A new sewage exfiltration model - parameters and calibration

Paramètres et étalonnage d'un nouveau modèle d'exfiltration des réseaux d'assainissement

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RÉSUMÉ

L'exfiltration d'eaux usées des systèmes d'égout représente un danger potentiel pour le sol et l'aquifère. Les modèles utilisés pour décrire le processus d'exfiltration, sont basés sur la loi de Darcy, et une considération plus ou moins détaillée de l'accroissement des fuites, les caractéristiques du sol et de la couche de saleté. Mais, en raison de la complexité du processus d'exfiltration, le calibrage de ces modèles inclut une incertitude significative. Ce papier présente une nouvelle approche de l'exfiltration, qui met en œuvre la dynamique du processus d'obstruction et les conditions structurelles proches des fuites d'égout. Le calibrage est effectué selon les études expérimentales et l'analyse d'infiltration de nappe phréatique aux égouts. En outre, les taux d'exfiltration et la sensibilité de l'approche sont estimés et évalués, respectivement, par les simulations de Monte-Carlo

ABSTRACT

Exfiltration of waste water from sewer systems represents a potential danger for the soil and the aquifer. Common models, which are used to describe the exfiltration process, are based on the law of Darcy, extended by a more or less detailed consideration of the expansion of leaks, the characteristics of the soil and the colmation layer. But, due to the complexity of the exfiltration process, the calibration of these models includes a significant uncertainty. In the paper, a new exfiltration approach is introduced, which implements the dynamics of the clogging process and the structural conditions near sewer leaks. The calibration is realised according to experimental studies and analysis of groundwater infiltration to sewers. Furthermore, exfiltration rates and the sensitivity of the approach are estimated and evaluated, respectively, by Monte-Carlo-Simulations.

KEYWORDS

Sewage, exfiltration, modelling, parameter, sensitivity, Monte-Carlo-simulation

1 INTRODUCTION

The exfiltration of sewerage water can deteriorate groundwater and soil quality. This represents a potential danger if the respective aquifer is used for water supply or irrigation purposes. Besides the loads of organic matter, ammonia and phosphorous the ecosystem is endangered by micro pollutants (e.g. pharmaceutical products and their derivatives) and pathogenic germs. The estimation of sewage exfiltration requires estimations of quantities and their spatial and temporal distribution. Exfiltration rates can be measured and modelled. Measuring methods (Rutsch et al., 2006) provide direct information about quantities of local exfiltration and can be used to calibrate and verify models for further examinations. But, normally measures are costly and the uncertainties are high.

Exfiltration models open up the potential to estimate and predict the dynamics, location and quantities of sewage exfiltration on different scales. Available approaches to model exfiltration rates are based on relatively simple approaches (Rauch and Stegner, 1994; de Silva et a., 2004; Klinger et al., 2005). In common approaches, clogging and break-up processes of the soil layer surrounding the sewer leaks are not implemented. Further, calibration and verification of exfiltration models are difficult due to a lack of knowledge about realistic exfiltration rates.

In order to improve the exfiltration modelling, a new approach was developed which includes the dynamics of the clogging layer in the vicinity of the sewer leaks. Further, information on the structural leakiness of pipes deduced from groundwater *infiltration* analysis, is included in the approach. By Monte-Carlo-Simulation the sensitivity characteristics of the approach is analysed. The paper shows the complexity of exfiltration hydraulics and how modelling can be managed on the basis of available data.

2 MATERIALS AND METHODS

In the following, the basics of the new exfiltration model concept are introduced. Further, data and methods, which were used for model and parameter identification will be presented.

2.1 Model concept and calibration

The basic equation of the exfiltration model is the Darcy equation (Eq.1).

$$Q_{EX} = \frac{K_C}{Z_C} \cdot \Delta H \cdot A_L = K_{EX} \cdot \Delta H \cdot L$$

$$K_{EX} = \frac{K_C}{Z_C} \cdot A_L = K_{EX,dynamic} \cdot K_{EX,sturctural} \qquad (1)$$

The exfiltration process is controlled by the potential height (ΔH), the leak area (A_L), the length of the sewer pipes (L), the hydraulic conductivity (K_C) and the thickness (Z_C) of the colmation layer between pipe and backfill material. The potential height depends on the water level in the sewer pipes (gravitation potential) and the matrix potential of the soil (Beal et al., 2004; Karpf et al., 2009).

Due to the lack of data regarding the leak properties and colmation parameters an integral exfiltration factor K_{EX} is introduced, which consists of a dynamic and a structural (non dynamic) component. The dynamic component of the exfiltration process is characterised by clogging and break-up processes of the colmation layer. The structural component includes the leak area, backfill and soil properties, which are stable during a certain period.

A direct calibration of the exfiltration factor K_{EX} and its subcomponents are not possible. Thus, experimental data will be used to describe the processes. Further, groundwater infiltration analyses are used to identify structural parameters, which are relevant for sewer leakiness.

2.2 Data

For deducing the parameter K_{EX}, data of experimental studies (Karpf et al., 2009) and groundwater infiltration analysis in the investigation area - the sewer catchment of the city of Dresden (Karpf and Krebs, in preparation-b) are used. An overview about the database and the use of it is given in Tab. 1.

Table 1: Basic data

Data	Use
exfiltration fluxes measured in laboratory experiments (Karpf et al., 2009) with - varying soils - varying boundary conditions (potential heights / saturation)	- description of the colmation process on empirical basis
infiltration fluxes based on MODFLOW–simulations (Karpf and Krebs, in preparation -a) with - varying leak structure (extension of leaks) - varying trench and soil properties (hydraulic conductivity of soil and backfill) infiltration analysis (Karpf and Krebs, in preparation-b)	- empirics-based description of the leak area
Dresden sewer network data - structural data - long-term simulations in sub-catchments	- distribution of input data of Monte-Carlo-Simulations

2.3 Statistical Methods

For the calibration of the colmation model, a non-linear regression method, which is based on the least-squares-approach, was applied. Furthermore, Monte-Carlo-Simulations, where the events space is represented by ranges and distributions of input parameters and a high number of combinations of them as inputs to simulations, were performed in order to estimate the sensitivity of the developed exfiltration approach.

The regression analysis and the MC-simulations were realised with the statistics software R (Crawley, 2008).

3 RESULTS

3.1 Identification of parameters and processes

3.1.1 Leak area

The leak area A_L (m^2m^{-1}) is expressed by an empirical non-linear approach (Eq. 2) according to infiltration analysis by MODFLOW-simulations (Karpf and Krebs, in preparation-a). The leak-area approach was developed for quadratic leak shapes (standardized leak shape) and is based on the infiltration factor K_{IN},($m^2s^{-1}m^{-1}$), which represents an indicator for the pipe condition class (extent of damages). The infiltration factor can be deduced from groundwater and sewerage flow data (Karpf and Krebs, in preparation-b). Further, an empirical factor α integrates the hydraulic conductivities of the trench backfill ($K_{S,T}$ (ms^{-1})) and the natural soil ($K_{S,S}$ (ms^{-1})), the depth of the backfill below the sewer pipes (D_T (m)), the trench width (W_T in m) and the width of the quadratic standard leak (a (m)).

$$A_L = \alpha \cdot K_{IN}$$

$$\alpha = \frac{a^2}{\left(0{,}72 \cdot a^2 + 2{,}23 \cdot a - 0{,}01\right) \cdot K_{S,T} \cdot y}$$

$$K_{S,S} < K_{S,T} \rightarrow y = MIN\left[1 - \left(\frac{11{,}01 \cdot a^{0{,}55} - 0.76}{-76{,}75 \cdot D_T + 29{,}21 \cdot W_T + 57{,}09 \cdot \frac{K_{S,S}}{k_{S,T}} - 8{,}07}\right), 1\right]$$

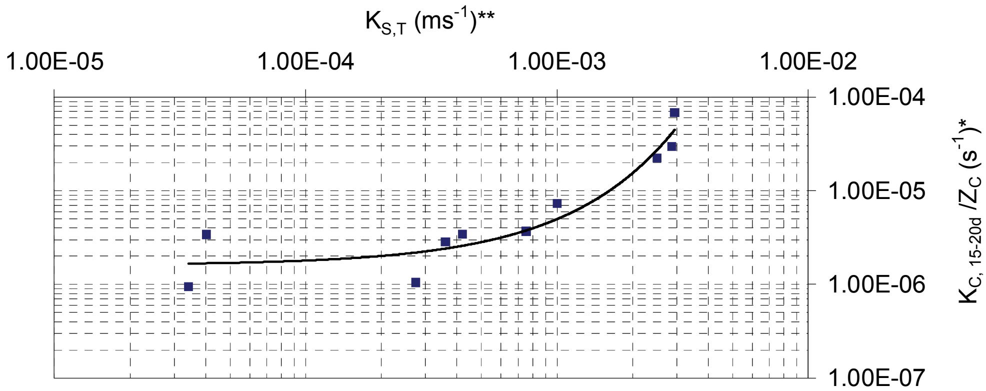
$$with \ \frac{K_{S,S}}{K_{S,T}} \geq 0.001 \qquad \frac{D_T}{W_T} \leq 0.2$$

$$for \ K_{S,S} = K_{S,T} \rightarrow y = 1 \tag{2}$$

3.1.2 Clogging process

Besides the examination of the potential height ΔH and its influence on the clogging process (Karpf et. al, 2009), the conductivity of the trench backfill was identified as a factor which has a major influence on the clogging process and thus the exfiltration rate. Fig. 1 illustrates an obvious increase of the leakage factor (K_C/Z_C) due to an increased hydraulic conductivity of the backfill. Further, it can be seen that the backfill conductivity must be higher than app. $5 \cdot 10^{-4}$ ms^{-1} to affect the clogging processes significantly (Fig. 1).

In order to build a clogging model, the colmation process was divided into two phases according to experimental results of Karpf et al. (2009). The first phase is characterised by a relatively rapid decrease of the exfiltration flow. Processes during the first phase are dominated by the physical clogging which is expressed by a combination of an exponential and a potential term (Eq. 3). The duration of the clogging process (T (d)) and the potential height (ΔH (m)) as an indicator for the initial flow were used as descriptors in the clogging approach (first phase of exfiltration rate decrease).



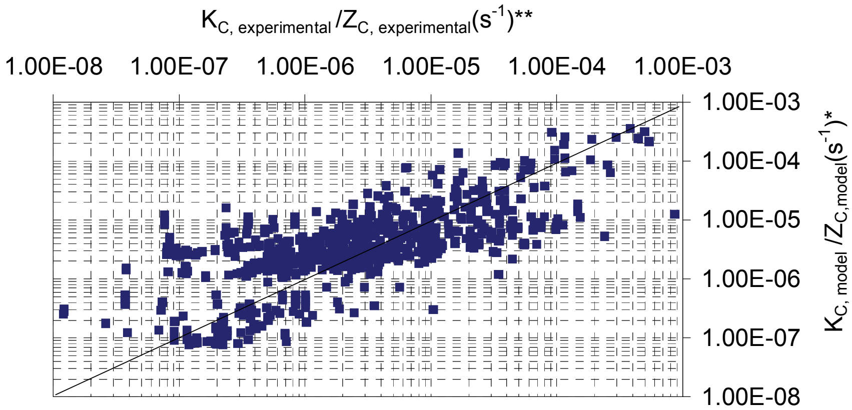
* mean leakage factor after 15-20 d clogging; ** hydraulic conductivity of the backfill
potential height: 0.1-0.2 m; maximum particle size of the waste water: 0,5 mm

Figure 1: Leakage factor (K_C/Z_C) and conductivity of the backfill

In the second phase, which is characterised by a slow decrease of of the exfiltration flow, a mixture of physical, chemical and biological processes during a longer period is considered (Karpf et al., 2009). Due to the different influences, which cannot be quantified separately, the process is simulated as a time-depended (T (d)) process (Eq. 3). The hydraulic conductivity $K_{S,T}$ (ms^{-1}) is decisive for the initial conditions of the clogging process and was described by a linear approach (Eq. 3).

$$\underbrace{\frac{K_C}{Z_C}}_{\text{leakage factor}} = \underbrace{(0{,}301 \cdot K_{S,T} + 0{,}00036)}_{\text{influence trench backfill conductivity}} \cdot \underbrace{e^{-9{,}19 \cdot Min(T,1) \cdot \Delta H} \cdot \left[Min\left(Max(T,1),3\right)\right]^{-1.73}}_{\text{first phase of the clogging process}} \cdot \underbrace{\left[\max(T-2,1)\right]^{-0{,}722}}_{\text{second phase of the clogging process}} \qquad (3)$$

Figure 2 illustrates the model fit by comparing the leakage factors (K_C/Z_C) which are resulting from the experiments with the values calculated with Eq. 3. The scattering of the data points indicates the uncertainty of the approach.



* simulated leakage factor; ** measured leakage factor

Figure 2: Measured and simulated leakage factors

3.2 The exfiltration model components

In order to complete the introduced exfiltration model (Eq.1) the structural component of the exfiltration factor ($K_{EX, structural}$) is expressed by Eq. 4 according to the calculation of the leak area (Eq. 2) and the influence of the trench backfill conductivity (Eq. 3).

$$K_{EX,structural} = \alpha \cdot K_{IN} \cdot (0{,}301 \cdot K_{S,T} + 0{,}00036) \qquad (\alpha\text{: see Eq. 3}) \qquad (4)$$

The dynamic component of the exfiltration approach (Eq. 1) is expressed by the dynamic terms of Eq. 3 (Eq.5)

$$K_{EX,dynamic} = e^{-9{,}19 \cdot Min(T,1) \cdot \Delta H} \cdot \left[Min\left(Max(T,1),3\right)\right]^{-1.73} \cdot \left[\max(T-2,1)\right]^{-0{,}722} \qquad (5)$$

3.3 Monte-Carlo-Simulations

Monte-Carlo (MC) simulations are used to consider the variation and sensitivity of the exfiltration rates. Below, input data and results are presented.

3.3.1 Distribution of input data

The input data of the MC-simulations were deduced from sewer network data and groundwater infiltration data of the City of Dresden. Fig. 3 illustrates the distributions of the structural input data.

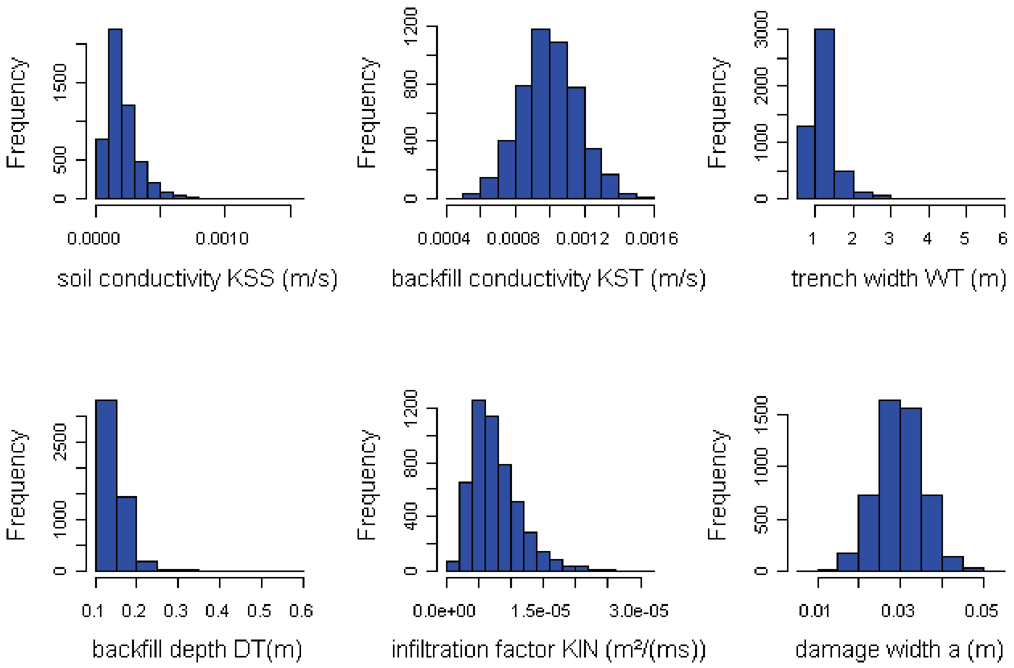


Figure 3: Structural Input data of the Monte-Carlo-Simulations

Trench widths W_T are calculated according to profiles and cross section areas of sewers and the German guidline ATV-DVWK (2001). The hydraulic conductivity of the soil $K_{S,S}$ was taken from a soil database. The distribution of infiltration factors K_{IN} was deduced according to infiltration analysis of Karpf and Krebs (in preparation-b). Finally, the damage width a of the quadratic standard leak in the sewer pipes was estimated on the basis of examinations by Wolf et al. (2006).

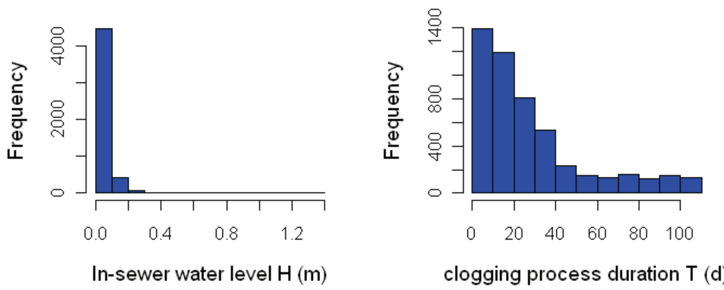
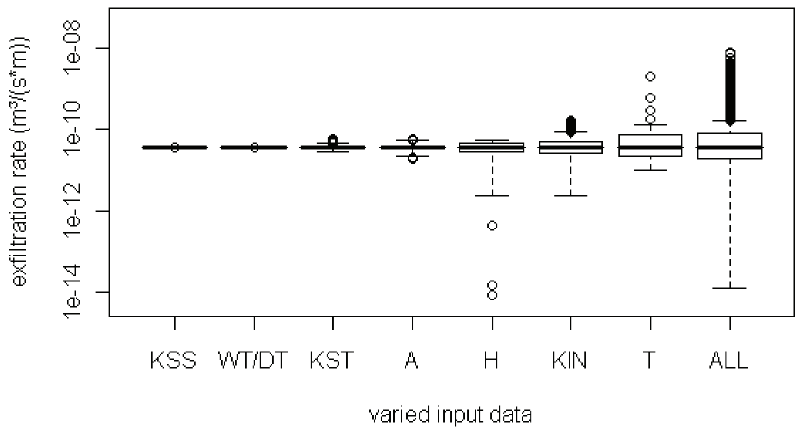


Figure 4: Distribution of input parameters, which influence the dynamics of the exfiltration process.

The distribution of the parameters, which influence the dynamics of the exfiltration factor are illustrated in Fig. 4. In-sewer water levels estimated with hydrodynamic simulations under dry-weather conditions. According to long-term simulations (1 year) in a sub-catchment the duration of the clogging process was estimated. According to increased shear stress during rain events and a possible break-up of the colmation layer a probable duration of the clogging process was estimated.

3.3.2 Exfiltration rates and sensitivity

In order to estimate the variation of exfiltration rates, 5000 simulations runs according to Eqs. 1, 4 and 5 were carried out with randomly combined input data sets. The sensitivity of the exfiltration approach induced by the variation of the input data was analysed by a systematic variation of these data. Results of the simulations are illustrated in Fig. 5.



KSS	hydraulic condictivity of the soil	A	leak width
KST	hydraulic condictivity of the backfill	T	duration of clogging
H	water level in the sewer	ALL	all input data
KIN	inflitration factor		
WT/ DT	trench width and depth below the sewer		

Figure 5: Exfiltration rates under dry-weather conditions as a consequence of variation of input data

It can be seen that the sensitivity of the exfiltration rate is low to nearly all structural input data (soil and backfill conductivity $K_{S,S}$ and $K_{S,T}$, trench measures W_T and D_T, damage width a). Merely the infiltration factor K_{IN} is proven to make the exfiltration rate react sensitively. Further, the calculations show that the dynamic input data (water level H and duration T of the clogging process) are important for the resulting exfiltration rates.

The mean value of exfiltration rates according to the distribution of all influencing input data (Figure 5, category: ALL) yields 12 $cm^3d^{-1}m^{-1}$. The 5% and 95% quantile value yield 0.65 and 44 $cm^3d^{-1}m^{-1}$, respectively, while the minimum and maximum values are 0.001 and 680 $cm^3d^{-1}m^{-1}$.

4 DISCUSSION

The new exfiltration approach integrates structural and dynamic influences. The approach consists of a rather detailed description of the leak area and the clogging process. In order to reflect the approaches structure transparently, the model parameters are distinguished into structural and dynamic parameters. Structural parameters are constant values which are deduced from structural conditions of the sewer pipes. Dynamic parameters depend on hydraulic conditions in the sewer pipes.

According to the sensitivity analysis it is shown, that the uncertainty of most structural properties does hardly influence the exfiltration calculation. Trench measures, the extension of the leak area and the hydraulic conductivity of the backfill can be estimated without significant impacts on the variance of the results. However, the backfill conductivity represents an important factor for the exfiltration process (Fig. 1), although, due to opposing effects of backfill conductivity within the leak area approach (Eq. 2) and the clogging process description (Eq. 3), its effects are dampened. In essence, through the complexity of the model approach there is no dominance of a single input parameter.

In summary, it can be stated that the infiltration factor, which characterises the condition of the pipes, the in-sewer water level, i.e. the potential height, and the duration of the clogging process should be estimated by suitable methods in order to minimize the uncertainty of simulated exfiltration rates. The infiltration factor can be calculated from groundwater infiltration data and to a certain extent also related to the pipe conditions (Karpf and Krebs, in preparation-b). Further, MC-simulations can be used to calculate the structural factor of the new exfiltration model (Eq.4) according to known structural parameters and estimations of parameters, which are not available. The potential height as a dynamic parameter can be gained from hydrodynamic modelling. The assessment of the duration of the clogging process is difficult. Break-up processes of the colmation layer are only considered qualitatively (Vollertson and Hvitved-Jacobsen, 2003; Ellis et al., 2003) and thus the duration of the clogging process and initial conditions of the re-clogging (values of the exfiltration factor after a break-up) are uncertain. Limits of boundary conditions (e.g shear stress), which control break-up and the re-clogging, must be estimated.

The simulated exfiltration rates during dry-weather conditions based on the varying input data give an idea of the quantities of exfiltration rates in a considered catchment. It is obvious, that the median value represents very low exfiltration rates with less than 0.1% of the dry-weather flow in the catchment of the city of Dresden. Thus, it may be questioned whether exfiltration is a relevant pollution source for groundwater and soil in this catchment. However, the quantification with the Monte-Carlo-simulations does not include the dynamics during rain events and floods. Further, local structural differences and boundary conditions are not considered by the applied method. In turn, local pollution effects might still be significant.

5 CONCLUSIONS

By combining experimental results and data of groundwater infiltration analysis, the Darcy model is extended to describe the exfiltration process in more detail. The following main conclusions can be drawn:

- The description of the exfiltration process can be improved by the combination of an experimentally deduced colmation approach and a leak-area approach, which is deduced from groundwater infiltration analysis. Essential parameters can be distinguished in structural and dynamic parameters.
- Trench measures, backfill conductivity and leak extension (damage width) have only a minor influence on the range of the simulated exfiltration rates.
- The potential height, the infiltration factor and the duration of the clogging process are crucial for the simulation of exfiltration rates.
- Based on hydrodynamic simulations the quantification and localisation of exfiltration rates can be improved. Simulations of scenarios will help to answer the question, whether the exfiltration of wastewater represents a relevant source of groundwater and soil pollution in a catchment.

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ACKNOWLEDGEMENTS

This work was supported by the German Research Foundation (DFG) within the project “Modelling of sewerage exfiltration with indicator parameters” (GZ: KR 2337/31). Also, the support of the City of Dresden is greatly acknowledged.