Towards a better knowledge and management of infiltration and exfiltration in sewer systems: the APUSS project

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ABSTRACT
Sewer systems constitute a very significant patrimony in European cities. Their structural quality and functional efficiency are key parameters to guarantee the transfer of domestic and trade wastewater to treatment plants without infiltration nor exfiltration. Infiltration of groundwater is particularly detrimental to treatment plant efficiency, while exfiltration of wastewater can lead to groundwater contamination. During the period 2001-2004, the European research project APUSS (Assessing infiltration and exfiltration on the Performance of Urban Sewer Systems) was devoted to sewer infiltration and exfiltration questions. It was structured on three main Work Areas dealing respectively with i) the development of new measurement methods based on tracer experiments and accounting for detailed uncertainty analyses, ii) the implementation of models and software tools to integrate structural and experimental data and to facilitate data display, operational management and decision making process and iii) the integration of economic and operational questions by means of costs estimation, economic valuation, performance indicators and multi-criteria methods applied to investment/rehabilitation strategies. This overview paper describes synthetically the objectives, methods and main achievements for each Work Area. References to both antecedent and companion papers are given for results and more detailed information.

KEYWORDS
Exfiltration, infiltration, measurement methods, modelling, performance indicator, sewer system.

INTRODUCTION
Urban sewer systems constitute a very significant patrimony in European cities. Their structural quality and functional efficiency are key parameters to guarantee the transfer of domestic and trade wastewater to treatment plants without infiltration nor exfiltration. Infiltration of groundwater is particularly detrimental to treatment plant efficiency (hydraulic overloading due to the infiltrated volume of water which can reach up to 100 % of the wastewater volume in some cities, dilution of pollutant concentrations leads to a lower pollutant removal efficiency), while exfiltration of wastewater can lead to groundwater

contamination (especially where groundwater is a water resource for drinking water production). Both problems are critical on a long term basis for sustainable urban water management and have important economic consequences for cities and sewer systems operators through the European Union. The European standard EN 752-2 (CEN, 1996) indicates basic performance criteria applicable to any sewer system. Among these criteria, the two following ones are especially relevant: i) receiving waters should be protected against pollution; ii) the structural integrity of urban sewer systems, including water tightness, should be guaranteed. In order to evaluate the performance of urban sewer systems, public and private operators need appropriate methods and techniques.

During the period 2001-2004, the APUSS project (Assessing infiltration and exfiltration on the Performance of Urban Sewer Systems), associating universities, SMEs (Small and Medium Enterprises) and municipalities in seven European countries and financed by the European Commission under the 5th R&D (Research and Development) Framework Programme, was devoted to sewer infiltration and exfiltration questions. It was structured on three main Work Areas dealing respectively with i) new measurement methods, ii) associated models and tools, and iii) socio-economic aspects linked to infiltration and exfiltration (I/E). After a brief introduction of the APUSS partners, the following paragraphs give a synthetic overview of the above three Work Areas: objectives, methods and main achievements. It is of course not possible to give all scientific and technical details in the limited frame of this paper: references are given to some companion papers where obtained results are presented, and to the APUSS website where all final reports and published papers are publicly available.

APUSS PARTNERS AND END-USERS

Ten scientific partners from seven European countries have defined and carried out the APUSS project. Some of them were associated to end-users (sewer operators) interested in I/E, who contributed by providing assistance, access to experimental sites, operational data, and additional funding (Table 1). The APUSS project has also been part of the 5th R&D Framework Programme European cluster CityNet including six individual projects dealing with integrated urban water systems (Schilling *et al*., 2002).

Table 1. APUSS scientific partners and associated end-users.

Scientific partner	Associated end-user
INSA de Lyon (France, co-ordinator)	Great Lyon
EAWAG (Switzerland)	city of Zürich
Dresden University of Technology (Germany)	city of Dresden, city of Berlin
Czech Technical University in Prague (Czech Republic)	city of Prague
DHI Hydroinform a.s. (Czech Republic)	city of Prague
Hydroprojekt a.s. (Czech Republic)	city of Prague
Middlesex University (United Kingdom)	Thames Water
National Laboratory for Civil Engineering (Portugal)	
Emschergenossenschaft (Germany)	city of Bottrop and Gladbeck
IRSA-CNR (Italy)	city of Rome

WORK AREA 1: NEW MEASUREMENT METHODS

Traditionally, the assessment of I/E in sewer systems is typically based on rather inaccurate methods of flow measurement, analysis of diurnal flow and load variation and balancing of water in-and outputs (De Bénédittis and Bertrand-Krajewski, 2004). One of the key objectives

of the APUSS project consisted to develop new measurement methods allowing differentiating sewer zones with infiltration and exfiltration, based on limited analytical effort and with little environmental risk. By means of an optimised design of the experiments and a detailed analysis of the resulting data and of their associated uncertainties, a higher degree of accuracy and a better quality knowledge than in traditional methods were expected. Work area 1 included the development, testing and validation of methods to accurately quantify:
- exfiltration from sewer reaches
- infiltration into sewer systems
- infiltration and exfiltration from house connections.

The methods are mainly based on selected chemicals and natural isotopic tracers and have been tested and validated under various operational conditions during dry weather, at different space scales (from the pipe reach to the whole catchment) and under different conditions (steady and dynamic groundwater levels, seasonal effects, etc.). They have been applied in different catchments chosen in the associated cities and compared to traditional approaches based e.g. only on flow rate measurements or on large scale water mass balance. Standard operation protocols and routines for data processing and detailed uncertainty analysis have been specifically established.

Exfiltration from sewer reaches

Two generic tracer methods have been developed to measure exfiltration along a sewer reach with a length of approximately 1-2 km. The first method is based on a set of tracer pulses (Rieckermann and Gujer, 2002).

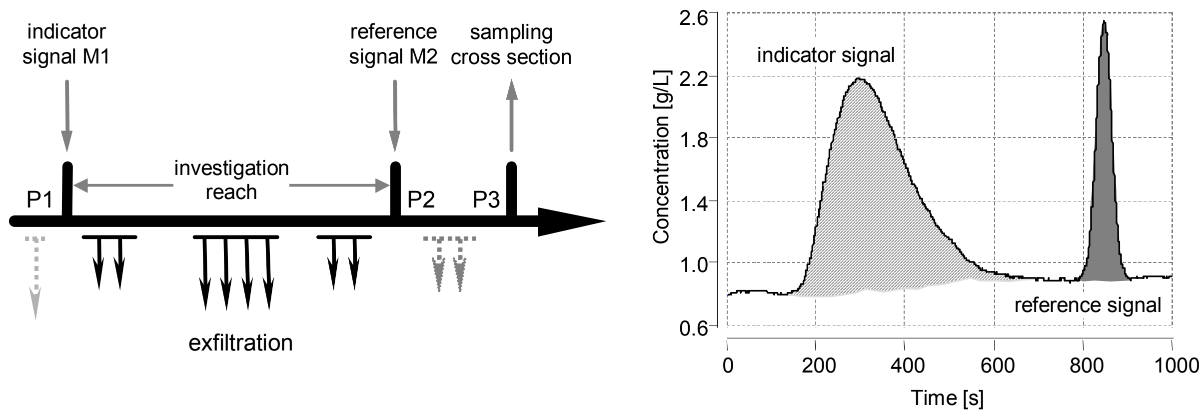

Figure 1. Principle of exfiltration measurement (adapted from Rieckermann and Gujer, 2002)

The principle (Figure 1) consists to inject a mass M1 of tracer (indicator signal) in the upstream extremity P1 of the sewer reach and to measure its transit in the reach outlet P3. A mass M2 of tracer (reference signal) is injected in P2 at a short distance upstream from the outlet, and its transit in P3 is measured. The exfiltration between P1 and P2 is evaluated by means of mass balances calculations: it is proportional to the fraction of the mass M1 which has been lost between P1 and P2. In order to decrease uncertainties in measurements and results, several indicator and reference pulses are used in each single experiment. The most frequently used tracer is sodium chloride, as it is cheap, safe and easy to measure continuously by mean of conductivity sensors directly installed in the sewer. However, there is a natural background conductivity in wastewater, which possible fluctuations during experiments may increase errors and uncertainties. As an alternative, Rhodamine® may be used as a tracer: background concentration is usually zero and continuous measurement is carried out by means of on-line fluorescence sensors. The main possible drawback of

Rhodamine® is its adsorption on sewers solids and particles, but adsorption is very limited in case of transit times not exceeding some tens of minutes.

The second method is based on continuous tracer injection (Rieckermann *et al*., 2003). Two tracers (lithium chloride as indicator tracer and sodium bromide as reference tracer) are injected respectively in P1 and P2 at constant flow rates, during a period of time long enough to observe stable concentrations for both tracers in P3 (concentration plateau). This second method solves some of the difficulties attached to the above tracer pulses method, but requires more equipment and preparation, and results are known only after laboratory analyses of samples as reliable on-line lithium and bromide sensors applicable in sewers are not yet available.

Whatever the tracer and the method, data processing and uncertainty analysis protocols have been established and implemented in R-script® codes, that allow measuring exfiltration rates with relative uncertainties of approximately 2 % (Rieckermann *et al*., 2005). Both tracer methods have been tested in various experimental sites during the APUSS project (e.g. De Bénédittis, 2004; Prigiobbe and Giulianelli, 2004; Rutsch *et al*. 2005). Additionally, laboratory tests have been carried out to evaluate i) the adsorption and interaction of tracers (especially Rhodamine) with wastewater solids, and ii) the effect of sewer solids and sediments on exfiltration. Regarding the later aspect, it has been observed that sewer sediments contribute to the clogging of sewer defects and consequently to a significant decrease of exfiltration rates (Ellis *et al*., 2003).

Infiltration into sewer systems

Two methods have been developed to measure exfiltration at sub-catchment scale. The first method is based on natural stable ^{16}O and ^{18}O oxygen isotopes (Kracht *et al*., 2003). If drinking water and groundwater have two distinct $\delta^{18}O$ isotopic ratios, and by assuming that infiltration water is groundwater and that domestic wastewater is used drinking water, the measurement of the $\delta^{18}O$ ratio at the outlet of a given sub-catchment, coupled to a mass balance equation, allows estimating the infiltration rate. The method is rather simple to apply and cheap, but is limited to sub-catchments where both drinking water and groundwater have homogenous isotopic signatures, and where only two components (one drinking water source, one groundwater source) are interacting. These strong limitations are the major drawback of this method which has been tested in various sites during the APUSS project (De Bénédittis, 2004).

The second method, which on the contrary may be used at the outlet of any sub-catchment where wastewater has mainly a domestic origin, is based on simultaneous and continuous measurement of flow rate and COD concentration. Flow rate is measured by means of best available flow meters, and COD concentration is obtained from optical measurements by means of a multi-wavelength UV/visible spectrophotometer. Assuming that infiltration water has a negligible COD concentration compared to domestic wastewater, and by fitting flow and concentration daily pattern models, mass balance equations allow calculating the infiltration rate (Kracht and Gujer, 2004). As for exfiltration, detailed analysis of uncertainties is part of the infiltration protocols.

Infiltration and exfiltration from house connections

The above methods are applicable to infiltration and exfiltration in public sewers pipes. But it is well known that house connections (HC) are also key components in I/E phenomena. Volumetric methods have been tested and applied on experimental sites to measure I/E in HC.

For infiltration, flow monitoring during a couple of days in manholes connecting a few houses to public sewers have allowed estimating the infiltration rate as equivalent to the minimum night flow. For exfiltration, two methods have been tested. The pressure method consists to block the HC pipe with sealing balloons, to fill it with water, and to measure the decrease of the water level as a function of time, from which the exfiltration rate is calculated. The free surface method consists to discharge a given volume of water in the HC pipe, to collect the volume downstream the HC pipe and to calculate the exfiltration rate from the comparison of both volumes. The first method overestimates exfiltration because of the pressure, while the second one requests an easy access in the public sewer downstream the HC, which is rarely possible. Finally, as there are many thousands of HC in a city, it is impossible in practice to measure I/E in all of them. This is the reason why a matrix procedure for extrapolation to wide catchment offering similar HC characteristics has been established, which is based on CCTV inspection records and HC defects ranking (Princ and Kohout, 2003).

WORK AREA 2: ASSOCIATED MODELS AND TOOLS

Measurements of infiltration and exfiltration rates in sewer pipes and house connections provide data and results which need to be integrated and adequately displayed in order to give end-users a clear representation and understanding of the phenomena affecting their sewer systems. Moreover, field data obtained by application of the methods developed in Work Area 1 shall be used in close relation to models, for calibration purposes and comparison of simulation results to field measurements. Complementary models and software tools have been thus developed in Work Area 2.

Models

Exfiltration is measured at the sewer reach scale, while infiltration is measured at sub-catchment scale. Accordingly, conceptual models respectively at sewer reach and sub-catchment scales for exfiltration and infiltration have been proposed. The involved key state variables are water levels in pipes h_W, surrounding groundwater levels h_{GWL} and I/E wetted perimeters P_W (Figure 2). The model parameters at reach and catchment scales reflect the structural state of the sewer pipes and need to be calibrated by means of field experiments and results. Additionally, field experimental data series have been used to establish and test the leakage approach model for both infiltration and exfiltration which were reproduced with their temporal variations (Karpf and Krebs, 2004a,b, 2005). But as I/E experiments and measurements likely can not cover all pipes within a city, a statistical method based on the similarity approach has been proposed in order to identify sub-catchments and groups of sewers which have similar characteristics and which potentially should have similar orders of magnitude in I/E rates (Franz and Krebs, 2005).

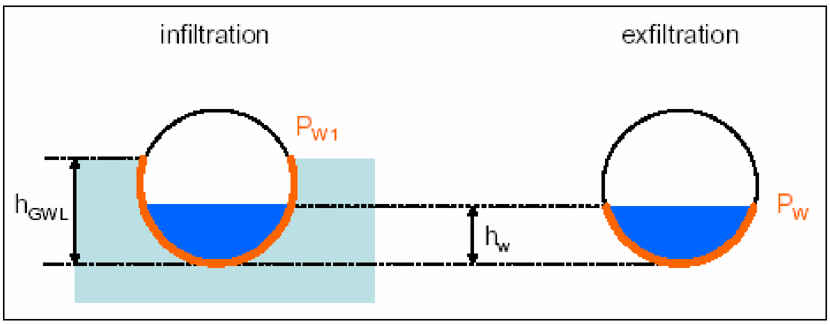

Figure 2. Key state variables used in the I/E models.

Data management software

An integrated tool has been developed in the frame of the AquaBase® software, which displays the map of the sewer system and the dry weather flow rates, the interpolated groundwater levels, and which includes data and time series containing experimental I/E results. Automatic calibration routines have also been developed and implemented in order to calibrate the models parameters according to the data and time series. Models and tools have been established and tested in the frame of a large scale example of general application of methods and models, with an end-user application perspective.

WORK AREA 3: ECONOMIC AND OPERATIONAL ASPECTS

Municipalities and/or sewer operators have to decide investment strategies to rehabilitate and upgrade efficiency and quality of their sewer systems. Frequently, such decisions are based on limited information and do not consider simultaneously the sewer pipes, the wastewater treatment plant and the environment, especially groundwater. In order to provide some elements to help operators in making decisions, Work Area 3 includes three topics: i) costs structure of sewer systems and costs of the new methods, ii) set of I/E specific performance indicators and iii) generic methodology to compare investment strategies.

Cost structure and costs of APUSS methods

A questionnaire sent to end-users has shown that the transfer of technical and financial information between different cities was not possible because of the large diversity of approaches and organisations. However, a new cost-structure for sewer systems has been developed, including six costs groups (material, wages and salaries, miscellaneous operational costs, disposal of waste, depreciation and calculated interest), which constitutes the basis for both cost-benefit analysis and benchmark studies. The application of the cost benefit analysis has been illustrated by means of four examples (rehabilitation vs. replacement in different installation depths). For comparison, yearly operation and investment costs were calculated, which revealed that the amortisation time of the planed measure was one of the main points in decision making.

For all measurement methods developed in Work Area 1, detailed ranges of costs (personal cost, cost for measuring equipment, and cost for consumption) have been evaluated. They must be considered as costs for a "prototype" measurement which could be reduced when measurements would be applied on a routine basis. Looking only at economical aspects, “classic” flow measurements appear more beneficial. However, the new measurement methods provide values of infiltration and exfiltration with better evaluation of uncertainty. The results obtained using these methods are more reliable than with the “classic” methods.

I/E performance indicators

A set of specific performance indicators (PI) has been developed to assess the impact of I/E on sewer systems and applied to three cases studies, as a means of aggregating information on system characteristics and experimental data from monitoring or modelling, and translate it into performance values. The PI have been calculated from sewer systems characteristics and I/E rates measured with the methods developed in Work Area 1. Once calculated, the PI are ranked in relation to good or bad performance, which allows a standardized and objective comparison of the performance of different sewer systems and constitutes a means to technically support the establishment of priorities for rehabilitation and/or construction investments taking into account I/E impacts (Cardoso *et al.*, 2002, 2005). Links have been established between the AquaBase® platform and the PI calculation software.

Generic methodology to compare investment strategies

When I/E problems are detected and evaluated, end-users usually have various investment and rehabilitation strategies to solve them (rehabilitation of the sewer system, adaptation of the downstream wastewater treatment plant (WWTP), storage tanks, or any combination of the above solutions). A generic methodology including modelling of the sewer system and of the WWTP has been established to compare these investment strategies, which accounts for different criteria (environmental, operational, financial, etc.) regarding the impacts of I/E. The multi-criteria method Electre III (Roy, 1996) is used to compare and to rank the various strategies. An example of application of the proposed methodology has been made for demonstration purposes. Data availability appeared as a key factor for an adequate application of the methodology. Depending on the criteria of interest, the preferable investment strategy may change completely, and thus case by case analyses shall be carried out.

CONCLUSION

During the period 2001-2004, the European research project APUSS (Assessing infiltration and exfiltration on the Performance of Urban Sewer Systems) was devoted to sewer infiltration and exfiltration questions.

New methods based on tracers experiments have been developed to measure infiltration and exfiltration in sewer systems: at sub-catchment scale for infiltration and at sewer reach scale for exfiltration. For all methods, protocols, uncertainty analysis and data processing codes have been established and are available. The methods have been applied in various experimental sites with different contexts, where both seasonal and after rainfall event variations of I/E rates have been observed. Volumetric methods have also been tested to measure I/E in house connections.

Conceptual models to simulate infiltration and exfiltration at various time scales have been tested and applied. A statistical method based on the similarity approach has been developed to facilitate the identification of representative catchments and the extrapolation of experimental values to wider catchment at the whole city scale. As a natural complement, a software platform has been implemented to describe sewer systems, to store experimental data series on groundwater levels and I/E rates, to calibrate the models and to display all results. A user manual and case study application have been provided.

The cost structure of sewer systems has been analysed, and a cost benefit analysis has been carried out for replacement and rehabilitation of sewers. The range of costs of the new I/E measurement methods have been estimated. Specific I/E performance indicators have been established and applied to various case studies, and a multi-criteria methodology has been elaborated to compare and rank investment and rehabilitation strategies.

All above elements are now available for end-users and will contribute to help them to get a better knowledge about I/E phenomena and to make decisions based on more accurate and elaborated information. All final reports, attached documents and published papers are publicly available on the APUSS website at http://www.insa-lyon.fr/Laboratoires/URGC-HU/apuss/. Beyond the tests carried out during the project, the application of the APUSS methods and tools by various operators in diverse contexts will contribute to their full evaluation and to their continuous validation and improvement.

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REFERENCES

Cardoso A., Almeida M.C., Coelho S.T. (2002). Evaluation of the infiltration impact on the performance of urban sewer systems. *Proceedings of the 9th National Congress on Water, Wastewater and Solid Waste*, Braga, Portugal, 16-19 September, 17 p. (in Portuguese).

Cardoso A., Prigiobbe V., Giulianelli M., Baer E., De Bénédittis J., Coelho S.T. (2005). Assessing the impact of infiltration and exfiltration in sewer systems using performance indicators: case studies of the APUSS project. *Proceedings of the 10th ICUD conference*, Copenhagen, Denmark, 21-26 August, 8 p.

CEN (1996). *European Standard EN 752-2 : Drain and sewer systems outside buildings – Part 2: Performance requirements*. Paris (France): AFNOR, 18 p.

De Bénédittis J. (2004). *Mesurage de l'infiltration et de l'exfiltration dans les réseaux d'assainissement*. PhD thesis : INSA de Lyon, Villeurbanne, France, 331 p. (in French).

De Bénédittis J., Bertrand-Krajewski J.-L. (2004). Infiltration in sewer systems : comparison of measurement methods. *Proceedings of the 4th International Conference on Sewer Processes and Networks*, Funchal, Madeira, Portugal, 22-24 November, 301-308.

Ellis J.B., Revitt D.M., Lister P., Willgress C., Buckley A. (2003). Experimental Studies of Sewer Exfiltration. *Water Science and Technology*, 47(4), 61-67

Franz T., Krebs P. (2005). Statistical methods towards more efficient infiltration measurements. *Proceedings of the 10th ICUD conference*, Copenhagen, Denmark, 21-26 August, 8 p.

Karpf C., Krebs P. (2004a). Sewers as drainage systems – Quantification of groundwater infiltration. *Proceedings of Novatech 2004,* Lyon, France, 6-10 June, vol. 2, 969-975.

Karpf C., Krebs P. (2004b). Application of the leakage model to assess exfiltration. *Proceedings of the 6th International Conference on Urban Drainage Modelling*, Dresden, Germany, 15-17 Sept., 217-224.

Karpf C., Krebs P. (2005). Assessment of extraneous water inflow in separated sewer networks. *Proceedings of the 10th ICUD conference*, Copenhagen, Denmark, 21-26 August, 8 p.

Kracht O., Gresch M., de Bénedittis J., Prigiobbe V., Gujer W. (2003). Stable isotopes of water as a natural tracer for infiltration into urban sewer systems. *Geophysical Research Abstracts*, vol. 5, 07852, 2 p.

Kracht O., Gujer W. (2004). Quantification of infiltration into sewers based on time series of pollutant loads. *Proceedings of the 4th International Conference on Sewer Processes and Networks*, Funchal, Madeira, Portugal, 22-24 November, 293-300.

Prigiobbe V., Giulianelli M. (2004). Design of tests for quantifying sewer leakages by QUEST-C method. *Proceedings of the 6th International Conference on Urban Drainage Modelling*, Dresden, Germany, 15-17 September, 205-216.

Princ I., Kohout D. (2003). Infiltration and Exfiltration from House connections. *Proceedings of the conference "Water Management Task 2003"*, Spindleruv Mlyn, Czech Republic, 23-24 November, 60-63.

Rieckermann J., Bares V., Kracht O., Braun D., Gujer W. (2003). Quantifying exfiltration with continuous dosing of artificial tracers. *Proceedings of the Hydrosphere conference*, Brno, CZ, 2-3 October, 4 p.

Rieckermann J., Borsuk M., Gujer W. (2005). Using Decision Analysis to Determine Optimal Experimental Design for Monitoring Sewer Exfiltration with Tracers. *Proceedings of the 10th ICUD conference*, Copenhagen, Denmark, 21-26 August, 8 p.

Rieckermann J., Gujer W. (2002). Quantifying exfiltration from leaky sewers with artificial tracers. *Proceedings of the international conference "SOM 2002 Sewer Operation and Maintenance"*, Bradford, UK, 26-28 November, 8 p.

Roy, B. (1996). *Multicriteria methodology for decision aiding*. Dordrecht (Netherlands): Kluwer Academic Publishers, 292 p.

Rutsch M., Rieckermann J., Krebs P. (2005). Quantification of sewer exfiltration – A review. *Proceedings of the 10th ICUD conference*, Copenhagen, Denmark, 21-26 August 2005, 8 p.

Schilling W., Bertrand-Krajewski J.-L., Eiswirth M., Krebs P., Saegrov S., Thévenot D. (2002). Integrated Urban Water Management Approaches: CityNet. *International Conference "AQUAECO : Science in support of European water policies - Sustainability of aquatic ecosystems"*, Stresa, Italy, 26-28 November, 4 p.