Quantification of sewer system infiltration using $\delta^{18}$O hydrograph separation

V. Prigiobbe and M. Giulianelli

ABSTRACT

The infiltration of parasitical water into two sewer systems in Rome (Italy) was quantified during a dry weather period. Infiltration was estimated using the hydrograph separation method with two water components and $\delta^{18}$O as a conservative tracer. The two water components were groundwater, the possible source of parasitical water within the sewer, and drinking water discharged into the sewer system. This method was applied at an urban catchment scale in order to test the effective water-tightness of two different sewer networks. The sampling strategy was based on an uncertainty analysis and the errors have been propagated using Monte Carlo random sampling. Our field applications showed that the method can be applied easily and quickly, but the error in the estimated infiltration rate can be up to 20%. The estimated infiltration into the recent sewer in Torraccia is 14% and can be considered negligible given the precision of the method, while the old sewer in Infernetto has an estimated infiltration of 50%.

Key words | $\delta^{18}$O, hydrograph separation method, sewer infiltration, sewer rehabilitation, uncertainty analysis

INTRODUCTION

The infiltration of parasitical water into urban sewer systems is due to the deterioration of all the components of the network. Gokhale & Graham (2004) group these damages into structural defects (e.g., cracks, fractures, joint displacements, deformations, and collapses), and operational damages (e.g., roots, siltation, and blockage). Infiltration leads to hydraulic overloading and dilution of the pollutant loads, which affect the operation of wastewater treatment plants. Therefore, sewer operators are interested in estimating the infiltration rates, detecting the sources of parasitical water, and the seepage locations along an urban sewer network.

The methods for estimating infiltration in active urban sewer systems during the dry period are either flow rate methods, based on the analysis of daily hydrographs (De Bénédictis & Bertrand-Krajewski 2005a), or chemical methods, based on the analysis of the dilution of pollutants or natural tracers (Kracht et al. 2003; De Bénédictis & Bertrand-Krajewski 2005b; Rutsch et al. 2005). In particular, Kracht et al. (2003) suggested the application of the hydrograph separation of two components, which was originally developed for natural catchments (Dincer et al. 1970; Martinec 1975; Fritz et al. 1976; Kendall & McDonnell 1998).

In this contribution, the two components are drinking water discharged into the sewer and the local groundwater in combination with the stable oxygen isotope, $^{18}$O, as a conservative tracer. This method was applied in two urban catchments in Rome (Italy) with distinct urban sanitation infrastructure, as well as different hydrological and geological characteristics. The Torraccia sewer was planned in a single stage and in accord with the urban planning in 1995, while the Infernetto sewer was built 40 years ago and was extended, and modified continuously to adapt to the evolving urban development. The regional geology in Torraccia is characterized mainly by tuffs, whereas the Infernetto area is dominated by alluvial sediments.
After a preliminary survey to verify the assumptions for the applicability of this method, we determined the infiltration ratios in these two urban areas. The experimental activity consisted of field campaigns and laboratory analyses. The field campaigns comprised:

- Collection of all materials for the characterization of the urban area: geology, hydrogeology, drinking water network, and sewer system network;
- Location of the measurement points: sewer system outlet, wells, and public fountains;
- Preliminary survey to characterize the isotopic composition of drinking and groundwater;
- Application of the method: Measurement of the wastewater flow rate, sample collection from sewer system, wells, and drinking water network.

The laboratory analyses consisted of the determination of the abundance of $^{18}O$ in all water samples.

Uncertainty analysis was performed to estimate the reliability of the result. Sources of error were identified and quantified and the errors were propagated through the model using Monte Carlo simulations.

**MATERIALS AND METHODS**

**Urban catchments**

Torraccia is about 0.85 km$^2$ in extent comprising 0.55 km$^2$ and 0.30 km$^2$ of residential and rural area, respectively (see Figure 1a). The urban area is entirely residential and the sewer was built 14 years ago as an egg-shaped combined, concrete system. It is located on a pyroclastic plateau 40 m above the sea level with good and excellent technical characteristics. The shallow subsoil consists of fine cinder and pumice produced by the Colli Albani and Monti Sabatini volcanoes and several clay lenses that act as aquitards by forming a multi-layer shallow groundwater system. This shallow system is underlain by 15 m of clay interbedded with silts and sands. At a depth of 30–32 m a confined aquifer exists in a calcareous sandy layer.

Infernetto is about 5.5 km$^2$ in extent and it is characterized by residential houses (see Figure 1b). The sewer is a circle-shape separated system made of concrete, ceramic, and PVC. The construction of the sewer began approximately 40 years ago. The north-east part is located in costal deposits 12–14 m above sea level, whereas the south-west part is located in alluvial deposits of the external Tiber river delta and only 2–3 m above sea level. A major part of the subsoil is characterized by silty sands and the rest by clay and gravel, both with poor technical characteristics. From north-east to south-west, the shallow groundwater table changes from 6–7 m to 3 m depth, while the altitude changes from 14 m to 2 m above sea level (Table 1). The shallow groundwater in this area is part of a larger aquifer coming from the north-east. This regional aquifer comprises mostly marine silts and sands.
Field equipment

To estimate the wastewater flow rate in the sewer as a function of time ($Q_w(t)$ in Equation 2), an area velocity flow meter based on the Doppler ultrasonic average velocity (model SIGMA 900MAX, American Sigma Inc., Medina, NY) was installed in the sewer system, at the downstream end of the investigated catchment (yellow points in Figure 1). This device was also used to sample 1.0 l of wastewater every hour, automatically. Single samples were taken from several locations in each drinking water network (blue points in Figure 1) and several groundwater wells (red points in Figure 1) distributed throughout each catchment. All samples were conserved in PVC bottles, completely filled to avoid contact with the atmosphere and evaporation, and stored no longer than four days at 4°C to minimize biological degradation.

To assess the variability in the conductivity of the drinking water a portable conductivity meter (model WTW 340 with a sensor Tetracon 325) was installed at a single public fountain within each investigated catchment. This measurement allows us to verify the main assumption necessary to establish if this method is applicable in these areas (second assumption cited in Modelling).

Laboratory analysis

From each collected drinking water/groundwater/wastewater sample, 3 ml were filtered and analyzed for stable oxygen isotopes. The $^{18}$O/$^{16}$O ratio was measured following the Epstein-Mayeda technique based on the water-CO$_2$ equilibrium (Epstein & Mayeda 1953). The samples were prepared manually and then analyzed with the mass-spectrometer Finnigan MAT. The isotopic ratio in the water samples was expressed in terms of per mille difference (‰) with respect to the isotopic ratio of Standard Mean Ocean Water (SMOW) defined by the International Atomic Energy Agency (IAEA).

$$\delta(‰) = \left[ \frac{R_{\text{sample}}}{R_{\text{reference}}} - 1 \right] \times 1000$$

(1)

where $R$ is the isotopic ratio $^{18}$O/$^{16}$O ($\cdot$).

Modeling

The hydrograph separation method, also called the mixing model, was applied to estimate the infiltration ratio of groundwater into the sewer pipes. It is based on the mass balance of a conservative tracer present in the two main water inflows into urban sewer systems: discharged drinking water and infiltrated natural groundwater.

The total flow at the end of the sewer system (Figure 1, yellow points) was expressed by a simplified equation that takes into account only these two main water contributions:

$$Q_w(t) = Q_d(t) + Q_g(t).$$

(2)

where $t$ is time (s), $Q_w$ is the resulting wastewater flow rate (m$^3$s$^{-1}$), $Q_d$ is the flow rate of the drinking water discharged into the sewer (m$^3$s$^{-1}$), and $Q_g$ is the flow rate of the groundwater infiltrated into the sewer system (m$^3$s$^{-1}$).

| Groundwater characteristics. Average $^{18}$O, conductivity and water table level in the two investigated urban catchments, Infernetto and Torraccia, respectively. The symbols correspond to the Figures 1a and b |
|---|---|---|
| Infernetto | Average $^{18}$O/SMOW, ‰ | Conductivity, $\mu$S cm$^{-1}$ | Depth of water table, m |
| I1 | $-5.88$ | $1,125$ | $1.8$–$2.0$ |
| I2 | $-5.79$ | $1,426$ | $-$ |
| I3 | $-5.80$ | $1,154$ | $6.0$–$7.0$ |
| I4 | $-5.87$ | $1,187$ | $7.0$ |
| I5 | $-5.73$ | $1,145$ | $11.0$ |
| I6 | $-5.57$ | $1,130$ | $-$ |
| I7 | $-5.66$ | $1,034$ | $6.0$–$9.0$ |
| I8 | $-5.79$ | $1,305$ | $9.0$ |
| I9 | $-5.51$ | $1,124$ | $9.0$ |
| I10 | $-5.47$ | $1,022$ | $-$ |
| I11 | $-5.63$ | $1,245$ | $11.0$–$12.0$ |
| I12 | $-6.33$ | $867$ | $8.0$ |
| Mean | $-5.75$ | $-$ | $-$ |
| St. dev. | $0.22$ | $-$ | $-$ |
| Torraccia | | |
| T1 | $-5.80$ | $584$ | $8.5$ |
| T2 | $-5.57$ | $641$ | $12.2$ |
| T3 | $-5.44$ | $734$ | $14.0$ |
| T4 | $-5.71$ | $518$ | $-$ |
| Mean | $-5.63$ | $-$ | $-$ |
| St. dev. | $0.18$ | $-$ | $-$ |
In this study, we used $^{18}$O as a natural tracer. The mass balance of $^{18}$O can be expressed in terms of $\delta^{18}$O-notation, defined in Equation (1), as:

$$
\delta^{18}O_{w}(t) Q_{w}(t) = \delta^{18}O_{d}(t) Q_{d}(t) + \delta^{18}O_{g}(t) Q_{g}(t).
$$

(3)

where $\delta^{18}O_{w}$ is the isotopic content of wastewater that varies over time ($\%_{o}$ vs. SMOW); $\delta^{18}O_{g}$ is the isotopic composition of drinking water supplied by the aqueduct ($\%_{o}$ vs. SMOW); $\delta^{18}O_{d}$ is the average isotopic content of groundwater in the investigated catchment ($\%_{o}$ vs. SMOW). The isotopic composition of drinking water and groundwater were assumed to be constant over time and were substituted with their average calculated from the samples collected throughout the catchment.

Substituting, $Q_{d} = Q_{w} - Q_{g}$ into Equation (3) and rearranging it, the infiltration flow rate was calculated from the following formula:

$$
Q_{d}(t) = \left( \frac{\delta^{18}O_{w}(t) - \delta^{18}O_{d}(t)}{\delta^{18}O_{g} - \delta^{18}O_{d}} \right) Q_{w}(t),
$$

(4)

where $\delta^{18}O_{d}$ and $\delta^{18}O_{g}$ are the average values. The infiltration ratio is given by:

$$
R_{inf}(t) = \frac{Q_{d}(t)}{Q_{w}(t)}.
$$

(5)

The application of the method is based on the following assumptions:

1. The isotopic composition of groundwater has a low spatial variability over the investigated area, and does not change during the investigated period, so that $\delta^{18}O_{d}(t,x) \equiv \delta^{18}O_{g}$.
2. The drinking water is supplied by a unique aqueduct, and its composition does not change during the investigated period, so that $\delta^{18}O_{d}(t) \equiv \delta^{18}O_{d}$;
3. The difference between $\delta^{18}O_{d}$ and $\delta^{18}O_{g}$ is larger than uncertainty introduced by the measurements of the isotopic composition of the samples (De Bénédittis & Bertrand-Krajewski 2005a);
4. The tracer is conservative, and no isotopic fractionation has occurred after the groundwater and the drinking water have been sampled.

### Uncertainty analysis

The sources of uncertainty affecting the calculated infiltration ratio were classified in three groups: **zeroth order errors** ($P_{0}$) (e.g., human errors, instrumentations errors, etc.), **first order errors** ($P_{1}$) (e.g., spatial variability, temporal variability, etc.), and **Nth order errors** ($P_{n}$) (e.g., conservation of the tracer, storage of the samples, etc.).

In this work, we considered the laboratory analyses for the $\delta^{18}$O determination and the measurement of wastewater flow rate as sources of the **zeroth order errors** ($P_{0}$). The spatial variability of $\delta^{18}$O in the shallow groundwater and drinking water, as well as the temporal variability of $\delta^{18}$O in the drinking water were considered as sources of the **first order errors** ($P_{1}$). Following Coleman & Steele (1999), $P_{1}$ is given by:

$$
P_{1} = \sqrt{P_{v}^{2} + P_{m}^{2}}
$$

(6)

where $P_{v}$ indicates either the spatial or the temporal variability without the measurement error, and $P_{m}$ is the measurement error, assumed equal to $P_{0}$.

The sources of **Nth-order errors** ($P_{n}$) were associated with: The isotopic difference between drinking water and groundwater, the variation of the isotopic content of the drinking water before and after the use of it, and the variation of the isotopic content during the sample storage.

The following paragraph reports the values of the errors associated with each source listed above together with the method used to quantify them. The errors, summarized in Table 2, were propagated through the model (Equation 5) by Monte Carlo simulation and, finally, the precision of $R_{inf}$ was estimated.

### RESULTS AND DISCUSSION

This paragraph is divided in three parts. In the first one, the quantification of the errors introduced by various sources of uncertainty, listed in **Uncertainty analysis**, are reported and discussed, and the assumptions for the applicability of the method, listed in **Modelling**, are verified for both catchment areas. In the second part, the data regarding the isotopic composition and the wastewater flow rate are reported together with the calculated $R_{inf}$, $Q_{d}$, and $Q_{g}$ by Equations
(2), (4) and (5). The third part summarizes the results from the propagation of the errors, listed in Table 2, through Equation (5).

**Quantification of the errors**

As mentioned above, the zeroth order errors \( P_0 \) were identified in the \( \delta^{18}O \) laboratory analyses and in the flow rate measurements and their errors were estimated to be \( \pm 0.20\% \) and \( \pm 0.20\% \), respectively.

The first order errors \( P_1 \) in Equation 6 included the spatial variability of \( \delta^{18}O \) in the shallow groundwater and in the drinking water \( P_{1s} \), and the temporal variability of \( \delta^{18}O \) in the drinking water \( P_{1t} \).

In the case of shallow groundwater, \( P_{1s} \) corresponded to the overall uncertainty calculated from isotopic content in the groundwater samples collected from the wells spread over the entire investigated area; similarly, \( P_{1s} \) in the drinking water corresponded to isotopic content in the samples collected from the fountains distributed over the entire investigated area, as well.

In Infernetto, \( P_{1s} \) in the shallow groundwater was estimated as large as \( 0.22\% \) and the spatial variability without the experimental error \( P_{ns} \) was equal to \( \pm 0.09\% \), which we considered not significant given the laboratory measurements errors of \( \pm 0.20\% \). The estimated \( P_{ns} \) for Torraccia, was even lower and assumed to be negligible (see Table 2).

The low spatial variability of the shallow groundwater in both catchments satisfies the first model assumption.

The value of \( P_{1s} \) in the drinking was equal to \( 0.06\% \) and \( 0.20\% \) in Infernetto and in Torraccia, respectively. Such low values, considering the laboratory measurement errors equal to \( \pm 0.20\% \), clearly indicate the uniqueness of the aqueduct, confirming the declaration of the drinking water operators.

The value of temporal variability of \( \delta^{18}O \) in the drinking water \( P_{1t} \) was determined indirectly using a conductivity probe placed in a public fountain in the sample areas. Using the correlation shown in Figure 2 that was pointed out by Lamb (2000), we obtained the temporal variability of \( \delta^{18}O \) from the conductivity measurements. The good fit \( (R^2 = 0.93) \) confirms that the results of Lambs are applicable in our case. From measurements carried out over a one-week period, we estimated a conductivity of \( 635.59 \pm 0.86 \mu S \cdot cm^{-1} \) and of \( 609.60 \pm 1.89 \mu S \cdot cm^{-1} \), in Torraccia and Infernetto, respectively. From the error propagation equation of linear models (Coleman & Steele 1999), we estimated a temporal variability of \( \delta^{18}O \) of \( \pm 0.03\% \) and \( \pm 0.07\% \) in Torraccia and in Infernetto, respectively. Assuming a measurement error \( P_m \) in equation 5) equal to zero for the conductivity probe, the values of \( P_{1t} \) are equal to \( P_{vt} \).

---

**Table 2** | Errors affecting \( R_{INF} \) and the methods of their estimation

<table>
<thead>
<tr>
<th>Source of error</th>
<th>Error, ‰</th>
<th>Torraccia</th>
<th>Infernetto</th>
<th>Method of estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_0 )</td>
<td>Laboratory analysis</td>
<td>0.20</td>
<td>0.20</td>
<td>Laboratory data</td>
</tr>
<tr>
<td>Flow rate</td>
<td>2.00</td>
<td></td>
<td>2.00</td>
<td>Technical sheets</td>
</tr>
<tr>
<td>( P_{1s} )</td>
<td>Spatial variability of groundwater</td>
<td>0.0</td>
<td>0.09</td>
<td>Field investigations</td>
</tr>
<tr>
<td>( P_{1t} )</td>
<td>Temporal variability of drinking water</td>
<td>0.03</td>
<td>0.07</td>
<td>Conductivity measurements</td>
</tr>
<tr>
<td>( P_n )</td>
<td>Water use</td>
<td>0.00</td>
<td>0.00</td>
<td>Field investigations</td>
</tr>
<tr>
<td>Sample storage</td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>Field investigations</td>
</tr>
</tbody>
</table>

---

**Figure 2** | Conductivity vs. \( \delta^{18}O/SMOW \) of the drinking water samples collected from Peschiera aqueduct in Torraccia and Infernetto. A linear regression of these data points gives a slope of 28.10 and an intersection of 859.53, with \( R^2 = 0.93 \).
Given the low values of the spatial and temporal variability of the drinking in both catchment areas, the second assumption for the application of the method was satisfied.

Finally, we consider the \textit{Nth-order errors} (\(P_n\)) originating from the following sources: The isotopic difference between drinking water and groundwater, the variation of the isotopic content of the drinking water before and after the use, and the variation of the isotopic content during the storage.

The isotopic difference between drinking water and groundwater is important to estimate, because the hydrograph separation method can be applied only if a significant difference in isotopic compositions between them exists (third assumption listed in \textit{Modeling}). \cite{De Benedittis2005} express the uncertainty affecting the infiltration ratio as a function of the isotopic difference between the two drinking water and groundwater. In our case, the isotopic difference between drinking water and groundwater was as large as 2.63‰ and 2.36‰, in Torraccia and in Infernetto, respectively. Applying the law given by \cite{De Benedittis2005}, we estimated an uncertainty of 5% that makes the hydrograph separation method applicable to our case. This conclusion was further strengthened considering the different origin of the two water sources and the isotopic compositions of their sources. In particular, the infiltration is due to a shallow and local groundwater recharged by local precipitation, while the drinking water is supplied by an aqueduct whose springs are located approximately 100 km from the study areas. The isotopic composition of the local precipitation in both investigated areas and the Peschiera springs, where the aqueduct originates, are reported by \cite{Longinelli2003}. They measured average oxygen isotopic composition of the local precipitation between \(-6\%^{00}\) and \(-5\%^{00}\), and of the springs between \(-9\%^{00}\) and \(-8\%^{00}\).

The other source of \textit{Nth-order errors} concerns the conservation of the oxygen isotopic composition during both the drinking water use and the sample storage. During the drinking water use, oxygen isotopic composition could vary because of chemical-physical reactions. In order to investigate that, a drinking water and wastewater composite samples were taken. In particular, the composite samples were collected over four hours at a house-connection. The isotopic compositions were \(-8.23\pm0.2\%^{00}\) and \(-8.49\pm0.2\%^{00}\), for the drinking water and for the composite wastewater samples, respectively. Since the difference between the two values was within the measurement error of 0.2‰, we assumed the tracer to be unaltered during the water use. During the storage of the wastewater samples, the \(\delta^{18}\)O could vary due to redox reactions (\cite{Kendall1998}). In order to hinder these reactions the amount of organic matter and oxygen in the samples has to be reduced as much as possible, and the conservation temperature needs to be low. Therefore, the samples were filtered with 0.45 \(\mu m\) filters, and kept at low temperature in PVC bottles, filled until the top. The conservation temperature was selected after analysing the variability of the isotopic composition of three samples: one determined immediately after collection, one after storage for 15 days at 4°C, and the third one after storage for 15 days at \(-4°C\). In all cases, the oxygen isotopic composition between the unstored sample and the two stored ones was within the measurement error (\(P_0\)) of the isotopic analysis.

Given the unchanged isotopic composition during the drinking water use and the sample storage, the fourth assumption for the applicability of this method was satisfied.

All calculated errors, summarized in \textit{Table 2}, were identified as random, and in order to calculate their contribution to the infiltration ratio \(R_{\text{INF}}\) (Equation 5), the Monte Carlo random sampling method was applied. The results are reported below in \textit{Error propagation}.

\textbf{Estimation of the infiltration ratio}

Two field campaigns were carried out to estimate \(R_{\text{INF}}\) in the two urban areas. In Torraccia, the experiment was nine hours long, from 11.00 am until 8.00 pm, while the duration was of 24 hours in Infernetto.

In Torraccia catchment:

- Three drinking water samples were taken from public fountains (blue dots in \textit{Figure 1a}) with a mean value of oxygen isotopic composition equal to \(-8.14\%^{00}\) (\textit{Table 1}).
- Four groundwater samples were collected from wells distributed evenly over the area (red dots in \textit{Figure 1a}).
with a mean value of oxygen isotopic composition equal to $-5.74\%/oo$ (Table 1).

- Five grab wastewater samples were taken from the sewer stream at the outlet of the sewer network (yellow dot in Figure 1a). At this location, the flow meter was also installed and the flow rate was measured during the sampling period (Figure 3).

The resulting oxygen isotopic composition of the three water sources is reported in Figure 4 over time. The $\delta^{18}O$ abundances in the wastewater samples are bounded by the values of the drinking water and the groundwater samples. Thus, wastewater can be considered a mixture of the two sources of water with a smaller contribution from groundwater.

The $R_{\text{INF}}$ for Torraccia area was calculated by applying Equation 5 and the values are also shown in Figure 4. Not surprisingly, $R_{\text{INF}}$ is very small, between 0.18–0.23, as a consequence of the very low groundwater contribution to the isotopic composition of wastewater samples. The peak in $R_{\text{INF}}$ around 1.30 pm (corresponding to 1.83 hr in the figure) can be ascribed to the variation of the drinking water use during the period of the campaign (Figure 4). Torraccia is a residential area, and the domestic water use was the lowest when we measured the highest $R_{\text{INF}}$ value. In the evening when the urban area was maximally populated, we measured the lowest $R_{\text{INF}}$ value. Thus, we assumed that the infiltration from groundwater into the sewer network remained almost constant, and the observed variation in $R_{\text{INF}}$ reflected the drinking water use.

In Infernetto catchment:

- Five drinking water samples were taken from different fountains (blue dots in Figure 1b) with a mean value of oxygen isotopic composition equal to $-8.11\%/oo$ (Table 1).
- Twelve groundwater samples were taken from the wells spread all over the investigated area fountains (red dots in Figure 1b) with a mean value of oxygen isotopic composition equal to $-5.75\%/oo$ (Table 1).
- Twenty three grab wastewater samples were taken from the sewer stream at the outlet of the sewer network (yellow dot in Figure 1b). At this location, the flow meter was also installed and the flow rate was measured during the sampling period (Figure 6).

The resulting oxygen isotopic composition of the three water sources is reported in Figure 5 over time. Also in this case, the wastewater was a mixture of the groundwater and drinking water, since oxygen isotopic composition of the former, reported in Figure 5, is within the values of the latter.
ones. But in contrast to Torraccia, the contribution due to the drinking water is larger since the oxygen isotopic composition of wastewater is more similar to the groundwater.

Figure 5 reports the $R_{INF}$ of Infernetto calculated by Equation (5). In Infernetto, $R_{INF}$ shows a very high variability. From midnight until 8.00 am (corresponding to 10 and 18 hr in the figure), it changed between 0.4 and 0.75, reaching the high-test value between 6.00 am and 8.00 am (corresponding to 16 and 18 hr in the figure).

Comparing the $R_{INF}$ with the flow rate, reported in Figure 6, we observed that during the night period the total measured flow rate, $Q_{w}$, and the drinking water flow rate, $Q_{d}$, decreased, whereas the infiltration flow rate, $Q_{g}$, calculated using Equation (4), remains constant, as a consequence $R_{INF}$ remained constant. Thus during the night, when the drinking water use is at the minimum level, $R_{INF}$ increased, given a constant groundwater infiltration, $Q_{g}$.

**Error propagation**

A Monte Carlo random sampling routine was implemented in the statistical package R and used to perform the error propagation through Equation (5). The sources of error used are reported in Table 2. From this analysis, we calculated an infiltration of $14.20 \pm 1.80\%$ with precision $\pm 21\%$ in Torraccia and $49.90 \pm 11.90\%$ with precision $\pm 20\%$ in Infernetto.

Given the uncertainty in the method as large as 20%, the infiltration rate in Torraccia was considered negligible in comparison to that of Infernetto. Such a result is consistent with the characteristics of the sewer systems. The one in Torraccia is recent, laid in tuff subsoil, and belonging to a new residential area, while the sewer in Infernetto is older, laid in alluvial, made by different construction material, i.e., concrete and PVC, and shapes, and serving an old residential area.

**CONCLUSION**

The hydrograph separation method based on isotopic composition has been applied to quantify the infiltration ratio in urban sewer systems. Two experimental campaigns were carried out in two urban areas in Rome, characterized by sewer networks with different characteristics.

The infiltration ratio estimated for the older sewer system is significantly different from zero, while the newer has a value within the precision of the method.

Uncertainty analysis and error propagation show that the precision of the hydrograph separation method based on isotope $^{18}$O is 20%. Despite the low precision, this method is useful for a preliminary survey to investigate the state of a sewer network in order to prioritize maintenance. In comparison to the traditional TV inspection, hydrograph separation method is cheaper, can be applied on a working sewer system without interrupting the service, and can be applied to large sewer systems within few days. The application of this method requires a good knowledge of the geology and of the shallow hydrogeology as well as of the sewer network (e.g., map, material, age, etc.). This information can usually been obtained from the local authority at relatively low cost.

Other costs for the application of the method derive from:

- The equipment to measure the flow rate and to collect samples from the wastewater stream;
- The field work;
- The isotopic analyses.

However, the field work will not contribute to additional costs indeed because it can be included into the personnel cost.
ACKNOWLEDGEMENTS

This study has been carried out within the framework of the European research project APUSS (Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems) which partners are INSA de LYON (FR), EAWAG (CH), Techn. Univ. of Dresden (DE), Faculty of Civil Eng. at Univ. of Prague (CZ), DHI Hydroinform a.s. (CZ), Hydroprojekt a.s. (CZ), Middlesex Univ. (UK), LNEC (PT), Emschergenossenschaft (DE) and IRSA-CNR (IT). APUSS is supported by the European Commission under the 5th Framework Programme and contributes to the implementation of the Key Action “Sustainable Management and Quality of Water” within the Energy, Environment and Sustainable Development Contract n° EVK1-CT-2000-00072. The project work of EAWAG is financially supported by the Swiss Federal Office for Education and Science (BBW).

Moreover, we would like to thank the ACEA S.p.A. for helping us during the installation of the equipment and Mr Mola of IGAC for his help during the isotopic analyses. Finally, I thank Marc Hesse for his valuable suggestions to improve the article.

REFERENCES


