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IMPACT OF ROUGHNESS CHANGES ON CONTAMINANT TRANSPORT IN SEWERS

Marek Sokáč*, Yvetta Velísková

The paper deals with question how the bed sediment or deposits impact transport processes in conditions of flow with low velocity and water depth. This is often a problem especially in case of flow in sewer network. For this reason, there were performed several tests in laboratory flume having the shape of a pipe with circular cross-section. To simulate the hydraulic condition in sewer pipe with sediments and deposits, some sand was inserted in the pipe with various layer thickness and granularity. It was used a sand of fraction 0.6–1.2 mm. In total, 4 sets of experiments with different layer thickness were performed: with layer thickness of 0 mm (no sediments), 8.5 mm (3.4% of the pipe diameter), 25 mm (10%) and 35 mm (14%) of sand sediment. For each thickness of the sediment layer a set of tracer experiment was performed with different discharges ranging approximately (0.14–2.5) l s^{-1}. Results of the tracer experiments show, that the value of the longitudinal dispersion coefficient D_x in the hydraulic conditions of circular sewer pipe with sediment and deposits decreases when the Reynolds number is decreasing too. The value of D_x reaches its minimal value in the range of the Reynolds number between 4500 up to 10 000. With Reynolds number below this range the value of D_x start to rise.

KEY WORDS: contaminant transport, longitudinal dispersion, bed sediment, roughness, sewers

Introduction

Flowing water in any natural conditions is connected with substances transport. This process consists basically of advection and dispersion. Substances transport is due primarily to advection, but there are many situations in which dispersion plays an important role and cannot be neglected. Knowledge of the rate at which substances disperse in streams is essential to stream management especially if the carried substance is toxic and means contamination for the stream.
Predicting of pollution spread is important for the environmental protection. In the field of water quality modelling, several authors (Chapra, 1997; Fischer et al., 1979; Graf, 1998; Runkel and Broshears, 1991; Marsalek, et al., 2004; Meddah, et al., 2015) presented different approaches to understand and interpret the basic concept of water quality problems. In a case an accidental discharge in a stream, the prediction of the pollutant transport is crucial in effective and rapid decision-making. On the other hand, in the case of an illegal release of a toxic substance, the determination of the source of the pollution is even more complicated, since it is an inverse task with a high degree of uncertainty. A way to solve that can be finding a simple, precise, a reduced computational time and a minimum input data consuming solution – equation. But in natural condition dispersion process is impacted by several hydrodynamic parameters of flow. One of them is occurrence of bottom sediment which changes the roughness. This effect can be significant especially at low speeds and water depths. These conditions often occur in sewer networks.
This paper describes partial results of the research of the influence of bottom deposits in a circular pipeline in laboratory conditions to the value of longitudinal dispersion coefficient as a parameter of dispersion rate.

Theoretical background

Dispersion is a combination of molecular and turbulent diffusion, advection and shear (Meddah, et al., 2015). It is created by the non-uniformity of velocity fields related to the different characteristics of the stream such as geometry, roughness, and kinematics. The dispersion zones are usually (Rutherford, 1994): the initial mixing zone, the mid-field mixing zone and the „far" field zone, where dispersion is considered longitudinal and one-dimensional in the flow direction. In the mathematical models, the effect of dispersion is accounted by means of the dispersion coefficient, for the evaluation of which several procedures are proposed, supported by experimental studies.
One-dimensional advection-dispersion equation (ADE) describes the mixing and transport phenomena, where the following assumptions are considered:

- Vertical and transversal dispersions are very small;
- The pollutant is completely miscible in water;
- Chemical reactions between the pollutant and its environment are absent;
- The overall mass of pollutant is maintained during transport.

The form of this equation is then as follows:

$$\frac{\partial C}{\partial t} + v_x \frac{\partial C}{\partial x} = D_x \left(\frac{\partial^2 C}{\partial x^2}\right) + M \qquad (1)$$

where
C – substance concentration [kg m^{-3}];
v_x – fluid velocity in longitudinal direction [m s^{-1}];
D_x – dispersion coefficient in the longitudinal direction [m^2 s^{-1}];
t – time [s];
M_s – express the substance sources or sinks [kg m^{-3} s^{-1}];
x – distance in the longitudinal direction [m].

Relatively simple analytical solution of Eq. (1) can be obtained by using various mathematical approaches. One of the most used approach is the general solution of the ADE by (Socolofsky and Jirka, 2005), and eventually by (Fischer et al., 1979; Martin and McCutcheon, 1998), and it could be written as

$$C = \frac{M}{A\sqrt{D_x t}}\ f\left(\frac{x}{\sqrt{D_x t}}\right) \qquad (2)$$

where
M – substance mass [kg];
A – cross-sectional area of the stream [m^2];
f – unknown function (“similarity solution “).

Other symbols meanings are the same as in the previous equation. The most-used one-dimensional analytical solution of the equation (2) for simplified conditions and immediate solute input has the form (Martin and McCutcheon, 1998)

$$c(x,t) = \frac{M}{2A\sqrt{\pi D_x t}}\ exp\left(-\frac{(x - v_x t)^2}{4\,D_x\,t}\right) \qquad (3)$$

where
v_x – velocity of water flow in x direction of flow [m s^{-1}].

Unfortunately, the analytical solution used in Eq. (3) is based on the assumption of symmetrical substance spreading up- and downstream (Gauss distribution) and thus it does not take into account the temporary storage zones (dead zones) (Weitbrecht, 2004; Gualtieri, 2008; Valentine & Wood, 1977; 1979) or other singularities influencing substance spreading. Use of this approximation in streams with large presence of those singularities can be problematic. Because of this, we used in our research also alternative formulation of the one-dimensional analytic solution of the ADE based on the assumption of asymmetrical substance spreading. This alternative solution is based on the Gumbel statistical distribution and it has the form (Sokáč et al., 2019):

$$c(x,t) = \frac{M}{A\sqrt{D_{x,G} t}} \exp\left[\frac{x - v_x t}{\sqrt{D_{x,G} t}} - \exp\left(\frac{x - v_x t}{\sqrt{D_{x,G} t}}\right)\right] \qquad (4)$$

where
$D_{x,G}$ – dispersion coefficient in the longitudinal direction [m^2 s^{-1}] used in the Gumbel distribution model.

Materials and Methods

The experiments were performed in the hydraulic laboratory of the WUT (Warsaw University of Technology). In aim to simulate the hydraulic conditions of a real sewer, experiments were conducted in a hydraulic flume with form of the pipe with circular cross-section. The inner diameter of the pipe was 250 mm, length was 12 m, slope of the pipe was 0.5 % (5 ‰). The pipe material was transparent plastic; every 2 m there were holes at the top of the pipe, enabling the access into the pipe (measuring devices, sediment insertion and retrieval). At the pipe inlet there was a storage tank with water inlet in the bottom part of the storage tank. After the water level rises above the pipe bottom, water starts to flow into the circular pipe. At the downstream end of the pipe was a free outfall into another storage tank with outflow in the tank bed (Fig. 1).
A drinking water was used for all the experiments, without recirculation, so there was no problem with the tracer background concentration increase. The inflow into the system was regulated with a lever valve; using this device it was very difficult to set up the same discharge in the experiments. Because of this, in all the experiments the discharge was measured individually for each individual experiment, using a simple volumetric method below the water free outfall in the downstream storage tank.
To simulate the hydraulic condition in sewer pipe with sediments and deposits, some sand was inserted in the pipe with various layer thickness and granularity. It was used a commercially available sand of fraction 0.6–1.2 mm; coarser material – fine gravel – was spread on the bottom of the sand layer to create hydraulic conditions similar to the real sewer pipes. After each insertion the sand was spread and finely compacted; then water was discharged approximately 20 minutes through the pipe to saturate the sand layer and to naturally form the top of the sand layer. To stabilise the velocity and to prevent the water level drop connected with sand outwash, it was necessary to form a small weir at the end of the pipe.
In total, 4 sets of hydraulic experiments were performed with layer thickness of 0 mm (no sediments), 8.5 mm of sand sediment (3.4% of the pipe diameter), 25 mm (10%) and 35 mm (14%) of sand sediment. The layer thickness was measured with a portable calliper at the locations of the openings in the experimental circular flume with accuracy of 0.1 mm. For each thickness of the sand layer sediment a set of tracer experiment was performed with different discharges ranging approximately from 0.14 l s^{-1} up to 2.5 l s^{-1}. The upper discharge limit was set up individually for each experiment and with respect the sand wash-out.
The dispersion (tracer) experiments were performed

using the Rhodamine and the salt as tracers, for the concentration measurement there were used a fluorometric and a conductivity probe. The fluorometric probe (Turner designs, Inc.) has declared mini-mum detection limit 0.01 ppb and linear range 0–1000 ppb (linearity 0.99 R^2). The conductivity probe has a detection range from 1 μS cm^{-1} up to 1000 mS cm^{-1}, manufacturer (WTW) typically declares the accuracy for the probes of this type ±0.5% of measured value. The probes were placed at the pipe end, approximately 200 mm prior the weir at the pipe end. Tracers were dosed manually at the pipe beginning.
Each tracer experiment (for each combination of the layer thickness and discharge) was repeated five times. The data were measured in one second interval and they were saved automatically in the storage unit of the corresponding measuring device.
During evaluation of the measured data we noticed, that the fluorometric probe responded better to the concentration changes, its response time was minimal, whereas the conductivity probe had the response time about 2–3 secs. Moreover, the measured values were probably time-averaged by the device software. Because of this, we used only the measured data from the fluorometric probe in the evaluation process.

Results and discussion

Five tracer experiments, measured for the same discharge and deposit layer thickness, form one dataset. The example of such dataset is on the Fig. 2. Each measured tracer experiment was evaluated to determine the dispersion parameters according the Eq. (3) and Eq. (4). For the numeric evaluation, the statistical approach was used. The best approximation between measured and modelled data, i.e. the optimal set of dispersion parameters was determined searching the minimal root square mean error (RMSE). For the numeric optimisation procedure, the built-in function Solver in MS Excel environment was used.
The dispersion parameters, evaluated from five tracer experiments were averaged. The complete results are shown in Table 1. Graphical evaluation of the experiment results can be seen on the Fig. 3, 4, 5 and 6.

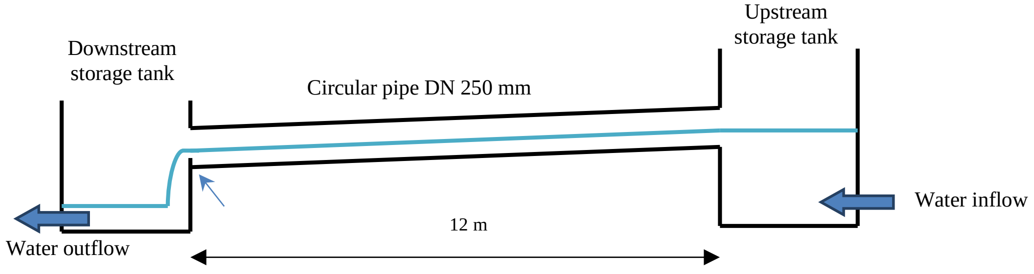

Fig. 1. Hydraulic scheme of the experimental device.

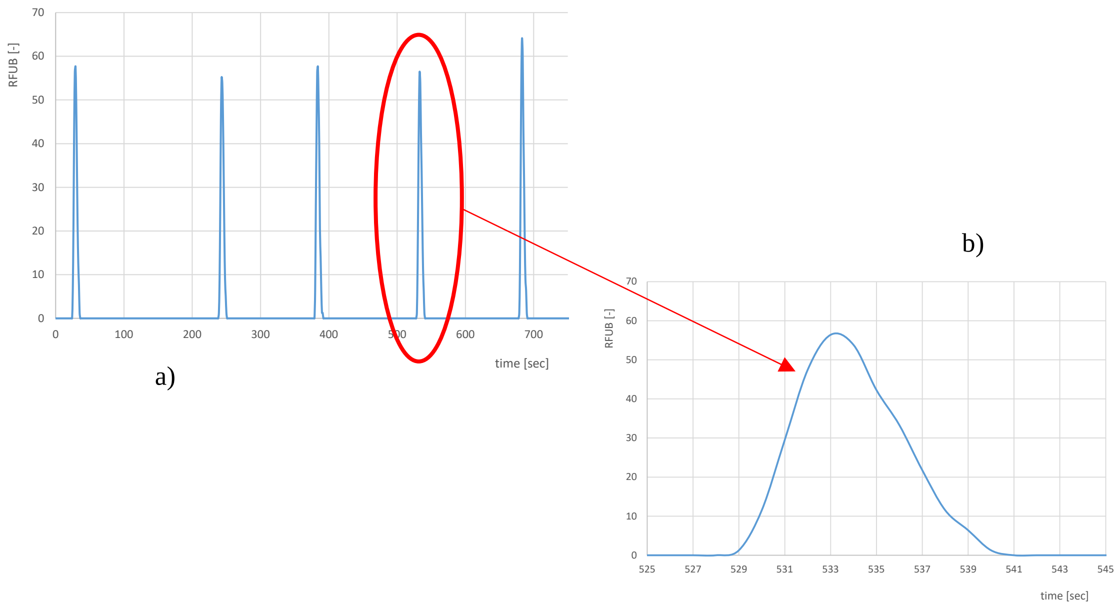

Fig. 2. Example of a dataset (a) and detail of a single experiment concentration time-course (b).

Table 1. Results of the tracer experiments

sediment	Dataset Nr.	Water depth	Discharge	Velocity	D_x	$D_{x,G}$
	[-]	[mm]	[l s^{-1}]	[m s^{-1}]	[m^2 s^{-1}]	[m^2 s^{-1}]
sediment 0 mm	37	10.4	0.145	0.211	0.011	0.016
	38	15.5	0.422	0.293	0.008	0.013
	11	19.6	0.505	0.324	0.008	0.014
	12	24	0.839	0.361	0.008	0.013
	13	29.6	1.170	0.385	0.009	0.015
	14	34.4	1.628	0.397	0.011	0.018
	15	40.3	2.237	0.458	0.014	0.023
sediment 8.5 mm	20	7.7	0.147	0.181	0.015	0.026
	20.1	16.6	0.410	0.232	0.010	0.016
	21	20.6	0.589	0.270	0.008	0.014
	22	24.7	0.799	0.306	0.008	0.013
	23	30.7	1.114	0.343	0.008	0.013
sediment 25 mm	28	5.9	0.140	0.157	0.021	0.038
	24	14.3	0.392	0.181	0.013	0.022
	25	18.1	0.600	0.220	0.008	0.013
	26	20.2	0.794	0.260	0.007	0.012
	27	24.6	1.227	0.330	0.007	0.013
sediment 35 mm	31	9.1	0.141	0.084	0.044	0.072
	32	14.2	0.410	0.155	0.015	0.024
	33	18.2	0.633	0.188	0.010	0.017
	34	21.1	0.876	0.224	0.008	0.014
	35	25.6	1.280	0.270	0.009	0.015
	36	30.2	2.070	0.370	0.012	0.021

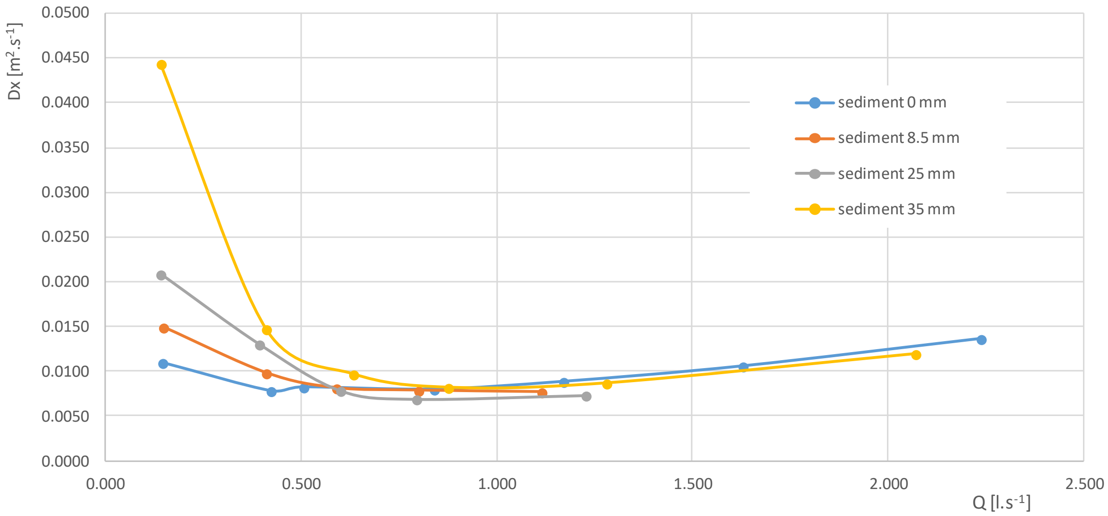

Fig. 3. Results of tracer experiments (D_x vs discharge Q).

From these figures it can be seen that the course of all evaluated dependencies is the same. The only difference is in the values of the dispersion coefficients: the values determined by using the Gaussian distribution are generally smaller than the values of the coefficient according to the distribution by Gumbel.

Interestingly, results of the tracer experiments also show that the value of the dispersion coefficient in the hydraulic conditions of circular sewer pipe with sediment and deposits reaches its minimal value in certain range of velocities (discharges), which are definitely not close to the minimal velocity. We assume that this phenomenon

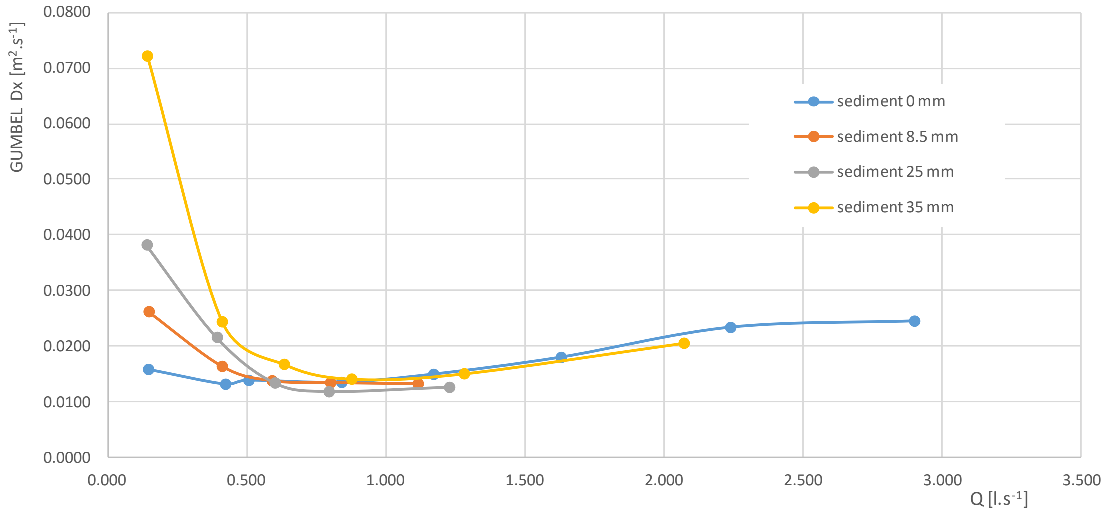

Fig. 4. *Results of tracer experiments ($D_{x,G}$ vs discharge Q).*

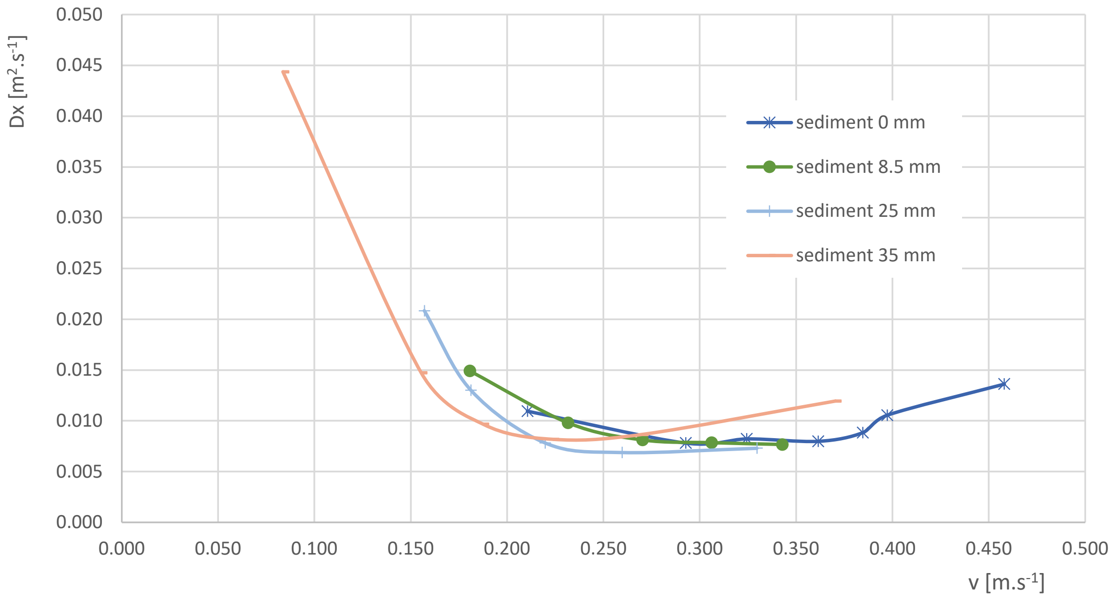

Fig. 5. *Results of tracer experiments (D_x vs velocity).*

can be caused due to specific hydrodynamic condition of the flow, which varies at shallow depths. However, this assumption needs to be further analysed.

In this study, we have tried to define the point with the minimum value of the dispersion coefficient, which has been not easy. One of the possible ways can be definition based on the Reynolds number, eventually based on geometric characteristics of the streambed (e.g. depth / width ratio).

In our case we have observed some dependency between the Reynolds number and the minimal value of the dispersion coefficient: the minimal values of the longitudinal dispersion coefficient occur for both applied distribution in the Reynolds number range from 4500 up to 10000 (Fig. 7 and 8).

Conclusions

The aim of this paper was to present the partial results of the study concerning dispersion processes in water flows with low velocity and occurrence of sediments or deposits. These results were obtained from the analysis of data from experiments in laboratory conditions. In this analysis there were used values of the longitudinal dispersion coefficient as a characteristic of mixing rate of flowing water. There were used two ways of their determination: by using Gaussian and Gumbel statistical distribution. These parameters were compared or put in the dependency with values of discharges and velocities in the various thicknesses of bed sediments conditions. Obtained values of the longitudinal dispersion coefficient have had a similar course of mentioned dependencies in both cases of used distributions, only values determined by using the Gaussian distribution are generally smaller than the values of the coefficient according to the distribution by Gumbel distribution. Results of the tracer experiments also have showed, that the value of the longitudinal dispersion coefficient in the hydraulic conditions of circular sewer pipe with sediment and deposits reaches its minimal value not in or close to the minimal velocity. Trying to define the point with the minimum value of this coefficient, we used the Reynolds number *Re* and analysed dependency of *Re* and D_x, eventually $D_{x,G}$. Results of analysis have showed that minimal values of the longitudinal dispersion coefficient occur in the Reynolds number range (4500–10000).

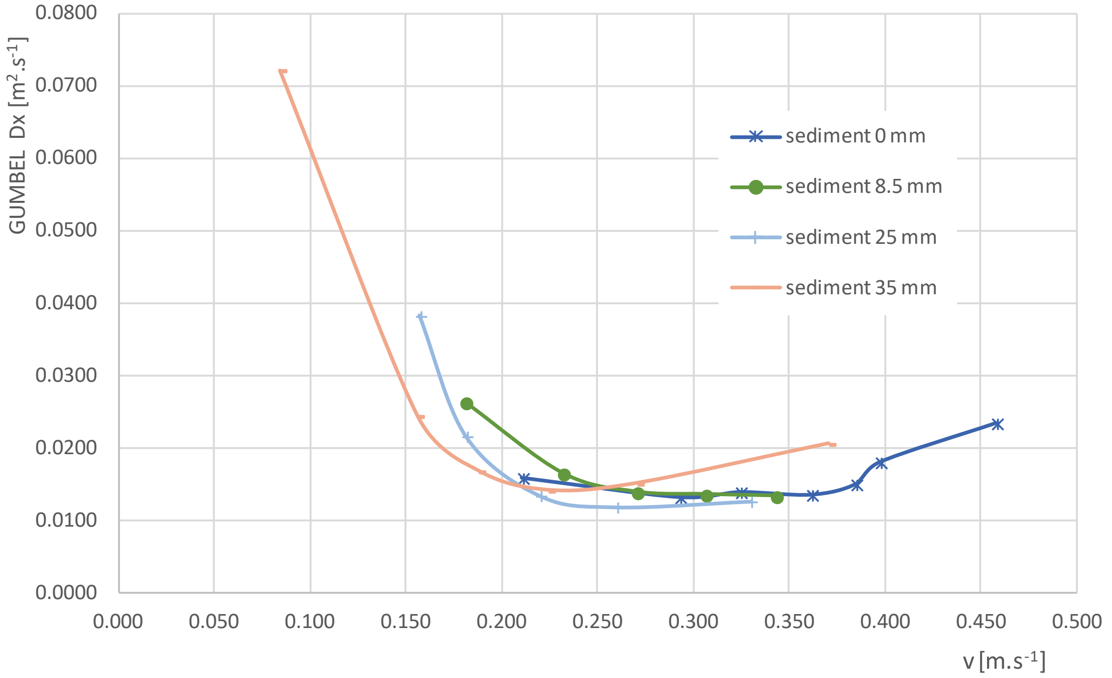

Fig. 6. *Results of tracer experiments ($D_{x,G}$ vs velocity).*

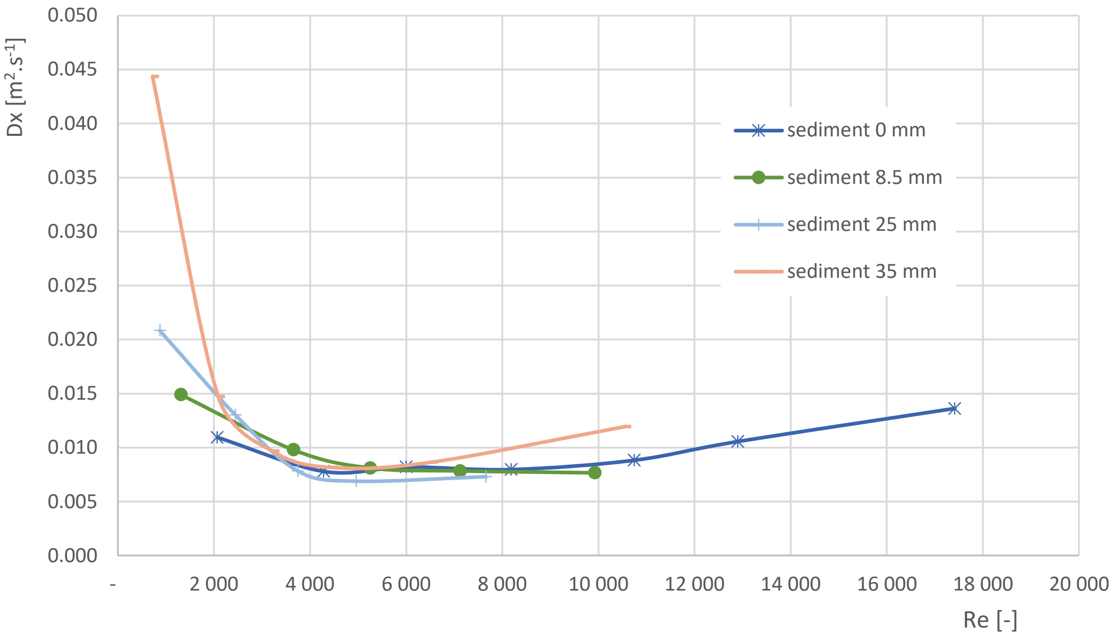

Fig. 7. *Results of tracer experiments (D_x vs Re).*

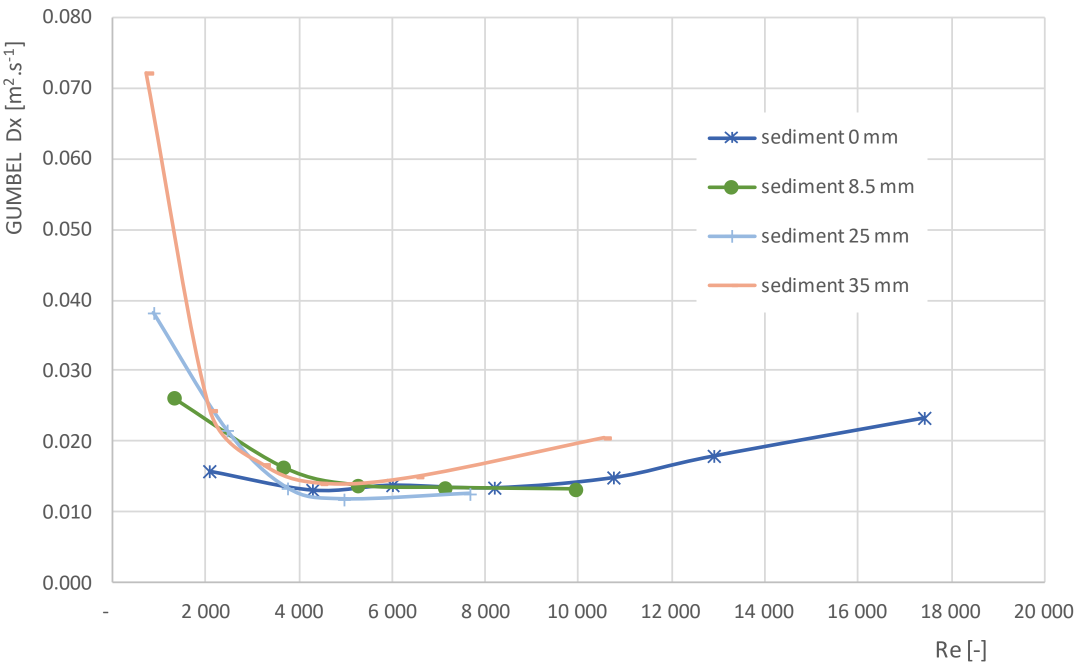

Fig. 8. *Results of tracer experiments ($D_{x,G}$ vs Re).*

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References

Fischer, H. B., et al. (1979): Mixing in Inland and Coastal Waters. New York: Academic Press.

Graf, W. (1998): Fluvial Hydraulics: Flow and Transport Processes in Channels of Simple Geometry. Hoboken, NJ, USA: Wiley.

Gualtieri, C. (2008): Numerical simulation of flow patterns and mass exchange processes in dead zones. Proceedings of the iEMSs Fourth Biennial Meeting: International Congress on Environmental Modelling and Software (iEMSs 2008), Barcelona, Spain.

Chapra, S. (1997): Surface Water-Quality Modeling. Series in Water Resources and Environmental Engineering ed. New York, NY, USA: McGraw-Hill.

Marsalek, J., Sztruhar, D., Giulianelli, M., Urbonas, B. (2004): Enhancing Urban Environment by Environmental Upgrading and Restoration. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Martin, J. L., McCutcheon, S. C. (1998): Hydrodynamics and Transport for Water Quality Modeling. s.l.: CRC Press, Inc..

Meddah, S., Saidane, A., Hadjel, M., Hireche, O. (2015): Pollutant Dispersion Modeling in Natural Streams Using the Transmission Line Matrix Method. Water, Issue 7, 4932–4950.

Runkel, R., Broshears, R. (1991): One-Dimensional Transport with Inflow and Storage (OTIS)–A Solute Transport Model for Small Streams. Boulder City, CO, USA: University of Colorado.

Rutherford, J. (1994): River Mixing. Chichester, U.K.: John Wiley & Sons.

Socolofsky, S. A., Jirka, G. H. (2005): Mixing and transport processes in the environment. Texas: Texas A&M University.

Sokáč, M., Velísková, Y., Gualtieri, C. (2019): Application of Asymmetrical Statistical Distributions for 1D Simulation of Solute Transport in Streams. Water, 11(10), p. 2145.

Valentine, E. M., Wood, I. R. (1977): Longitudinal dispersion with dead zones. Journal of Hydraulics Division, ASCE, 103(9), 975–990.

Valentine, E., Wood, I. (1979): Experiments in Longitudinal Dispersion with Dead Zones. Journal of Hydraulics Division, ASCE, 105(HY9), 999–1016.

Weitbrecht, V. (2004): Influence of dead-water zones on the dispersive mass-transport in rivers. Dissertationsreihe am Institut fuer Hydromechanik der Universitat Karlsruhe ed. Karlsruhe: Universitatsverlag Karlsruhe.

Doc. Ing. Marek Sokáč, PhD. (*corresponding author, e-mail: sokac@uh.savba.sk)
Ing. Yvetta Velísková, PhD.
Institute of Hydrology SAS
Dúbravská cesta 9
84104 Bratislava
Slovak Republic