ASSESSING EXFILTRATION FROM A SEWER BY SLUG DOSING OF A CHEMICAL TRACER (NaCl)

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1. Introduction

Water resources in urban areas comprise both natural and man-made water bodies, including surface waters and groundwater. Groundwater aquifers can be recharged from several sources, some of which may transport high concentrations of organic and inorganic pollutants. Such sources include exfiltration from leaky sewer pipes that could pose a serious threat to groundwater quality because of large extent of urban drainage systems. When the shallow unconfined and confined aquifers are connected, the transport of organic and inorganic compounds and pathogenic organisms may cause serious pollution. Consequently, the deep confined groundwater aquifers could become polluted and their water would require advanced treatment if used as a source of drinking water.

Several methods exist to evaluate the structural state of sewers. Some of these consist in direct surveying inside the sewer pipes (i.e., by closed circuit television, CCTV) and others in quantifying the exfiltration rates by the detection of wastewater markers in the groundwater [1].

The QUEST method [2] (QUantification of Exfiltration from Sewer with artificial Tracers) serves to assess directly the exfiltration from flowing sewers in dry weather. It is based on establishing a tracer mass balance for the investigated pipes. The solutions of a tracer (NaCl) are dosed in two manholes of the investigated reach, and at a downstream location, the conductivity of sewage is measured by in-line probes.

The sources of errors affecting the exfiltration rate originate from the experimental results and data analysis. In particular, they are due to: flow rate, natural wastewater conductivity, shape of the tracer signals at the measuring point, transport of tracer and general disturbances in the sewer (caused for example by turbulence or solids). To minimise the errors in experiments and data analysis, preliminary measurements of flow rate, in-sewer background conductivity and tracer transport should be carried out.

In the paper that follows, the results of application of the QUEST method to an urban sewer network in a suburban area of Rome and the importance of site-specific preliminary tests are presented.

2. Study area and experimental methods

2.1 EXPERIMENTAL CATCHMENT

The experiments were carried out in one section of the sewer network serving the Torraccia suburb of Rome.

The sewer section studied is a part of a thirteen-year-old combined sewer system built of egg-shaped concrete pipes. The investigated reaches are 4-9 m below the ground and their total length was 724 m, with a slope of 0.9%. The tested section consists of two parts (shown in red in Fig. 1): the first one is egg-shaped with dimensions 120x180 cm and 407 m of the total length of 483 m were included in the test section, the second one is egg-shaped, 120x210 cm, and the upstream 151 m of the total length of 241 m were tested.

Since the tracer should be fully mixed at the measuring cross-section, a sufficient mixing length has to be ensured. For neutrally-buoyant tracers, the recommended mixing length for rivers is 100d - 300d (d = the channel width) [3], and application of this formula to the sewer studied yields a length of about 100 m.

The geology of the catchment area is characterised by cracked tuff and pozzolan, but the material surrounding the sewer pipes is coarse gravel used as backfill. Groundwater inundates the sewer only in wet weather, because during the dry weather the infiltrated water drains quickly through the highly permeable cracked tuff into a deeper aquifer.

![Fig. 1. Tested sewer network produced in the AquaBase software developed by DHI under the European Project APUSS (studied reaches = solid line, L = 724 m)](image)

Although the measurements were carried out only in a part of the entire sewer system of the experimental catchment (solid line in Fig. 1), the homogeneous characteristics of the area allow extrapolation of results to the entire Torraccia sewer system.

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2.2 EXPERIMENTAL MATERIALS

The equipment used consisted of one submerged probe for water level and velocity measurements (Sigma 900max) and three WTW conductivity probes (model LF 197 with sensor TetraCon 325). Conductivity data were recorded by a datalogger (GRANT SQ400) with a time resolution of one second. The chemical tracer applied was 97% pure NaCl.

3. METHODS

Sewer exfiltration was measured by the QUEST method [2], which has been developed in the European Project APUSS (Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems). In QUEST, tracer slugs of a known concentration are injected at two different manholes along the tested sewer pipe and the tracer cloud is observed at a downstream point (Fig. 2).

![Fig. 2. Conceptual scheme of the QUEST method (modified after [2])](image)

At the first (upstream) manhole of the investigated pipe, a known mass of the tracer is injected and as the tracer moves downstream, it is affected by exfiltration from the sewer. At the measuring manhole (Fig. 2), sewage conductivity is recorded. When the tracer cloud arrives at this section, a peak concentration is detected and called the indicator peak, because it allows evaluation of the residual tracer mass.

At the second (downstream) manhole the tracer slug dosing serves to estimate the flow rate, and the conductivity peak measured further downstream is called the reference peak. Between the second manhole and the measuring manhole, the exfiltration rate is not assessed, because it affects both the indicator and the reference signals equally.

In Fig. 3, the reference and indicator conductivity signals are shown together with the flow hydrograph.

If complete mixing occurs, the relative loss of tracer equals that of wastewater and the sewage exfiltration fraction (= exfiltrated mass/incoming mass) can be calculated as:

$$exf = 1 - \frac{M_{\text{mon}}}{{M_{\text{tracer}}}}$$  \hspace{1cm} (1)
where $M_{\text{change}}$ is the dosed NaCl mass [g] and the “measured” mass $M_{\text{meas}}$ is evaluated by the following equation:

$$M_{\text{meas}} = \int Q(t)*e*(C(t) - C_{\text{baseline}}(t))dt$$  \hspace{1cm} (2)

![Graph](image)

**Fig. 3.** Conductivity and flow rate vs. time (peaks numbered 1, 2, 4 and 5 are reference signals, peaks numbered 3 and 6 are indicator signals)

In eq. (2), $span \text{ ind.}$ index refers to the time interval, during which the conductivity peak of the indicator signal passes through the measuring manhole; $Q(t)$ is the flow rate during the indicator peak passage [L/s]; $C(t)$ is the measured indicator signal conductivity [$\mu$S/cm]; $e$ is the conversion factor evaluated in the laboratory ($e = 0.0006$ g/cm$^2$/L$^2$*µS); and, $C_{\text{baseline}}(t)$ is the background conductivity of wastewater during the indicator peak passage [$\mu$S/cm].

4. **Experimental design**

The experimental design concerned the following aspects of tracer dosing: (i) selecting a location of tracer injection along the investigated reach to obtain good indicator and reference signals, (ii) selecting a location for measuring conductivity, (iii) choosing tracer dose, and (iv) deciding whether to overlap the reference and indicator signals.

Concerning the first two points above, the selection of manholes for injecting and measuring tracer does not depend only on the investigated section of the sewer, but also on the location of point inflows into the sewer. Thus a set of continuity and
is evaluated

(2)

tracer mass balance equations should be developed. For the sewer investigated that set was written in order to define the locations of the points of injection and the measurement (see Section 4.2). A critical aspect of this procedure is the flow model, so before solving the continuity and mass balance equations, different Q(t) functions were studied (Section 4.1) and then used to evaluate the exfiltration ratio by eq. (2). The results are then discussed in Section 5. The model of the flow rate serving to evaluate the exfiltration fraction appeared more reliable if chosen on the basis of the structural state of sewers. It was used to solve the set of equations in Section 4.2.

The dosed amount of tracer should be such that the peak-baseline ratio is as high as possible, but salt precipitation is avoided (360.0 g/L at 20°C [4]).

Regarding the fourth point listed above, the analysis of baseline and discharge trends was carried out. The natural conductivity of wastewater and the flow rate were recorded for three days in order to identify the period of the day when they were as steady as possible. During this period it is possible to avoid the overlapping of peaks, because the baseline can be modelled satisfactorily with a linear function and the unknown flow during the tracer passage can be obtained from the reference peaks measured just after and before the indicator peak. An advantage of using the QUEST method without overlapping is that the peak fitting does not have to be used [2], but some preliminary tests need to be carried out to determine the shape of the peak at the end of each investigated reach. The knowledge of the peak shape is needed to evaluate the time interval between two subsequent tracer injections.

4.1 FLOW RATE MODELS

The models of the flow rate during the indicator passage can be developed using the data from both reference peaks and the in-line probe for discharge measurement. The following models can be used for this purpose:

1. the mean value of flow rate measured by reference peaks (see Fig. 4 - a);
2. linear regression between the mean value of flow calculated from the two reference peaks before the indicator peak and the two peaks after it (see Fig. 4 - b). The equation for the calculation of flow rate from the reference peak is:

\[
Q_{\text{ref}} = \frac{M_{\text{ref}}}{\int_{\text{ref}}^{t} (C(t) - C_{\text{baseline}}(t)) dt}
\]  

3. discharge measured by means of the submerged probe (see Fig. 4 - c);
4. discharge measured by the probe, of which readings is corrected by factor \( K \) (see Fig. 4 - d):

\[
K_i = \frac{Q_{\text{ref},i}}{Q_{\text{mean}}(M_{\text{ref}})}
\]  

\[ i = 1 : \text{number of reference peaks} \]
\[
\bar{K} = \frac{\sum_{i=1}^{n_{\text{ref}}} K_i}{n_{\text{ref}}}
\]  

(5)

Each model above (called the Q(t) function) was used in eq. (2) to estimate the exfiltration fraction. The first two models should be adopted when it is impossible to use on-line probes in measurements. In particular, the first model is well suited when flow is rather steady, and the second one is well applicable when the flow rate greatly varies. The third model is recommended for use when the discharge strongly varies and it is possible to install flow measuring devices. The fourth is applicable when it is possible to install a flow meter, but its accurate calibration is not possible.

4.2 EQUATION SYSTEM

The system of equations consists of three continuity equations, three mass balance equations and three exfiltration fraction equations. For the sewer investigated (Fig. 5), the equations can be written as:

\[ Q_i = Q_{i-1} + Q_{i+1} + \alpha x_{f2i} * Q_i \]  

(6)

\[ Q_i = Q_{i-1} + Q_{i+1} + \alpha x_{f3i} * Q_i \]  

(7)

\[ Q_i = Q_{i+1} - Q_{i+1} + Q_i - \alpha x_{f2i} * (Q_{i+1} + Q_i) \]  

(8)

\[ M_j = M_i + \alpha x_{fj} M_i \]  

(9)

\[ \alpha x_{fj} = \frac{M_j}{M_i} \]  

(10)

\*

where: \( Q_i \) = inflow rate [L/s]; \( Q_j \) = flow rate measured at point 2 [L/s]; \( Q_k \) = flow rate measured at point 3 [L/s]; \( Q_l \) = flow rate from a lateral inflow [L/s]; \( Q_4 \) = flow rate measured at point 4 [L/s]; \( M_i \) = tracer mass injected [g]; \( M_{1,1} \) = tracer masses measured [g]; \( Q_{12} \) = exfiltration rate from the first reach; \( Q_{23} \) = exfiltration rate from the node; \( Q_{34} \) = exfiltration rate from the second reach; \( \alpha x_{f2i} \) = exfiltration fraction from the first reach; \( \alpha x_{f3i} \) = exfiltration fraction from the joint; and, \( \alpha x_{f3i} \) = exfiltration fraction from the second reach.

The model is based on an assumption that the tracer is completely mixed 100 m downstream from the injection manhole, and further downstream from this point, the loss of tracer equals the loss of wastewater.

In the above set of equations, there are five degrees of freedom, so five values need to be determined by experimental measurements. The experimental procedure was set up (see Fig. 5) as follows: (1) measuring at point 2 to determine \( M_2 \) and \( Q_2 \); (2) measuring at point 3 in order to determine \( M_3 \) and \( Q_3 \); (3) measuring at point 4 in order to determine \( M_4 \); and, (3) measuring at point 1.
5. Results

The results presented here were produced in three experimental surveys carried out for the application of the QUEST method [2]. The dosed tracer masses were chosen such as to produce peak concentrations 2-3 times higher than the average value of the baseline, for the concentration of tracer solution of 130 g/L, well below the limiting concentration of 360 g/L at 20°C [4]. In Table 1 the results of the three experiments evaluated by using different flow models are shown. Because the exfiltration fractions calculated from the mean values of Q for reference peaks are more reliable for sewers with a good structural state, the system of equations (Section 4.2) was solved using this model of the Q(t)-function. The exfiltration fractions for the sections upstream and downstream of the node are shown in Table 2.

![Peaks of Reference and Indicator Pulses and Fluorescein](image)

**Fig. 4.** Conductivity [μS/cm] and flow rate [L/s *100] vs. time [s].

The four panels show different ways to estimate Q(t) during the passage of the indicator peak: (a) the flow rate equals the average value of the flow rate measured by means of reference pulses; (b) the flow rate is determined by a linear regression of
average values measured by means of reference pulses; (c) the flow rate is measured by the probe; and, (d) the values of the discharge measured during the 1-reference peak passage are scaled by means of average value of factor k (eqs. (4) and (5)).

![Diagram](image)

**Fig. 5.** Sketch of the investigated sewer network with the injection and measuring manholes. 1 = tracer dosing for indicator signal; R1 = tracer dosing for reference signal; 2,3 and 4 = measuring points, Q3 = lateral inflow.

<table>
<thead>
<tr>
<th>Experiment 100703</th>
<th>Q mean</th>
<th>Q Linear</th>
<th>Q measured</th>
<th>Q modified by mean K-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 240703</td>
<td>7.08</td>
<td>6.17</td>
<td>-116.150</td>
<td>12.25</td>
</tr>
<tr>
<td>Experiment 300703</td>
<td>0.72</td>
<td>0.53</td>
<td>-81.220</td>
<td>5.83</td>
</tr>
<tr>
<td>Mean</td>
<td>3.73</td>
<td>5.11</td>
<td>-87.84</td>
<td>7.99</td>
</tr>
<tr>
<td>st.dev.</td>
<td>2.81</td>
<td>3.39</td>
<td>20.94</td>
<td>3.01</td>
</tr>
</tbody>
</table>

In Table 2, the results obtained for models A and B, respectively, are shown.

| Table 2 - Exfiltration fraction [%] evaluated for the two tested reaches |
|-----------------------------|-----------------------------|-----------------------------|
| First Reach | 10th July 2003 | 24th July 2003 | 30th July 2003 | Mean | st.dev. |
| -0.123 | -0.235 | -0.211 | -0.190 | 0.059 |
| Second Reach | 2.959 | 2.157 | 2.137 | 2.418 | 0.469 |
Discussion

In this section, the data presented in Tables 1 and 2, and the principal sources of uncertainties are discussed.

The results shown in Table 1 correspond to the exfiltration fraction for the entire investigated sewer, but calculated by using various $Q(t)$-functions. The fraction varies greatly; the large negative values are caused by overestimation of discharge due to systematic errors in the measurements. The results vary during the individual surveys, because eq. (2) is very sensitive to the choice of the $Q(t)$-function and the function output is further affected by several factors. Some of these factors do affect the leakage (e.g., the wastewater flow level, soil saturation, etc.), while others reflect such sources of uncertainty as:

1. Conductivity peak shape
2. Peak distance
3. Natural conductivity of wastewater (baseline)
4. $Q(t)$-function during the passage of the indicator peak
5. Solids in sewage (e.g., toilet paper, plastics, etc.) and flow turbulence, and
6. Tracer mixing.

So a special care has to be taken to reduce the effect of these factors.

6.1 PEAK SHAPE AND TIMING

In order to reduce the uncertainty in the determination of the start and end points of the peak records, some preliminary testing has to be carried out in the investigated reach before proceeding with the experiment. Furthermore, from these tests, the duration of the peak has to be determined in order to avoid the peak overlap and to decide the timing for the tracer solution injection during the experiment. The experiment duration has to be as short as possible, because the shorter the experiment, the smaller the variability of natural conductivity and flow during a quasi-steady period of the day.

6.2 BACKGROUND CONDUCTIVITY

The errors due to the variation of the natural sewage conductivity can be reduced if the experiment is carried out when the conductivity is steady. So the experiment was carried out when the maximum variability was not more than 100 µS/cm.

In eq (2) the function $C_{\text{baseline}}(t)$ is unknown during the peak duration and it has to be modelled. The model used was a first-order polynomial using 200 data points equally distributed before and after the peak (see Table 3). Since the number of regression points influences the distance between the peaks, it was desirable not to consider more than 200 data points in order to reduce the duration of the experiment as much as possible.

6.3 $Q(t)$-FUNCTION DURING THE PASSAGE OF THE INDICATOR PEAK

The discharge variability during the experiment and the availability of a suitable site
for the installation and calibration of the flow meter determine, which of the Q(t)-functions to use in eq.(2). Eq.(2) is very sensitive to the choice of the Q(t)-function (see Table 1). If no other discharge measurements are available, the flow rate can be measured by means of the reference signals and the overlapping QUEST method is recommended. Otherwise, to apply the non-overlapping QUEST method, measurements over three to four days need to be carried out to find the time of the day when the flow is steady. The more variable the flow, the less reliable are the flow values calculated from reference peaks just before and after the indicator peak.

Table 3. Actual* and estimated** areas under the indicator peak overlapped at natural conductivity background and the error [%] between the actual area and the estimated one.

<table>
<thead>
<tr>
<th>Real Area</th>
<th>Area under the peak [μS/cm²/cm]</th>
<th>Relative Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of regression points</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>190536.00</td>
<td>0.00</td>
</tr>
<tr>
<td>100</td>
<td>192243.61</td>
<td>0.78</td>
</tr>
<tr>
<td>50</td>
<td>192591.68</td>
<td>1.03</td>
</tr>
<tr>
<td>50</td>
<td>193265.76</td>
<td>1.17</td>
</tr>
</tbody>
</table>

* Calculated by subtracting the background conductivity from the peak.
** Calculated by subtracting the modelled conductivity from the peak.

The manhole used as the measuring station allowed the installation of the flow meter, but its calibration was not accurate. In the experiments on July 30 and 24, the maximum discharge variability was 5 L/s, while during the experiment on July 10, it was 12 L/s. Thus, for the experiments carried out on the 30th and 24th July, the reliable exfiltration fractions are those which were calculated by considering the flow rate linearly averaged for the four reference peaks (Section 4.1). For the experiments carried out on July 10, the reliable values are obtained by scaling Q(t)-function by a K-factor (Section 4.1).

6.4 SOLIDS IN THE FLOW AND FLOW TURBULENCE

Suspended solids and air bubbles may disrupt conductivity measurements. Therefore, the conductivity probe was protected by metal netting wrapped around the probe and the measuring cross-section in the sewer was located far away from any sewer junctions or invert drops.

6.5 TRACER MIXING

To obtain reliable exfiltration values by the QUEST method [2], the loss of the tracer mass has to equal the loss of wastewater, and the length of the investigated sewer has to be such as to ensure complete mixing. To confirm that this was the case in this study, two probes were installed in the sewer and the coefficient of variation of their readings was 0.98 %, which is a minimum value suggested by Rutherford [3].

The magnitudes of exfiltration obtained from model A (Table 2) were expected,
because (a) the tested sewer pipes are relatively new, (b) there is no traffic load on
the ground overlying the sewer, (c) the sewer is laid in tuff, and (d) the ratio of the
wastewater depth to the pipe height was low (Table 1). The negative values of the
exfiltration fraction in the upstream reach are caused by the errors occurring during
the measurements and data analysis, rather than by additional tracer sources, because
there are no house connections along the investigated pipe reach that might discharge
salt.

7. Conclusions

Preliminary results were presented for estimating exfiltration from an urban sewer
system by a novel method QUEST, which was developed by EAWAG in the
European APUS project. The application of this method to a structurally sound
sewer in Rome proved that the method allows the assessment of exfiltration in an
expedient and economic way. These results have provided reliable exfiltration rates
on the basis of a sewer structural state. However, the QUEST method cannot replace
the use of common conventional techniques (e.g., CCTV) for finding exact locations
of pipe defects. The paper highlighted the importance of preliminary testing (peak
shape study, conductivity and flow rate measurements) and sewer system
categorisation, in order to reduce the uncertainty in the results obtained from the
proposed models.

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