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Dispersion process in conditions of real sewer systems – in situ experiments

Marek SOKÁČ*, Yvetta VELÍSKOVÁ

A general assumption of most current models used to simulate flow in sewer systems (pipes) is that the sewers are considered as prismatic channels. However, in real conditions there are many factors, which affect the real flow. One of them is the occurrence of the sediments and deposits in sewer pipes, which significantly changes the flow conditions, as well as the dispersion process in sewer systems by creation of "dead zones". Paper describes the effects of these zones on hydrodynamic dispersion process, which are particularly noticeable in hydraulic conditions of low flow rates in sewer system (sanitary, flow rates during dry period without rain …). In the study, there were applied two types of tracers and both used substances give identical results.

Experimental results show that even though sewer pipes are considered as prismatic hydraulic channels, in the real conditions some irregularities resulted with dead zones creation are presented. Their influence on the mass concentration time-course shape is depending on the sediment layer thickness. Gaussian approximation of the one-dimensional advection dispersion equation for instantaneous pollution entry is not suitable for the sewer pipes with sediments occurrence. In case of sediments presence, the GEV and Gumbel's approximation function looks to be more accurate.

KEY WORDS: sewer systems, sediments, hydrodynamic dispersion, dispersion coefficient, in situ-experiments

Introduction

Transport of substances in flowing water is influenced by the hydraulic conditions of streams. When dangerous substances are transported, the situation is much worse at low flow rates. In this case, there is a higher risk of exceeding the concentration limits of these substances (Čubanová et al., 2021). In real conditions on streams, the situation is even more complicated. Some rate of simplifications or schematizations is necessary for modelling, which of course also distorts the result. Therefore, when applying hydrodynamic models, one must be careful consider their appropriate application.

Sewer systems (pipes) are typically regarded as prismatic and regular hydraulic channels. This is also typical approach of most current models used for the simulation of the water quantity and quality in the sewer. However, in real conditions there are many factors, which affect and distort the flow and dispersion processes by forming so-called "dead zones". Generally, dead zones are formed in sewer systems by all obstacles and irregularities, which occur in the flow profile. These can be caused by various solid substances and objects that get into the sewer network, but also enlargements and narrowing of the flow profile (e.g. in shafts) as well as the irregularities in the sewer pipes slope and consequently caused backwater effects. This phenomenon becomes evident especially in conditions of low discharges (dry weather flows) and of course in case of lower sewer construction quality (irregular slopes, sewer settlement due to the ground consolidation) (Sokáč and Velísková, 2016).

We assume as the one of the most important factor of the of dispersion processes distortion the occurrence of the sediments and deposits in sewer pipes. These significantly changes the hydraulic conditions, as well as the dispersion process in sewer systems.

Modelling of the mass or pollution transport is currently practically an integral part of all hydrodynamic models, including models of runoff from urbanized areas to sewer systems. In this case, the transport models are typically reduced to 1D modelling, using the advection dispersion equation (1D ADE) in form (Martin et al., 2018; Rutherford, 1994).

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

where

- v_x – is the velocity of water flow in a given direction of flow [m s^{-1}],
- C – is the concentration of a substance [g m^{-3}],
- D_x – is the dispersion coefficient in the longitudinal direction [m^2 s^{-1}],
- S_s – is a function representing the sources of pollution [g m^{-3} s^{-1}],

x – is the spatial coordinate – distance [m],
t – is the time [s].

Such approach is fine from a formal point of view, but ADE does not take into account a very important fact (phenomenon), which occurs in real conditions: the occurrence of so-called dead zones. The dead zones are in fact water accumulation zones, where the water is temporarily stored and consequently released into the main flow (Czernuszenko and Rowiński, 1997; Gualtieri, 2010). Of course, this applies also to the substances suspended in the water.

As stated above, in the existing models sewer pipes are considered as a prismatic hydraulic channel with clearly defined hydraulic parameters. However, in the practice, after some time of the sewer pipe operation, the prismatic shape of the sewer pipes can be substantially changed due to the sediments and deposits at the bottom of the pipe. The deposits typically occur in sewer systems with small slopes (flat urban areas) and in sanitary sewer systems. In the combined sewer systems, the sediments are subject of spatial and temporary changes due to the stormwater flow in these systems. This phenomenon must be taken into account in the modelling the dispersion and flows in sewer systems (Manina et al., 2020).

However, also in combined sewer systems can fine sediment particles form so-called cohesive sediment, which is hardly removable by the self-cleaning ability of the sewer pipes (insufficient shear stress induced by the stormwater flows) (Stransky et al., 2016). Such sediments can be removed only by using mechanical cleaning procedures and technology, applied by the sewer system operator. Such cleaning shall be carried out regularly, but this is often omitted due to various reasons.

During our research, we encountered such conditions in sewer systems and we found out, that the sediments in sewer pipes significantly changes not only the hydraulic conditions compared to the original assumptions, but they also significantly change the dispersion process in sewer systems. The changes of the dispersion process are especially visible under low water flows conditions, e.g. sanitary flows (flow rates during dry period without rain in combined systems).

Material and methods

Dispersion coefficients characterise the intensity of dispersion or mixing, so it is one of the most important parameters for the pollution transport (dispersion) simulation. For application of the hydraulic model in real condition, it was necessary to verify the up-to date knowledge in this field as well as check if there are singularities, which distract the theoretical character of dispersion process (dead zones, deposits, sediments, obstacles etc.) (González-Pinzõn et al., 2013). For the most precise determination of dispersion coefficient value, we perform tracer experiments in real sewer pipes.

The experiments were performed in Petržalka, the right-bank part of the Bratislava city. The field experiments were performed in four campaigns, namely in May and June 2019, August 2021 and January 2022. All the experiments were performed within the research in the H2020 project SYSTEM. The research work in this project comprises laboratory as well as field experiments and development of a specific model, simulating the pollution spread in sewer systems (Fig. 1).

The first two campaigns were focused on experiments and data measurements for the dispersion coefficient determination in specific sewer sections (pipes) with various parameters and conditions, e.g. pipe diameter, pipe filling (flow depth). The third and fourth campaign was focused as complex experiments for the evaluation and calibration of the developed localisation model. In that case, large sections of the sewer systems were used, comprising several consecutive pipe sections with different diameters. This paper deals mainly with the first two campaigns, however it can be mentioned also some reference to the last campaign.

The lengths of the examined sewer sections were from 100 m up to 250 m. Experiments were performed in sewer pipes with diameter of 300 up to 3200 mm, in straight sections, without diameter changes. Because one of the main assumptions of the developed model was the presence of uniform and steady-flow, we performed all experiments during dry weather flows in sewer system, so only with the sanitary flow conditions in the sewer system.

As a tracer the kitchen salt and the colouring agent Rhodamine was used. The concentration of the salt (NaCl) was 1 kg of the salt in 10 litres of drinking water (approx. 110–115 mS cm^{-1}) and 1 ml of the 20% Rhodamine solution. Tracer dose (10 litres) was flushed in the upper manhole at a specific time. Measuring manhole was located in a specific distance downstream in the same sewers section. The measuring manhole was equipped with devices automatically registering time-courses of conductivity and fluorescence. The fluorescence was measured using portable fluorometric probe for Rhodamine (Turner designs) with data logger for data recording in specified intervals (the minimal interval can be set to 1 second). The conductivity was measured using portable conductivity meter (WTW Multi 3410) with data logger (the minimal record interval can also be set 1 second). The fluorescence / conductivity time-course data can be subsequently transferred into the concentration data.

Recorded time-courses were transferred into the MS Excel environment. Based on the registered concentration time-courses, it was possible to determine the dispersion coefficient value for the corresponding sewer section.

Values of dispersion coefficients obtained from the experiments were statistically evaluated.

Statistical evaluation was performed for each measured sewer branch using the specific approximation methods (Gauss, Gumbel and GEV). This procedure was focused on finding the best fit between the measured values and the approximation according to the considered method, i.e. to find the optimal set of the given method parameters providing the best goodness of fit based on the minimal root mean square error (RMSE) between the measured and approximated values, i.e.

a) b) c) d)

Fig. 1. Documentation of the experiment steps: a) tracer preparation, b) tracer dosing, c) measuring probes in the confluence manhole, d) data loggers for recording the measured data.

$$RMSE = \sqrt{\frac{\sum_{t=t_1}^{t=t_2}(c_{m,t}-c_{a,t})^2}{n}} \quad (2)$$

where
RMSE – is the root mean square error [kg m^{-3}],
$c_{m,t}$ – is the measured value (concentration) at the time t [kg m^{-3}],
$c_{a,t}$ – is the approximated value in the time t [kg m^{-3}],
t_1 – is the measurement start time [sec],
t_2 – is the measurement end time [sec],

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{c_{\max}-c_{\min}} \quad (3)$$

where
NRMSE – is the normalised root mean square error [-],
c_{max} – is the maximal concentration in each particular experiment [kg m^{-3}],
c_{min} – is the minimal concentration in each particular experiment [kg m^{-3}].

The optimal sets of parameters were analysed and set up using the built–in Excel Solver function. The target value is the main indicator for the optimization process, looking for a minimum value for this indicator. In our case it was the RMSE value.

Results and discussion

Expected results of the first two campaigns of performed experiments were the determination of dispersion coefficient values for the selected pipes and the selection of the best applicable formula for the dispersion coefficient calculation. Another expected result was a verification, if the theoretical dispersion formulas fit with the experiment results. In case of differences, it was necessary to search for the reasons and try to modify the theoretical model basis. A typical reason of the differences could be occurrence of dead zones.

One of the secondary goals was also assessment of the tracer experiments technology. As it was mentioned above, the kitchen salt as well as the florescent dye was used as a tracer in experiments. An example of the comparison of the results, achieved by both tracers can be seen on the Fig. 2.

When evaluating measurements and experiments, we came to result, that every tracer has its advantages and disadvantages. The advantage of the Rhodamine tracer is the fact, that its background concentration is zero (or values close to zero), so there is clear distinction of the experiment's concentration from all influences (released pollutants) that may occur in the sewer network during the experiment. This does not fully apply to the second tracer – the salt. The background concentration (measured as the conductivity) is not equal to zero and the measurement can be substantially affected by the fact that in the sewer network can be various sources of substances or pollutants affecting the wastewater conductivity (wastewater from washing, dishwashers, small industry). Such small disturbances can be also seen on the Fig. 2 in the time 12:14 and later (red line).

The disadvantage of the Rhodamine tracer was the high sensitivity of the measuring device – in many aspects, this fact is rather an advantage, but for this reason, it was necessary to clean the measuring probe regularly in the sewer environment. This can be also seen on the disturbances on the Fig. 2 – blue line before the time 12:07, where decreases of the measured values caused by the impurities on or close to the measuring probe appeared. The probe of the conductometric device was more practical in this respect and less prone to failures.

The common problem of both tracers was the determination of the dose to perform successful measurements in the entire device measuring range. With an insufficient tracer dose, the minimum detection sensitivity of the used device may be exceeded, and with an excessive dose, the measuring range of the device may be exceeded. The later one can be also seen on the Fig. 2 – the upper measurement limit for the fluorimeter was 500 000 RFUB (Raw Fluorescence Units Blanked) units. This limit was exceeded in the time around 12:07 (blue line), so the time course peak is "cut off".

From this point of view, it was very useful to use both tracers. This allows us during the evaluation of the measurements clearly determine whether it is a device error or a random fluctuation in the measured values.

Summary of field measurement parameters and result values of the dispersion coefficients are presented in Table 1.

Because the experimental area (Petržalka) is flat, the sewers are often in very small or minimal slopes. This naturally causes deposits to occur. This assumption was confirmed, and we really found large presence and thickness of sediments and deposits in some sewer branches (see Table 2). This concerns particular for the sewer branches with small diameters (less than 500 mm), where the flow rates were relatively small. In sewer branches with larger diameters, typically larger flow rate of wastewater was present, so the occurrence of sediments was more rarely. In large sewer collectors, no sediments were present.

As found by measurements evaluation, the presence of sediments affects (deforms) in large extent the shape of the concentration time-courses. This finding inspired us to continue this research also in laboratory conditions (Sokáč and Velísková, 2020).

Values of the dispersion coefficients D_x, calculated in this study, are in line with our results from previous studies (Sokáč and Velísková, 2016; Velísková et al., 2009). The range of the dispersion coefficient in these studies

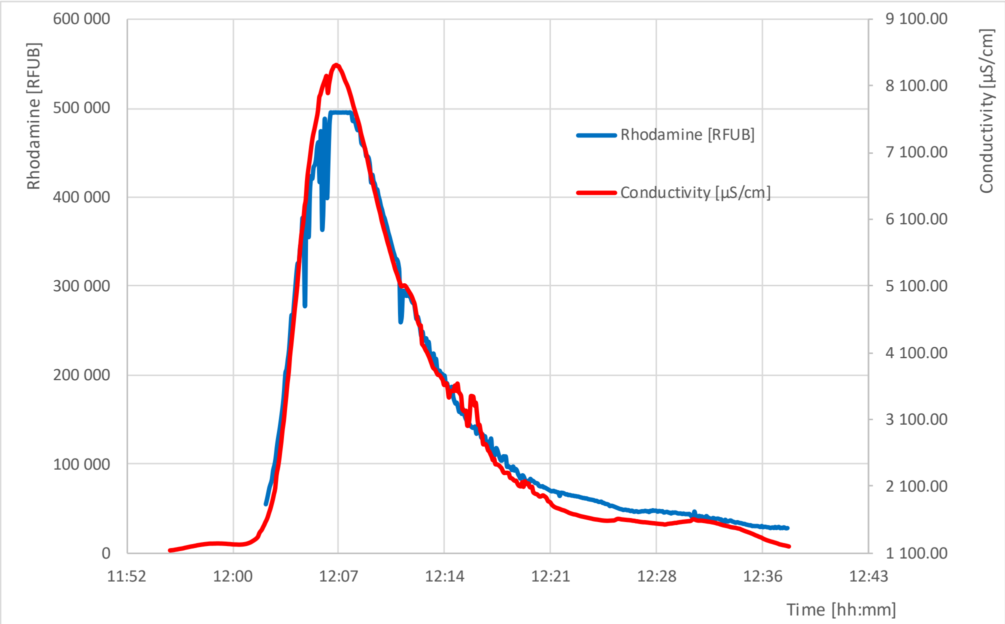

Fig. 2. Example of the experiment records (Rovniankova str., DN 400, 25th of June 2019).

Table 1. **Results of field experiments**

Exp. Nr	Sewer diameter (DN)	Sewer branch length	Flow velocity	Dispersion coefficient D_x-Gauss	Dispersion coefficient D_x-Gumbel	Dispersion coefficient D_x-GEV	Shape coefficient GEV
	[mm]	[m]	[m s^{-1}]	[m^2 s^{-1}]	[m^2 s^{-1}]	[-]	[-]
11	300	141	0.200	0.337	0.529	0.653	0.425
12	300	141	0.150	0.135	0.216	0.315	0.469
13	400	152	0.298	0.112	0.191	0.192	-0.049
14	400	152	0.280	0.111	0.192	0.192	-0.042
22	400	325	0.213	0.519	0.707	0.706	0.112
23	400	102	0.060	0.120	0.192	0.252	0.497
24	400	102	0.060	0.058	0.095	0.098	0.179
19	500	114	0.080	0.061	0.104	0.114	0.193
27	500	353	0.131	0.114	0.197	0.197	-0.025
17	600	130	0.195	0.035	0.059	0.060	0.111
18	600	130	0.192	0.025	0.042	0.043	-0.026
28	600	268	0.289	0.070	0.115	0.116	-0.095
15	3200	153	0.371	0.088	0.153	0.154	-0.116
16	3200	153	0.359	0.065	0.113	0.121	-0.246
25	3200	362	0.333	0.068	0.120	0.123	-0.197
26	3200	362	0.327	0.059	0.106	0.106	-0.192

Table 2. **Results of field experiments – NRMSE**

Exp. Nr	Estimated sediment thickness	NRMSE		
		Gauss	Gumbel	GEV
	[mm]	[%]	[%]	[%]
11	40	10.87	6.95	5.39
12	40	13.01	6.83	2.00
13	50	5.54	3.09	2.96
14	50	5.50	2.46	2.34
22	50	8.34	4.01	3.45
23	100	11.20	6.65	3.26
24	100	8.79	3.30	1.58
19	80	9.31	4.58	3.68
27	20	6.27	2.21	2.15
17	10	6.84	3.50	3.06
18	10	4.11	2.04	2.01
28	30	4.32	2.95	2.49
15	0	5.29	5.32	5.10
16	0	3.51	6.57	3.41
25	0	2.65	4.44	2.24
26	0	3.14	4.47	1.73
	Average	6.79	4.34	2.93
	Min	2.65	2.04	1.58
	Max	13.01	6.95	5.39

was determined in range 0.085–0.12 m^2 s^{-1}, but it is necessary to mention that this research was performed in clean and new sewer pipes. We can also state a good agreement with the study of (Rieckermann et al., 2005), where the average value of 0.16 m^2 s^{-1} was set up (10- percentile was 0.05 m^2 s^{-1} and 90-percentile was 0.36 m^2 s^{-1}).

The extent of dead zones and their influence on asymmetricity (distortion) of the dispersion process could be expressed by the value of the shape coefficient ξ, used in the GEV approximation (see eq. 7). This shape parameter (see Table 1) expresses the asymmetry of the concentration distribution in time. A 'neutral' value of the shape parameter, which corresponds to the shape of the Gaussian approximation function is -0.288 (in case of dead zones are not present). Higher values of this coefficient are caused by dead zones and corresponding asymmetricity of the concentration distribution in time (represented by longer "tails" of the time concentration curves). Higher values of the shape parameter ξ in this way indirectly characterise the extent of dead zones.

As can be seen in Table 1, greater influence of the dead zones was found in case of smaller sewer pipe diameters and higher sediment layer thickness (see Table 2), whereas larger sewer pipe diameters showed less impact of the dead zones.

For the evaluation of all experiments we used the analytical solution of the equation presented in form (Rapp, 2016), (Cunge et al., 1980):

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

where

D_x – is the longitudinal dispersion coefficient [$m^2\,s^{-1}$],

$C(x,t)$ – is the concentration of solute in a particular distance and time [$g\,m^{-3}$],

G – is the mass of solute [g],

A – is the discharge area in a stream cross-section [m^2],

v_x – is the mean flow velocity [$m\,s^{-1}$],

t – is the time [s],

x – is the distance [m].

All measured results from tracer experiments were statistically evaluated, whereas the main result was the value of the dispersion coefficient D_x determination. Because experiments with the presence of sediments showed presence and influence of "dead zones", we found the evaluation of the dispersion coefficient using the eq. 4 as insufficient and therefore we used alternative equations based on asymmetrical probability (tracer concentration) distributions, e.g. on the Gumbel or GEV distribution (Sokáč et al., 2019).

As the 1-D analytic solution of the ADE (eq. 1) coming from the Gumbel statistical distribution (Loaiciga and Leipnik, 1999; Sokáč et al., 2019) this relation was applied:

$$c(x,t) = \frac{M}{A\sqrt{D_{x,G}t}} \exp\left[\frac{x-u\,t}{\sqrt{D_{x,G}t}} - \exp\left(\frac{x-u\,t}{\sqrt{D_{x,G}t}}\right)\right] \tag{5}$$

where

$D_{x,G}$ – is the longitudinal dispersion coefficient [$m^2\,s^{-1}$] by the Gumbel's approximation model.

Both the Gaussian approximation model (eq. 4) and the Gumbel's approximation model (eq. 5) are two-parametric models, where the first parameter is the dispersion coefficient and the second parameter is the peak time (mean), expressed through the velocity of water flow u.

Even better results and conformity between models and data from real measurements can be obtained using the three parametric Generalised Extreme Value (GEV) distribution model (Sokáč et al., 2019):

$$c(x,t) = \frac{M}{A\sqrt{D_{x,GEV}\,t}} \, z(t)^{\xi+1} \, e^{-z(t)} \tag{6}$$

$$z = \left(1 + \xi\left(\frac{\bar{v}.t-x}{\sqrt{D_{x,GEV}\,t}}\right)\right)^{-\frac{1}{\xi}} \tag{7}$$

where

$D_{x,GEV}$ – is the longitudinal dispersion coefficient [$m^2\,s^{-1}$] used in the GEV distribution model,

ξ – is the shape parameter. It express the asymmetry of the concentration distribution in time.

An example of one of measured parameter time courses (in this case a conductivity time course) is shown on Fig. 3. As it can be seen on this graph (Fig. 3), the approximation using eq. 4 (Gauss) is not appropriate, this approximation does not reflect the asymmetry of the tracer concentration time-course. Much better was the approximation based on the Gumbel's approximation and the best agreement was obtained by using GEV model approximation. This was also confirmed by the statistical tests – results of the statistical evaluation

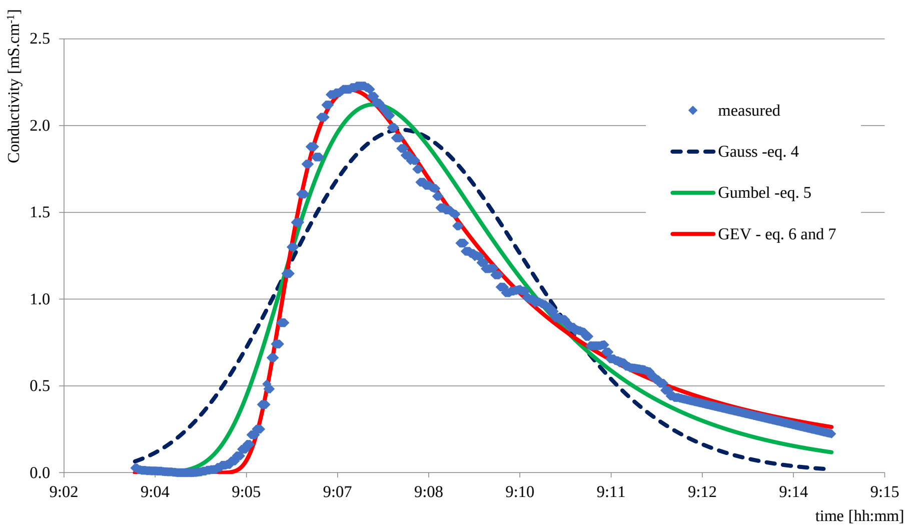

Fig. 3. Example of the experiment record and its approximations.

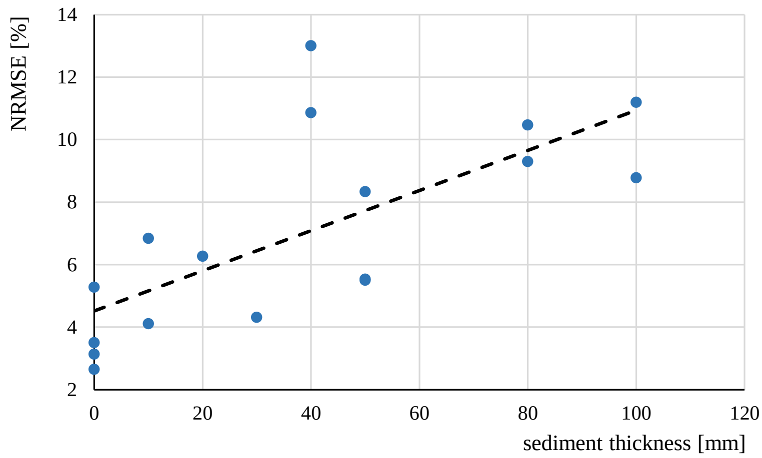

Fig. 4. Relation between the sediment thickness and the NRMSE of Gaussian approximation.

are presented in the Table 2.

As it can be seen in this table (Table 2), the best approximation results are achieved using different approximation methods than the Gaussian one. An interesting fact is that the NRMSE of the Gaussian approximation value increases with increasing sediment thickness, as documented on the Fig. 4. It points out that the Gaussian approximation (eq. 4) is suitable only for the clean sewer pipes without sediments. Larger sediment layers form in sewer pipes transient storage (dead) zones, which deforms the shape of the concentration time course in the downstream measuring profile of a tracer experiment. The correlation coefficient of the sediment thickness and the NRMSE is approximately R^2=0.5.

Conclusion

The performed tracer experiments give us a lot of experience and new knowledge. Regarding practical experience, the use of each tracer has its advantages and disadvantages. In terms of obtained results (dispersion coefficients, eventually other approximation parameters), both used substances give identical results. The use of both tracers simultaneously proved to be a great advantage, as this allowed us to distinguish random fluctuations and detect measurement errors.

Analyse of the obtained results shows following facts:

1. even though sewer pipes are considered as prismatic hydraulic channels without dead zones, in the real conditions the dead zones are present,
2. the presence of sediments and deposit in sewer pipes is one of the most important factor of the dispersion process distortion, especially in low flows conditions (dry weather flows),
3. the volume (size) of these dead zones and their influence on the time-course shape (deformation) is depending on the sediment layer thickness and
4. the Gaussian approximation of the one-dimensional advection dispersion equation for instantaneous pollution entry (eq. 4) is not suitable for the sewer pipes with sediments occurrence.

The comparison of the used approximation methods shows that the GEV approximation function (eqs. 6 and 7) was the most precise, thus the most suitable for application in real sewers. This approximation was in case of all experiments more precise than the Gaussian (eq. 4) and the Gumbel's approximation (eq. 5) functions. It is a result of the fact that the GEV approximation function is a three – parametric function, whereas the first two ones are only two – parametric functions. The Gumbel's approximation function proved to be more accurate for experiments with sediments presence, whereas for the clean sewer pipes the Gaussian approximation function was more accurate.

In the sewer pipes with large diameters, the effect of the dead zones was not so significant. This is because the self-clean ability of those sewer pipes is bigger than the small ones. In general, the flow rate in such big sewer pipes is larger, so the ratio of the sediment thickness and the water depth is small, thus the dead zones volume comparing to the flowing water volume is small, as well.

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Assoc. Prof. Ing. Marek Sokáč, PhD. (*corresponding author, e-mail: sokac@uh.savba.sk)
Ing. Yvetta Velísková, PhD.
Institute of Hydrology SAS
Dúbravská cesta 9
841 04 Bratislava
Slovak Republic