INTEGRATING LEAKY SEWERS INTO NUMERICAL GROUNDWATER MODELS

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Abstract
Since the protection of urban groundwater as a drinking water resource is of growing importance it becomes necessary to quantify the interaction between the technical part of the urban water system and the urban aquifer representing the natural reservoir. A potential cause for water quality deterioration are leaky sewer systems. The paper documents the process of estimating the environmental impact of leaky sewers at the city of Rastatt (SW-Germany) and shows an approach of their integration into numerical groundwater models.

Keywords: leaky sewers, urban water systems, groundwater, marker species, transport model, sewer exfiltration.

INTRODUCTION

General comments on the role of groundwater in urban water management

It is evident and almost trivial that both a sustainable water supply and a functioning water drainage system are essential for anybody living in an urban community. However, planning and operation of the different parts of the urban water cycle are traditionally in the hands of different institutions and research in the field of urban drainage has often not taken account of research in the field of water resources and vice versa. As Rauch et al.(2002) noted, the construction and operation of municipal drainage systems has historically focussed on public hygiene and flood prevention. Only later the aspect of pollution control became important and treatment facilities were introduced to preserve the aquatic ecosystem (Rauch et al. 2002). However, even this new trend in engineering practise does not think in urban water balances which must include the major resource for drinking water, namely the groundwater. With medium population densities in former decades it was also easy to exploit drinking water resources from unaffected areas at the borders of the urban community. But with population growth, especially in urban areas, this situation has changed significantly and now more than 40 % of the groundwater used for drinking water in Western Europe comes from urban aquifers. Without an adequate knowledge base of the current status of urban water resources, and an understanding of the processes involved, the health and safety of the people who depend on urban groundwater as drinking water cannot be assured. (Eiswirth et al 2002)

Interactions between urban surface water infrastructure and groundwater

Common interactions between urban surface water infrastructure and the urban groundwater resource are:

- Exfiltration from water supply systems
- Infiltration of groundwater into and exfiltration of sewage out of sewer systems
- Decreased groundwater recharge due to surface sealing
- Increased groundwater recharge due to new infiltration systems

- Exchange of water between rivers/lakes and groundwater
- Deterioration of groundwater quality due to decentralised wastewater treatment plants
- Closing of water supply wells due to groundwater pollution

Most of these processes mainly have a quantitative effect on the urban water balance. In almost all environments, urbanisation leads to an increase in recharge (Lerner 2002). Especially water mains losses can exceed the natural groundwater recharge and lead to rising groundwater levels. Rising groundwater levels are not only detrimental to buildings stability but also responsible for increased infiltration into sewer systems which causes additional cost in the wastewater treatment plants. The realisation of innovative urban drainage concepts like decentralised stormwater infiltration systems has also led to rising groundwater levels in several cases (Göbel et al. 2003).
Prominent from an ecological viewpoint is the deterioration of groundwater quality due to the exchange with sewer systems and polluted urban rivers. Unlike rivers which are commonly regarded in urban drainage modelling as the only receiving water bodies, wastewater entering the groundwater from leaky sewers has never passed a wastewater treatment plant. For instance, leaky sewer systems are the most likely cause for findings of Escherichia Coli in a drinking water supply well in Hesse (Treskatis 2003). Leaky sewers are suggested in many publications as a possible source for contaminants in urban aquifers (e.g. Barret et al. 1999, Sacher et al. 2001, Dohmann 1999, Härig & Mull 1992, Ellis 2002). The European Union standard EN 752-2 has recognised this problem and therefore demands that the structural integrity of urban sewer systems including their water-tightness should be guaranteed (Keitz 2002).

Principles of sewer-groundwater interaction

The key factors for sewer-groundwater interaction are:

- Vertical position of the sewer in relation to variable groundwater level
- Infrastructural condition of the sewer (e.g. leak size)
- Effectiveness of colmation processes
- Soil or rock type in the immediate sewer surrounding
- Flow regime in the sewer

Most of these factors are problematic in their assessment. While the determination of the vertical position of the sewer in relation to the groundwater table is a rather easy task using GIS systems (although seldom applied yet), the infrastructural condition assessment of the sewers is already ambiguous. CCTV-inspections are the standard method but give only rough hints of the water tightness of the sewer, especially at the pipe joints (more research on alternative inspection methods can be found in Eiswirth et al 2001, Wolf 2003). Colmation processes have a dominant effect on the exfiltration rates but their behaviour is not sufficiently understood. Attempts to develop a deterministic formula (Dohmann et al 1999, Vollertsen & Hvitved-Jacobsen 2003) have not succeeded. Furthermore a removal of the colmation layer during storm events occurs irregularly. The hydraulic conductivity of the soil and rocks surrounding the sewer determines a maximum exfiltration rate and is the dominating factor concerning the wastewater travel times to the groundwater and consequently the adsorption and degradation of contaminants in the unsaturated zone.

Approach in Rastatt

The study area of Rastatt has approximately 50.000 inhabitants and is located 30 km south of Karlsruhe in the Upper Rhine Valley, SW-Germany. The aquifer commonly used for drinking water supply and industrial processes is the Upper Gravel Layer underneath the urban area. Its quaternary sediments consist of unconsolidated sand and gravel with occasional silty lenses. The aquifer is tapped downstream of Rastatt for the drinking water supply and the northern area of the city lies within the groundwater protection zone of the local water works. In order to assess the problems of sewer-groundwater-interaction at the scale of the city of Rastatt it has been attempted to use a known spatial distribution of sewer defects together with the hydrogeological boundary conditions for the estimation of the sewer-groundwater interaction. In order to validate the calculations, comprehensive hydrochemical samplings, including a series of new marker species, were conducted in the urban aquifer. A regional numerical flow model has been set up but research is currently focussed on a small scale transport model in the surrounding of well documented sewer leaks.

Marker species

The challenge in using marker species lies in linking it to the wastewater as only possible source or in locating and quantifying all other sources. In Rastatt mostly substances with concentrations between µg/l and ng/l have to be used as marker species, requiring a high analytical effort.

Wastewater from leaky sewers does not only contain illegally discharged hazardous substances like chlorinated hydrocarbons. In addition, a constant and highly diverse mixture of legally used chemicals runs through the sewer system, containing many substances for which no adequate toxicological knowledge is available yet. These so-called “emerging pollutants” include e.g. pharmaceutical residues, endocrine disruptors and personal care products (PCP).

Much research work is currently going on to detect these emerging pollutants in surface waters (Ternes 2002). The main entrance pathway to the surface water is seen in the incomplete removal of those substances in the wastewater treatment plants. However, wastewater leaking from defect sewers has never passed a treatment plant so that the pollutants are directly released into the urban drinking water resource. It is still an open question whether this direct release might have an even worse ecological impact.

The ecotoxicology of endocrine disruptors is the topic of current research. Most of the adverse endocrine effects reported up to now deal with feminization of fishes and amphibians (Kloas 2001).

Personal Care Products (PCP) such as liquid bath additives, soaps, skin care products, shampoos and dental care products are produced and used in enormous amounts world wide. In the early 1990´s the annual production volume in Germany was more than 550000 metric tonnes. Considerable persistence and bioaccumulation potential has been shown for a number of PCP´s like musk fragrances, disinfectants, antiseptics, some repellents and sunscreen agents (Ternes 2002).

Pharmaceutical residues have already been detected in the drinking water of Berlin, Germany. Clofibric acid, used as a blood lipid regulator was found in 64 tap water samples in Berlin with concentrations between 10 and 165 ng/l (Stan et al.1994; Heberer 2002). Likewise, it has also been detected in deeper groundwaters below the outskirts of Berlin as a result of sewage farm operation (Scheytt et al. 2000).

Other possible marker species proposed by Barret el al. (1999) and Ellis & Revitt (2002) like chlorination by-products (THM), faecal steroids (coprostanol), synthetic oestrogens, detergents, chlorinated solvents and stable isotopes (15N) have not been screened for in Rastatt but may be incorporated in future analytical programmes.

METHODS

Hydrochemical Analysis

In addition to the extensive hydrochemical database existing at the Landesanstalt für Umweltschutz (LfU, Karlsruhe), three sampling campaigns covering ground, surface, and waste water have been conducted by the Department of Applied Geology in the period 2001-2003. All water samples taken were analysed for major anions using ion chromatography while major cations were analysed using atomic absorption spectrometry. Analyses for Boron and heavy metals were conducted at the Institute for Mineralogy and Geochemistry (Karlsruhe) using Inductive Coupled Mass Spectrometry

(ICP-MS). Testing for pharmaceutical residues was performed at TZW (Center for water technology, Karlsruhe) using solid phase extraction and LC-MS-MS as described in Sacher et al. (2001). Detection limits for pharmaceuticals and iodated x-ray contrast media are at 10 ng/l in groundwater.

Condition Assessment of the Sewer System

In reaction to modifications in German law, the City of Rastatt has recently surveyed more than 90% of its sewer network using CCTV inspections. Each damage noticed was classified according to ATV-advisory leaflet M143 (1991) and stored in a database. In a second step the sewer defect database was given spatial reference in the GIS system (Fig.1). Partial reviewing of the videotapes has shown that there is a considerable underestimation of defects on the sewer bottom as the sewers were not always completely dry during the inspection and water was obscuring the sewer bottom. This is of special importance as the bottom section of the sewer is always filled with base flow sewage and prone to constant exfiltration.

Observation Wells

A total number of 47 wells have been selected for regular monitoring of groundwater level. All wells are located in the topmost aquifer with a maximum depth of 23 m. During the first project phase wells were selected for an even distribution in the city area. During the second phase eight focus observation wells were constructed in the direct vicinity of defective sewers. For the site selection of the focus observation wells the GIS-managed sewer defect database (Fig.1) provided a very good instrument. Large diameter sewers with defects at the sewer bottom were identified by using the sewer defect database (Fig.2).

Numerical Models

The proprietary finite element code FEFLOW 5.0 was applied for the groundwater flow and transport model. A regional steady state flow model was set up by Klinger (2003) using 21557 cells and calibrated with measured groundwater levels. Later the flow field was extracted from the large scale model and rebuilt in a small scale model.

RESULTS AND DISCUSSION

Estimation of wastewater exfiltration

The evaluation of the CCTV-inspection results via the sewer defect database has shown that there is a large number of defects in the sewer system through which interaction with the groundwater is possible. Within the length of a 208 km long sewer system (combined and separate), a total number of 31006 defects have been noticed. In detail the defects consist of 13646 damaged or improperly installed house connections, 7363 joint displacements, 4109 cracks, 2100 obstacles, 1584 root intrusions, 1563 corrosion problems and 641 other defects. It has to be emphasized that the city of Rastatt has an exceptionally good rehabilitation department and that these figures are describing a rather well maintained sewer network.

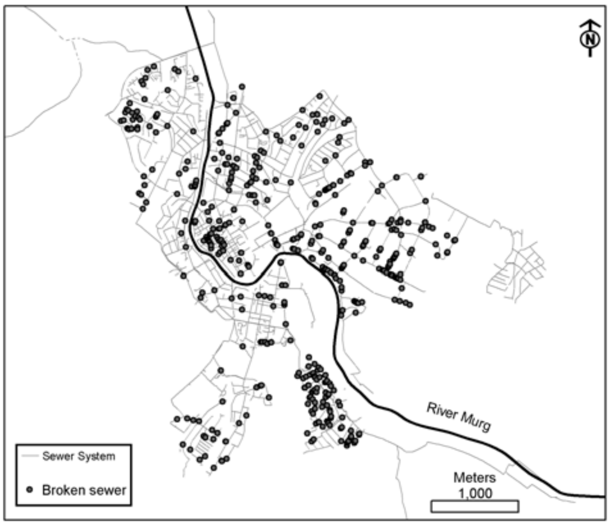

Fig. 1: Spatial distribution of major sewer defects in Rastatt.

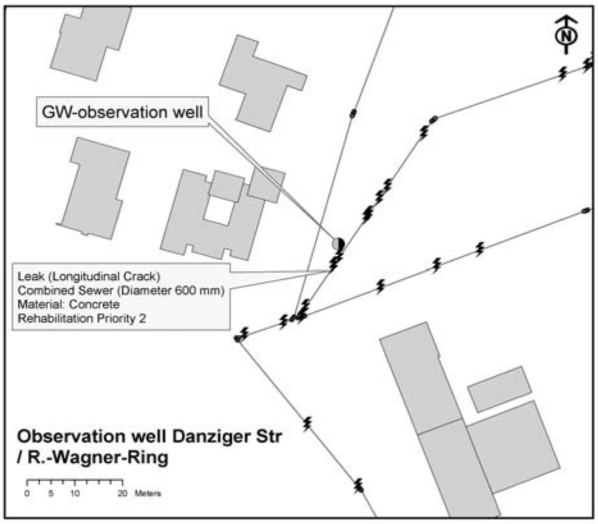

Fig. 2: Detail from the sewer defect database used for site selection. Thunderbolts indicate cracks in the sewer.

Of the factors relevant for exfiltration listed in the introduction, the leak position can be taken directly from the sewer database while the leak size can only be roughly calculated from the opening width recorded in the CCTV protocols. However, the length of the cracks is often not recorded properly and an average value has to be assigned. The average flow regime in the sewer can be extracted from hydraulic sewer network models in detail, which remains to be done in future. Vollertsen & Hvitved-Jacobsen (2002) found exfiltration rates for holes and cracks to be 0.06 l d-1cm^2 after the development of a clogging layer which almost sealed the leak. However, when simulating storm events Vollertsen & Hvitved-Jacobsen (2002) found leakage rates to be up to 56 times higher than the exfiltration rate during sealed conditions. A sewer exfiltration test site operated by the University of Karlsruhe at the wastewater treatment plant in Karlsruhe showed higher exfiltration rates of app. 0.35 l d-1cm^2 at constant conditions and up to ten times higher rates after only minor damaging of the clogging layer had occurred (Forschergruppe Kanalleckagen 2002).

The total area available for sewer-groundwater-interaction was roughly calculated from the sewer defects database as 0.96 m^2 for a 475000 m^2 part of the city center.

Using the exfiltration rate of 0.35 l cm-2 d-1 a discharge rate of 3469 l d-1 wastewater would exfiltrate into the aquifer in the city center. In relation to the total area affected, this equals a recharge rate of 2,67 mm a-1. Rainfall intensities >10 mm d-1 occured on 9.8 % of all days during the year 2000 in Rastatt. Assuming that the clogging layer is significantly altered or removed by those rain events, as indicated by Vollertsen & Hvitved-Jacobsen (2002), an exfiltration rate of 3.5 l cm-2 d-1 would be effective for 9.8 % of the year. This results in a total recharge rate of 5,06 mm a-1 using the data from Karlsruhe. Applying the exfiltration rates from Vollertsen & Hvitved-Jacobsen (2002) produces a total recharge rate of 2.88 mm a-1 for the city center of Rastatt.

These recharge rates are further influenced by groundwater level as a constraint for wastewater exfiltration. As shown in Fig. 3 several sewers are located beneath the water table even in the summer. For September 2001 about 13 % of the sewers were actually below the groundwater table. However, the calculations on exfiltration rates have many uncertainties and can only be taken as a first guess. A lot of work remains to be done on the estimation of leak sizes and the exfiltration rate itself, which is a strongly time transient parameter, mainly depending on the condition of the clogging layer at the leak. A significant underestimation may be caused by the wrong number of leaky joints which can not be detected by CCTV-inspections. In addition to that, recent field measurements in real sewers using double packer systems point to significantly higher exfiltration rates. Setting up a chain of more precise deterministic models for the quantification of exfiltration rates is one major aspect in the AISWURS project (Eiswirth et al 2002) and more detailed results are to be expected from this side.

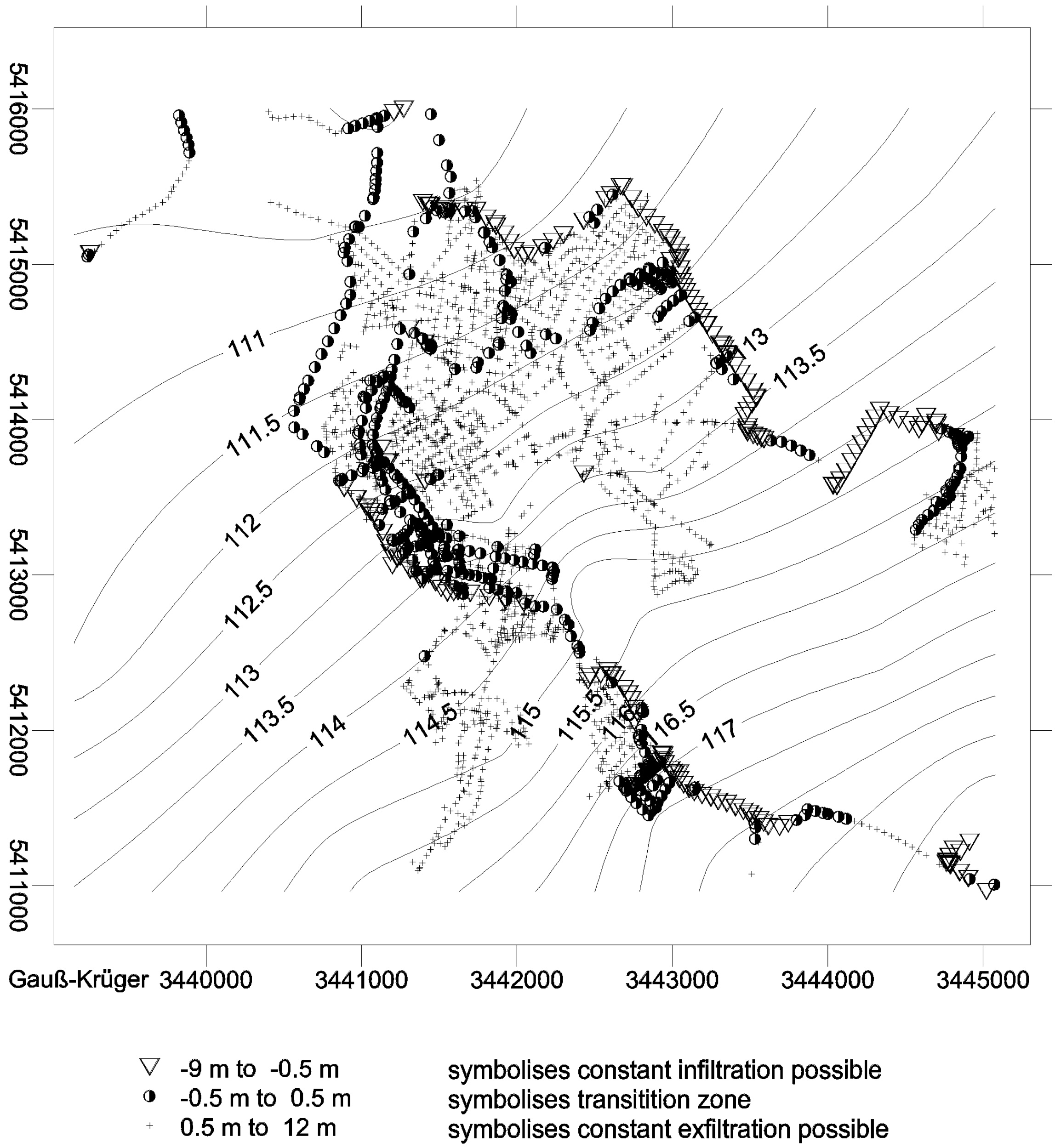

Fig. 3: Position of sewers in Rastatt in relation to groundwater level (m.a.m.s.l. measured at 7.9.2001).

Hydrochemical sampling

Boron, potassium, phosphorous and sodium showed elevated concentrations in the groundwater beneath the city centre and close to focus observation wells (see Table 1). Elevated concentrations of otherwise readily consumed ammonium indicated fresh wastewater influence from a close source. As boron and potassium cannot be considered as single source marker species it was attempted to use more sewage specific substances like pharmaceutical residues or iodated x-ray contrast media as sewage markers. Within the current analytical programme pharmaceutical residues could not be detected in the urban groundwater of Rastatt. However, several findings of iodated x-ray contrast media prove the exfiltration from leaky sewer systems beneath the city centre. In particular amidotrizoic acid was detected in concentrations up to 360 ng/l. The only other possible source for input of iodated contrast media would be the River Murg which showed amidotrizoic acid concentrations below the detection limit. Combining the different findings it can be stated that hydrochemical evidence of significant wastewater exfiltration could be found in the urban aquifer. Furthermore, elevated bacterial counts were detected in the whole city area with pronounced peaks at the sewer focus observation wells. Besides the traditionally used Escherichia coli, enterococci showed especially good potential as a wastewater indicator (Paul et al 2004).

Numerical Modelling

Based on the spatial sewer defect distribution stored in the GIS-system and drawing back on the available knowledge of exfiltration rates the leaky sewers can be integrated into numerical groundwater models as point sources with a defined discharge. In order to start with a model ready for validation only small scale (1000 m^2) transport models were calculated for this paper. The results of the numerical modelling show that the quantitative effect of a single sewer leakage with an exfiltration rate of 1 m^3/day is quite limited in a 20 m thick aquifer with hydraulic conductivities of 1*10-3 m/s. The corresponding rise in groundwater level is less than 1 cm in a distance of 10 m from the leak. However, the qualitative impact considering a conservative species extends much further and elevated concentrations (e.g. boron) should be measurable in 70 m distance from the leak (Fig 4).

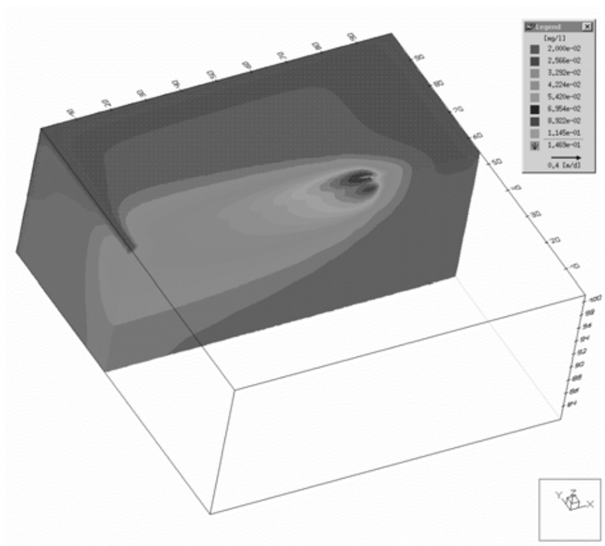

Fig. 4: 3-dimensional modelling of a single leaking sewer in Rastatt.

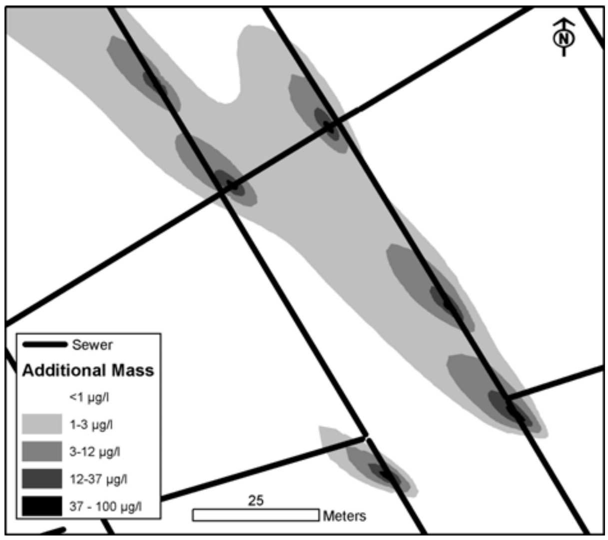

Fig. 5: Implementing sewer leaks as point sources into numerical groundwater models.

Calculations considering the large number of sewer defects and the consequent superposition of contamination plumes are currently being performed. First conceptual results are shown in Fig 5. While it remains difficult to estimate the actual exfiltration rate from the sewer because no working deterministic model exists, the numerical groundwater models can be used to calculate different scenarios to account for this uncertainty.

CONCLUSIONS

It has been demonstrated that the quantitative and qualitative assessment of the interaction between urban drainage systems and groundwater is a necessary component of sustainable urban water management. The environmental impact of wastewater exfiltrating from sewer systems beneath a medium sized city has been assessed. The extrapolation of laboratory results to the field scale still beholds many uncertainties and further research is needed. Actual deterioration of the groundwater quality has been observed using multiple marker species. The integration of sewer leaks as point sources into numerical groundwater transport models can be used to predict the effect of a large number of sewer defects on the urban groundwater and enables scenario analysis.

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