Quantifying exfiltration from leaky sewers with artificial traces

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Abstract
A novel approach to directly quantify exfiltration from leaky sewer systems is presented. The loss of wastewater is computed using a mass balance for an artificial tracer substance. The method is developed and tested and an application study for validation purposes is 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 data analysis are identified and discussed. Further development of the method should concentrate on the assessment of the measurement uncertainty.

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

INTRODUCTON

The watertightness of a drainage system is explicitly mentioned as a basic performance requirement in the EU standard EN 752-2. Exfiltration of wastewater is critical because of its negative impact on soil and groundwater. Although the recent belief was that the self-cleaning capacity of the soil is sufficient to degrade pollutants from eventually occurring seepage, cases are reported where exfiltration has led to environmental pollution, health hazards and even death (Bishop *et al.*, 1998).

In the past decades, the awareness that leakage from sewers is a problem has increased and considerable effort has been put into the development of procedures to assess the magnitude of wastewater exfiltration from sewer systems. *Indirect* methods investigated the surrounding soil or groundwater (e.g. groundwater contaminant modelling (Härig, 1991)), whereas *direct* methods have been applied within the sewer pipe (e.g. pressure testing of structural defects (Decker, 1994)).

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.

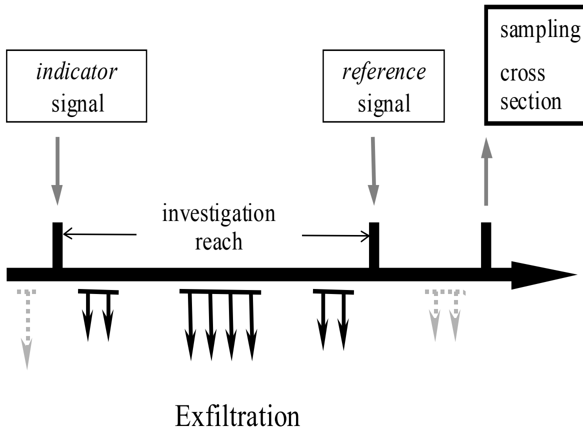

Figure 1 Conceptional sketch of experimental set-up with the QUEST method

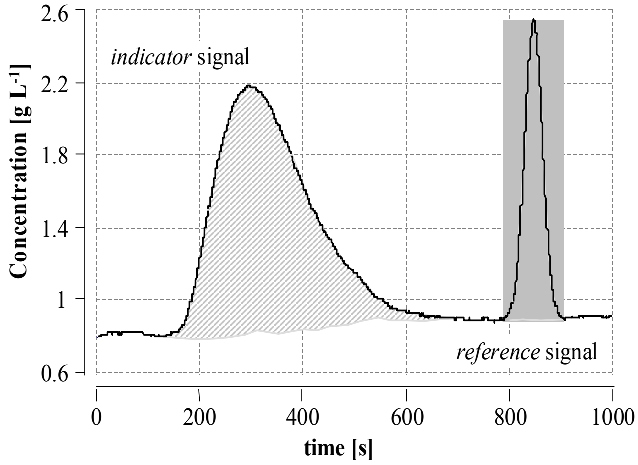

Figure 2 Concentration time series from a QUEST experiment with clearly identifiable *indicator* and *reference* pulses

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.

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.

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 the structural condition of the sewer section was very good, 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 $<2\%$ ($\sigma=0.002$).

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

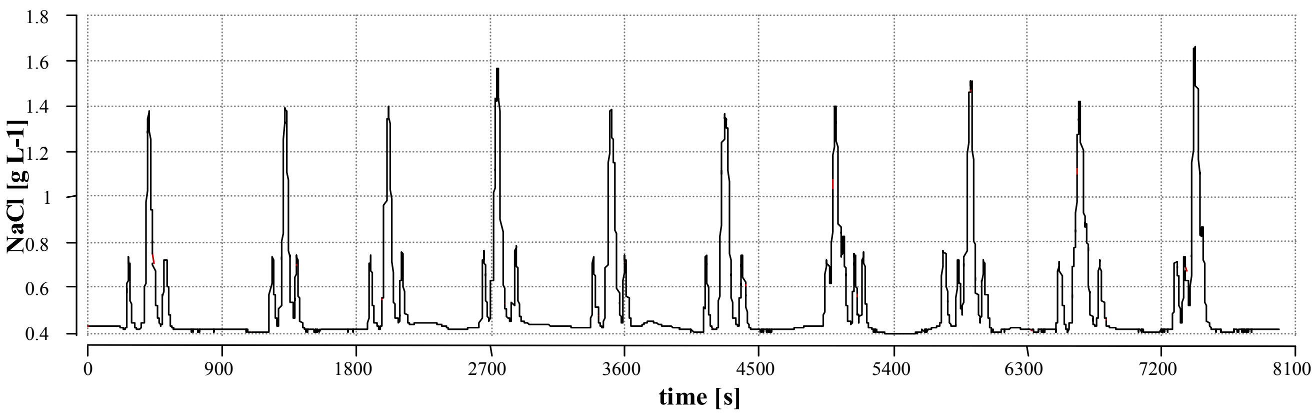

Figure 3 Concentration time series from QUEST experiment

Table 1 Summary of results from 10 QUEST experiment

	mean	*sd*
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. To transform conductivity readings to NaCl concentrations, a calibration coefficient was estimated from a series of standard additions to equal 0.551 (mg L^{-1})(mS cm^{-1})$^{-1}$ (σ= 2.5*10^{-3}, R^2= 0.999).

Data analysis

To calculate exfiltration from the experiment, the concentration time series (CTS) has 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 parametrisation 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). 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

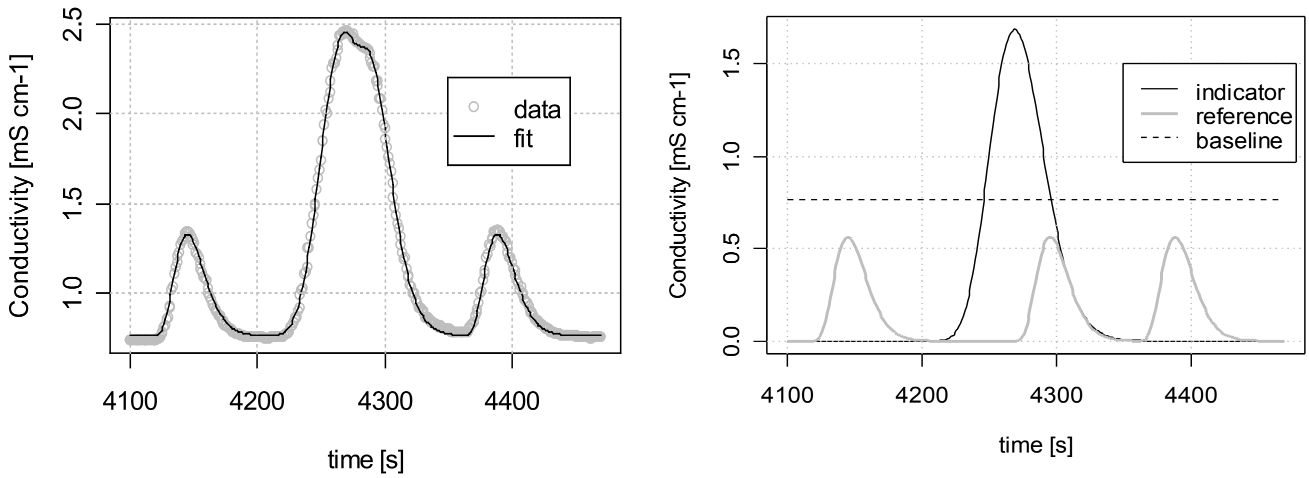

Figure 4 Successful fitting of CTS from QUEST experiment (left); Different components of the CTS can be identified (right)

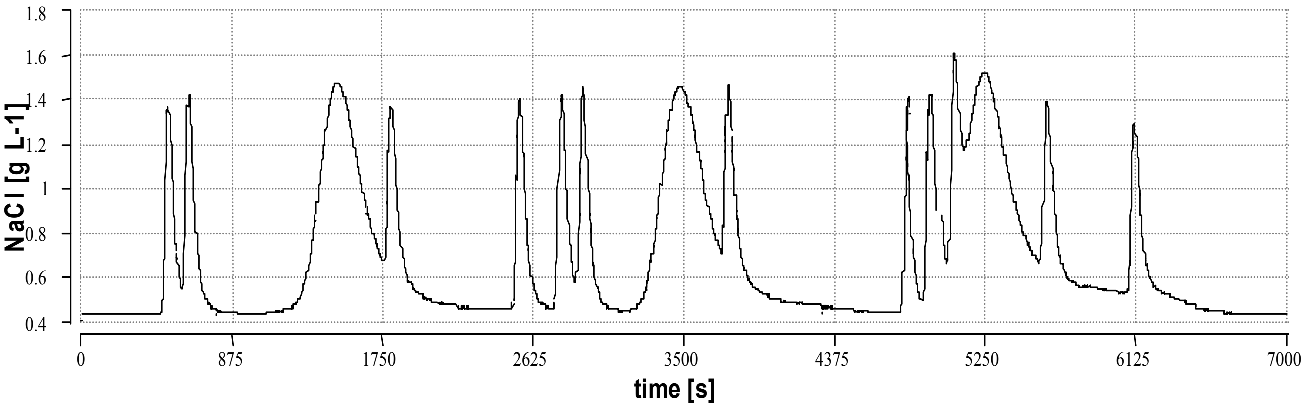

Figure 5 CTS of the application study. The length of the corresponding investigation reach was 2130 m

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 parametrisation 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 same experimental set-up was used as in the controlled experiment and in total 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 calibration coefficient to calculate the NaCl concentrations from conductivity readings was estimated to equal 0.548 (mg L-1) (mS cm-1)-1 (σ= 2.2*10^{-3}, R^2= 0.999).

The data analysis procedure 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). 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.

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}

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.
The results from this application 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.

DISCUSSION

In the application study, some aspects of the QUEST method with NaCl were identified that might affect and limit its applicability and which should be addressed in more detail.

Assumptions on sewer flow

Constant discharge during the time of passage of the pulses was assumed for data analysis. For short 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. Another possibility is to use additional information on discharge in the data analysis. Although flow measurements are most likely to contain systematic errors, the relative accuracy obtained from depth/velocity measurements should be sufficient to improve the reliability of exfiltration results.

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 our studies, 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.

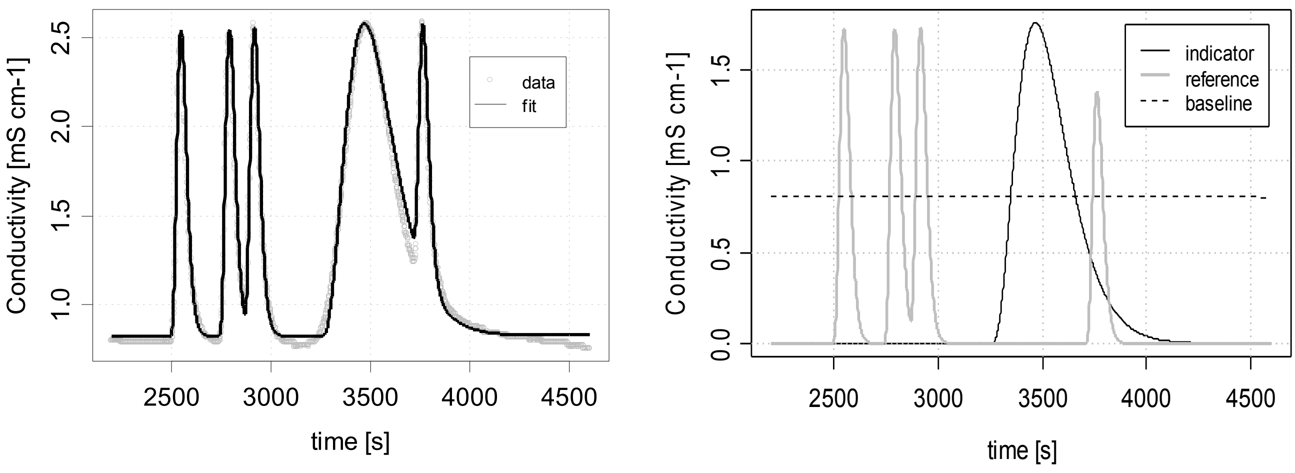

Figure 6 Unsuccessful fitting of CTS from QUEST experiment (left); Different components of CTS are identified (right)

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.

Parametrisation 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 are calculated from a mass balance of a tracer substance which is 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% of the labelled wastewater. 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. First, the use of NaCl as a tracer has a negative impact due to a relatively dynamic baseline and density-born difficulties in mixing. Second, the assumption on constant discharge is questionable if the passage time of the pulses is long.

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 possibility of incorporating additional information from flow patterns should be explored.

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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