Experiences with riverbank filtration and infiltration in Germany

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Introduction

In Germany, groundwater is used for drinking water production wherever possible. When compared with surface water, groundwater is well protected against most types of pollution, is of relatively regular quality and temperature, and its abstraction can be easily adjusted to short-term fluctuations in consumption. However, exploitation of groundwater sources is restricted with regard to quantity. In Germany, this limitation is not given to such an extent for surface waters. However, surface water, particularly river water, is exposed to dangers of permanent and sudden pollution by wastewaters or to disturbances due to storage, transport or application of water-endangering substances, thereby always reflecting its function as receiving water. In order to preserve the protective character of groundwater at least partly when utilizing surface water for drinking water preparation, surface water is subjected to an underground passage via bank filtration or artificial groundwater recharge.

To clarify the terms bank filtration and artificial groundwater recharge, the typical historical development of water extraction facilities in an intensively exploited river valley is described in figure 1. Case A shows, how groundwater that is originating from precipitation usually flows towards the river and percolates particularly in low-flow periods into the flowing wave of the river. In times of high flow, however, river water infiltrates vice versa into the aquifer. Thus, the flow direction of the groundwater is variable under natural conditions even without any anthropogenic extraction of groundwater. In major river bends, at barrage weirs or in cases where the river bed is located on an alluvial cone, an infiltration of surface water takes place permanently. By construction of a production well in the river valley, as shown in case B, water, that is withdrawn from the production well, comes from slope-sided native groundwater as long as the pumping water level is not lowered too much. Increased pumping action creates a pressure head difference between the river and the aquifer and induces the river water to flow through the riverbed towards the pumping well that consequently extracts a mixture of groundwater originally present in the aquifer and bank filtrated surface water from the river. The proportions of both kinds of water in the extracted water can vary depending on both extraction rate and river flow.

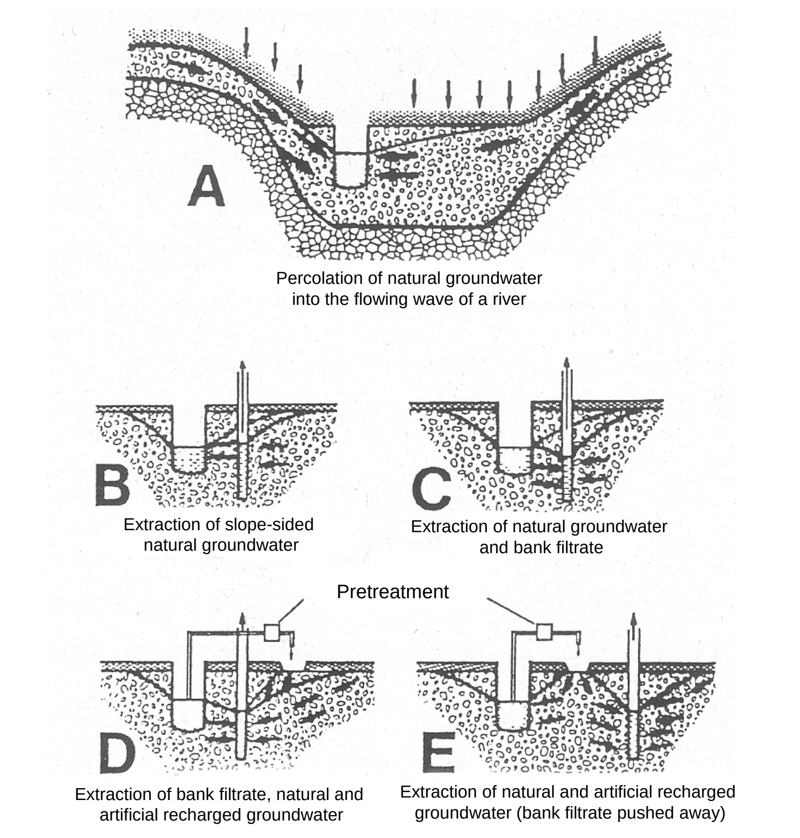

Fig. 1. Riverbank filtration and infiltration (artificial groundwater recharge).

The time variable origin of the extracted groundwater often causes quality fluctuations. The danger of contaminations in the groundwater percolating from the hinterland requires protection of its catchment area by allocation of water protection zones. However, even in cases where the existing usage type of the given site between riverbank and water catchment area does not allow for a consequent application of adequate restrictions in protection zones, water suppliers should not abandon bank filtration as water treatment stage, since it facilitates the following water treatment processes in any case.

Natural groundwater was early recognized as being free of pathogens and was, in comparison to well-processed surface water, more clear, more attractive and had a refreshing taste. The drawback was, however, that natural groundwater was rarely available in the amounts necessary to cover the demand of large cities. The task set was to increase the supply of natural groundwater by the infiltration of surface water. Thus, the historical development of waterworks located at rivers took place mostly in such a manner that in the first instance natural groundwater, than mixed groundwater and later on almost pure bank filtrate was extracted. Since at smaller rivers even the bank filtrate was not sufficient, river water was impounded at some sites. Riverbed clogging was overcome by massive ground loosening. With the construction of artificial ditches and side channels further infiltration zones were created. To improve water quality and to achieve easier cleanabilities of infiltration zones, a specific sand layer was later incorporated in percolation ditches, channels, and ponds. A further stage of development was finally the construction of recharge basins similar to those found in nearly all artificial groundwater recharge plants nowadays. In these recharge basins, raw water is passed through a filtering medium that consists of a layer of sand. Artificial groundwater recharge can be used, as shown in case D, in addition to bank filtration, but can also be employed as protection tool to push away riverbank filtrate (case E). Operation of recharge and water catch at a longer distance from the riverbed results in systems that are widely unaffected by riverbank filtrate interference.

The effectiveness of bank filtration and artificial groundwater recharge has long been recognized in Germany. As a consequence of various bacterial diseases caused by drinking water from waterworks with direct intake from rivers in the late 19th century (e.g. outbreak of epidemic cholera in Hamburg in 1892/93), direct extraction of surface water for public-water supply fell into discredit and was replaced or supplemented by artificial or natural subsoil passage of river water due to its efficiency in removing microorganisms from the infiltrating surface water. Nowadays, approximately 16 % of the drinking water in Germany is produced from bank filtrate or infiltrate. Because of pollution, direct treatment of river water has dropped to 1 %. Water suppliers in Berlin produce approx. 75 % of the drinking water by bank filtration and artificial groundwater recharge. In Germany, more than 300 water works use bank filtration and roughly 50 plants are based on artificial groundwater recharge. In particular, major water suppliers often make use of artificial recharge in drinking water production. The retention time in both techniques may vary from 5 to 100 days and more. In practice, riverbank filtration produces a mixture of waters with different retention times.

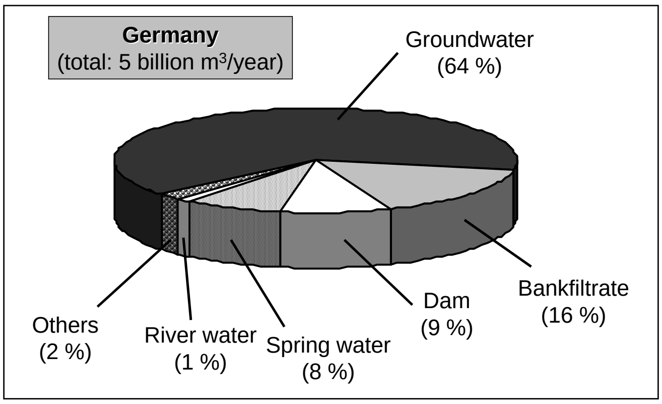

Fig. 2. Sources used for drinking water treatment in Germany.

As the pollution of the rivers was very low throughout the first half of the 20th century, it was possible to use bank filtrate for drinking water without further treatment. However, increasing chemical pollution, especially in areas with significant human activities, which may result in high concentrations of ammonia, organic compounds, and micropollutants in the river water, necessitated introduction of supplementary pre- and post-treatment steps to build up a multiple-barrier system. A variety of technologies may be applied to treat bank filtrate and infiltrate and treatment strategies may be quite different depending on the river water quality. Aeration or ozone may be used to oxidize iron and manganese that are picked up in anaerobic aquifers and activated carbon can be used for adsorption and protection against more-persistent contaminants. Today nearly all water utilities situated along large rivers use granular activated carbon filters, often combined with ozonation and filtration.

To ensure a sufficient velocity during infiltration, river water destined for artificial groundwater recharge may require particle removal by flocculation, sedimentation, or filtration. In order to protect the groundwater against contamination by the infiltrate, even further pretreatment steps such as ozonation and adsorption may be used under special circumstances. Infiltration is often applied when the quantity of water by bank filtration is not enough, bank filtration is impossible due to the geological circumstances, or groundwater sources at the river bank are highly contaminated.

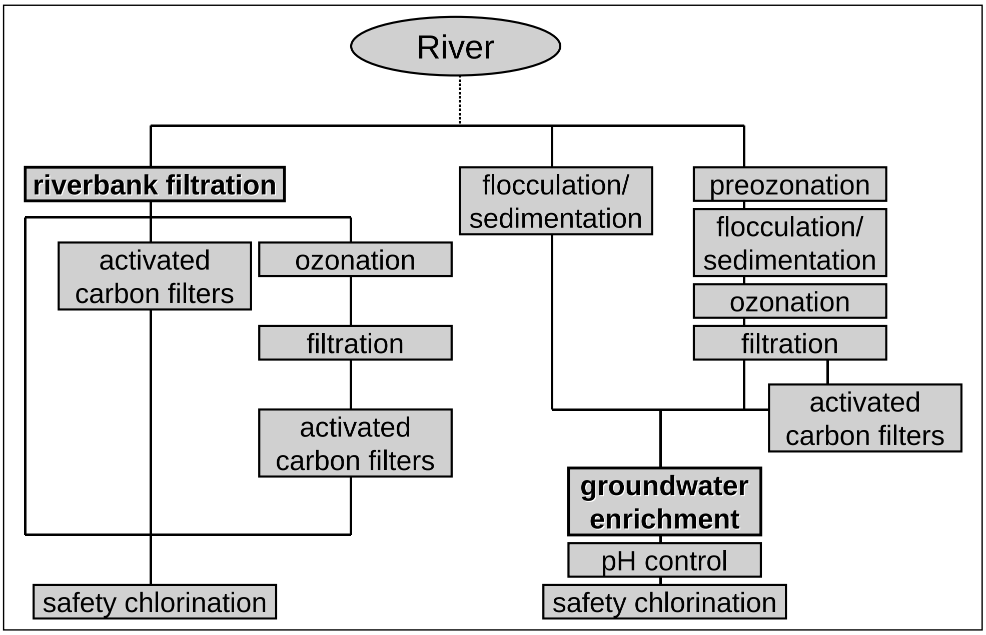

Fig. 3. Process scheme development of river water treatment in Germany.

The purification process of the underground passage starts in the infiltration zone in which sievable suspended matter and sediments, that provide an adsorption power for hydrophobic substances, are accumulated. During infiltration of river water, purification processes take place that are similar to the self-cleaning properties found in surface waters, but proceed in the infiltration zone much more intensively. As in the river, the self-cleaning capacity of bank filtration and artificial groundwater recharge are available free of cost and do per se not require any application of treatment chemicals. Thus, these procedures reduce costs and technical requirements for achieving distinct water quality standards. The infiltration layer can be characterized as a gelatinous, biological highly active biofilm which consists of algae, bacteria, fungi and protozoa as well as of organic and inorganic particles. During infiltration, the water with its dissolved components meets multifaceted biogenous and abiogenous surface structures that aid in intensifying most of the self-cleaning mechanisms that are in principle also present in the free surface water.

However, during long-term usage, the infiltration layer becomes thicker and begins to hamper infiltration. This is, for instance, caused by the production of biomass during the purification process. Thus, to maintain an acceptable filtration rate, it is necessary to clean the infiltration zone periodically in either case. In artificial groundwater recharge plants, the clogged zone can be easily removed from the clogged filter (along with a small amount of sand) by skimming off following drying-up or by suction-cleaning under water. Ultimately, filter bed performance is improved after each cleaning. Prepurification procedures can extend operational periods several times.

More problematic is the compaction of the riverbed (colmation) that would sooner or later cause complete termination of the riverbank filtration process. However, certain natural regeneration processes take place in the riverbed. These are caused by an increase in flow velocity giving rise to removal and restorage of the clogged layers, an intermittent reversal of the flow direction during water drawdown and in part by digging activities of the animal stock at the river bottom.

Effects of riverbank filtration and artificial infiltration

Shock loads

Bank filtration is an excellent protection tool to compensate peak concentrations and shock loads resulting for instance from chemical spills or defects in industrial wastewater plants, as can be seen in figure 4. The figure depicts a 1986 contamination of 1,2-dichloroethane in the Rhine River. The example demonstrates how a short-term peak pollution in the river turns into a longer-lasting pollution of very low concentration in the aquifer bank filtrate.

Underground passage reduces the effects of concentration peaks because of the varying distances covered by the water molecules from the river to the well. In the production well, the withdrawn water is a mixture of water that left the river at different times within a large period. As a rule of thumb, the waterworks in the Rhine valley calculate that in case of a sudden short lasting spill, only about one to five percent of the concentration can be found in the bank filtrate. Therefore, bank filtration is a safety barrier against high peak concentrations following accidents.

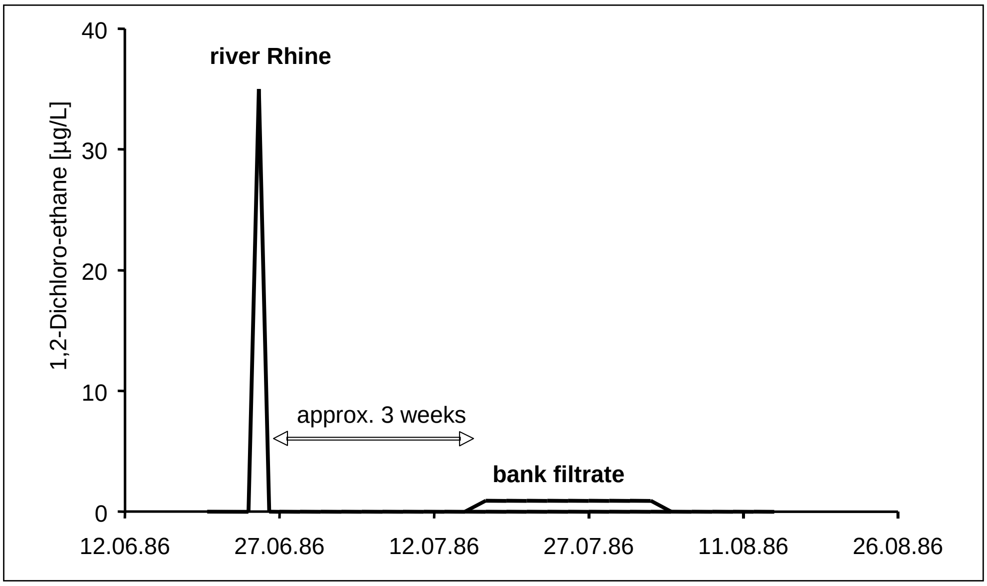

Fig. 4. Example of the protection against shock loads by bank filtration

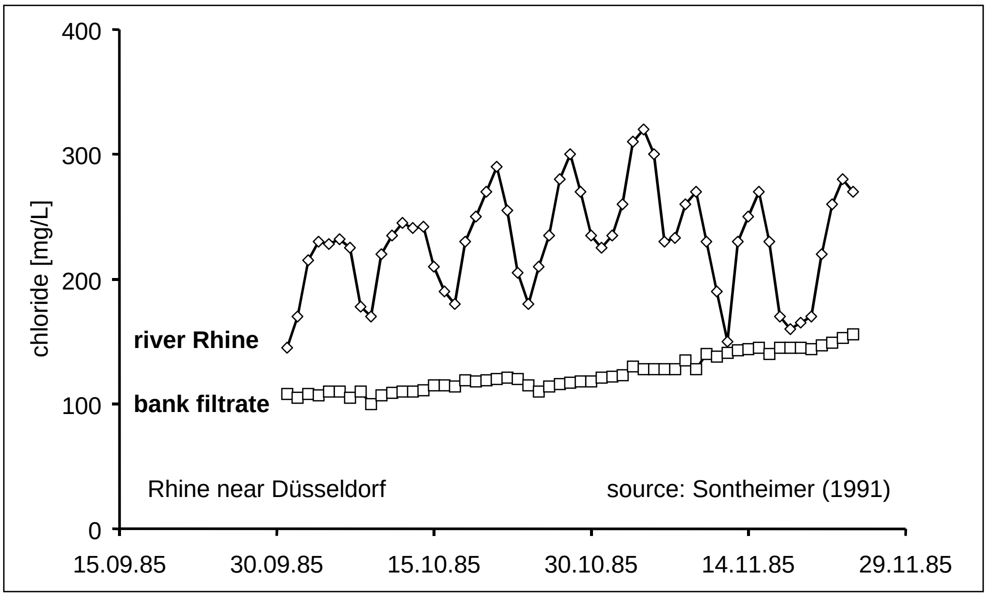

Fig. 5. Example of the concentration compensation by bank filtration

How bank filtration equalizes concentration peaks is also demonstrated in figure 5 showing the weekly fluctuating chloride concentration profile in the Rhine River due to an industrial effluent discharge by potash mines operating at the upper Rhine region. The bank filtration smoothes out this fluctuating concentration, as shown by the chloride concentration in the production well. Since chloride is typically not eliminated during underground passage, the slightly lower chloride concentration in the bank filtrate is a consequence of mixture effects with native groundwater in the well.

Temperature equalization

An underground passage is the only possibility to attain a cost-effective equalization of fluctuating surface water temperatures. These days, this is especially relevant for rivers receiving, even during the warm season, cooling water from power stations. In general, temperature equalization is more effective in longer subsoil passages (figure 6). Bank filtrate is usually cooler than surface water in summer and warmer in winter, resulting in a more constant water temperature.

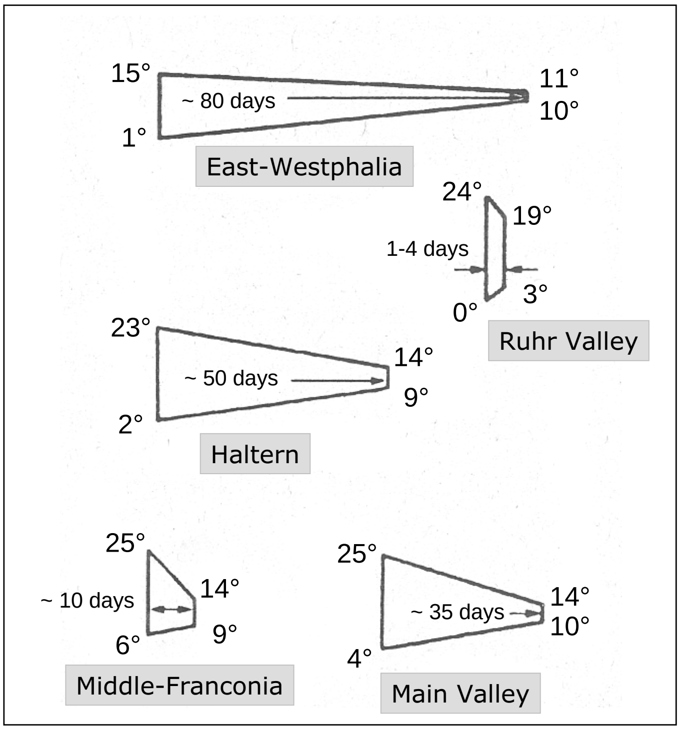

Fig. 6. Temperature equalization during underground passage.

Behavior of inorganics

Trace elements such as iron, manganese, and various heavy metals are eliminated during ground passage, mainly by sorption processes. In aerobic aquifers, removal is achieved by ion exchange processes at negatively loaded surfaces of clay minerals, amorphous ferric oxides and alumina, and organic solid matter. In anoxic aquifers, the removal of metal ions is dominated by precipitation reactions with sulphide. Removal efficiencies for heavy metals during riverbank filtration at the River Rhine are presented in Table 1. It is apparent from these long-lasting data sets that the percentage removals vary widely for the different elements, ranging from 0 to 94 %. All in all, interactions with the ground provide a considerable retention of heavy metals in subsoil. Furthermore, heavy metals can be removed by ground filtration for a long time and they cannot be easily remobilized with one exception:

if conditions in the aquifer become anaerobic, iron and manganese undergo chemical reduction and appear in the water, necessitating their elimination by treatment.

While chloride and sulfate are usually unaffected by ground passage, phosphate can be removed by this treatment step due to precipitation in the form of calcium, iron or aluminum phosphate in the ground. In aerobic aquifers, ammonium is transferred to nitrate by nitrification in the presence of oxygen. Due to analogous nitrification processes in the river, ammonium concentrations are usually rather low in surface water. However, even low ammonium concentrations cause an extensive oxygen depletion during infiltration. Formed nitrate can eventually be denitrified under anoxic conditions.

Tab. 1. Heavy metal removal by riverbank filtration at the lower Rhine*

Metal	Concentration in µg/L		Percentage Removal
	Rhine River	Bank Filtrate	
Zn	180	33	82
Cu	31.8	7.5	51
Pb	12.6	3.2	75
Ni	9.5	4.7	51
Cr	7.9	0.5	94
Sn	4.5	3.6	20
As	4.2	0.3	93
Cd	2.0	0.5	75
Se	1.8	1.6	11
Ag	0.5	0.5	0
Hg	0.3	0.2	33
Be	0.1	0.1	0

*mean values 1975-1978

Behavior of biological contaminants

Surface waters are often contaminated with pathogenic microorganisms excreted by humans, cattle, and various domestic and wild animals; however, the main sources are discharges of municipal wastewater effluents and runoff of livestock wastes and from fields receiving manure. Biological contaminants in surface water include protozoa, bacteria, and viruses. Underground passage for the removal of biological contaminants is, in principle, an efficient system. During the passage of pathogens through soil, their numbers are reduced by a combination of processes including adsorption to aquifer materials and inactivation.

The removal process is most efficient when groundwater velocity is slow and when the aquifer consists of granular materials with an open pore space for water flow around the grains what is improving the contact of the organisms with the grain surface. Given sufficient flow-path length and time, microbial contaminants will be removed or inactivated to levels protective of public health. Under optimal conditions, underground passage can achieve up to

8-log virus removal over a distance of 30 m in about 25 days. However, efficiency will be diminished by short path lengths, high heterogeneity, coarse matrices, high gradients, and accompanying high velocities. Thus, to assure an efficient removal of pathogenic organisms, water suppliers should favorably install or establish underground passages with high flow-path lengths and residence times.

Removal of organics

Natural organic matter (NOM) is a complex mixture of dissolved and particulate organic material present in surface waters including humic acids, hydrophilic acids, proteins, lipids, amino acids and hydrocarbons. NOM in surface water is a major concern for water utilities, since it contributes to odor and deterioration of taste in drinking water and is the main precursor for disinfection and oxidation byproducts, such as trihalomethanes (THMs) and haloacetic acids (HAAs), which are potentially carcinogenic.

Many authors reported on the removal potential of bank filtration and artificial infiltration for NOM after monitoring various sum parameters, such as total organic carbon (TOC), dissolved organic carbon (DOC), biodegradable organic carbon, ultraviolet absorbance of water at 254 nm (SAK) and assimilable organic cabon (AOC).

Figure 7 compares DOC concentrations in river water with those in bank filtrate for a waterworks in the central Rhine area over the past 25 years. In this time the DOC concentration in the Rhine dropped significantly due to improvements in wastewater treatment. A corresponding decrease was also found in the bank filtrate. Within the time interval depicted, the percentage of the DOC reduction between the river and bank filtrate was nearly constant at approximately 50 %.

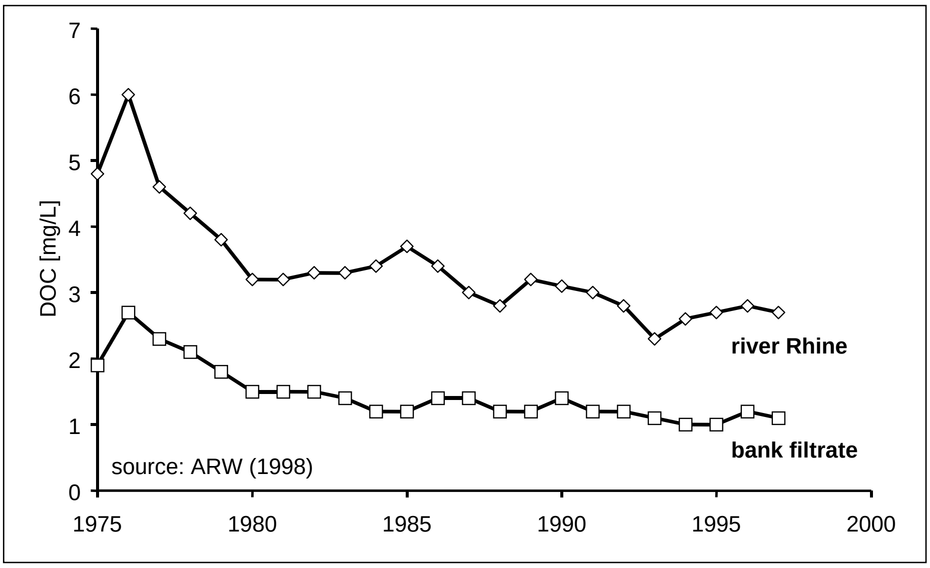

Fig. 7. DOC concentration in river water and bank filtrate.

As demonstrated in figure 8 for the mean annual DOC concentrations of bank filtrate from the Rhine River, retention time in the aquifer is an important factor controlling the removal efficiency of riverbank filtration. The data clearly demonstrates the favorable effect of higher residence times on water quality.

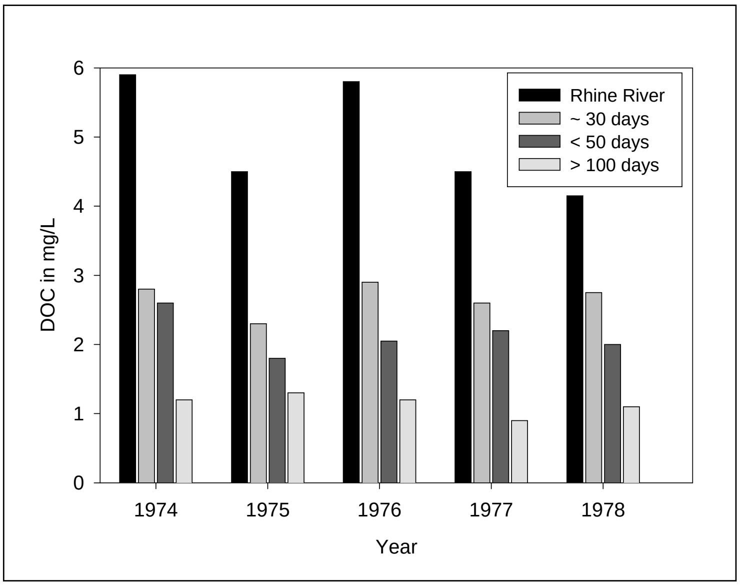

Fig. 8. DOC removal in bank filtration with different retention times.

Bank filtration also improves the microbiological quality of the water, which can be measured as a decrease in the concentration of assimilable organic carbon (AOC), what means the fraction of total organic carbon in water that can be used for microbiological growth and characterizes the ability of a water to support bacterial growth. Figure 9 gives an example of AOC concentrations in the course of various treatment steps in a waterworks.

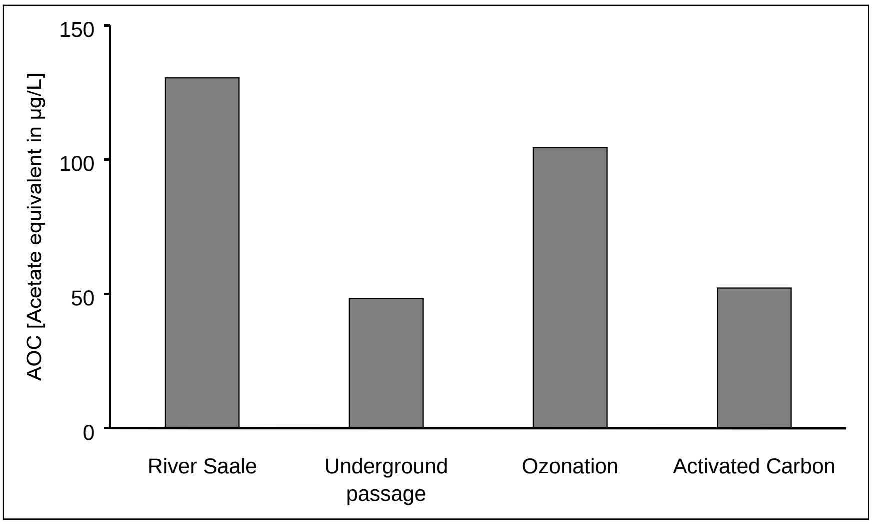

Fig. 9. Effect of bank filtration on biological regrowth.

Underground passage caused a clear decrease in AOC. As expected, a subsequent ozonation step increased the AOC again due to the oxidation of organics, which become more biodegradable. Finally, biologically active GAC filters (granular activated carbon) caused another AOC reduction. According to these results, bank filtrate is a fairly biologically stable water with a lower disinfection or oxidation demand.

Surface water is affected by industrial, agricultural, and domestic pollution. Various organic micropollutants have been detected in surface waters. The fate of these substances is mainly determined by adsorption mechanisms and biological transformations. The biological processes responsible for their elimination occur predominantly within the first few meters of infiltration. Polar organic molecules, such as complexing agents, pesticides, industrial products like aromatic sulfonates, pharmaceutical compounds, and personal care products, are of recent concern. However, numerous studies and long-time investigations in Germany demonstrated the efficiency of bank filtration and artificial infiltration in regard to many organic compounds. For pesticide residues, removal efficiencies employing artificial infiltration can vary between 10 % (atrazine) and 100 % (lindane) depending on the properties of the compound (figure 10).

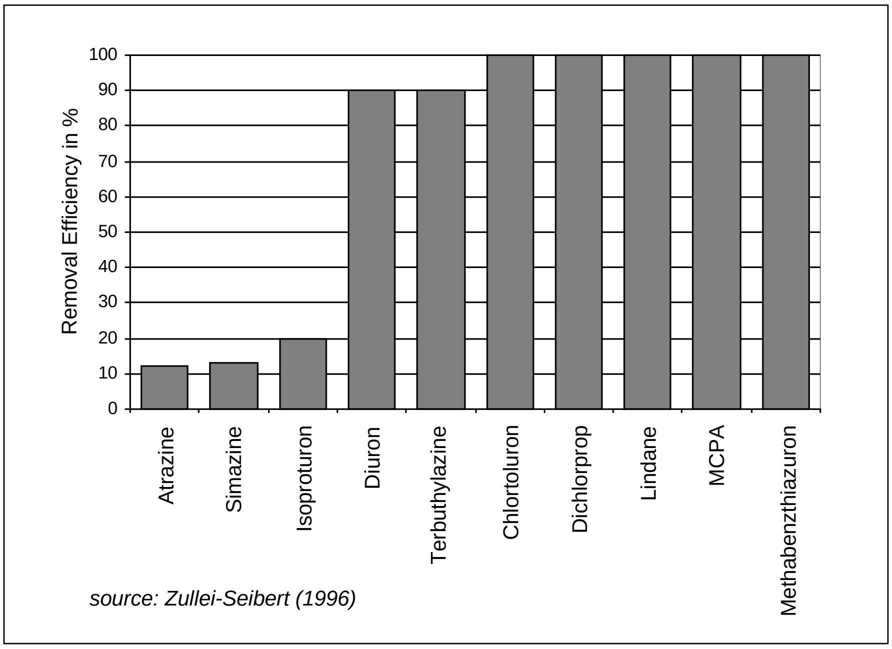

Fig. 10. Removal efficiency of artificial groundwater recharge for pesticide residues.

Figure 11 indicates the removal efficiency of bank filtration for different polar micropollutants and various sum parameters. It is obvious that many of the target compounds present in the Rhine River water are eliminated during bank filtration. On the other hand, some mobile and persistent organic micropollutants show a lower removal tendency. However, the compounds found in bank filtrate raw waters can in most cases be totally removed by subsequent treatment steps, like ozonation or GAC filtration.

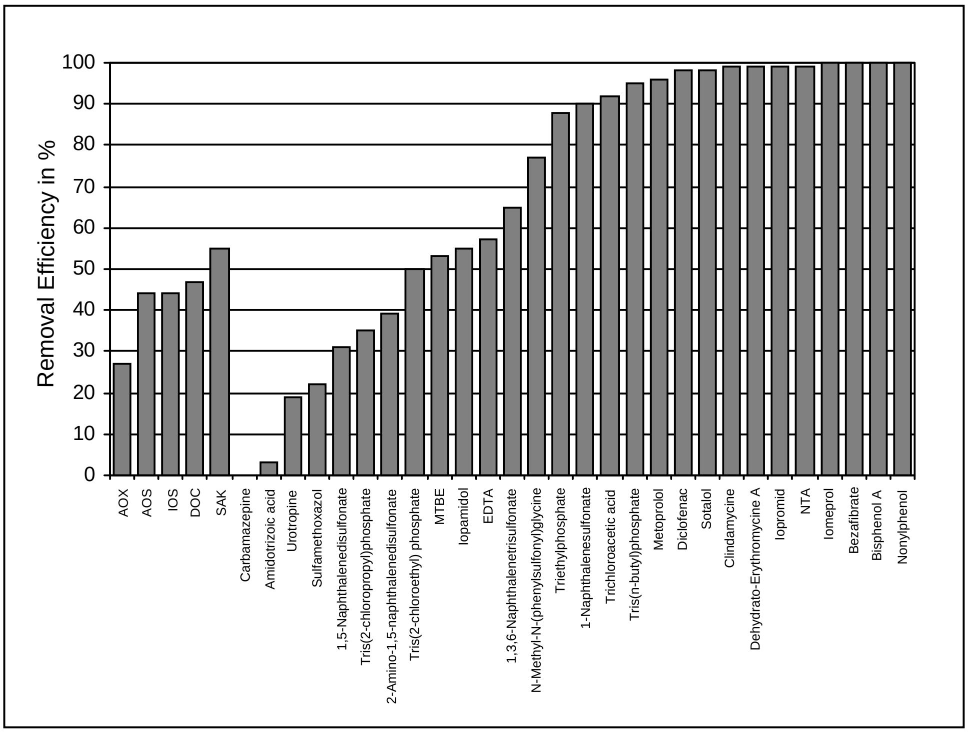

Fig. 11. Removal efficiency of riverbank filtration for micropollutants at the lower Rhine.

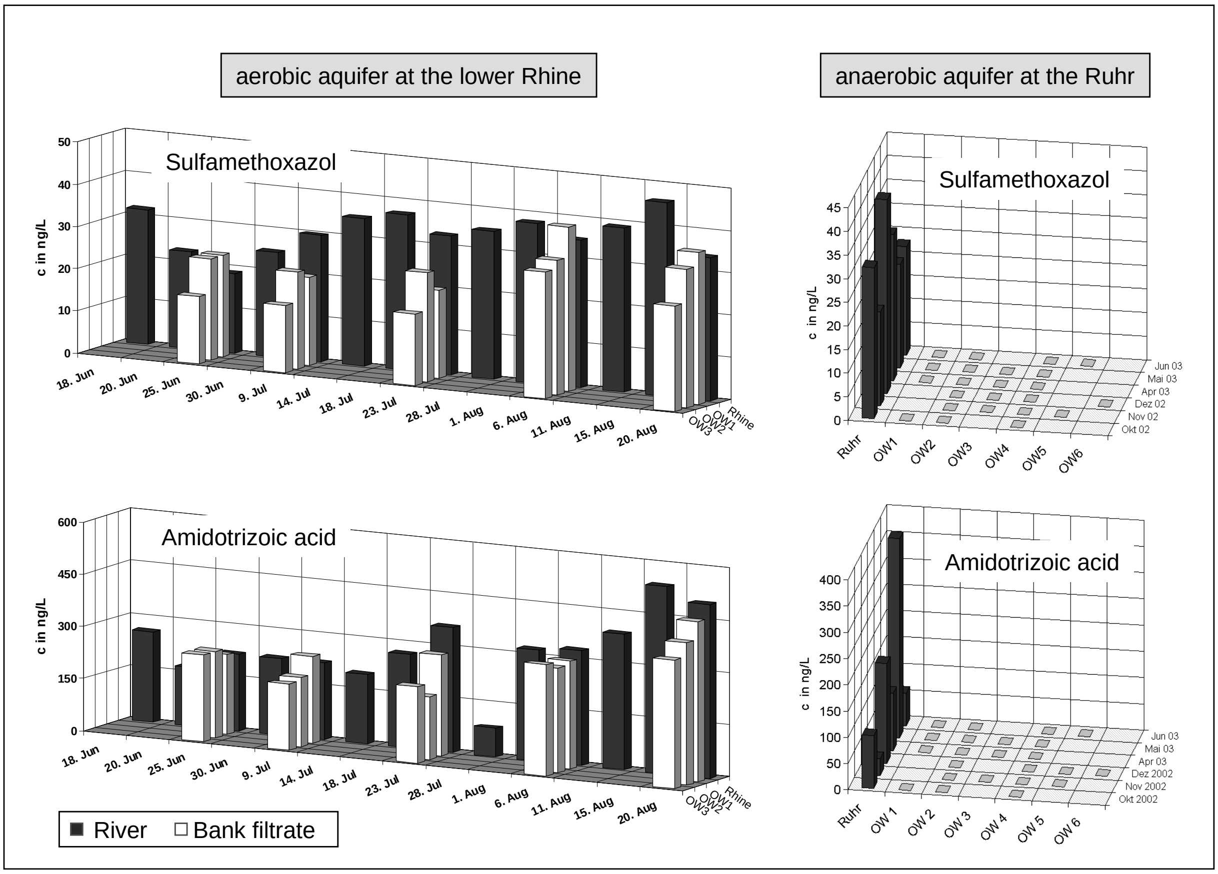

Fig. 12. Behavior of sulfamethoxazol and amidotrizoic acid during aerobic and anaerobic bank filtration [OW: observation well; increasing numbers indicate higher flow path lengths]

Detailed studies demonstrated, that levels of many organic micropollutants present in German rivers can be reduced or even eliminated during both aerobic and anaerobic underground passages. However, the elimination of others turned out to be clearly dependent on the underlying redox processes in the groundwater. Figure 12 demonstrates, how sulfamethoxazol (an antibiotic) and amidotrizoic acid (a X-ray contrast agent) are well eliminated in an anaerobic aquifer, but are only slightly reduced during an aerobic underground passage.

Due to their physico-chemical properties lipophilic industrial chemicals and pesticides like DDT or heptachlor are mostly sufficiently reduced by sorption processes at inorganic and organic soil materials. Another point of recent concern are cyanobacteria and their toxins that can adversely affect water quality, especially in summer during algae bloom. However, artificial groundwater recharge and bank filtration result in an efficient removal of cyanobacterial toxins and cells, except in very massive bloom situations.

Further Aspects

Treatment steps based on an underground passage can significantly lower the concentrations of many surface-water pollutants; however, precise predicting and quantifying those reductions is often difficult, since the efficiency of the underground passage depends on several factors. These include the river water quality, geological conditions, porosity of the soil, residence time of the water in the soil, temperature, pH-conditions, and oxygen concentration. Thus, the behavior of chemicals and microorganisms during infiltration and underground passage of water depends on many different interacting factors. In general, however, the efficiency of underground passage is such that water quality is significantly improved.

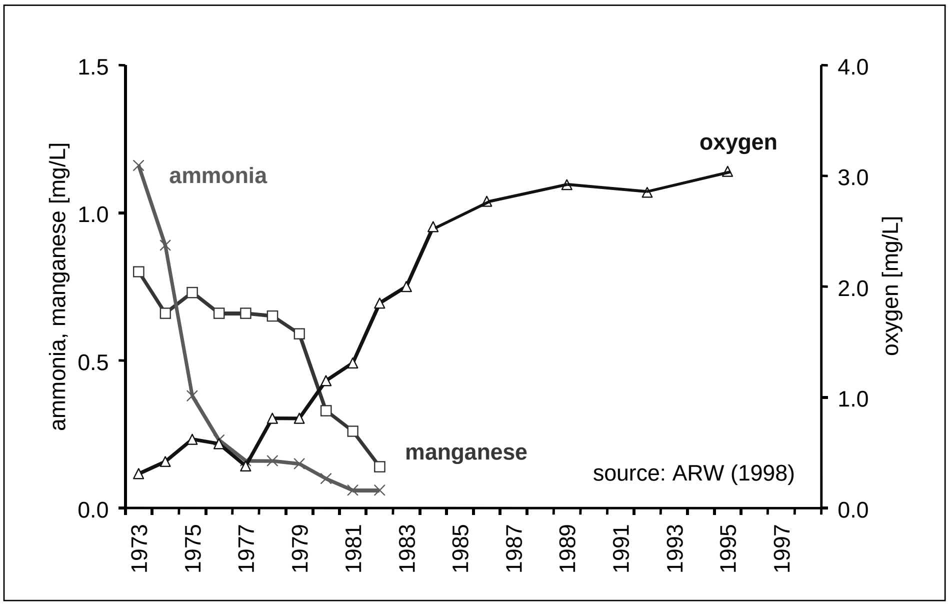

Fig. 13. Development of bank filtrate quality at the Rhine River.

Characteristics of the bank filtrate are affected by changes of the surface water quality that is characterized by the number of particles, concentration of dissolved organic matter from natural and artificial sources, oxygen, ammonia, nutrients, microorganisms, and other pollutants. The Rhine River is an excellent example how changes in surface water quality influence the characteristics of the corresponding bank filtrate. Figure 13 summarizes the concentrations of ammonia, manganese, and oxygen in the bank filtrate of the Rhine River over a period of several years.

In the early 1970s, Rhine water was highly polluted. Ammonia was present and nearly no oxygen. Due to the reduction of biodegradable organic material during infiltration the little oxygen present in the surface water and even nitrate were consumed, the aquifer was characterized by an anaerobic redox status, in which iron and manganese were reduced and released from the soil. In the mid 1980s, Rhine water quality improved because of better municipal and industrial wastewater treatment and its oxygen concentrations increased. As a consequence, conditions in the aquifer became aerobic, iron and manganese stayed in the insoluble oxidized form (Fe^{3+}, Mn^{4+}) and finally disappeared in the bank filtrate.

Another example demonstrating the direct dependency of the bank filtrate condition on the quality of the surface water is the long-lasting development of AOX concentrations (figure 14). The term AOX (adsorbable organic halogens) means the amount of organic halogens present in water. In the 1970s and early 1980s, high AOX concentrations were found in the Rhine water. Over the years, paper mills replaced chlorine bleaching by oxygen treatment due to the pressure of drinking water suppliers and, as a consequence, AOX levels in the Rhine dropped. It is obvious how the efforts to reduce the AOX levels in the Rhine during the last years resulted also in a higher bank filtrate quality.

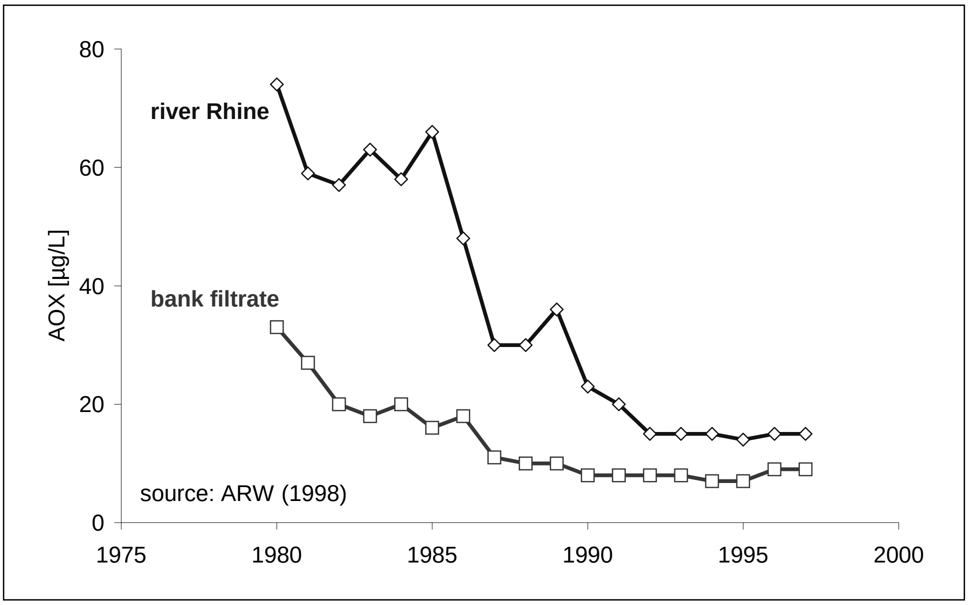

Fig. 14. Development of AOX concentrations in river water and bank filtrate.

Benefits

Based upon the above discussions, it is clear that river bank filtration and artificial infiltration can help utilities in various ways. Both techniques provide several advantages, such as the protection against shock loads, temperature equalization, and the removal of particles, biological contaminants and biodegradable compounds. Underground passage is a very natural step and is able to replace and specially to support other treatment steps. The underground passage improves the drinking water quality and makes drinking water safer and more acceptable for the consumer. Thus, one of the more unrecognized values of underground passage are avoided medical cost and longer life span.

When looking at the various types of purification processes intentionally allowed to occur in the aquifer during bank filtration and artificial infiltration, the question inevitably arises whether these processes will be exhausted or whether the underground passage can be used continuously. In Germany, bank filtration and artificial groundwater recharge have been used for the drinking water supply at several sites making use of different subsoil characteristics for decades and no loss of purification capacity could be noticed. This was also confirmed by several intensive investigations concerning this aspect. Despite considerable quality fluctuations of surface waters, natural processes did always (even following temporarily massive interruptions) turn back to normal. Furthermore, no alarming accumulation of persistent pollutants could be ascertained by investigation of various subsoils used for underground passages.

The costs for establishing riverbank filtration or artificial groundwater recharge systems depend on many factors, including aquifer characteristics, type of well-screen installation, facility design, and distance to the population served. However, costs can be classified as moderate.

Conclusions

Riverbank filtration and artificial groundwater recharge are well established techniques in Germany and are most often used as an important component of the established multiple barrier system. Passage of water underground provides several benefits for drinking water treatment. Experience demonstrates that during infiltration and underground transport, processes such as filtration, sorption, and biodegradation produce significant improvements in raw water quality. Underground passage as water treatment procedure combines particle removal, pathogen removal, organic and inorganic chemical removal, peak smoothing in spills, temperature equalization, reduction in DBP formation, and production of a more biologically stable water. However, polar, persistent organic substances are often not completely removed during underground passage. Elimination rates of these substances vary with residence time and length of the subsoil passage and sometimes depend on the redox status. This deficiency is well known; therefore, many water-treatment systems rely on additional treatment barriers such as oxidation and adsorption.

However, on the basis of a comprehensive evaluation of the available data material, it is obvious that the water quality is improved and subsequent treatment steps may be supported and simplified leading to decreased water treatment costs. Due to the significant reduction of DOC concentrations the run-time of activated carbon filters can be extended. Since bank filtration or infiltration remove biodegradable substances naturally, residuals requiring water treatment are lowered and less chemicals are necessary in subsequent flocculation and oxidation steps. Furthermore, the removal of particles and microorganisms during bank filtration supports other treatment steps such as filtration, membrane technologies, or disinfection.

References

Arbeitsgemeinschaft Rhein-Wasserwerke e.V. (ARW), 55. Jahresbericht 1998, *Köln, ARW (1999)*

BMI - Bundesministerium des Inneren (Ed.), Uferfiltration – Bericht des BMI-Fachausschusses “Wasserversorgung und Uferfiltrat”, *Bonn (1975)*

BMI - Bundesministerium des Inneren (Ed.), Künstliche Grundwasseranreicherung – Stand der Technik und des Wissens in der Bunderepublik Deutschland, *Berlin, Erich Schmidt Verlag (1985)*

Brauch H-J, Sacher F, Denecke E, Tacke T, Wirksamkeit der Uferfiltration für die Entfernung von polaren organischen Spurenstoffen, *gwf Wasser Abwasser (2000) 141(4), 226-234*

Brauch H-J, Müller U, Kühn W, Experiences with riverbank filtration in Germany, *Proceedings, International Riverbank Filtration Conference (2001) Rheinthemen, 4:33-39*

Brauch H-J, Sacher F, Kühn W, Riverbank filtration: A very efficient treatment process for the removal of organic contaminants?, *Proceedings, 2nd International Riverbank Filtration Conference (2003) 137-141*

German Association for Water Resources and Land Improvement (DVWK), Artificial Groundwater Recharge, Volume I – 1. Regional aspects of artificial groundwater recharge, 2. Artificial groundwater recharge in water resources management, *DVWK Bulletin No. 11, Hamburg, Berlin, Verlag Paul Parey (1982)*

German Association for Water Resources and Land Improvement (DVWK), Artificial Groundwater Recharge, Volume II – 3. Geological conditions of artificial groundwater recharge, 4. Qualitative goals for the water to be infiltrated, *DVWK Bulletin No. 12, Hamburg, Berlin, Verlag Paul Parey (1982)*

German Association for Water Resources and Land Improvement (DVWK), Artificial Groundwater Recharge, Volume III – 5. Quality changes during infiltration and underground passage, *DVWK Bulletin No. 13, Hamburg, Berlin, Verlag Paul Parey (1982)*

German Association for Water Resources and Land Improvement (DVWK), Artificial Groundwater Recharge, Volume IV – 6. Methods and practical experiences of plants using artificial groundwater recharge, 7. Legal regulations and regional planning aspects, 8. Summary and conclusions, *DVWK Bulletin No. 14, Hamburg, Berlin, Verlag Paul Parey (1982)*

Kühn W, Müller U, Riverbank filtration – an overview, *Journal AWWA (2000) 92, 60-69*

Preuß G, Schulte-Ebbert U, Artificial Groundwater Recharge and Bank Filtration, *In: Rehm H-J, Reed G (Eds.) Biotechnology Vol. 11c, 2.Auflage, Weinheim, Wiley-VCH (2000) 425-444*

Ray C, Melin G, Linsky RB (Ed.), Riverbank filtration – improving source-water quality, *Dordrecht, Boston, London, Kluwer Academic Publishers (2002)*

Sacher F, Brauch H-J, Experiences on the fate of organic micropollutants during riverbank filtration. *In: Ray C (Ed.): Understanding contaminant biogeochemistry and pathogen removal, Dordrecht, Boston, London, Kluwer Academic Publishers (2000) 135-151*

Sacher F, Brauch H-J, Kühn W, Fate studies of organic micropollutants in riverbank filtration, *Proceedings, International Riverbank Filtration Conference (2001) Rheinthemen, 4:139-148*

Sacher F, Lange FT, Brauch H-J, Blankenhorn I, Pharmaceuticals in groundwater – analytical methods and results of a monitoring program in Baden-Württemberg, Germany, *Journal of Chromatography A (2001) 938, 199-210*

Schmidt CK, Lange FT, Sacher F, Baus C, Brauch H-J, Assessing the fate of organic micropollutants during riverbank filtration utilizing field studies and laboratory test systems, *Geophysical Research Abstracts (2003) Vol. 5, 08595*

Schmidt Kh, Water quality aspects of artificial groundwater recharge – General overview as a keynote, *Artificial Recharge of Groundwater. International Symposium Helsinki (1996) 145-154*

Sontheimer H, Experiences with riverbank filtration along the Rhine River, *Journal AWWA (1980) 72, 386-390*

Sontheimer H, Trinkwasser aus dem Rhein? Bericht über ein Verbundforschungsvorhaben zur Sicherheit der Trinkwasserversorgung aus Rheinuferfiltrat, *Sankt Augustin, Academia Verlag (1991)*

Zullei-Seibert N, Pesticides and artificial recharge of groundwater via slow sand filtration – elimination potential and limitations, *Artificial Recharge of Groundwater. International Symposium Helsinki (1996) 247-253*