Quantification of sewer leakage - a review

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ABSTRACT
One of the goals of the APUSS project (Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems) is to assess sewer exfiltration, in order to support cities and operators to define problem-oriented rehabilitation strategies. In this paper, we review various methods currently used for the estimation of exfiltration and discuss data needs and applicability for rehabilitation planning. Although, each approach has its individual advantages and drawbacks, we identified pressure tests and tracer methods to have the highest potential for decision support in rehabilitation planning. With regard to future challenges (e.g. micro pollutants) such methods might play a key role in integrated sewer management.

KEYWORDS
Sewer leakage; exfiltration; groundwater recharge; rehabilitation management

INTRODUCTION
Sewer deterioration and the associated problems of waste water leakage became more and more aware within the last decades. Concerning amount and significance of exfiltration two contradictory viewpoints can be found.

- The overall impact of exfiltration from urban sewers does not appear that severe (Barrett et al., 1997, Vollertsen and Hvitved-Jacobsen, 2003). Exfiltration expressed as a percentage of dry-weather flow (dwf) is estimated as being less than 1-5% (i.e. Fenz, 2003), respectively.
- The exfiltration of wastewater causes significant impacts on soil and groundwater. Eiswirth et al. (1997) specify leaky sewers as the main source of groundwater contamination, even though the impacts of exfiltrating wastewater on groundwater seem to be strongly variable. With a Nitrogen balance in groundwater Wakida and Lerner (2005) identified an exfiltration rate of 13 %. Ellis et al. (2003) postulate exfiltration rates of 5-10 % dwf flow based on laboratory investigations.

Recently, concern on sewer leakage is being driven by future problems due to new pollutants (e.g. the environmental and human health risk associated with endocrine disrupters) and high investment cost for rehabilitation of sewers due to their increasing age. Hence, investigations of exfiltration deal on one hand with a quantification of exfiltrating water volume. On the other hand, advanced issues as risk assessment of the environmental hazards of exfiltration and the fraction of urban groundwater recharge are investigated. In this review, we describe different approaches to quantify exfiltration from leaky sewers and discuss their suitability for rational rehabilitation planning. For this purpose, we classify the methods as "indirect" and "direct" approaches, distinguishing the direct methods further into field and laboratory studies. Important aspects, such as data needs and limitations are pointed out. As in most strategic planning with considerable investments, urban water managers often face incomplete or uncertain information. Therefore, we especially consider the uncertainty associated with the measurement results to provide a thorough basis for the assessment of suitability of the individual methods for distinct rehabilitation concerns.

METHODS

Indirect methods use information on exfiltration as part of urban recharge from groundwater monitoring and/or a water and solute mass balance of the considered catchment to evaluate effects of exfiltration on groundwater quality. This provides an average figure of sewer leakage on the catchment scale. Direct methods perform pressure tests of single pipes or damages or balance tracer substances within a certain sewer distance. A special case of the direct methods are laboratory investigations which are conducted at pipe scale on test rigs. We present results from 6 indirect methods and 6 direct methods, 3 of which were performed in the laboratory.

Indirect Methods

Groundwater modelling: For estimating urban recharge Lerner (2002) recommends a holistic approach with a calibrated groundwater flow model and additional solute balances, as complexity of cities and scarcity of data lead to high uncertainties in quantifying urban recharge. In this context, Yang et al. (1999) presented an investigation in the City of Nottingham, UK. They focused on spatial and temporal quantification of the main contributions to total recharge: precipitation, leakage from water mains and sewage exfiltration. A groundwater flow model to estimate total recharge was calibrated using historical data. Additionally, solute balances for Chloride, Sulphate and total Nitrogen were considered, partly based on historical data, partly based on groundwater sampling. Estimated exfiltration rates for the period 1958 to 1995 lead to a mean value of 10 mm/year. This represents 5% of the total recharge. For the same area and data, Wakida and Lerner (2005) point out that 13 % of the nitrogen load in groundwater is due to sewer leakage. Barrett et al. (1997) performed a large scale groundwater sampling campaign in the City of Nottingham, UK. They propose a combination of stable nitrogen isotopes and microbiological indicators as most effective parameters to for the quantification of recharge by sewer leakage. Their investigations give evidence for the presence of sewage in shallow groundwater (2-6 m below surface). Location and amount of the point source sewage exfiltration could not be located precisely. Fenz et al. (2004) combined groundwater flow modelling with monitoring of the antiepileptic drug carbamazepine. Drug concentration in groundwater and waste water in the City of Linz, Austria was under inverstigation. Carbamazepine is discharged only via domestic waste water. The average carbamazepine load per capita was calculated from measurements at the waste water treatment plant and compared to the carbamazepine load in groundwater. The average exfiltration rate amounts to 1% dwf. Wolf (2004) performed sampling campaigns covering sewage, groundwater and surface water in Rastatt, Germany, to investigate on the suitability of various chemical signatures to detect exfiltration from leaky sewers. Additional information was obtained by closed-circuit-television (CCTV) investigations and pressure tests at selected single damage sites. Significant exfiltration of waste water into the urban aquifer was reported, but regional exfiltration rates were not reported.

Water balance from flow measurements: Trauth et al. (1995) focus on the water balance of a small urban catchment. Inputs are rainfall runoff, drinking-water consumption, sewage flow data and information on the behaviour of the inhabitants. For an interval of 10 days, exfiltration rates cover a range of 0.018 – 0.046 l/s/km. Karpf and Krebs (2004b) transferred their leakage model of infiltration (Karpf and Krebs, 2004a) to the exfiltration process. The estimation of the groundwater level at each pipe and the groundwater-influenced pipe surface of the sewer is based on interpolation of groundwater measurements, the water level in the sewer is simulated with a hydrodynamic model. Infiltration was assessed by comparing wastewater flow to average drinking water consumption. The calibration of the leakage model requires long time-series, from which the history of each pipe is analyzed to identify a mean leakage factor. For the years 1997 to 1999, the simulated exfiltration rate ranges from 1.3% to 3.8% of the dry-weather flow.

Assessment of uncertainty: It must be assumed that all the results of the introduced studies are subject to high uncertainties due to incomplete or uncertain input data (soil structure, hydraulic conductivity, groundwater levels) as well as model structure uncertainty and sampling errors. Yang et al. (1999) present the only study on catchment scale with comments on the sensitivity of its results to input parameter variability. They estimate the confidence interval to be 100% (single standard deviation), which might be attributed to scarce groundwater quality data and insufficient information on the local variability of the sewage composition, due to discrete sampling techniques.

Direct Methods

Laboratory investigations are being performed on many types of pilot plants from soil columns to specific test rigs. The former are used to investigate the process of colmation and soil clogging, whereas test rigs allow to simulate exfiltration in order to correlate exfiltration rates to specific types of pipe damages. We concentrate on observations carried out in test rigs. For laboratory investigations, boundary conditions such as soil, size and location of damages, waste water composition and water level are known and thus reduce the uncertainty of the evaluation.

Laboratory investigations: Vollertsen and Hvitved-Jacobsen (2003) investigated the behaviour of leaks during constant flow conditions and effects of flow variations, different sizes and types of leaks and alternating infiltration/exfiltration in a test rig. Open joints exhibit an average exfiltration rate of 0.02 l/d/cm², cracks 0.06 l/d/cm². The exfiltration rate showed a rapid decrease and reached a more or less constant rate after a few hours. The comparison of different soil types showed no systematic dependency of the exfiltration rates. A reduction of soil permeability was not detected, although the decreasing exfiltration rate was attributed to a clogging zone with a relatively high concentration of organic matter. The exfiltration rate increased with increasing water pressure and leakage area. A similar development was observed by Blackwood et al. (2005), with observed exfiltration rates ranging form 100 – 10 l/d/cm² of the dry-weather flow. The study of Rauch and Stegner (1994) proposed the Darcy equation to describe the percolation process. Exfiltration rates measured with constant soil conditions, constant leak area (15 cm²), and constant amount of settleable solids are shown in Table 1.

Assessment of uncertainty: None of the mentioned laboratory scale investigations includes an assessment of uncertainty of the results.

Table 1: Exfiltration rates measured by Rauch and Stegner (1994)

Water level [m]	Exfiltration rate [l/d/cm²]
0.02	0.87
0.07	2.87
0.12	5.2

Field investigations (pipe scale): Ullmann (1994) observed exfiltration at an army base in Veitshöchheim, Germany, using pressure tests as well as soil and groundwater sampling. He obtained exfiltration rates ranging from 0 to 540 l/d/leak for half-filled sewers. The exfiltration rate cannot be expressed in l/d/cm² to compare it to other results. Dohmann et al. (1999) studied the exfiltration rate by conducting pressure tests in 68 sewers under operation. Exfiltration rates were calculated for particular damages, known from CCTV records. One important result was that a certain pressure head was required to start the exfiltration process. This effect was attributed to a temporary sealing in the sewer caused by sediments and bio films. A small exfiltration rate was observed in case of low pressure, followed by a fast and strong increase of the exfiltration rate with rising pressure. Dohmanns findings confirm the results of laboratory studies, which indicate that exfiltration is a very dynamic process that varies from defect to defect. Although clean water was used for testing, the exfiltration rates obtained were claimed comparable to those of wastewater. Laboratory studies of the same author claim no significant difference between the exfiltration rates of waste water and clean water (Dohmann et al. 1999). Table 2 gives mean exfiltration rates obtained from low pressure tests, i.e., the tested pipe was half-filled at maximum.

Table 2: Exfiltration rates at dry-weather flow conditions (Dohmann et al., 1999)

Damage	Exfiltration rate [l/d/cm²]
crack (invert, right)	1.1
crack (crown, right, left)	0.4
crack (circumference)	0.5
deviation	0.04

Field investigations (reach scale): The integrated sewer leakage from a whole sewer reach can be measured by tracer experiments (Knudsen et al., 1996, Rieckermann et al., 2005a, b). Precisely-known amounts of tracer are injected at the beginning and at the end of the investigated sewer. The mass balance over the investigation reach can then be computed from downstream samples. Given the tracer is equally diluted in waste water, any tracer loss is directly correlated to the leakage in the reach. Exfiltration, which is computed as a ratio relative to the labelled flow, is systematically wrong if the tracer concentrations are reduced or magnified in the sewer reach. Similarly, one has to account for a substantial random error if the analysis of the tracers in wastewater is not very precise. Within the APUSS project two methods have been developed that avoid systematic errors by an efficient experimental design and rigorously assess the uncertainty in the obtained results (Rieckermann et al., 2005a, b). Both methods were applied under a variety of conditions in different European cities and it was found that uncertainty of exfiltration ratio is in the order of a few percent of the labelled flow, but often depends on the specific conditions at the experimental site (Prigiobbe, 2004, Rutsch and Krebs, in prep. 2005).

Assessment of uncertainty: None of the mentioned field investigations on pipe scale included an assessment of uncertainty of the results. Dohmann et al. (1999) documented the uncertainty of measuring devices, however, an uncertainty analysis was not performed. On the reach scale, the two tracer methods developed in the APUSS project (Rieckermann et al., 2005a, b) routinely assess uncertainty by Monte Carlo simulations and Gaussian error propagation.

RESULTS

Table 3 shows a compilation of the methods currently used for estimating exfiltration, evaluated according to data needs, applicability, and support for rehabilitation planning. All methods except Barrett et al. and Wolf deliver exfiltration rates.

Table 3: Compilation of approaches

Study	Method	Aim	Result	Assessment of Uncertainty	Data needs	Decision support potential
Yang et al. (1999)	Groundwater flow modelling, solute balances (catchment scale)	Spatial and temporal amounts of urban recharge	10 mm/year (±100 %)	Sensitivity of target solute concentrations to changes of mains and sewer recharge	Time series of groundwater flow and quality	low
Barrett et al. (1997)	Groundwater sampling (catchment scale)	Spatial and temporal amounts of urban recharge	Qualitative statement on sewer leakage	-	groundwater flow and quality, sewage flow and quality, rainfall, river flow and quality, and mains water flow and quality	low
Fenz et al. (2004)	Groundwater flow modelling, solute balances (catchment scale)	Identification and quantification of exfiltration	1% dwf	-	groundwater flow and quality	low
Wolf (2004)	Link of pipe information, hydrogeology, and solute balances (catchment scale)	Quantification, feasibility of marker species	Significance of exfiltration proved	-	CCTV data, groundwater flow and quality, hydrogeological data	medium
Trauth et al, (1995)	Balancing time series (catchment scale)	Quantification of ex- and infiltration	0.018-0.46 l/s/km	-	Sewage flow and drinking water consumption, rain data	low
Karpf and Krebs (2004)	Balancing time series (catchment scale)	Quantification of exfiltration	2.8% dwf	-	Long time series of sewerage flow and drinking water consumption, groundwater levels	medium
Ullmann (1994)	Pressure tests, soil and groundwater sampling (pipe scale)	Quantification, inspection and rehabilitation planning	0-9.66 l/d/joint 0- l/d/m	-	CCTV data, groundwater quality	high
Dohmann et al. (1999)	Pressure tests with clean water (pipe scale)	Quantification, Correlation exfiltration-damage	0.04-1.1 l/d/cm²	-	CCTV data	high
Rieckermann et al. (2005)	Balance of artificial tracer load (reach scale)	Quantification and assessment of uncertainty	11% dwf (± 2%)	Monte Carlo simulations, Gaussian error propagation	Experimental data (tracer, flow, laboratory analysis) for uncertainty analysis	high
Rutsch and Krebs. (in prep. 2005)	Balance of artificial tracer load (reach scale)	Quantification and assessment of uncertainty	5-20 % dwf (± 30%) 7-150 l/d/cm²	Monte Carlo simulations, Gaussian error propagation	Experimental data (tracer, flow, laboratory analysis) for uncertainty analysis	high
Vollertsen and Hvitved-Jacobsen (2003)	Circling waste water through leaky pipe (laboratory scale)	Quality and Quantity of exfiltrating water	0.02-0.06 l/d/cm²	-	-	none
Blackwood et al. (2005)	Circling waste water through leaky pipe (laboratory scale)	Quantification and effects of bedding	100-10 l/d/cm²	-	-	none
Rauch and Stegner (1994)	Flowing waste water through leaky pipe (laboratory scale)	Process description, quantification of exfiltration	0.87-5.2 l/d/cm²	-	-	none

Large scale investigation

Within large scale investigation sites, areas primarily affected by exfiltration can be identified by well-calibrated groundwater flow models. By making use of groundwater samples from piezometers at sites of interest, a qualitative evaluation of the recharge source is possible.

However, due to the data needs for groundwater modelling this approach is often considered too cost intensive to be applied as a standard method for rehabilitation planning. Also, within areas of heterogeneous aquifers, calibration of a detailed groundwater flow model might not be feasible due to the lack of detailed soil hydraulic properties. Avoiding these difficulties, Karpf and Krebs (2004 a, b) use time series analysis of flow data and identify large diameter sewers as the main source of exfiltration in their catchment. This is due to the high water levels and thus large wetted perimeter. However, a very comprehensive data base is required. From groundwater sampling Barrett et al. (1997) conclude that house connections are the main source of groundwater contamination. As the above findings are contradictory, we conclude that decision support for rehabilitation planning appears to be specific to particular investigation sites and cannot be generalized.

Pipe scale investigations

Observations at the pipe scale require CCTV records to pre-select appropriate sewer sections for investigation. Preliminary groundwater quality monitoring can be used to focus on areas affected by sewage exfiltration. The pipe scale investigations aim at finding a correlation between sewer damage type and exfiltration rates. Extensive testing revealed that an accurate prediction of exfiltration rates on the base of CCTV records is most likely to fail. Processes of biological clogging or colmation have significantly more influence on exfiltration rates than a specific type of sewer damage. Therefore, exfiltration rates of single investigated damages are difficult to extrapolate to overall exfiltration rates. Pressure testing of a certain sewer distance would give integral information, which might lead to a better transferability of exfiltration rates but requires significant effort and expensive hardware. Nevertheless, for rehabilitation planning it would be of outstanding importance if direct correlations of CCTV recorded damages and exfiltration rates would be available. However, it would be indispensable to be provided with detailed assessment of the uncertainty of the involved methods, measuring devices and model input data. The advantage of the presented laboratory investigations is that variability can be reduced by choosing specific boundary conditions. This makes such kind of studies attractive, because the underlying processes of exfiltration can be identified most accurately and detailed. For the existing studies it is though not yet known if the special laboratory conditions regarding damage types and especially the artificial soil conditions allow transferring the findings to real-world sewer systems.

Reach scale investigations

Possible investigation sites are pre-selected by information of the sewerage operators. CCTV records are only required if details on location of damages are needed and for a plausibility test of the results. With the obtained exfiltration rate and its uncertainty operators decide whether a rehabilitation of the sewer is necessary. Succeeding CCTV or pressure testing may indicate the exact locations of the actual damage. The accuracy of results can be adjusted to the user's requirements by a careful experimental design. For sensitive areas, such as sewer pipes in drinking water protection areas, experimental layouts can be set up with repetitive measurements and different tracer substances. As the uncertainty analysis formally assesses the level of confidence in the obtained results, the decision for or against sewer rehabilitation can be taken on a more scientific basis. Conducting a measurement is relatively quick and thus cost-effective. Yet, accurate measurements in the sewer environment are not trivial. Installation of measuring devices demands skilled personnel to operate equipment specially designed to match the requirements in the sewer. To obtain optimal results, a detailed examination of the site including preliminary flow measurements and tracer background recordings is necessary. In the APUSS project we found that the actual performance of the methods depends on the location and suitable boundary conditions. As a tracer test is performed over a distance of several 100 m, the hydraulic property of a sewer network might lead to difficulties in the correct interpretation of the results.

DISCUSSION

Methods suitable for rehabilitation planning: Groundwater flow modelling, coupled with solute balances alone provides a rather broad view on urban recharge, and in particular sewer exfiltration. It is difficult to downsize the result to a specific reach of interest to obtain information for rehabilitation planning. Furthermore, sewers can often not be singled out as the only source of pollution. In any case, a simple balance of sewerage flow, rainfall data, and drinking water consumption appears to be unsuitable to support rehabilitation planning due to the large uncertainty of the measured flow and rainfall data. The common indirect approaches are based on many more or less uncertain assumptions, so that it appears difficult to draw overall conclusions. Furthermore the local variability of the dominating processes is not considered. Direct methods on the pipe scale rely on small scale information such as CCTV records or asset data. To draw conclusion on general sewer leakage from CCTV records and pressure tests might overestimate the exfiltration rate, as not all damages are necessarily leaky (Vollertsen and Hvitved-Jacobsen, 2003). They suggest to compute a maximum exfiltration rate that would contribute to risk assessment. CCTV and asset data are assumed to contain as much uncertainty as groundwater information, and flow measurements in real sewers are subject to large systematic and random measurement errors. Regrettably, only few detailed analysis of uncertainty of the computed exfiltration is reported in literature. Tracer measurements require a high accuracy but provide an exfiltration rate over a certain sewer distance including an uncertainty analysis. Laboratory investigations specify the processes of exfiltration and succeeding colmation. This provides understanding of mechanisms under controlled conditions; however, it is often difficult to transfer the results to real sewers.

Is exfiltration from sewers relevant? In the past, rehabilitation planning mainly focused on structural integrity and sufficient hydraulic capacity of the sewer system. In order to take into account the pollution potential of exfiltrating waste water with its impact on public health, an integrated management approach for rehabilitation planning is urgently needed. Even if many studies indicate, that conventional pollutants are degraded to a certain degree (e.g. Dohmann et al., 1999, Hua et al., 2004), industrial pollutants (PAK), micropollutants and endocrine disruptors might pose a substantial risk to the environment and human health. The studies on catchment scale exhibit a wide range of sewer leakage from 1 to 13 % dwf. Further figures of exfiltration are 90 l/d/cm² (corresponding to 8% dwf) with tracer tests and 1.1 l/d/cm² (pressure tests). These results underline the strong variability of experiments in the sewer and the need of assessing uncertainties within the measurements. Results from laboratory tests, cover a large range from 0.02 to 100 l/d/cm². However, the practical use of such figures might lead to over-investments.

This study discusses methods which can be applied to investigate exfiltration from main sewers or whole catchments. Though, exfiltration from house connections cannot be identified with these tools. Interestingly, field investigations on the magnitude of this phenomena are scarce and models are lacking completely. One important reason might be severe practical difficulties in performing such investigations (ikt, 2003). For a large campaign of CCTV inspections and pressure tests of house connections in Göttingen, Germany, Ballweg (2002) reported that 92 % of the considered cases do not meet the criteria on pressure testing. However, this does not necessarily mean that under normal operating conditions these house connections are heavily leaking. To give a comprehensive description of waste water leakage, private sewers should be included in the regular schedule of sewer inspection and testing. This would not only lead to a more comprehensive view on the performance of sewer systems with regard to leakage and structural deterioration, but could also help clarifying whether decentralized systems are an alternative to present urban drainage systems.

CONCLUSION

To overcome problems of sewer leakage and possible contamination of water resources, integrated management of sewerage, drinking water mains, and water resources is required. Preliminary groundwater monitoring is an indispensable prerequisite for problem orientated rehabilitation planning in order to assess existing pollution. Once the level of impact of exfiltrating sewage on ground water is known, two methods can be applied to locate and evaluate the sources of exfiltration (leaky sewers). In a more catchment orientated approach a groundwater model can be used together with groundwater samples to describe the basin exfiltration characteristics. Starting from here, it is possible to downscale the area of impact with the aid of CCTV records. Then pressure tests can be used in a further step to assess the potential level of groundwater pollution from specific damages or sites. With a second, more site specific approach it is possible to directly measure exfiltration on the basis of tracer mass balancing. This approach is best suited for main sewers and to check on lines which are suspected to contribute to groundwater pollution. It is difficult to compare exfiltration rates, because the authors use a wide range of different exfiltration units which sometimes cannot be compared directly. A standardization of exfiltration units would lead to a better comparability of methods and uncertainties, bringing benefit to all the researchers involved in this area.

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