Dispersion Process in Sewer Pipes with Sediments and Deposits

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Abstract. This paper describes the dispersion process in sewer pipes, which is from the hydraulic point of view a prismatic stream channel with relatively constant roughness of streambed. In such hydraulic conditions should the effect of “dead zones” not occur, but this effect was observed during the field experiments. The reason for this was the presence of bed sediments and deposits, which form together with other small obstacles irregularities in the sewer pipe such dead zones. Dead zones are areas with small flow velocities, which act as a zone with transient (temporary) storage, where the pollution is accumulated and released gradually later. This process modifies the dispersion process in sewer systems and causes irregularities in the transport process. Field experiments were performed in a straight sewer section and also in the part with directional changes of sewer line, both under dry weather flow conditions, i.e. with relatively low pipe filling, discharges and velocities. Sewer pipes had a low slope, so a lot of deposits and sediments were present. Paper presents the results of field experiments and analyse the impacts of sediments and deposits in sewer system on the transport and dispersion process, which is reflected in the value of dispersion coefficient. In the case of sewer pipelines, the most important is the longitudinal dispersion coefficient $D_L$. Comparing the values of $D_L$ in the straight part and in the part with directional changes, $D_L$ values in the straight part were higher than from the section with directional changes. The maximal value of the dimensionless longitudinal dispersion coefficient $p$ reached 25.2 in a straight section; in the part with the directional changes $p$ it was up to 39.3. This result indicates that in the straight part of the sewer line, the longitudinal dispersion of the substance is dominant in the total dispersion process, whereas in the sewer part with directional changes, the transversal (lateral) dispersion contributes to the whole mixing process (dispersion process is also influenced by the velocity gradient in the transverse direction). Within the measured channel section, there were three directional changes - angles of 90°, 135° and 105°. The influence of the direction change angle to the longitudinal dispersion coefficient within the performed measurements has not been clearly determined yet.

1. Introduction
Dispersion, from a hydrodynamic point of view, is the spreading of mass from highly concentrated areas to less concentrated areas in flowing fluid. Mass dispersion with advection is basic motion mechanics of particles, transported in water. Reductions of maximum concentrations are results of their effects. The main characteristics of dispersion are dispersion coefficients in relevant directions.
Determination of these dispersion characteristics is the key task for solving the problem of pollutant transport in flowing water and for modelling of that phenomenon [1-3]. Spreading and mixing processes in flowing water can be influenced by the occurrence of so-called “dead zones” or “transient storage zones” in a stream [4-6]. There are zones that deform the concentration distribution of the transported substance or particles because they have been accumulated in these zones and released gradually later. That distorts the concentration time course curve, which becomes asymmetrical.

Sewer pipes are from the hydraulic point of view a prismatic stream channel with relatively constant roughness of streambed. But in such hydraulic conditions the effect of “dead zones” could occur because of sediments and deposits along the pipes or because of other irregularity appearance.

It could seem that dispersion process is not so important for the transport of substances or particles in sewer pipes, but this knowledge could be very useful in case of the outlet of dangerous illegal substances and the necessity to identify the source [7-9].

2. Theoretical basis

The simplest description of the mass spreading in flowing water, especially in sewer pipes, is a one-dimensional advection-dispersion equation, which describes the phenomenon in longitudinal direction x (uniform distribution of a mass concentration is required along with a depth and a width of a stream). The form of this equation is:

\[
\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} = -AKC + C_s q_s
\]

(1)

where: \(C\) is a mass concentration (kg.m\(^{-3}\)); \(DL\) is the longitudinal dispersion coefficient (m\(^2\).s\(^{-1}\)) – \(D = df + \varepsilon\), where \(df\) is the coefficient of turbulent diffusion, \(\varepsilon\) is the coefficient of molecular dispersion, \(\varepsilon\) is often neglected, because \(df \gg \varepsilon\) in flowing water streams; \(A\) is a discharge area in a stream cross-section (m\(^2\)), \(Q\) is a discharge in a stream (m\(^3\).s\(^{-1}\)), \(K\) represents a rate of growth or decay of contaminant (s\(^{-1}\)), \(C_s\) is the concentration of a source, \(q_s\) is a discharge of a source, \(x\) is a distance (m), \(t\) is time (s).

Such a one-dimensional approach is applicable for rivers or streams with comparatively non-wide channel or, as it was mentioned, for sewers. In this case, the pollutant spreading has markedly one-dimensional character.

As it follows from references [2-5, 10-17], the longitudinal dispersion coefficient \(DL\) determination is achieved by several ways: from the own experience or that from the references, over the qualified estimates, up the special calculations application.

Most of the published relations for the \(DL\) determination are based on experimental results from laboratory physical models or directly from the field measurements at the rivers, rarely in sewers (see Table 1). Such relationships are often in the following form [2]:

\[
DL = p.h.u_\ast
\]

(2)

where \(p\) is the empirical dimensionless coefficient, \(h\) is the mean river section depth (m), \(u_\ast\) is the friction velocity (m.s\(^{-1}\)).

Another form of the equation for \(DL\) prediction, which is based on hydraulic parameters, is expressed in the form [1]:

\[
DL = q \frac{u^2 B^2}{u_\ast h}
\]

(3)

where \(q\) is the empirical dimensionless coefficient (according to Fischer \(q=0,011\)), \(u\) is the mean velocity (m.s\(^{-1}\)), \(B\) is the water surface width (m).
Table 1. Values of longitudinal dispersion coefficients $D_L$ and dimensionless dispersion coefficient $p$ from experiments

| Author                | Conditions                                      | $D_L$ [m$^2$.s$^{-1}$] | $p$  |
|-----------------------|-------------------------------------------------|------------------------|------|
| Říha et al.           | Svitav River                                    | 5.2-8.1                | 100-250 |
|                       | $B=11.5$m; $h=0.9$m; $Q=(2-3)$m$^3$.s$^{-1}$; $u=0.5$ms$^{-1}$ |            |      |
| Brady, Johnson        | Wear River                                      | 4.4-87.22              | 94.9-2 200 |
|                       | $B=(20-27.6)m$; $h=(0.45-1.85)m$; $Q=(1.62-3.93)$ m$^3$.s$^{-1}$; $u=(0.07-0.15)$ms$^{-1}$; $i=(0.004-0.17)%$ |            |      |
| Velísková, Pekárová  | Ondava River (upper part)                       | 0.84-1.36              | 49.3-80 |
|                       | $B=12m$; $h=0.28$m; $Q=0.9$ m$^3$.s$^{-1}$; $u=0.35$ ms$^{-1}$; $i=0.0033$ |            |      |
| Glover                | South Plate River                               | 15.7                   | 500   |
|                       | meandering stream                               |                        |      |
|                       | $R=0.46$m; $Q=15$ m$^3$.s$^{-1}$; $u=1.33$ ms$^{-1}$; $n=0.028$ |            |      |
| Glover                | Mohawk River                                    | 6.0                    | 800   |
|                       | complicated flow conditions (power station, reservoir, tributaries, inflows...) |            |      |
|                       | $h=6$m; $Q=30$ m$^3$.s$^{-1}$                   |                        |      |
| Duarte, Boaventura    | Mondego River                                   | 14-51                  |       |
|                       | $Q=40$ m$^3$.s$^{-1}$; $u=(0.47-0.53)$ ms$^{-1}$ |            |      |
|                       | $Q=(100-140)$ m$^3$.s$^{-1}$; $u=(0.95-1.1)$ ms$^{-1}$ | 52-61                 | -     |
|                       | Tagus River                                     | 7.3-14.8               |       |
|                       | $Q=23$ m$^3$.s$^{-1}$; $u=(1.11-1.16)$ ms$^{-1}$ |            |      |
| Fischer               | Laboratory rectangular flume                    | 0.0072-                | 8.7-30 |
|                       |                                                 | 0.063                  |      |
| Fischer               | Laboratory triangular flume                     | 0.123-0.415            | 190-640 |

$B$ – width, $h$ – depth, $Q$ – discharge, $u$ – flow velocity, $i$ – longitudinal bed slope, $R$ – hydraulic radius, $n$ - roughness

3. Field measurements
The field measurements were performed near to the experimental hydrological base of Institute of Hydrology in Liptovský Mikuláš (Slovakia). The part of the sewer network, which was built in 2004-2005 under the EU Cohesion Fund project, was selected for field measurements.

The collector has profile DN 500 mm with slopes in the range from 2% to 9.5 %. After more detailed reconnaissance there were selected two sections for field experiments – the first one is a straight sewer section above Podtureň village and the second part is close to the place Borová Sihoť, near Liptovský Hrádok (see figure 1 and figure 2).
In both parts were selected several sewer sub-sections with various length, with diverse tracer inlets and measuring stations (manholes). The experiment was repeated in each section at least three times to obtain three valid tracer concentration time courses.

In the second section, there are three sewer direction changes (angles of 90°, 135° a 105°) in which the distributions of tracer concentration in time were measured at various parts of the sewer. The aim was to determine the influence of these trajectory diversions on the dispersion coefficient (see figure 2).
The common (kitchen) salt (NaCl) was used as a tracer. Various tracer concentrations influenced the variation of wastewater conductivity. The colouring agent (fluorescein) was added to the tracer to monitor the passage of tracer substance in the manhole of measurements. The dosage of tracer was 5 l and it was discharged to sewer instantaneously.

The measurement of conductivity was performed with the electric conductivity meter device in the selected manholes. The conductivity meter probe was situated in the centre of the wastewater stream.

All measurements were performed in dry weather conditions, so the pipe filling ranges from 10 up to 25% of the pipe diameter. Velocity in the pipe was in the range from 0.25 up to 1.2 m.s\(^{-1}\). A total of 61 tracer experiments were performed, but only about 54 datasets are identified as reliable for further data processing. The most common cause for dataset excluding was a missing part or irregular shape of the conductivity distribution in time due to measurement devices failures, etc.

4. Material and methods
The determination of longitudinal dispersion coefficient from experiment results was performed in two ways: the first one consists of a simulation of tracer experiment (concentration distribution) for various values of longitudinal dispersion coefficient.

The base for this numerical simulation is the analytical solution of Eq. (1) for instantaneous injection of tracer [18]:

\[
C(x,t) = \frac{G}{2A\sqrt{\pi D_t t}} \exp\left[-\frac{(x-ut)^2}{4D_t t}\right] \tag{4}
\]

where \(C(x,t)\) is a mass concentration (kg.m\(^{-3}\)) in a place and time; \(D_t\) is the longitudinal dispersion coefficient (m\(^2\).s\(^{-1}\)); \(A\) is a discharge area in a stream cross-section (m\(^2\)), \(G\) is the mass of a tracer (kg), \(u\) is a mean velocity (m.s\(^{-1}\)), \(x\) is a distance (m), \(t\) is time (s).

The difference between the measured and simulated values was evaluated. The minimum of difference squares determines the value of the longitudinal dispersion coefficient for each one of the experiments.

The second way for evaluation of the longitudinal dispersion coefficient is based on direct determination of the statistical parameters (\(\sigma\), standard deviation) of the acquired conductivity time courses. Principle of this method is to find the time, corresponding to the 15.87 and 84.13 percentile of the cumulative concentration curve [6]. The distance of these two points is equal to \(2\sigma\) and dispersion coefficient can be determined as:

\[
D_t = \frac{u^2\sigma^2}{2t} \tag{5}
\]

5. Results
The output of field measurements is the record of tracer concentration time courses, deducted from the wastewater conductivity time courses in the sewer. All results of field measurements in the dimensionless form of time courses are shown in figure 3. The examples of graphic expression of a single tracer time courses records (in real units) are shown in figure 4, 5 and 6.
The principle of experiment results evaluation was described in the previous part. For experiment series at lower discharge (and thus also lower water level), the measurement processing revealed that some pipe irregularities could exist in some measurement sections which influence the flow conditions and create so-called „dead zone“ in pipe flow. This phenomenon showed up in section with the 90° curve the most significantly (it was the lowest water depths there).

In this dead zone, the tracer has been accumulated and released gradually later. That skews the conductivity time course curve, it becomes asymmetrical and a „tail“ was formed because of the later tracer release. This can be seen in figure 6.

6. Discussion
It is necessary to mention a fact which occurred during the practical implementation: during evaluating the results of the measurements - it was found that the conductivity and the measured concentration of the tracer have no linear dependency in the full extent. This was verified and confirmed by conductivity meter calibration. The calibration curve was applied for the measurements evaluation.
Figure 5. Behaviour of concentration distribution in the manhole of measurement record (manhole Nr. 127), experiment Nr. 7, 6th August 2008 (an inlet of tracer – manhole Nr. 133)

Figure 6. Behaviour of concentration distribution in the manhole of measurement record (manhole Nr. 157), experiment Nr. 2, 7th August 2008 (an inlet of tracer – manhole Nr. 161)

The result longitudinal dispersion coefficient values from both determination ways of tracer experiments are summarized in Table 2.

Values of longitudinal dispersion coefficients from both ways of determination were compared. It could be established that the first approach (based on numerical simulations by Eq. 4) generally gives lower values of $D_L$ approximately by 10% (the range is from 50 to 110%, average 89.2%), relating to the direct statistical parameters determination. Experiments with bigger irregularities (asymmetry) in the shape of conductivity time courses were especially problematic.

Table 2. Statistical results of field experiments

| Evaluation method | Model approach | Statistical approach |
|------------------|----------------|---------------------|
|                  | Straight sewer line | Part with directional changes | Both parts together | Straight sewer line | Part with directional changes | Both parts together |
| Nr. of experiments | - | 24 | 30 | 54 | 24 | 30 | 54 |
| Average           | m².s⁻¹ | 0,14 | 0,06 | 0,10 | 0,19 | 0,07 | 0,12 |
| Max.              | m².s⁻¹ | 0,20 | 0,24 | 0,24 | 0,65 | 0,24 | 0,65 |
| Min.              | m².s⁻¹ | 0,09 | 0,02 | 0,02 | 0,12 | 0,03 | 0,03 |
| Std. deviation σ  | m².s⁻¹ | 0,025 | 0,056 | 0,059 | 0,102 | 0,03 | 0,010 |
For comparison, we also found empirical relationships for the determination of the longitudinal dispersion coefficient value for comparable conditions in the literature.

Taylor (by [19]) derived the relationship for $D_L$ in a straight line of circular pipeline and turbulent flow condition:

$$D_L = 10.1ru_0$$  \(6\)

where $r$ is a radius of pipeline [m]. Using this relationship for our flow conditions in the straight part, we received $D_L$ values in the range from 0.14 to 0.23 m$^2s^{-1}$. Despite that $D_L$ values calculated according to this relationship in section with directional changes were significantly higher (almost double) as measured. Therefore, this relationship was considered to be inappropriate for this case, but for straight parts of pipelines, it can be stated that this relatively simple relationship is applicable to the determination of the longitudinal dispersion coefficient. In the case of natural streams using this relationship has to be carefully considered.

Noticeable differences of values came from a comparison of the measured values and the values obtained from the application of relationship that was derived by Parker [15], who modified Eq. (6) to form valid for open channel:

$$D_L = 14.28R^{2/3}\sqrt{2gi}$$  \(7\)

where $R$ is a hydraulic radius [m], $g$ is the gravity acceleration [m.s$^{-2}$] and $i$ is a longitudinal bed slope.

Using this relationship, the $D_L$ values for the straight part were in the range of 0.69 to 0.92 m$^2s^{-1}$. On the other hand, for the part with directional changes, this relationship gives somewhat underestimated results in comparison with the measured $D_L$ values (0.026 to 0.054 m$^2s^{-1}$). We can conclude that the use of this relationship for our conditions is limited (also considering that this relationship was derived for open channels with different cross section shape and roughness of the bed). This example also points out the importance of taking into account conditions under which and for which applied empirical relations are derived.

As it was mentioned earlier, during evaluating the results of the measurements it was found that in a series of experiments with lower discharge the measurement results showed the presence of "dead zones" in the measuring section. Therefore, it was appropriate to use the following relationship for $D_L$ derived by Krenkel [13] for open channels with the appearance of "dead zones":

$$D_L = 9.1u_0h$$  \(8\)

Using this relationship for the conditions in the sewer collector, we received $D_L$ values in the range from 0.02 to 0.053 m$^2s^{-1}$. We can say that the range of $D_L$ values corresponds to the measured values.

Even better results were obtained using relationship by Thackston (by [4]). For its derivation the potential effect of "dead zones" and the impact of transversal flow have been taken into consideration:

$$D_L = 7.25u_0h\left(\frac{u}{u_*}\right)^{1/4}$$  \(9\)

Applying this relationship in the straight part we found a relatively good match with the measured values (0.054-0.12 m$^2s^{-1}$), mainly in the case of the higher values. When used in a curved sewer section, the $D_L$ values ranged from 0.033 to 0.068 m$^2s^{-1}$.

Relatively good results were also obtained by $D_L$ quantifying according to the relationship, derived for open channels with low hydraulic resistance by Yotsukura and Fiering (by [4]) with consideration of the transverse velocity distribution:
$D_L = 13 \, u \cdot h$  \hspace{1cm} (10)

$D_L$ values calculated according to this relationship were in the range 0.03-0.08 m$^2$s$^{-1}$. This relationship is due to its simple form relatively sensitive to the $h$ value, so for higher depths, the calculated longitudinal dispersion coefficient value was outside the values obtained by measurements.

All mentioned examples show the importance of condition evaluation for which the empirical relationships are derived and valid.

Finally, we would like to go back and discuss the “dead zones” occurrence problem and asymmetry of tracer concentration time courses. Explanation of the time course asymmetry mentioned and described in the previous part can be as following: time course of the tracer is principle always asymmetric, because of the advection and dispersion in flowing water related to the stationary placed measurement device; it results inter alia from the form of analytical solution (4). Further asymmetry related to the analytical solution is probably caused by local backwater effects, caused by sediments or deposits in the bed of pipe or by irregular sewer pipes slope caused by damage or breakdown of pipe bed.

Such backwater acts in dry weather condition as tracer (pollutant) storage, it accumulates the tracer and slowly releases the tracer into the main stream. We assume that 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). These conclusions are confirmed also by the fact, that in the section with lowest water depths (section with the 90° curve) was the time course asymmetry most evident.

7. Conclusions
This paper presents the results of longitudinal dispersion coefficients estimations from field tracer experiments under the flow conditions in sewer pipes as in a prismatic channel with relatively constant roughness of streambed. Both in the straight line and also in the sewer section with directional changes, the measurement results showed that in a given measuring section was a backwater accumulation located downstream, which resulted in the creation of "dead zones" in the examined section. This phenomenon was visible in the section with 90° direction change the most significantly. Consequently to the tracer retention and its gradual release, the conductivity distribution curve was deformed creating a tracer concentration "tail".

The comparison of $D_L$ values obtained from experiments in sewer pipes with those one obtained in natural streams or channels shows significant differences. $D_L$ values obtained in the sewer pipe were rather close to the values obtained in laboratory conditions. In addition, $D_L$ values in the straight part were higher than from the section with directional changes. This result indicates that in the straight part of the sewer line the longitudinal dispersion of the substance is dominant in the total dispersion process, whereas in the sewer part with directional changes the transversal (lateral) dispersion contributes to whole mixing process (dispersion process is also influenced by the velocity gradient in the transverse direction). The influence of the direction change angle to the longitudinal dispersion coefficient within the performed measurements has not been clearly determined yet.

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