  Journal of Water Supply: Research and Technology—AQUA | 55.4 | 2006

Pratical Paper

Over 130 years of experience with Riverbank Filtration in Düsseldorf, Germany

P. Eckert and R. Irmscher

ABSTRACT

Since 1870 Riverbank filtration (RBF) on the river Rhine, Germany has been used successfully by the Düsseldorf waterworks as the first step for treating drinking water. The aim of this article is to present the experience in applying RBF with a focus on the purification efficiency of this natural treatment process. At the Düsseldorf waterworks, the influence of long-term as well as periodic changes of the river water quality on the RBF processes were investigated.

While for the first 80 years drinking water treatment was based only on RBF, additional technical treatment became necessary together with the decreasing Rhine water quality in the 1960's. The decontamination of the river was attended successfully by the waterworks along the Rhine. As a result of the increased river water quality the purification processes during RBF became again more efficient. However, periodic changes of river water quality and hydraulics influence the natural purification processes during RBF and have to be considered. Flood events are accompanied by shorter travel times and less effective natural purification. The changing river water temperature trigger a string of subsequent hydrogeochemical reactions within the aquifer. The performed investigations show that even during flood events and during extreme low water, the multi protective barrier concept including both natural and technical purification has proven to be a reliable method for drinking water production.

Key words | drinking water treatment, hydrochemistry, riverbank filtration

P. Eckert (corresponding author)
R. Irmscher
Stadtwerke Düsseldorf AG,
Höherweg 100, 40233, Düsseldorf,
Germany
Tel: ++492118359
Fax: ++49211778359
E-mail: *peckert@swd-ag.de*

INTRODUCTION

Riverbank filtration (RBF) is a process during which surface water is subjected to subsurface flow prior to extraction from vertical or horizontal wells. From a water resources perspective, RBF is characterised by an improvement in water quality (Kühn & Müller 2000). Therefore, RBF is a well proven treatment step, which at numerous sites is part of a multi barrier concept in drinking water supply. Grischek *et al.* (2002) report about the intense application of RBF along the European rivers Danube, Rhine, and Elbe. In the United States RBF is receiving increased attention especially with regard to the removal of parasites and the prevention of disinfection byproducts precursors (Ray *et al.* 2002; Tufenkji *et al.* 2002; Gollnitz *et al.* 2003; Weiss *et al.* 2004).

The aim of this article is to present the experience of more than 130 years with RBF at a particular site with a particular river characteristic. RBF is used by the Düsseldorf Waterworks as a first natural treatment step. River water quality has been recognized to have an important influence on the efficiency of the RBF processes and therefore on the raw water quality. The correlation of river water quality and hydrochemical processes during RBF is discussed in numerous articles (e.g. Schwarzenbach *et al.* 1983; Jacobs *et al.* 1988; Von

doi: 10.2166/aqua.2006.040

Gunten *et al.* 1991; Stuyfzand & Kooiman 1996; Doussan *et al.* 1998; Grischek *et al.* 1998). The objective of this article is to determine the processes from the point of view of a water supplier.

Site description

The city of Düsseldorf is situated in the North-West of Germany, in the lower Rhine valley (Figure 1). The raw water is discharged from a quaternary aquifer with a proportion of 50 to 90% of bank filtrate. At present 600,000 inhabitants are supplied with treated bank filtrate by four waterworks including vertical wells and horizontal collector wells. A water demand of about 60 million m^3/year and up to 210,000 m^3/day has to be provided. Depending on the hydraulic situation, the residence time of the bank filtrate in the aquifer varies between one week and several months (Schubert 2002*a*; Eckert *et al.* 2005).

The river Rhine, with a length of 1,320 km and a catchment area of 185,000 km^2, is the third biggest river and the largest source of drinking water in Europe. The mean discharge of the Rhine at Düsseldorf is 2,200 m^3/s while the water works use less than 2 m^3/s. During flood events the discharge increases up to 10,000 m^3/s. The width and the dynamics of the River Rhine allow a sustainable application of RBF for drinking water supply.

Historical development of the water supply in Düsseldorf

In the Summer of 1866, there were 57 cases of cholera in the urban area of Düsseldorf. About half of those who contracted the disease died. This forced the town council to adopt a resolution to construct and operate a waterworks. The English engineer William Lindley was called in to provide expert advice on the choice of the location and planning of the technical equipment. This well site – Flehe, on the banks of the Rhine – has been continuously used, right up to the present day. On May 1, 1870, the waterworks was put in operation for the first time. Up to that point of time, the population had obtained water from rainwater storage tanks, as well as from open and pumped wells.

In the following years, the increasing water demand had to be met (Figure 2). Driven by the increasing population and the industrial water demand, the extension of the water supply was the main task for the next 100 years. In the eight years between 1948 and 1956, the water requirement nearly doubled. While the increasing water demand could be met

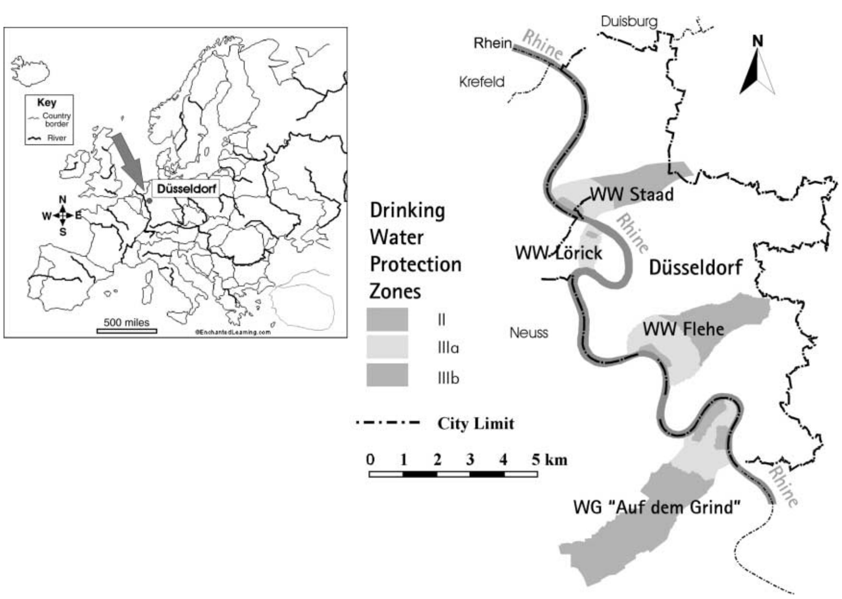

Figure 1 | Geographic location of Düsseldorf in Europe and the drinking water protection zones of the well fields for the Düsseldorf drinking water supply.

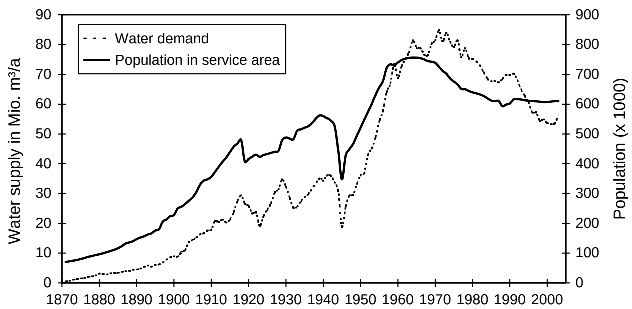

Figure 2 | Development of water demand and population in the city of Düsseldorf, Germany.

by the continuous development of well fields, the decrease of the river water quality posed an additional challenge.

METHODS

The raw water discharged at the production well consists of a mixture of infiltrated river water and groundwater recharged on the landside catchment. Therefore, the evaluation of RBF processes based on the well water chemistry is not always possible. As a result of the continuous infiltration of river water at an operating RBF site, the monitoring wells between the river and the production well enable the sampling of nearly 100% bank filtrate. The observed chemistry of the bank filtrate is influenced only by the river water chemistry and the hydrogeochemical processes within the aquifer. In order to assess the purification processes on the flowpath between the river bed and the production well, the monitoring of the river water together with the bank filtrate has been successfully applied at various sites (Grischek *et al.* 1998; Schubert 2002*b*; Gollnitz *et al.* 2003).

At the waterworks Flehe (Figure 1) a test site was installed consisting of two multi-level wells (A,B) which are situated between the river Rhine and the production well (Figure 3). The monitoring program includes chemical as well as biological parameters relevant for drinking water quality. The concentration of almost all important chemical parameters in the river water show a significant temporal variation. In addition it was assumed that the hydrogeochemical processes were not at steady state. Therefore, the monitoring process had to consider these temporal variations.

RESULTS AND DISCUSSION

General processes of Riverbank Filtration at the RBF site Flehe

The amount of river water infiltrating into the aquifer is dependent on the distance between the river and the

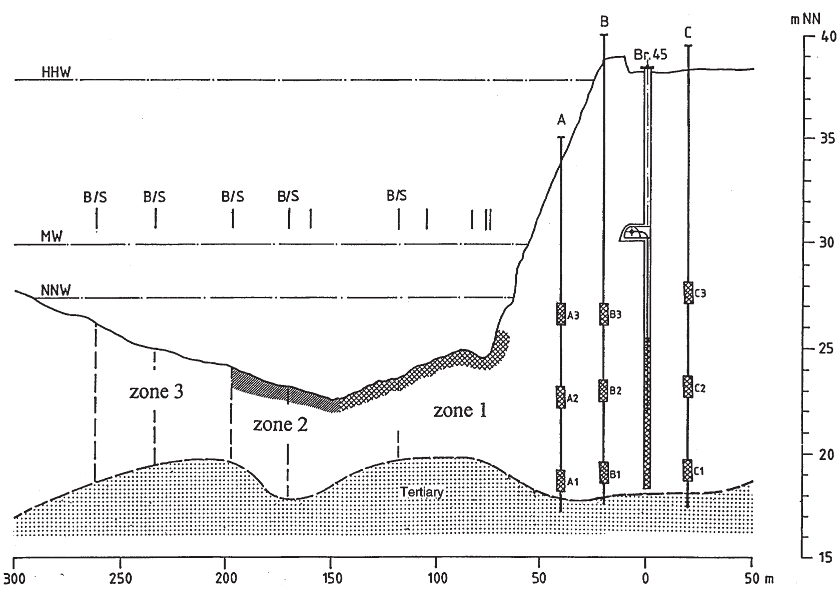

Figure 3 | Cross-Section through the River Rhine and the aquifer showing the production well Br.45 and the depth oriented monitoring wells A,B and C. Zones 1 to 3 indicate the different composition of the riverbed.

production well together with the rate of raw water discharged at the production well. In addition the fluctuating river water level has a significant influence on the infiltration process (Schubert 2002*a*). During flood events the hydraulic gradient between the river and the adjacent aquifer increase significantly. At the Flehe site, where the production well is situated at a distance of 70 m to the river bank (Figure 3), a permanent inflow of river water occurs. Suspended silt and particles in the infiltrating river water are filtered and deposited in the upper layer of the aquifer. The filtration efficiency is obvious in the low turbidity value of less than 0,1 FNU. As a consequence of the filtration process a part of the riverbed is clogged. In 1987, an investigation of the riverbed conducted with a diving bell revealed a zone of nearly 80 m which obtained a fixed ground and was entirely clogged by suspended soil (Schubert 2002*b*). The expansion of the clogged area (zone 1) is limited especially by bed load transport in the river. In regions with sufficient shear force the deposits are whirled up and removed. Figure 3 shows the detected zones at the Flehe site which are characterized by a different permeability. The infiltration occurs mainly in the middle of the river (zone 2).

Another important process during bank filtration is the microbial degradation of organic compounds. Von Gunten *et al.* (1991) propose the aerobic degradation of organic matter according the equation:

$$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 138\,O_2 \rightarrow 106\,CO_2 + 16NO_3^- + HPO_4^{2-} + 122\,H_2O + 18\,H^+ \qquad (1)$$

Depending on the amount of biodegradable organic carbon the microbes use other electron acceptors following the consumption of oxygen. The development of distinct redox zones might be observed (von Gunten *et al.* 1991; Grischek *et al.* 1998). At the Flehe site, water samples which were taken from a depth of 60 cm beneath the river bed revealed that the main microbial activity is already performed within the first meter of the flow path (Schubert 2002*b*). The concentration of organic carbon and oxygen in the downstream monitoring well A and B (see Figure 3) was similar to the sample beneath the river bed. Indicating that no significant microbial activity occurs along the further flow path. The high microbial activity at the river/aquifer interface is in accordance with the observation made at other RBF sites (Jacobs *et al.* 1988; Matsunaga *et al.* 1993; Doussan *et al.* 1998; Grischek *et al.* 1998). The fact that organic carbon is oxidized just below the infiltration areas confirms that biodegradation processes are very similar to slow sand filtration (Cleasby 1990).

RBF is also known to be very effective in reducing or eliminating bacteria, viruses and parasites (Hiscock & Grischek 2002; Schijven *et al.* 2002; Gollnitz *et al.* 2003). Investigations at slow sand filtration systems revealed that the removal of pathogens is based on filtration, sorption and biological processes (Preuß & Schulte-Ebbert 2000). Protozoa like flagellates, ciliates and amoebas are an important factor for the elimination of pathogens during artificial groundwater recharge. In general the highest removal efficiency is observed within the uppermost infiltration layer where microfauna is most abundant. Gollnitz *et al.* (2003) confirmed these processes for RBF based on field studies using monitoring wells installed close to the river bed. The investigations performed at the Düsseldorf waterworks showed that bacteria are removed by approximately 3 log orders during RBF (Schubert 2002*c*). Parasites have not been detected in the bank filtrate and the viruses observed in the River Rhine were in general inactivated during RBF. These observations are in line with investigations performed in the Netherlands by Stuyfzand (1989).

Long-term changes of the Rhine water quality

For the first 80 years of central drinking water supply in Düsseldorf, RBF alone without additional treatment (only disinfections), sufficed in order to obtain safe drinking water. After 1950, the quality of the Rhine water began to deteriorate. The water pollution was caused by rapidly growing industrial activities and increasing density of urban settlements in the Rhine valley after World War II (Friege 2001). In the 1950s and 1960s, sewage systems in the destroyed cities had been built prior to waste water purification plants leading to increasing pollution of the rivers. The oxygen concentration in the river Rhine decreased continuously until the beginning of the 1970s (Figure 4). A low point was marked by an enormous death rate of fishes in 1969, caused by the insecticide Endosulfan accidentally released by the chemical industry and oxygen concentration of less than 4 mg/l (Friege 2001).

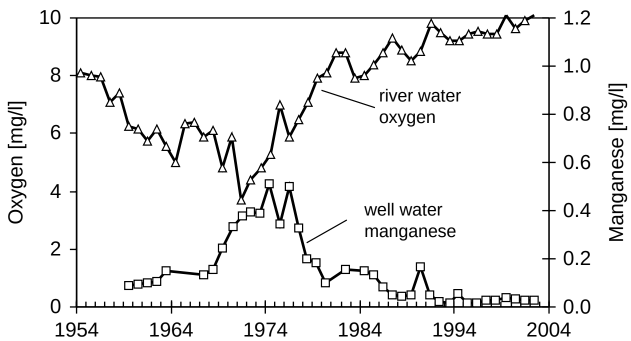

Figure 4 | Oxygen concentrations in the River Rhine and manganese concentrations in the raw water of the production well.

Despite the low river water quality in the middle of the last century drinking water supply based on RBF remained possible. The attenuation processes during RFB made a significant contribution to ensure drinking water production. The efficiency of these attenuation processes is visible in the degradation of dissolved organic carbon (DOC). Between 1975 and 1980 the river water DOC showed values higher than 7.5 mg/l, while the raw water concentration never exceeded 3 mg/l (Figure 5). During that period the microbial degradation within the aquifer led to the total consumption of oxygen and the reduction of manganese. Therefore, dissolved manganese appeared in the raw water (Figure 4).

Besides the manganese concentrations, odour and taste problems in the well water made technical treatment steps complementary to the natural treatment by RBF necessary. The development and installation of the "Düsseldorf Treatment Process" was fulfilled in 1967 at all three water works. Based on the combination of ozonation, biological filtration and adsorption on granular activated carbon (GAC) the drinking water limits were met at all times. The main effects of the treatment steps are listed in Table 1.

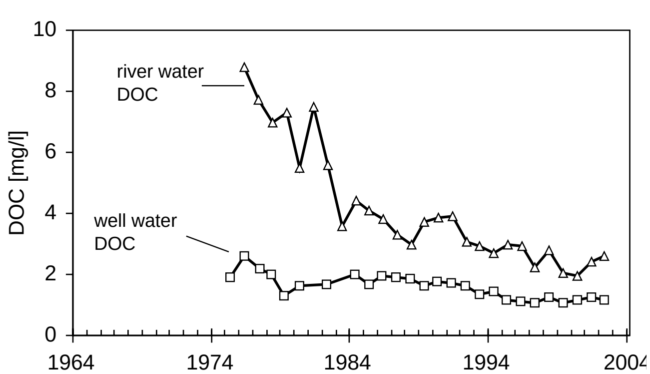

Figure 5 | DOC concentrations in the River Rhine and in the raw water of the production well.

As a reaction to the decreasing water quality of the river Rhine the waterworks started to follow two different targets. One target was the development of a treatment process to supplement the natural purification capacity of bank filtration. At the same time the water works reinforced their efforts to achieve a better river water quality by the formation of a common organisation. The International Association of Waterworks in the Rhine Catchment Area (IAWR) was founded in the year 1970 in Düsseldorf, Germany. In 1973, the IAWR published a first "Memorandum" on raw water quality serving as a yardstick for administrations and for the public debate on Rhine water quality.

The important role of the waterworks in the public discussion comes from

- the international organisation as a pressure group,
- the quality of their co-ordinated scientific work on water pollution supported by a number of universities,
- the joined monitoring programs of the waterworks and the authorities often leading to pressure on certain dischargers.

As a consequence of the efforts of the waterworks and the government, the role of the chemical industry changed from an opponent to that of a critical partner now publishing their efforts and success in reducing industrial effluents (Friege 2001).

Since the mid 1970s, the water quality has increased enormously. Many actions to reduce nutrients and pollutants were necessary. These measures comply with the best available technology in production, as well as wastewater treatment along the Rhine. The return of the salmon in the year 2000 is a visible sign of the success of this programme. Figure 4 and Figure 5 show the development of oxygen and DOC concentrations representing the Rhine water quality. The oxygen concentrations reached saturation at the beginning of the 1990s. The DOC concentration decreased to a level of between 2 and 4 mg/l. The higher oxidation capacity together with a lower oxygen demand of the infiltrating river water led to more efficient natural attenuation processes within the aquifer. This enabled the waterworks to reduce their

Table 1 | Characteristics of the "Düsseldorf Treatment Process"

Treatment steps	Effects	Remarks
Ozonation	Disinfection Oxidation of iron and manganese Removal of disturbing substances (odour, taste) Formation of biological degradeable substances	Formation of bromate has to be controlled
Biological filtration	Removal of remaining ozon Removal of iron compound through filtration Reduction of permanganate to manganese dioxide and removal through filtration Biological oxidation of inorganic (ammonia) and biodegradable organic compounds (reducing microbial regrowth capacity)	
Adsorption on GAC	Removal of adsorbable species in particular micropollutants (e.g. pesticides) Reducing the microbial regrowth capacity by lowering the DOC concentration	Run time is controlled by measurement of DOC- and micropollutant concentrations in the effluent

treatment expenses. The Düsseldorf water works decreased their average ozon addition from 3.0 to 0.5 mg/l. However, the occurrence of micro-pollutants in the Rhine water, like pesticides and pharmaceuticals, has to be considered (Verstraeten *et al.* 2002; Schmidt *et al.* 2004). The decrease of the DOC concentration in the raw water by nearly 100% (Figure 5) afforded an enhanced adsorption on GAC of micropollutants which are not eliminated during RBF.

Periodic changes of the River water

The investigations into the impact of periodic changes of the River water composition on RBF-processes were studied at the test field of the waterworks Flehe (Figure 3). The groundwater samples representing the bank filtrate chemistry were obtained from the monitoring well B2 (Figure 3). During low water in the Rhine the infiltrated river water reached the monitoring well after a travel time of 30 to 40 days, while during flood events the travel time is shortened to only one week (Eckert *et al.* 2005).

Figure 6 shows that during the year 2003 the temperature of the river water varied between 3 and 26°C. The sharp temperature increase during spring was observed with retardation in the bank filtrate. The temperature of the bank filtrate never exceeded 20°C indicating the thermal absorption capacity of the aquifer. The yearly changing river water temperature has a direct influence on the oxygen concentration of the river water (Figure 7). During the winter, in the cold river water, the oxygen concentration ranged between 11 and 13 mg/l, while, the concentration decreased to 7 mg/l in the summer due to lower solubility of oxygen in the warm river water. The oxygen concentration of the bank filtrate is not only influenced by the river water oxygen, but also by the varying oxygen consumption within the aquifer. During spring time the aerobic degradation of organic carbon increased with the rising temperature leading to a maximum oxygen consumption of 11 mg/l. Despite a still increasing temperature during the summer, the microbial activity decreased again. Obviously the lower oxygen concentration became the limiting factor (Eckert *et al.* 2005). Nevertheless, the biological activity was so high that anaerobic conditions

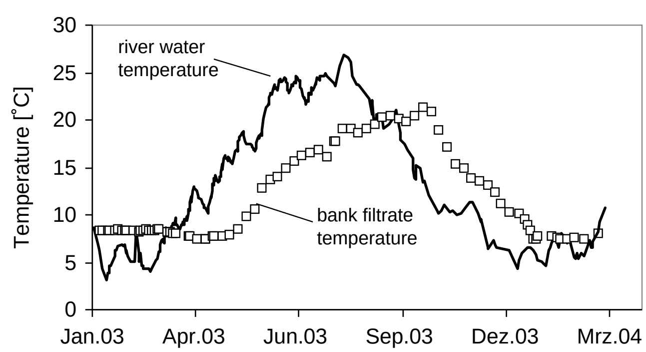

Figure 6 | Temperatures in the River Rhine and bank filtrate.

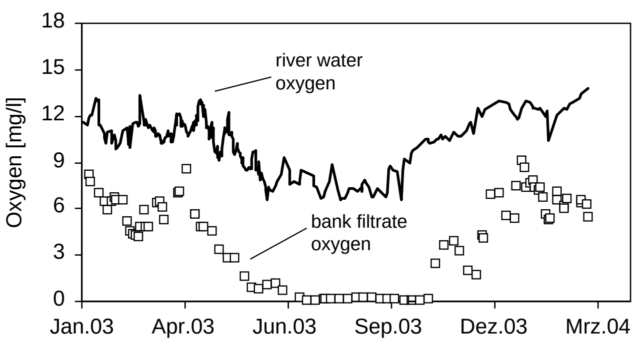

Figure 7 | Oxygen concentrations in the River Rhine and bank filtrate.

appeared within the aquifer over a period of nearly three months (Figure 7).

The changed redox conditions are of particular interest with respect to drinking water treatment. During the anaerobic period additional micropollutants were already degraded within the aquifer (Schmidt *et al.* 2004). Only a part of the low concentrated nitrate (7–10 mg/l) in the infiltrated river water was reduced. Therefore, no dissolved iron or manganese appeared in the raw water.

The purification capacity of riverbank filtration is obvious in the degradation of total organic carbon (TOC). Between February and December 2003 the TOC concentration of the infiltrating river water was decreased to a level of 1 mg/l in the bank filtrate (Figure 8). Despite varying TOC concentrations in the river water of between 2 and 4 mg/l, the observed concentrations in the bank filtrate remained stable at a level of 1 mg/l. This suggests that the above described variations of the microbial oxygen consumption during RBF coincide with the varying TOC concentrations in the infiltrated river water. An increase of organic carbon in the bank filtrate appeared only following the flood event in January 2004. During the flood event the increase of the TOC concentration correlates with an increased hydraulic gradient within the aquifer. Therefore, the mass flux of TOC in the infiltrating river water increased significantly and exceeded for a short time the microbial degradation capacity. In general the increased TOC concentrations in the bank filtrate following flood events are accompanied by a higher ozone demand within the technical treatment process.

Figure 9 shows the *E.coli* counts, an indicator for pathogenic bacteria, of the river water and the well water. In the river water *E. coli* were detected at between 100 and 10,000 counts. During medium and low water level of the River Rhine no *E. coli* were observed in the well water indicating the high removal capacity of RBF, similar to slow sand filtration systems (Preuß & Schulte-Ebbert 2000). In the well water a breakthrough of *E. coli* was observed only following a flood event (Figure 9). The flood event was accompanied by an increased hydraulic gradient within the aquifer. Therefore, the mass flux of *E. coli* infiltrating into the aquifer exceeds for a short time the removal capacity based on filtration, sorption and biological processes. In addition, it must be considered that the flood event coincided with the rising of the groundwater table. The biological processes responsible for the removal of pathogens are not immediately established in the parts of the aquifer which were unsaturated prior to flood events (Schubert 2002*c*). The issue of streambed scour as discussed by Gollnitz *et al.* (2003) could possibly also have an influence on the decreased removal capacity. From a hygienic point of view, disinfection of the well water at the Düsseldorf site is essential following flood events. This technical treatment step is performed by ozonation ensuring a high drinking water quality.

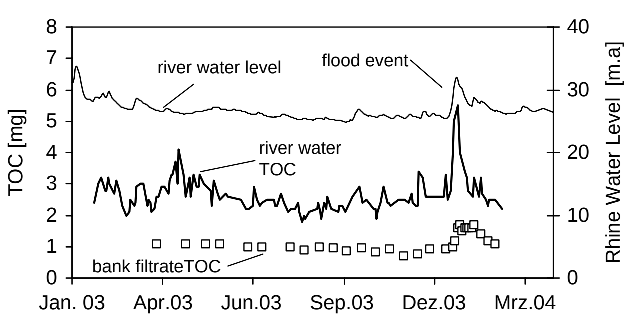

Figure 8 | TOC concentrations in the River Rhine and bank filtrate; Rhine water level.

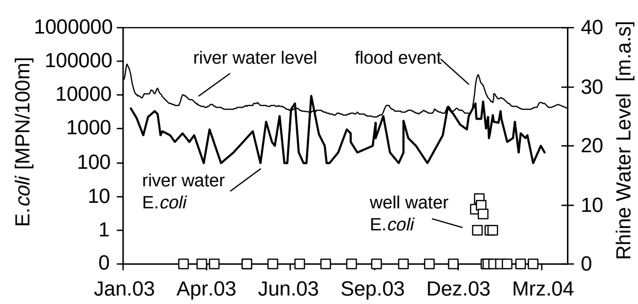

Figure 9 | *E. coli* counts in the River Rhine and the well water; Rhine water level.

CONCLUSIONS

The experience of more than 130 years in drinking water supply underline the reliability of RBF. The underground passage of the infiltrated Rhine water leads to a significant improvement of the water quality concerning biodegradable organic substances and hygienic parameters. Even during the period of bad Rhine water quality, RBF was an important purification step prior to technical drinking water treatment. However, the decontamination of the river, which was successfully attended by the waterworks along the Rhine, was a major step towards a more sustainable drinking water supply. As a consequence, the expense for technical treatment reduced during the last 20 years according to the strategy of the latest IAWR memorandum.

In order to ensure the production of high quality drinking water, a profound knowledge of the natural attenuation processes within the aquifer is essential. Temporal changes of river water quality and hydraulics influence the natural attenuation processes during bank filtration. They have to be well understood to design and maintain adequate treatment steps and to define specific target values on river water quality. Periodical variations of the river water composition are obvious in the parameters dissolved oxygen, total organic carbon and temperature. The annual changes of the river water temperature trigger a string of subsequent reactions within the aquifer. The microbiological activity has, together with the varying composition of the river water, a significant impact on the quality of the raw water. During stable hydraulic conditions the infiltrated organic carbon was decreased to a value of only 1 mg/l. Over a period of 12 weeks anaerobic conditions were observed combined with an increased degradation of micro-pollutants. While mostly the raw water already fulfills the European Drinking Water Standard, elevated colony counts were observed in the production wells following the flood event. Flood events are accompanied by shorter travel times and a less effective natural purification. Even during extreme low water and during flood events, the multi protective barrier concept including both natural and technical purification has proven to be a reliable method for drinking water production.

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First received 28 July 2004; accepted in revised form 25 January 2006