ASSESSING EXFILTRATION FROM SEWERS WITH DYNAMIC ANALYSIS OF TRACER EXPERIMENTS

Jörg Rieckermann[1], Vojtěch Bareš[2], Daniel Braun[3], Oliver Kracht[1], Valentina Prigiobbe[4], Willi Gujer[1]

Abstract
A direct approach to quantify exfiltration from sewers is the QUEST-C tracer method. In this study, the authors present a novel approach for the dynamic analysis of a tracer experiment, considering information on varying sewer flow. An assessment of uncertainty is developed that accounts for systematic and random errors in the measurements and the sampling scheme. It is shown that the precision of the exfiltration measurement with tracers can be significantly improved by the dynamic analysis.

Keywords: Exfiltration, sewers, tracer, QUEST-C

Introduction

If sewer leaks are situated below the groundwater table, clean ground water may infiltrate sewer pipes; if the leak lies above the groundwater table, raw sewage may exfiltrate into the surrounding soil. In order to assess the magnitude of exfiltration, several attempts have been undertaken to develop measurement methods in the last decades. *Indirect* methods try to deduct information on exfiltration from groundwater monitoring or a catchment-wide water balance. *Direct* measurements perform pressure testing on cracks or use tracer substances to identify leakage. Vollertsen et al. (2002) conclude:

> *"The indirect methods for determination of the magnitude of the exfiltration are assessed to be based on such large a number of assumptions that they are considered non-conclusive. The direct determinations are based on measurement of very small differences in flow and are consequently difficult to perform with precision."*

However, no detailed analysis of uncertainty of the computed exfiltration is reported in literature. In this paper, the QUEST-C tracer method is presented together with experimental results. As the traditional assumption of steady discharge during the experiment is rather weak, a novel approach for the analysis of QUEST-C experiments is presented that accounts for dynamic flow.

The quantification of exfiltration from sewers with tracers

The basic principle of exfiltration measurements with tracers is to dose a well-known amount of tracer to the sewer under investigation and to apply a mass balance on the investigation reach.

[1] Swiss Federal Institute of Aquatic Science and Technology (EAWAG)) and Swiss Federal Institute of Technology (ETH) 8600 Dübendorf, Switzerland, e-mail: willi.gujer@eawag.ch
[2] Czech Technical University in Prague (CTU), Laboratory of Ecological Risks in Urban Drainage(LERMO), Thakurova 6, Prague 6, 166 29
[3] Swiss Federal Institute of Technology (ETH), 8093 Zürich, Switzerland
[4] Università degli Studi di Roma "Tor Vergata" Rome and IRSA CNR, Rome, Italy

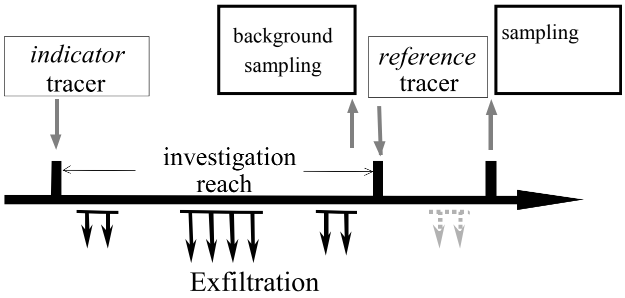

Figure 1 Conceptual sketch of the QUEST-C method to quantify exfiltration

Given conservative behavior of the substance, the tracer loss is directly related to the leakage in the reach. In order to obtain most accurate results, losses of the indicator tracer are mostly identified relative to a reference tracer which is not affected by exfiltration (Figure 1). Therefore, exfiltration (E) is expressed as a ratio relative to the labeled flow:

$$E = 1 - \frac{mass_{REF,in}}{mass_{IND,in}} \cdot \frac{mass_{IND,out}}{mass_{REF,out}} = 1 - \frac{\int c_{REF} \cdot q(t)_{REF}\, dt}{\int c_{IND} \cdot q(t)_{IND} dt} \cdot \frac{\int Q(t) \cdot C_{IND}(t) dt}{\int Q(t) \cdot C_{REF}(t) dt} \tag{1}$$

c_{REF} and c_{IND} = tracer concentration of the donsing solution, q_{IND} and q_{REF} = dosing rates of the tracer solutions, C_{IND} and C_{REF} = tracer concentrations in the sample

Often, a constant tracer dosing is applied which has the advantage that, if the discharge in the sewer was steady, a single grab sample would be sufficient for exfiltration measurement.

Obviously, the computed exfiltration ratio is systematically wrong if the tracer concentrations are reduced or magnified in the sewer reach (e.g. adsorption or natural tracer background in the wastewater). Similarly, one has to account for a substantial random error if the analysis of the tracers in wastewater is not very precise. It might be for these reasons that early studies chose very specific tracer substances which are unlikely to be present in wastewater. Ohlsen and Genders (1993) used radioactive isotopes ^{82}Br and Tritium, whereas Knudsen (1996) and Jensen and Madsen (1996) only report the use of "trace substances". The main criticism of these studies is that no assessment of uncertainty is documented. Most probably, only the precision of the analytical procedure for tracer analysis is reported.

The QUEST-C method

The QUEST-C method (Quantification of Exfiltration from Sewers with Tracers-Continuous dosing) was specifically developed with regard to an optimized management of uncertainty (Rieckermann et al. 2003). One key aspect of the method is that it comprises a complete uncertainty analysis by linear error propagation. However, the data analysis is still based on the traditional assumption of constant discharge during the tracer experiment. As sewer flow is hardly ever steady, this is a critical assumption which will be investigated in this article.

<u>Application study Rümlang, CH</u>

A QUEST-C experiment was performed to quantify wastewater exfiltration in a trunk sewer at the village of Rümlang (CH). 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 wheather was 24.4 l s^{-1} with an average water depth of 0.11 m and a mean velocity of 0.48 ms^{-1}. The investigation reach has no lateral inflows and is in very good structural conditions. The supposed watertightness makes it possible to check the computed result for bias.

Tracer substances

A 15 g l^{-1} Li^+ solution of Lithium Chloride was used as indicator tracer. The reference tracer was a 25 g l^{-1} Br^- solution of Sodium Bromide. The natural background of Lithium in this sewer was negligible low. Bromide concentrations showed small fluctuations, which were corrected for by additional background sampling at the dosing point. All samples were analyzed by ion chromatography (IC) (Metrohm Compact IC) which showed a very good reproducibility (Li^+: 1% , Br^-: 0.5 %). The results of laboratory batch tests suggest a conservative behavior of the tracers in wastewater and in the sample bottles.

Equipment

Multi-channel peristaltic dosing pumps (ISMATEC BVK, ISMATEC MV-CA4) were used for the dosing of the tracer solutions. Both containers with tracer dosing solution were placed on scales (OHAUS DP150) in order to record the pumping rates. Time-proportional composite sampling over 10 minutes was effectuated with further peristaltic pumps. The discharge during the experiment was measured with two flow meters based on the Doppler ultrasonic average velocity principle (SIGMA 950, American Sigma) which were installed at the end and the beginning of the sewer reach. The ratio Br^-/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 in order to avoid systematic errors. The exfiltration ratio was calculated directly from the IC measurement readings, which are expressed as concentration equivalents (C_{eq} and c_{eq}). Together with the assumption of steady discharge, equation 1 is modified to

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

$c_{eq,Br}$ 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. From the first series, an average exfiltration ratio of -0.05 % was calculated. For series 2 we calculated –0.31 %. Because of the good structural condition of the sewer, the obtained results are in good accordance with our expectations.

Assessing uncertainty under the assumption of steady flow

The underlying concept of the QUEST-C method is to assess systematic errors by redundant information where possible. Random errors are calculated by Gaussian error propagation on eq. (2) which hypothesizes steady flow. Details of the uncertainty analysis procedure are documented by Rieckermann et al. (2003), where the standard deviation in the computed exfiltration rate σ_E was computed to 2.4 % and 2.6 % for the two data sets. The largest error contributions were identified as those of the Bromide and Lithium concentration equivalents in the samples ($C_{eq,Br}$ [69.7 %] and $C_{eq,Li}$ [28.0 %]) and the concentration equivalents of the Lithium and Bromide standards ($c_{eq,Lr}$ [0.9%] and $c_{eq,Br}$ [0.01%]).

The Gaussian error propagation is a useful tool to identify the main error contributions, but the results are conditional on the assumption of steady discharge. When the variation of the tracer loads during the experiment is plotted (Figure 2), it can be noticed that the time-dependent fluctuations of the resulting exfiltration (black line) follow a certain pattern and are not random. As fluctuations in time cannot be accounted for in the steady state analysis, it is supposed that the computed error of 2% stems to some extent from the variability of the discharge over time. Consequently, the remaining stochastic uncertainty will be reduced if the model for exfiltration analysis properly considers the dynamics of the system.

Dynamic analysis of the QUEST-C experiment: Including information on the discharge

Although the tracer dosing rates were very constant during the experiment, variations in the ratio of tracer concentrations are observed (Figure 2). It must be noted that discharge fluctuations result in waves which travel at a higher speed than the main water body. Henderson (1966) estimates that kinematic waves travel with a speed of 5/3 of the mean velocity. Generally spoken, this means that the two tracer substances that have been dosed to the same water element (which travels with a mean velocity) are diluted differently at their dosing points. This effect blurs the precision of the computed exfiltration, if eq.(2) is applied.

When information on the dynamic discharge is included in the QUEST-C method eq. (2) is modified to

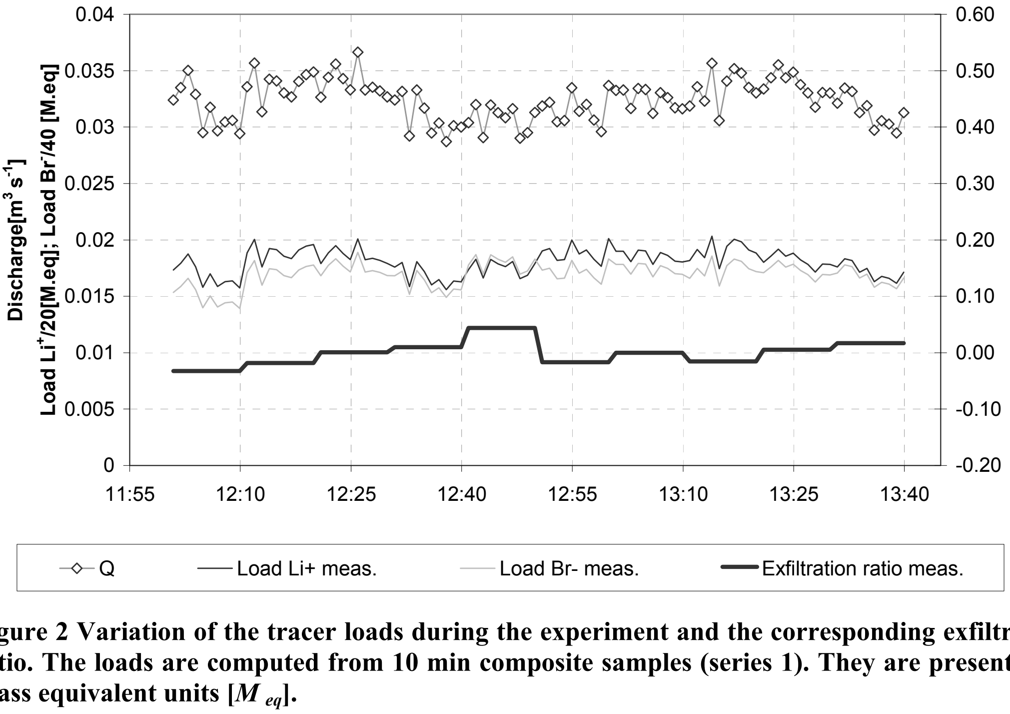

Figure 2 Variation of the tracer loads during the experiment and the corresponding exfiltration ratio. The loads are computed from 10 min composite samples (series 1). They are presented in Mass equivalent units [M_{eq}].

$$E = 1 - \left(\frac{c_{eq,Br}}{c_{eq,Li}} \frac{w_{Li}}{w_{Br}} \right) \cdot \frac{q_{Br}}{q_{Li}} \cdot \frac{\int Q(t) \cdot C_{eq,Li}(t)dt}{\int Q(t) \cdot C_{eq,Br-Br,back}(t)dt} \tag{3}$$

Applying eq.(3) to data set 1, we compute an exfiltration of -0.12 %. However, this intermediate result raises questions: what is the uncertainty in the computed exfiltration ratio and how can it be evaluated?

Assessment of uncertainty for the dynamic analysis

We propose a Monte Carlo approach in which the uncertainty from the field and laboratory measurements (here: measurement error) and the uncertainty that results from the dynamic flow (here: transport error) are separated. It is assumed that the transport error is a) independent from the measurement error and b) additive to it.

With regard to measurement errors, one must consider that information on the discharge introduces extra error contributions:

- ***Errors in the flow measurements (Area-velocity method:)*** Systematic errors in the level stem from an erroneous installation of the device and a false estimation of the sewer diameter. Random measurement errors affect the velocity readings and each water level measurement. As the sewer is circular the error contribution to the discharge is non-linear and is not cancelled out from eq. 3.
- ***Errors in the tracer ratio in the samples from the starting point of sampling:*** The starting point of sampling in the field always has an impact on the concentration ratio in the sample, because the varying discharge continuously causes fluctuations in the tracer concentrations. It depends on the experimental setup, the number of samples and the duration of sampling.
- ***Integration error by different time resolution of flow monitoring and sampling:*** The tracer concentrations in the composite samples (10 min) have a different resolution than the flow data (1 min). For the computation of the load, a steady concentration over the sampling interval (Figure 2) is assumed.

<u>Assessment of the measurement error</u>

All error contributions for the individual model parameters have been summarized in Table 1. Almost all parameters of the error distributions are empirical estimates from the experimental data. Only w_{Li}, w_{Br} and v were obtained from information of the manufacturer (scale and flow measurement device). The systematic and random error estimates on the water level (h_{syst}, h_{rand}) were assessed from practical experience. The systematic deviation of the diameter of the measuring cross-section d_{sewer} was estimated from general assumptions on construction and the installation of the flow meter. In order to not over-predict error contributions from rectangular distributions, uncertainty estimates that reflect practical knowledge were considered to be normally distributed.

After Evans et al. (2000) the standard deviation of a uniform distribution with [-a, +a] is transformed into the standard deviation of a normal distribution by

$$sd_{rect} = \frac{a}{\sqrt{3}} \tag{4}$$

Table 1 All error contributions for the model parameters of the exfiltration model (eq. (3)). All parameters were assumed to be normally distributed with mean=0 and the specified standard deviations. ("n.c."= not considered "—" = not required)

Parameter (p)	Unit	Description	$\sigma_{p,\ systematic}$	$\sigma_{p,\ random}$
h	[m]	water level measurement	0.02/(3^0.5)	0.006/(3^0.5)
d_{sewer}	[m]	sewer diameter	0.015/(3^0.5)	--
v	[m s^{-1}]	velocity measurement	n.c.	0.05 v_{meas}
$c_{eq,Li}$	[conc. eq.]	Standard concentration	--	0.032
$c_{eq,Br}$	[conc. eq.]	Standard concentration	--	0.069
w_{Br}	[g]	precision scale	--	2 E-04
w_{Li}	[g]	precision scale	--	2 E-04
q_{Br}	[g s^{-1}]	peristaltic dosing pump	n.c.	3 E-08
q_{Li}	[g s^{-1}]	peristaltic dosing pump	n.c.	9 E-08
$C_{eq,Li}$	[conc. eq.]	IC measurement, conc. equiv.	n.c.	0.012 $C_{eq\ Li,meas}$
$C_{eq,Br}$	[conc. eq.]	IC measurement, conc. equiv.	n.c.	0.005 $C_{eq\ Br,meas}$
$\Delta exf_{\ transport}$	[-]	transport error	assessed separately	

2000 simulations of eq.(3) were performed for the Monte Carlo error propagation without considering correlation of parameters. First, the discharge and the loads were computed. Then, the ratio of the integrated tracer loads and the input loads ratio are calculated, which yields the exfiltration estimate.

For the first series, the overall standard deviation in the exfiltration due to the measurement error is 0.5 % with a median of –0.1% (Figure 4a). For the second series of samples we compute a standard deviation of 0.5% and a median of -0.3%.

<u>Assessment of the transport error</u>

As each reach has its transport characteristics (length, roughness, slope, etc.) a hydrodynamic model is needed to properly assess the error contribution of dynamic flow. A transport model of the Rümlang sewer reach was implemented in AQUASIM (Reichert 1994) and calibrated by estimating the roughness coefficient (k_{st} = 80 $m^{1/3}s^{-1}$) and the grid space (Δx= 0.25 m) from concentration and discharge data. A dispersion coefficient was not included in the model, because the grid size was chosen such that the numerical dispersion accounted for the real dispersion in the sewer system.

The Rümlang experiment was modeled with the input data of discharge, pumping rates and the concentrations of the dosing solutions. The upper two graphs in Figure 3 show that the computed discharge is in good agreement with the data. It can also be seen, that Lithium and Bromide are affected differently by the dynamic flow pattern.

From Figure 3, it can be concluded that, even in periods with relatively low flow dynamics, grab sampling is worse than composite sampling, because grab sampling can easily introduce an error of 10% in the exfiltration ratio.

In order to properly assess the transport error in the experimental results, a bootstrap resampling was performed on simulated discharge and tracer loads. This is necessary,

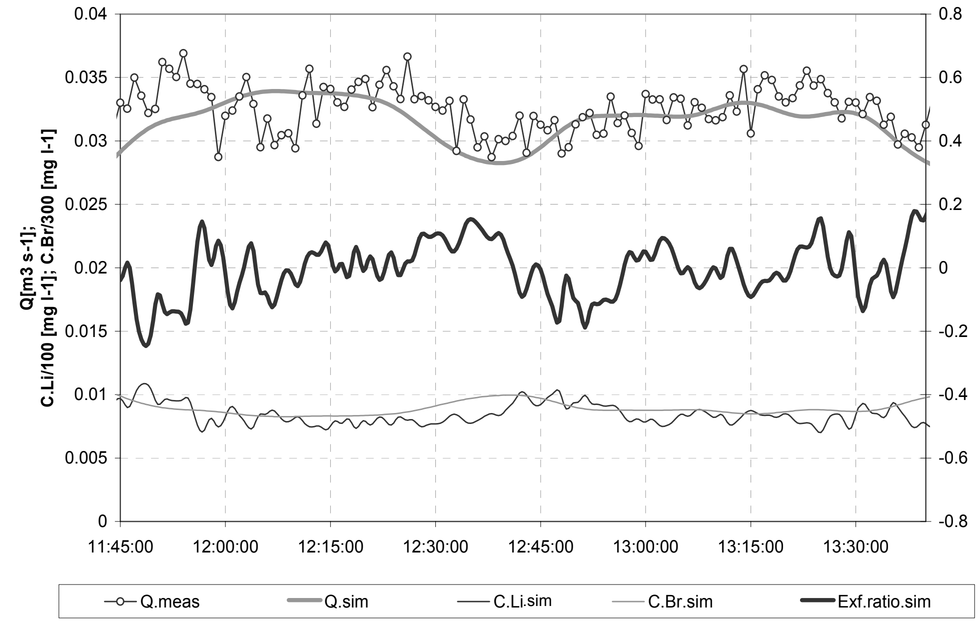

Figure 3 Investigation of the transport error with hydrodynamic modeling

because from the composite samples it cannot be concluded whether the start of sampling in the Rümlang experiment was a period of overestimation or underestimation of the exfiltration.

We estimate the error of transport and the starting point of sampling computing the exfiltration from a large number of randomly-drawn time-series of simulated data. Flow data from 6 subsequent days were used in the bootstrap procedure. In order to obtain reliable results, only the data in the time period of the experimental study were used for the data analysis. Eq. 3 was used to estimate the exfiltration from each time-series. From 1000 bootstrap simulations a median of 0.2% and a standard deviation of 0.8% was computed (Figure 4b).

<u>Assessment of the combined uncertainty from measurements and dynamic transport</u>

The combined uncertainty of the exfiltration ratio was computed under the assumption of additive errors. From the samples of series 1 we estimate the exfiltration in the reach to 0 % (median) with an uncertainty of 1 % (expressed as one standard deviation) (Figure 4c). For sample series 2 we calculate the same values.

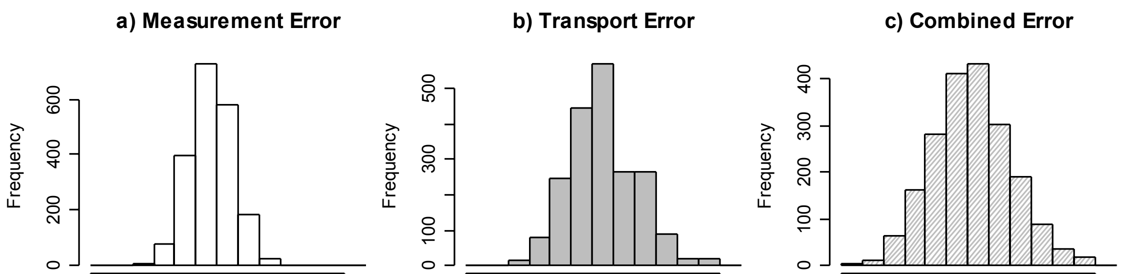

Figure 4 a) Error estimation from the measurement uncertainty; b) Estimated error contribution from the dynamic behavior of the system c) Combined uncertainty of both error contributions to the exfiltration ratio

Discussion

The dynamic analysis of this QUEST-C experiment at the sewer system of Rümlang yielded a substantial lower uncertainty (1%) than the steady state analysis (2%). However, it must be taken into account that minor effort has been put into the assessment of the uncertainty of the hydrodynamic computations. In order to assess the impact of the uncertain parameters (k_{st}, Δx), an error propagation on the results of the hydrodynamic model would be necessary. Furthermore, the model structure uncertainty is not fully accounted for by calibration; a cross-validation on further sewer data would increase the belief in the model results. The purpose of this paper is to emphasize and benefits of dynamic approaches to data analysis. Further investigations would have gone beyond the scope of this article.

Conclusions

- It is possible to accurately quantify exfiltration from sewers with the QUEST-C method. The discharge should be measured during each experiment and it is further recommended to include the information on the discharge in the analysis.
- A general statement of the uncertainty of the methodology ((Ohlsen and Genders 1993), (Knudsen 1996), etc.) does not seem reasonable. Ideally, an individual error assessment for each experiment according to the procedures discussed here should be performed and documented.
- The choice of a very specific tracer does not necessarily improve the accuracy of the estimated exfiltration.

References

Evans, M., N. Hastings, and B. Peacock. 2000. Statistical distributions, 3rd edition. John Wiley & Sons, New York.

Henderson, F. M. 1966. Open Channel Flow.

Jensen, A., and P. G. Madsen. 1996. Udsivning fra utætte kloakledninger. Stads og havneingeniøren:38-39.

Knudsen, L., Andersen, U., Ørskov, P., Pederesen, C. M. 1996. Undgå forurening af drikkevandet. Stads og havneingeniøren:34-36.

Ohlsen, B., and S. Genders. 1993. Udsivning fra kloakledninger. Stads- og havneingeniøren:5-58.

Reichert, P. 1994. AQUASIM - A tool for simulation and data analysis of aquatic systems. Water Sci. Tech. **30**:21-30.

Rieckermann, J., V. Bareš, O. Kracht, D. Braun, and W. Gujer. 2003. Quantifying exfiltration with continuous dosing of artificial tracers. Pages 229-232 *in* Hydrosphere 2003, Brno, CZ.

Rutherford, J. C. 1994. River Mixing. Wiley.

Vollertsen, J., K. Vorkamp, and T. Hvitved-Jacobsen. 2002. Udsivning af spildevand fra afløbssystemer. Miljøprojekt Nr. 685, Aalborg Universitet, Afdeling for Miljøteknik;, Aalborg.

Acknowledgements

The writers would like to thank the Swiss Federal Office for Education and Science (BBW) for financial support. 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), Technical University of Dresden (DE), Faculty of Civil Engineering at University of Prague (CZ), DHI Hydroinform a.s. (CZ), Hydroprojekt a.s. (CZ), Middlesex University (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 APUSS is part of the CityNet, the network of European research projects on integrated urban water management.