Validation of tracer dilution methods for the quantification of exfiltration from sewer systems through laboratory tests.

Validation des méthodes de mesures de l'exfiltration en réseaux d'assainissement par traçage artificiel au NaCl avec un modèle de laboratoire.

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RESUME

Récemment, la communauté scientifique a porté une attention croissante aux phénomènes d'exfiltration dans les réseaux d'égout. Les performances structurelles et hydrauliques des systèmes urbains de drainage et la qualité des eaux souterraines sont menacées par les écoulements accidentels dans ou hors des conduits. Cet article étudie les applications sur site développées afin de quantifier les exfiltrations des systèmes d'égout au moyen de NaCl comme traceur artificiel. Cette méthode, appelée QUEST (Rieckermann et Gujer, 2002), est basée sur le calcul d'un bilan masse du traceur sur une longueur donnée d'égout. Afin de valider les hypothèses de la méthode, et pour évaluer l'incertitude liée aux différentes sources d'erreurs qui affectent normalement les méthodes *in situ*, un circuit de 140 m de long (Ø 200mm) a été construit en laboratoire. L'objectif était de tester la fiabilité de QUEST dans des conditions hydrauliques (flux, vitesse) différentes, avec des taux d'exfiltration différents et des quantités de traceur injecté différentes, permettant ainsi d'évaluer la plage d'applicabilité et la précision maximale attendue de la méthode elle-même.

ABSTRACT

The importance of exfiltration phenomena in sewer systems has captured growing attention within the scientific community in the last recent years. The structural and hydraulic performance of urban drainage systems as well as groundwater quality are clearly threatened by liquid accidentally flowing into or out of the conduits. This paper examines well known field applications developed to quantify exfiltrations from sewer systems using NaCl as an artificial tracer. The method, called QUEST (Rieckermann et Gujer, 2002), is based on the calculation of a tracer mass balance over a certain sewer length. In order to validate the fundamental assumptions of the method, as well as to assess the uncertainty related to the different sources of error which normally affect field methods, a 140m long (200mm diameter) pipe circuit has been built in laboratory. The aim was to test the reliability of the QUEST under different hydraulic conditions (flow, velocity), different exfiltration rates and different amount of tracer injected, assessing therefore the range of applicability and the maximum expected accuracy of the method itself.

KEYWORDS

Exfiltration; Laboratory model; NaCl; QUEST; Sewer systems; Tracer dilution.

THE QUEST METHOD

The application of the basic principles of the tracer dilution method over a certain reach of a sewer network makes possible to compute a mass balance of the tracer injected as well as to give an estimate of the flow value.

Moving from these concepts the so called QUEST method (Niesel, 2003; Rieckermann et al., 2002; 2005a), has been developed within the APUSS project. A defined tracer mass is added at the beginning of the chosen investigated reach (indicator signal, figure X). The tracer flows across the conduit and, if any leakage occurs, a certain unknown amount of tracer is lost together with the sewage.

The percentage loss of tracer over the investigation distance is considered equal to the percentage loss of sewage related to the flow value at the upstream injection point. A second tracer injection (reference signal, figure 1) is then required from a point close to the downstream measuring section. From the application of the tracer mass balance on both signals it is possible to determine how much of the indicator mass and also of the sewage has exfiltrated along the investigated reach.

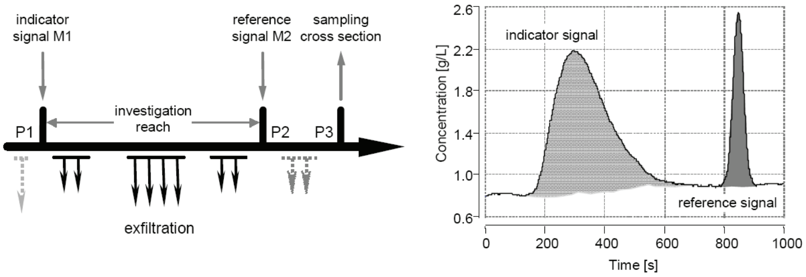

Figure 1 – Principle of exfiltration measurement (Bertrand-Krajewski et al., 2005)

$$\varepsilon = \frac{Q_{EXF}}{Q_{IND}} = 1 - \frac{M_{REF}}{A_{REF}} \cdot \frac{A_{IND}}{M_{IND}} \tag{1}$$

Where ε is the exfiltration rate; Q_{EXF} is the wastewater lost; Q_{IND} the wastewater discharge at the upstream point; M_{REF} and M_{IND} are the mass of tracer injected for the reference and the indicator signals; A_{REF} and A_{IND} are the painted areas under the signals in figure X. The exfiltration rate ranges from 0 (no loss, perfectly tight conduit) to 1 (total loss).

The tracer chosen is NaCl: cheap, easily purchasable and almost continuously measurable by mean of a conductivity sensor

1 THE PURPOSE

The traditional tracer measurements (Bolognesi et al., 2006) are affected by many error sources, whose influence gets higher in the QUEST method due to the particular conditions of the sewer environment (De Benedittis and Bertrand-Krajewski, 2005; Prigiobbe, 2005).

The uncertainty refers either to the experimental activity or to the numerical data processing strategy. A first step in order to reduce the uncertainty could be the improvement of the accuracy of field procedures, such as the determination of the mass injected or the definition of a correct and reliable tracer injection technique, but anyway if the purpose is, for example, to define the effect of a standard injection technique, repeatable and for which the precision is known, field experiments alone cannot give suitable answers. In fact it is almost impossible to know exactly what kind of processes are taking place inside the investigated conduit. Has the complete mixing occurred? Are there any dead zones where the tracer could be trapped? Is there something like biofilm on the pipe walls or simply toilette paper which may have caused tracer adsorption? Is the method affected by the nature of the exfiltrations?

It is not possible to give reliable answers to these and other question concerning for example the background conductivity value, therefore it is not possible to estimate how much a change in the experimental procedure produces an effective error reduction. In fact the previously mentioned unpredictable factors within the sewer conduit often determine uncertainties comparable to the improvements we would like to assess. This indetermination does not allow to quantify the maximum achievable accuracy of the method nor to verify its fundamental hypotheses. Therefore in order to test the effectiveness of the QUEST method and to prove the assumptions on which it is based, a pipe circuit, reproducing a sewer reach has been realized in laboratory.

Laboratory test have then been carried out in order to validate the method in a controlled environment, where all the unknown parameter such as the leakages and their position, are known.

2 THE MODEL

A pipe circuit has been set up in the new hydraulics laboratory of the University of Bologna. The purpose was to reproduce a sewer reach having constant slope.

The compromise between space, cost and characteristics of the laboratory facilities has lead to choose a 200 mm diameter PVC pipe. In order to obtain the longest possible reach, depending on the space available, a serpentine path has been chosen (figure 2), where the pipes are placed on wood supports, equally spaced, in order to obtain a 0.3% slope.

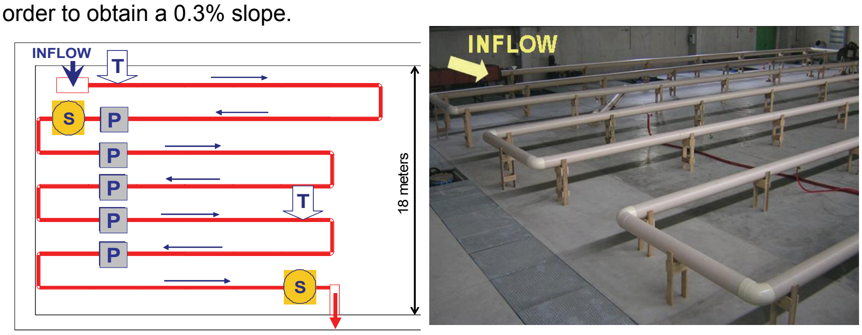

Figure 2 – (Left) Schematic plan of the pipe circuit; T = tracer injection points; S = conductivity probes; P = leakage points; (Right) partial view of the pipe circuit.

The experimental reach has a total length of 140 m, water flows directly from the water supply facility into the PVC circuit. Two points have been arranged for tracer injection (figure X) : one for the indicator signal, close to the upstream section and one for the reference signal, about 40 m from the downstream section. There are also two points where measuring instruments (conductivity meters) can be installed, the first is about 40 m downstream of the upstream section, while the second (the most important) is placed almost at the end of the reach. Finally, five taps have been installed on the bottom of the pipe, allowing to activate, control and measure leakages along the experimental reach.

The upstream inflow is measured by an electromagnetic flow meter, with an expected accuracy of 0.1%. A calibrated Thomson weir is placed immediately downstream of the last conduit. The leakages are controlled by taps placed along the experimental reach and they are repeatedly measured with the volumetric method (volume filled in a given time) obtaining therefore a mean value and a confidence interval for each assigned condition. All the experimental tests were run under steady state conditions, with upstream flow values ranging from 3 to 12 l/s, in order to examine different water depth conditions.

3 THE EXPERIMENTAL TESTS

As already mentioned, the laboratory tests aim to reproduce the field ones, but operating them within a system where almost all variables are kept under control and the boundary conditions are known. This should allow to validate the fundamental hypotheses of the QUEST method and to give an indication about its accuracy limits. In synthesis, all error sources which commonly affect field tests, are here strongly reduced or almost eliminated.

For what concerns the tracer mass determination, small doses of tracer are prepared with an high precision scale (0.01 g). No precision is required for the volume of water in which the NaCl is dissolved, because the purpose is not to create an accurate solution, but just to completely dissolve the amount of tracer necessary for a single injection. A small amount of tracer unavoidably remains attached to the container used for the solution and to the funnel used for the injection. This quantity has been estimated to be about 0.5 g and has shown not to depend on the NaCl mass dissolved.

The base conductivity of the liquid flowing into the experimental reach (tap water) is substantially constant. Anyway, its variations have appeared to be regular, easily detectable and do not require any particular numerical strategy for the so called ”baseline removal”.

Because of the regular pattern of the conductivity value, the presence of dead zones where the tracer may be trapped or its adherence to the conduit walls, both causing a gradual release of tracer, can be easily detected. Anyway, these phenomenon are unlikely to occur due to the smoothness of the PVC conduits.

The achievement of complete mixing has been a threatening problem, especially being short the distance available for the reference signals propagation. Anyway, complete mixing has always been reached, maybe thanks to the presence of elbow bends and it has been successfully proved placing two probes in the downstream measuring point.

The coefficient of the linear relation between conductivity and concentration (which is indeed not relevant for the determination of the exfiltration) has been experimentally obtained for each of the conductivity probe used, redefining also its confidence intervals.

About the important issues of signal parameterization and their deconvolution, it was chosen not to overlap the signals. Because of the steady state conditions, a reference signal close enough to the indicator can be treated as if they were overlapping. Moreover the parameterization of signals, necessary for their decomposition could be a relevant source of error, especially in this context, where the quick propagation of signals (1-2 min), related to the minimum acquisition time step (5 sec), makes the signal curve described by a small number of conductivity data.

4 RESULTS

In order to avoid the overlapping of signals, a standard injection sequence has been adopted. For each indicator tracer pulse, two reference pulses are added at a given time, aiming to obtain the standard layout shown in figure 3, for each test, at the downstream measuring point.

This signal constellation has been chosen not just for being practical to achieve and easy to elaborate in the post processing phase, but also because it resulted to be the best experimental design according to a decision analysis performed on 100 different layouts (Rieckermann, 2005b).

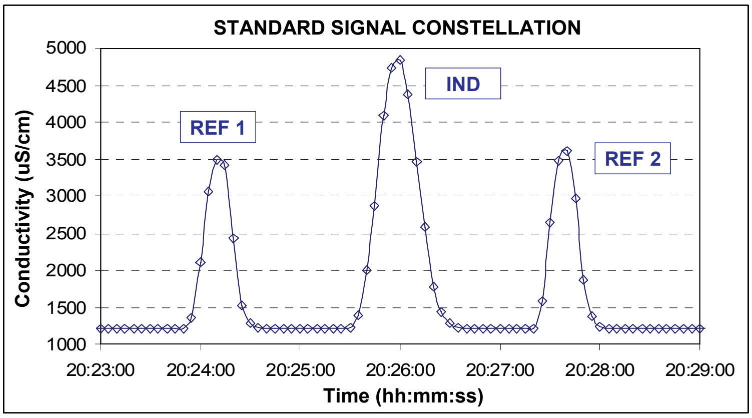

Figure 3 – Standard signal layout obtained for each run at the downstream measuring point

4.1 Uncertainty analysis

The tests performed can be divided in two main groups:

- tests with no leakages induced
- tests with one or more leakages induced

For each of those two conditions, regarding different flow rates and different tracer mass injected for both “reference” and “indicator” signals, the uncertainty analysis was performed, according to the traditional propagation of errors.

The propagation of uncertainty has been performed either on the values measured by laboratory instruments (electromagnetic flow meter and volumetric method) or on those calculated with the (1). Individual uncertainty values such as the scale or the conductivity meter precision have been therefore propagated (De Benedittis, 2004) in order to obtain the uncertainty associated to each single exfiltration (Tables 1 and 2). For tests performed without leakages, there is obviously no uncertainty affecting measured exfiltration value.

The results obtained are presented in tables 1 and 2, where each row represents a single test (i.e. one indicator and two reference signals injected) and:

- *Qin* is the flow entering the upstream end of the circuit, measured by the electromagnetic flow meter;
- *Lkg* is the sum of all the losses occurring along the circuit, measured with the volumetric method;

- *ExfM* is the exfiltration rate computed as the ratio between *Lkg* and *Qin*;
- *Exf1* and *Exf2* are the exfiltration rates calculated according to the QUEST (1), considering respectively the REF1 and REF2 signals, as shown in figure X;
- *ΔExfM, ΔExf1 and ΔExf2* are the respective calculated uncertainties.

Qin [l/s]	*Lkg* [l/s]	*ExfM*	*Exf1*	*ΔExf1*	*Exf2*	*ΔExf2*
7.91	0	0	0.015	±0.001	0.012	±0.000
4.81	0	0	0.021	±0.002	0.013	±0.000
	0	0	-0.022	±0.002	-0.001	±0.001
5.06	0	0	0.022	±0.001	0.021	±0.001
9.16	0	0	0.002	±0.000	-0.001	±0.000
	0	0	-0.010	±0.002	-0.004	±0.002

Table 1 – Summary of the tests performed with no leakages induced

Qin [l/s]	*Lkg* [l/s]	*ExfM*	*ΔExfM*	*Exf1*	*ΔExf1*	*Exf2*	*ΔExf2*
5.06	0.667	0.132	±0.003	0.150	±0.009	0.111	±0.007
				0.128	±0.008	0.124	±0.008
				0.138	±0.007	0.147	±0.008
10.52	1.437	0.137	±0.003	0.116	±0.006	0.127	±0.004
	1.437	0.137	±0.003	0.155	±0.008	0.130	±0.008
	0.912	0.087	±0.002	0.073	±0.002	0.081	±0.009
11.75	1.451	0.123	±0.002	0.102	±0.005	0.109	±0.006
	1.451	0.123	±0.002	0.112	±0.006	0.115	±0.006
	0.923	0.079	±0.001	0.101	±0.005	0.097	±0.005
5.34	1.338	0.251	±0.004	0.246	±0.013	0.255	±0.013
2.56	0.492	0.192	±0.003	0.185	±0.010	0.182	±0.010

Table 2 – Summary of the tests performed with one or more leakages induced

All results presented in tables 1 and 2 are summarized by the following graphs. Figure 4 shows the comparison between measured and calculated exfiltrations relative to the tests performed with one or more leakages. Each point is represented with uncertainty bars regarding both laboratory measurements and QUEST errors.

A cumulative distribution of the differences between measured and calculated exfiltration values (i.e. accuracy values) is shown in figure 5. The analysis of the accuracy of the method reveals an almost unbiased distribution, which means practically absence of systematic errors. Furthermore, the accuracy of the QUEST method, relative to the exfiltration rate value, has a 90% confidence interval estimated as [-0.02; 0.02].

In addition to the accuracy analysis, some of the fundamental hypothesis of the QUEST method have been verified. Results obtained have in fact demonstrated that, in terms of percentage, the tracer mass lost over the investigation distance is actually equal to the liquid volume lost. It has also been proved that any leakage occurring between the reference injection point and the downstream measuring section cannot be detected by the method and therefore it does not affect its results relative to the investigation reach.

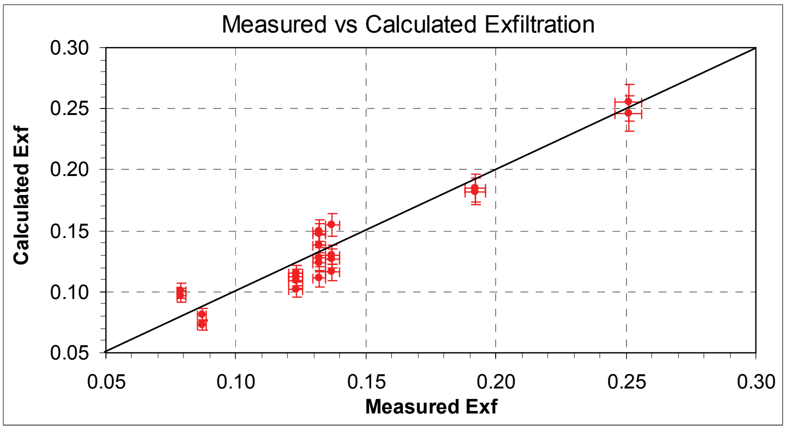

Figure 4 – Scatter plot of measured and calculated (QUEST) exfiltration values, for the tests performed with one or more leakages.

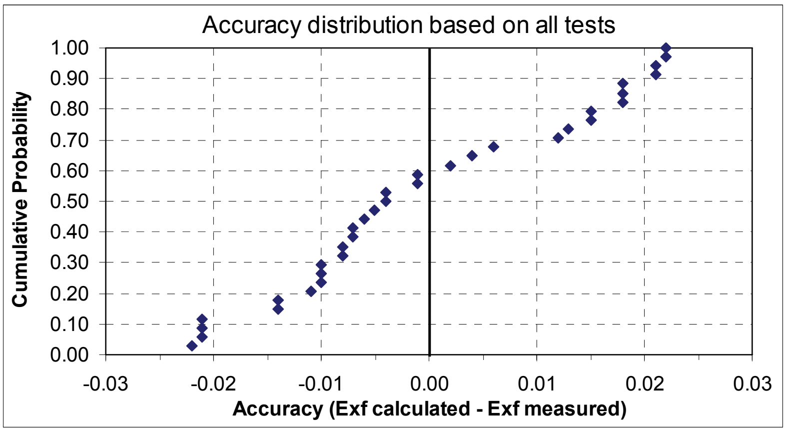

Figure 5 – Cumulative distribution of accuracy values (differences between Exf calculated by QUEST and Exf measured), relative to all tests performed

5 DISCUSSION

The small deviations between measured (through laboratory instruments) and calculated (according to the QUEST method) exfiltrations may found their explanation in the following hypothesis.

The conductivity meter accuracy declared by the manufacturer (0.5%) is probably one of the most relevant factor. That uncertainty value can directly affect the computation of A_{IND} and A_{REF} (1) and then the exfiltration value too.

The differences between measured and calculated exfiltration (more evident in the tests without leakages, where no uncertainty affects the “zero” measured value) appear slightly above 1% and almost never over 2%. It is therefore easy to understand the relevance assumed by that 0.5% value. Besides this factor and considering also any possible (although minimal) accidental errors due to the experimental operator, another important issue may arise from the limited number of conductivity data used to define each pulse. The length of the pipe circuit does not allow dispersion mechanism to fully develop and therefore the signal transit times recorded in the downstream measuring section are barely greater than a couple of minutes, either for reference or indicator signals. Being 5 seconds the minimum time step of the conductivity meter, each pulse is described by slightly more than 10 points. According to the overall precision of the tests, this aspect cannot be ignored as a further potential source of error.

6 CONCLUSIONS

Results obtained from laboratory tests have confirmed the validity and the reliability of the tracer dilution method (QUEST) for the quantification of leakages from sewer conduits. Almost 20 tests and 40 exfiltration estimates have been computed according to the (1) and then compared to the laboratory measured values, eventually determining a 90% confidence interval of [-0.02; 0.02] for the exfiltration rate value. The main hypothesis on which the QUEST is based have also been successfully proved. Possible explanations for the observed (although minimal) deviations may be found in some limits of the conductivity meter (0.5% accuracy and 5 sec minimum time step), and also in the insufficient length of the pipe circuit. The laboratory is a controlled environment, where all conditions and variables can be continuously checked. Therefore, out of a laboratory facility, both precision and accuracy obtained are quite unlikely to be improved. Anyway, if careful installations and proper injection techniques are adopted, it is reasonable to suppose that the accuracy of field experiments might be not too distant from the one reached in laboratory.

LIST OF REFERENCES

Bolognesi A., G. Gottardi, M. Maglionico, (2006). Discharge measurements in a small ungauged river: comparison between conventional current-meter and tracer dilution methods; Proceedings of the River Flow 2006, Lisbon.

Bertrand-Krajewski J.-L., Cardoso M. A., Ellis B., Frehmann T., Giulianelli M., Gujer W., Krebs P., Pliska Z., Pollert J., K. Pryl. (2005). Towards a better knowledge and management of infiltration and exfiltration in sewer systems: the APUSS project. Proceedings of 10th ICUD Copenhagen.

De Bénédittis J., (2004). Mesurage de l’exfiltration en réseaux d’assainissement par traçage artificiel au NaCl., PhD thesis, INSA Lyon

De Bénédittis J. and Bertrand-Krajewski J.L., (2005). Mesurage de l'exfiltration en réseaux d'assainissement par traçage artificiel au NaCl, Houille Blanche, 5, 26-34.

Prigiobbe, V., (2005). Analysis and Application of Novel Method for Quantifying Infiltration and Exfiltration in Urban Sewer Systems, PhD thesis, Università di Roma “Tor Vergata”.

Niesel, K., (2003). Applicability of sodium chloride for the quantification of exfiltration from urban sewer systems. Master’s thesis, Fachbereich Landeskultur und Umweltschutz, University of Rostock.

Rieckermann J., W. Gujer, (2002). Quantifying Exfiltration from Leaky Sewers with Artificial Tracers. Proceedings of the International Conference on "Sewer Operation and Maintenance 2002", Bradford, UK.

Rieckermann (a), J.; Borsuk, M.; Reichert, P.; Gujer, W., (2005). A novel tracer method for estimating sewer exfiltration. Water Resources Research, 41(5), pW05013.

Rieckermann (b), J.; Borsuk, M. and Gujer, W; (2005). Using Decision Analysis to Determine Optimal Experimental Design for Monitoring Sewer Exfiltration with Tracers Exfiltration from Sewers. Proceedings of the 10th ICUD, Copenhagen.