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Quantifying exfiltration from leaky sewers with artificial tracers

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Abstract
In this paper, the authors present a novel approach to directly quantify exfiltration from sewer *systems with the help of tracers. The loss of wastewater is computed with a mass balance for the* reach under study. An experimental method was developed and tested, and an application study for validation purposes was analysed. It is shown that the use of sodium chloride as a tracer implies certain drawbacks that mainly originate from the varying natural background concentrations. Problems concerning the experimental procedure and the data analysis procedure are identified and discussed. As a proven method for the quantification of exfiltration should have a low measurement error, further development of the tracer method should concentrate on the assessment of the overall measurement uncertainty.

Keywords
exfiltration, leaky sewer systems, environmental monitoring, sewage, tracer

Introduction

Sewer systems are built for the reliable collection and transport of rain and wastewater and the limitation of flooding events is one of the most important performance indicators. Nevertheless, the major driving forces for drainage construction have always been the safeguard of public health and the control of environmental pollution. Therefore, the watertightness of a drainage system is considered a basic requirement (EN 752-2, 1995).

Due to ageing, insufficient maintenance strategies and poor construction technique, sewers are not considered entirely watertight. Infiltration of groundwater is generally recognised as a problem for the treatment works and the sewer network, but exfiltration of wastewater can have an even worse impact on the environment. Cases where leakage caused pollution, health hazards and even death are reported world wide (Bishop P.K., et. al. 1998).

To assess the magnitude of the exfiltration problem, considerable research has been undertaken and various methods for the quantification of exfiltrating wastewater have been developed during the last decades. *Indirect* methods investigate the urban aquifer (e.g. groundwater transport- and contaminant modeling (Härig, 1991), groundwater quality measurements ((Deutsch, 1963), (Kreitler *et al.*, 1978)). D*irect* methods are applied within the sewer pipe (e.g. pressure testing of leaks (Decker, 1998), georadar techniques (Fritzsche, 1994) and water balancing (Härig, 1991), (Trauth *et al.*, 1995)).

Despite some promising approaches, still no proven method of exfiltration measurement on a wider scale is available. The *indirect* measuring methods are mostly too complicated for sewer operators to apply. The *direct* procedures yield exfiltration rates for single leaks, but the extrapolation to overall exfiltration rates is questionable due to the inhomogeneity of defects. In general, there is still poor knowledge on leakage and it is not surprising that hardly any sewer operator can provide information on exfiltration of wastewater from his/her system, let alone use it for rehabilitation planning. In this paper, a novel approach is presented which uses artificial tracers to directly quantify the loss of wastewater from a sewer of interest.

The QUEST method

The basic idea of the QUEST method (Quantification of Exfiltration from Sewers with artificial Tracers) is that exfiltration measurement is feasible by a mass balance of a tracer substance over the desired sewer line. At the beginning of the *investigation reach* a known mass of tracer is dosed which is defined as the *indicator* signal (Figure 1). This tracer is passed through the sewer line and if exfiltration occurs, tracer substance is lost with the seeping wastewater. If 5% of the tracer is lost, 5% of the wastewater that it labelled has also been lost from the sewer and consequently, the loss of tracer substance can be used to estimate exfiltration.

A key feature of the QUEST method is that no flow measurement is necessary to calculate the mass balance. Instead, a downstream *reference* signal is used to quantify exfiltration. This is possible because only the indicator tracer is diminished by exfiltration. The other signal is not influenced and can be used as a reference to quantify the effect.

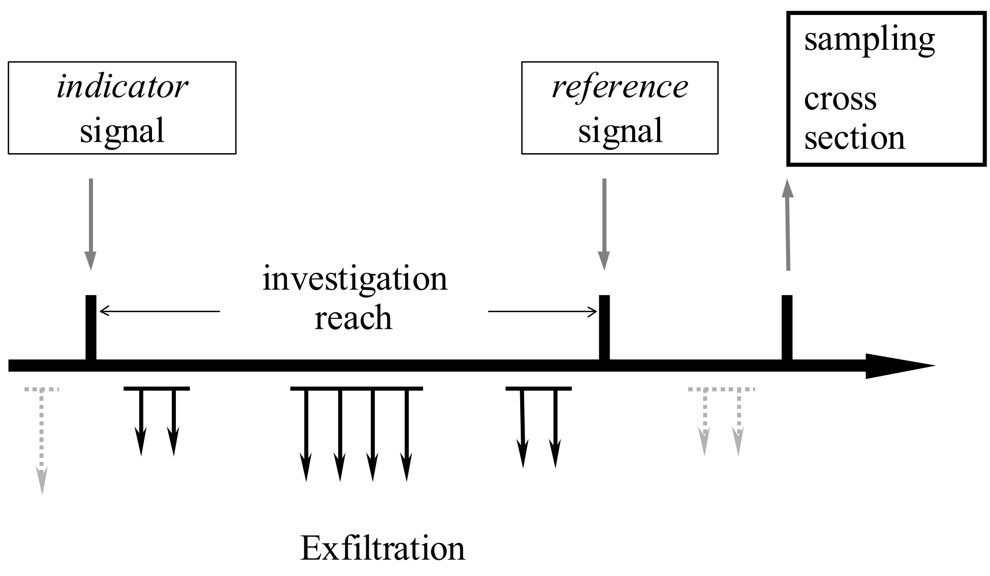

Figure 1 Conceptual sketch of the experimental set-up of the QUEST method

An exemplary concentration time series (CTS) from the sampling point shows that the indicator and reference peaks can clearly be separated from each other (Figure 2). The indicator pulse travels a greater distance and the effect of longitudinal dispersion is more pronounced than in the reference signal. The latter is less dispersed, because it is usually injected near the sampling cross section. Assuming that the discharge is constant for the duration of an experiment, exfiltration is calculated by a comparison of the areas under the peaks

$$\varepsilon = 1 - \frac{\int_t C_{ind}(t)dt}{\int_t C_{ref}(t)dt} \cdot \frac{M_{ref}}{M_{ind}} \tag{1}$$

where ε is the exfiltration relative to the labelled wastewater; C_{ind} is the concentration resulting from the indicator signal; C_{ref} is the concentration component from the reference signal; M_{ref} is the mass of tracer injected as reference signal and M_{ind} is the mass of indicator tracer injected at the start of the investigation reach.

With a QUEST experiment, exfiltration can only be identified in the *investigation reach* between the dosing stations. Leakage outside of this stretch can not be detected, but also does not affect the measurement. If leakage occurs downstream of the reference, the relative loss of tracer is the same for both tracer signals and (1) yields the same result. This characteristic is also valid for most systematic deviations in the sensors and the measuring chain, because the calculated exfiltration is not affected if an error applies equally to both signals.

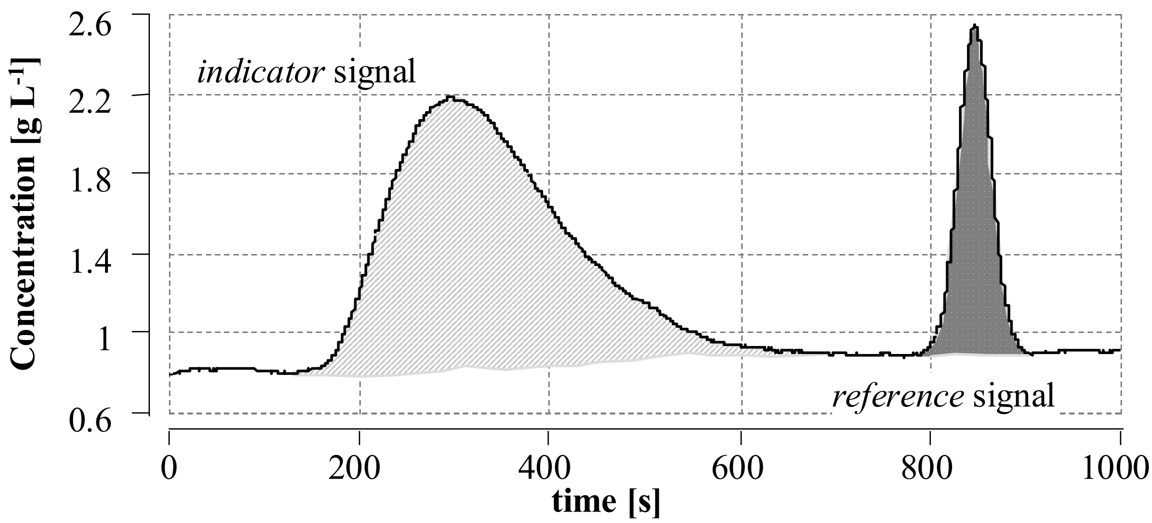

Figure 2 Concentration time series from a QUEST experiment with clearly identifiable *indicator* and *reference* pulses

Development of the method

Using sodium chloride (NaCl) as a tracer

NaCl was preferred to more selective tracers like fluorescent dyes, specific ions or radioactive substances due to a range of advantages. The tracer signals resulting from slug injections are highly dynamic and *in-line* measuring technology with a measuring frequency of a few seconds is available. NaCl is well monitored by conductivity measurements because in the measuring range from 0.3 mS cm^{-1} to 7 mS cm^{-1} there is a linear correlation between NaCl concentration and conductivity. The tracer has a conservative behaviour in the wastewater matrix because it is neither pH-dependent nor does it adsorb to organic matter or sewer biofilm. Furthermore, it is environmentally safe and does not contaminate the surrounding soil or groundwater in case of exfiltration. The disadvantages are a high natural background concentration and complicated mixing properties due to density differences between a NaCl tracer solution and wastewater.

Field testing

Several field experiments were conducted in the sewer system of Rümlang, Switzerland, to develop the method and test its feasibility. A collector sewer with no lateral inflow, a diameter of 0.7 m and a constant slope of 2 ‰ was chosen. The mean dry weather flow is 25 L s^{-1} and the average conductivity of the wastewater is 0.8 mS cm^{-1}. The tracer solution had a concentration of 200 g NaCl L^{-1} and was prepared with common road salt and tap water. The conductivity was recorded with a time resolution of one second, which allowed for a smooth monitoring of the tracer pulses. Conductivity was measured with 2 spade-shaped conductivity probes (model TetraCon 325S, WTW GmbH Weilheim, Germany) which were installed in a model boat. Intensive testing proved that the use of a streamlined floating device guarantees clog-free performance even in heavy particle-laden wastewater. The length of the investigation reach was 285 m and, because of the excellent structural condition of the sewer section, no exfiltration was expected. The measuring point was located 100 m further downstream after a drop in the sewer line which ensured complete cross-sectional mixing. An empirical study in which mixing was measured with 6 probes equally distributed over the cross section showed a coefficient of variation of <2% (σ=0.002).

In total, 10 indicator pulses were dosed, each with 2 to 4 corresponding reference pulses (Figure 3). The average background conductivity during the experiment was 0.8 mS cm^{-1}. The travel time of

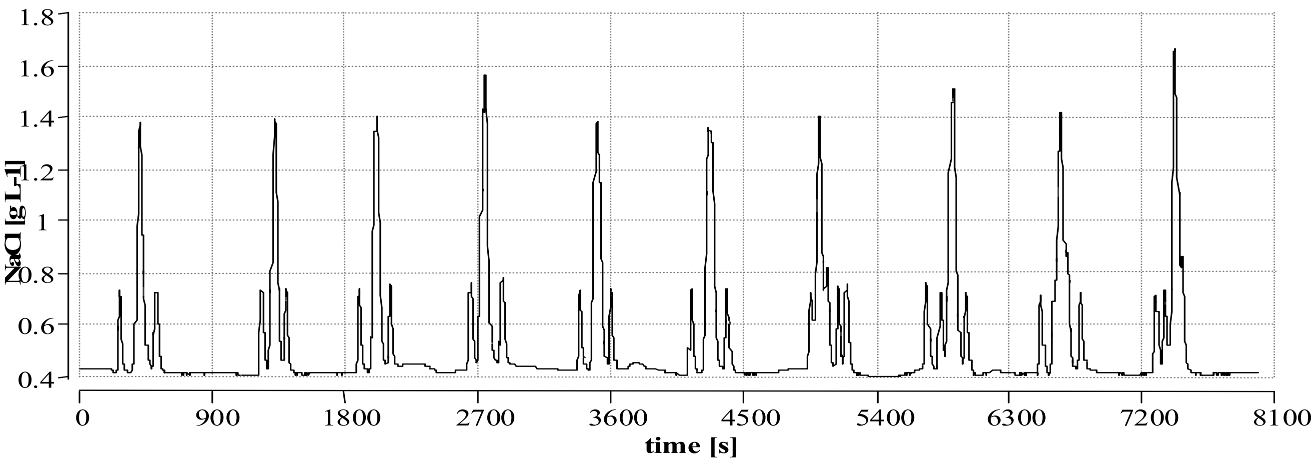

Figure 3 Concentration time series from QUEST experiment

Table 1 Summary of results from 10 QUEST experiments

	mean	standard deviation
Δtracer [g]	*-28.25*	*56.36*
ε [-]	*0.014*	*0.029*
sd_{res}	*0.0161*	*0.003*
p-value	*0.031*	*0.037*

the indicator pulses was 6 minutes, and the time of passage at the sampling point was 2 minutes. Indicator and reference pulses have an almost symmetric shape and showed no tailing.

Data analysis

To calculate exfiltration from the experiment, the concentration time series (CTS) had to be split between the indicator signal, the reference signal and the baseline. For the identification of the 3 components, a model was applied to the data under the following assumptions: the discharge is constant for the time of passage of an indicator pulse, a reasonable description for the stochastic baseline can be found, and the pulses have the shape of a known statistical distribution.

A parameterisation of the tracer pulses with a known distribution has the advantage that an overlap of several pulses is feasible, which keeps the total time of passage of the pulses as short as possible. In this way, maximum information on the baseline is gained and the error that is introduced by an interpolation of the baseline under the pulses is minimised. This is of importance because the calculated exfiltration is very sensitive to deviations of the baseline model. An under- or overestimation of the indicator peak would directly alter the identified exfiltration. The baseline was approximated with a linear function and the pulses were described with a Pearson-III distribution, which is a skewed function with 3 parameters. Its physical expression is the output curve from a series of completely stirred tank reactors, and it is often used for data analysis in water sciences (Bobée and Ashkar, 1991).

The curve fitting procedure was successful in identifying the injected indicator pulse and the 3 corresponding reference pulses (Figure 4). In total, less than 2 % exfiltration was calculated in the 285 m long investigation reach (Table 1).

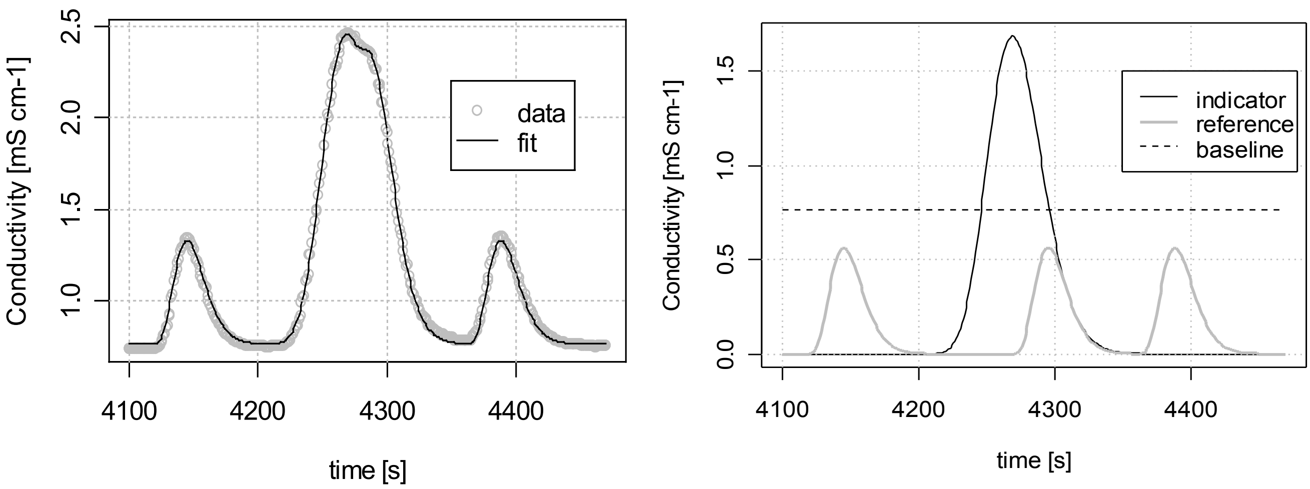

Figure 4 Successful fitting of CTS from QUEST experiment (left); Different components of the CTS can be identified (right)

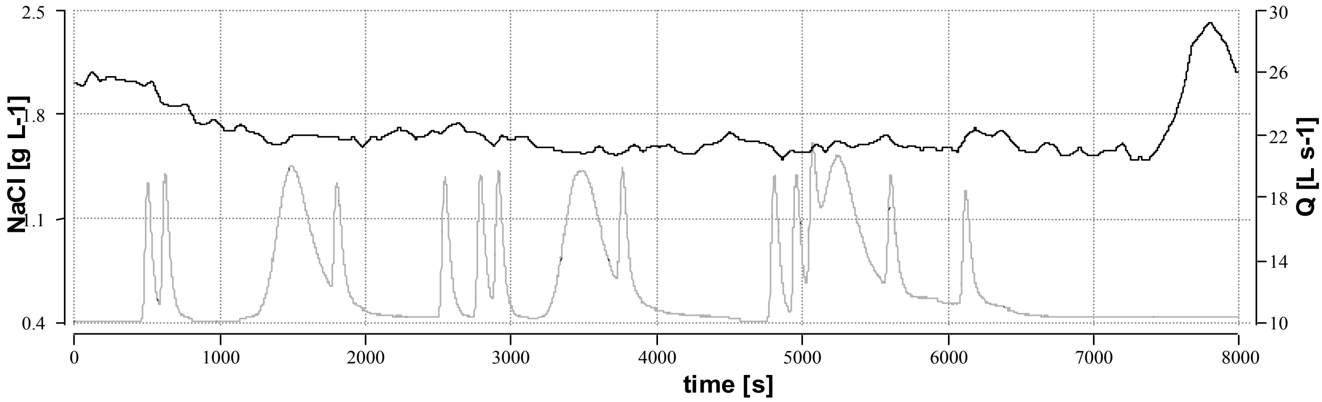

Figure 5 CTS of the application study (grey) with measured flow (black). The length of the corresponding investigation reach was 2130 m

The goodness of fit of the model is described by the standard deviation of the residuals (sd_{res}) and the p-value of a statistical *runs test*, which is useful to identify systematic deviations between the model and measured data (Cromwell *et al.*, 1994).The small deviation in the residuals shows a good model fit, whereas the p-value of 0.031 expresses that the residuals are not entirely independent. However, for the relatively simple parameterisation of this model the result expresses a good fit. In general, the data were matched well and the computed exfiltration rates are on the order of a few percent. As no exfiltration was expected in the well-defined sewer reach, these results were considered satisfactory.

Application study

To test the QUEST method, exfiltration was measured from an investigation reach of 2130 m. This included sewers of different diameters, slopes and shapes as well as retention tanks and a CSO. No information on the structural condition of the entire reach was available.

The experimental set-up was the same as in the controlled experiment, except that, in addition to conductivity, discharge was measured at the sampling cross section with a flow meter based on the Doppler ultrasonic average velocity principle (SIGMA 950, American Sigma, Medina, NY). In the application study, 3 indicator pulses were dosed, together with 12 reference pulses. The mean travel time of the indicator signal was 78 minutes and the time of passage at the sampling cross section was 20 minutes (see Figure 5). Due to the greater influence of longitudinal dispersion, the indicator pulses are broader than the reference pulses and the skewness indicates the presence of dead zones in the flow where the tracer was held back.
The data analysis procedure for the CTS yielded a mean exfiltration of 7 % in the 2130 m long sewer line. In general, the measured data could be fit by the model but in contrast to the investigation over the short distance, the fit of the model in this case was not satisfactory (Table 2).

Table 2 Summary of results of the application study

No.	1	2	3	mean	sd
Δtracer [g]	-320	-674	-173	*-389*	*257.53*
ε [-]	0.058	0.123	0.032	*0.071*	*0.046*
sd_{res}	0.050	0.050	0.052	*0.051*	*0.001*
p-value	$4.92*10^{-66}$	$2.47*10^{-26}$	$1.41*10^{-27}$	$8.70*10^{-27}$	$1.39*10^{-26}$

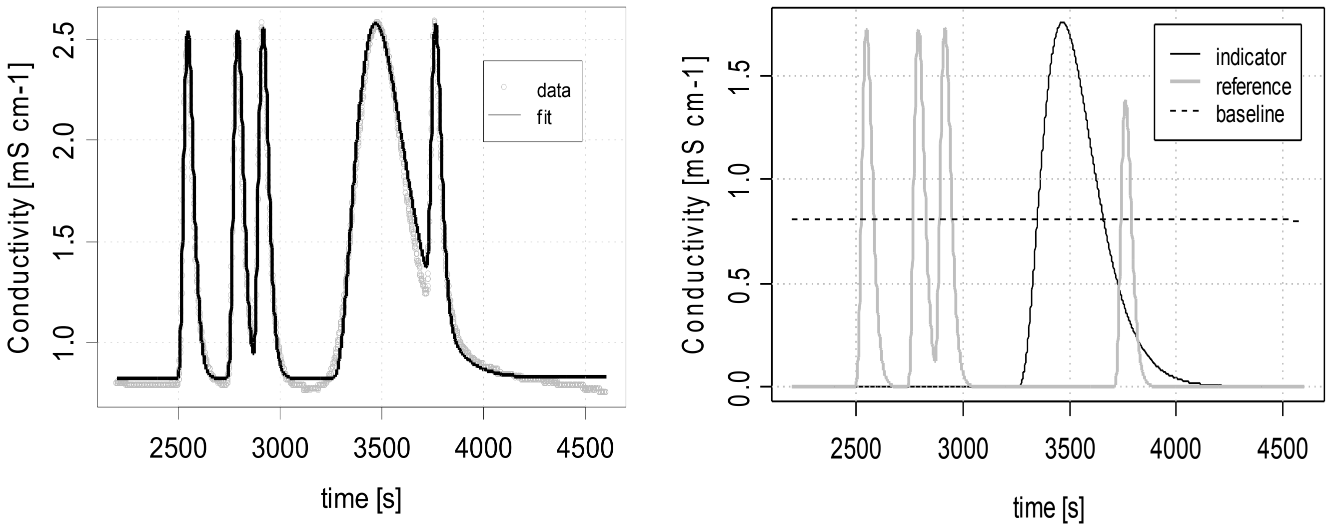

Figure 6 Unsuccessful fitting of CTS from QUEST experiment (left); Different components of CTS are identified (right)

The standard deviation in the residuals, sd_{res}, is quite high and from the p-values of the statistical test there is evidence that the systematic deviations in this investigation are higher than in the previous study.

In the second experiment from this study, the baseline is overestimated by the model and the indicator and reference pulses are not matched well (Figure 6). This indicates that the tracer mass of the indicator pulse is underestimated, which would lead to an overestimation of exfiltration. However, it is difficult to assess the overall uncertainty in the calculation of exfiltration because the baseline, the indicator tracer, and the reference signal are identified simultaneously.

Using additional information on the flow

One postulation for the computation of exfiltration from a CTS was that the discharge is constant for the duration of an experiment. Figure 5 shows that the mean flow was 21.4 L s-1 during the passage of the pulses. A coefficient of variation of 2% and a maximum deviation of 5% from the mean value show that it was reasonably constant.

To check the sensitivity of the experiment to variations in the discharge, the information on the flow pattern was used. Replacing the previously assumed constant discharge with the measured flow pattern, the computed results should have a lower uncertainty due to the additional information. The absolute accuracy of discharge measurements is generally not very high, but the relative variation of water depth and velocity should be accurate to a few percent. This is favourable for the QUEST experiment, because it should not be sensitive to systematic errors which apply to both indicator and reference signals. Therefore, the data analysis procedure was applied to the tracer load instead of the concentration.

The newly computed exfiltration yielded a mean exfiltration of 14 % which is twice the exfiltration under the assumption of a constant discharge. The fitting of the model was in general agreement with the data, but the result was even less satisfactory than the analysis of the CTS.

Table 3 Summary of results of the application study, incorporating information on flow patterns

No.	1	2	3	mean	sd
Δtracer [g]	1006	1067	225	766	470
ε [-]	0.184	0.195	0.041	0.140	0.086
sd_{res}	1.422	1.127	2.025	1.525	0.458
p-value	$6.59*10^{-46}$	$6.71*10^{-65}$	$3.17*10^{-110}$	$2.20*10^{-46}$	$3.80*10^{-46}$

The exfiltration rates from the three experiments vary from 19.5 –4.1 % and the p-values reflect a bigger deviation of the model from the data than in the previous analysis (Table 3).

In the second experiment from this study the area of indicator pulse is clearly underestimated and there is considerable deviation from the measured baseline (Figure 7), which might explain the greater exfiltration rates. In general, the question arises whether there is a real benefit from incorporating the flow pattern in the analysis. The gain from the additional information might as well be paid with a less successful fitting of the model. Therefore, it is not clear, whether the computed results really contain less uncertainty than those of the previous analysis.

The results from this application study show that the model does not fit the measured data well and that the identified exfiltration rates, which are on the order of only a few percent, might be considerably misestimated. Errors mainly seem to result from the model and the fitting procedure because errors in the data can be compensated for by including information on the flow.

Discussion

In the application study, some aspects of the QUEST method with NaCl were identified that might affect and limit its applicability. To path the way for an improvement of the method, they should be addressed in more detail.

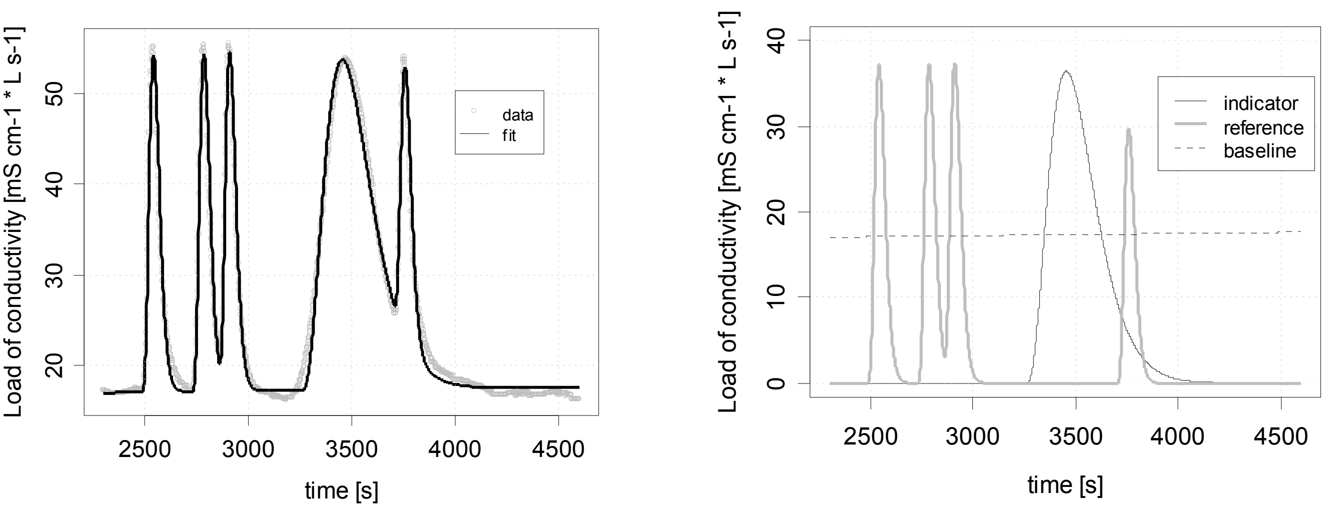

Figure 7 Unsatisfactory fitting of model to the load of the tracer; In general, different components of CTS are identified successfully(right)

Assumptions on sewer flow

The approach in which constant discharge during the experiment was assumed, the calculated exfiltration rates were in the order of a few percent. For narrow peaks pulses with passage times of seconds or minutes, this is a reasonable assumption, but if an indicator puls travels over long distances, it might well travel on the order of half an hour or more. For larger time scales, varying flow might lead to considerable error in the measurement. To reduce this error, several reference pulses were dosed during the conducted experiments.
In a second step, information on the flow was incorporated, which yielded considerably higher exfiltration rates. On the one hand, the additional information should guarantee results that are more reliable. On the other hand, the goodness of fit of the model deteriorates due to the greater variation in the data. To balance the gain on information against the loss in quality of model fitting is a difficult task which should to be tackled in the future.

Fitting a deterministic model to a stochastic baseline

As mentioned before, considerable error results from a wrong estimation of the baseline. However, the longer the investigation reach, the more dispersed are the indicator pulses and the more variation is expected in the baseline. Using more complex functions for a baseline model was tested but yielded no major improvement of the results. The best solution with regard to the baseline problem would be the choice of a tracer substance with zero or constant background. In the studies outlined in this paper, maximum information on the natural background was gained by dosing the reference pulses on top of the indicator peaks. This keeps the unknown baseline under the pulses as short as possible, but pulse fitting is more complicated when the pulses overlap. An additional monitoring of the baseline before the dosing of the reference signal would enable a better separation of this component.

However, this approach is questionable because a second sampling point is necessary and the user is still left with the problem of estimating the baseline under the indicator pulse.

Parameterisation of the tracer curves

Assigning a defined shape to the peaks introduces error into the results if the distribution does not correspond to the breakthrough curves. Although good results were obtained using the Pearson-III distribution during the development of the method, it failed to reproduce the skewed shapes of the indicator pulses from the application study. One solution would be to choose another distribution that better accounts for the effect of tailing. This could be achieved in the combination of two Pearson-III, corresponding to a transport model with two series of retention tanks.

Mixing of the NaCl tracer solution in wastewater

One of the most important assumptions is that cross sectional mixing is sufficient to yield a uniform tracer concentration at the cross section. As mixing theory predicts an infinite length to achieve complete mixing, in practice 98% (coefficient of variation <0.02) is recommended for tracer studies (ISO TR 11656, 1993). Unfortunately, a tracer solution of NaCl normally has a higher density than wastewater and significant density currents occur which make mixing more difficult. As there is no theoretical formula available to estimate the mixing of such dense slug injections, a mixing length model for a constant rate injection (e.g. CORMIX (Jirka *et al.*, 1991)) could provide a first estimate of the distance needed for sufficient mixing. Nevertheless, the empirical proof through multi-sampling over the cross section is recommended to avoid gross errors. If no natural turbulence (drop, vortex, etc.) is available, the provision of additional turbulence by a submersible pump before the sampling cross section proved successful in preliminary investigations. Another result was that density currents reform, if turbulence diminishes, which has some importance for the interpretation of the results. Exfiltration rates are only correct if the leaks are uniformly distributed over the wetted parameter of the sewer. Otherwise, incomplete mixing leads to different tracer loss if the leak is at the bottom or at the side of the sewer. The use of a tracer solution with appropriate density allows the use of theoretical equations for estimation of mixing distances, but as there is still a lack of understanding how flow parameters influence mixing, the possibility of gross errors still remains.

Conclusions

We introduced the novel QUEST approach for the measurement of exfiltration from sewer systems. Losses of wastewater were calculated from a mass balance of a tracer substance which was monitored over the investigation reach. The method was developed and tested in field experiments using NaCl as a tracer. An application study on a sewer reach of 2 km is presented where three consecutive experiments yielded a mean exfiltration of 7.1% , when the CTS were analysed. A mean exfiltration of 14% was computed when the measured flow pattern was incorporated into the analysis.

Although the method seems to produce reasonable results with an accuracy of a few percent over short sewer lengths, problems arise in the use over larger distances. Firstly, the use of NaCl as a tracer has a negative impact due to a relatively dynamic baseline and density-born difficulties in mixing. Secondly, the assumption on constant discharge is questionable if the passage time of the pulses is long. Analysing the tracer load instead of its concentration is recommended to improve the computed results. Nevertheless, the goodness of fit seems to suffer from this strategy and it is not possible to quantify the overall benefit.

A valuable method for the quantification of losses from sewers is supposed to have a detection limit of a few percent of exfiltrating wastewater. Therefore, the most critical factor for the general applicability of the QUEST method is the overall uncertainty in the exfiltration results. The next step to be taken in the development of the QUEST method is the assessment of the combined uncertainty of the experiment and the data fitting procedure. Furthermore, the usage of a more specific tracer substance with fewer baseline effects should be tested. The benefit of incorporating additional information from flow patterns should be explored further.

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Symbols and units

M_{ind} [M]= Tracer mass used for the indicator pulse
M_{ref} [M] = Tracer mass used for the reference pulse
C_{ind} [M V^{-1}]= Concentration resulting from of indicator tracer measured at sampling cross section
C_{ref} [M V^{-1}]= Load of reference tracer measured at sampling cross section
Δtracer [g]= Difference of identified tracer mass to injected indicator tracer
ε [-] = exfiltration in the investigation reach, relative to the labelled waste water
sd_{res} = standard deviation of the residuals from the model fitting procedure
p-value = p-value from *runs test*; here used as an indicator for systematic deviations in the result