

# Quantifying exfiltration with continuous dosing of artificial tracers

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## Abstract

In this paper the authors present a method to quantify the exfiltration from sewers with artificial tracers. In an application study Lithium and Bromide were used as ionic tracers. The results from an error analysis indicate that the main problems with the application of the method originate from the time-varying sewer flow. Accurate information on exfiltration could be used in innovative sewer operation and maintenance strategies.

## Introduction

The exfiltration of wastewater from sewer systems is a severe problem, because of its negative impact on the surrounding soil and groundwater. To accurately quantify leakage rates from long sewer reaches the QUEST (Quantification of Exfiltration from Sewers with artificial Tracers) method was developed (Rieckermann J. and Gujer W., 2002). It is based on slug injections of one single tracer solution and the application of inline measurement devices. However, the operation of inline measurement devices for tracer measurements in sewerage is difficult if a high measurement accuracy is needed. Therefore, the QUEST-C method (Quantification of Exfiltration from Sewers with artificial Tracers- Continuous dosing) was developed in which grab sampling is used in combination with laboratory analysis.

## Methodology

The QUEST-C method uses two different tracer substances which are continuously dosed upstream and downstream of the reach under investigation. The underlying principle is that one signal is affected by exfiltration, the other is not (Fig. 1). In the case that the same amount of tracer is dosed at both locations, the flow is steady and no exfiltration occurs in the reach, the concentration of the two substances in each sample is the same. If leakage occurs, the concentration of the indicator tracer is lower, because some tracer mass has been lost with the exfiltrating wastewater. Exfiltration downstream of the investigation reach affects both substances in the same way and has no impact on the calculated exfiltration ratio  $E$ . From a mass balance over the investigation reach we obtain:

$$E = 1 - \frac{c_{ref} q_{ref} (C_{ind} - C_{ind,back})}{c_{ind} q_{ind} (C_{ref} - C_{ref,back})} \quad (1)$$

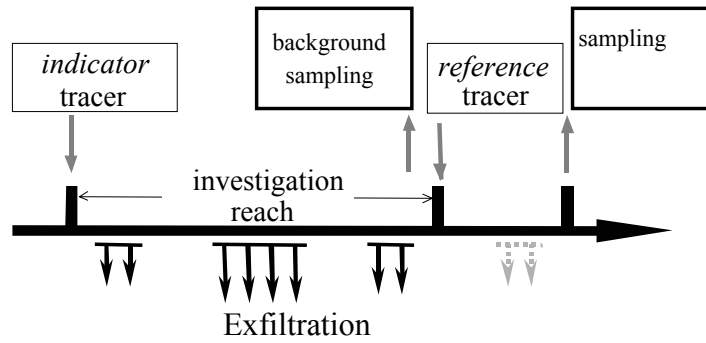
$c_{ind}$  and  $c_{ref}$  = concentration of tracer dosing solutions,  $q_{ind}$  and  $q_{ref}$  = tracer dosing rates,  $C_{ind}$  and  $C_{ref}$  = tracer concentrations in the sample,  $C_{ref,back}$  and  $C_{ind,back}$  = background concentration of tracers in wastewater

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**Fig.1** Conceptual sketch of the QUEST-C method to quantify exfiltration

One critical aspect of the method is the variation of the background concentrations of the tracers in the wastewater. To minimise the resulting error, the background of the reference tracer is sampled. The background of the indicator tracer cannot be monitored, because inflows into the investigation reach cannot be taken into account. A second difficulty is the instability of discharge which causes waves to travel faster than dissolved compounds (Huisman J.L. et al., 2000). As sewer flow is never steady the computed exfiltration ratio is impacted by the different transport processes of momentum and mass. To avoid gross errors, it is firstly recommended to identify periods of quasi-stationary flow conditions at the sampling point. Secondly, the discharge during the experiment is monitored with a flow meter in order to check for instationarities. Thirdly, time or flow proportional composite sampling is recommended.

### Application study

The experiment presented here was performed in a trunk sewer at Rümplang (CH) which has no lateral inflows and is in very good structural conditions. The diameter of the circular sewer is 0.9 m. The investigation reach was 643 m long, the total length of the section was 760 m. The average discharge during dry weather was  $24.4 \text{ l s}^{-1}$  with an average water depth of 0.11 m and a mean velocity of  $0.48 \text{ ms}^{-1}$ . The experiment was conducted from 11:00 – 13:30 which was identified as a period of quasi-steady flow from previous flow measurements.

### Tracer substances

In the experiment a  $15 \text{ g l}^{-1} \text{ Li}^+$  solution of Lithium Chloride was used as indicator tracer and the reference tracer was a  $25 \text{ g l}^{-1} \text{ Br}^-$  solution of Sodium Bromide. In laboratory batch tests the tracers showed a conservative behaviour in wastewater. Additional criteria for the selection of these tracers were a low background concentration in combination with an accurate analytical procedure in the wastewater matrix. All samples were analysed by ion chromatography (IC). The natural background of Lithium in this sewer was negligible small.

### Equipment

Multi-channel peristaltic dosing pumps were used for the dosing of the tracer solutions. Both containers with tracer dosing solution were placed on balances to record the pumping rates. Further peristaltic pumps were used for time-proportional composite sampling over 10 minutes. The discharge during the experiment was measured with a flow meter based on the Doppler ultrasonic average velocity principle. To quantify exfiltration, the ratio  $\text{Br}^-/\text{Li}^+$  in the sample was measured together with a laboratory standard, which was prepared by mixing definite amounts of both tracer solutions on a precision scale. As the exfiltration ratio was calculated from the IC measurement readings, which are expressed as concentration equivalents  $c_{eq}$ , equation 1 is modified to:

$$E = 1 - \left( \frac{c_{eq,Br} w_{Li}}{c_{eq,Li} w_{Br}} \right) \cdot \frac{q_{Br}}{q_{Li}} \cdot \frac{C_{eq,Li}}{(C_{eq,Br-Br,back})} \quad (2)$$

$c_{eq,Br}$  and  $c_{eq,Li}$  = tracer concentration equivalents of laboratory standard,  $w_{Br}$  and  $w_{Li}$  = masses of tracer solutions in the laboratory standard,  $q_{Li}$  and  $q_{Br}$  = dosing rates of the tracer solutions,  $C_{eq,Li}$  and  $C_{eq,Br-Br,back}$  = tracer concentration equivalents in the sample

## Results

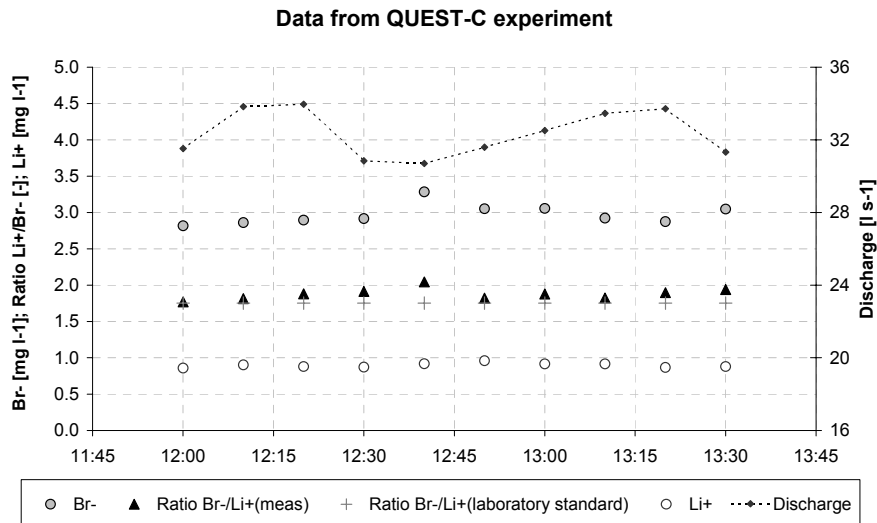
During the experiment two series of 10 samples were taken at the measuring point. The results of the first series, from which an average exfiltration ratio was calculated to -0.05 %, are presented in Fig. 2. For series 2 we calculated -0.31 % and considering all 20 samples of the two series, the estimated exfiltration ratio is -0.18 %. Because of the good structural condition of the sewer we expected the exfiltration to be zero which is in good accordance with the obtained results.

### Assessing uncertainty in the computed exfiltration ratios

To apply the method in practice, the overall error must be in the order of a few percent to give reliable results. In this experiment, although the maximum variation of the discharge was less than 10 %, we observed the separation of wave and concentration (Fig. 2). The bromide concentration shows a better correlation to the discharge at the sampling point than the concentration of lithium. A linear error propagation was performed in order to assess the different error contributions. The standard deviation of the computed exfiltration ( $\sigma_e$ ) is estimated to:

$$\sigma_E = \sqrt{\sum_{i=1}^n \left( \frac{\partial E}{\partial p_i} \right)^2} \cdot \sigma_{p_i}^2 \quad (3)$$

All model parameters were assumed to be normally distributed, the mean values and standard deviations were estimated from the experimental data (Table 1). Only the standard deviation of the masses  $w_{Li}$  and  $w_{Br}$  was obtained from the manufacturer of the precision scale. From the two data sets,  $\sigma_E$  was computed to 2.4 % and 2.6 %, respectively. Considering all 20 samples we obtained a standard error of 2.0 %. The largest error contributions are those of the Bromide and Lithium concentration equivalents in the samples ( $C_{eq,Li}$  and  $C_{eq,Br}$ ) and the concentration equivalent of the Bromide standard ( $c_{eq,Br}$ ). The variation of the tracer concentrations in the samples mostly stems from the unsteady flow, whereas the variation in the bromide standard concentration equivalent only originates from errors of the analytical procedure. Most optimisation potential is seen in the experimental design and the data analy-



**Fig.2** Concentration equivalents ( $Li^+$ ,  $Br^-$ ) and discharge from QUEST-C experiment at Rümmlang

**Table 1 Samples of series 1 (n=10), parameters, uncertainties and corresponding error contributions from a linear error propagation.**

Parameter (p)	$\mu_p$	$\sigma_p$	$\partial E / \partial p$	$(\partial E / \partial p) \cdot \sigma_p$
$c_{eq,Li}$ [mg l-1]	1.348	0.003	0.742	1.95E-03
$c_{eq,Br}$ [mg l-1]	4.132	0.054	-0.242	1.30E-02
$w_{Br}$ [g]	1.011	2.02E-04	-0.990	2.00E-04
$w_{Li}$ [g]	1.798	3.60E-04	0.556	2.00E-04
$q_{Br}$ [kg s-1]	0.002	3.67E-08	566.294	2.08E-05
$q_{Li}$ [kg s-1]	0.003	8.94E-08	-296.908	2.65E-05
$C_{eq,Li}$ [mg l-1]	0.897	0.010	-1.116	1.09E-02
$C_{eq,Br}$ [mg l-1]	2.946	0.050	0.340	1.71E-02
$E$	-0.0052	0.024		

sis procedure: QUEST-C experiments should be performed under most steady flow conditions. Including the information on the discharge in the analysis procedure should improve the precision of the method.

## Conclusions

- The QUEST-C method was developed to provide an alternative procedure to the QUEST method to accurately quantify exfiltration from sewers. The advantage of QUEST-C lies in the possibility of grab sampling and laboratory analysis.
- The QUEST-C method has been tested in an application study and yielded satisfactory results with moderate random errors. The standard error on the exfiltration ratio in this experimental study was 2 % of the total flow.
- Most optimisation potential is seen in the experimental design and the data analysis procedure. The overall precision of the method could be improved by including the information on the discharge in the data analysis procedure.
- The QUEST-C method bears the potential for a quick screening of large sewer reaches. It is cost-effective and can be applied to gain additional knowledge on a sewer system. This information supports sewer authorities in the optimisation of rehabilitation and investment strategies.

## References

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