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author(s): **Thomas Grischek**
University of Applied Sciences Dresden, Germany, grischek@htw-dresden.de

Dagmar Schoenheinz
University of Applied Sciences Dresden, Germany, schoenh@htw-dresden.de

Paul Eckert
Stadtwerke Düsseldorf AG, Germany, peckert@swd-ag.de

Chittaranjan Ray
University of Hawaii at Manoa, United States, cray@hawaii.edu

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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 from 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 normally characterised by an improvement in water quality (Kuehn, Mueller, 2000). Therefore, RBF is a well-proven treatment step, which at numerous sites is part of a multi-barrier approach to drinking water supply. Grischek et al. (2002) report about the extensive 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 by-product precursors (Ray et al., 2002; Tufenkji et al., 2002).

RBF in Germany provides about 8% of drinking water supplies. The city of Duesseldorf, situated on the River Rhine, is entirely supplied with drinking water from RBF. In the Rhine basin, more than 20 million inhabitants receive drinking water which is directly or indirectly derived from river water, mostly via bank filtration. In the city of Dresden public water supply on average relies on up to approximately 32% bank filtrate and 66% surface water from reservoirs.

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 Duesseldorf. 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 location and planning of the technical equipment. The first well field at Flehe of Duesseldorf, on the banks of the River Rhine, was put in operation for the first time on May 1, 1870 and has been continuously used since then till the present day. Up to that point in 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. In the period between 1948 and 1956, the water requirement almost doubled. While the increasing demand could be met by the continuous development of well fields, the simultaneous decrease of the river water quality posed an additional challenge (Eckert, Irmscher, 2006).

In Dresden, there exist three RBF waterworks. The first waterworks, the Dresden-Saloppe Waterworks 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 1880s exceeded the capacity of the Dresden-Saloppe Waterworks. 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 building a test well on 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 from 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, the Dresden-Tolkewitz Waterworks, 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. A significant decrease in the water demand after the reunification of Germany in 1989 allowed for the closure of the well fields in April 1992 in order to plan a general reconstruction of the waterworks. After intensive construction works, the Dresden-Tolkewitz Waterworks and the well fields were put into operation again in February 2000. The maximum capacity is now 35,000 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 from the prior aerobic to anoxic conditions. It became necessary to treat the pumped raw water to remove iron, manganese and ammonium in addition to organic micro-pollutants. At many sites, subsequent technologies such as ozone treatment, biological filtration or granular activated carbon (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 agrochemical storage facility 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 on the river 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 contaminate the water source in the adjacent aquifer. This accident has given fresh impetus to the improvement of pollution control on the Rhine and was the reason for projects aimed at understanding and managing the effects of accidental shock loads on RBF plants (Sontheimer, 1991).

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 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. 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 resulting oxygen concentration of less than 4 mg/L (Friege, 2001). 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 RBF made a significant contribution to ensuring safe drinking water production. After pollution control and sanitation measures were undertaken, oxygen concentrations reached saturation at the beginning of the

1990s. The higher oxidation capacity together with a lower oxygen demand in the infiltrating river water led to more efficient natural attenuation processes within the aquifer. This enabled the waterworks to reduce their treatment expenses.

A similar situation has to be reported for the River Elbe. The industries along the Upper Elbe River valley previously discharged a wide range of organic contaminants into the river. Hence, together with urban sewage, the dissolved organic carbon (DOC) comprises a complex mixture of easily degradable and refractory substances. In addition to 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 on the left bank of the River Elbe at Dresden-Tolkewitz was 24 mg/L and the UV-absorbance at a wavelength of 254 nm was 55 m^{-1}. Along a flow path length of approximately 100 m at 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, foul taste and odour, and the formation of disinfection by-products. 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 RBF 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 show that the period of strong pollution of Elbe river water did not limit the further use of the Dresden-Tolkewitz site.

CLOGGING OF RIVER BEDS

A very important aspect of the sustainability of river bank filtration is the effect of particulate organic matter which can intensify clogging of the riverbed and significantly reduce the well yield. 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 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 shear stress. 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 periods of rising water levels following storm events. 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. Otherwise 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 at Duesseldorf and Dresden, respectively, have previously 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 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 sediments (Schubert, 2002). 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.

At Dresden-Tolkewitz, a significant decrease in groundwater levels was observed between 1914 and 1930 and attributed to riverbed clogging by suspended materials caused by increased infiltration rates since 1901. In the 1980s strong river water pollution caused by organics from pulp and paper mills in conjunction with high water abstraction led to unsaturated conditions beneath the riverbed, especially at the Dresden-Tolkewitz Waterworks. 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 calculated a leakage coefficient of about 1×10^{-4} s^{-1} for the riverbed without bank filtration and a mean value of 5×10^{-7} s^{-1} at RBF sites in and around Dresden. After improvement of river water quality from 1989 to 1993, the hydraulic conductivity of the riverbed increased. In 2003, groundwater flow modelling was used to test former assumptions about groundwater flow towards the production wells and clogging of the riverbed. From model calibration, a reliable leakage coefficient of 1×10^{-5} s^{-1} was determined.

Looking at the long-term operation of the waterworks, it is clear that the observed clogging of the riverbed did not result in the closure of wells under the existing erosive conditions in the river. After a period of additional organic pollution and observed slime on the riverbed surface (assumed to act as an organic outer clogging layer) there is a marked recovery of hydraulic conductivity in 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 RBF systems were able to overcome extreme conditions with respect to poor river water quality, and to withstand spills in the rivers. Drain pipes at the Dresden-Saloppe Waterworks have been in operation for more than 130 years whilst four production wells at the Dresden-Tolkewitz Waterworks had to be replaced only after 60 years. In Dresden, severe clogging of the riverbed occurred in the 1980s mainly due to high loads of organics from pulp and paper mills upstream. Following improvement of river water quality in the 1990s, no problems with riverbed clogging or foul taste and odour 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 can be 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 over time was observed. Long-term experiences and results of the evaluation of historic and recent data and of investigations using modern modelling tools strongly indicate that RBF is a sustainable water resource for water supply in Germany.

The authors see enormous potential for wider use of RBF worldwide, especially given that the removal of microbial pathogens from surface water through RBF would be a crucial factor (Ray, 2008; Sandhu et al., 2010). Thus, it could serve as a preferable 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 of 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.

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