Groundwater infiltration, surface water inflow and sewerage exfiltration considering hydrodynamic conditions in sewer systems

Christian Karpf, Stefan Hoeft, Claudia Scheffer, Lothar Fuchs and Peter Krebs

ABSTRACT

Sewer systems are closely interlinked with groundwater and surface water. Due to leaks and regular openings in the sewer system (e.g. combined sewer overflow structures with sometimes reverse pressure conditions), groundwater infiltration and surface water inflow as well as exfiltration of sewage take place and cannot be avoided. In the paper a new hydrodynamic sewer network modelling approach will be presented, which includes – besides precipitation – hydrographs of groundwater and surface water as essential boundary conditions. The concept of the modelling approach and the models to describe the infiltration, inflow and exfiltration fluxes are described. The model application to the sewerage system of the City of Dresden during a flood event with complex conditions shows that the processes of infiltration, exfiltration and surface water inflows can be described with a higher reliability and accuracy, showing that surface water inflow causes a pronounced system reaction. Further, according to the simulation results, a high sensitivity of exfiltration rates on the in-sewer water levels and a relatively low influence of the dynamic conditions on the infiltration rates were found.

Key words | exfiltration, hydrodynamic modelling, infiltration, inflow

INTRODUCTION

Groundwater infiltration and surface water inflows have an impact on the efficiency and the operation of sewer systems and wastewater treatment plants (Franz 2007). Exfiltration of sewerage may deteriorate soil and groundwater quality (Ellis et al. 2003). Thus infiltration, inflow and exfiltration (I/I/E) represent a field which is in the focus of operators and environmental authorities.

The quantification of the flows between the natural and the technical system is often uncertain due to the interaction and simultaneity or the time shift between interrelated processes. Further, it can be stated that the understanding of the hydraulics of the exchange processes, which is mainly controlled by the hydraulic potential, requires detailed modelling. This is especially important for the assessment of I/I/E during extreme events, i.e. floods as a consequence of large-scale or basin-wide events or local rain events with extreme short-term intensity.

Due to the importance of the hydraulic potential to the dynamics of I/I/E, the linking of hydrodynamic sewer network modelling with groundwater and surface water levels is a prerequisite to improve the description of I/I/E processes. By now conceptual model approaches (Belhadj et al. 1995; Gustafsson et al. 1999; Raynaud et al. 2008) and physical approaches (Gustafsson 2000; Rodriguez et al. 2005) have been developed. The coupling of infiltration and exfiltration approaches with hydrodynamic models is realised e.g. in the SWMM-model (Rossman 2004) and the model MIKE SHE (Gustafsson et al. 1997; Gustafsson 2000). The hydrodynamic consideration of surface water inflows is considered e.g. by Gomez & Russo (2005), Ciliberti et al. (2008), Schmitt et al.
Thereby surface water modelling is based on 1D and 2D approaches, which are coupled one- or bi-directionally with 1D sewer network models. The integrated coupling of hydrodynamic sewer, surface- and groundwater models was realised e.g. by Sommer et al. (2009), who coupled a sewer network model (1D) with a surface water model (2D) and a groundwater model (3D). Besides the complexity of the model coupling, the collection of the data needed and its processing, the set-up of the model structure and definition of boundary conditions are very labour-intensive. Such complex modelling tools are applied to assess the flood risk and the local capacity of the sewer system.

In contrast to these tasks, the paper focuses on the balance of I/I/E rates considering the hydrodynamic conditions in the sewer network. Numerical approaches for the exchange rate were interlinked with a hydrodynamic sewer network model. Ground and surface water hydrographs are implemented as boundary conditions, which are essential for control of the exchange rates. An idea will be given of the effects, which can be modelled by this linkage of hydrodynamic models and I/I/E approaches. Further, the results of hydrodynamic modelling are compared to estimations based on simplified approaches representing steady-state conditions.

**METHODS AND MATERIALS**

**Hydrodynamic model and linkage approaches**

HYSTEM-EXTRAN (itwh 2002) is a hydrodynamic sewer model. It consists of two modules, which are coupled in series. The module HYSTEM is used to calculate the rainwater inflows into the sewer system based on several options for the simulation of the rain-runoff process. The module EXTRAN simulates the hydrodynamic transport processes in the sewer system, based on the equation system of de Saint Venant.

The module EXTRAN was extended by a wrapper software in order to integrate the interface for the processing of groundwater and surface water. As essential component, the wrapper code includes model approaches to calculate the exchange fluxes between sewer system, groundwater and surface water (Table 1).

The main driver of the fluxes between the domains (Q\textsubscript{IN}, Q\textsubscript{EX}, Q\textsubscript{SW}) is the hydraulic potential (ΔH\textsubscript{IN}, ΔH\textsubscript{EX}, ΔH\textsubscript{SW}). Further, coefficients (K\textsubscript{IN}, K\textsubscript{EX}, K\textsubscript{SW}), respectively, describe specific conditions of the particular process (Karpf et al. 2007). The infiltration coefficient (K\textsubscript{IN}) integrates shape and area of sewer leaks, hydraulic conditions near the leaks (pressure loss) and soil characteristics in vicinity of the leaks (e.g. conductivity of the soil). The exfiltration coefficient K\textsubscript{EX} describes similar characteristics to K\textsubscript{IN}, but it is different in magnitude due to the influence of the sewage water, that is, clogging of the soil in the vicinity of sewer leaks (Blackwood et al. 2005). The surface water coefficient K\textsubscript{SW} includes characteristics of discrete inflow points, e.g. shape and area of openings. In- and exfiltration fluxes are related to the length L of the sewer pipe.

The calibration of the parameters K\textsubscript{IN} and K\textsubscript{SW} was realised by a multiple regression method (Karpf et al. 2007), which is based on a regression function to describe the dynamics of the dry-weather flow Q\textsubscript{DW} (Equation (1)). The independent variables B\textsubscript{IN} and B\textsubscript{SW} are calculated according to groundwater and surface water level measurements and the exchange approaches given in Table 1 for each pipe i and each inflow point j (Equation (1)). Further, the sewage flow rate Q\textsubscript{S} as constant and the inflow Q\textsubscript{SW,permanent} as a seasonally changing input of permanent drainage and surface water inflows are included in the regression function. A validation of the parameters K\textsubscript{IN} and K\textsubscript{SW} was realised by the application of the regression function for a second set of ground and surface water and flow data. For the exfiltration parameter (K\textsubscript{EX}), it is assumed that the maximum exfiltration in the catchment during dry-weather periods yields 5% of the total dry-weather flow in the catchment (according to Ellis et al. (2003) and Reynolds & Barrett (2003)). Based on this

Table 1: Approaches to simulate the water exchange between groundwater, surface water and sewer system

<table>
<thead>
<tr>
<th>Process description</th>
<th>Model approach</th>
<th>Physical basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater into sewer pipes</td>
<td>Q\textsubscript{IN} = K\textsubscript{IN}·ΔH\textsubscript{IN}·L = K\textsubscript{IN}·B\textsubscript{IN} with B\textsubscript{IN} = ΔH\textsubscript{IN}·L</td>
<td>Darcy</td>
</tr>
<tr>
<td>Sewage water into groundwater</td>
<td>Q\textsubscript{EX} = K\textsubscript{EX}·ΔH\textsubscript{EX}·L</td>
<td>Darcy</td>
</tr>
<tr>
<td>Surface water into sewer pipes</td>
<td>Q\textsubscript{SW} = K\textsubscript{SW}·√ΔH\textsubscript{SW} = K\textsubscript{SW}·B\textsubscript{SW} with B\textsubscript{SW} = √ΔH\textsubscript{SW}</td>
<td>Torricelli</td>
</tr>
</tbody>
</table>
assumption and the exchange approach (Table 1) the \( K_{EX} \) coefficient is assumed to be a constant (Equation (2)).

\[
Q_{DW} = K_{IN} \cdot B_{IN} + K_{SW} \cdot B_{SW} + Q_t + Q_{SW \text{ permanent}}
\]

with \( B_{IN} = \sum_j \Delta H_{IN,j} / \sum_j L_i \) \hspace{1cm} (1)

and \( B_{SW} = \sum_j \sqrt{\Delta H_{SW,j}} \)

\[
K_{EX} = \frac{Q_{EX}}{\sum_i \Delta H_{EX,j} / \sum_j L_i}
\] \hspace{1cm} (2)

For the linking of I/I/E approaches to the hydrodynamic sewer network model some details of the exchange routine control are important.

Groundwater infiltration and sewage exfiltration are directly controlled by the potential between groundwater level and sewer water level or by the pressure in the sewer pipes, respectively. Ground and surface water levels were imported in the model as hydrographs. The inflow of surface water depends on its level above the ground surface (manhole or gully covers) or above the weir crest of outlets. If water levels in the sewer system rise above the ground surface or the weir crest, the inflow is controlled by the potential between water (or pressure) levels in the sewer system and the surface water. The outflow from regular outlets is influenced by varying water levels in the receiving water. In order to represent the overflow through manholes, the ground surface is varied according to the water level during the simulation time. By this trick a local flooding through manholes is only possible if the pressure of the surface water level is exceeded by the pressure in the sewer system. Due to the complex interaction of surface water level and sewer water (pressure) levels on flooded manholes, the time steps of the exchange should be chosen short in order to prevent oscillation of simulated water levels.

**Investigation area, data and model structure**

The model was applied to the sewer system of the city of Dresden. The catchment covers an area of 98 km with approximately 470,000 inhabitants and significant contributions to the waste water discharge from industrial areas. The sewer system consists of 900 km combined sewers, 380 km foul sewers and 340 km storm water pipes. During flood events the water of the river Elbe may enter the sewer system via flooded manholes and leaky overflow-gates which should cut off sewer from river system when the water level in the latter is higher. Parts of the sewer system are temporarily or permanently influenced by the aquifer.

Besides the structural data of the sewer network, precipitation, groundwater and surface water data were used. The considered model structures are based on a 100-year flood event in order to assess extreme conditions and their impacts in the catchment. As rainfall event a virtual rain with a duration of 12 h and a frequency of 1 a \(^{-1} \) and a rain height of 56 mm is generated as a rectangle-shaped rainfall according to rain statistics in the Dresden catchment. Groundwater levels are taken from a groundwater simulation of a 100-year flood event, which was realised with a hydrodynamic 3D model (Sommer et al. 2009). Surface water levels are generated by a linear interpolation of the river water level during a 100-year flood event. The time-resolution of the hydrographs of groundwater and surface water input is 1.

In order to evaluate effects of the boundary conditions and the combination of them, four model structures were set up and simulated. As a reference case, a model structure without considering the boundary conditions of groundwater and surface water was simulated (REF). A further two model structures considering groundwater and surface water impacts (RW1, RW2) and one model structure considering the impact of groundwater only (DW1) were performed. An overview of the simulations is given in Table 2.

Furthermore, in order to compare the I/I/E results based on hydrodynamic simulations to describe the flow conditions in the sewer system to a steady-state calculation, the I/I/E approaches in Table 1 are used to calculate quantities in a daily resolution without using the information of varying water levels in the sewer system.

**RESULTS**

**Dynamics of I/I/E in the catchment**

Simulation results show the influence of an intense local rain event on the courses of I/I/E during an extreme large-scale

**Table 2 | Model structures and considered processes**

<table>
<thead>
<tr>
<th>Model structure</th>
<th>Boundary conditions</th>
<th>OG</th>
<th>Rain</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>DW1</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>RW1</td>
<td>Yes</td>
<td>Yes</td>
<td>Controlled</td>
</tr>
<tr>
<td>RW2</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

OG...overflow gates of combined sewer overflows
Rain...simultaneous rain event (12 h, 1 a \(^{-1} \))
event in terms of river water and groundwater levels (Figure 1). Generally, groundwater response to large-scale rain events is slower than surface water response, and thus the increase of infiltration is delayed compared to the increase of inflow. On the other hand, the response of exfiltration is parallel to that of inflow since it is dependent on the water level in the sewer only, which reflects a flow rate increase immediately. The intense local rain event causes a sudden water level increase in the sewers and hence affects I/I/E: inflow and infiltration are decreased through a reduction of the hydraulic potential, whereas exfiltration is increased. However, the influence of the local event is of a temporary nature, as the effect on water and groundwater levels is minor and the water level increase in the sewers quickly levels out to the undisturbed level.

**Consideration of effects in the sewer system**

In Figure 2 influences of I/I/E on the hydrodynamics of the sewer system are evaluated by comparing the number of junctions and conduits that are subject to flooding and to backwater effects, respectively, for the model structures defined in Table 2, the reference structure REF, RW2, where infiltration and exfiltration is considered, and the model structure RW1, where additionally surface water inflows are incorporated in the model.

By comparing the model structures REF and RW2 it becomes obvious that the impact of groundwater infiltration and sewage exfiltration on flooding and backwater is relatively low. In contrast, the effects of surface water inflows are dominant with regard to overload of the sewer system, as the number of flooded junctions and conduits influenced by backwater effects is increased by factors of approximately 8 (flooding) and 4 (backwater), respectively.

The importance of surface water inflows during extreme events for hydrodynamics features in the system is also illustrated by Figure 3, showing the results of simulations in a subarea. Similar to the statements above, it is visualised that surface water inflows (Figure 3c) significantly affect the result. Besides, concerning the number of backwater effects, a linear interpolation of surface water levels (river levels) yields a comparable, somewhat pessimistic result (Figure 3d).

**Comparison of the dynamic simulation and the steady-state calculation**

An essential question concerns the benefit of hydrodynamic modelling as compared to steady-state calculation of I/I/E without consideration of the hydrodynamic conditions in the sewer system, i.e. the variation of water pressure in the sewer pipes. In Figure 4 results of simulations with and without hydrodynamic simulation of in-sewer flow are compared.
assuming no local rain event on top of the 100-year flood event (DW1 in Table 2). It can be seen that daily values of groundwater infiltration and surface water inflows do not differ significantly. The estimation of surface water inflows is higher with steady-state calculations than with hydrodynamic in-sewer simulations because backwater effects and the overload of manholes in flooded areas are not considered and, therefore, the hydraulic head is overestimated. In turn, risen water levels due to these effects described in hydrodynamic simulations prevent or reduce the inflow of surface water. Comparing the infiltration of groundwater resulting from steady-state and dynamic calculations shows a similar peak infiltration rate, while the dynamic simulation yields a later increase and a later decrease of the infiltration rate due to a quicker increase of the in-sewer water level before the peak.

Again, the difference between the more precise simulations and the simplified calculations is much more
pronounced for the estimation of the exfiltration process. Estimated exfiltration rates considering the in-sewer hydrodynamics show a significant increase as compared to the estimation based on steady-state in-sewer water levels.

The low sensitivity of the estimated infiltration/inflow rates on the consideration of the in-sewer hydrodynamics can be explained by the fact that they are mostly driven by surface and groundwater level, whereas the high sensitivity of the estimated exfiltration rate exhibits that this process is driven by in-sewer water levels and thus hydrodynamic simulations really matter.

Boundary conditions and system reaction

By relating surface water data to the simulation results, functions for infiltration and inflow can be deduced, which are helpful for a rough estimate of I/I on catchment scale 

(Figure 5). The functions illustrate I/I during the 100-year flood event discussed above. The inflow of surface water is directly interlinked to the surface water level. The reason for the overproportional inflow increase is the progressive increase of flooded area with rising river water level and thus the corresponding increase of the number of inflow points. This effect can be obviously seen if inflows via the combined sewer overflows are compared to the sum of all inflows (Figure 5, left). Groundwater infiltration is dampened and follows a hysteresis curve with relatively fast increase and slow recession of the infiltration rates (Figure 5, right).

DISCUSSION

The exchange processes between sewers, groundwater and surface water are of complex nature. However, their

Figure 4 | Comparison of groundwater infiltration, surface water inflow and sewage exfiltration during a 100-year flood event.

Figure 5 | Inflow and infiltration related to the river water level.
incorporation into hydrodynamic network modelling is crucial to represent flow and flux conditions in the sewer system appropriately, especially during flooding events. The model set-up, parameter calibration and namely pre-processing of surface water and groundwater data are challenging and labour-intensive and require experience in handling large datasets. Against this background the benefit of such an expansion of hydrodynamic modelling, which is normally focused on rain-runoff process, needs to be valued.

First of all, the study showed that the dynamics of infiltration, inflow and exfiltration can be modelled in that way. Their inclusion in hydrodynamic modelling helps to understand the complex interlinkage of the sewer and the neighbouring compartments and to quantify the influence of rain events and dynamics of surface water and groundwater on the in-sewer flow features. This is obviously an improvement compared to simplified approaches.

Further, it was found that during flood events surface water inflows are essential to estimate the real system reaction whereas groundwater infiltration does not so significantly influence the flow conditions in the sewer system. These findings are explained by a dampened response of the groundwater level and a more pronounced and steeper rise of surface water levels accompanied by a sudden increase of the number of inflow points in case of flooding.

Backwater effects and local flooding cannot be simulated satisfactorily without considering inflows. As an alternative, a simple linear interpolation of available surface water levels may serve to receive a better picture of local floodings and sewer overloadings than without any inflow assumption. In total, inflow information is the crucial information to identify flow and overloads in sewers during a flood event. Further, it must be noted that the model concept does not include bi-directional coupling and a surface water flow simulation, which would be important to describe flooding effects with more accuracy. If flooding is the focus of an investigation, a 2D/1D coupling of surface and sewer network flow is recommended. Nevertheless, the simulation results give an idea about the system reaction.

For a catchment-wide estimation of groundwater infiltration and surface water inflows a hydrodynamic simulation is often not necessary, since the short-term dynamics of the in-sewer water level does not exhibit a major influence on I/I. An approach with constant water levels in the sewer pipes yields a good approximation of the estimations based on hydrodynamic in-sewer flow simulations and seems good enough for simple general statements about I/I. However, for the analysis of local, hydrodynamics-driven effects hydrodynamic simulations are beneficial.

In contrast to I/I simulations, the estimation of exfiltration is improved significantly by hydrodynamic simulations. This is related to distinct changes of water levels in the pipes due to flood and rain events and the fact that the water level in the sewer is the main driver of exfiltration. In the model, a constant exfiltration factor approach was used. However, in reality the exfiltration factors depend on the hydrodynamics and groundwater conditions. Further, if the processes of destruction and recovering of the clogging layer were implemented in the model, the range of exfiltration rates would increase even more. Thus, hydrodynamic modelling is essential to estimate exfiltration dynamics.

An important issue of the described methodology is the simulation time. In the case study a network model with approximately 7,500 junctions was used. The time step of the simulation was chosen as 0.1 s in order to keep the failure of the volume balance below 1%. Simulation time with a standard computer (CPU with 4 GHz) yielded up to 1/10 of real time. Thus long-term simulations in the order of year(s) are not feasible for such a setup and require a much more powerful engine. As an alternative for long-term simulations it can be recommended to split the simulation into periods of distinct dynamics (groundwater, surface water or precipitation) where hydrodynamic simulations are used and in periods of only gradually varying conditions where simplified simulations (e.g. with constant in-sewer water levels) are sufficient.

**CONCLUSIONS**

In the study, hydrodynamic simulations of in-sewer flow were combined with approaches to describe groundwater infiltration, surface water inflow and sewerage exfiltration. Concerning the potential and the limitations of the combined modelling, the following conclusions can be drawn.

- By linking a hydrodynamic network model to infiltration, exfiltration and surface water inflow approaches, infiltration, inflow and exfiltration can be described with a higher reliability and accuracy.
- The analysis of a flood event shows that the inflow of surface water causes a pronounced system reaction characterised by backwater effects and the local flooding of surface area, whereas groundwater infiltration and sewerage exfiltration do not significantly influence the hydrodynamic conditions under these circumstances.
- The exfiltration process requires a hydrodynamic simulation due to the high sensitivity of exfiltration rates to the water levels in the sewer pipes.
Catchment-wide estimation of infiltration and inflow by a simplified approach with day-wise stable water levels in the sewer pipes exhibits satisfactory results when compared to the hydrodynamic simulations.

The present study clarifies the potential and limitations of hydrodynamic sewer network simulations in improving the estimation of infiltration, inflow and exfiltration processes. Further investigations are carried out to describe long-term processes and to improve the exfiltration modelling by implementing approaches to describe clogging and breakup processes of the colmation layer below pipe leaks.

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REFERENCES


Gomez, M. & Russo, B. 2005 Comparative study among different methodologies to determine storm sewer inlet efficiency from test data. 10th International Conference on Urban Drainage.

Gustafsson, L. G. 2000 Alternative drainage schemes for reduction of inflow/infiltration - prediction and follow-up of effects with the aid of an integrated sewer/aquifer model. 1st International Conference on Urban Drainage via Internet.


