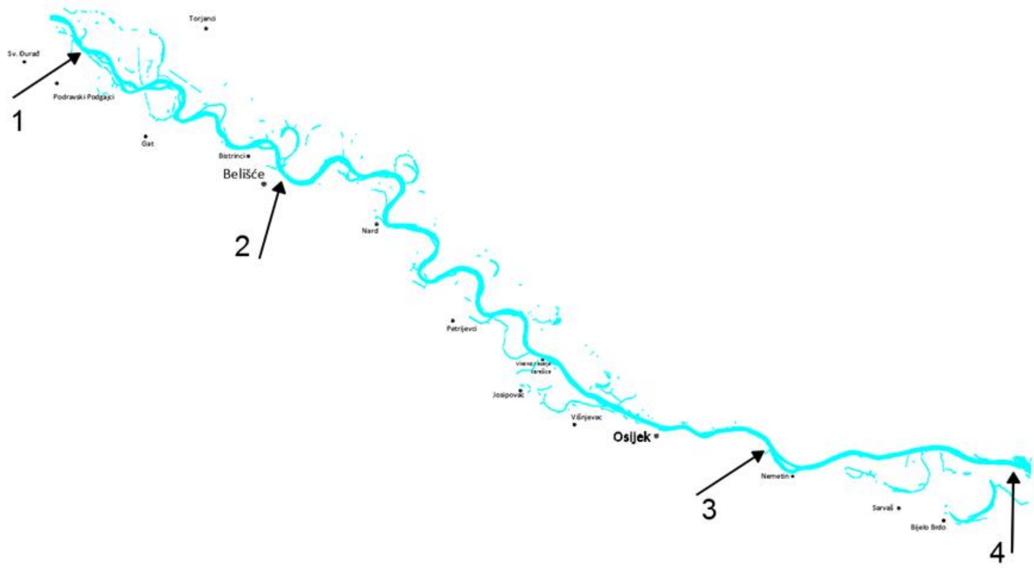


Figure 4 Schematic of the Drava River section showing the specified input locations

6 RESULTS AND DISCUSSION

As previously stated, the two-day long fictional failure of the Belišće WWTP was modeled. The main goal of this simulation was to understand how untreated wastewater from the WWTP would affect the Drava River in terms of its water quality. The spatial influence of the WWTP failure on the Drava River was analyzed, along with the temporal concentration change of different water quality parameters. The virtual failure occurred at midnight on January 16, 2015, and lasted 48 h. This winter period was chosen because the lowest discharges appear in this part of the year, and the river is more vulnerable to water quality deterioration. During that time, untreated industrial and municipal wastewater started to flow into the river, which led to a significant increase in pollutant concentrations.

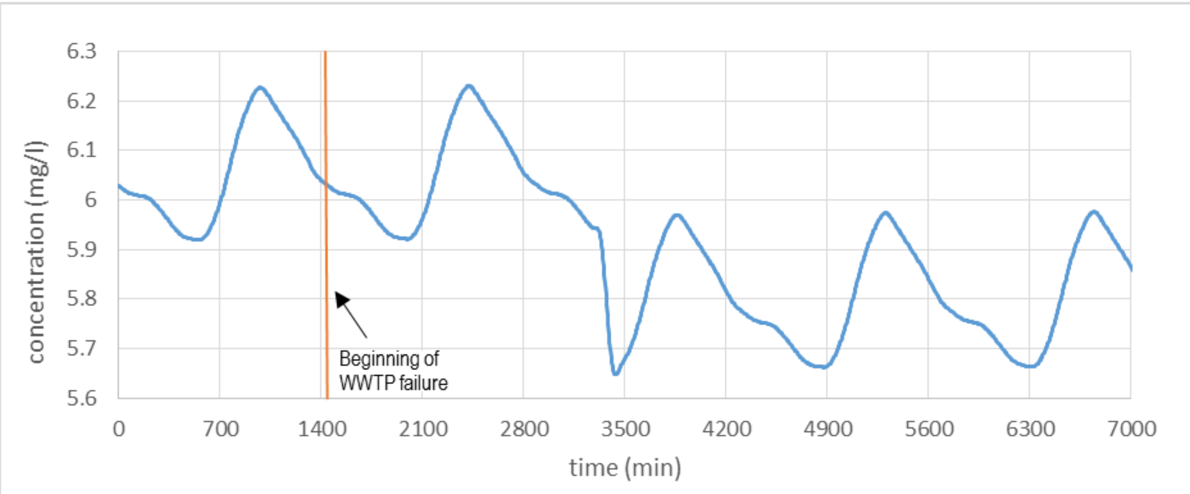


Figure 5 Change in dissolved oxygen concentration at 00 + 543 rkm in the period between January 14, 2015 (11:59 p.m.) and January 19, 2015 (11:59 p.m.)

Figure 5 illustrates the behavior of the dissolved oxygen concentration at the end of the analyzed river section (00 + 543 rkm) during a four-day period: a day before the failure, the two days during the failure, and one day after reparation. A rapid decrease in dissolved oxygen can be noticed after approximately a day and a half, 2000 minutes after the failure (Figure 5). Because the observed cross-section is at the downstream end, 54 km away from the WWTP, it is logical to presume it took a certain amount of time for the lower quality wastewater to reach and flow through the analyzed cross-section. The graph also shows oscillations in dissolved oxygen concentrations as a result of mixing with and transportation by natural river water.

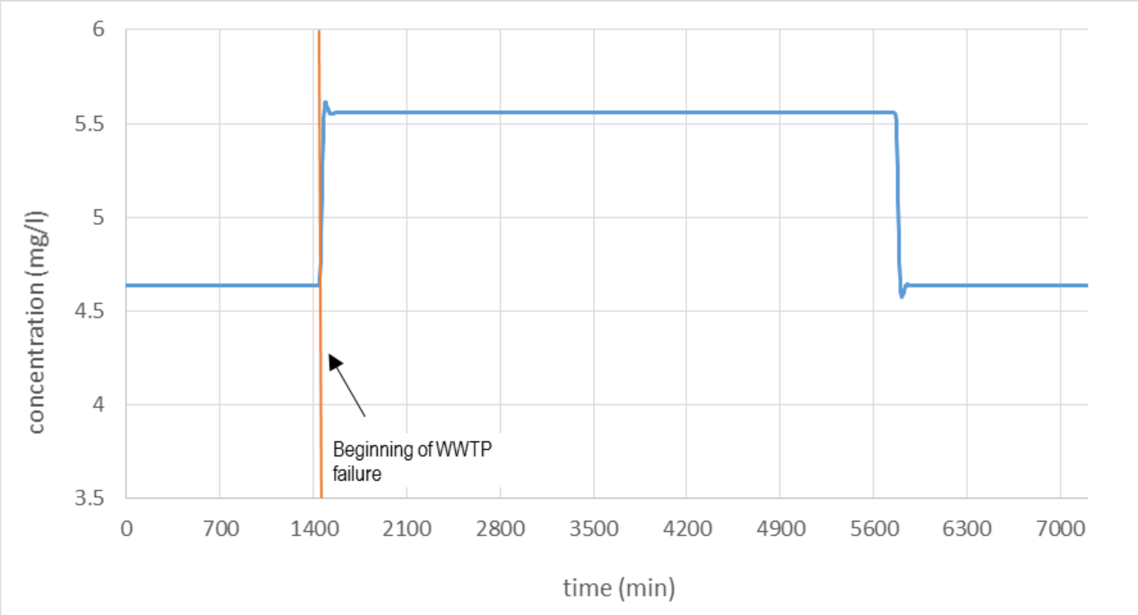


Figure 6 Change in BOD_5 concentration at 53 + 360 rkm in the period between January 14, 2015 (11:59 p.m.) and January 19, 2015 (11:59 p.m.)

Figure 6 presents the BOD5 concentration change during a four-day period: a day before the failure, the two days during the failure, and one day after. There is a sharp increase in BOD_5 concentration at 1441 min, which is the time when failure occurred (midnight of January 16, 2015). Concentrations changed from 4.633 mg/l, prior to failure, to 5.556 mg/l, during failure. When the WWTP was repaired, the concentration immediately returned to the values observed before the failure. Although the WWTP failure caused an untreated wastewater flow with BOD_5 as high as 1867.64 mg/l, the concentrations of this parameter only increased by 0.923 mg/l in the river, since the WWTP is only discharging a small volume of water compared to that of the Drava River.

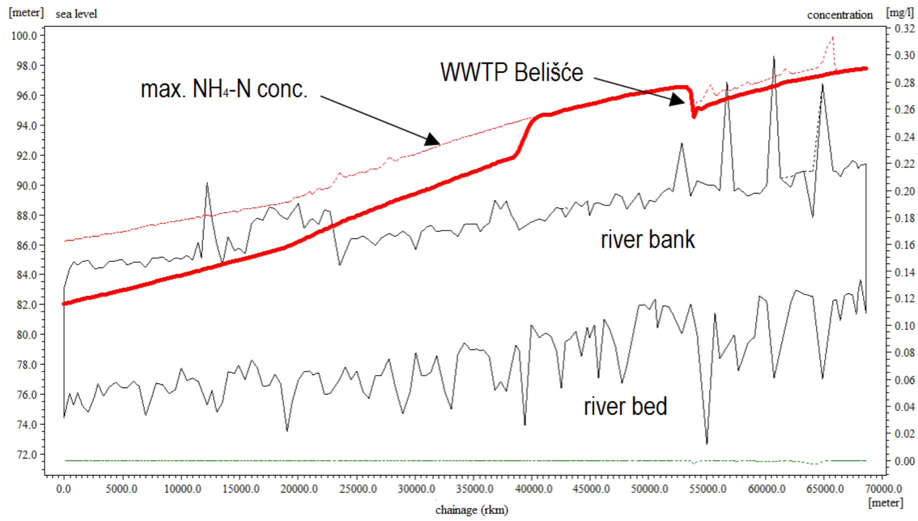


Figure 7 Spatial distribution of ammonia nitrogen concentration (NH3-N) (mg/l) after the Belišće WWTP failure

Figure 7 shows the situation on January 17, 2015, at 7:39 a.m., more than 7 h after the WWTP failure. The increase of the ammonia nitrogen concentration has already been distributed in the river section downstream of the WWTP (approximately from 40 + 000 rkm to 55 + 000 rkm). The increased pollution concentration was then spread out across the whole downstream river section from the Belišće WWTP (see the line of maximum concentrations shown in Figure 7).

7 CONCLUSION

After running the simulation, using the MIKE 11 software, of the hypothetical scenario of the WWTP failure and analyzing the resulting concentrations of dissolved oxygen, BOD_5, and ammonia nitrogen, it can be concluded that the Drava River has a distinct self-purification capacity, even during low flow discharges, and is able to receive higher concentrations of pollutants. According to these results, the Drava River can reach its initial quality status in rather a short time period because the modeled pollution was biodegradable organic matter and had acceptable concentration values. However, this model of the Drava River was simplified, without the inclusion of the qualitative or quantitative impacts of tributaries or non-point pollution sources. Nevertheless, the results achieved show that mathematical modeling is an appropriate tool for modeling complex water quality processes in natural watercourses. Using the described/presented method, it is possible to model the impacts of various pollution control measures and their resulting consequences on water quality. The presented modeling results may be used as a motivation for further research and analysis.

References

[1] European Environment Agency, 2013: Environmental Indicators report 2013, pp. 59–74, http://dx.doi.org/10.2800/94121
[2] Ostroumov, S.A. 2005: On some issues of maintaining water quality and self-purification. Water Resources 32(3), pp. 337–346, http://dx.doi.org/10.1007/s11268-005-0039-7
[3] Karrasch, B.; Parra, O.; Cid, H.; Mehrens, M.; Pacheco, P.; Urrutia, R.; Valdovinos, C.; Zaror, C. 2006: Effects of pulp and paper mill effluents on the microplankton and microbial self-purification capabilities of the Biobio River, Chile, The Science of the Total Environment, 359(1-3), pp. 194-208, http://dx.doi.org/10.1016/j.scitotenv.2005.03.029
[4] GuoLiang, Wei.; ZhiFeng, Yang.; BaoShan, Cui.; Bing, Li.; He, Chen, JunHong Bai, ShiKui Dong, 2009: Impact of Dam Construction on Water Quality and Water Self-Purification Capacity of the Lancang River, China, Water Resour Manage 23, pp. 1763–1780, http://dx.doi.org/10.1007/s11269-008-9351-8
[5] Sokač, M., Jerković, M., Veliskova, Y., Tadić, L. (2016): Mathematical Simulation of short term water quality development in the Drava River, Acta Hydrologica Slovaca Journal (accepted for publication)
[6] Tockner, K., Uehlinger, U., Robinson T. C. 2009: Rivers of Europe, First Edition, Academic Press, London, pp. 59–113, ISBN 978-0-12-369449-2.
[7] Bregović A., Gradski muzej 2004.: Život uz Dravu nekad i danas, Gradski muzej Varaždin, Varaždin, ISBN 9536877082
[8] DHI Water and Environment, 2003.: MIKE 11, A modelling system for Rivers and Channels, User Guide, pp. 343-344 (https://www.tu-braunschweig.de/Medien-DB/geooekologie/mike11usersmanual.pdf) (Accessed 14.4.2016.)
[9] Sztruhár, D., Sokáč, M., Holienčin, A. And Markovič, A., 2002: Comprehensive assessment of combined sewer overflows in Slovakia. Urban Water, 4(3), pp. 237-243, http://dx.doi.org/10.1016/S1462-0758(02)00008-0
[10] Sokáč, M. 2010: The influence of discontinuous pollution sources on the receiving water body (in Slovak). Slovak University of Technology, Bratislava, Faculty of Civil Engineering, Edition of scientific works, ISBN 978-80-227-3328-1
[11] Hidroing Osijek i SCE Nantes, 2012: Eastern Slavonia - Valpovo & Belišće water supply & sewerage project, preparation of investment projects under EU financing for water supply and sewer systems improvement, Feasibility study