Evaluating the success of sewer reconstruction by using carbamazepine as anthropogenic marker in groundwater

Katerina Ruzicka, Matthias Zessner, Alfred P. Blaschke, Robert Fenz, Manfred Clara and Helmut Kroiss

ABSTRACT

The antiepileptic drug carbamazepine is a useful anthropogenic marker in groundwater to detect and quantify sewer exfiltration. In 2003 its application on a city wide scale enabled the identification of a trunk sewer in extremely bad structural status with an exfiltration (of wastewater into groundwater) rate in the adjacent area of around 5% compared to an average of approximately 1% in other parts of the city. After a reconstruction of the trunk sewer investigations were carried out again in 2008. Due to the reconstruction a decrease in exfiltration to roughly 3% could be achieved, which equals a reduction of exfiltration by about 45%. Thus carbamazepine emerged as suitable anthropogenic marker to assess sewer exfiltration and to evaluate the success of reconstruction measurements on a regional scale.

Key words | carbamazepine, sewer exfiltration, monitoring method, groundwater contamination

INTRODUCTION

Owing to the frequently reported bad structural integrity of many sewer systems, contamination of groundwater, as a result of sewer leakage, has become a matter of public concern. In Germany, investigations on the status of sewer systems revealed average damage frequencies varying from 40 to more than 100 damages per km (Stein 1999). The structural integrity of sewers is usually checked by TV inspections, although this method has several disadvantages, e.g. not detecting leaking pipes and difficulties to indentify leaking joints.

Different approaches to identify leaks and to quantify exfiltration rates have been tested so far. Possible methods are pilot scale or full scale experiments at representative sewers, in order to extrapolate the results on a larger scale. Tests conducted at laboratory test rigs by Dohmann et al. (1999) indicated average leakage rates between 140 l.km⁻¹.d⁻¹ and 650 l.km⁻¹.d⁻¹ for foul sewers and combined sewers, in which no pressurized flow occurs in the pipes. These investigations resulted in a probable loss of 1% of sewage flow to the underground, which is similar to the exfiltration rates experimentally recorded by Vollertsen & Hvitved-Jacobsen (2002).

Other methods include the use of tracers, such as boron, sulphate and sodium chloride (Härig & Mull 1992; Eiswirth & Hötzl 1997; Rieckermann & Gujer 2002), but due to varying natural background concentration this kind of tracers is subject to a given limitation, as they have natural background concentrations or can emerge from other sources than wastewater. Studies attempting to quantify exfiltration using tracers resulted in exfiltration rates varying from 1.2 m³.km⁻¹.d⁻¹ for Rastatt (Eiswirth & Hötzl 1997) to 17.3 m³.km⁻¹.d⁻¹ for Hannover (Härig & Mull 1992).

In 2003, the antiepileptic drug carbamazepine was selected as tracer to quantify sewer exfiltration on a city-wide scale. In contrast to many other marker species, this drug is discharged into the environment only via wastewater. Results of this study indicated an average exfiltration rate of 1.8%, but revealed high leakage rates of around 5% in
one part of the study area. Visual inspections of the adjacent trunk sewer proved its extremely bad structural status and led to its reconstruction (Fenz et al. 2005).

In 2008, the possible success of this reconstruction was evaluated by using the marker carbamazepine again. Results and outcomes of this second study are presented in this work.

Case study area

Figure 1 shows the sampling sites in the case study area in Linz, which is the third largest city in Austria with about 190,000 population. The sewage system is a combined system with total length of 550 km (private sewers not included) and four trunk sewers (TS 1-5, Figure 1), at which TS 2 is reconstructed.

A total of 44 groundwater sampling sites, two surface water sampling sites (river Traun and Danube) and one wastewater treatment plant sampling site, were investigated. According to their hydrogeological characteristics, the groundwater sampling sites were made up of eight subzones (see Figure 1). Sampling sites numbers 31 and 52 label the river Danube and Traun, respectively.

In terms of geology (Fenz et al. 2005) the investigated area consists of two areas, which are the Danube lowland and lower terrace as well as the high terrace. Danube lowland and the lower terrace cover almost all sampling sites (except 1, 12, 15 and 44 - subzone 1) and are dominated by a 5 to 15 m thick aquifer consisting of quaternary gravel. Kf of this layer varies between \(3.0 \times 10^{-3}\) m/s and \(5.0 \times 10^{-3}\) m/s. Sewers are mainly situated in this gravel layer, predominantly a few metres above groundwater level. In the high terrace, in which the sampling sites 1, 12, 15 and 44 (subzone 1) are located, the ground water elevation is 10–20 m higher than in the lower terrace. In this part a 10–15 m thick clay layer separates the gravel layer from the anthropogenic accumulations. Sewers are mainly situated in this low permeable clay layer, 10–20 m above groundwater level (Figure 1).

MATERIAL AND METHODS

Characteristics of carbamazepine

Carbamazepine is applied as a drug for the epilepsy control since the 1970s. It is also effective in the treatment of trigeminal neuralgia and manic depressive illness. Although new drugs for epilepsy treatment have been developed during the last 10 years, carbamazepine is still one of the most widely used.

The consumption of carbamazepine in Austria amounts to 6.3 tons (Sattelberger 1999) resulting in a specific use of nearly 1 g carbamazepine per inhabitant a year. Carbamazepine is predominantly eliminated in the liver, where it is metabolized into carbamazepine 10,11-epoxide and other derivates. Approximately 10% can be detected in municipal sewage with concentration of around 1 µg/l (Ternes 1998; Heberer 2002; Clara et al. 2004). Several investigations at wastewater treatment plants implied that carbamazepine is hardly removed during sewage treatment (if any then less than 10%). As a result carbamazepine concentrations of up to several hundred nanograms per litre can be found in different surface waters (Sacher et al. 1998; Ternes 2001).

Comprehensive investigations at a 7000 p.e. conventional activated sludge treatment plant in Austria suggested that carbamazepine is neither degraded nor adsorbed in the treatment plant, including several additional treatment steps such as a polishing lagoon, gravel filters and infiltration ponds, nor during the underground/groundwater passage.
after infiltration of the treated wastewater. Calculation of the temporal and spatial distribution of the infiltrated wastewater in the groundwater was based on measured boron concentrations in treated wastewater and uninfluenced groundwater (Clara et al. 2004). Drewes et al. (2003) found similar results at two water reuse sites in the US, where treated wastewater is used for subsequent ground water recharge. Several field studies demonstrated that carbamazepine is not or just slightly attenuated during bank infiltration (Brauch et al. 2000; Heberer et al. 2001). Preuss et al. (2001) studied the behaviour of carbamazepine during artificial groundwater recharge and reported poor removal during soil passage.

Thus, characteristics such as the frequent use, the poor biodegradability and the anthropogenic source identified carbamazepine as a perfect tracer for wastewater.

**Analytical method**

Samples were analysed for carbamazepine by an HPLC-tandem MS method. The practical determination limit for carbamazepine was 1 ng/l. The calibration was linear in the tested range of 1–1000 ng/l. Detailed information on carbamazepine analyses can be found in Fenz et al. (2005).

**Onsite sampling**

In total, 41 samples were taken on a city-wide scale with special focus on the area around the reconstructed trunk sewer 2. The monitoring covered existing wells and boreholes, which were constructed for either regular hydrological monitoring (groundwater level) or groundwater use (mainly air conditioning). Most of the selected sites have also been part of the monitoring programme in 2003.

The sampling campaign was carried out in July 2008. In addition, daily composite samples from the inflow of the wastewater treatment plant as well as river samples of Traun and Danube rivers were collected. Thus the concentrations of carbamazepine in the sewers and in the infiltrating river water were achieved. Samples were refrigerated and transported to the laboratory immediately. In addition to carbamazepine analysis, classical physical and chemicals parameters were measured onsite and in the laboratory.

**Calculation of groundwater flow**

The calculation of groundwater flow was carried out by a civil engineer bureau based on several borehole data throughout the city (Donau Consult, Machowetz and Partner 2005). Groundwater flow is predominantly in east-north-east direction, turning to north-east near trunk sewer 2. The average hydraulic gradient varies between 0.1–0.2% and the average groundwater velocity has been calculated to be 5 m/d.

The main groundwater inflow is located in the region south of the Danube River (inflow A in Figure 2; 960 l/s). A bit further north small groundwater inflows originate from a small hilly catchment west of subzone 6 (inflow B in Figure 2; 30 l/s). Close to the Danube, the groundwater flow is mainly dominated by infiltrating river water (inflow C1 in Figure 2; 210 l/s), as this stretch is dammed due to a power station located some kilometres downstream. Further east, the exchange between groundwater and the Danube is completely cut off by sealing walls on both sides of the river and thus requires pumping of groundwater into the Danube. Danube water also infiltrates to the groundwater north of the river, but most of the infiltrating river water (inflow C2 in Figure 2; 650 l/s) is collected in a drainage system nearby and pumped back to the Danube. Further north, there are only...
small groundwater inflows from the northern hilly area (inflow D in Figure 2; 60 l/s).

In the area south of river Traun groundwater flow is characterised by lateral groundwater inflow and infiltrating river water of rivers Traun and Danube (inflow E1, 60 l/s, E2, 50 l/s and E3, 60 l/s in Figure 2).

Local groundwater recharge from precipitation (190 l/s) is of little relevance for the groundwater balance as compared to the groundwater inflow.

**Quantification of sewer exfiltration**

Assessment and quantitative estimation of sewer exfiltration was performed for the zone between the rivers Traun and Danube, as there was not enough data available for the water balance in the areas north of the Danube and south of the Traun. The resulting region was subdivided in four balancing areas (BA, see Figure 2), whereas the reconstructed trunk sewer 2 is located in BA 3.

Assuming that the carbamazepine load in the groundwater is the result of exfiltration from leaky sewers, the rate of exfiltrating wastewater into groundwater can be calculated out of the carbamazepine load in groundwater and in the sewers.

The load of carbamazepine in the sewers of the four balancing areas was computed out of the number of inhabitants in the area (numbers from 2003 were updated for 2008) and an estimated carbamazepine emission of 0.12 g per inhabitant per year (Fenz et al. 2005).

Carbamazepine load in the groundwater of the four balancing areas results from multiplying the groundwater flow in each area with the average carbamazepine concentration downstream of the area.

Prerequisites for this method are a quantifiable groundwater flow, almost constant and significant carbamazepine concentration (available only in bigger cities) and a low carbamazepine loading of the inflowing groundwater). Costs for carbamazepine analysis amount to about €150 per sample.

### RESULTS AND DISCUSSION

#### Carbamazepine concentrations in groundwater

The study area was divided into eight subzones, of which six have already been investigated during the monitoring in 2003. In those six subzones, the carbamazepine concentrations in groundwater of 2003 and 2008 were matched. The biggest change of carbamazepine concentration in groundwater has been observed in subzone 5, which is located close to the reconstructed trunk sewer TS 2. Subzone 3 still featured a decline of 6 ng/l in 2008, as it received the groundwater flow from subzone 5 (see Table 1).

#### Quantification of sewer exfiltration

Carbamazepine loads in the rivers Danube and Traun were similar in 2008 and 2003. Assuming about 11 million inhabitants in the upper Danube river catchment, the measured daily loads result in a yearly load of 0.12 g per inhabitant. Considering the number of connected inhabitants, the carbamazepine loads in the inflow of the wastewater treatment plant produce a yearly load of 0.11 g per inhabitant. Thus the average carbamazepine emission of 0.12 g per inhabitant per year (Fenz et al. 2005) seems to be a sufficient value for the calculation of carbamazepine loads in the sewer.

The four balancing areas (BA 1–BA 4) for the assessment and quantification of sewer exfiltration rates are shown in Figure 2. Table 2 displays the carbamazepine loads in the groundwater and the sewers as well as the resulting exfiltration rates in the four balancing areas in the year 2008. In the BAs 1, 2 and 4 the exfiltration rate of wastewater into groundwater is lower than 1%, which corresponds with data reported in literature (Dohmann et al. 1999; Vollertsen & Hvitved-Jacobsen 2002). As the carbamazepine load in the groundwater of BA 4 is partly influenced by the inflow of BA 3, the exfiltration rate is given as <1.1% (whereas 1.1% is the calculated exfiltration rate assuming that carbamazepine load in groundwater originates only from BA 4).

In BA 3 (area, in which the reconstructed trunk sewer is located) the assessed exfiltration rate is 3%, which is still higher than in the other areas. However, compared to the year 2003 the exfiltration rate in BA 3 has declined from...
approximately 5.4% to 3% (see Table 3), which means a reduction of roughly 45%.

This decrease in BA 3 resulted in an exfiltration rate of around 1.3% for the whole city in 2008 compared to approximately 1.8% in 2003. Thus the reconstruction of the trunk sewer TS 2 reduced the exfiltration of wastewater into groundwater by 33% on city-wide scale.

CONCLUSIONS

The results of this study confirm the applicability of carbamazepine as anthropogenic marker to quantify sewage exfiltration into groundwater. In contrast to many other potential tracers, e.g. boron and chloride, carbamazepine features no natural background concentrations, as no natural sources occur in the environment. Further attributes such as marginal biodegradability in wastewater treatment plants or during groundwater passage complete its quality as tracer material. Thus the introduced method is a useful tool to identify areas with sewage losses provided that certain conditions are fulfilled (e.g. quantifiable groundwater flow, almost constant and significant carbamazepine concentration and low carbamazepine loading of the inflowing groundwater). Furthermore the success of sewer reconstruction and the consequent decrease in sewage exfiltration into groundwater can be evaluated.

ACKNOWLEDGMENTS

This research was financially supported by Linz AG.

REFERENCES


