Application of a leakage model to assess exfiltration from sewers

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Abstract The exfiltration of wastewater from sewer systems in urban areas causes a deterioration of soil and possibly groundwater quality. Beside the simulation of transport and degradation processes in the unsaturated zone and in the aquifer the analysis of the potential impact requires the estimation of quantity and temporal variation of wastewater exfiltration. Exfiltration can be assessed by the application of a leakage model. The hydrological approach was originally developed to simulate the interactions between the groundwater and surface water, it was adapted to allow for modelling of interactions between groundwater and sewer system. In order to approximate the exfiltration specific model parameters infiltration specific parameters were used as a basis. Scenario analysis of the exfiltration in the City of Dresden from 1997 to 1999 and during the flood event in August 2002 shows the variation and the extent of exfiltration rates.

Keywords Wastewater exfiltration; leakage model; leakage factor; infiltration; groundwater level

Introduction
The exfiltration of sewage water from sewer systems in urban areas represents a threat for groundwater and soil. Due to the characteristics of wastewater specific substances, due to degradation rates, mobility and toxicity exfiltration needs to be assessed. Especially in protected zones (i.e. in restricted parts of drinking water extraction areas) the quality of groundwater resources can be deteriorated by sewage water.

In order to examine transport and degradation of wastewater-specific substances in groundwater and soil it is essential to quantify exfiltration rates and their variations depending on boundary conditions.

Exfiltration rates can be estimated by various methods (Härig and Mull, 1992; Ullmann, 1994; Burn et al., 1999; Dohmann et al., 1999; Rieckermann and Gujer, 2002; Fenz et al., 2005). Modelling of exfiltration rates allows the estimation of exfiltration and its variation and moreover scenario analysis to assess rehabilitation concepts. Still, exfiltration models are not widely applied. This fact can be explained by the difficulty to calibrate parameters. On laboratory scale the processes are described quite well (Rice, 1974; Rauch and Stegner, 1994; Dohmann et al., 1999; Ellis et al., 2003; Vollertsen and Hvittvet-Jacobsen, 2003). But on a catchment scale the application of models is difficult due to a lack of essential data.

In this paper an approach is introduced, which facilitates the parameter estimation on a catchment scale. This is realized by coupling the exfiltration process and the reverse process of groundwater infiltration. Thus, the data needed for modelling can be reduced.

The application of the method is tested in a catchment of the City of Dresden. Exfiltration rates from 1997 to 1999 exhibit the extent and variation of exfiltration typically encountered in urban catchments. A particular focus of the work was the estimation of exfiltration and its dynamics during flood events.

During the flood event in 2002 in Dresden the sewer system was directly influenced by the river Elbe. The wastewater treatment plant (WWTP) and the sewer system in the vicinity of the river Elbe were flooded turning major parts of the sewer system into...
pressurised conditions. At the same time the groundwater table in the city rose up to a level that was never recorded before. In order to assess the exfiltration during the extreme conditions of the flood event a scenario analysis was performed.

Application of the leakage model
For modelling exfiltration from sewers a leakage model was used which was originally developed to simulate interactions between groundwater and surface water and which was adapted to describe the process of groundwater infiltration into sewers (Gustafsson et al., 1997; Karpf and Krebs, 2004). Exfiltration rates depend on the groundwater level near the pipes (if it is not below the pipe), the water level in the pipes and the dimension of the pipes. Furthermore, a specific leakage factor to characterise the soil surrounding the pipes and the permeability of the pipes, is used. Adapted from the leakage model of surface water exfiltration into groundwater (Han, 1997) the exfiltration of wastewater from sewer pipes can be expressed by Equations 1 and 2.

\[ Q_{\text{exfiltration},T} = k_{L,\text{exfiltration}} \sum_{i=1}^{n} A_{i,T} \cdot (h_{G,i,T} - h_{S,i,T}) \quad (\text{with } h_{S,i,T} > h_{G,i,T} > h_{P,i}) \]  

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Where:
- \( Q_{\text{exfiltration},T} \) is the exfiltration rate at time \( T \)
- \( A_{i,T} \) is the exfiltration-effective surface of pipe \( i \) (inner surface of pipe \( i \) which is influenced by wastewater) at time \( T \)
- \( h_{S,i,T} \) is the water level in pipe \( i \) at time \( T \)
- \( h_{G,i,T} \) is the groundwater level near pipe \( i \) at time \( T \)
- \( h_{P,i} \) is the pipe bottom level of pipe \( i \)
- \( k_{L,\text{exfiltration}} \) is the average exfiltration specific leakage factor

The groundwater level can be interpolated based on groundwater measurements. The pipe water level should be simulated with a hydrodynamic pipe-network model. The exfiltration-effective pipe surface represents the inner surface of the pipe which is influenced by wastewater. It can be calculated with data on pipe geometry and pipe water level. The exfiltration-specific leakage factor must be calibrated. The problem is that there is still a lack of reliable methods to measure exfiltration rates, which are necessary for calibration. Therefore, the leakage factor was estimated by using the infiltration-specific leakage factor of the respective pipes.

Estimation of exfiltration specific leakage factors
The approximation of an exfiltration specific factor is based on the calibration of infiltration specific leakage factors (Karpf and Krebs, 2004). This factor is to be transformed into an exfiltration specific factor.

The boundary conditions of exfiltration processes cause a lower value of the exfiltration specific leakage factor compared with the infiltration factor. Due to the attributes of wastewater causing soil clogging and sedimentation in pipes (Rice, 1974; Rauch and Stegner, 1994; Dohmann et al., 1999; Ellis et al., 2003; Vollertsen and Hvitvet-Jacobsen, 2003) and due to a lower conductivity of the unsaturated soil, exfiltration processes are slower than infiltration processes and the leakage factor of exfiltration must be lower than the factor characterising infiltration processes.
The influence of soil clogging and sedimentation processes are difficult to examine on the catchment scale. For the following scenario analysis these processes will not be considered.

The difference of the conductivity depending on the water saturation of the soil was estimated in a simplistic way after Mutschmann and Stimmelmayr (2002). The conductivity under unsaturated conditions (similar to the exfiltration condition with a groundwater level below the pipe bottom) is estimated to be roughly half the $k_f$-value under saturated conditions (similar to infiltration condition). Since typically exfiltration takes place into unsaturated soil conditions while infiltration is induced from saturated conditions due to a high groundwater level, the ratio of conductivity under unsaturated ($k_{f, unsat}$) and saturated ($k_{f, sat}$) soil conditions is assumed to be equal to the ratio of the leakage factors for exfiltration ($k_{L, exf}$) and infiltration ($k_{L, inf}$), respectively:

$$\frac{k_{L, exf}}{k_{L, inf}} = \frac{k_{f, unsat}}{k_{f, sat}} = 0.5$$

The calibration procedure of Karpf and Krebs (2004) for the infiltration leakage factor makes use of long term data, from which the history of each pipe reach is analysed to identify a mean $k_L$-value over time for an individual pipe. Based on this procedure and on Equation 3 an average exfiltration leakage factor was estimated.

By analysing the calibration of the leakage model for the assessment of infiltration rates it was found that the overall behaviour of the system could be simulated reasonably well by applying a simplified approach with a mean leakage factor for all pipes. Thus the exfiltration specific leakage factor is approximated as a mean factor for all pipes of the study area, using Equation 4:

$$k_{L, exf} = \frac{k_{f, unsat}}{k_{f, sat}} \cdot \frac{\sum_{i=1}^{z} \sum_{T=1}^{T_{max}} \frac{Q_{inf,T}}{(h_{G,I,T} - h_{S,I,T}) \cdot A_{S,I,T}}}{z}$$

By applying a single exfiltration-specific leakage factor the problem is avoided that only for pipes that have gone through infiltration a leakage factor could be determined. Therefore, the approach is based on the assumption that the structural states of the reaches, for which the infiltration-specific leakage factor was calibrated, are representative for all pipes.

The estimation method does not include all possible influencing factors. Namely the parameters characterizing soil clogging and sedimentation processes are not involved. Thus, the results of the following simulation studies represent maximum exfiltration rates.

**Application of the model**

The leakage model was applied to a main part of the catchment of the City of Dresden. The catchment is drained by a combined sewer system with a total pipe length of about 227.
600 km. For the application of the exfiltration model the groundwater level and the water level in the pipes are essential. The groundwater level was interpolated from long term groundwater measurements.

The water level in the pipe was simulated with the hydrodynamic runoff model HYSTEM-EXTRAN. Water levels in pipes depend on structural data of the sewer system (dimension of pipes, slope, etc.), sewage flow and extraneous water inflow/infiltration into the system. Sewage flow was estimated from measurements of drinking water consumption. Extraneous water, which is besides inflows of water from the surface mainly caused by groundwater infiltration, was estimated for pipes depending on the groundwater influence and pipe dimension. Due to seasonal variations of the groundwater level the water level of each pipe was simulated under the boundary conditions of a minimum and maximum groundwater infiltration. Water levels between the minimum and maximum levels were interpolated depending on the estimated infiltration rates. Infiltration rates which are also needed to calibrate the exfiltration specific leakage factors were balanced by calculating the difference of wastewater flow and the daily consumption of drinking water.

The exfiltration specific leakage factors were approximated with Equation 4. For this, 144 measurements of groundwater level and referring data on WWTP inflow and drinking water consumption in the period from 1997 to 1999 were used.

Exfiltration rates of two scenarios were examined. The first scenario represents the exfiltration without any influence of surface water on the sewer system. Sewer pipes were not flooded by the river Elbe. This scenario was simulated for the entire period from 1997 to 1999. The second scenario includes backwater effects caused by the river Elbe, inasmuch as pipe water levels are directly influenced by the water level of the river. This scenario represents the situation during the flood event in August 2002.

Exfiltration rates from 1997–1999

In Figure 1 the results of the exfiltration simulation for dry-weather conditions in the period from 1997 to 1999 are illustrated. The exfiltration rates were estimated to a mean value of 70 m$^3$/h. This corresponds to 2.8% of the mean dry-weather flow of the test study area. The simulated exfiltration rate during the study period of three years varies from a minimum of 1.3% to a maximum of about 3.8% of the dry-weather flow.

The relatively low value of exfiltration rates – a common value of groundwater infiltration rate amounts to 30 and 40% of the dry-weather flow – originate from the low water levels in pipes during dry-weather periods. Storm-weather runoff and direct inflow of surface water cause an increase of the exfiltration rate.

In periods of a low groundwater table, i.e. below the pipe’s bottom, the exfiltration rate is maximum. During winter and spring time, the period of a rising groundwater table, the exfiltration rate is decreasing. The exfiltration process shows inverse behaviour to the variation of groundwater infiltration.

Exfiltration rates during extreme flood events

During the flood event of the river Elbe in August 2002 the sewer system was directly influenced by the surface water inflow and through backwater effects from the Elbe. Parts of the sewer system became pressurised. Therefore, for the simulation of exfiltration rates the water level in the sewer system or the pressure horizon was referred to the water level of the river.

Results of the exfiltration simulation are shown in Figure 2. A comparison of simulated exfiltration rates of the years from 1997 to 1999 (Figure 1) and during 13 days in August 2002 (Figure 2) gives an impression of the significant increase of exfiltration...
rates (note the logarithmic scale of the vertical axes). During 13 days of the flood event the average value of exfiltration yields about 1,120 m³/h representing an increase of about 1,500% as compared to the average value of exfiltration from 1997 to 1999. Maximum exfiltration rates during the flood event were estimated to be more than 10,000 m³/h.

The main reason for this increase is the risen head originating from the higher water level in the pipes and even more from the pressurised conditions in parts of the sewer network. This by far over-compensates the potential reduction of exfiltration through the risen groundwater level (Equations 1 and 2). Figure 2 indicates that above a water level of approximately 5.5 m in the river Elbe a significant increase of exfiltration rates is simulated. Below this value exfiltration rates are not depending on the water level in the river, and below 5 m Elbe water level the exfiltration rates are the same as the average value of exfiltration in the period from 1997 to 1999.

Discussion
The distribution of the exfiltration rates in the sewer system is illustrated in Figure 3. The simulations exhibit that for the years 1997 to 1999 the main fraction of the sewage loss of 48% is attributed to sewer pipes with a profile height between 0.9 and 1.8 m by the
The contribution of smaller pipes is relatively little; only 12% of exfiltration is simulated to originate from pipes with a profile height smaller than 0.9 m. The dominant exfiltration from large sewers can be explained by the facts that the water depth above the bottom is higher and that the wetted perimeter is larger than in small pipes and thus the exfiltration area is larger.

For the flood event in 2002 the distribution of the relative contribution of diameter classes to exfiltration has changed. Exfiltration rates of smaller pipes with profile heights from 0.1–0.9 m are now an important contributor at 38%, whereas the relative contribution of trunk sewers with a profile height of more than 2.7 m decreased from 18% to 3%. This is because the exfiltration rates from smaller pipes increase dramatically rather than due to a reduction of the exfiltration from the largest sewers. Small pipes react more sensitively to backwater and may exhibit pressurised conditions relatively quickly during a flood. The change from free surface flow to pressurised flow changes the behaviour of smaller pipes much more distinctly as compared to that of larger pipes, since the relative change in head is by far more pronounced.

The finding that under normal conditions exfiltration originates predominantly from large sewers is similar to the findings by simulating infiltration (Karpf and Krebs, 2004) yielding major infiltration (80%) for sewers larger than 1.2 m. This is the case when the groundwater level varies from below to above the water level in those sewers. This is typically the case for the large sewers of Dresden whose surrounding aquifer is strongly influenced by the water level variation in the river Elbe.

Conclusions

The application of a leakage model allows the estimation of exfiltration rates and their temporal variation depending on the boundary conditions. Model parameters can be approximated by the adaptation of averaged sewer specific parameters derived from the calibration of the infiltration process. The method can be upgraded with data on soil structure, pipe condition and wastewater characteristics.

The estimation of the exfiltration in the major part of the catchment of the City of Dresden shows that during dry-weather periods the average exfiltration rate is about 2.8% of the dry-weather runoff in the catchment and reaches a maximum of 3.8% during periods of low groundwater table. A direct influence of surface water during flood events causes a dramatic increase of exfiltration rates since backwater effects and surface inflow cause pressurised flow conditions in large parts of the sewer system.

Figure 3 Percentage of exfiltration from 1997 to 1999 and during the flood event of 2002 classified by the profile height of pipes.
The simulation results exhibit similar findings for exfiltration and infiltration rates, that is, the main contributors are the large pipes.

In order to assess the potential threat to the groundwater aquifer by sewage exfiltration, the estimated exfiltration rates can be used as an input for models which describe the processes in the unsaturated zone and in the groundwater.

Acknowledgement
This work was supported by the German Ministry of Education and Research within the research project “Effects of the flood event in August 2002 on the groundwater in the City of Dresden” (FKZ: 0330493). Parts of the study have been carried out within the framework of the European research project APUSS (Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems) whose partners are INSA de LYON (FR), EAWAG (CH), Technical University of Dresden (DE), Faculty of Civil Engineering at University of Prague (CZ), DHI Hydroinform a.s. (CZ), Hydroprojekt a.s. (CZ), Middlesex University (UK), LNEC (PT), Emschergenossenschaft (DE) and IRSA-CNR (IT). APUSS is supported by the European Commission under the 5th Framework Programme and contributes to the implementation of the Key Action “Sustainable Management and Quality of Water” within the Energy, Environment and Sustainable Development Contract no. EVK1-CT-2000-00072. Also, the support of the City of Dresden is greatly acknowledged.

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