Application of the leakage model to assess exfiltration

Christian Karpf, Peter Krebs

Institute for Urban Water Management, Dresden University of Technology, D-01062 Dresden, Germany (E-mail: christian.karpf@mailbox.tu-dresden.de, pkrebs@rcs.urz.tu-dresden.de)

Abstract
The exfiltration of waste water 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 waste water exfiltration. Exfiltration can be assessed by the application of the leakage model. The hydrological approach was originally developed to simulate the interactions between 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
waste water 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 waste water 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.

The examination of exfiltration consists of two parts. On the one hand it is necessary to quantify exfiltration and variations of exfiltration depending on boundary conditions. On the other hand processes of transport and degradation in the soil and in the groundwater have to be analysed.

Exfiltration rates can be estimated by various methods. Due to the fact that specific exfiltration rates are relatively low, the uncertainties of the methods are high. Model approaches allow the estimation of exfiltration rates and the performance of scenario analysis to assess the variation and extent of exfiltration and the resulting impacts to soil and aquifer.

The estimation of exfiltration rates was realised in a catchment of the City of Dresden. Exfiltration rates from 1997 to 1999 were compared with exfiltration rates during the flood event in August 2002. During the flood in 2002 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 the 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 (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, 1999) the exfiltration of waste water from sewer pipes can be expressed by Equations 1 and 2.

$$Q_{exfiltration,T} = k_{L,Exfiltration} \sum_{i=1}^{i} A_{i,T} \cdot (h_{G,i,T} - h_{S,i,T})$$ **(with $h_{S,i,T} > h_{G,i,T} > h_{P,i}$)** **Equation 1**

$$Q_{exfiltration,T} = k_{L,exfiltration} \sum_{i=1}^{i} A_{i,T} \cdot (h_{S,i,T} - h_{P,i})$$ **(with $h_P > h_{G,i,T}$)** **Equation 2**

$Q_{exfiltration,T}$	exfiltration rate at time T
$A_{i,T}$	exfiltration-effective surface of pipe i (inner surface of pipe i which is influenced by waste water) at time T
$h_{S,i,T}$	water level in pipe i at time T
$h_{G,i,T}$	groundwater level pipe i at time T
$h_{P,i}$	pipe bottom level of pipe i
$k_{L,Exfiltration}$	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 waste water. 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 waste water 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 this processes will not be considered individually but included in the exfiltration leakage factor.

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 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:

$$\frac{k_{L,exf}}{k_{L,\inf}} = \frac{k_{f,unsat}}{k_{f,sat}} = 0.5 \qquad \text{Equation 3}$$

$k_{f,unsat}$ conductivity of unsaturated soil
$k_{f,sat}$ conductivity of saturated soil

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 to be 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:

$$k_{L,exf} = \frac{k_{f,unsat}}{k_{f,sat}} \cdot \frac{\sum_{z=1}^{z} \frac{Q_{\inf,T}}{\sum_{i=1}^{n} \left[\left(h_{G,i,T} - h_{S,i,T} \right) \cdot A_{S,i,T} \right]}}{z} \qquad \text{Equation 4}$$

$k_{L,exf}$ average exfiltration specific leakage factor
$Q_{inf,T}$ balanced infiltration of groundwater at time T
$h_{G,i,T}$ groundwater level at the sewer pipe i at time T
$h_{S,i,T}$ water level in the sewer pipe i at time T
$A_{S,i,T}$ groundwater-influenced pipe surface of pipe i at time T
z number of calibration points T

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.

APPLICATION OF THE MODEL

The leakage model was applied in a catchment of the City of Dresden. 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 water flow and parasite water input into the system. Sewage water flow was estimated from measurements of drinking water consumption. Parasite water, which is mainly caused by groundwater infiltration, was estimated for pipes in dependence of 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 level were interpolated in dependence of 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 m³/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.

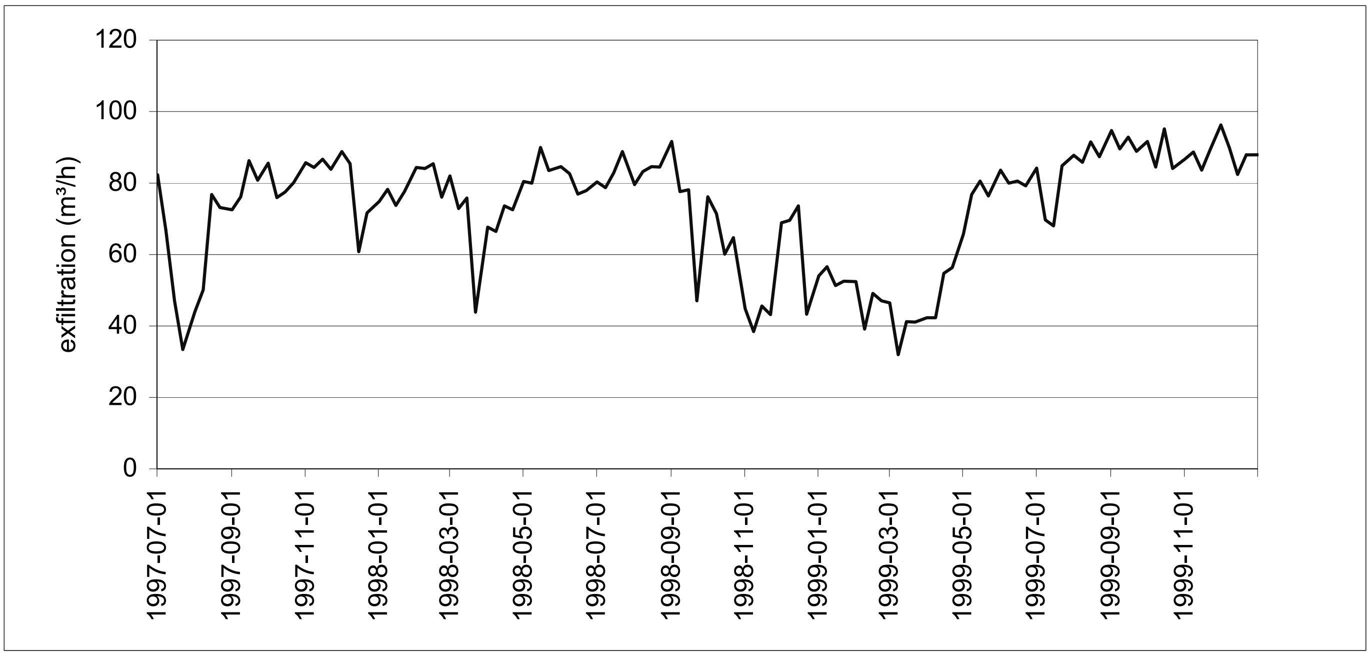

Figure 1 Simulated exfiltration rates from 1997 to 1999 in a catchment of Dresden

In periods of a low groundwater table, i.e. below the pipes 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 1120 m^3/h representing an increase of about 1500% as compared to the average value of exfiltration from 1997 to 1999. Maximum exfiltration rates during the flood event were estimated to more than 10’000 m^3/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.

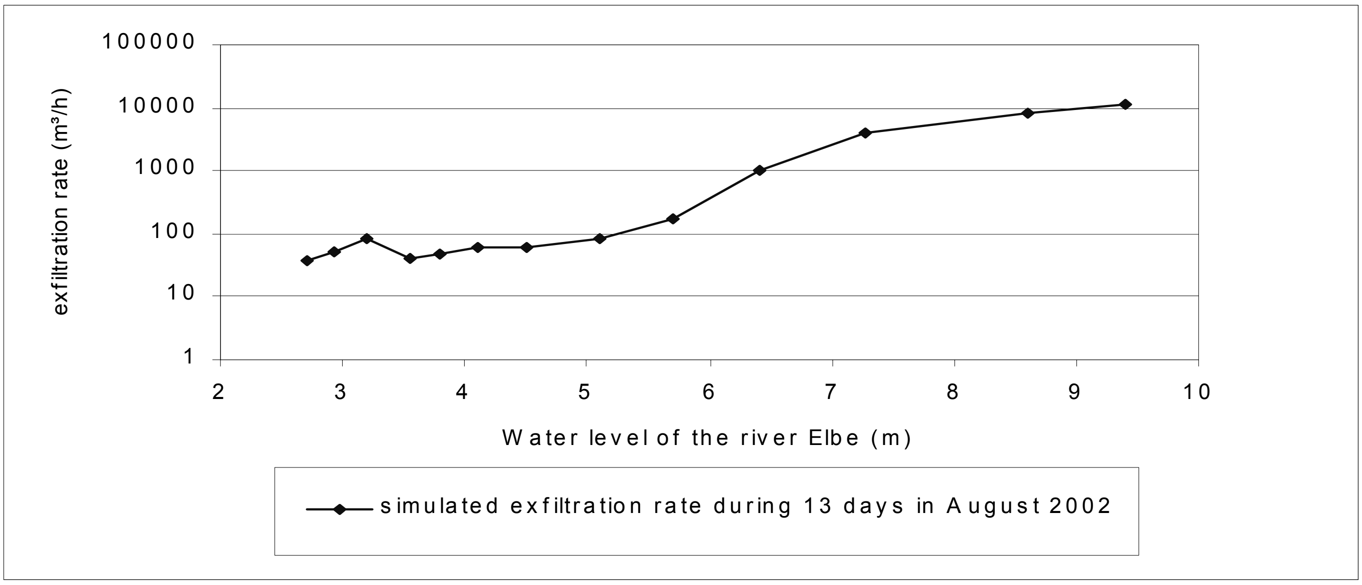

Figure 2 Exfiltration rates during 13 days of the flood event in August 2002 in dependence on the water level of the river Elbe

DISCUSSION

The distribution of the exfiltration rates in the sewer system is illustrated in Figure 3. For the years from 1997 to 1999 the main sewage loss with 48% is attributed to sewer pipes with a profile height between 0.9 and 1.8 m by the simulation. 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.

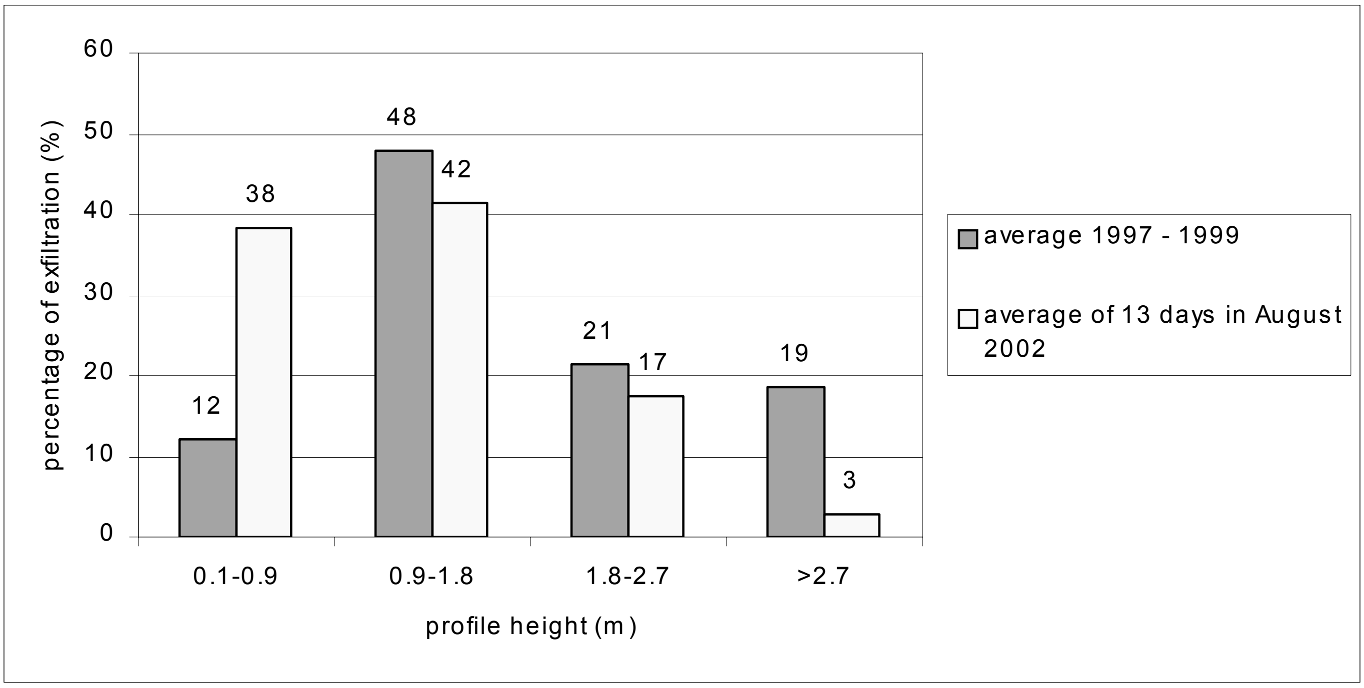

Figure 3 Percentage of exfiltration from 1997 to 1999 and during the flood event 2002 classified by the profile height of pipes

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 with 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 sensitive 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 distinct 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 the leakage model allows the estimation of exfiltration rates and their temporal variation in dependence of the boundary conditions. Model parameters can be approximated by the adaptation of sewer specific parameters derived from the calibration of the infiltration process.

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.

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 of the groundwater aquifer by sewage exfiltration, the estimated exfiltration rates must be used as an input for models which describe the processes in the unsaturated zone and in the groundwater.

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