Design of experiments for quantifying sewer leakages by QUEST-C method

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Abstract
The structural state of sewer pipe is a crucial problem in urban areas because infiltrations and exfiltrations can occur and consequently contaminate the surface and deep water bodies, respectively.
In this paper the application of a new method to quantify the sewer leakages (called exfiltrations) with tracers during dry weather is discussed.
This method, called QUEST-C (*Quantification of Exfiltration from Sewers with the help of Tracers-Continuous Dosing*) and developed by EAWAG (CH) within the European project APUSS, allows to estimate the exfiltrations by a mass balance of chemical tracers dosed continuously in a wastewater stream of operating sewers.
In the paper, we sum up our experience from a number of field experiments in order to discuss the application of the method in the field, critically: (i) planning of the experiments; (ii) the reliability of the obtained results; (iii) the overall applicability of the method in an urban area.
Finally, some findings with regard to the practical application and recommendations are presented for the future development of the method.

Keywords
Artificial tracer; exfiltration; sewer; leakages; uncertainty

INTRODUCTION

The quantification of the sewer leakages can be an useful tool for assessing the sewer performances, that is the structural state of the pipe. The not watertight pipes should be substituted with new ones because the wastewater leakages transport in the urban environment (e.g. subsoil and groundwater) organic and inorganic pollutants.
This paper deals with the application in Rome by IRSA (IT) of a novel method that has been developed within the European project APUSS (*Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems*) by EAWAG (CH) for quantifying the exfiltration in the urban sewer systems.
An experimental design by a general uncertainty analysis was approached for individuating the most critical variables of the applied model (Rieckermann et al., 2003A). The final aim of this kind of analysis was to understand how to measure the variables of interest in order to achieve reliable results and optimize the technical and economical efforts. Then, three experiments were carried out in an urban sewer network in Rome, and the results are shown and discussed.

STUDY AREAS

The experiments were carried out on three reaches of a sewer network in an urban area in Rome, called Torraccia. In this area the sewer, dated thirteen years, is an egg-shaped combined system build in concrete material. The investigated reaches are 4-9 m under the ground level with a slope of 0.9 %.
In Figure 1 the tested reaches are shown, in particular: the Reach 1 is 400 m long and egg-shaped 120x210 cm, the Reach 2 is 482 m long and egg-shaped 120x210 cm and the Reach 3 is 680 m long and egg-shaped 180x120 cm.
All the pipes are in subsoil characterized by cracked tuff and pozzolan. The groundwater submerges the sewer pipes only during the wet weather and it is quickly drained towards a deeper aquifer for the high permeability of cracked tuff.
The principal differences among the investigated reaches are: the flow rate, the number of house connection and nodes, the traffic load and the vegetation. A summarizing description of the tested reaches in terms of these characteristics is in Table 1.

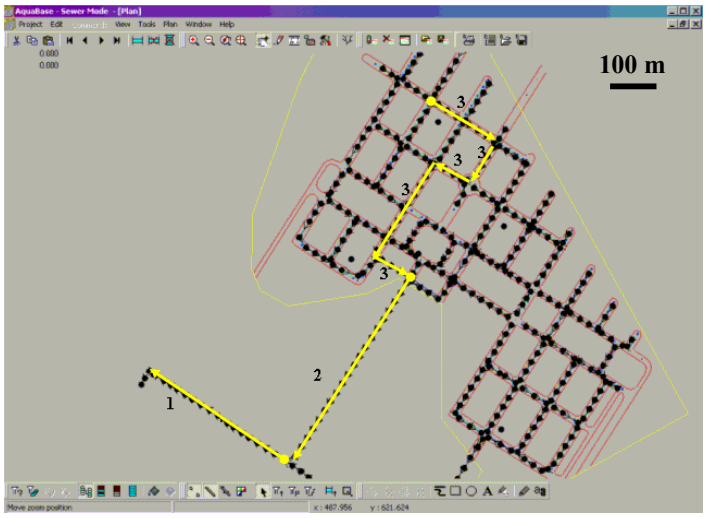


Figure 1. Scheme of the tested sewer network implemented in AquaBase software developed by Hydro Project and Hydro Inform (CZ) within European Project APUSS.

Table 1. Different features of the investigated pipes.

	Reach 1	**Reach 2**	**Reach 3**
Average Flow rate [L/s]	28.20 ± 1.97	19.97 ± 2.04	9.50 ± 1.35
Water depth [cm]	13.35± 1.97	7.59 ± 1.97	7.49 ± 1.97
Number of HC	0	0	23
Number of nodes	0	0	7
Traffic	No	No	Yes
Vegetation	Grass	Grass	Eucalyptus

METHOD QUEST-C

The method QUEST-C allows quantifying the exfiltration in urban sewer pipes (Rieckermann et al., 2003 A and B; Rieckermann et al., 2004). It consists of a continuous dosing of two different tracer solutions (LiCl and NaBr) at two different locations along a tested sewer. The LiCl solution has to be dosed for measuring the discharge at the beginning of investigated reach (Q_1 in Figure 2), the NaBr solution has to be dosed for measuring the discharge at the end of investigated reach (Q_2 in Figure 2). The wastewater samples taken at Manhole 3 are to be analyzed by means of IC in order to determine the Li^+ and Br^-. The background concentration of Br^- is determined by sampling at Manhole 2.

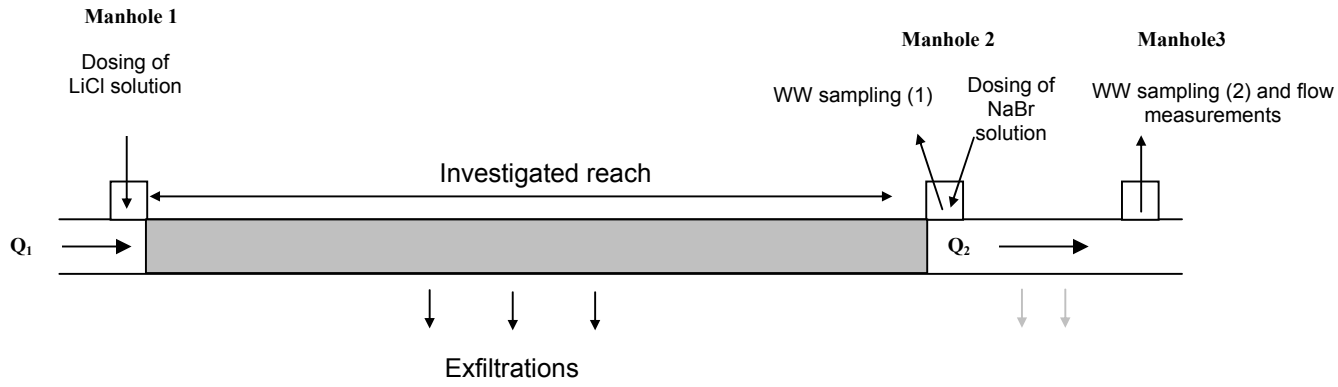


Figure 2. Scheme of tracer dosage and sampling of QUEST-C method (Modified from Rieckermann et al., 2003B)

The exfiltration ratio percentage is calculated by the following equation (1):

$$exf. = \left(\frac{Q_1 - Q_2}{Q_1} \right) * 100 \qquad (1)$$

In particular, considering a steady flow the latter equation becomes:

$$exf. = \left(1 - \frac{\frac{c_{solBr} * q_{solBr}}{C_{wwBr}}}{\frac{c_{solLi} * q_{solLi}}{C_{wwLi}}} \right) * 100 \qquad (2)$$

where: $c_{solBr(Li)}$ [mg/L] is the Br^- (Li^+) concentration in the dosed solution; $q_{solBr(Li)}$ [L/s] is the flowrate of the peristaltic pump dosing NaBr (LiCl) solution; $C_{wwBr(Li)}$ [mg/L] is the concentration of Br^- (Li^+) in the wastewater samples. The $q_{solBr(Li)}$ is checked during the experiment in order to control the stability of the dosed tracer masses.
The equation (2) is applicable when the flow is quite steady during the trials, in this case Rieckermann et al. (2003B) estimated that the standard deviation of exfiltration ratio percentage changed between 2.4% - 2.6%, and Rieckermann et al. (2004) observed that it decreased at 0.5% as the flow rate variability was taken into account.
In the present paper the exfiltration ratio was calculated by the equation (2) because the flowmeter installation at the manhole 3 was not always possible, thus all the experiments were carried out in a period of the day chosen after measuring the flowrate for two days before.

Measurements and analyses
The equipments used during the experiments are summarized in the Table 2 and differentiated on the grounds of the location of installation in Figure 2.

Table 2. Equipments used for the experimental campaigns

Manhole 1	Manhole 2	Manhole 3
Peristaltic dosing pump (Velp, mod. SO311)	Peristaltic dosing pump (Velp, mod. SO311)	Peristaltic sampling pump (Watson&Marlow, mod. SCIQ 323)
	Peristaltic sampling pump (Watson&Marlow, mod. SCIQ 323)	Flowmeter Area-velocity (SIGMA900 Max)*
		Each sample was filtered in the field by means of wathman filters with porosity 0.45 μm

*The flow measurements need to check the flow variability.

The laboratory analyses for the determination of the Li^+ and Br^- concentrations were carried out by means of Dionex Dx100 (anion column AS14 and cation column CS12).
The tracer concentrations in the dosed solution during the investigation were calculated by a mass balance on the basis of the solubility limits of NaBr and LiCl at 20°C in water, which are 905 gr/L and 832 gr/L, respectively. The dosage flow rates were calculated by a mass balance over the node knowing the average flow rate during the experiments from previous investigations (for two days about), the minimum detectable concentration by IC device and the solubility of NaBr and LiCl at 20°C in water.

GENERAL UNCERTAINTY ANALYSIS FOR PLANNING THE QUEST-C EXPERIMENTS

Before the application of the QUEST-C method a general uncertainty analysis was carried out in order to plan accurately the experiments and for investigating if the tests were feasible with the proposed model (i.e. equation 2) by means of those equipments and in that experimental area.
Thus, for each variable in the equation 2, the UMCs (Uncertainty Magnification Factors) and the UPCs (Uncertainty Percentage Factors) were calculated. The first factors indicate the influence of the uncertainty in that variable on the uncertainty in the result, and the second ones (Uncertainty Percentage Factors) give the percentage contribution of the uncertainty in that variable to the squared uncertainty in the result (Coleman & Steele, 1999). In practice, let us consider the observation equation:

$$f = f(X_i) \qquad (3)$$

where X_i is the vector of the measured variables. The UMFs and the UPCs for a equation (3) are defined as:

$$UMF_i = \frac{X_i}{f}\frac{\partial f}{\partial X_i} \qquad (4)$$

$$UPC_i = \frac{\left(\frac{\partial f}{\partial X_i}\right)^2 \left(U_{X_i}\right)^2}{\left(U_f\right)^2} * 100 \qquad (5)$$

where U_{X_i} is the uncertainty of the variable X_i and U_f is the uncertainty in the result of the observation equation calculated by error propagation equation for a linear model of random variables statistically independent.
For our purpose the observation equation is the equation 2 and the UMF and UPC values were calculated for each variable after analyzing the sources of uncertainty that affect the QUEST-C method (Rieckermann et al., 2003B; Rieckermann et al., 2004) and the most important ones are summarised in the Table 3.

Table 3. Relevant sources of uncertainty for each variable in equation 2

	Preparation		Field application				Laboratory Analysis	
	Weight of chemical tracer	Dilution	Dosing of tracer solution	Adsorption on solid matter in sewer	Transport	Sampling	Storage of samples	Ion - Chromatograph
c_{solLi}	x	x	x					x
c_{solBr}	x	x	x					x
q_{solLi}			x					
q_{solBr}			x					
C_{wwLi}				x	x	x	x	x
C_{wwBr}				x	x	x	x	x

The paragraphs below discuss the applied methodology for quantifying the uncertainty from every source in Table 3. No difference between random and systematic uncertainties was taken in account at this stage, because we used the same equipments for measuring the similar variables in the numerator and in the denominator of equation 2 in order to minimize the systematic errors in the result. Generally spoken the ratio of two test results can have a lower systematic uncertainty than the systematic uncertainty in either of individual test results (Chakroun et al., 1993; Coleman & Steele, 1999).

Preparation
The errors during the preparation of the chemical tracer solutions were principally due to:

- scale for weighting the solid tracer (i.e.: NaBr and ClLi)
- graduated flask for the dilution of the solid tracer
- human

The scale (trade Sartorious mod. BL1500) had an accuracy of ± 0.1 gr. The graduated flask had an accuracy of ± 0.4 mL at 20°C. However, as the tracer solutions dosed during the experiment were analyzed by means of IC, the $c_{solBr(Li)}$ parameters in Table 3 can only be affected by the uncertainty coming from the IC.

Field application
Dosing of tracer solution
The dosage flow rates to be used during the tests were calculated on the grounds of the solubility of dosed tracers and the expected sewer discharge. The uncertainty during the tracer dosage could be due to:

- Instability on the dosing pump flow rate

- Stratification of the tracer in the bottle where it was stored

In order to estimate the errors coming from these two aspects, laboratory trials were carried out reproducing the field situation (e.g. the same pumps, the same tracer concentrations, the same bottles and the same pumping duration). Two calibrated bottles were put on two scales (trade OHAUS mod. GT4800) one with 50 grNaBr/L solution and another with 20 grLiCl/L one; the dosing pump flow rates were 50 mL/min and 12 mL/min, respectively. The level of the solution in the bottle and the weight were recorded for 70 minutes about.
No instability of the dosing pump flow rate and no tracer stratification were observed (Figure 3) at those concentrations for those tracers, at those pumping rates and duration. Anyway, the authors suggest recording the dosed tracer solution during the experiment in order to check the steady dosage that could be affected by possible pump inefficiency.

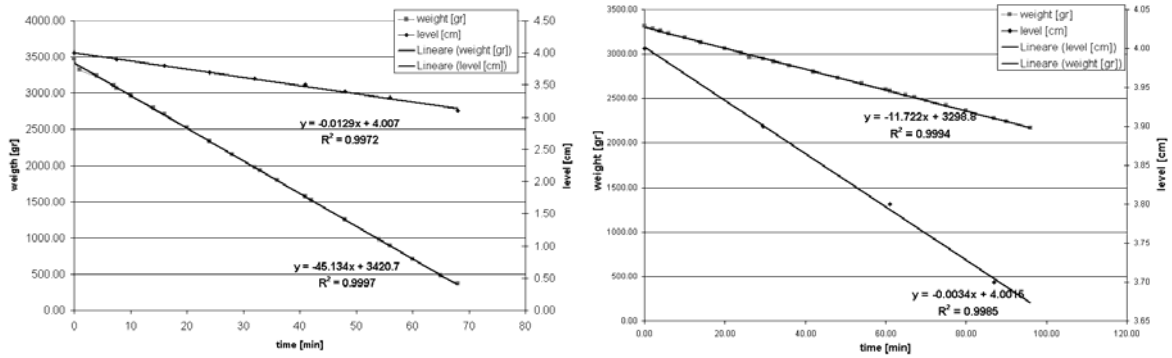


Figure 3. Weights and levels of tracer dosed solution in a tank vs. time, right graph for NaBr and left one for LiCl

Adsorption
The tracer adsorption on the solid matter during the transport from the dosage manhole up to the sampling one in the sewer stream and on the biofilm that grows on the sewer wall was estimating in laboratory as by Ellis & Revitt (2003).
9.9 mgBr^-/L were dosed into two beakers with 125 mL of raw wastewater in one of these biofilm (2.5 gr of biofilm taken from the wall of the investigated reach) was dispersed inside, too. The same test was separately carried out with 3.3 mgLi^+/L. The duration of the trials was 120 min about. The results in Figure 4 show that the adsorption could be neglected in the beakers with WW for both chemical tracers, but the concentration decreases of 2 mg Br^-/L in those ones with Br^-, WW and dispersed biofilm.
The results show at these concentrations that the loss for adsorption onto bio-solids is 2 mgBr^-/L, so it was advisable to reduce it, anyway as the maximum residential time of Br^- in the tested sewer was estimated equal to 7 minutes about the adsorption on the solids could be considered negligible.
The adsorption during the storage period was not considered because the wastewater samples were immediately filtered in the field by means of filters with 0.45μm of porosity.

Transport
The tracer transport can affect the exfiltration results because of the waves which might be due to sudden discharges in the urban catchment. The wave propagates faster than the average flow velocity

(*Henderson, 1966*) and Huisman et al. (*2000*) showed experimentally that in sewer system the hydraulic wave separated from the fluid. Thus if a wave is labelled with the tracer the celery causes the wave to travel faster than the dosed tracer solution that had labelled it and then the flowrate measured is uncorrected.

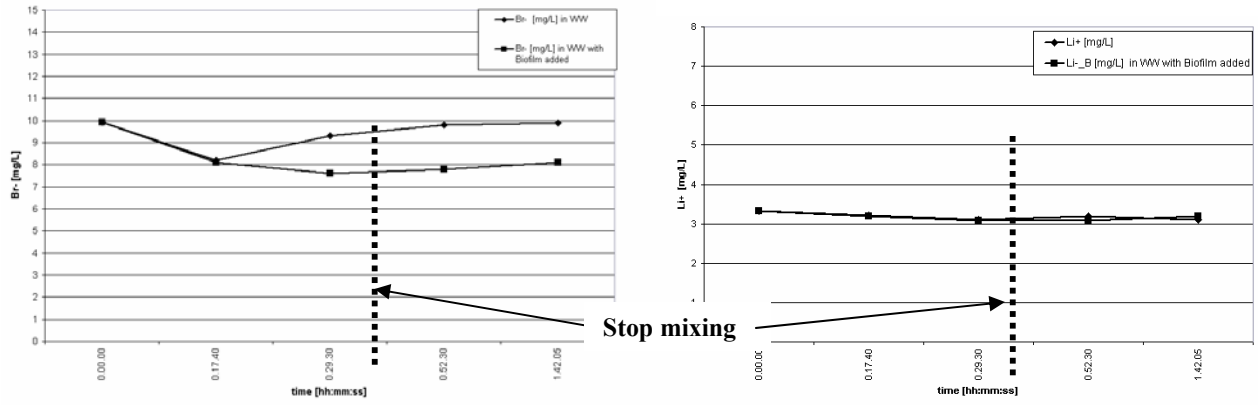


Figure 4. Tracer concentration vs. time; right graph for Br^- and left one for Li^+

In Rieckermann et al. (2004) a dynamic analysis of the QUEST-C was approached in order to asses the error due to the transport in the resulting exfiltration ratio. From this analysis a systematic error of 0.2% and a standard deviation of 0.8% was computed. Thus, in order to reduce the uncertainty coming from the transport previous measurements of the flow rate should be carried out and the period when the discharges are quasi-steady would have to be chosen for investigations (Figure 5). Otherwise, the discharge values should be considered in computing the exfiltration ratio.

In order to quantify the error due to the transport only, one of the reach (i.e. Reach_1 in Figure 1) was modelled with AQUASIM software (Reichert, 1994). The simulations consisted of virtual application of QUEST-C method, dosing 50 grLiCl/L and 20 grNaBr/L and flow rates 50 mL/min and 20 mL/min, respectively. The roughness coefficient (Ks= 55 $m^{1/3}s^{-1}$) and the dispersion coefficient (D= 0.1m^2s^{-1}) were calculated by parameter estimation tool in AQUASIM using concentration peaks of a slug dosage of NaCl tracer and measured discharge, the grid space for the calculation was 0.50 m (Di Giulio, 2003). At first in order to find out when investigating with low disturbance by flow variability the Reach 1 was tested with several 90 minute long flow trends, without any inflow/infiltration and exfiltration. The more accurate results were obtained with the flow pattern from 10.00 a.m. to 11.30 a.m.. The standard deviations of Li^+ and Br^- concentrations during this period were used for UMP and UPC computations (Table 5).
Then, further simulations were carried out with this flow pattern, but exfiltrations of 0.5 L/s and 3.0 L/s and inflows of 5.0 L/s and 20 L/s were imposed and located along the investigated sewer as in Figure 5 (Table 4). The aim was to quantify the error in the exfiltration ratio when a dilution occurs for constant inflow/infiltration.
From the previous simulations on the Reach 1 and from the results in Table 4 the following observations can be argue:

- Lower flow variability and smaller losses, higher the accuracy of the results
- Higher constant inflow/infiltration, smaller the accuracy of the results. Consequently the method could be applied in the night on the urban sewer with sufficient water depth and whenever on the main sewer.

- The exfiltration ratio is very sensitive to the relative location of the exfiltration and inflow/infiltration because of the dilution of the stream labeled by the indicator tracer.

Sampling
As the tracer has to be fully mixed at the measuring cross section, a sufficient mixing length has to be provided. For non-buoyant tracers a recommended mixing length in river is 100-300 * d (d is water width) (Rutherford, 1994). In particular, for the investigated reaches called 1, 2 and 3 in Figure 1 the minimum mixing lengths were 130 m, 75 m and 75 m, respectively.

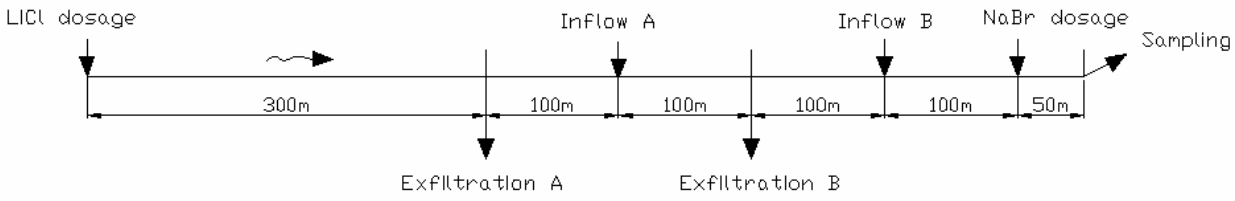


Figure 5. Simulated pipe scheme

Table 4. Summary and results of simulations with AQUASIM (Reichert, 1994)

	Sim_0	**Sim_1**	**Sim_2**	**Sim_3**
Inflow A [L/s]	5.00	5.0	5.0	5.0
Inflow B [L/s]	5.00	0.00	0.00	5.0
Exfiltration A [L/s]	0.00	0.5	0.00	0.5
Exfiltration B [L/s]	0.00	0.00	0.5	0.5
True Exf. Ratio [%]	0.00	2.16	2.16	4.33
Calculated Exf. Ratio [%]	0.65±1.17	2.65±1.15	2.58±1.16	4.65±1.17
	Sim_4	**Sim_5**	**Sim_6**	**Sim_7**
Inflow A [L/s]	20.00	20.0	20.0	20.0
Inflow B [L/s]	20.00	0.00	0.00	20.0
Exfiltration A [L/s]	0.00	3.0	0.00	3.0
Exfiltration B [L/s]	0.00	0.00	3.0	3.0
True Exf. Ratio [%]	0.00	12.98	12.98	25.97
Calculated Exf. Ratio [%]	0.57±1.16	7.23±1.06	12.73±1.24	18.87±1.51

Laboratory analysis

Sample storage
Samples of WW and dosed tracer solution were taken during the field experiments and then stored for some hours until some days in the refrigerator at +4°C. The WW samples were filtered with two filters (1.2 μm and 0.45 μm) just after sampling in the field. Thus the concentration variation during the storage because of dissolved solids was neglected.

IC analyses
The laboratory analyses consisted of determining the Li+ and Br- concentrations in the WW samples and the dosed tracer solutions by means of IC. The values were measured with 8÷10 % uncertainty (*APAT-IRSA/CNR, 2003*).

RESULTS AND DISCUSSION

In Table 5 below the values of each considered source of uncertainty are shown. A example of UMFs and UPCs are in Figure 6, they concern a previous investigation of the Reach 1. As a matter of the fact, they change as the absolute values of the model variables vary. UMPs assume the same value for every parameter (Figure 6) and they are more than 1, the influence of the uncertainty in the variable is increased as it propagates through the equation 2 into the exfiltration ratio (Coleman & Steele, 1999).

Table 5. Standard deviation of each source of uncertainty

	Preparation		Field application				Laboratory Analysis	
Parameters	Weight chemical tracer [gr]	Dilution [mL]	Dosing of tracer solution	Adsorption on solid matter in sewer [mg/L]	Transport [mg/L]	Sampling	Storage of samples	Ion – Chromato-graph [%]
c_{Li}	0.1	0.4	0					10
c_{Br}	0.1	0.4	0					10
q_{Li}			0					
q_{Br}			0					
C_{Li}				0.0	0.108	0	0	10
C_{Br}				0.0-2.0	0.016	0	0	10

From the UPCs calculation we obtained two different results (Figure 6):

1. C_{Br} is the principal source of uncertainty on the exfiltration ratio when the adsorption of Br^- on the solid matter is considered equal to the estimated value (Figure 4), consequently the exfiltration by equation 2 could be underestimated. Thus, the distance between the Manhole 2 and 3 should be calculated just for an accurate tracer mixing;
2. C_{Li} is the principal source of uncertainty on the exfiltration ratio when the adsorption of Br^- on the solid matter is neglected. This means the errors affecting C_{Li} (e.g.: transport and IC analysis) have to be carefully reduced. In order to reduce the effect of the transport the exfiltration ratio should be evaluated by the average concentrations of the tracers.

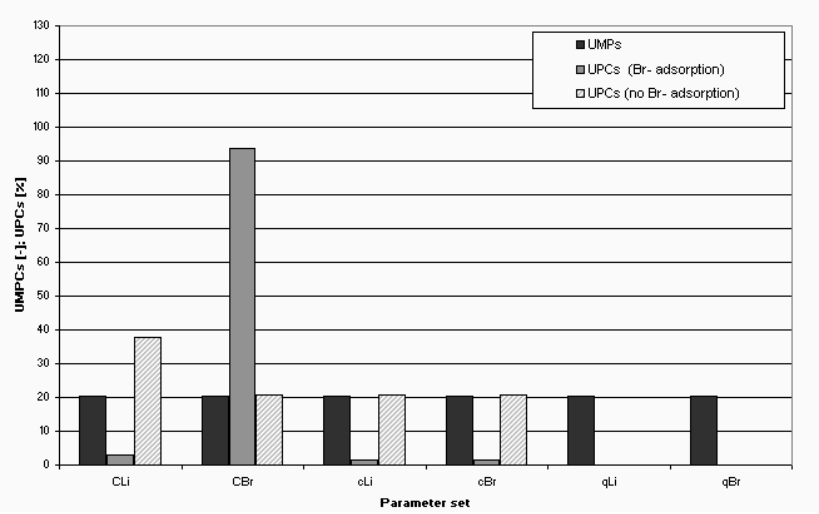


Figure 6. UMF and UPC values

In accordance to the discussion above three experiments were carried out in the Torraccia catchment to test the watertightness of the reaches in Figure 1 and in Table 6 the experiment settings and the exfiltration ratio percentage computed by the average concentration of the tracers are summarized. In Figure 7 the trends of tracer concentrations and the flow rate are shown; each concentration value is referred to the Li^+ and Br^- content in the sample taken for 10 minutes as from the indicated beginning. In Figure 7.A and C the flowrate was recorded at Manhole 3 while in the Figure 7B at Manhole 1.

Table 6. QUEST-C experiment setting and exfiltration ratio percentage in the investigated reaches

	Reach 1	**Reach 2**	**Reach 3**
cLi [gr/L]	18.04	20.10	24.22
cBr [gr/L]	50.35	58.86	50.98
qLi [mL/min]	62.61	45.43	28.44
qBr [mL/min]	62.91	36.32	23.75
Exfiltration [%]	-8.69±0.62	-1.73 ± 4.69	20.80 ± 4.46

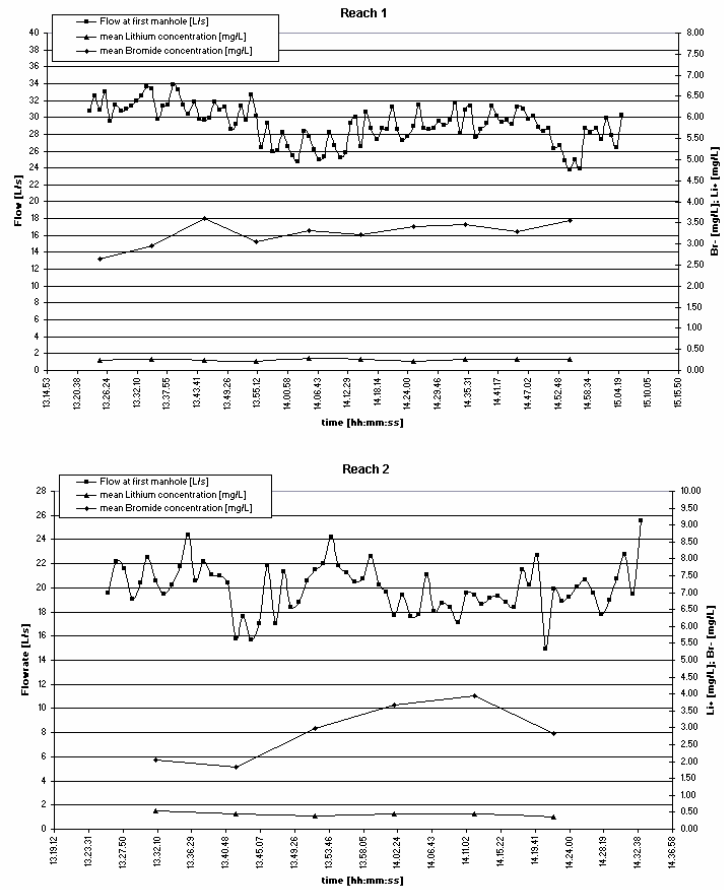
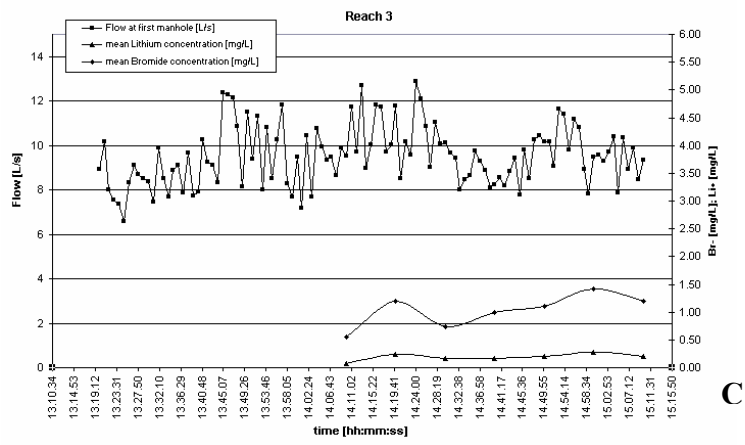


Figure 7. Tracer concentrations and flow rate vs. time. A. test on reach_1; B. test on reach_2; C. test on reach_3.



C

Figure 7. continues

The computed exfiltration ratios in Table 6 show two negative values. The negative exfiltration from the Reach 1 can very likely be due to some illicit Lithium discharges in the sewer during the experiment because of the strong deviation from zero that is more than the uncertainty estimated (Rieckermann et al., 2004).
Instead the negative absolute value of exfiltration ratio in Reach 2 is within the uncertainty value of the QUEST-C results, then we can assume that the exfiltration from this pipe was negligible during the investigation, as matter of the fact the expected value was zero because of the good structural state of sewer.
Finally, the high exfiltration ratio computed for the Reach 3 means that there are some important damages along the investigated pipes, but it is difficult to say if the calculated value is representative of the structural damages.

CONCLUSION

In this paper a critical approach for the application a novel method called QUEST-C and developed in the European Project APUSS by EAWAG (CH) which allows to quantify the exfiltration in the urban sewer network is presented.
A general uncertainty analysis was carried out for individuating the most critical variables in the model applied was used. Specifically, the analysis was done using numerical data from a experiment carried out in a catchment in Rome in order to design the experiments to be done in this catchment, with the same equipments and tracers. Every considered source of uncertainty was studied individually and specifically for our experiment sets (e.g.: wastewater quality, sewer geometry, concentration of dosed tracer solution etc.), and then three experiments were done in accordance with the results of the general uncertainty analysis.
The experiments distinguished by the number of inflows along the investigated pipes, as a matter of the fact two reaches could be compared to a main sewer pipe and one to an urban sewer pipe.
The calculated exfiltration ratio percentage were for the two tests in accordance with the expected results because of the estimated structural state of the pipe.
Finally, the QUEST-C method allows assessing reliable leakage values for reaches like main sewer (e.g. low inflow compared to the main stream), but the results seem to be affected by small accuracy when many inflows are along the investigated reach as happens in urban area sewer or in sewers partly submerged by groundwater.

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