Longitudinal Dispersion Coefficient in Natural Streams in Slovakia

D. Halmova, P. Miklanek, J. Pekar, B. Pramuk and P. Pekarova

Längsdispersionskoeffizient in natürlichen Flüssen der Slowakei

Introduction

The use of models for simulation of pollution in the stream is encountering the lack of information on the size of the mixing dispersion coefficient, either in the longitudinal or transverse direction. The value of the coefficient can influence the outcome of the calculations or simulations of leaking substances into the flow. Therefore, accurate determination of the values of this coefficient is an important part in solving the problems of pollution transport in the stream. In general, we can use the values of the mixing coefficients referred in the literature (approximate table values), or estimated using approximate empirical relationships, or determine them on the basis of field measurements.

In our field investigation, we have focused on the longitudinal dispersion coefficient determination based on experimental saline experiments in various small streams in Slovakia. Model of the pollution dispersion in rivers SIRENIE was used to estimate the dispersion coefficient.

Method

Hydrodynamic models of the spread of contamination in the flow are based on the three-dimensional advection-diffusion equation:

Zusammenfassung

Der Beitrag behandelt die Abschätzung des Längsdispersionskoeffizienten bei Verunreinigungen durch Unfälle in kleinen, natürlichen Flüssen. Es werden kurz der theoretische Hintergrund und die Erkenntnisse aus Feldbeobachtungen für die Bestimmung des Längsdispersionskoeffizienten umrissen. Diese Werte bestimmen die Berechnungsergebnisse von Sickerzufluss in das Gewässer. Daher ist die zuverlässige Bestimmung dieser Werte für die Beschreibung des Schadstofftransports sehr wichtig. In der zugrundeliegenden Studie werden die Ergebnisse von Feldversuchen zur Bestimmung des Längsdispersionskoeffizienten an verschiedenen Flüssen der Slowakei zusammengefasst.

Schlagwörter: Dispersionskoeffizient, Modellierung der Wasserqualität.

Summary

The paper deals with the estimation of the longitudinal dispersion coefficients of accidental pollution in the small natural streams. The paper briefly reviewed the theoretical background and the results of field experiments needed to determine the longitudinal dispersion coefficient. The values of the coefficients can influence the outcome of the calculations or simulations of leaking substances into the flow. Therefore, accurate determination of the values of these coefficients (also on the basis of field measurements) is an important part in solving the problems of pollution transport in the stream. In this study, we summarized the results of our field experiments in the various Slovak streams on identifying the coefficient of longitudinal dispersion.

Key words: Dispersion coefficients, water quality modeling.

$$\frac{\partial c}{\partial t} + v_x \frac{\partial c}{\partial x} + v_y \frac{\partial c}{\partial y} + v_z \frac{\partial c}{\partial z} = \frac{\partial}{\partial x} D_x \frac{\partial c}{\partial x} + \frac{\partial}{\partial y} D_y \frac{\partial c}{\partial y} + \frac{\partial}{\partial z} D_z \frac{\partial c}{\partial z} \pm Kc \pm F \tag{1}$$

where:

t – time [s],
c*(x,z,y,t)* – mass concentration of pollutant [kg.m^{-3}],
D_x, D_y, D_z – longitudinal, transverse and vertical dispersion coefficients [m^2.s^{-1}],
v_x, v_y, v_z – depth-averaged longitudinal, transverse and vertical velocities [m.s^{-1}],
Kc – reaction coefficient (degradation, self-purification), which expresses the self-purification effect on the change of pollutant concentration [s^{-1}],
F(x,y,z,t) – function representing the sources of pollution [kg.m^3.s^{-1}],
x, y, z – coordinates [m].

A number of numerical models have been prepared on the basis of equation (1) (Jolankai, 1997; Pekarova & Veliskova, 1998; Kosorin & Dulovicova, 2000; Veliskova et al., 2013, 2014).

We estimate the longitudinal dispersion coefficient using the model SIRENIE, which was developed in our department. This two-dimensional model for simulation of accidental non-conservative point source pollutant events is based on the analytical solution of the equation:

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} - Kc \tag{2}$$

which can be written for the full bank effect in the form (Pekarova & Pekar, 1993):

$$c(x,y,t) = \frac{G}{4\pi h t (D_x D_y)^{1/2}} . \exp\left[-\frac{(x - v_x t)^2}{4 D_x t}\right] . \exp(-Kt) . \sum_{n-\infty}^{\infty} \left\{ \exp\left[-\frac{(y - y_o - 2nB)^2}{4 D_y t}\right] + \exp\left[-\frac{(y + y_o + 2nB)^2}{4 D_y t}\right] \right\} \tag{3}$$

where:

B – width of the stream [m],
y_o – distance of pollution source from the bank [m],
G – mass of the pollutant discharged instantaneously into the stream [kg],
v_x – average velocity in the profile [m.s^{-1}].

Velocity components from the Equation 1, in the case of small flows, can be neglected. If the contaminant is conservative, and assuming steady-state flow and full mixing of the contaminant, Equation 2 can be simplified to the form:

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} - v_x \frac{\partial c}{\partial x}$$

where:

v_x – average velocity in the profile [m.s^{-1}];
D_x – longitudinal dispersion coefficient [m^2.s^{-1}].

The analytical solution of this equation for the initial condition c (x, 0) = 0 (for t = 0), boundary condition c (0, t) = 0 (for x = 0) and the amount of pollution G [kg] has the form:

$$c = \frac{G}{2A(\pi D_x t)^{1/2}} \exp\left(-\frac{(x - ut)^2}{4 D_x t}\right) \tag{4}$$

To determine the longitudinal dispersion coefficient we have compiled a Model SIRENIE, which is based on analytical solutions of the advection-diffusion equation.

Study areas and data collection

In this study, we summarized the results of our field experiments in various streams for assessment of the coefficient of longitudinal dispersion. Since 1991 to 2014, we have conducted a series of salt experiments at different flows for various hydrological and vegetation conditions in three regions. The electric conductivity was measured in the middle of the stream (Rybarik and Vydrica streams) or at the right and left banks at Jalovecky stream. The selected regions are:

- The Central Slovakia at Povazska Bystrica, in the experimental microbasins of Rybarik and Lesny creeks, the parts of the experimental Mostenik brook basin (Fig. 1b). The Field Hydrological Laboratory of IH SAS (Institute of Hydrology Slovak Academy of Science) was established in 1958 and since 1986 started a chemical program in the basin. The total area of the Rybarik basin is 0.119 km^2. The length of the stream from spring to closing profile is 256 m, channel slope is 9.1 %. The elevation is from 369 to 434 m above the sea level. The long-term annual discharge in Rybarik is 0.00087 m^3.s^{-1}. The area of the Lesny basin is 0.086 km^2, the channel slope is 7.1 %. The basic hydrological characteristics of the microbasins can be found e.g. in Pekarova et al., 2009. We have measured specific conductivity in the middle of the stream and at the same time, we draw samples for Cl- concentration analyses.

- The Northern Slovakia, in the Western Tatra Mountains region, in experimental basin of Jalovecky creek, (DOSA et al., 2011; HOLKO et al., 2013; MIKLANEK et al., 2013). The catchment area is 45 km^2 and the average annual flow was 0.91 m^{3}s^{-1} in 2008. We have measured specific conductivity simultaneously on the left and right side of the stream at a distance of 220 m from the site of injection (Fig. 1c). The width of the stream at the place of measurements is approximately 8 meters.
- The Western Slovakia at Bratislava, in protected area of the Little Carpathians, in Vydrica creek. The total flow length is 17 km; rises at an altitude of 505 m above sea level and the catchment area is 22.6 km^2. The average monthly flow during 1931–1960 at gauging station Cerveny Most was 0.161 m^3.s^{-1} (the minimum daily flow rate is of 0.001 m^3.s^{-1} and maximum daily discharge 7.5 m^3.s^{-1}). The width of the stream at the place of measurements is approximately 3 meters and specific conductivity was measured in the middle of the stream at a distance of 50 and 100 m from the site of the salt injection (Fig. 1d).

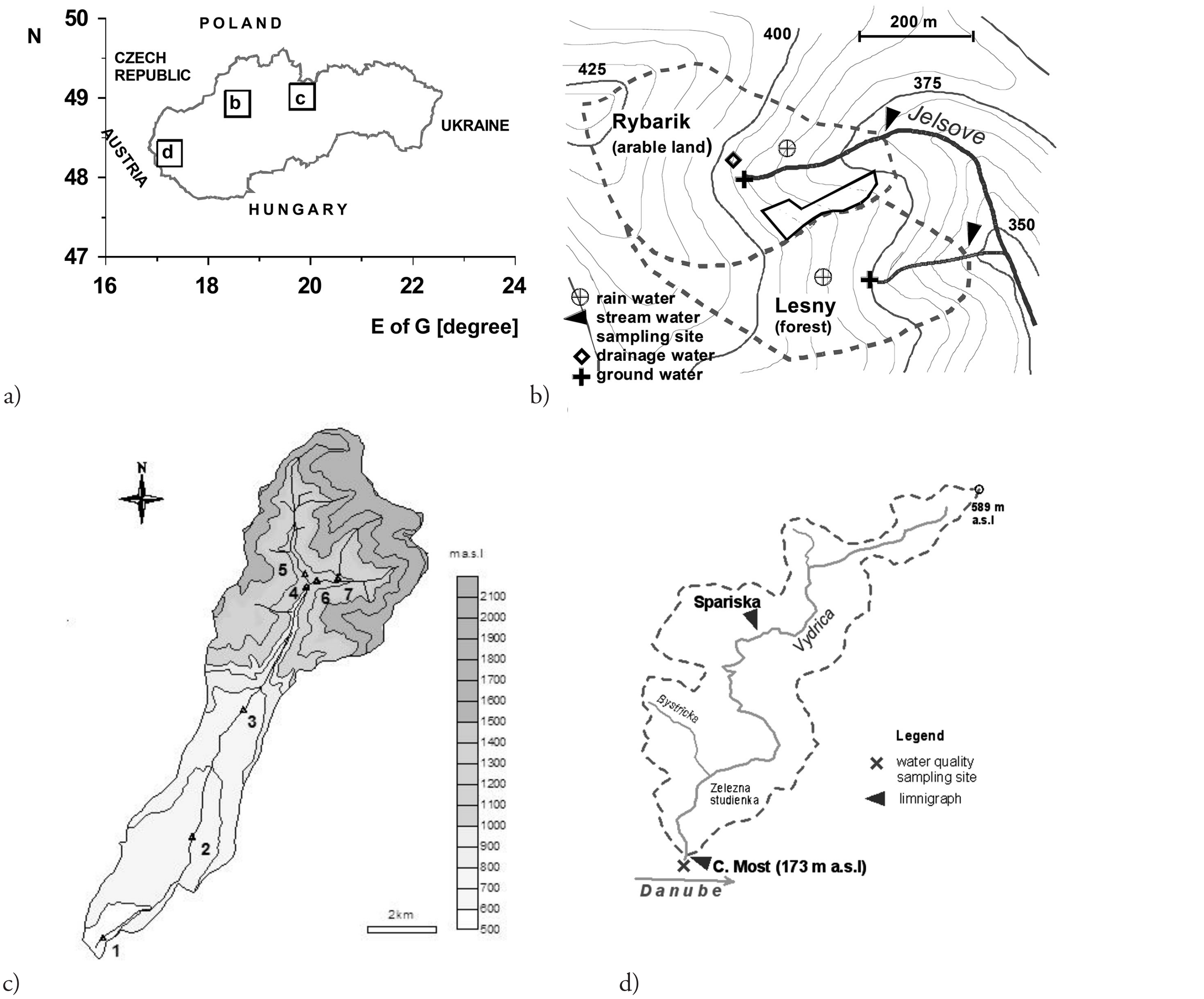


Figure 1: a) Location of the experimental basins in Slovakia; b) experimental basins of Rybarik and Lesny creeks; c) experimental basin of Jalovecky creek; d) experimental basin of Vydrica creek

Abbildung 1: a) Lage der experimentellen Einzugsgebiete in der Slowakei; b) Einzugsgebiet Rybarik und Lesny Bach; c) Einzugsgebiet Jalovecky Bach; d) Einzugsgebiet Vydrica Bach

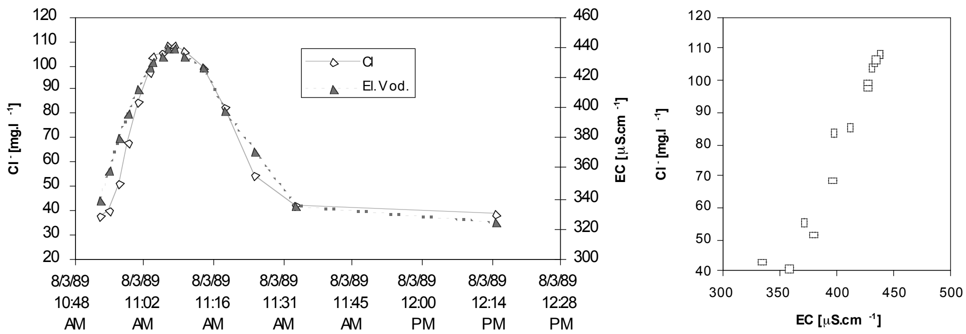


Figure 2: Results of experiment on 03. 08. 1989, Rybarik creek, application of 75 g NaCl
Abbildung 2: Ergebnisse des Tracerexperiments vom 3. 8. 1980 am Rybarik Bach nach 75 g NaCl-Gabe

Results

We started the experimental assessment of stream water quality and measurements of pollution dispersion in small streams in basins of Rybarik a Lesny in1989. The first salt experiments were carried on in 1989. Table salt (75 g) was applied to the stream near to the spring and the water samples were taken at the outlet of the basin. The electric conductivity was measured in the middle of the stream at the same time (Fig. 2). The samples were taken for Cl^- concentration analyses (Photo 1). The Cl^- and EC [$mS.cm^{-1}$] waves were identical. Therefore the electric conductivity only was measured during consecutive samplings (Fig. 3). The spreading of chlorides in the stream was modeled by the model SIRENIE. Coefficient of the longitudinal dispersion was modeled in the way to minimize the differences between measured and modelled values.

In the Rybarik and Lesny creeks, the coefficients D_x estimated on the basis of the experiments are in the range 0.2–0.7 $m^2.s^{-1}$ (Fig. 3).

Similarly we proceeded in the years 2005–2012 when we have determined longitudinal dispersion coefficients in Jalovecky creek. We have measured specific conductivity, simultaneously at the left and right side at a distance of 220 m from the application of the salt into the water. The coefficients D_x estimated on the basis of the experiments are in the range 1.5–2.5 $m^2.s^{-1}$ (Fig. 4).

The same experiments were performed during the years 2013–2014 when we have determined longitudinal dispersion coefficients in the middle of the Vydrica creek. The coefficients D_x, estimated on the basis of the experiments, are in the range 0.4–0.6 $m^2.s^{-1}$ (Fig. 5).


a)


b)

Photo 1 a) Taking the samples for Cl-concentration analyses, Rybarik creek – in the middle of the stream, b) specific conductivity measurements at Jalovecky creek – left and right sites

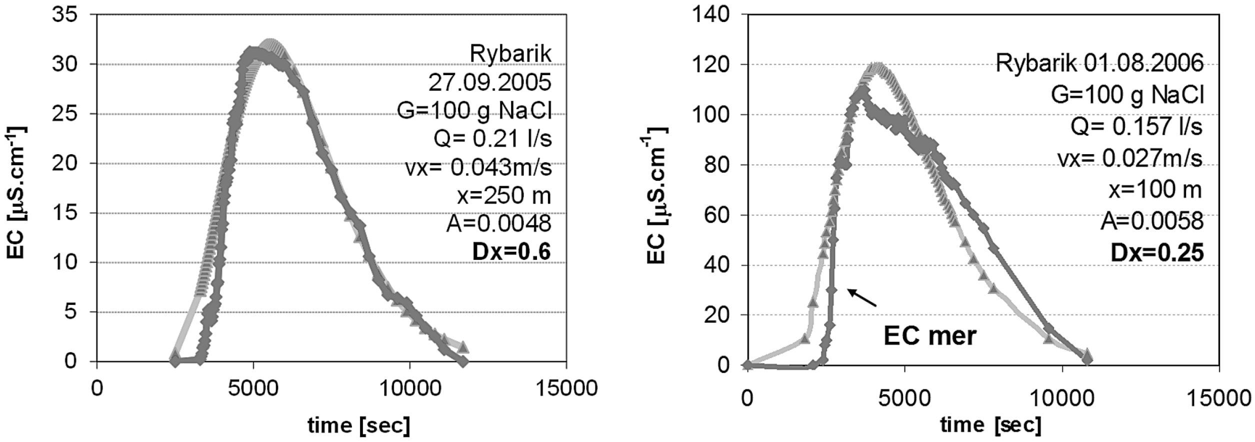
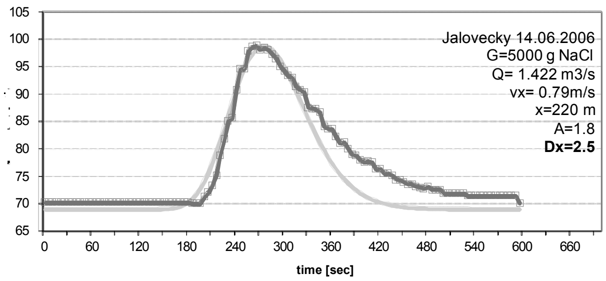


Figure 3: Measured and modelled conductivity [mS.cm-1], 27.09.2005 and 01.08.2006, Rybarik creek, 100 and 250 meters from the delivery of the solution; application of 100 g NaCl

Abbildung 3: Gemessene und modellierte Leitfähigkeit am 27.9.2005 und 1.8.2006 am Rybarik Bach, 100 bzw. 250 Meter unterhalb des Einspeisungspunktes nach Zugabe von 100 g NaCl

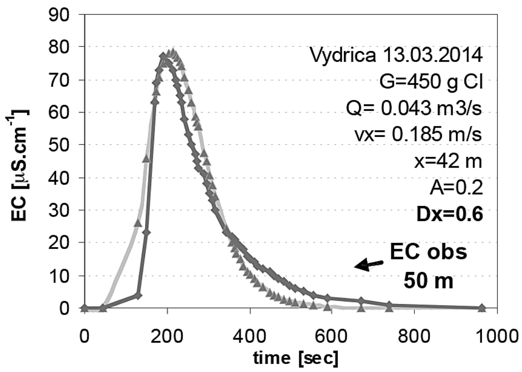
a)



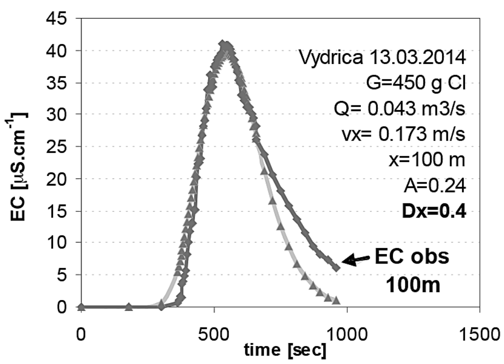
b)

Figure 4: a) The course of measured and modelled conductivity [mS.cm-1] during the experiment on 14.06.2006, 220 meters from the delivery of the solution; application of 5000 g NaCl, at the right bank of the stream; b) The equipment for conductivity measurement

Abbildung 4: a) Gemessene und modellierte Leitfähigkeit am 14.06.2006, 220 Meter unterhalb des Einspeisungspunktes nach Zugabe von 5000 g NaCl; b) Messgeräte zur Leitfähigkeitsmessung



a)



b)

Figure 5: The course of measured and modelled conductivity [mS.cm-1] during the experiment on 13.03.2014, 50 (a) and 100 (b) meters from the delivery of the solution, application of 450 g NaCl

Abbildung 5: Gemessene und modellierte Leitfähigkeit am 13.03.2014, 50 (a) und 100 (b) Meter unterhalb des Einspeisungspunktes nach Zugabe von 450 g NaCl

Conclusions and discussion

There exist several indirect relations for determination of coefficients of longitudinal dispersion of pollution in the stream based on different characteristics of the stream (e.g. mean profile velocity of the stream, channel width, channel slope and others). However, the direct measurements of dispersion of substances in the stream give the best, and the most real results.

The estimated coefficients D_x on the basis of the experiments are in the range 0.2–0.7 $m^2.s^{-1}$ in the Rybarik and Lesny streams, in the range of 0.4–0.6 $m^2.s^{-1}$ in the Vydrica stream, and in the range 1.5–2.5 $m^2.s^{-1}$ in the Jalovecky stream, respectively.

Dispersion coefficients are higher in unregulated streams and at the higher flow rates. These coefficients are widely used; they can be also used to simulate the dissemination of accidental pollution in the streams.

The dependence of D_x on discharge in small streams is depicted in Fig. 6 and it is expressed by mathematic relation, which can be used for estimation of the coefficient in similar streams.

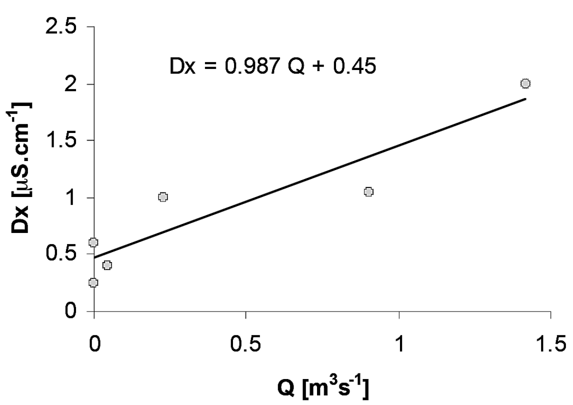


Figure 6: Dependence of D_x on discharge in small streams
Abbildung 6: Abhängigkeit von Dx vom Abfluss in kleinen Flüssen

The environmental problems caused by the increasing of pollutant loads discharged into natural water bodies are very complex. For that reason the cognition of transport mechanism and mixing characteristics in natural streams is very important.

The computer simulations based on mathematical models of pollution mixing in streams can be used (for example) for prediction of spreading of accidental contaminant waves in rivers. The mathematical and numerical models have become very useful tools for solving several problems in water management.

Acknowledgement

This publication is 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. This work was supported by project VEGA 2/0009/15.

References

Dosa, M., Holko, L. & Kostka, Z. (2011): Estimation of the mean transit times using isotopes and hydrograph recessions. Die Bodenkultur, 62 (1–4), 47–52.

Holko, L., Danko, M., Dosa, M., Kostka, Z., Sanda, M., Pfister, L. & Iffly, J. F. (2013): Spatial and temporal variability of stable water isotopes in snow related hydrological processes. Die Bodenkultur, 64 (3–4), 39–45.

Jolankai, G. (1997): Basic river water quality models. IHP-V. Technical Documents in Hydrology 13. UNESCO, Paris, 52 s.

Kosorin, K. & Dulovicova, R. (2000): To methodical problems of multi-dimensional computer simulation of surfacewater and groundwater movement. Acta Hydrologica Slovaca, 1, 217–222 (in Slovak).

Miklanek P., Martincova M., Dosa M. & Pekarova P. (2013): Long term trend of water quality in the Bela River Die Bodenkultur 64 (3–4) 73–78.

Pekarova, P. & Veliskova, Y. (1998): Modelling of water quality in Ondava basin. VEDA, Bratislava, 256 pp. (in Slovak).

Pekarova, P., Miklanek, P., Onderka, M. & Kohnova, S. (2009): Water balance comparison of two small experimental basins with different vegetation cover. Biologia, 64/3, 487–491.

Pekarova, P. & Pekar, J. (1993): Experimental methods for determining the coefficients of mathematical model of longitudinal dispersion and self-purification. J. Hydrol. Hydromech., 41, 6, 398–411.

Veliskova, Y., Halaj, P. & Sokac, M. (2013): Sensibility of HEC-RAS model to changes of dispersion coefficient as input model parameter. Acta Hydrologica Slovaca, 14, 2, 392–401. (in Slovak).

VELISKOVA, Y., SOKAC, M., HALAJ, P., KOCZKA BARA, M., DULOVICOVA, R. & SCHÜGERL, R. (2014): Pollutant Spreading in a Small Stream: A Case Study in Mala Nitra Canal in Slovakia. In Environmental Processes – An International Journal, 1, 3, 265–276. ISSN 2198–7491.

Address of authors

Dana Halmova, Pavol Miklanek, Branislav Pramuk, Pavla Pekarova, Institute of Hydrology SAS, Racianska 75, 831 02 Bratislava, Slovakia
Jan Pekar, Dept. of Applied Mathematics and Statistics, FMPI CU Bratislava, Slovakia

Corresponding author

Dana Halmova, Institute of Hydrology SAS, Racianska 75, 831 02 Bratislava, Slovakia
halmova@uh.savba.sk