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EXPERIMENTAL INVESTIGATION OF RESIDENCE TIME IN COMMUNAL SEWERS

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ABSTRACT

When pollution flows into the sewage system, following an accident, the most important piece of information to be considered is the anticipated time elapsed between the inflow and outflow of pollution into and out of the sewage system at a given flow rate. This is done in order to estimate the time available for preparing intervention measures. Since sewage water contains a great amount of degradable organic materials and degradation in the sewage system occurs in an anoxic environment, after a certain residence time degradation can cause inconvenient odours and corrosion. Sewage network maintainers have to avoid the decrease of sewage water quality in order to prevent anaerobic degradation. Flow time is indispensable in planning the appropriate intervention method.

In the experimental investigation presented in this article, the authors aimed to validate a hydraulic model of the sewage system. Sewage water was dyed with fluorescent dye in one section of the sewage system and the dye was detected by visual observations and optical concentration measurements. Experiments were conducted at average daytime, daytime maximum and nighttime minimum loadings. The hydraulic model of the investigated system contained approximately 10000 sewer sections and 8000 partial catchment areas. The simulation method in the investigated cases gave the value of the residence time with an acceptable accuracy for planning practices.

Keywords: dyeing, residence time, sewer

1. INTRODUCTION

When unwanted pollution flows into the sewage system, the most important piece of information to be considered is the anticipated time elapsed between the inflow and the outflow of the pollution into and out of the sewage system (at a given flow rate), in order to estimate the time available to prepare interventions. The accurate residence time is of high importance in cases where the receiving water is a natural water source. Residence time is the minimal period of time elapsed between the inflow and outflow of a given section of the sewage system. It can be defined and modelled in every section of the sewage system. To define the residence time of the whole sewage system in detail, a model is indispensable. When using the hydraulic simulation model, some parameters (e.g. surface roughness of the conduits of different wall materials) can be only estimated, and therefore the calculations need to be validated against on site residence time measurements similarly to [1],[2]. In the case presented in this article, the residence time was measured in a 5-kilometre long section of the Budapest sewage system for different operation modes, using a method utilized by geologists [6], [7]. Measurement results were compared with calculation results.

The experimental investigation was supported by the Budapest Sewage Works Ltd by carrying out the flow rate measurements in the given sewer tract and by helping in the installation of the optical sensor.

2. THE EXAMINED SECTION

The experimental investigation introduced in this article was conducted in one section of the main sewer connected to the Ördögárok outlet in Budapest. The examined combined (communal sewage with rain water) sewer section has an open surface flow driven by gravity. A relief sewer runs parallel with the main sewer in the upper 30% of the examined section. The aim of the relief sewer is to lead away sewage water produced during dry weather periods, when the water level is too low, giving rise to the deposition of the drifted solid content. The smaller diameter canal section is connected to the larger one at approximately 30% of the entire length of the investigated section. When defining the residence time, these parallel sections are important, because the flow velocity in the smaller conduits is significantly higher than that in the larger cross-section conduits.

3. MEASURING METHOD

3.1. The instrument

The residence time was measured by means of the propagation of a tracer material placed in the sewage system. At the outflow of the examined section, instrumental detection was conducted.

The appropriate tracer was chosen according to specific features. It had to be a chemically stable material that dissolves well in water and it was also essential to avoid adsorption in the particles floating in the sewage water. The background concentration of the tracer had to be low in the sewage system and it had to be an easily detectable material. The sodium salt of fluorescein was suitable for all of these requirements.

The tracer was injected in a solution form, because in this form it could combine faster with sewage water.

The GGUN-FL Fluorometer is a device that is suitable for measuring the concentration of opalescent materials such as the sodium salt of fluorescein. The instrument is made up of two parts: a detector and a data recorder. The detector can be installed in the flow and is connected to the data recorder placed on the bank of the sewer with a 15-metre long waterproof cable (Figure 1.). The detector contains an optical system through which the water and the dissolved tracer can flow without any obstacle. A lamp in the detector blinks every ten seconds. With the help of a filter, this lamp emits light at an excitation wavelength that is characteristic of the given tracer. Due to this, the dye flowing through the detector will fluoresce, and a photosensor will receive the optical signal. The instrument amplifies the signal before transmitting it to the data recorder. The signal intensity is proportional with the concentration of the tracer material flowing through the instrument.

The data recorder contains a data-collection unit and a battery (accumulator) (Figure 1.). Measurement data are stored in a memory card, and the results can be followed continuously on a portable computer. Technical parameters of the instrument are shown in Table 1.

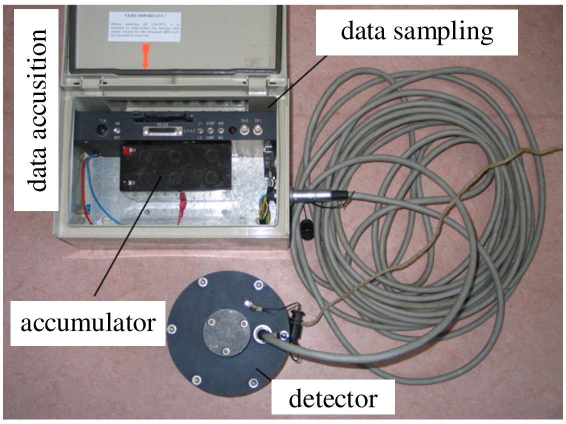

Figure 1. Main parts of the GGUN-FL Fluorometer

Table 1: Technical parameters of GGUN-FL Fluorometer

Applied tracer material	Sodium salt of fluorescein
Detection limit	0.05 ppb
Measurement limit	486 ppb
Measurement frequency	10 second
Reproductivity	99%

3.2 Installation of the instrument

The instrument was installed immediately prior to measuring. The installation was carried out by divers from the Budapest Sewage Works Ltd. The detector unit was installed at the base elevation level of the flow so that the flow through opening of the instrument would always be under the actual water-level. Consequently, the necessary and appropriate flow into and out of the instrument was ensured.

3.3. Measuring conditions, operation modes

Unfortunately, the measurement of the flow rate simultaneously with the dyeing experiment was not possible due to the high water level of the receiver river, and therefore earlier data had to be used for setting the input flow rate of the simulation model.

The flow rate measurements were carried out in January 2008 by the staff of the Budapest Sewage Works Ltd. at the Ördögárok outlet. Volume flow rate, temperature and water depth were recorded in every other minute for 14 days. This outlet was the end-point of the examined section, through which the sewage water was emitted into the river Danube.

On the basis of the measurement data, a trend could be defined, which describes the amount of daily sewage. It has been found useful to distinguish between workdays and holiday. According to the observations, it is enough to divide the trend into 15-minute intervals. Measurement data was then sorted out in two groups: workdays and holidays in 15-minute intervals. Averaging the measurement date in one interval, the observable noise in the data disappears and the average curve clearly shows the value of the amount of water that belongs to a given time of day. The daily trends can be seen in Fig.2. The standard deviation of the total daily sewage volume is 7.6 % of the average daily volume for working days, and 6.0 % on holidays.

The volume flow rates in three characteristic operation modes of the sewage system could be estimated on the basis of the trends. Peak-load could be characteristically observed in the morning hours, when the volume flow rate was 550 l/sec at the outlet (end-point). Minimum load was characteristic in the early hours (after midnight), when the volume flow rate was 200 l/sec. In the afternoon, the amount of running off water was more or less stable, with the volume flow rate being 450 l/sec which was considered as the average daytime load.

The specific (per capita) emission in the hydraulic model was set on the basis of the above average flow rate values.

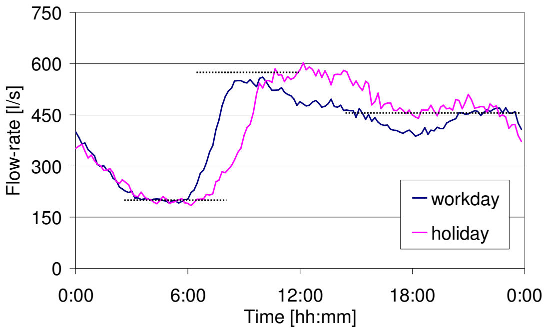

Figure 2: Daily distribution of sewer flow-rate

4. MEASUREMENT RESULTS

The flow time was measured in operation modes determined by the different loadings of the sewage system. In conducting the measurements, for the periods of minimum and average load, the dyeing was carried out during the examined period as the periods were long enough to do so. Being that the peak load period was shorter, it was necessary to fix the time of water dyeing in a way that the dye would arrive at the outlet in the given peak load period.

The first measurement took place in the average afternoon period. During this measurement, the concentration was oversaturated because too much dye was used, and therefore the signal exceeded maximum measurable value. The measurement results (Figure.3) show that the dye concentration was delayed before arriving at the detection unit. Since the flow velocity was not constant in the sewer cross-section, the dye was dispersed in the carrier medium as a result of turbulence and diffusion [3], [4], [5].

In the measured concentration curve, the average time value of inflow was taken into consideration, because the residence time in the hydraulic simulation model was defined with the average velocity.

The dye was injected at 11:34:05, and the first detection was at 12:35:25, with the peak concentration being measured at 12:41:35.

The effect of the relief sewer which can be found in the upper part of the section is noticeable in the trend line of the first measurement. The sewage water that first flows in the sewer of larger cross-section is conducted into the smaller relief sewer through several links. However, a part of the sewage water containing dye presumably continues flowing in the large sewer and gets into the relief sewer through linking lines which lie farther downstream. The flow velocity is significantly lower in the large cross-section conduit than in the relief sewer, therefore the sewage water following the latter route arrives at the detector later. This could be the possible explanation for the delayed arrivals in the concentration curve.

The second measurement took place during the morning peak (Figure 4.). The dye was injected at 8:43:52. According to the experience of the first measurement, the amount of dye applied in this case was appropriate and the detector was not saturated. The first detection was at 9:42:46, with the peak concentration being measured at 9:48:16.

The minimal load measurement was started at 4:45:24. The first arrival was found at 6:20:39, and the peak concentration arrived at 6:24:41.

The residence time in Table 2 has been calculated on the basis of the time instant of the maximum dye concentration, because it was assumed to be in the best correlation with the average velocity and thus comparable with the results of the hydraulic model. The instant of first appearance of dye can be related to the maximum velocity within the channel cross-section. The ratios of residence times calculated from the instants of first appearance of dye to those of the maximum concentrations were 0.96, 0.91 and 0.91 for the minimum, mean and maximum utilisation cases respectively.

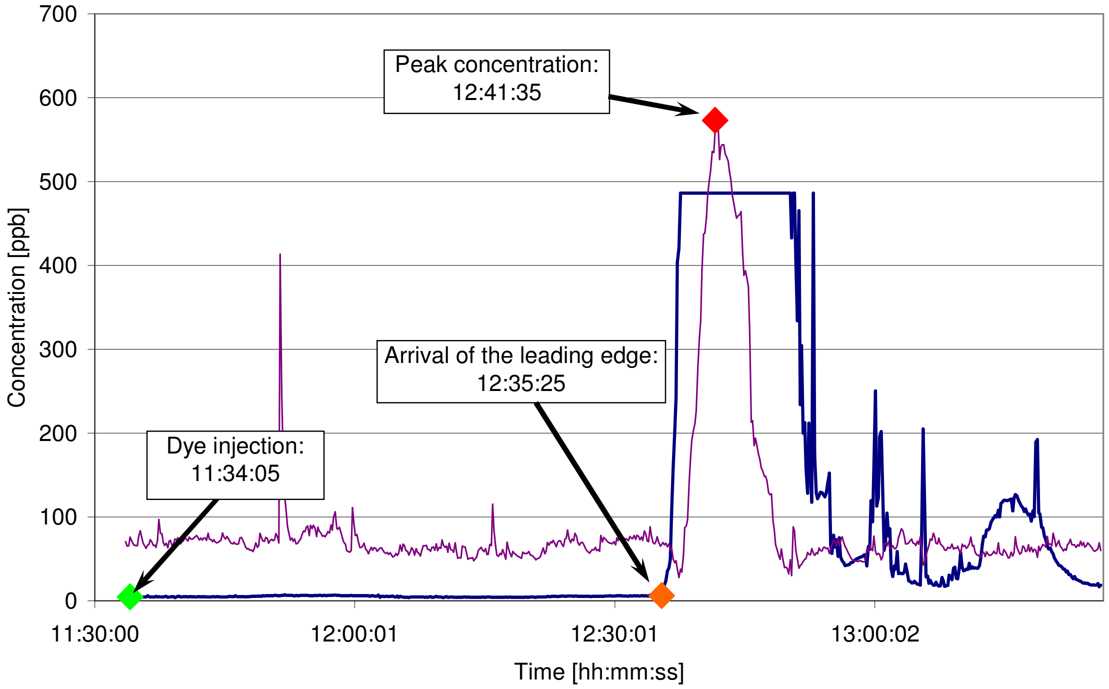

Figure 3. Dye concentration measured in average flow-rate case

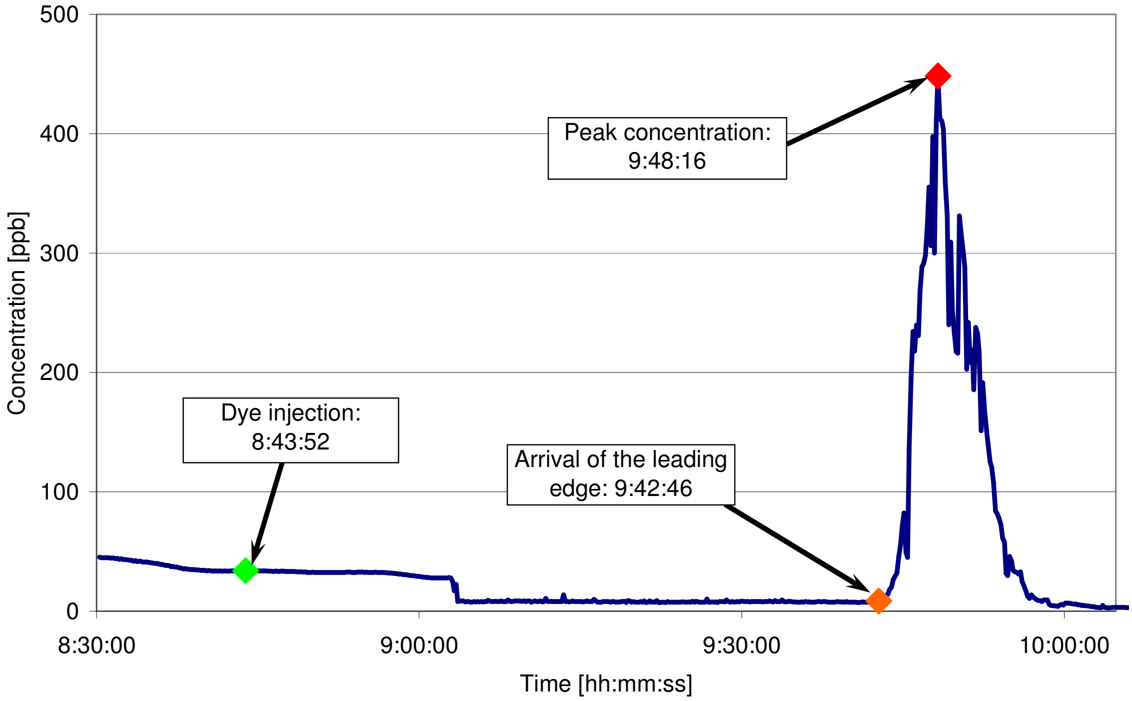

Figure 4. Dye concentration measured in the peak flow-rate case

Table 2. Measured residence time

Load	Dye injection [hh:mm:ss]	Peak conc. [hh:mm:ss]	Residence time [min]
Minimal	4:45:24	6:24:41	99.28
Mean	11:34:05	12:41:35	67.5
Peak	8:43:52	9:48:16	64.4

4. HYDRAULIC SIMULATION MODEL

4.1 Model elements

The residence time was calculated by using the KANAL++ hydraulic software with the hydraulic solver DYNA in steady state flow mode. The hydraulic solver uses the Complex Parallel Step Method, which bases complex solution of St. Venant equation [8]. The hydraulic model of the examined main sewer was built, and contains approximately 10000 sections (conduits). The catchment area was divided into 8000 sub-catchment areas for which the specific population density, as a proportional value with the emission, had to be specified. Head losses in the sewer sections were computed by means of the Prandtl-Carman-Colebrook formula. The parts of the simulation model and sections where the residence time was investigated are shown in Figure 5. and Figure 6. The main flow direction was from north-west to south-east.

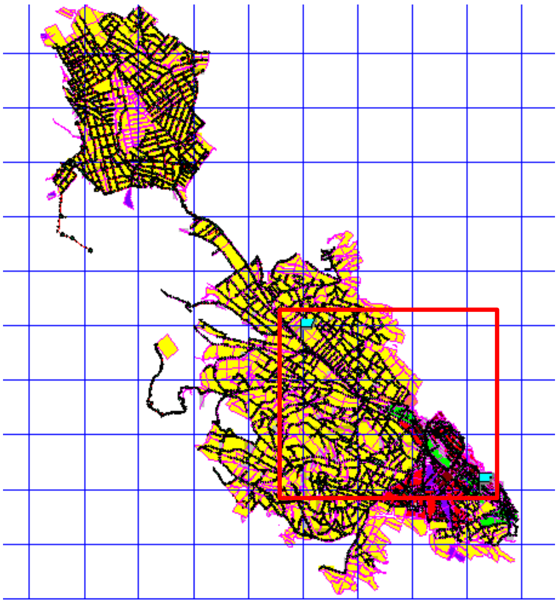

Figure 5: Catchment are included in the hydraulic analyses

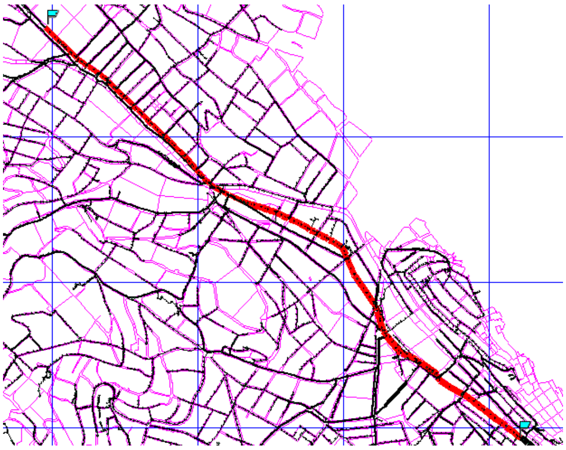

Figure 6: Investigated section of the sewer

4.2 Model parameters

The wall roughness value parameters were classified into 2 classes, with the applied values shown in table 3.

Table 3. Roughness classes

Wall material	Roughness height [mm]
Concrete, reinforced concrete, masonry,	3
Stone, PVC, PE	0.5

Sensitivity studies were carried out in order to characterize the role of the wall roughness of the pipe. Within an acceptable range of wall roughness, the change of the residence time was under ± 5%. The Manning roughness model was also been tested and found to be insufficient for calculating the residence time in communal sewer networks.

The parameterisation of the sub-catchment areas was carried out according to table 4.

Table 4. Partial catchment classes

Type	Population density [1/ha]	Colour on the map
Irrelevant	0	🟪
Green belt	10	🟩
Garden city	40	🟨
2-3 storey houses	100	🟧
Panel buildings	200	🟥
Buildings in unbroken row	350	🟫
Street	0	⬜

The simulation model calculates only the average velocity in every cross-section, and consequently, an average residence time was obtained from the simulation results. After computing the residence times for all sections, the time that the sewage water needed in order to reach the end-point could be defined for any section with the help of a summation procedure.

The procedure should begin at the outlet and the residence times of the individual sections should be summarized while marching against the direction of flow. If the section can be reached by different routes, the smaller value was used as a pessimistic approximation, and thus the lumped residence time was always single-valued. The map showing the flow times of each section, the minimum value of residence time may be presented, which is desirable in the case of tracing a certain contaminant.

5. SIMULATION RESULTS

Comparing the simulation and measurement results, an acceptable correspondence was found.

Table 5. Simulated and measured values of residence time

Load	Flow-rate at the receiving water [l/s]	Residence time [min]	
		Calculated	Measured
Minimal	200	97.35	99.28
Mean	450	74.1	67.5
Peak	600	69.3	64.4

In the minimal load case, the measured residence time was higher than the calculated, and the difference was – 1.9 %. In the average utilisation case, the calculated value overestimated the real residence time and the difference was +9.5%. This deviation could have been partly caused by the uncertainty of the calculation of the flow rate, which was set as an input parameter in the simulation model. In the peak utilisation case, the measured residence time was higher than the calculated, and the difference was + 7.1 %.

6. SUMMARY

When accidental pollution gets into the sewage system following an accident, the actual position of the pollution front and the residence time must be known to prepare intervention. In this paper an experimental investigation has been presented which was used for validating the hydraulic model. Flow rate measurements were made in order to identify the hourly per-capita sewage water emission for working days and for holidays, in the examined territory. The residence time was measured by observing the time required for the movement of the dye cloud on a 5 km long sewer section for 3 different degrees of utilisation. The results of the dyeing measurement were compared with simulation results and a good correspondence was found. The difference between the measured and simulated values had a maximum value in the mean load case. In this time interval the flow rate was fluctuating, which could introduce larger errors into the estimation of the amount of water.

For a realistic range of wall roughness, the change of the residence time was under ± 5%.

The ratios of residence times calculated from the instants of first appearance of dye and the instants of observation for the maximum concentrations were 0.96, 0.91 and 0.91 for the minimum, mean and maximum utilisation cases, respectively.

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