Transferability of Exfiltration Rates from Sewer Systems

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Abstract

Background, Aim and Scope. Models describing in- and exfiltration of sewer systems require a large amount of data for calibration. These are often difficult and expensive to measure and to acquire. Therefore, this paper aims at clarifying whether results from various measurement campaigns might be joined to broaden the basis of an exfiltration model. Within this context, the transferability of exfiltration rates from one sewer (or catchment) to another is one of the crucial points.

Materials and Methods. Exfiltration rates derived from field measurements and from literature (field and laboratory investigations) are compared with respect to

- Catchment characteristics
- Applied methods: tracer tests, blocking tests, and laboratory investigations
- Experimental site: laboratory and field studies
- Leakage area: Closed-circuit television (CCTV) serves as a substitute for sewer characteristics. From those records the leakage area is obtained calculating an exfiltration rate per day and cm² leakage area.

Exfiltration was measured in two catchments and the findings were compared with published data for two catchments and two laboratory studies. As expected, exfiltration rates exhibit a wide range. We investigated whether the experimental design dominates the variance of measured data. The results are compared by means of statistical methods (Kruskal-Wallis analysis of ranks, Bootstrapping, and analysis of covariance-ANCOVA) to reveal significant differences in means.

Results. The statistical analysis yields significant differences in exfiltration rates comparing the results obtained (i) in either field or laboratory and (ii) with different methods. Exfiltration rates measured in various catchments are not significantly different.

Discussion. It can be shown that exfiltration rates obtained from field studies are affected by the measurement technique, whereas for laboratory investigations, the measurement technique does not influence the result in the first place. It is therefore difficult to jointly analyse laboratory and field experiments, i.e. a transfer of exfiltration rates from laboratory investigations to operational sewers is hardly feasible. It is also shown that results from different catchments are better suited for a joint assessment than results from differing methods.

Conclusions. A joint assessment of exfiltration rates obtained in various studies is not feasible with the available datasets.

Recommendations and Perspectives. A standardisation of methods would allow for optimal analysis of exfiltration rates measured by different researchers or operators.

Keywords: Exfiltration; experimental design; sewer leakage; sewerage; significance test; transferability; variability

Introduction

Sewer leakage encompasses two distinct processes: there is infiltration of groundwater into the pipe, and exfiltration of wastewater from pipes into soil and groundwater. If we want to understand the impact of exfiltration on soil and groundwater, we need to receive more detailed attention. In this context, Hornef (1983) and Bishop (1998) claim exfiltrating wastewater from sewers a major source of groundwater contamination. Nevertheless, the impact of exfiltrating wastewater on groundwater is strongly variable depending on the permeability and length of the soil passage (e.g. Eiswirth and Hötzl 1997, Ellis and Revitt 2002). Exfiltration on the large scale has been estimated by groundwater monitoring and modelling (Fenz et al. 2005, Yang et al. 1999) and balancing wastewater flow and drinking water consumption (Amick and Burgess 2000, Karpf and Krebs 2005). Exfiltration on the pipe scale has been studied by means of pressure tests (Dohmann et al. 1999, Ullmann 1994), exhibiting exfiltration rates of 0.04 to 109 l/d·cm⁻². Tracer tests published by Rieckermann et al. (2005, submitted) and Rutsch (2006) report exfiltration rates from 2 to 167 l/d·cm⁻². Laboratory tests, which have been conducted on test rigs cover ranges of 0.02 to 86 l/d·cm⁻² (Rauch and Stegner 1994, Vollandt and Hvitved-Jacobsen 2003, Blackwood et al. 2005). The international discussion on sewer leakage clearly shows that we are yet lacking understanding of processes regarding i) the quantity of leakage and ii) the impact of sewer leakage on the environment. Although several studies...
provide data on exfiltration from leaky sewers, the amount of data in each study does not suffice to give a general statement on sewer exfiltration or to identify a valid parameter set of a model describing exfiltration.

In order to overcome the hurdle of small numbers of available consistent measurements we tested whether the fusion of results from different studies on exfiltration leads to a reliable singular model. The question arises if a combination of exfiltration data from different studies is possible in order to increase the information content regarding exfiltration. Alongside differing catchment characteristics, the varying experimental design of the studies makes it difficult to compare the results. In this study, we therefore focus on the following questions:

- Are the mean exfiltration rates significantly different in different catchments?
- Does experimental design significantly affect exfiltration rates?

The answer to these questions yields information on the possibility of a joint analysis of exfiltration rates obtained in different studies and might also help to identify the variables that most affect exfiltration.

1 Material and Methods

1.1 Data

63 experiments on exfiltration derived from own field measurements and from literature (field and laboratory investigations) in different catchments are analysed in the following investigations. Blocking tests and gravitational tests in field and laboratory were considered. The dependent variable is the exfiltration rate \([\text{ld}^{-1}\text{cm}^{-2}]\), with the leakage area as one possible predictor variable. The results used in this examination have been selected according to the data availability within the reported results in literature, in particular the experimental design and the leakage area. The selected predictor variables are: catchment, method, and location. Table 1 details predictor variables, number of measurements, and mean exfiltration rate for the particular catchment.

Exfiltration rates are compared with respect to the following predictor variables and objectives:

Catchment. Measurements were performed within the five catchments named in the first column in Table 1. AAC, VEIT, LR, and MAL are 4 homogeneous catchments exhibiting different pipe and catchment characteristics, LAB are laboratory measurements. The intention here is to see whether the variable catchment significantly affects wastewater exfiltration.

Method. Blocking tests are realized by blocking the upstream and downstream side of the sewer pipe, observing the water level decrease over time. Gravitational tests are tests under normal flow conditions. Gravitational tests conducted in laboratory test rigs determine water loss according to the backfill composition and the damages in the pipe, arranged as a pipe with circulating wastewater. Gravitational tests in sewers are tracer tests providing the fraction of tracer which is lost from a sewer line according to the damages (recorded by visual inspection) and the wastewater flow in the pipe (Rieckermann et al. 2005, submitted).

Location. Laboratory test rigs and their simulated damages cannot represent the proportions of real sewer systems and soil conditions are different as well. However, in long term laboratory investigations soil conditions can approximate the soil conditions below sewers. Field studies always require a high effort to obtain reliable results, this is particularly the case in hostile sewer environments. Overall, the varying experimental setup makes it difficult to compare the results. Hence, results from laboratory studies have been tested to ascertain whether they differ significantly from field studies.

1.2 Significance testing with non-parametric statistics

Non-parametric tests are applied to analyse the dependent variable (leakage rate) for small samples and for variables with an unknown distribution. Non-parametric tests are assumed to have less statistical power than parametric tests. This is due to the smaller number of samples and the use of only the ordinal information of data (Bortz et al. 2000, Conover 1999). The selected non-parametric tests (Mann-Whitney u-test, analysing 2 independent samples, and Kruskal Wallis analysis for more than two independent samples) compare the pre-assigned ranks of the values rather than the values for the dependent variable. The Mann-Whitney u-test serves, on the one hand, as a means of determining reasonable intervals to describe the data, i.e., if two adjacent groups do not differ significantly (the groups yield similar results and \(H_0\) hypothesis is corroborated), both groups can be merged into one group. The effect of a variable on

| Table 1: Summary of data, dependent variable exfiltration rate \([\text{ld}^{-1}\text{cm}^{-2}]\) |
|-----------------|---------------|--------------|--------|----------|--------------|
| Catchment       | Method        | Location     | No. of runs | Mean    | Standard deviation |
| AAC a           | Blocking      | Sewer        | 7       | 42.12   | 36.26        |
| LAB1 ab         | Blocking      | Laboratory   | 4       | 0.626   | 0.706        |
| LAB2 a          | Gravitational | Laboratory   | 18      | 1.85    | 3.29         |
| VEIT c          | Blocking      | Sewer        | 20      | 12.05   | 18.61        |
| LR c            | Gravitational | Sewer        | 8       | 96.17   | 72.09        |
| MAL d           | Gravitational | Sewer        | 5       | 77.04   | 64.96        |

a Dohmann et al. 1999 
b Krug 2005 
c Ullmann 1994 
d own measurements