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ORIGINAL ARTICLE

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# Assessing sewer–groundwater interaction at the city scale based on individual sewer defects and marker species distributions

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**Abstract** By combining a sewer defect database and hydrogeological information, it has been attempted to assess sewer–groundwater interaction at the scale of the city of Rastatt (SW-Germany). Comprehensive hydrochemical samplings, including a series of new marker species, have been conducted in the urban aquifer and used for validation. The iodated X-ray contrast media, amidotrizoic acid and iothalamic acid, can be considered as highly specific for wastewater influence and have been found in several groundwater observation wells.

**Keywords** Urban groundwater · Sewer system · Sewer defects · Marker species

## Introduction

### Problem definition

Global population growth and changing climatic conditions result in water scarcity in many areas worldwide, especially in the big cities which are growing fast and are often located in unfavourable places. While urban aquifers are often perceived as being of lesser relevance for the drinking water supply, in fact over 40% of the water supply of Western and Eastern Europe and the Mediterranean region are coming from urban aquifers, which are indeed the only natural resource for drinking water supply. In spite of strong efforts initiated by the European Union and other international organisations in the past 20 years, groundwater pollution from industry, traffic, sewers, and agriculture is still high. The complex transport processes of groundwater flow are responsible for the wide distribution of recharged water and contaminants. There is evidence that urban downstream aquifers are contaminated by inorganic, organic, and microbial pollution. In addition to the temporary and single-event contaminations caused by spillages and accidents, leakages from defective sewer systems also provide a continuous source of contaminant input. The European legislation has already included the environmental implications of leaking sewers into the European standards. The European standard EN 752-2 indicates basic performance criteria applicable to any sewer system. In particular, it requests that receiving waters should be protected against pollution and that the structural integrity of urban sewer systems, including water tightness, should be guaranteed. The European Water Framework Directive has also recognised the need for research. The Handbook of the EU-WFD (Von Keitz 2002) cites figures derived from Dohmann et al. (1999) according to which exfiltration rates for the former Western Germany are in the range of 31–445 million cubic meters per year from public sewers. Defective private sewers are expected to significantly increase this amount. The exfiltration of wastewater can lead to raised levels of sodium, chloride, nitrogen compounds, and sulphate in the aquifer (Eiswirth and

Hötzl 1997). Contaminants illegally discharged into the sewer system (e.g. trichlorethene) can also enter the groundwater.

### Description of the case study city

The study area of this work is the city of Rastatt, which has approximately 50,000 inhabitants and is situated 30 km south of Karlsruhe in the Upper Rhine Valley, SW-Germany (Fig. 1). The aquifer most used for drinking water supply and industrial processes is the Upper Gravel Layer beneath the urban area. Its quaternary sediments are made up of unconsolidated sand and gravel with occasional silty lenses (Fig. 2). The aquifer is tapped downstream of Rastatt for drinking water supply and the northern area of the city lies within the groundwater protection zone of the local water works. Recharge takes place mainly through direct infiltration, infiltration from surface water bodies (River Murg, River Rhine, and numerous smaller creeks), flows from the mountain ridge of the black forest, and water mains losses under the city.

Besides the concern for water quality in the aquifer, the local wastewater treatment plant (WWTP) has to deal seasonally with up to 50% excess water due to infiltration into the sewer system. These infiltrations result from high groundwater levels, which are controlled by the River Rhine and the River Murg.

## Methods

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. To validate the calculations, comprehensive hydrochemical samplings, including a series of new marker species, were conducted in the urban aquifer.

### Hydrochemical analysis

In addition to the extensive hydrochemical database existing at the Landesanstalt für Umweltschutz (LfU, Karlsruhe), three sampling campaigns covering ground, surface, and wastewater 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 flame absorption spectrometry. Analyses for boron and heavy metals were conducted at the Institute for Mineralogy and Geochemistry (Karlsruhe) using inductive coupled mass spectrometry (AXIOM). Gadolinium measurements were performed by Prof. Peter Möller (GFZ Potsdam) using solid-phase extraction and GC–MS as described in Bau and Dulski (1996).

### Measurement of pharmaceutical residues and iodated X-ray contrast media

Testing for pharmaceutical residues has been performed at TZW (Center for Water Technology, Karlsruhe) using solid-phase extraction and LC–MS–MS as described in Sacher et al. (2001). Detection limit for pharmaceuticals and iodated X-ray contrast media is at 10 ng/l in groundwater.

### Condition assessment of the sewer system

Corresponding to the 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 (1999) and stored in a database. In a second step, the sewer defect database was given spatial reference in the GIS system. Partial reviewing of the videotapes has shown that there is a considerable underestimation of defects at 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.

### Hydrogeological mapping

To provide a better understanding of the vulnerability of the urban aquifer in Rastatt, a hydrogeological reconnaissance survey was done (Osswald 2002). The survey was based on direct field observations and a digital elevation model as well as on the evaluation of 272 existing drilling logs. Additionally, 22 drillings were executed to fill information gaps. One of the results directly relevant for the exfiltration problem is the isopach map of the thickness of clayey cover layers on top of the urban aquifer. These layers provide some protection of the urban aquifer from direct pollution but are missing at many places. For the sewer system, it is important to note whether a leaking sewer is inside these low hydraulic conductivity sediments or not.

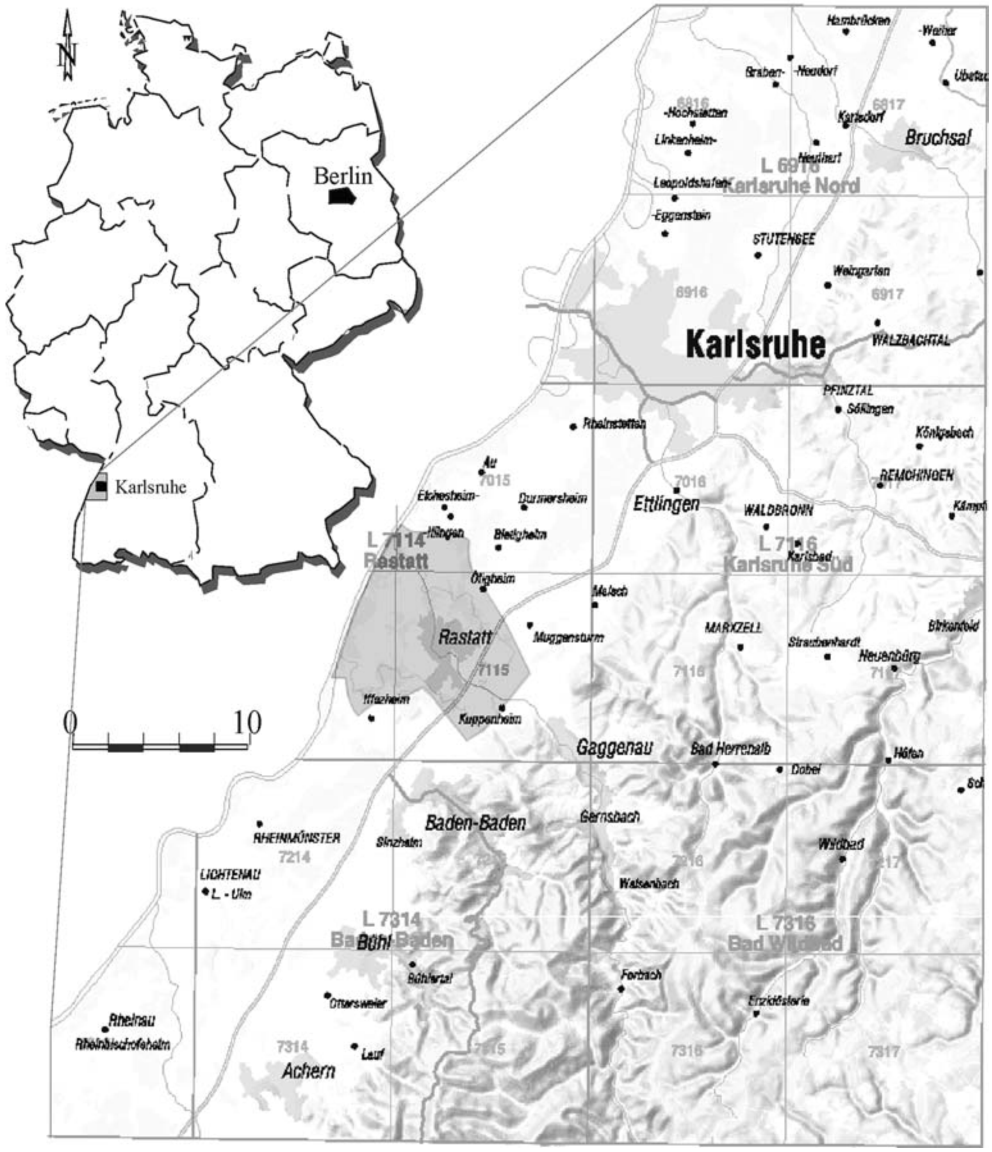



**Fig. 1** Location of the case study site Rastatt in SW-Germany

Observation wells

A total number of 47 wells have been selected for regular monitoring of groundwater level (Fig. 3). All wells are in the topmost aquifer (OKL) 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 selection of locations of the observation wells the GIS-managed sewer defect database was a very good instrument. By using the database large diameter sewers with defects at the sewer bottom were identified (Fig. 4)

## Results and discussion

Infrastructure and hydrogeological boundary conditions

The evaluation of the CCTV inspection results, via the sewer defect database, has shown that there are a large number of defects in the sewer system through which interaction with the groundwater is possible. Within the length of a 208 km sewer system (combined and separate), a total number of 31,006 defects have been noticed. In detail the defects consist of 13,646 damaged or improperly installed house connections,

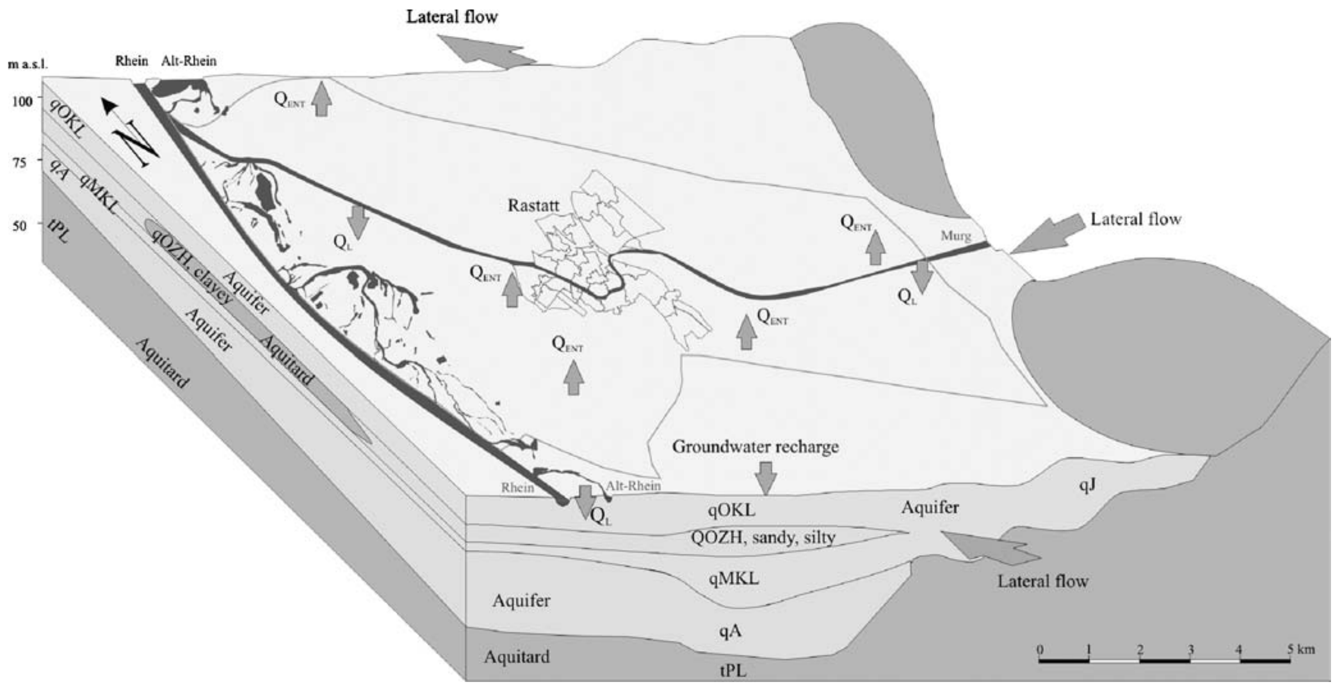
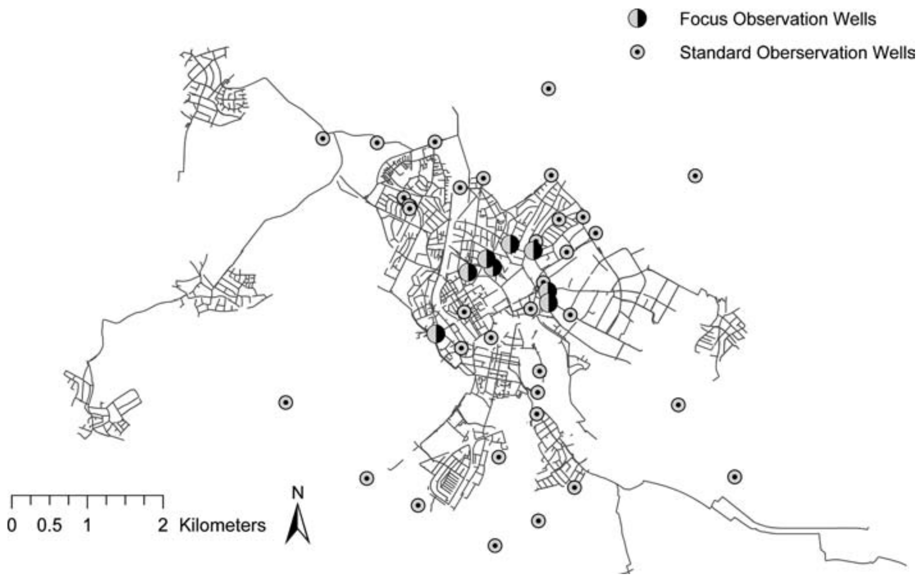



**Fig. 2** Schematic hydrogeological model of Rastatt (modified from Eiswirth 2002)

**Fig. 3** Network of selected groundwater observation wells in Rastatt. *Lines* represent the sewer system




7,363 joint displacements, 4,109 cracks, 2,100 obstacles, 1,584 root intrusions, 1,563 corrosion problems, and 641 other defects. While citing this information, it has to be emphasised that the city of Rastatt has an exceptionally good rehabilitation department and that these figures are describing a rather well-maintained sewer network. To produce an environmental risk assessment of these defects it is necessary to describe the boundary conditions for groundwater–sewer interaction in detail:

- Leak size
- Leak position inside the sewer (e.g. bottom or top)
- Flow regime in the sewer
- Vertical position of the sewer in relation to variable groundwater levels

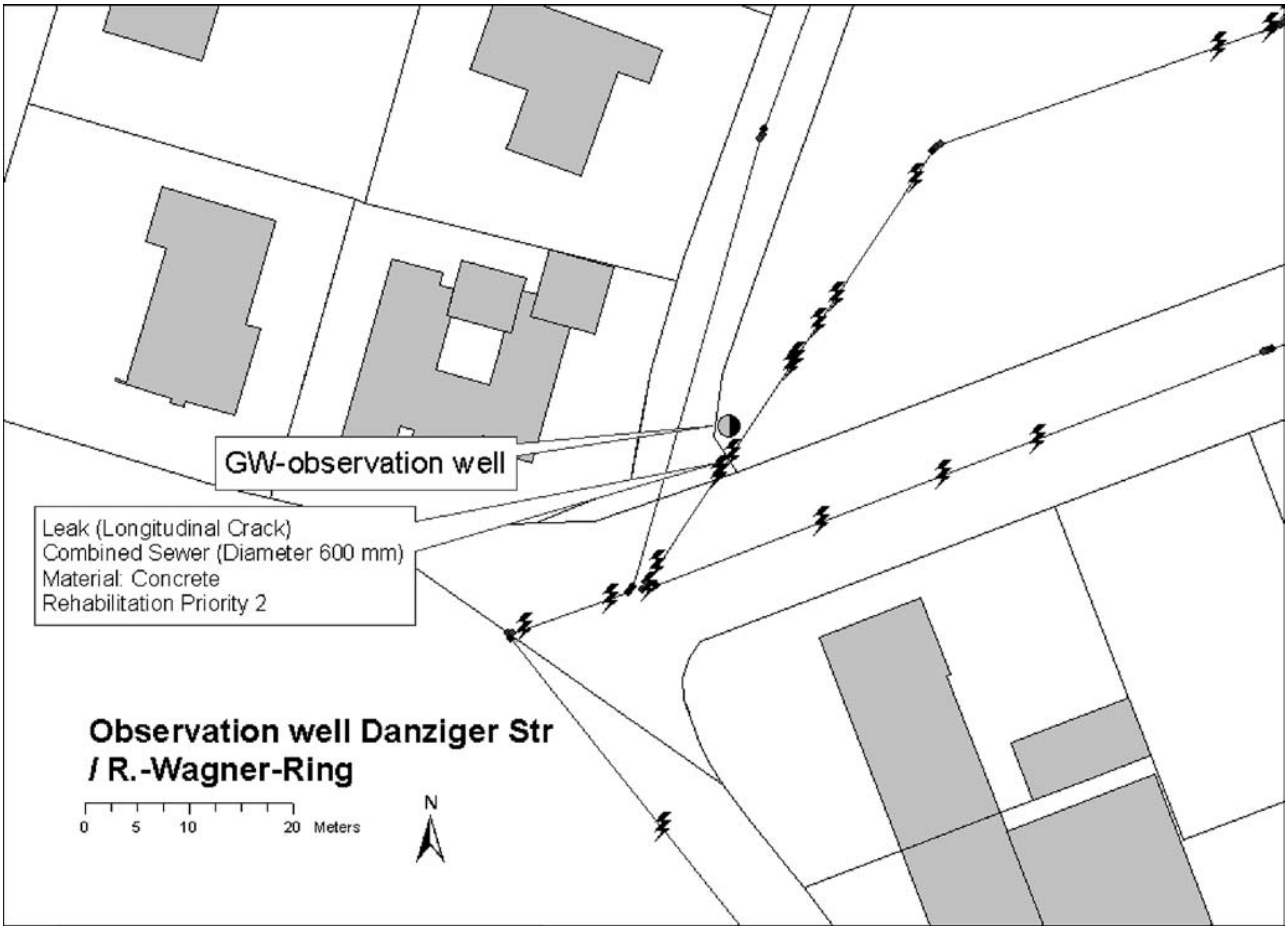



**Fig. 4** Detail from the sewer defect database used for site selection. *Thunderbolts* indicate cracks in the sewer

- Soil or rock type in the immediate sewer surroundings
- Clogging and self-sealing of the leaks

Of these factors, 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 and an average value has to be assigned. The average flow regime in the sewer could be extracted from hydraulic sewer network models in detail, which remains to be done in future.

Vollertsen and Hvitved-Jacobson (2002) found exfiltration rates for holes and cracks to be 0.06 l $day^{-1}$ $cm^{-2}$ after the development of a clogging layer which almost sealed the leak. However, when simulating storm events, Vollertsen and Hvitved-Jacobson (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 approximately 0.35 l $day^{-1}$ $cm^{-2}$ at constant conditions and up to ten times higher rates after only minor damaging of the clogging layer had occurred.

The total area available for sewer–groundwater interaction was roughly calculated from the sewer defects database as 0.96 $m^2$ for a 475,000 $m^2$ part of the city centre.

Using the exfiltration rate of 0.35 l $day^{-1}$ $cm^{-2}$, a discharge rate of 3,469 l $day^{-1}$ wastewater would be exfiltrating into the aquifer in the city centre. In relation to the total area affected, this equals a recharge rate of 2.67 mm $a^{-1}$. Rainfall intensities $>10$ mm $day^{-1}$ did occur 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 and Hvitved-Jacobson (2002), an exfiltration rate of 3.5 l $day^{-1}$ $cm^{-2}$ 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 and Hvitved-Jacobson (2002) produces a total recharge rate of 2.88 mm $a^{-1}$ for the city centre of Rastatt.

These recharge rates are further influenced by groundwater level as a constraint for wastewater exfiltration. As shown in Fig. 5, several sewers are beneath the water table even in 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. Recent field measurements in real sewers using double packer systems as well as real world sewer test sites point to significantly higher exfiltration rates. Further information on these measurements including the uncertainty involved will be published soon by the authors.

## Marker species distributions

For an independent direct assessment of the sewage exfiltration, comprehensive hydrochemical samplings of potential marker substances in the groundwater of Rastatt were conducted. Apart from major ions, microbiological parameters, rare earth elements, dissolved organic carbon, boron, and pharmaceutical residues were analysed.

Although the major ions show distinctively different concentrations in sewage and groundwater, usually they cannot be used as indicator due to the manifold parameters affecting their concentration in the groundwater. Elevated chloride concentrations, for instance, might also originate from road de-icing in winter.

Of the major cations Na, K, Mg, and Ca, none showed a pattern corresponding to the extension of the city area, where the effects of sewage exfiltration should be pronounced. The concentrations are mainly controlled by different aquifer lithologies, the influence of infiltrating surface water bodies (especially the River

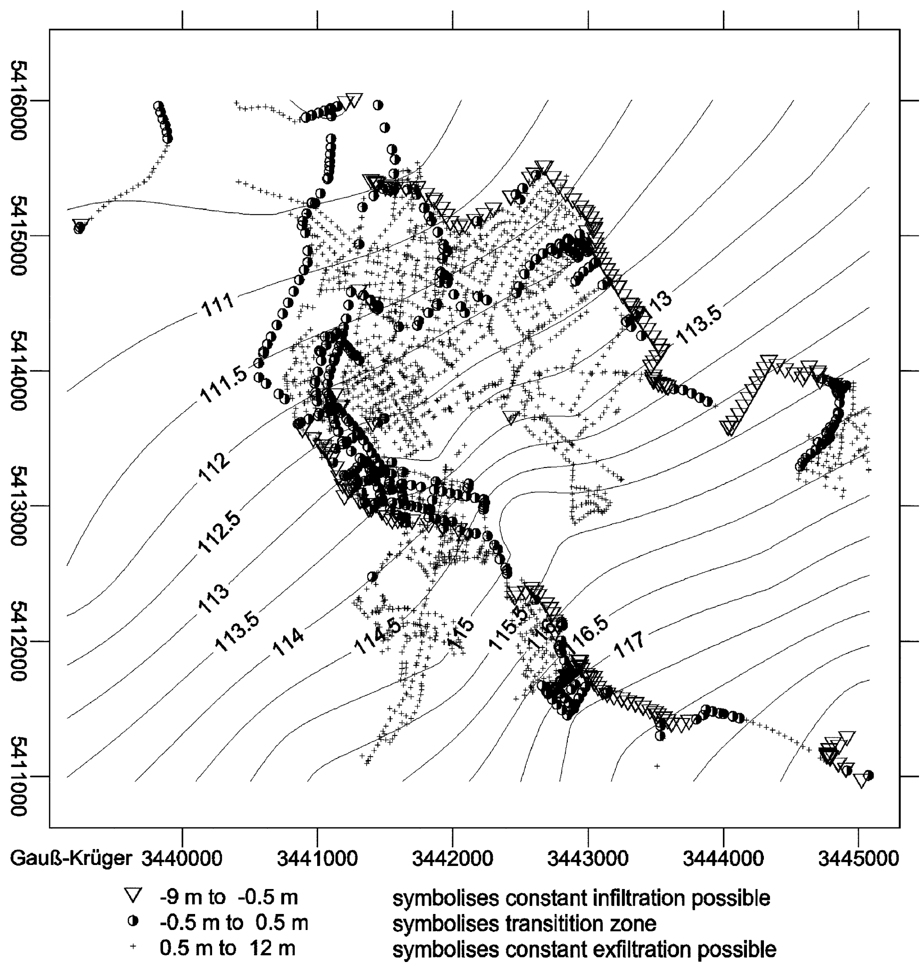



**Fig. 5** Position of sewers in Rastatt in relation to groundwater level (m.a.m.s.l. measured at 7.9.2001)

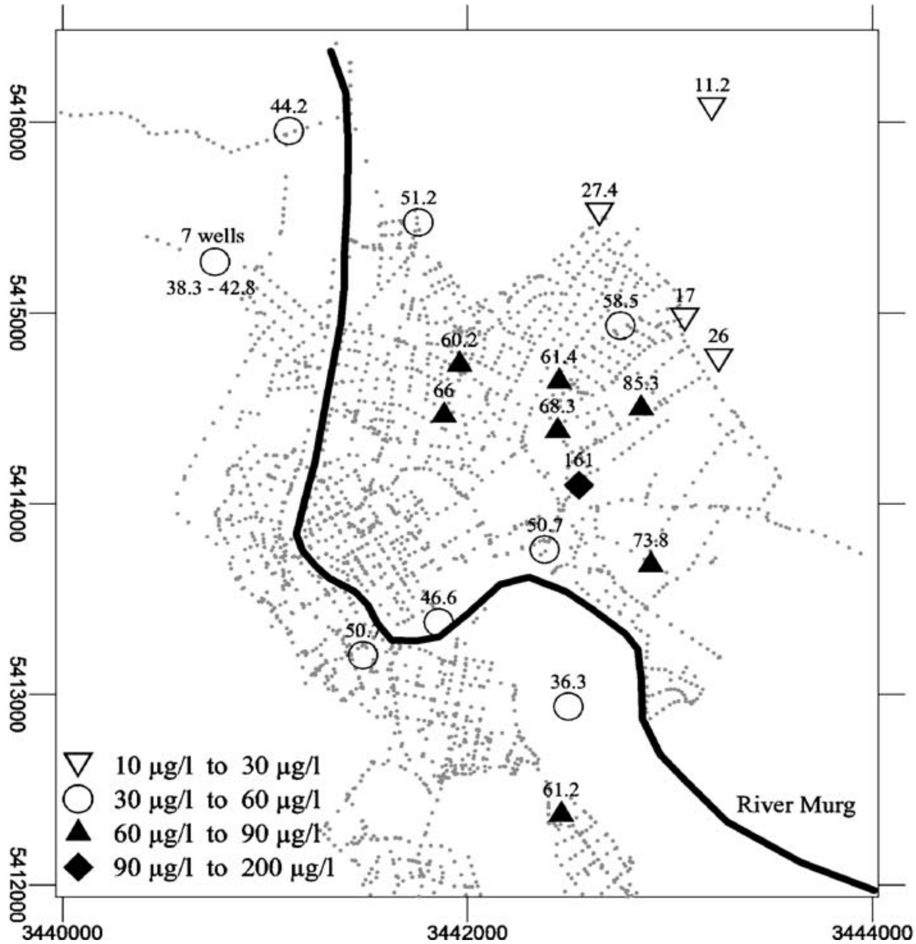



**Fig. 6** Boron concentrations measured in the urban aquifer of Rastatt (28–30.11.2001). *Light grey dots* indicate the position of the sewer system

Murg), and different soil types which affect recharge composition. The same situation was found for major anions.

Elevated concentrations in the groundwater below the Rastatt city centre have been found for boron. Boron has been widely used in detergents in the past and is only slowly replaced by other substances. Concentrations in the sewage range between 690 and 2,066 µg/l B (Fig. 6).

While gadolinium as a tracer substance for wastewater has successfully been used in surface and groundwater in several other studies (Möller et al. 2000), no significant anomalies could be detected in the aquifer of Rastatt. This was due to elevated geogenic background values for rare earth elements and the sparse use of gadolinium-containing contrast media in local hospitals.

Pharmaceutical residues have been found in many German rivers and also locally in groundwater (Sacher et al. 2001). However, none were found in a series of groundwater samples taken in 2002 in Rastatt, although significant loads were present in the wastewater (Table 1). One soil water sample taken from a suction cup (SK7) beneath a sewer leak showed bezafibrate concentrations of 440 ng/l but the groundwater of observation well GWM 6 at a distance of 4 m to the suction cup showed no concentrations above the detection limit. It is reasonable to assume that the pharmaceutical residues are subject to microbiological decomposition and adsorption effects on their passage through the unsaturated zone. Another explanation might be that the leakage rate is too small and the dilution with the unaffected groundwater is lowering concentrations below the detection limits.

In contrast to the pharmaceutical residues, the iodated X-ray contrast media proved to be useful, thanks to their high persistivity (Baus 2002; Ternes and Hirsch 2000) in the aquatic environment and uniqueness in their use (Table 2). Elevated concentrations in the Rastatt city centre have been measured for the iodated contrast media, amidotrizoic acid (66 ng/l) and iothalamic acid (72 ng/l). At the inflow of the wastewater treatment plant, concentrations of 610–930 ng/l iothalamic acid and 840–1,200 ng/l amidotrizoic acid were measured in the wastewater. Considering that the natural concentration of iodated X-ray contrast media

**Table 1** Pharmaceutical residues (in ng/l) detected in groundwater, soil water, and wastewater in Rastatt

| Substance | Groundwater | | | | | | | Soil water | Wastewater | |
|---|---|---|---|---|---|---|---|---|---|---|
| | GWM 6, 12.3.02 | GWM 5, 12.3.02 | GWM 1, 12.3.02 | 112/221, 12.3.02 | AGIP P1, 12.3.02 | Metz P9, 12.3.02 | ELF P1, 12.3.02 | SK7, 12.3.02 | Inflow WWTP, 12.3.02 | WW sewer, 12.3.02 |
| Bezafibrate | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | 440 | 1,900 | 6,000 |
| Carbamazepine | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | 42 | – | 970 |
| Clofibric acid | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | 340 | < 50 |
| Diazepam | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | 310 | 120 |
| Diclofenac | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | 260 | 4,100 | 8,400 |
| Etofibrate | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 50 | < 50 |
| Fenofibrate | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | – | < 50 |
| Fenofibric acid | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | 94 | 740 | 190 |
| Fenoprofen | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 50 | < 50 |
| Gemfibrozil | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | 81 | 190 | < 50 |
| Ibuprofen | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | 120 | 3,800 | 2,100 |
| Indometacin | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | 220 | 76 |
| Ketoprofen | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 50 | < 50 |
| Naproxen | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | 540 | < 50 |
| Pentoxifyllin | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 20 | < 50 | < 50 |

**Table 2** Iodated X-ray contrast media [ng/l]

| Substance | Groundwater | | | | | | | | SW | Wastewater | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AGIP P1, 12.3.02 | GWM 1, 30.4.02 | 0156/2 11-1, 29.4.02 | Metz P9, 29.4.02 | 0021/2 11-6, 29.4.02 | 0154/2 11-1, 29.4.02 | ELF P1, 29.4.02 | BK1-102, 29.4.02 | SK7, 29.4.02 | WW test site, 30.4.02 | WWT inflow, 8.5.02 | WWT inflow, 12.3.02 |
| Iopamidol | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | 24 | < 10 | < 10 | 1,000 | < 100 |
| Iopromide | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | 1,700 |
| Iomeprol | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | 165 | 21,000 | 12,000 |
| Amidotrizoic acid | 66 | < 10 | 20 | 13 | 15 | < 10 | < 10 | 23 | 17 | < 10 | 1,200 | 840 |
| Iodipamide | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 100 |
| Iohexol | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | 960 |
| Iopanic acid | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 100 |
| Iothalamic acid | 72 | < 10 | 12 | 12 | < 10 | < 10 | < 10 | < 10 | 14 | < 10 | 930 | 610 |
| Ioxalagic acid | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 100 |
| Ioxithalamic acid | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | < 10 | 5,900 | 710 |

in groundwater is zero and assuming that iodated X-ray contrast media are conservative this would indicate a range between 5 and 12% of wastewater in groundwater. However the concentrations of iodated X-ray contrast media in the sewer close to the groundwater observation might well be significantly higher than that at the wastewater treatment plant and some natural background might be given from infiltration of anthropogenically influenced river water.

## Conclusions

The combined infrastructural and hydrogeological risk assessment of the sewer system in the case study city of Rastatt has shown significant potential for sewer–groundwater interaction. CCTV observations were used for the assessment of the exfiltration potential based on individual defects. It has to be noted that CCTV inspections cannot directly assess the water tightness of the sewer and can lead to an underestimation of leaks. The hydrogeological constraints on sewage exfiltration have been identified and stored within a geographical information system. The acquired database now allows better positioning of groundwater observation wells, which is essential for assessing the hazard potential of sewer leakages. It is recommended for each city using CCTV inspections to store the results in similar databases, which link infrastructure and environmental information.

A variety of marker species have been tested for their applicability in the urban aquifer of Rastatt. While the rare earth element gadolinium and pharmaceutical residues produced no hints on major sewage exfiltration in

Rastatt, it was possible to analyse iodated X-ray contrast media in five of the eight groundwater wells with maximum concentrations of 66 ng/l amidotrizoic acid and 72 ng/l iothalamic acid. Compared with concentrations in the sewage, this points to a percentage of approximately 5–12% of sewage in the groundwater in this area. Elevated concentrations of boron in the city centre further corroborate these findings.

Future research must lead to more precise estimations of exfiltration rates, quantification of leak sizes from CCTV inspections, and more extensive sets of marker species data. Up to date information may be found at www.urbanwater.de.

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## References


ATV-M143E (1999) Advisory leaflet—inspection of sewers and drains, part 2: optical inspection. ATV-DVWK, Hennef

Bau M, Dulski P (1996) Anthropogenic origin of positive gadolinium anomalies in river waters. Earth Planet Sci Lett 143:245–255

Baus Ch (2002) Vorkommen von iodierten Röntgenkontrastmitteln und ihr Verhalten bei der Trinkwasseraufbereitung. DVGW-TZW, Karlsruhe, Veröff. Technologiezentrum Wasser 18, pp 13–30

Dohmann M, Decker J, Menzenbach B (1999) Untersuchungen zur quantitativen und qualitativen Belastung von Boden-, Grund- und Oberflächenwasser durch undichte Kanäle. In: Dohmann M (ed) Wassergefährdung durch undichte Kanäle—Erfassung und Bewertung, Springer, Berlin Heidelberg New York, 306 pp

Eiswirth M (2002) Bilanzierung der Stoffflüsse im urbanen Wasserkreislauf—Wege zur Nachhaltigkeit urbaner Wasserressourcen. Postdoctoral lecture qualification, University of Karlsruhe

Eiswirth M, Hötzl H (1997) The impact of leaking sewers on urban groundwater. In: Chilton J (ed) Groundwater in the urban environment. Problems, processes and management, vol 1. Balkema, Rotterdam, pp 399–404

Möller P, Dulski P, Bau M, Knappe A, Pekdeger A, Sommer-von Jarstedt C (2000) Anthropogenic gadolinium as a conservative tracer in hydrology. J Geochem Explor 69–70:409–414

Osswald J (2002) Hydrogeologische und hydrochemische Zustandsbeschreibung Rastatts im Hinblick auf anthropogene Beeinflussung. Diploma Thesis, University of Karlsruhe, 169 pp

Sacher F, Lange T, Brauch H-J, Blankenhorn I (2001) Pharmaceuticals in groundwaters—analytical methods and results of a monitoring program in Baden-Württemberg, Germany. J Chromatogr A 938(1–2):199–210

Ternes Th, Hirsch R (2000) Occurrence and behaviour of x-ray contrast media in sewage facilities and the aquatic environment. Environ Sci Technol 34:2741–2748

Vollertsen J, Hvitved-Jacobson T (2002) Exfiltration from gravity sewers: a pilot scale study. Water Sci Technol 47(4):69–76

Von Keitz S (ed) (2002) Handbuch der EU-Wasserrahmenrichtlinie. Erich-Schmidt, Berlin, 447 pp

Wolf L, Held I, Eiswirth M, Hötzl H (2004) Environmental impact of leaky sewers on the groundwater quality beneath a medium sized city. Acta Hydrochim Hydrobiol 32(4–5):361–373