

**APPLICATION OF HEC-RAS WATER QUALITY MODEL TO ESTIMATE
CONTAMINANT SPREADING IN SMALL STREAM**

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Abstract

The paper presents study of some aspects of HEC-RAS water quality model connected to simulation of contaminant transport in small stream. Authors mainly focused on one of the key tasks in process of pollutant transport modelling in streams - determination of the dispersion characteristics represented by longitudinal dispersion coefficient D . Different theoretical and empirical formulas have been proposed for D value determination and they have revealed that the coefficient is variable parameter that depends on hydraulic and morphometric characteristics of the stream reaches. Authors compare the results of several methods of coefficient D assessment, assuming experimental data obtained by tracer studies and compare them with results optimized by HEC-RAS water quality model. The analyses of tracer study and computation outputs allow us to outline the important aspects of longitudinal dispersion coefficient set up in process of the HEC-RAS model use.

Key words: longitudinal dispersion coefficient, HEC-RAS, water quality modeling

INTRODUCTION

The present legislation evaluating the quality of water bodies in Slovakia is based on implementation of the Water Framework Directive (2000/60/ES) (Torma and Fazekášová 2007). Concerning this Directive the monitoring of chemical and ecological parameters of surface waters is required and goal represents evaluation of anthropogenic impact on the waters. It does not refer to river bed only, but simultaneously the state of the environment near to stream is taken into consideration. Climate and hydrological changes, modification of physical conditions in streams affect, inter alia, transport phenomena including pollution propagation in stream channel (Babošová et al. 2006; Boltižiar, Michaeli & Mojses 2012; Čimo and Šiška 2006; Šiška and Čimo 2006). The water quality predictions affect uncertainty in inputs related to the analyzed transport process [Igaz et al. 2008; Igaz, Čimo & Horák 2010; Macura et al., 2012). Computational fluid mechanics advances of the past few decades enable new approaches in water quality modelling and intensive development of environmental fluid mechanics. A major connection between this latter field and pure fluid mechanics lies in the determination of terms needed to specify the transport and mixing rates for a given parameter of interest (Rubin, and Atkinson, 2001).

The theory of pollution dispersion in water

The basic governing equation based on the principle of conservation of mass and Fick's law is the Advection-Dispersion Equation (ADE). The main characteristics of dispersion are dispersion coefficients in relevant directions. Determination of the dispersion characteristic is the key task for solving problem of pollutant transport in streams and modelling of water quality. The common description of the mass spreading in water is form of one-dimensional ADE (Velísková and Sokáč 2011):

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} - \frac{\partial}{\partial x} \left[AD \frac{\partial C}{\partial x} \right] = -AKC + C_s q \quad (1)$$

where:

- C - mass concentration (mg.l⁻¹)
- D - longitudinal dispersion coefficient (m².s⁻¹),
- A- discharge area in a stream cross-section (m²),
- Q - discharge (m³.s⁻¹),
- K - rate of growth or decay of contaminant (s⁻¹),
- C_s - concentration of a source (mg.l⁻¹),
- q - discharge of a pollution source (m².s⁻¹).

To solve the ADE (1) the values of dispersion coefficient in the longitudinal, transverse and the vertical directions (D_x, D_y, and D_z) together with the initial and boundary conditions have to be known (Ashan 2008). The initial and boundary conditions are obtained during field measurements. The dispersion coefficient has to be assessed on basis of dispersion process theory and values of measurable characteristics. For determination of longitudinal dispersion coefficient several theoretical and empirical formulations have been proposed (Velísková and Sokáč 2011).



Figure 1. Straight reach of the Malá Nitra River



Figure 2. Location of the tracer injection and sampling points on the Malá Nitra River

MATERIALS AND METHODS

Experimental reach of the stream - the Mala Nitra River is situated at the southwest part of Slovakia (Figures 1. and 2.). Mala Nitra is small modified stream with basin area $A = 76.6 \text{ km}^2$. Discharge regime is affected by flow regulation of the weir located 15 km upstream in bifurcation point with the Nitra River. Cross sections changed by natural

morphological processes had originally trapezoidal shape with bed width $b = 4 \text{ m}$, height $h = 2.5 \text{ m}$ and slope 1:2. Longitudinal bed slope was various due to natural morphological changes ($S_0 = 0.0015$, 0.00023 and 0.0003). Measured discharge during field experiments were within the interval $0.230 \text{ m}^3 \cdot \text{s}^{-1}$ and $0.235 \text{ m}^3 \cdot \text{s}^{-1}$. Roughness coefficient determined on base of field measurements was $n = 0.035$.

Field measurement method

To determine the longitudinal dispersion coefficient the tracer with a known quantity and concentration was dosed into the geometric centre of the stream width at the beginning of measured section instantaneously. The salt solution (NaCl) was used as a tracer that caused a change of water conductivity in the stream. A single dose of tracer was 120 or 180 l with mass 10 000g or 15 000 g NaCl. Subsequently, the time course of tracer concentration was monitored in sampling location along the stream. Sampling points were at 60, 120, 180, 410 and 1340 m (Figure 2). Conductivity measurements were completed with portable conductivity meters, located in the centre of the measured cross-section width.

Tracer experiment was repeated minimally three times. Conductivity values of surface water were recorded in 0.5 m station distances of each measured cross-section. The channel morphology, velocity distribution and actual discharge were measured in every cross-section for whole set of tracer experiments. Figure 3. shows structure of point velocities in cross section at sampling point 2.

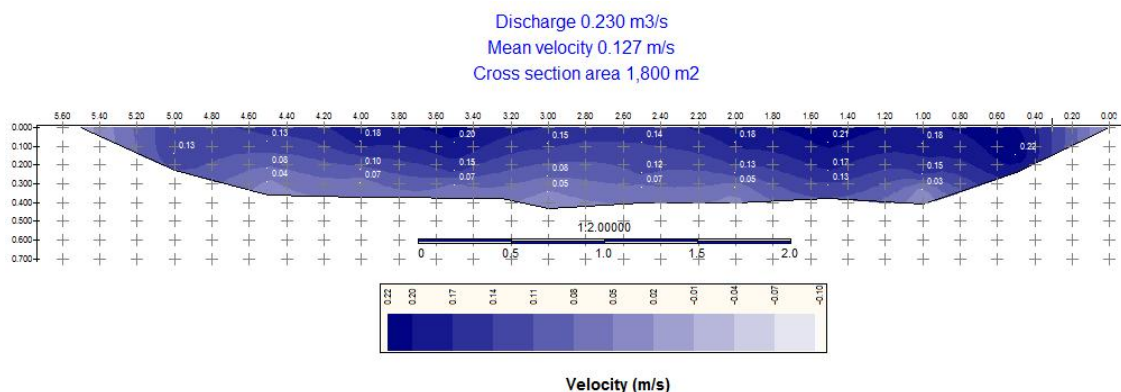


Figure 3. Schematic view on measured velocity field in cross section at sampling point 2., 120 m downstream from tracer injection point

Methods for longitudinal dispersion coefficients determination

An assessment of longitudinal dispersion coefficients was carried out on base of results of field measurements. We used three various methods: analytical solutions of ADE, using of tracer concentration bell shaped curve characteristics and by using of numerical model.

The determination of longitudinal dispersion coefficient by analytical solutions of ADE was based on equation applicable for instantaneous injection of tracer (De Smedt 1989):

$$C = \frac{M / A}{2(\pi D t)^{1/2}} \exp\left[-\frac{(x - vt)^2}{4 D t}\right] \quad (2)$$

where A is a discharge area in a stream cross-section (m^2), m is the mass of a tracer, v is a mean velocity in cross section ($m.s^{-1}$). Equation (2) was used for simulation of tracer experiment (concentration distribution) for various values of longitudinal dispersion coefficient. The difference between the measured and simulated values is evaluated. The minimal difference determines the value of the longitudinal dispersion coefficient for each one of the experiments (Figures. 5 - 7).

The second way for the longitudinal dispersion coefficient from the width δt of the bell shaped curve (Figure 4.) at concentration value $(C_{\max} - C_0)/2$ (De Smedt 1989):

$$D \approx \frac{v^3 (\delta t)^2}{16 \ln^2} \quad (3)$$

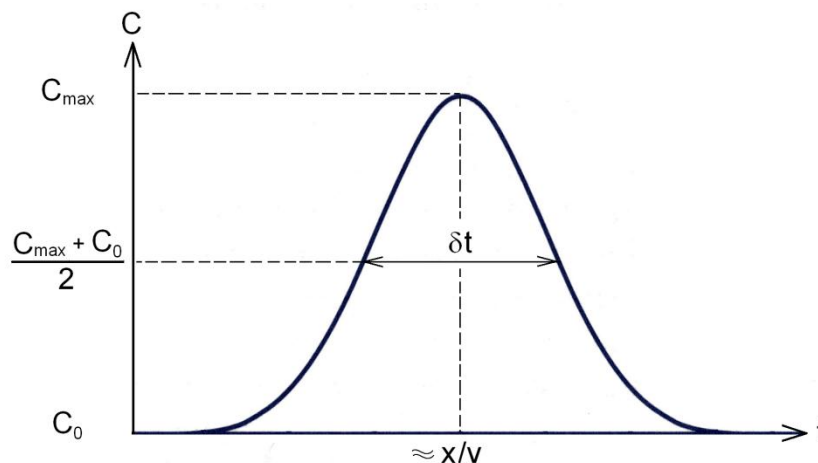


Figure 4. Characteristics of bell shaped curve of tracer concentration versus time

As the third method we used numerical model. In the case of longitudinal dispersion coefficient assessment it was model HEC-RAS. This model was developed by the United States Army Corps of Engineers (USACE 2006) and is designed to model complex phenomena and processes in the river systems. This software allows calculations of one-dimensional steady non-uniform and unsteady flows, 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. This module applied the QUICKEST-ULTIMATE explicit numerical scheme to solve the one-dimensional ADE using a control volume approach.

RESULTS AND DISCUSSION

Results of the tracer experiment no. 5 with comments are referred to below. Figures 5. – 7. represent concentration profiles obtained with HEC-RAS model for different parameters set up and measured during tracer experiment in sampling points. Figure 8. shows schematic plot of time and spatial spreading of concentration profile in 200 m long reach of the Mala Nitra River (HEC-RAS model output modified by authors)

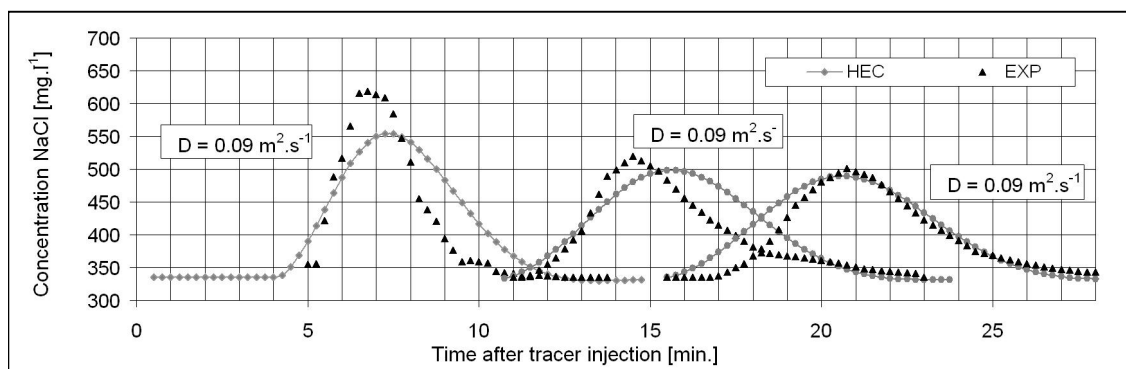


Figure 5. Comparison of concentration profiles obtained with HEC -RAS model and the results measured during tracer experiment in sampling points at distance 60 m, 120 m and 180 m from injection point, considering 10 kg of NaCl injected in the river channel for discharge $0.230 \text{ m}^3 \cdot \text{s}^{-1}$, average flow velocity of $0.17 \text{ m} \cdot \text{s}^{-1}$, dispersion coefficient $0.09 \text{ m}^2 \cdot \text{s}^{-1}$ and computational cell size 5 m.

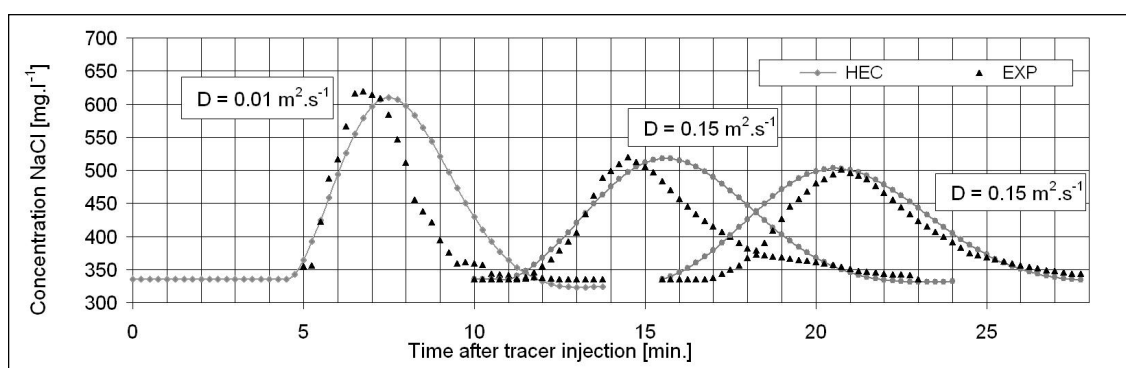


Figure 6. Comparison of concentration profiles obtained with HEC -RAS model and the results measured during tracer experiment. Condition remained the same as for previous tracer experiment. Cell size was reduced to 2 m and D value was changed to obtain the best match.

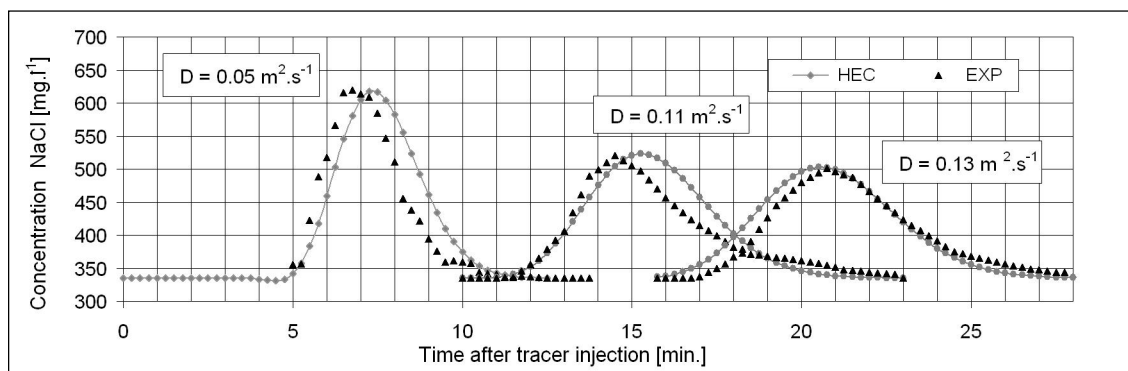


Figure 7. Comparison of concentration profiles obtained with HEC -RAS model and the results measured during tracer experiment. Condition remained the same as for previous tracer experiment but D value was optimized to reach the best match for all concentration profiles.

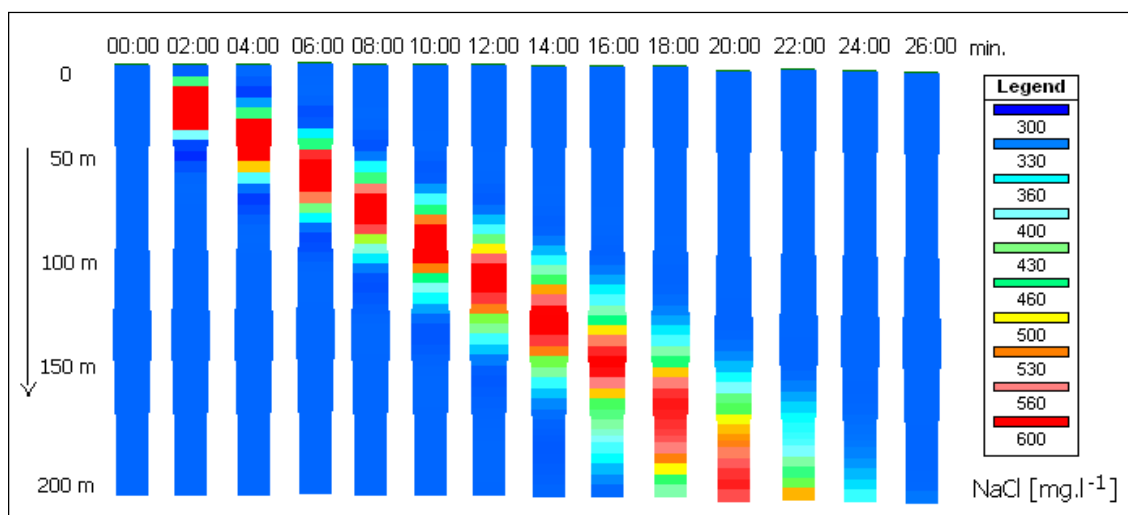


Figure 8. Schematic plot of time and spatial spreading of concentration profile (HEC-RAS model output modified by authors)

To evaluate the match of concentration profile pairs (HEC-RAS ver. experiment) we define values r_x , r_σ and r_{cmax} which represents the ratio of arithmetic average, standard deviation, maximal concentration and travel time of concentration peak of experimental and by model obtained data for given sampling points. The results of the analysis are presented in table 1.

Table 1. Analysis of concentration profiles characteristics for particular sampling points

Sampling point	1	2	3	1	2	3	1	2	3
SP distance (m)	60	120	180	60	120	180	60	120	180
Cell size (m)	5	5	5	2	2	2	2	2	2
D (m.s ⁻¹)	0.09	0.09	0.09	0.01	0.15	0.15	0.05	0.11	0.13
r _x	0.946	1.092	1.073	1.151	1.220	1.170	1.041	1.124	1.070
r _σ	1.011	1.010	1.008	1.020	1.018	1.017	1.007	1.005	1.003
r _{cmax}	0.895	0.958	0.977	0.985	0.995	1.003	0.997	1.006	1.003
r _t	1.035	1.045	0.991	1.053	1.045	0.991	1.035	1.034	0.991

The results presented in Table 1. show that characteristics of concentration profile curves calculated by HEC-RAS model are sensitive on model parameters setup mainly for river stations close to injection point where tracer isn't homogeneously spreading across the cross section. To achieve the best match between measured and modelled results close to injection point it's recommended to set up shorter cell size and precisely specified D coefficient in these reaches. Analysis of modelled concentration profile shows transmission effect of D coefficient value when change of D in given reach evokes the optimisation of D value at downstream reaches.

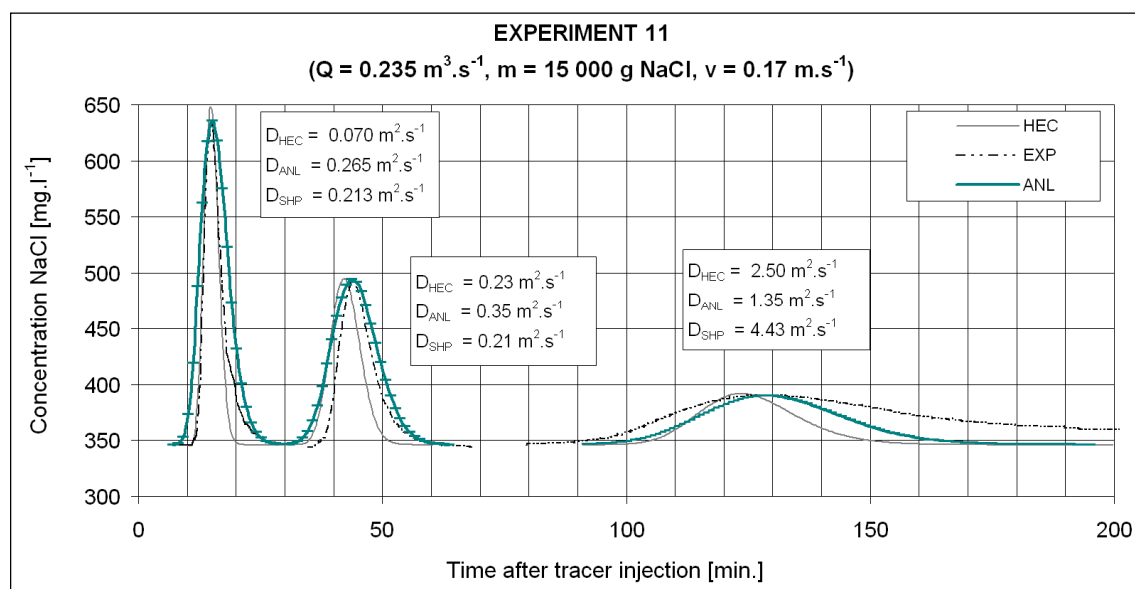


Figure 9. Comparison of concentration profiles in sampling points at distance 120 m, 410 m and 1340 m from injection point

Figure 9. presents comparison of concentration profiles in sampling points (SP2, SP4 and SP5) at distance 120 m, 410 m and 1340 m from injection point obtained with HEC-RAS model, by analytical solution and on base of measured concentrations during tracer experiment. D values are assessed and optimised to get best match by three methods (HEC-RAS, analytical solution and Δt value of the concentration profile curve). The range of mean values of the D coefficient determined on base of analytical solution of the advection-dispersion equation (Eq.2) is $0.265 - 1.35 \text{ m}^2.\text{s}^{-1}$, Δt value of the concentration profile is $0.21 - 4.43 \text{ m}^2.\text{s}^{-1}$ (Eq.3) and HEC-RAS model is $0.070 - 2.50 \text{ m}^2.\text{s}^{-1}$. The differences among values of D coefficient are not so distinct. It is convenient to mention, that ranges of values obtained by Eq.1 and Eq.2 are closer to values obtained in laboratory flume than in natural conditions (Fischer et al. 1979). Coefficient D values obtained by the HEC-RAS model are more variable along investigated part of the river. It can be the consequence of that the model simulates the flow conditions more precisely than analytical relation and values derived from concentration profile curve. Although comparison of travel time of peak concentration profiles in sampling points at distance 120 m, 410 m and 1340 m from injection point obtained with HEC-RAS model and values of measured concentrations during tracer experiment shows good match (Figure 10.) in the shape of concentration curve are some differences. Asymmetrical shape of observed solute concentration profile characterized by steep leading edges and prolonged tails in Figure 9. (1340 m from injection point) is due to retardation of solute migration. It is caused by transient storage occurrence when portions of transported solute become temporarily isolated from main stream in channel (De Smedt, Brevis & Debels, 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.

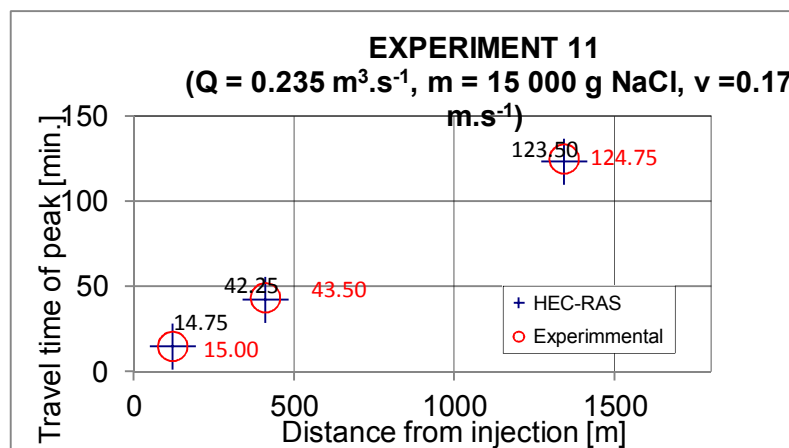


Figure 10. Comparison of travel time of peak concentration profiles in sampling points at distance 120 m, 410 m and 1340 m from injection point obtained with HEC-RAS model and values of measured concentrations during tracer experiment

CONCLUSIONS

The application of HEC-RAS software, that includes water quality model showed good match with experimental data, 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, use of the model has limited confidence unless previously calibrated in the particular river reach under consideration. 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 hyporheic zones.

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