Water and contaminant flow in an aquifer under urban stress

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Abstract Urban groundwater resources are a matter of growing concern. Surface sealing and the urban subsurface infrastructure, such as water mains and the sewage system, can influence groundwater quality and quantity. To this end, groundwater deterioration within an urban watershed was assessed. An extensive monitoring programme concerning groundwater quality was combined with a numerical 3-D groundwater flow model of the study site. Results of the quality assessment revealed a pronounced influence of urban land use on the groundwater concentrations of the inorganic contaminants nitrate and boron. Within the urbanized part of the study area, groundwater recharge is high and characterized by a fast response to rainfall. Here, the high degree of surface sealing does not necessarily contribute to surface runoff and enables fast infiltration of rainwater to groundwater through cracks and joints. Annual water and contaminant flow from the study area were estimated using the numerical groundwater model.

Key words urban groundwater; monitoring; groundwater recharge; pharmaceuticals and personal care products; contaminant mass flow

INTRODUCTION

Worldwide, the quality and quantity of urban groundwater resources are a matter of growing concern (Howard, 2001). Due to the land use practices, the water balance of urban agglomeration is strongly affected. Infiltration and natural groundwater recharge may be reduced due to surface sealing. However, large quantities of drinking water and wastewater are transported in subsurface infrastructures. Losses from water mains and the sewage system can form artificial groundwater recharge (Lerner, 2002). The natural, as well as the artificial recharge in urban areas, can transport considerable amounts of inorganic, organic and microbiological contaminants to the groundwater (Eiswirth et al., 2004).

The major problem in assessing urban water resources and their sustainable use is the spatial and temporal heterogeneity of water flow, contaminant mass flow and attenuation processes. Water flow heterogeneity results from the variability of land use, evapotranspiration and thus, groundwater recharge (Mohrlok et al., 2008). Contaminant mass flow heterogeneity results from the spatial distribution and temporal activity of sources such as sewer leaks (Musolff, 2009).

It is hypothesized that a holistic approach to urban groundwater is feasible to describe heterogeneous water and contaminant flow in an urban aquifer. To this end, water quality and quantity of groundwater, surface water and wastewater within an urban watershed are taken into account. This paper focuses on the annual groundwater and contaminant flow within an urban watershed, incorporating the sewage system as both a source for contaminants and a sink for groundwater.

MATERIAL AND METHODS

Study area

The study area has a size of 18 km\textsuperscript{2} and is located within the city of Leipzig, Germany (Fig. 1). In the southern part, urban land use with residential areas as well as industrial areas dominates. The northern part is characterized by a forested flood plain. The aquifer consists of shallow and highly permeable sands and gravels from the Quaternary. In the northern part, sands and lignites from the...
Tertiary and in the southern part Proterozoic and Permian bedrock are underlying the Quaternary; for details refer to Musolff et al. (2007, 2008). Based on the groundwater surface, a watershed can be defined that is congruent to the catchment area of the sewage system (sewershed). This study focuses only on the sewershed. It has an area of 5.37 km², with a total length of sewer section of 55 km. Wastewater is flowing to a pumping station in the northwest and pumped to a wastewater treatment plant (WWTP, see Fig. 1) outside of the study area. Data on the daily pumped amount of wastewater was provided from the municipal operator of the WWTP. A database for daily precipitation and the estimation of evapotranspiration was provided by a weather station in the northeastern part of the study area and from a weather station 9 km northwest of Leipzig.

On the basis of remote sensing and topographic maps, a detailed map of land use and surface sealing could be derived. Within the sewershed 24.6% of the area is fully sealed (roads and buildings) and 31.8% is partly sealed (see Fig. 1). Surface runoff from the sewershed is transported in the sewage system only, as there is no receiving surface water.

Field work

Fieldwork included a monitoring of water quality over a period of 13 month from April 2007 to April 2008. Beside major ions, several species of wastewater-bound emerging contaminants, such as pharmaceuticals, personal care products, and endocrine disrupting industrial chemicals were also analysed in wastewater, surface water and groundwater. Here, emphasis is put on the urban groundwater contaminants nitrate, sulfate, chloride and boron. Contaminant sources are manifold in urban areas and may for instance derive from wastewater losses (boron, nitrogen species), leachates
from construction waste (sulfate) and industrial sites (sulfate, boron), infiltrated runoff from roads (chloride) and fertilizers from urban parkland (nitrate) (Barrett et al., 1999; Howard, 2001).

The quarterly groundwater sampling included 22 observation wells. In this paper, measurements from 8 wells placed directly in the urban used area (7 within the sewershed) and 5 wells in the wooded flood plain are taken into account.

Groundwater surface was measured automatically with the help of pressure transducers in two of the urban wells.

**Data analysis**

Hydrochemical and *in situ* parameters (temperature, pH, Eh) from the groundwater samples were analysed by descriptive univariate statistics. Multivariate statistics such as correlation and factor analysis were applied for organic and inorganic marker substances and published elsewhere (Musolff et al., 2008).

The daily amount of pumped wastewater from the sewershed was used to estimate the amount of surface runoff to the sewage system in response to rainfall. In a uniform manner to river hydrograph separation, the daily amount of raw wastewater without the influence of surface runoff was derived. By relating the length of sewer beneath the groundwater table at different times of the year to the amount of collected wastewater, the groundwater discharge to these sewer sections was estimated.

Water flow computations are based on a 3-D groundwater flow model (FEFLOW, DHI-Wasy GmbH). This model takes three aquifers, three aquicludes and one aquitard into account. Boundary conditions are constant heads for the surrounding rivers and no-flow boundaries along streamlines of groundwater. Groundwater recharge was numerically modelled for 1-D profiles using Penman-Monteith evapotranspiration and precipitation on a daily base (HYDRUS 1-D). From the geological model, 16 soil profiles were derived and combined with different upper (atmospheric boundaries for grass, wood, crop and garden) and lower boundaries (different groundwater heads). For the central urban area, the 1-D approach was not capable of reproducing the dynamics of the water table fluctuations. Therefore, groundwater recharge was derived directly from measuring the water table fluctuations following the procedure given in Crosbie et al. (2005). Results of the latter method were evaluated based on of the annual percolation rate using the method of Wessolek et al. (2008).

This paper presents the annual flow of recharge and of groundwater from the watershed domain of the 3-D groundwater model (steady-state solution). The combination of computed water flow in groundwater and measured median contaminant concentrations yielded the annual contaminant mass flow.

**RESULTS AND DISCUSSION**

**Groundwater quality**

Groundwater quality is characterized by a pronounced urban impact. Shallow groundwater temperature was 2.0°C higher in the urban area compared to the wooded flood plain. Groundwater quality analysis revealed elevated concentrations of sulfate (median in urban area: 454.7 mg L$^{-1}$), boron (0.48 mg L$^{-1}$), chloride (58.3 mg L$^{-1}$) and nitrate (28.7 mg L$^{-1}$). Sulfate and chloride concentration did not change much when groundwater transits the wooded areas. This is probably due to a geogenic influence from the Tertiary strata. Median nitrate and boron concentration in the wooded flood plain decreased to 1.37 mg L$^{-1}$ and 0.76 mg L$^{-1}$, respectively.

Emerging contaminants are ubiquitously present in groundwater in the ng L$^{-1}$ to µg L$^{-1}$ range (Musolff et al., 2008). Compared to the relatively small temporal variability of inorganic contaminants, emerging contaminants were characterized by concentration variations up to an order of magnitude between the quarterly samplings.

Multivariate and geostatistical methods were used to discuss sources of the inorganic and organic groundwater contamination (Musolff et al., 2007, 2008). While elevated boron and sulfate...
concentrations result from industrial leachates, emerging contaminants are associated with wastewater input from sewer leakages and the infiltration of contaminated surface water. As a result of different input pathways as well as different transport and removal processes, inorganic and organic contaminations showed no correlation.

**Water and contaminant flow**

Key water flow rates from and to the urban sewershed/watershed can be found in Table 1.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Flow rate (m$^3$ day$^{-1}$)</th>
<th>Flow rate (mm year$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>9721</td>
<td>663</td>
</tr>
<tr>
<td>E_0</td>
<td>5344</td>
<td>364</td>
</tr>
<tr>
<td>R_0</td>
<td>951</td>
<td>65</td>
</tr>
<tr>
<td>D_rch</td>
<td>3549</td>
<td>242</td>
</tr>
<tr>
<td>D_ww</td>
<td>3029</td>
<td>207</td>
</tr>
<tr>
<td>D_gw-ww</td>
<td>704</td>
<td>48</td>
</tr>
</tbody>
</table>

$P$ – precipitation; $E_0$ – potential evapotranspiration (Penman-Monteith, grass reference); $R_0$ – surface runoff to the sewage system; $D_rch$ – groundwater recharge; $D_ww$ – amount of wastewater without the influence of surface runoff and exfiltrated groundwater; $D_{gw-ww}$ – discharge of groundwater to the sewage system.

Over a third of the annual precipitation contributes to groundwater recharge. Thus, groundwater recharge was found to be higher than expected from the high amount of surface sealing. Water table fluctuations revealed a fast positive response of the groundwater table to rainfall. Based on a cross correlation of hourly rainfall and water table data this positive response has a peak between 18 and 28 h and ends 41–66 h after rainfall (mean water level 1.2 m to 2.7 m below surface). Moreover, surface runoff response to rainfall was lower than expected. Only 10% of the sewershed area contributes surface runoff to the sewage system. As actual surface sealing is higher, it is concluded that large amounts of surface runoff infiltrate through cracks and joints in the pavement. This imbalance between actual surface sealing, reducing the evapotranspiration, and surface sealing contributing runoff may lead to the observed fast and high groundwater recharge rate.

As parts of the sewage system are located beneath the groundwater table (mean of 29% of the total sewer length), groundwater is infiltrating into the sewer pipes. This drainage was considered as a sink in the numerical flow model. The presented key water flow rates do not consider losses from water mains and from the sewage system to the groundwater. These features may have an influence (Lerner, 2002), but cannot be quantified so far based on the available data.

To estimate annual contaminant mass flow from the sewershed the annual water flow through a control plane (northern boundary of the sewershed, length of 4.87 km) and the median annual concentrations of the target substances in groundwater was considered. Mass flow was estimated for sulfate at 314.25 t year$^{-1}$, chloride at 40.29 t year$^{-1}$, nitrate at 19.81 t year$^{-1}$ and boron at 0.33 t year$^{-1}$. Mass flow of the emerging contaminants should consider heterogeneities of concentrations and water flow in time and space, and will be estimated based on the transient groundwater flow model.

**CONCLUSIONS**

The applied holistic approach proved to be capable of assessing the impact of urban land use on the water balance, and especially on groundwater resources. The urban watershed is a source for
considerable amounts of inorganic and organic water contamination. The sewage system acts as a source of contaminated water (the amount of water was not estimated here). However, parts of the sewage system that are located beneath the water table act as a sink for groundwater. Surface sealing within the study area leads to a reduction of actual evapotranspiration, but not to an equivalent increase of surface runoff. Thus, groundwater recharge is characterized by a fast and pronounced response to rainfall. This has negative consequences in terms of residence times of contaminants in the unsaturated zone, and thus attenuation processes (Mohrlok et al., 2008). Despite the results from the water table fluctuation method the aim is a physically-based estimation of groundwater recharge in the urban parts of the study area. Future work will also incorporate computed daily mass flow of groundwater to estimate mass flow of emerging contaminants.

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REFERENCES