The impact of leaking sewers on urban groundwater

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ABSTRACT: Contamination of urban groundwater by sewage leakage from damaged sewers is an increasing matter of public and regulatory concern. It is estimated that in Germany several 100 million m^3 waste water leaks every year from partly damaged sewerage systems into soil and groundwater. In many cities damaged sewerage systems are the main sources for groundwater contamination with sulphate, chloride and nitrogen compounds. Besides the ecological point of view, damaged sewerage systems exhibit essential economic problems because groundwater can also infiltrate into the sewers. This paper presents the results of comprehensive groundwater-quality studies carried out during the last 3 years in the City of Rastatt situated in the Upper Rhine Valley, Southern Germany.

1 INTRODUCTION

Urban groundwater (or groundwater that underlies urban areas) is a distinct subdomain of hydrogeology (Lerner 1996). In contrast to rural areas, urban groundwater shows some specific features. For example, the recharge of urban groundwater is heavily affected by extensive sealing of surfaces, leaking water mains, sewers, and stormwater recharge. Additional large spatial variations in recharge rates are typical. Beside this, urban groundwater is also effected by geotechnical interactions (e.g. deep basements, tunnels). The quality of urban groundwater is mainly affected by the input of the muniplicity of urban features. Table 1 shows the main possible sources for urban groundwater contamination.

Table 1. Possible sources for urban groundwater contamination.

- waste sites and solid waste disposals
- septic tanks and cesspools
- polluted precipitation of surface runoff
- road deicing
- gasoline stations
- water treatment effluents
- mine tailings and brines
- runoff from tank pipeline and storage leakage
- industrial impacts (cooling water, process water)
- chemical dry cleaners
- agricultural impacts, e.g. parks and gardens (fertilisers, soil amendments, pesticides, animal wastes, stockpiles)
- traffic accidents (dangerous goods)
- deep buildings (grout injections within the groundwater)
- leaky sewerage systems (industrial and urban waste water)

In order to understand the impacts of leaky sewerage systems within the framework of a research and development project "leakage detection for old sewers and sewerage systems in areas with fluctuating groundwater tables", the correlation between damaged sewerage systems, soil and groundwater and contamination have been investigated by co - operation between science and municipal practice. The research has been carried out by the Department of Applied Geology, University of Karlsruhe and the Municipal Department of Civil Engineering, City of Rastatt and partly the Federal Institution of Hydraulic Engineering, Karlsruhe.

One scientific aim of the research and development project was to estimate the possible risk of sewage exfiltration into soil and groundwater and to develop and test nondestructive leakage detection methods for damaged sewers. This paper deals with the assessment of potential risks due to damaged sewers; the results of other parts of the project are presented elsewhere (e.g. Eiswirth et al. 1995a, 1995b).

The feasibility for detecting and ascertaining the extent of sewerage leakages has been tested on an old very damaged sewer pipe section in the City of Rastatt at "Rheinauer Murgdamm". This old sewer has been assembled in an earth dam, used as a flood dam for the River Murg (Eiswirth et al. 1994). Further research has been carried out in a specially constructed sewerage test site in a suburb of Rastatt, and hydrochemical investigations have been carried out in order to assess the influence of sewage effluents on groundwater and soil quality.

Chilton, J. et al. (ed): Groundwater in the urban environment, p. 399-404

2 GEOLOGY AND HYDROGEOLOGY

In Plittersdorf, a suburb of the City of Rastatt, groundwater levels are mainly effected by natural fluctuations of the nearby River Rhine and its tributary river, the Altrhein (Figure 1).

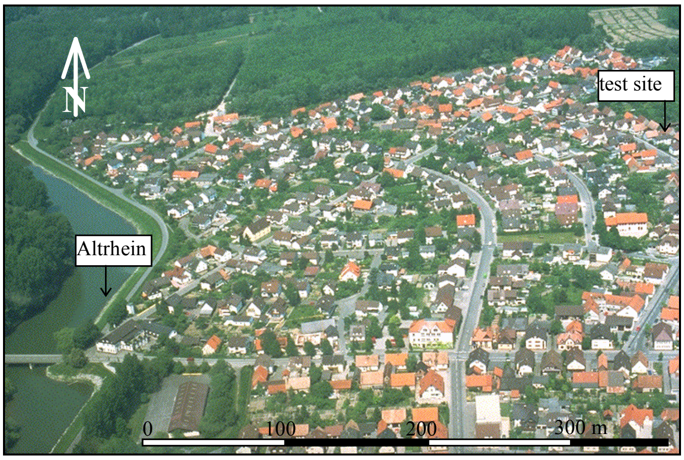

Figure 1. Aerial view of Plittersdorf (suburb of the City of Rastatt).

The geology of the Upper Rhinegraben in the area of Rastatt/Plittersdorf can be divided into four main tectonic units: a graben block, a downfault block, a marginal block (fore hills), and an outlier zone (basement) (Figure 2). The graben is bordered by the Black Forest and the Vosges. During Holocene times, the river Rhine excavated the Lower Terrace Formations within the present Rhine depression and filled it up with recent material in various thickness. With a generally clearly rising slope, the Rhine depression borders the valley terrace that in this region corresponds to the uniform flat Lower Terrace plain. Along the mountain border, a Holocene channel was created by the rivers Kinzig, Murg and others coming down from the mountains. As shown in Figure 2 in the region of Rastatt the thickness of the Pleistocene sediments is some 60 m and increases continuously in northward direction (Bartz 1967).

On the graben block the thickness of the Upper and Middle Pleistocene gravel layer is about 33 m. Below, the Lower Pleistocene Rhine sediments follow: the base of the Quaternary sediments is build by impermeable Pliocene sediments at an elevation of about 55 m a.s.l. (Figure 2). The Quaternary can be divided into three gravel layers (main aquifers) separated by two less permeable intervals, and a lower less permeable sandy-silty layer (Lower Quaternary). The main aquifer (Upper gravel layer) in the area of Plittersdorf has a thickness of about 20 m.

The local geology of Plittersdorf is dominated by a 5 to 11 m thick gravel layer and by 1.5 to 4 m thick Holocene sands/silts in channels. Beside these sediments anthropogenic infill can be found everywhere in Plittersdorf (Figures 3 and 4).

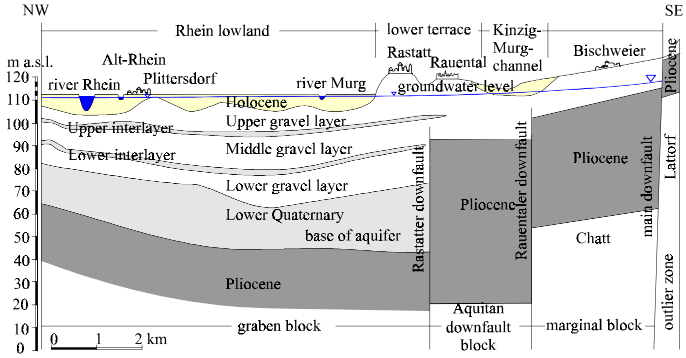

Figure 2. Geological cross section (NW-SE) through the Upper Rhine Valley in the area of Rastatt.

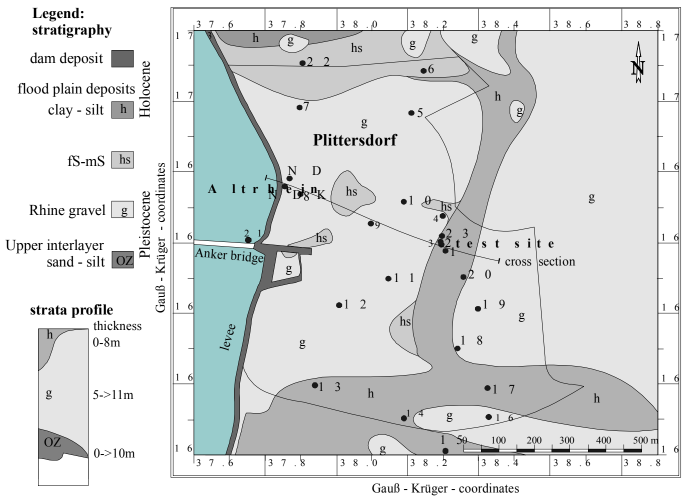

Figure 3. Schematic local geological map of Plittersdorf and location of groundwater observation wells.

The suburb of Plittersdorf is bordered by a levee against high floods from the Altrhein river in the west.

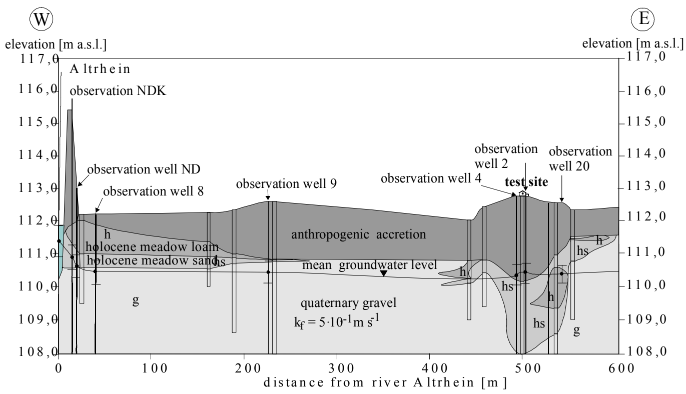

Figure 4. Schematic geological cross section (location is indicated in Figure 3).

Groundwater flow in Plittersdorf during periods of low water level of the Altrhein river is in a northwest direction with a low hydraulic gradient of 0.26 % (Figure 5).

Groundwater velocities in this area have been calculated with the 3D numerical groundwater flow model FEFLOW®. For example the numerical model indicates a mean groundwater flow velocity during low water level at groundwater observation well 9 of about $v_x = 0.8$ m/d (to the west) and $v_y = 1.4$ m/d (to the north).

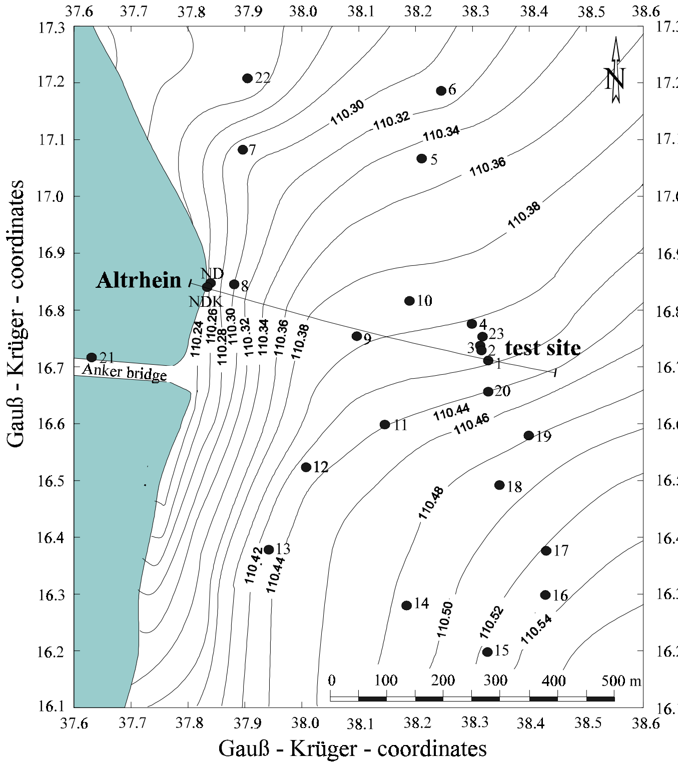

Figure 5. Map of groundwater level in Plittersdorf during low river water level on 10.11.1993 [m a.s.l.].

3 TEST SITE DESCRIPTION

In April 1993, an artificially constructed sewer test site was built in the area of the sewage pumping station in Plittersdorf. This sewer section, with separated storm and sanitary sewers, was connected directly to the separate sewerage system of the city (Figure 6).

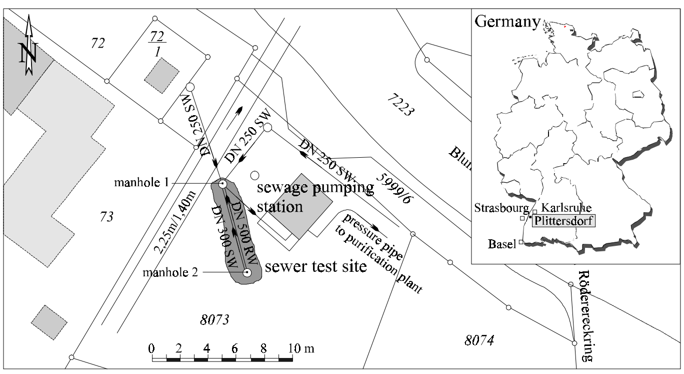

Figure 6. Location of waste water test site in Plittersdorf (Southern Germany).

This sewer test system allows flushing with municipal sewage as well as flushing of the storm sewer with rain water under nearly “natural“ conditions. This kind of a mesoscale model was constructed to study physical, chemical and microbiotic processes in the soil and groundwater, including transport and degradation of leaking sewage. Details are presented in Eiswirth et al. (1995a,b).

4 HYDROCHEMICAL INVESTIGATIONS

Hydrochemical groundwater investigations can define the risk assessment for soil and groundwater caused by sewage exfiltration from damaged sewers. The subsurface migration behaviour of the contaminants is mainly influenced by the soil composition, e.g. content of clay, organic matter and pH-value. For detailed description of the hydrochemical changes in groundwater chemistry during subsurface transportation, water samples have been taken from bore holes along the line shown in Figure 5. Beside the seasonal and regional variation in groundwater chemistry, areas with anomalous chemistry diverge chemical contents have been detected (Figures 7-11).

The hydrochemical anomalies in groundwater below the test site (groundwater observation well 2) could only be caused by the influence and mixture with sewage leaking from the sewer. For example, consider the specific electric conductivity (SEC). The groundwater in observation well 2 is significantly influenced by waste water with a mean SEC of 1000 µS/cm (Figure 7). This is clear evidence for active leakage of sewage from the test site. This result is confirmed by the variations in sulphate and potassium concentration (Figure 8).

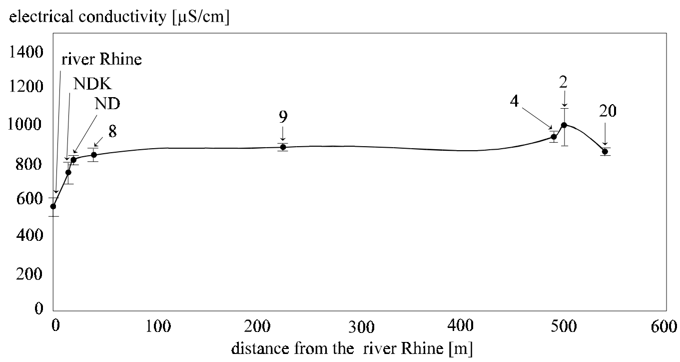

Fig. 7: Variations of the specific electric conductivity in groundwater along the hydrochemical profile (confidence of means with 95% level of significance).

The mean sulphate concentrations in the groundwater of observation well 2 are low compared to the other observation wells (Figure 7). This is due to desulphurisation processes (mean sulphate concentration in waste water 80 mg/l) in the anaerobic groundwater zone below the damaged sewer test site.

Potassium concentrations in the groundwater of Plittersdorf are relatively constant at 8 mg/l. At observation well 2 the mean potassium contents are higher (11 mg/l) due to the influence of waste water (mean potassium concentration in waste water 38 mg/l).

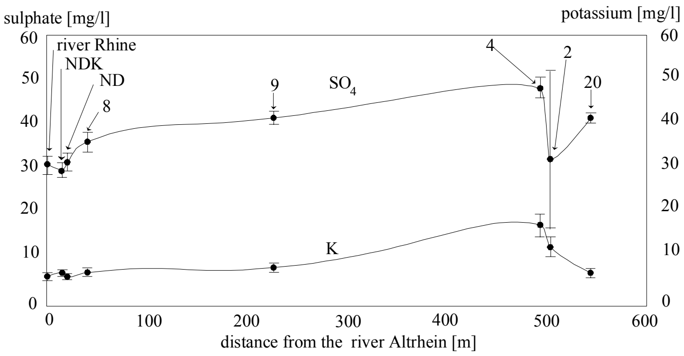

Figure 8. Variations of sulphate and potassium concentrations in groundwater along the hydrochemical profile.

The mean chloride concentrations in the groundwater of Plittersdorf are relatively constant. Only at observation well 2 the mean chloride contents are higher (69 mg/l) due to the influence of waste water (mean chloride concentration in waste water 110 mg/l).

The mean nitrate concentrations in the river water are very low (4 mg/l) compared to the high nitrate concentrations in the groundwater of Plittersdorf (Figure 9). At observation well 2 the nitrate concentrations are nearly zero (0.7 mg/l) due to (incomplete) denitrification / nitrification processes in the anaerobic zone below the test site. During these microbiological processes nitrate is mainly reduced to nitrogen gas (see equation 1 in section 5).

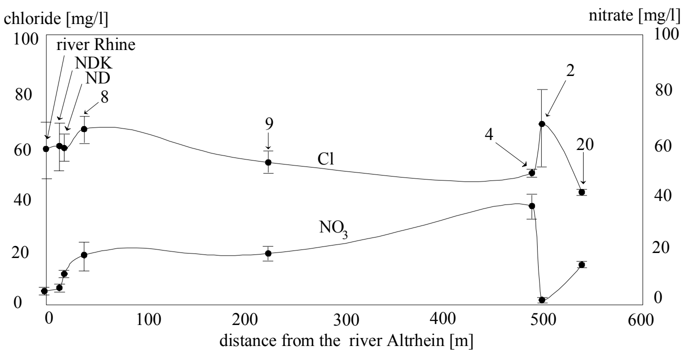

Figure 9. Variations of chloride and nitrate concentrations in groundwater along the hydrochemical profile.

Bicarbonate concentrations in groundwater of Plittersdorf correspond to SEC variations. At observation well 2 the bicarbonate contents are significantly elevated (Figure 10) while calcium concentrations in the groundwater of Plittersdorf are relatively constant at 110 mg/l.

The CO_2-concentrations in the groundwater of Plittersdorf are relatively constant while at observation well 2 the mean CO_2 contents are higher (80 mg/l) due to microbial degradation of the waste water effluents in the sub-surface (Figure 11).

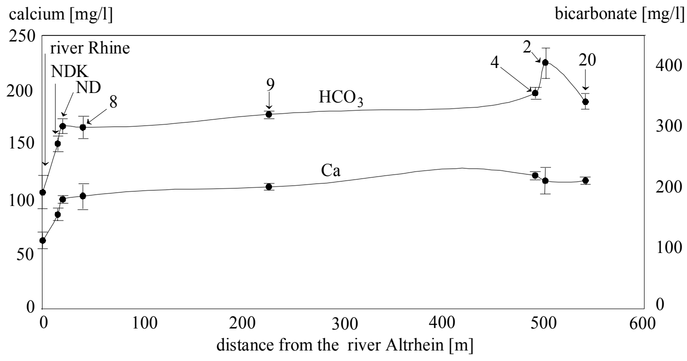

Figure 10. Variations of bicarbonate and calcium concentrations in groundwater along the hydrochemical profile.

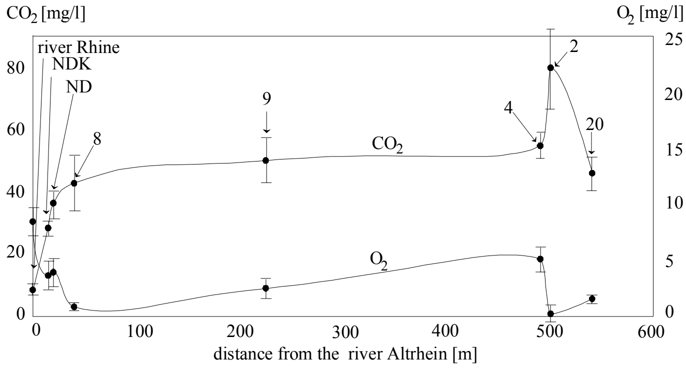

Figure 11. Variations of carbon dioxide and oxygen concentrations in groundwater along the hydrochemical profile.

While CO_2 is produced by aerobic biodegradation in the unsaturated zone below the sewer leakages, oxygen is consumed. Therefore the mean O_2-concentrations in groundwater are nearly zero and anaerobic conditions have been established (Eiswirth & Hötzl 1996).

The various transformation reactions occurring in the unsaturated subsurface below the damaged sewers as well as in groundwater are summarized in the following section.

5 TRANSFORMATION REACTIONS

Various transformation reactions occur in the subsurface environment of damaged sewers. For example, mineralisation of organic nitrogen produces nitrate, which may then be reduced to nitrogen gas (= denitrification, equation 1) or ammonium (= dissimilatory nitrate reduction, equation 2) as follows:

$$4\,NO_3^- + 5\,CH_2O = 2\,N_2(g) + 5\,HCO_3^- + H^+ + 2\,H_2O \quad (1)$$

$$NO_3^- + H_2O + 2\,CH_2O = NH_4^+ + 2\,HCO_3^- \quad (2)$$

Microbial degradation of waste water in the subsurface is mainly influenced by the concentration and availability of free O_2 and other electron acceptors (e.g. sulphate and nitrate). Therefore organic matter is partly oxidized to ammonium (= ammonification, equation 3). If there is enough oxygen avail-

$NH_4^+ + 2\,O_2 = NO_3^- + 2\,H^+ + H_2O$ (4)

The described aerobic biodegradation processes decrease the dissolved O_2 content and increases the dissolved CO_2 concentration in pore water and groundwater. The biodegradation can also be described using glucose $C_6H_{12}O_6$ representing organic matter (Brun and Engesgaard 1994, equation 5).

$$C_6H_{12}O_6 + 12\,H_2O \Rightarrow 6\,CO_3^{2-} + 36\,H^+ + 24\,e^-$$

$$CO_3^{2-} + 2\,H^+ \Rightarrow CO_2(aq) + H_2O \quad (5)$$

Following a release, oxygen is depleted and carbon dioxide in the soil air is increased as a result of aerobic respiration (Figure 12). As soon oxygen levels diminish, anaerobic processes become dominant. Under highly anaerobic conditions the biodegradation can produce high levels of carbon dioxide and methane (equation 6):

$$C_6H_{12}O_6 \Rightarrow 3\,C_2H_4O_2 \Rightarrow 3\,CO_2 + 3\,CH_4 \quad (6)$$

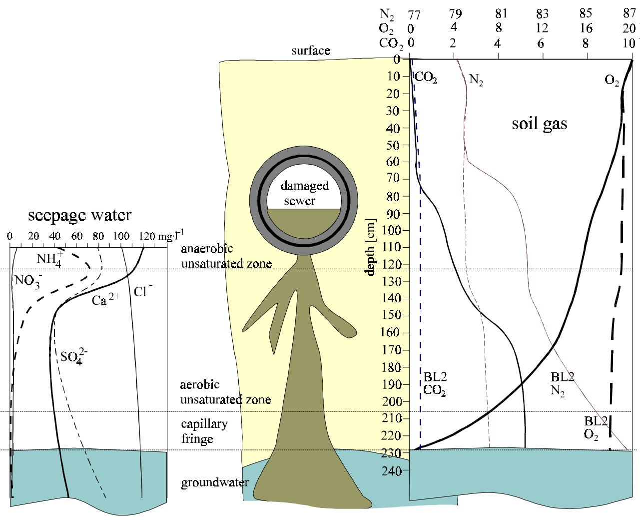

Figure 12. Variations in waste water chemistry and soil gas composition during the effluent seepage through the subsurface below a damaged sewer

During the investigation in Plittersdorf the following major transformation processes have been identified during the seepage of waste water effluents through the subsurface below damaged sewers:

- precipitation of iron sulphides, anaerobic oxidation, fermentation and ammonification within a thin anaerobic zone immediately below the sewer leakages (Figure 12).
- biodegradation (oxidation) of organic matter, dissimilatory nitrate reduction and bicarbonate buffering within an aerobic unsaturated zone above the capillary fringe (Figure 12).

6 BALANCING THE IMPACT OF WASTE WATER EFFLUENTS

The sewerage system of Plittersdorf/Rastatt was built mainly in the years 1965 to 1970. The complete sewerage system can be subdivided into a total length of 9882 m storm water sewers (mean diameter 300 mm) and 9955 m waste water sewers (mean diameter 250 mm). In Plittersdorf about 87 % of the sewerage system is situated within the zone of fluctuation of the groundwater table. Therefore the groundwater level is influencing the ex- or infiltration behaviour of damaged sewers. As indicated in Figure 13 the waste water discharge at the sewage pumping station in Plittersdorf for 1993 and 1994 is strongly influenced by the groundwater level. The mean daily waste water discharge for Plittersdorf is 890 m³/d. Using the mean daily water demand for Plittersdorf (320 m³/d), a total of 570 m³/d of additional water was pumped through the pumping station. Subtracting the rain runoff from households (106 m³/d), the groundwater infiltration rate is calculated to be 409 m³/d for Plittersdorf (Figure 13). This means that nearly 52 % of the total waste water discharge is infiltrated by groundwater.

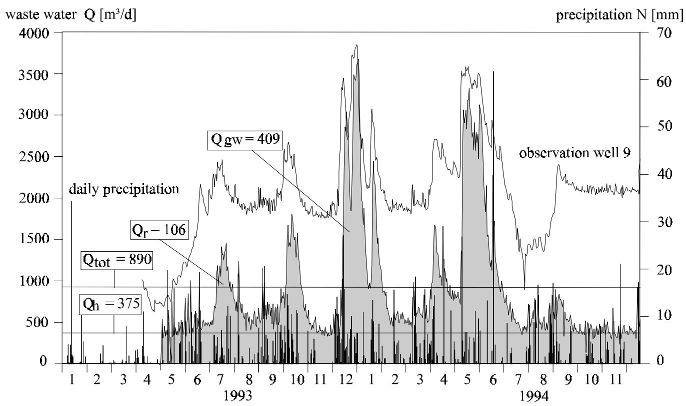

Figure 13. Waste water discharge and daily precipitation at the sewage pumping station in Plittersdorf for 1993 and 1994 (Q_{tot} = total discharge; Q_r = storm water runoff, Q_h = runoff from households; Q_{gw} = groundwater infiltration).

For Plittersdorf we calculated a groundwater infiltration rate of 46600 l/d·km and a waste water exfiltration rate of 1200 l/d·km. In other German cities, e.g. Hannover, infiltration of groundwater (198720 l/d·km) into the sewerage system is also higher than exfiltration of waste water (17300 l/d·km) (Härig and Mull, 1992).

As listed in Table 2, in Plittersdorf the impact of leaking sewers on groundwater quality is indicated mainly from sodium (mean annual input 153 kg/ha·a), ammonium-N (80 kg/ha·a), potassium (55 kg/ha·a), sulphate (55 kg/ha·a), organic nitrogen (33 kg/ha·a) and phosphate (16 kg/ha·a). In Hannover it is mainly sulphate (160 kg/ha·a), chloride (120 kg/ha·a), ammonium-N (30 kg/ha·a), potassium (20 kg/ha·a) and phosphate (13 kg/ha·a) which are leaking into the subsurface from damaged sewers

Table 2. Mean sewage composition and mean annual input from damaged sewers into soil and groundwater in two German cities (Rastatt and Hannover).

	Rastatt			Hannover*)		
	mean concentration in sewage [$mg \cdot l^{-1}$]	mean annual load 4400 $m^3 \cdot a^{-1}$ [$kg \cdot a^{-1}$]	mean annual input 0,030 km^2 [$kg \cdot ha^{-1} \cdot a^{-1}$]	mean concentration in sewage [$mg \cdot l^{-1}$]	mean annual load $6{,}5 \cdot 10^6$ $m^3 \cdot a^{-1}$ [$kg \cdot a^{-1}$]	mean annual input 84 km^2 [$kg \cdot ha^{-1} \cdot a^{-1}$]
potassium	38	167	55	25	160000	20
sodium	111	488	153			
ammonium-N	55	242	80	35	230000	30
organic nitrogen-N	23	101	33			
chloride	101	444	150	150	980000	120
nitrate	7	31	10			
sulphate	38	167	55	200	1300000	160
boron	1.96	9	3	1,7	10000	
phosphate	11	48	16	17	110000	13
lead	0.034	1.5	0.48	0.035	230	0.03
cadmium	0.005	0.022	0.007	0.003	15	0.002
chromium	0.0010	0.004	0.001	0.035	230	0.03
copper	0.062	0.27	0. 09	0.115	730	0.09
nickel	0.027	0.12	0.05	0.035	230	0.03
zinc	0.85	3.7	1.2	0.29	1900	0.22

*) 395 km combined sewerage systems; separated systems: 1060 km waste water sewers. 845 km storm sewers; 84 km^2 area in which all waste water sewers are always above the groundwater level (Härig and Mull, 1992).

7 CONCLUSIONS

The results of hydrochemical groundwater analysis and detailed investigations concerning the movement of sewage show that damaged sewerage systems are the main sources for groundwater contamination in Plittersdorf with sodium, chloride, nitrogen compounds and sulphate. The following migration and fate of the contaminants in soil and groundwater essentially depends on the geology und mineralogy of the sewer´s surrounding. Because most of the waste water compounds leaking to the underground are attenuated and biodegraded within the unsaturated zone the groundwater quality is influenced only within a narrow zone next to the sewer leakages. Therefore the impact of leaking sewers on urban groundwater is strongly variable and the chemical content of industrial and urban effluents mainly produce the potential risk for soil and groundwater.

Acknowledgement

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