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NUMERICAL SIMULATIONS IN THE MALA NITRA STREAM BY 1D MODEL

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Abstract. The development of the computer technologies enables us to solve the ecological problems in water management practice very efficiently. Hydrodynamical models which simulating transport of pollution in surface water are very demanding on input data and calculation time, but on the other side, they are able to simulate detailed effect of dispersion in surface waters. The paper deals with 1-dimensional numerical model HEC-RAS and its response on various values of dispersion coefficient. This parameter is one of the most important input data for simulation of pollution spreading in streams. Getting fair value, however, is in practice very difficult. One option is the most accurate simulation of tracer experiments carried out on the ground on the natural surface flow. For the pilot application was selected flow Small Nitra. Of longitudinal dispersion coefficient in the flow, or the flow of a similar nature (with and limit the rate of flow), were in the range 0.05 to 2.5 $m^2 \cdot s^{-1}$. The next task was carrying out the model sensitivity analysis, which means to evaluate input data influences, especially longitudinal dispersion coefficient, on outputs computed by 1-dimensional simulation model HEC-RAS. Sensitivity analysis model HEC-RAS also showed its adequate response to changes of the input parameter. Given the present results it can be stated that the HEC-RAS model responds to changes in the values of the longitudinal dispersion coefficient appropriately. HEC-RAS model has demonstrated its applicability to simulation of pollution in streams, and therefore is an appropriate tool for decision making related to the quality of water resources.

Key words: surface flows, spread of pollution, longitudinal dispersion coefficient, model HEC-RAS, sensitivity analysis

INTRODUCTION

The Water Framework Directive (WFD) is a key initiative aimed at improving water quality throughout the EU. It applies to rivers, lakes, groundwater, and coastal waters. The Directive requires an integrated approach to managing water quality on

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a river basin basis; with the aim of maintaining and improving water quality. The Directive requires that management plans be prepared on a river basin basis and specifies a structured approach to developing those plans. It requires that a programme of measures for improving water quality be brought into effect by 2012 at the latest. River Basin Management Plans are to be prepared and renewed in six year cycles and the first plans cover the period to 2015.

The development of the computer technologies enables us to solve the ecological problems in water management practice very efficiently. The mathematical and numerical modelling allows evaluating various situations of spreading of contaminants in the rivers (from everyday wastewater disposal up to the fatal discharges of the toxic substances) without immediate destructive impact to the environment. There has been developed a lot of mathematical and numerical models to simulate the water quality. These models are able to simulate the real situation at streams, however the range of the reliability and accuracy of the results is very wide [Abbott 1978, Jolánkai 1992, Pekárová and Velísková 1998, Říha et al. 2000, Rankinen et al. 2002, McInstyre et al. 2005].

When a conservative pollutant is released into a river, physical processes such as advective transport and dispersion determine the movement and change in concentration of the pollutant. The transport process of the pollutant can be conveniently viewed as being composed of three stages. In the first stage, the pollutant is diluted by the flow in the channel because of its initial momentum. In the second stage, the pollutant is mixed throughout the cross-section of the river by turbulent transport processes. And in the third stage, after the cross-sectional and the vertical mixing is complete, longitudinal dispersion tends to erase any longitudinal variation in the pollutant concentration [French 1986]. So, from this moment it is possible to simulate pollution transport one-dimensionally.

This study deals with evaluation and quantification of input data influences on outputs of dispersion simulation models, especially with longitudinal dispersion coefficient impact as one of the main parameter of dispersion process in 1-D simulations. This publication is the result of the project APVV-0274-10, which is concentrated on the evaluation of abilities, limitations, strengths and weaknesses of the current level of how to solve the qualitative problems of surface flows, with a focus mainly on approach for hydrodynamic dispersion in surface water. It is also the result of the project implementation ITMS 26240120004 Centre of excellence for integrated flood protection of land supported by the Research & Development Operational Programme funded by the ERDF.

MATERIAL AND METHODS

The transport of pollution in surface and subsurface waters is generally described with the advection-dispersion equation (ADE). The ADE distinguishes two transport modes: advective transport as a result of passive movement along with water, and dispersive/ /diffusive transport to account for diffusion and small-scale variations in the flow velocity as well as any other processes that contribute to solute spreading. ADE comes from the mass balance equation [Van Genuchten et al. 2013], which can be formulated in a general manner by considering the accumulation or depletion of solute in a control volume over time as a result of the divergence of the flux (i.e., net inflow or outflow), possible reactions, and the injection or extraction of solute along with the fluid phase. A variety of solute source or sink terms may need to be implemented in the ADE. Many other processes such as biodegradation or inactivation, radioactive decay, and production may affect the contaminant concentration. For relatively simple transport scenario's, the ADE can be represented in the one-dimensional form:

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} - u \frac{\partial C}{\partial x} - \mu C + \vartheta \tag{1}$$

where:

u – the flow velocity, $\mathrm{m \cdot s^{-1}}$,

C – the pollution concentration expressed as mass per unit volume of water, $\mathrm{kg \cdot m^{-3}}$,

D_x – the longitudinal dispersion coefficient accounting for the combined effects of ionic or molecular diffusion and hydrodynamic dispersion, $\mathrm{m^2 \cdot s^{-1}}$,

x – the longitudinal distance/coordinate, m,

μ – a general first-order decay rate, $\mathrm{s^{-1}}$,

ϑ – a zero-order production term, $\mathrm{kg \cdot m^{-3} \cdot s^{-1}}$.

Longitudinal dispersion is difficult to determine as it depends upon too many variables and their nonlinear inter-relationships. A large disparity exists between the values of dispersion coefficients obtained for idealized and simplified systems (such as irrigation channals) and for rivers [Rutherford 1994]. Such a disparity suggests that the processes contributing to dispersion in rivers are not well understood.

The knowledge of accurate value of longitudinal dispersion coefficient D_x is important for determining self-purifying characteristics of streams, devising water diversion strategies, designing treatment plants, intakes and outfalls, and studying environmental impact due to injection of polluting effluents into the stream [David et al. 2002].

Investigated part of the stream was approximately 1340 m long stream – the Mala Nitra River, situated at the southwest part of Slovakia. The Mala Nitra River is a small, modified stream with basin area $A = 76.6\ \mathrm{km^2}$. Discharge is regulated by operation with the weir located 15 km upstream in bifurcation point with the Nitra River. Mean annual discharge is $0.550\ \mathrm{m^3 \cdot s^{-1}}$.

Cross sections had originally double-trapezoidal shape with bed width $b = 4$ m, height 2,5 m and bank slope 1 : 2 with concrete revetments. However, the channel geometry along the stream has been slightly changed by natural morphological processes during the years. There exists relatively long straight part with small water depths (max. 0.65 m). Longitudinal bed slope is 1,5‰. Measured discharge value during field experiments were $0.46\ \mathrm{m^3 \cdot s^{-1}}$. On base of field measurements of water level between balanced cross sections the roughness coefficient ($n = 0.035$) was determined by energy grade line slope calculation. Tracer experiments, during which the tracer spreading in the current stream hydraulic conditions was monitored, were done in Velky Kyr settlement region (N+48°10'50", E+18°09'19"). The solution of common salt (NaCl) was used as a tracer. A single dose of tracer was 2 kg NaCl in 50–60 l of water, representing approximately 11% of the actual discharge in the stream. The time course of tracer concentration, channel morphology and basic hydraulic parameters of water flow were monitored in several cross-sections downstream from injection point and lasted until the background concentration value was reached. Velocity distribution and discharge were determined on base of measurements with Acoustic Doppler Velocimeter, Sampling cross-section profiles were at 60, 120, 180, 410 and 1340 m distance from injection point (Fig. 1). Concentration measurements were carried out in 6 points of each monitored cross sections profiles in given sampling of the river. On base of field measurement results there were determined the values of longitudinal dispersion coefficient. The next aim was the evaluation of input data influences, especially longitudinal dispersion coefficient, on outputs of 1-D simulation model HEC-RAS ver. 4.1 (USACE, 2010), which can simulate the dispersion in streams. This model was developed by the United States Army Corps of Engineers and it is designed to modelling complex phenomena and processes occurring in surface waters of the river systems. This software allows the calculation of one-dimensional steady non-uniform and unsteady flow, solving of hydraulic engineering tasks, design of modifications stream channels, design of water works, pollution transport modelling, modelling of temperature of surface water, bed load transport, modelling of accumulation-erosion processes in stream channels, etc. An advection-dispersion module is included with the used version of HEC–RAS. This new module uses the QUICKEST-ULTIMATE explicit numerical scheme to solve the one-dimensional ADE using a control volume approach.

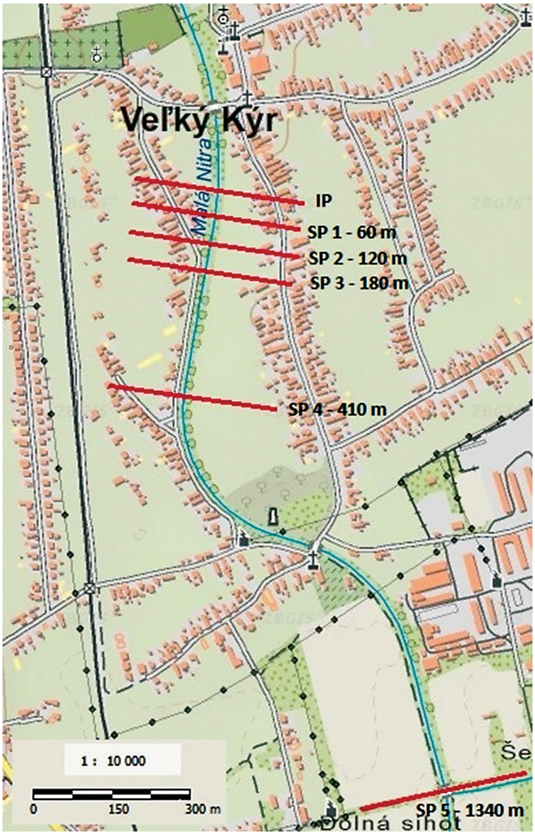

Fig. 1. Location of the tracer injection and sampling points on the Mala Nitra River

RESULTS AND DISCUSSION

As mentioned above, the longitudinal dispersion coefficient is one of the most important input data for the simulation model of dispersion in a stream. On the other hand, determination of this parameter is very difficult as it depends upon too many variables and their nonlinear inter-relationships. Various approaches to determine this value exist: from the own experience or that from the references, over the qualified estimates, up the special calculations application. Empirical relations have often limited validity: values given by them are applicable only in specific conditions and in some cases it is not possible to use any of them. Therefore it is necessary to give attention to conditions in which the relations were obtained and if those conditions were approximately consistent with conditions in which the relations will be applied. Next way how to find out value of D_x is an application of one-dimensional simulation model. In this case, the fluctuations of D_x values are more significant. It can be supposed that the model simulates the flow conditions in more details, so the obtained values would be more accurate.

Firstly, we use monitored and measured data for determination of longitudinal dispersion coefficient. We have simulated tracer experiments with various values of longitudinal dispersion coefficient by model HEC-RAS. Results of simulations were compared with measured data obtained during field measurements. Minimal difference determines the value of the longitudinal dispersion coefficient for each one of experiments. Fig. 2 presents a comparison of concentration distributions obtained with HEC-RAS model and the results measured during tracer experiment in sampling cross-section profiles at distance 60 m, 120 m and 180 m from injection point, considering 10 kg of NaCl injected in the river channel for discharge 0.230 $m^3 \cdot s^{-1}$, average flow velocity of 0.17 $m \cdot s^{-1}$ and computational cell size 2 m.

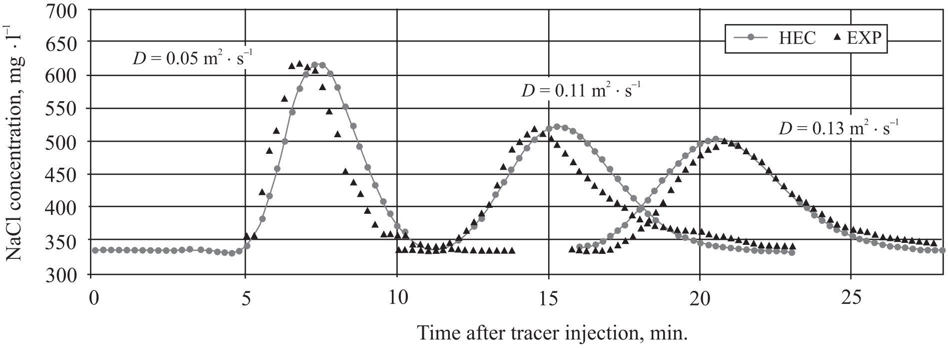

Fig. 2. Comparison of concentration distributions obtained with HEC-RAS model and the results measured during tracer experiment in sampling points at distance 60 m, 120 m and 180 m from the injection point

The range of mean values of the longitudinal dispersion coefficient determined on the base of numerical model application was 0,05–0,13 $m^2 \cdot s^{-1}$, for the other flow condition it was 0,07–2,5 $m^2 \cdot s^{-1}$ or 0,28–0,6 $m^2 \cdot s^{-1}$. It is convenient to mention, that these ranges of values are closer to values obtained in laboratory flume than in natural conditions [Fischer

1979, Říha 2000]. Next, the values of this coefficient obtained by the model seem to be variable along investigated part of stream. It can be in consequence the model simulates the flow conditions in details and partially takes into consideration also transverse spreading through velocity distribution. The results from HEC-RAS could also indicate that so-called mixing length (length along which the tracer spreads across whole width of a stream) was not estimated right. In Fig. 3 there is the next result of modelled situation in the Mala Nitra stream. It can be seen an asymmetrical shape of observed solute concentration curve, characterized by steep leading edges and prolonged tails (especially at 1340 m from injection point). It is probably caused by transient storage occurrence when portions of transported solute become temporarily isolated from main stream in channel [De Smedt et al. 2005]. In our case it is due to existence of aquatic vegetation and dead zones in places of the bank failure in the downstream reach of the river. On base of obtained results we may state that transient storage is important factor that is not included in water quality module of HEC-RAS software that in cases of some specific conditions (relatively narrow river channel with dense aquatic vegetation) may affect model outputs.

The next goal was to evaluate the impact of longitudinal dispersion coefficients as an input data on computed outputs of 1-D simulation model HEC-RAS. We simulated the pollution spreading in the Mala Nitra stream during the same flow conditions (discharge and velocity distribution), with the same tracer/mass injection volume, only values of longitudinal dispersion coefficient were different. For this numerical experiment we chose three different values: 0.04 $m^2 \cdot s^{-1}$, 0.4 $m^2 \cdot s^{-1}$ and 4 $m^2 \cdot s^{-1}$.

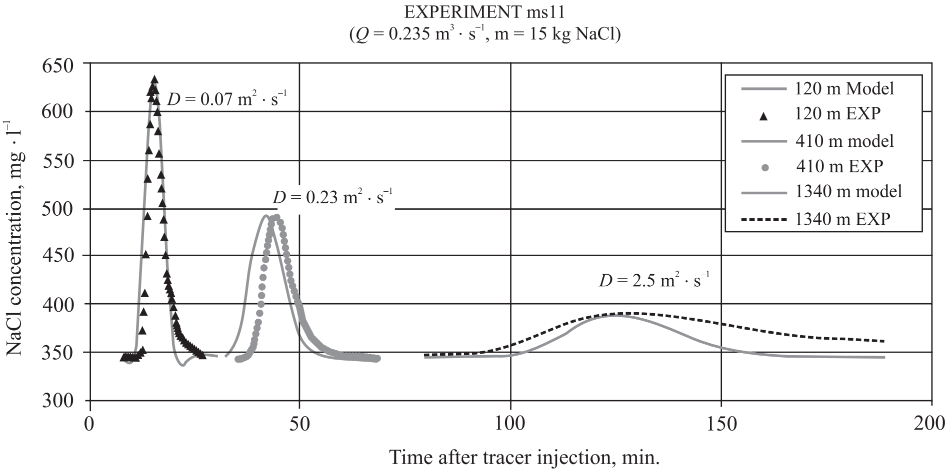

Fig. 3. Concentration distribution during the experiment time – comparison of experiment results and results of numerical model HEC-RAS in sampling cross-section profile at distance 120 m, 410 m and 1340 m from injection point

Outputs from the model were compared with measured values from experiment with similar conditions. As it can be seen in Fig. 4, model HEC-RAS responds to D_x value changes adequately, suitably and proportionately. Besides, results of these kind of numerical experiments show that lower value of D_x (0,04 $m^2 \cdot s^{-1}$) is more acceptable at beginning part of monitored length of the stream, with distance from injection point the value of longitudinal dispersion coefficient increases. However, the value 4 $m^2 \cdot s^{-1}$ looks quite a high one and for this stream and flow conditions is unreal and unsuitable.

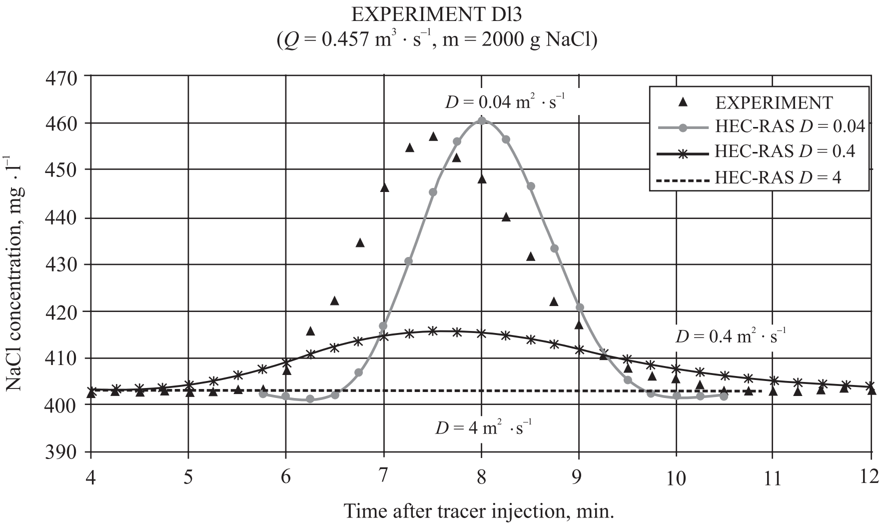

Fig. 4a. Concentration distribution by HEC-RAS model – discharge 0.457 $m^3 \cdot s^{-1}$; injection amount 2 kg NaCl; distance from injection point 100 m

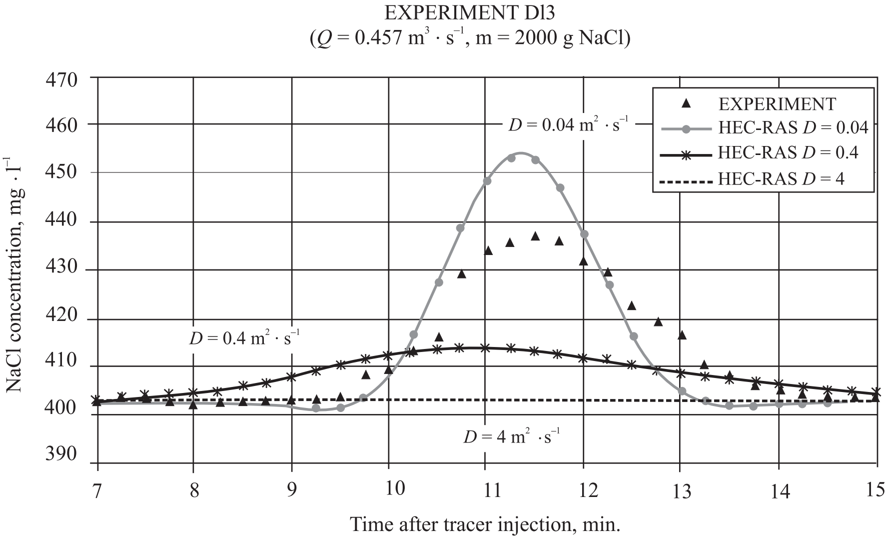

Fig. 4b. Concentration distribution by HEC-RAS model – discharge 0,457 $m^3 \cdot s^{-1}$; injection amount 2 kg NaCl; distance from injection point 150 m

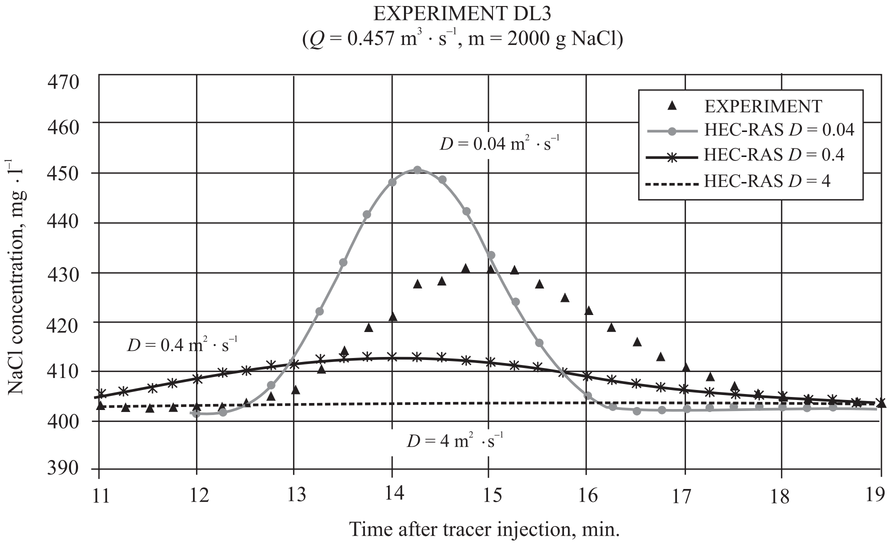

Fig. 4c. Concentration distribution by HEC-RAS model – discharge 0,457 $m^3 \cdot s^{-1}$; injection amount 2 kg NaCl; distance from injection point 200 m

The application of model HEC-RAS demonstrated eligibility for simulation of pollution spreading in streams, which means that it is a suitable tool allowing a reasonable support in decision making process connected to river water quality management. Although model is able to predict the parameters for practical applications, its use without previous calibration has limited reliability. This task is very urgent in rivers with many natural factors that may influence the longitudinal dispersion e.g. in-stream vegetation, geometric irregularities or existence of any kind of dead zones.

CONCLUSION

The issue of pollution of natural waters is very timely and increasingly gets the attention. Slovakia's accession to the EU as a result of the adoption of the principles of Directive no. 2000/60/EC of the European Parliament and of the Council of 23 October 2000 on the establishment of a framework for progress in the field of water policy (EU Water Framework Directive) changed virtually all legislation in the field of water management, including the protection of the quantity and quality of water resources. The Directive defines a strategy for improving water quality and its implementation is binding for the Slovak Republic. Solve environmental problems of water management practice allows very efficient computing. By using mathematical modeling can assess the different situations spread of pollutants in streams (from the normal discharge of waste water to the emergency escape of toxic substances), without direct damage to the environment. The paper deals with the analysis of the application of one-dimensional numerical model HEC-RAS to solve these types of problems. In numerical models of hydraulic type that address pollution transport in surface streams is one of the important input parameters, the value of dispersion coefficient. Getting fair value, however, is in practice very difficult. One option is the most accurate simulation of tracer experiments carried out on the ground on the natural surface flow. For the pilot application was selected flow Small Nitra. Of longitudinal dispersion coefficient in the flow, or the flow of a similar nature (with and limit the rate of flow), were in the range 0.05 to 2.5 $m^2 \cdot s^{-1}$. Sensitivity analysis model HEC-RAS also showed its adequate response to changes of the input parameter. Given the present results it can be stated that the HEC-RAS model responds to changes in the values of the longitudinal dispersion coefficient appropriately. HEC-RAS model has demonstrated its applicability to simulation of pollution in streams, and therefore is an appropriate tool for decision making related to the quality of water resources.

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SYMULACJA LICZBOWA W STRUMIENIU MAŁA NITRA PRZY UŻYCIU MODELU 1D

Streszczenie. Rozwój technologii komputerowej umożliwia bardzo skuteczne rozwiązywanie problemów ekologicznych w praktycznym zarządzaniu zasobami wodnymi. Modele hydrodynamiczne symulujące transport zanieczyszczeń w wodach powierzchniowych są bardzo wymagające, jeśli chodzi o dane wejściowe i czas obliczeniowy, a z drugiej strony są w stanie symulować szczegółowy wpływ dyspersji w wodach powierzchniowych. Praca dotyczy jednowymiarowego modelu numerycznego HEC-RAS i jego reakcji na różne wartości współczynnika rozproszenia. Parametr ten jest jedną z najważniejszych danych wejściowych w przypadku symulacji rozprzestrzeniania się zanieczyszczeń w strumieniach. Uzyskanie rzetelnych danych okazuje się jednak w praktyce bardzo trudne. Jedną z opcji jest najbardziej dokładna symulacja doświadczeń wskaźnikowych przeprowadzanych na obszarze naturalnych cieków powierzchniowych. Niewielki ciek o nazwie Mała Nitra został wybrany jako aplikacja pilotażowa. Jako współczynnik rozproszenia wzdłużnego cieku lub cieku o podobnym charakterze (pod względem prędkości cieku) przyjęto zakres od 0,05 do 2,5 $m^2 \cdot s^{-1}$. Kolejnym zadaniem było wykonanie analizy modelu czułości, co oznacza określenie wpływu danych wejściowych, a w szczególności współczynnika rozproszenia wzdłużnego, na dane wyjściowe wyliczone przez jednowymiarowy model symulacji numerycznej HEC-RAS. Analiza czułości modelu HEC-RAS pokazała także jej adekwatną odpowiedź na parametry danych wejściowych. Biorąc pod uwagę uzyskane wyniki, można stwierdzić, że model HEC-RAS reaguje odpowiednio na zmiany wartości współczynnika rozproszenia wzdłużnego. Model HEC-RAS okazał się przydatny do symulacji zanieczyszczeń w strumieniach i dlatego jest właściwym narzędziem przy podejmowaniu decyzji dotyczących jakości zasobów wodnych.

Słowa kluczowe: cieki powierzchniowe, rozprzestrzenianie się zanieczyszczeń, współczynnik rozproszenia wzdłużnego, model HEC-RAS, analiza czułości

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