Influence of Aquatic Vegetation on Dispersive Parameters as a Part of Hydrodynamic Conditions in Natural Streams

Marek Sokáč 1, Radoslav Schügerl 1, Yvetta Velísková 1, Renáta Dulovičová 1

1 Institute of Hydrology, Slovak Academy of Sciences, Dúbravská cesta 9, 84104, Bratislava, Slovak Republic
marek.sokac@uh.savba.sk

Abstract. Submerged and emergent aquatic vegetation is a natural and organic component of natural rivers and streams. It plays an important role in all physical, chemical and biological processes in the stream bioocenosis. This type of vegetation has also a non-negligible impact on flow conditions. It influences the discharge, hydraulic roughness, velocity as well as other hydraulic parameters. Important part of the river hydrodynamic processes are also dispersive processes and its parameters, which defines the speed and intensity of the dispersive processes in the natural stream. This paper analyses these aspects of the stream hydrodynamics, which are influenced by aquatic vegetation and analyses the influence of the submerged and emerged vegetation on mixing processes in a river. Presented results are findings of hydrometric measurements and tracer experiments at the Šúrsky kanál stream, located in south-west part of Slovakia. The Šúrsky kanál stream is a typical lowland stream, where significant changes in the vegetation are present during different periods of a year. The hydrometric and tracer experiments were performed on 1700 m long straight reach of the stream with a relatively prismatic cross-section profile during the growing as well as non-growing season of a year. The results show, that the level of vegetative growth has a significant influence on the hydrodynamic parameters of the stream, as well as on the dispersive process. The dispersive process is influenced not only by the velocity and concentration gradients, but also by the fact that the vegetation forms in the stream so-called dead zones. Such dead zones modify the velocity profiles of a stream and affect dispersive mass transport within the stream by collecting and separating parts of the tracer from the main current. Subsequently, the tracer is slowly released and incorporated back to the main current in a stream. This process deforms the shape of the tracer concentration distribution in time. All these facts were confirmed by the experiments results described in this paper, which contains also the analysis of the dead zones effect on the dispersive process.

1. Introduction
Water becomes one of the most important human resources, influencing almost all human activities. Quantitative as well as qualitative water resources protection becomes one of the most important human tasks. An important tool for water resources planning, management and decision making are the mathematical and numerical models because their ability to simulate various development scenarios and their consequences on the water resources. It is necessary to realize that for successful use of numerical models it is necessary to know (or estimate) wide range of parameters coefficients and test their validity by the model verification. Another aspect of the modelling process is the fact that the model parameters might be not constant, but can vary depending on different reasons. One of
such reasons can be the yearly seasonal factor and its implications on the aquatic vegetation in a watercourse.

Submerged and emergent aquatic vegetation is a natural and organic component of natural rivers and streams. It plays an important role in all physical, chemical and biological processes in the stream biocoenosis. This type of vegetation has also a non-negligible impact on flow conditions. It influences the discharge, hydraulic roughness, velocity as well as other hydraulic parameters. Important part of the river hydrodynamic processes are also dispersive processes and its parameters, which defines the speed and intensity of the dispersive processes in the natural stream.

In this paper we will analyse the impact of the seasonal vegetation on the dispersion processes in a watercourse according to the values of dispersion coefficient obtained and determined from tracer experiments in different vegetation periods.

2. Theoretical basis

Basic hydrodynamic description of dispersion processes in flowing water represents the advection–dispersion equation (ADE). One-dimensional ADE form can be written as [1]:

$$\frac{\partial C}{\partial t} + v_x \frac{\partial C}{\partial x} = D_x \left( \frac{\partial^2 C}{\partial x^2} \right) + M_s$$

where \( t \) is the time (s), \( C \) is the concentration of a substance in the stream (kg.m\(^{-3}\)), \( D_x \) is the dispersion coefficient in the longitudinal direction (m\(^2\) s\(^{-1}\)), \( v_x \) is the water velocity in longitudinal direction (m.s\(^{-1}\)), \( M_s \) is a function representing the sources of pollutant substance (kg.m\(^{-3}\) s\(^{-1}\)), \( x \) is the spatial coordinate distance (m).

For pollution transport in streams with transient storage (dead zones), Eq. (1) can be enlarged by the term expressing the exchange between dead zones and the main part of flow in the channel. After that the equation can be written in the form [2], [3]:

$$\frac{\partial C_m}{\partial t} = D_x \left( \frac{\partial^2 C_m}{\partial x^2} \right) - v_x \frac{\partial C_m}{\partial x} - \alpha (C_m - C_s) + S_s$$

$$\frac{\beta}{\partial t} \frac{\partial C_s}{\partial x} = \alpha (C_m - C_s)$$

where \( C_m \) is the mean concentration of the substance in the storage zone (kg.m\(^{-3}\)), \( C_s \) is the mean concentration of the substance in the main part of a stream (kg.m\(^{-3}\)), \( S_s \) is the parameter representing substance source (kg.m\(^{-3}\) s\(^{-1}\)), \( \alpha \) is the mass exchange coefficient between the main part of a flow in the channel and the storage zone (s\(^{-1}\)), \( \beta \) is the ratio between the areas of the main part of a flow in the channel and the storage zone in a stream cross-section (-). If \( \alpha \) or \( \beta \) becomes zero, Eq. (3) is reduced to Eq. (1).

In our study we have analysed the impact rate of aquatic vegetation occurrence on the dispersion coefficient value. This coefficient presents the dispersion rate of a stream. For its determination a numerical simulation model based on two different 1D analytical solutions of the ADE (Eq. 1) for simplified conditions and instantaneous solute input has been used.

The first one was in form [4]:

$$C(x, t) = \frac{M}{2A \sqrt{\pi D_x t}} \exp \left( - \frac{(x - \bar{v}t)^2}{4 D_x t} \right)$$

where \( M \) is the substance mass (kg), \( A \) is the cross-sectional area of the watercourse (m\(^2\)) and \( \bar{v} \) is the average flow velocity in the watercourse.

This analytical solution of ADE is the most applied one in the practice [5] and it uses the Gaussian distribution.

The second analytical solution has a form [6]:

$$C(x, t) = \frac{M}{A \sqrt{D_{x,0} t}} \exp \left( \frac{x - \bar{v}t}{\sqrt{D_{x,0} t}} \right) - \exp \left( \frac{x - \bar{v}t}{\sqrt{D_{x,0} t}} \right)$$

2
where $D_{x,G}$ is the dispersion coefficient in the longitudinal direction (m$^2$ s$^{-1}$) used in the model approach by [6]. This analytical solution of ADE is not applied in the practice very often, but as it will be showed later, it is more suitable for modelling of substance spreading in natural streams with so-called dead zones. It is based on the Gumbel’s distribution application.

The simplified conditions comprise a prismatic streambed, steady uniform flow and a conservative pollutant, as well as assumption of lateral and vertical homogeneous concentration of transported substance (it is the necessary condition for 1D application of ADE); so theoretically, this equation can be applied after achieving complete cross-sectional mixing in the stream. Initial and boundary conditions are typically zero background concentration for the solute substance in watercourse and no lateral inflows, but using the superposition principle and dividing the watercourse to parts, different (nonzero) initial and boundary conditions could also be imposed [7].

3. Field experiments
The tracer experiments were carried out at the reach of the Šúrsky kanál stream, located close to the Svatý Jur village (Slovakia, N48.232957°, E17.202934°). The Šúrsky kanál stream is a modified watercourse, typical for the lowland areas in south – west Slovakia. The constructed cross-section profile of this watercourse was significantly influenced by vegetation (Fig 1.).

Measured discharge in the examined watercourse reach during the experiments was 0.061 - 0.093 m$^3$s$^{-1}$ (61-93 l.s$^{-1}$). The water level slope specified by levelling measurements was 0.3 – 0.33 ‰, the total length of the experimental stream reach was 1700 m, the measured flow velocity was very low in growing season due the aquatic vegetation occurrence – 0.05 up to 0.06 m.s$^{-1}$, but significantly higher in non-growing season – 0.32 m.s$^{-1}$. The stream shape along the examined stream reach can be considered prismatic, the width was around 4 m, the average depth was 0.25 m [8].

The experiments were performed during various seasons of the year, when different vegetation covering was present in the watercourse. In April, there was almost no vegetation on the watercourse bank, as well as minimum submerged vegetation inside the watercourse. On the contrary, in high summer (August), the stream was covered by vegetation in high extent - approximately up to one meter of emerged vegetation on both banks, as well as submerged vegetation in the central part of the channel (Figure 1). Both kinds of aquatic vegetation (emerged along the stream banks and submerged in the stream bed) formed dead zones from the flowing point of view.

![Figure 1. The Šúrsky kanál stream near the Svatý Jur village (GPS N48.232957°, E17.202934°). Both pictures show the same stream reach during the different vegetation periods. Figure left – during non-growing season (April), Figure right – during growing season (August).](image-url)
4. Results and discussion
The time course of the tracer concentrations (pollutograms) from the tracer experiments during different period of a year are shown on Fig. 2. Because of different mass of the tracer used in particular tracer experiments, the graph is presented in the modified scale – the measured values were adjusted that the total weight of the tracer was always the same in each particular tracer experiment.

All field experiments were performed on the same watercourse section of the Šúrsky kanál stream, but during the different seasons as it was mentioned above: in the spring (April) and in the summer (June, August); so the experiments were done in different hydraulic conditions mainly due to aquatic vegetation occurrence, which caused strong deformation of the measured tracer concentration time course curve – it got a pronounced asymmetrical shape (see Fig. 2–5.) Based on the stream reach reconnaissance and evaluation of hydro-morphological conditions, the presence of transient storage zones was detected and confirmed. These zones were established by channel irregularities, but mainly by aquatic vegetation in the stream - the vegetation not only close to the stream banks, but also in the main flow zone of the channel.

Experience, obtained during the tracer experiments in natural stream conditions, indicates that the existence of aquatic vegetation and subsequent forming of transient storage zones in the streams is a fundamental problem for the substance modelling (prediction).

The dispersion coefficient was determined by using the Eq. 4 and Eq. 5 with simultaneous application of the built-in nonlinear regression in the standard Excel worksheet. The aim of this numerical process was to minimise the sum of differences square between the measured and simulated (by mentioned Eq. 4 and 5) values. The examined variables were the dispersion coefficient value, as well as the velocity and the coefficient for the fitting of tracer mass to keep the mass balance. The resulting values of the dispersion coefficient and other parameters are shown in Tab 1.

Due to the different flow conditions, it is reasonable to evaluate the dispersion coefficient also in the form of dimensionless dispersion coefficient. The dimensionless dispersion coefficient \( a \) is defined as [9]
\( a = \frac{D_x}{d \cdot u^*} \) \hspace{1cm} (6)

where \( D_x (D_{x,G}, \text{respectively}) \) is the dispersion coefficient in the longitudinal direction (m\(^2\) s\(^{-1}\)), \( d \) is a characteristic dimension (m); in general the water depth can be considered as the characteristic dimension, \( u^* \) is the shear stress velocity (m.s\(^{-1}\)), defined as [10]

\[ u^* = \sqrt{g \cdot d \cdot S_f} \] \hspace{1cm} (7)

where the \( g \) is the gravitational constant \([g=9.81 \text{ m.s}^{-2}]\) and \( S_f \) is the friction slope [-].

### Table 1. Results of the field tracer experiments

| Nr.  | Date   | \( D_x \) \text{ Eq. 4} | \( \bar{v} \) \text{ Eq. 4} | \( D_{x,G} \) \text{ Eq. 5} | \( \bar{v} \) \text{ Eq. 5} | \( \alpha \) \text{ Eq. 4, 6} | \( \alpha \) \text{ Eq. 5, 6} |
|------|--------|--------------------------|-------------------------|---------------------------|-------------------------|---------------------|---------------------|
| Exp. 1 | 06 / 2018 | 1.16 (mm-yyy) | 0.0578 (m.s\(^{-1}\)) | 2.483 (m.s\(^{-1}\)) | 0.0597 (m.s\(^{-1}\)) | 89.2 (-) | 114.5 (-) |
| Exp. 2 | 08 / 2018 | 0.48 (mm-yyy) | 0.0526 (m.s\(^{-1}\)) | 1.307 (m.s\(^{-1}\)) | 0.0529 (m.s\(^{-1}\)) | 62.7 (-) | 157.0 (-) |
| Exp. 3 | 04 / 2019 | 2.18 (mm-yyy) | 0.318 (m.s\(^{-1}\)) | 3.89 (m.s\(^{-1}\)) | 0.325 (m.s\(^{-1}\)) | 218.8 (-) | 389.5 (-) |

Matching of pollutograms from field experiments and numerical simulations by Eq. 4 and Eq. 5 are shown on Fig. 3 - Fig. 5. Pollutograms represented numerical simulations presents the best fitted outputs from single equation application.

![Figure 3. Pollutogram from tracer experiment Nr. 1 (06-2018).](image-url)
Dispersion coefficient values in Tab. 1 confirm that the presence of submerged and emerged vegetation in the stream can substantially change the dispersion parameters and hydrodynamic characteristics of the solute substance spreading. As it was shown in this table (Tab.1), the dispersion coefficient can be almost double in case without vegetation presence. Of course, the experiments were performed in various hydraulic conditions, because also stream velocity was affected by the vegetation presence. To compare these experiment cases performed in different seasons and flow conditions, we
used the dimensionless dispersion coefficient $a$. The comparison of this dimensionless dispersion coefficient confirms the previous statements – the vegetation presence reduces the value of the dispersion coefficient two to three times in case of our experiments. The reason for this is probably the fact, that the vegetation reduces the speed of the stream. This reduces also the stream flow turbulence.

Statistical analysis of the results showed that the measured concentration time courses do not have the character of the Gaussian normal distribution (or more precisely the character of concentration distribution by Eq. 4) in large number of the experiments, performed in other locations with aquatic vegetation presence.

For this reason, we consider the use of the analytical solutions for dispersion modelling by Eq. 4 as problematic and limited in the case of streams with heavy vegetation presence. The influence of dead zones in the dispersion process can be evaluated incorrectly (see also [11]). As an alternative it seems to be appropriate to use the simplified mathematical models by [12] or the other ones, which takes into account the transient storage in the stream (Eq. 2-3), [13] [14], [15], [6]. However, these models require input parameters of the transient zones (e.g. cross-sectional area ratio between dead and mainstream zone, transfer coefficients, etc.) again. These parameters can be determined in several ways, but with a lot of difficulties and uncertainties. The most reliable way is to perform the tracer experiment and to determine required values on the basis of the measurements.

5. Conclusions
Paper analyses results of tracer experiments in the Šúrsky kanál stream. Experiments were performed on the same part of this lowland stream during the different seasons and by this way with different rate of aquatic vegetation presence. The submerged and emerged vegetation forms so called dead (transient storage) zones in the stream and presence of dead zones causes deformation of the tracer concentration time courses. These tracer concentration time course shape changes appear problematic, because they result weak conformity of measured data and modelled outputs based on generally used Gaussian distribution. For this reason, there was applied the next approximation - the distribution by Gumbel, which seems to be more appropriate for the application in a stream with transient storage zones.

Values of the longitudinal dispersion coefficient, determined from tracer experiments are presented in Table 1. As it can be seen in this table, the differences among the obtained longitudinal dispersion coefficient values are significant, the decrease of the dispersion coefficient value due to the vegetation is two to three times compared to the case without vegetation. This result is confirmed also by comparison of the dimensionless dispersion coefficient, which eliminates different flow rate conditions. The reason for the dispersion coefficient decrease is probably the fact, that the vegetation reduces the speed of the stream – this reduces also the stream turbulence.

The influence of the submerged and emerged vegetation on the process of hydrodynamic dispersion is very complex and variable. To elucidate the overall impact of vegetation on dispersive processes more experiments and research are needed, especially in cases of streams with extensive cover of emerged and submerged vegetation – which will be the next objective of our research in the future.

Acknowledgments
This paper was prepared with the support of the Scientific Grant Agency VEGA within the scientific project Nr. VEGA 1/0085/20 “Prediction of a point pollution source position in a watercourse network – a hydrodynamic approach”, project of the H2020 program SYSTEM, grant agreement Nr. 787128. It was also supported by the Scientific Grant Agency APVV within the implementation of the project no. APVV-18-0205 “Management of crisis situations in water supply with respect to climate change”.

References
[1] S. A. Socolofsky and G. H. Jirka, Mixing and transport processes in the environment, Texas: Texas A&M University, 2005.
[2] C. Nordin and B. Troutman, “Longitudinal dispersion in rivers: The persistence of skewness in observed data,” *Water Resour. Res.*, vol. 16, no. 1, pp. 123-128, 1980.

[3] F. De Smedt, W. Brevis and P. Debels, “Analytical solution for solute transport resulting from instantaneous injection in streams with transient storage,” *J. Hydrol.*, no. 315, pp. 25-39, 2005.

[4] H. B. Fischer, E. List, R. Koh, J. Imberger and N. Brooks, Mixing in Inland and Coastal Waters, New York: Academic Press, 1979.

[5] D. Halmová, P. Miklánek, J. Pekár, B. Pramuk and P. Pekárová, “Longitudinal Dispersion Coefficient in Natural Streams,” *Journal for Management, Food and Environment: Die Bodenkultur - Austrian Journal of Agricultural Research*, vol. 65, no. 3-4, pp. 23-29, 2014.

[6] M. Sokáč, Y. Velísková and C. Gualtieri, “An approximate method for 1-D simulation of pollution transport in streams with dead zones,” *Journal of Hydrology and Hydromechanics*, vol. 66, no. 4, pp. 437-447, 2018.

[7] T. Julínek and R. Říha, “Longitudinal dispersion in an open channel determined from a tracer study,” *Environ Earth Sci.*, no. 76, p. 592, 2017.

[8] R. Schügerl, “Field study for determine Manning’s roughness coefficient with different flow conditions,” *Acta Hydrologica Slovaca*, vol. 20, no. 2, pp. 145 - 150, 2019.

[9] Y. Velísková and J. Kohutiar, “Determination of transverse mixing coefficient in wide and shallow rivers. (In Slovak),” *Journal of hydrology and hydromechanics (Vodohospodárska časopis)*, vol. 40, no. 6, pp. 506-516, 1992.

[10] M. Manina and P. Halaj, “Sensitivity analysis of input data in surface water quality models,” *Acta horticulturnae et regiotecturae*, vol. 22, no. 2, pp. 84-87, 2019.

[11] I. Tenebe, A. Ogbiye, D. Omole and P. Emenike, “Estimation of longitudinal dispersion coefficient: A review,” *Cogent Engineering*, vol. 3, no. 1, July 2016.

[12] R. L. Runkel, One-dimensional transport with inflow and storage (OTIS): A solute transport model for streams and rivers, *Water Resources Investigations Report 98–4018* ed., Denver, Colorado: U.S. Geological Survey, 1998.

[13] F. De Smedt, W. Brevis and P. Debels, “Analytical solution for solute transport resulting from instantaneous injection in streams with transient storage,” *J. Hydrol.*, no. 315, pp. 25-39, 2005.

[14] P. Halaj, V. Bárek, Y. Velísková, A. Báreková, K. Pecháčová and A. Stredňanská, “Longitudinal dispersion coefficient impact assessment on HEC-RASs water quality model outputs,” Albena, BULGARIA, 2013.

[15] L. Szomorová and P. Halaj, “Numerical simulations in the Mala Nitra stream by 1D model,” *Acta Scientiarum Polonorum-Formatio Circumiectus*, vol. 14, no. 2, pp. 185-194, 2015.