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Sustainability of River Bank Filtration in Germany

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ABSTRACT: Since 1870, bank filtration along the River Rhine in the city of Duesseldorf and since 1875 along the River Elbe in the city of Dresden has been an important source for public and industrial water supply. Infiltration has been induced by pumping of wells and installation of drain pipes. Today, some of the old systems are still in operation. Periods of poor river water quality in the 70's and 80's have been overcome. Available historical data from water quality and clogging investigations are compared with results from recent investigations. Waterworks were modernised and treatment technologies adapted. Long-term experiences and results of the evaluation of historic and recent data and of investigations using modern modeling tools prove that river bank filtration is a sustainable water resource for water supply in Germany.

INTRODUCTION

River Bank Filtration (RBF) is a process during which surface water is subjected to subsurface flow prior to extraction from vertical or horizontal wells. The raw water discharged at the production well consists of a mixture of infiltrated river water and groundwater recharged on the landside catchment. From a water resources perspective, RBF is characterised by an improvement in water quality (Kuehn and Mueller, 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).

RBF is important in Germany where groundwater derived from infiltrating river water provides about 16% of drinking water supplies. Duesseldorf, situated on the River Rhine, is entirely supplied with drinking water from bank filtration. In the Rhine basin, more than 20 million inhabitants receive drinking water which is directly or indirectly prepared from river water, mostly via bank filtration. The water demand of the city of Dresden can be met either by raw water production from bank filtrate and artificially recharged groundwater or from reservoir water. Having almost half a million inhabitants, public water supply relies on average up to approx. 32% on bank filtrate and 66% on surface water from reservoirs. But the maximum capacity of RBF and artificial recharge is about 107,000 m^3/d to ensure stable water supply in case of algae blooms or other problems with the main water source, which is the reservoir. These independent raw water sources are the basis for a sustainable and safe water supply.

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 along 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, 2002a).

HISTORY OF RIVER BANK FILTRATION IN DUESSELDORF AND DRESDEN

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

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was called in to provide expert advice on the choice of the location and planning of the technical equipment. The well site Flehe, on the banks of the River Rhine, has been continuously used since then till the present day. On May 1, 1870, the waterworks Flehe 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. 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 period between 1948 and 1956, the water requirement almost doubled. While the increasing water demand could be met by the continuous development of well fields, the decrease of the river water quality posed an additional challenge.

In Dresden, there exist three RBF waterworks. The first waterworks Dresden-Saloppe was built between 1871 and 1875 on the bank of the River Elbe. Drain pipes were installed near the river bank to abstract raw water. Due to geological boundary conditions, more than 90% of the abstracted water is bank filtrate. Today, the waterworks is still in operation and produces up to 12,000 m^3/d for industrial water supply.

Increasing water demand at the end of the 1880's exceeded the capacity of the waterworks in Dresden-Saloppe. In 1891 the city council assigned the building officer, Bernhard Salbach, to write an expert's report on the future water supply of the city. Salbach proposed to build a test well at the left bank of the river, which abstracted 4,000 m^3/d in 1891. Four more wells were completed in 1893 resulting in a total water abstraction at the left bank of 20,000 m^3/d. Wells were connected using a siphon pipe and a collector well. Between 1896 and 1898 the second waterworks, Dresden-Tolkewitz, was constructed. A further rise in water demand resulted in the construction of four more wells and a second siphon pipe in 1901 to raise the capacity to 40,000 m^3/d. In the 20th century the number of wells was again increased and the water treatment facilities improved. Between 1919 and 1928 a third siphon pipe with 39 wells was built. Figure 1 shows the final system of pipes and wells at Dresden-Tolkewitz. A significant decrease in the water demand after the reunification of Germany in 1989 allowed for the closure of this water abstraction in April 1992 in order to plan a general reconstruction of the waterworks. After intensive construction works, the waterworks Dresden-Tolkewitz was put into operation again in February 2000.

The maximum capacity is now 35,000 m^3/d. Normally, only a fraction of the full potential is tapped with a certain volume of water continuously pumped to enhance stable redox conditions in the aquifer between the river and the wells. This also ensures stable mixing ratios of bank filtrate, having low nitrate and sulfate concentrations, and land-side groundwater, having high nitrate and sulfate concentrations.

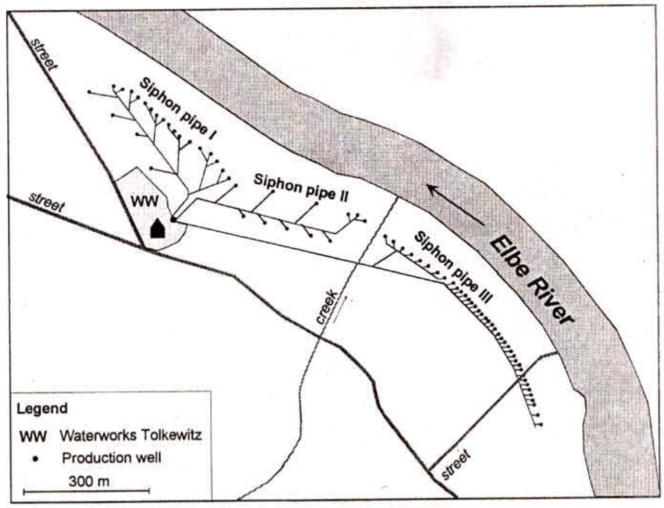

Fig. 1: Location map of the bank filtration scheme of waterworks Dresden-Tolkewitz

From 1908 a third waterworks, Dresden-Hosterwitz, started operation. Whilst at the beginning bank filtration was applied, between 1928 and 1932 the main technology was shifted to artificial groundwater recharge. Pre-treated river water was infiltrated in large basins to increase the capacity to 50,000 m^3/d. Increasing water demand in the 1970's induced further expansion of the infiltration basins and treatment facilities until construction works between 1983 and 1990 resulted in a final capacity of 72,000 m^3/d.

RIVER WATER QUALITY

During the first 80 years (1870–1950), the quality of the river water in Germany permitted the production of drinking water without further treatment; the well water had only to be disinfected. After 1950, the quality of the river water began to deteriorate gradually. Increasing quantities and insufficient treatment of effluents from industry and communities caused a noticeable drop in the oxygen concentration of the river water. The consequence of this and the increasing organic load in the river water changed the redox situation in the adjacent aquifer: it switched from former aerobic to anoxic conditions. It became necessary to treat the pumped raw water to remove iron, manganese and ammonium and additionally organic micropollutants. At many sites, subsequent technologies such as ozone treatment, biological filtration or GAC adsorption were established. Increased contamination of surface waters with persistent organic compounds threatened the use of bank filtrate for drinking water purposes.

Furthermore, spectacular industrial spills underlined the need for sanitation measures and pollution control. On November 1, 1986, a fire broke out in an agro-chemicals store of a chemical plant in Basel, Switzerland. Insecticides, herbicides and fungicides were carried into the adjoining River Rhine with the fire-fighting water. The effects of this accident on the Rhine were serious. On the stretch of the Rhine up to the Middle Rhine region, the entire stock of eel was destroyed. Other species of fish were also affected and damaging effects were detected on fish food organisms up to the mouth of the river Mosel. The question then arose, whether such a wave of poison could simultaneously destroy the basis for water procurement in the adjacent aquifer. This accident has given fresh impetus to the improvement of pollution control on the Rhine and was the reason for different projects to understand and to manage the effects of accidental shock loads on river bank filtration plants.

In the Rhine valley the water pollution was caused by rapidly growing industrial activities and increasing density of urban settlements after World War II (Friege, 2001). In the 1950's and 1960's, 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 1970's (Figure 2). 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 2 and Figure 3 show the development of oxygen and Dissolved Organic Carbon (DOC) concentrations representing the Rhine water quality. 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 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 3). During the period of heavy pollution before 1980 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 2). The oxygen concentrations reached saturation at the beginning of the 1990's. The DOC concentration decreased to a level 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 treatment expenses.

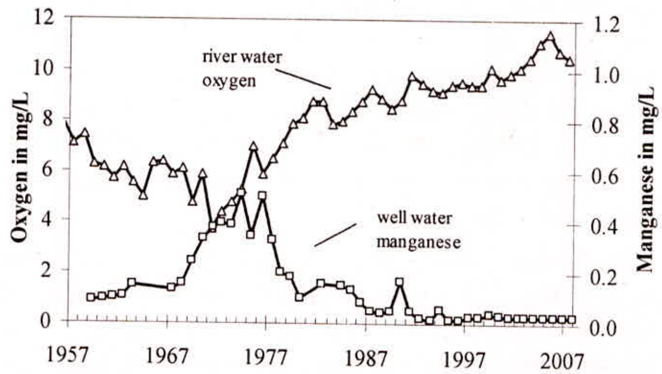

Fig. 2: Oxygen concentrations in the River Rhine and manganese concentrations in the raw water of the production well

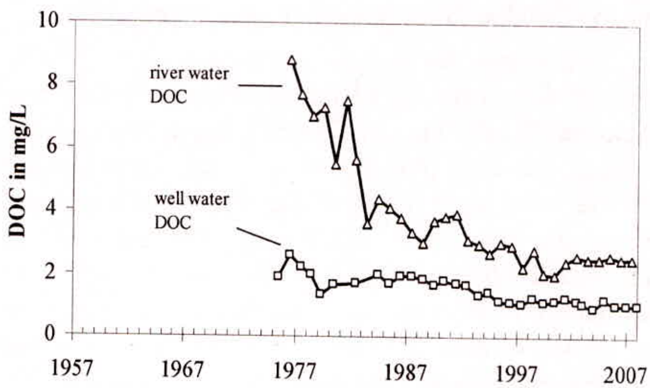

Fig. 3: DOC concentrations in the River Rhine and in the raw water of the production well

A similar situation has to be reported for the River Elbe. The industry along the Upper Elbe River valley previously discharged a wide range of organic contaminants into the river. Hence, together with urban sewage, the DOC comprises a complex mixture of easily degradable and refractory substances. Among the industrial effluents, paper mills, cellulose processing plants and the pharmaceutical industry played an important role in the 1980's. From 1988 to 1990 the average DOC concentration at the left bank of the River Elbe at Dresden-Tolkewitz was 24 mg/L and the UV-absorbance at a wavelength of 254 nm (UVA_{254}) was 55 m^{-1}. Along a flow path length of approx. 100 m along a cross-section at Dresden-Tolkewitz, the DOC concentration was reduced to about 20% of the input concentration (Nestler *et al.,* 1991). Problems with bank filtrate quality occurred due to the high load of organic pollutants, bad taste and odour, and the formation of disinfection byproducts. Figure 4 gives an impression of the organic load in the River Elbe from 1987 to 1992. The small data set does not allow the calculation of mean concentrations. Furthermore the variation is very high and the sampling point at the left river bank in Dresden was affected by waste water inputs a few kilometres upstream.

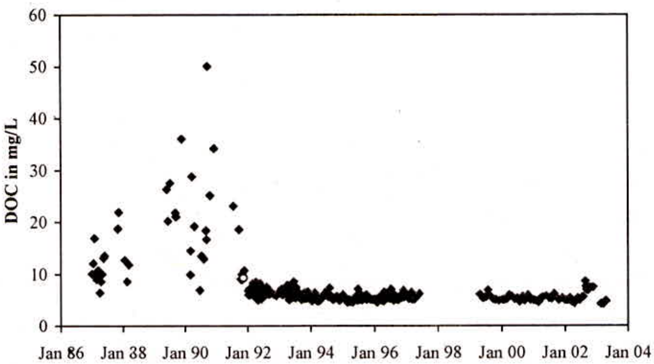

Fig. 4: DOC concentration (mg/L) in Elbe River water 1986–2004

Results from 17 measurements in 1991/92 at a cross section at Dresden-Tolkewitz showed a mean DOC concentration of 6.9 mg/L in River Elbe water and 3.4 mg/L at an observation well near a production well. From that, a reduction of DOC concentration of about 50% can be seen as an effect of river bank filtration processes. Investigations in 2003 at the same cross section included 7 samples. In 2003 the mean DOC concentration in River Elbe water was 5.6 mg/L and 3.2 mg/L in bank filtrate at the same observation well sampled in 1991/92. The mean DOC concentration in raw water from all wells was found to be 2.6 mg/L as a result of mixing with groundwater. These results prove that the period of strong pollution of Elbe river water did not limit the further use of the site. An extreme flood in August 2002 caused a significant increase in DOC concentration in river water, but no increase in DOC concentration in the bank filtrate.

As many waterworks were facing problems with deteriorating river water quality and subsequently decreasing bank filtrate quality, the International Association of Waterworks in the Rhine Area (IAWR) was founded in 1970. International commissions for the protection of the Rivers Elbe, Rhine and Danube were founded in 1990, 1993 and 1994, respectively. The combined activities of waterworks, authorities and industries resulted in a significant improvement of river water quality, e.g. the River Rhine since 1980 and the River Elbe since 1990. Together with installed monitoring programmes, bank filtration has again become a reliable resource for raw water abstraction. At many sites, simple treatment technologies such as pH-regulation, rapid sand-filtration and disinfection are sufficient for meeting drinking water standards today.

CLOGGING OF RIVER BEDS

A very important aspect for the sustainability of river bank filtration is the effect of particulate organic matter which can intensify clogging of the riverbed and thus reduce the well yield significantly. The proportion, and thus volume, of pumped bank filtrate strongly depends on riverbed clogging. Clogging is the formation of a layer on top of or within the riverbed which has a lower hydraulic conductivity and therefore reduces the flow rate of the filtrate through the riverbed. It is the result of the infiltration and accumulation of both organic and inorganic suspended solids, precipitation of carbonates, iron- and manganese-(hydr)oxides and biological processes. Erosive conditions in the river and floods limit the formation of a clogging layer by disturbing the riverbed via increased flow velocity and increased turbulence.

The permeability of clogged areas varies with the flow dynamics of the river. There are not only variations in the pressure head between the river and the aquifer but also remarkable variations in the concentration of suspended solids in the river water. The concentration of suspended solids in the River Rhine varies from 10 to more than 400 mg/L with an average concentration of less than 40 mg/L. Highest values appear in the phase of rising water level.

Due to difficulties in determining the thickness of the clogging layer, the term leakage coefficient L is introduced, which is defined as hydraulic conductivity of the clogging layer in metres per second divided by the thickness of the clogging layer in metres. Under specific conditions, the leakage coefficient can be calculated for RBF sites using water levels in the river and two observation wells positioned between the river and the production borehole using an analytical solution by *Girinsky* (Beims *et al.,* 2000) or it has to be determined by calibration procedures in groundwater flow modelling. Based on water levels and known pumping rates, the leakage coefficients of the River Rhine and the River Elbe in Duesseldorf and Dresden respectively, has been determined for different river stages and measuring campaigns and compared with former data.

A first field study of the riverbed adjacent to the Flehe waterworks (Duesseldorf) was done in 1953 and 1954 with a diving cabin. In 1987 a second study of the riverbed at the Flehe waterworks was carried out. This investigation revealed a zone of almost 80 m which had a fixed ground and was entirely clogged by suspended soil (Schubert, 2002b). The expansion of the clogged area is limited especially by bed load transport in the river. In regions with sufficient shear force the deposits are whirled up and removed. The zones at the Flehe site are characterised by a different permeability. The infiltration occurs mainly in the middle of the river. Based on the knowledge of the properties of the infiltration areas and the data of the alluvial deposits beneath the riverbed, a research project on river-aquifer interactions was designed and started in 1988 (Sontheimer, 1991). One result of this project was a three-dimensional (3D), dynamic flow and transport simulation model, which describes the effect of shock loads, resulting from accidental pollution of the river, on the raw water in the wells.

At Dresden-Tolkewitz, a significant decrease in groundwater levels was observed between 1914 and 1930 and attributed as a result of riverbed clogging due to the increased infiltration rates since 1901 and clogging by suspended materials. In the 1980's strong river water pollution caused by organics from pulp and paper mills in conjunction with high water abstraction caused unsaturated conditions beneath the riverbed, especially at the waterworks at Dresden-Tolkewitz. However, investigations of riverbeds using a dive-chamber showed that the material responsible for the pore clogging in the gravel bed consisted of up to 90% inorganic materials (Heeger, 1987). Heeger (1987) calculated a leakage coefficient of about $1 \times 10^{-4}\ s^{-1}$ for the riverbed without bank filtration and a mean value of $5 \times 10^{-7}\ s^{-1}$ at RBF sites in and around Dresden. The long-term process of riverbed clogging includes a series of building and destruction phases, which overlay a mean value. During floods, with sufficient hydraulic transport energy, the riverbed is eroded and the hydraulic conductivity of the riverbed is subsequently increased. Similarly long, low-flow periods result in decreasing leakage values.

After improvement of river water quality in 1989–1993, the hydraulic conductivity of the riverbed increased. In 1992 similar water levels as in 1930 were observed. In 2003, groundwater flow modeling was used to analyse former assumptions on groundwater flow towards the production wells and clogging of the riverbed. From model calibration, a reliable leakage coefficient of $1 \times 10^{-5}\ s^{-1}$ was determined. Water level measurements in 2004 at low flow conditions also indicated a slight decrease in clogging.

Looking at the long-term operation of the waterworks, it is obvious that observed clogging of the riverbed did not result in the closure of wells under the given conditions of an erosive river. After a period with additional organic pollution and observed slime at the riverbed surface (assumed to act as an organic outer clogging layer) there is a recovery of hydraulic conductivity of the riverbed.

CONCLUSIONS

Two examples from Germany—from the Lower Rhine region and the Upper Elbe River—have been presented where river bank filtration has been employed for more than 130 years. During this time the schemes were able to overcome extreme conditions with respect to poor river water quality, and to withstand spills in the rivers. Drain pipes at waterworks Dresden-Saloppe have been in operation for more than 130 years whilst four production wells at waterworks Dresden-Tolkewitz had to be replaced only after 60 years. In Dresden, severe clogging of the riverbed occurred in the 1980's mainly due to high loads of organics from pulp and paper mills upstream. After improvement of river water quality in the 1990's, no problems with clogging of the riverbed or bad taste and odor of the drinking water have been encountered.

Field studies are part of ongoing efforts to establish the risks of river bank filtration and to obtain knowledge of the best practice for sustainable operation of bank filtration plants. Raw water quality and treatment are optimised by managing specific mixing ratios of bank filtrate and land-side groundwater. Pumping rates were reduced to get longer retention times in the aquifer and higher attenuation rates of organic compounds. No indication of a decrease in attenuation capacity of the aquifer with time was observed. Long-term experiences and results of the evaluation of historic and recent data and of investigations using modern modeling tools prove that river bank filtration is a sustainable water resource for water supply in Germany.

The authors see a huge potential for wider use of RBF in India, especially as the removal of microbial pathogens in drinking water from surface water through RBF would be a crucial factor. Thus, it could serve as an alternative to direct river water abstraction. At a minimum, bank filtration acts as a pre-treatment step in drinking water production. In some instances, it can serve as the final treatment just before disinfection. Good quality drinking water is not only a long-term benefit of RBF, but also leads to reduced medical costs and improved productivity for the consumer. Bank filtration also serves as an asset to water suppliers by way of capital cost reduction through lower maintenance, improved reliability as source-water and enhanced community supply by lowering the total dissolved solids concentration. Nevertheless, the application and adaptation of RBF is very much site specific and demands careful investigations into hydrological, hydrogeological, hydrochemical and hydrobiological conditions, especially clogging of river or lake beds and redox reactions in the aquifer (Grischek *et al.*, 2005; Sandhu *et al.*, 2006; Ray, 2008).

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