Drink. Water Eng. Sci. Discuss., 2, 101–126, 2009
www.drink-water-eng-sci-discuss.net/2/101/2009/

**Drinking Water
Engineering and Science
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Impact of decreasing water demand on bank filtration in Saxony, Germany

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Received: 15 July 2009 – Accepted: 31 July 2009 – Published: 27 August 2009

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Published by Copernicus Publications on behalf of the Delft University of Technology.

Abstract

Bank filtration has been of main importance for the drinking water supply in Germany for many decades. The water quality of pumped raw water from bank filtration sites depends to a high degree on the water quality of the infiltrating surface water and the landside groundwater, the mixing portion of both as well as the flow and transport conditions in the aquifer. Since the improvement of river water quality and a drastic decrease in water demand during the last 15 years in Germany, the influence of landside groundwater quality has become more important for the raw water quality of waterworks relying on bank filtration. The hydrogeologic analysis of three bank filtration sites in Saxony and the management of abstraction rates and well operation in response to fluctuating water demand are discussed. In conclusion, a general overview on management options for bank filtration sites is provided.

1 Bank filtration in Germany

In Germany, only 3% of the annually available water resources are needed for the public water supply. In 2007, main sources are groundwater and spring water (70%), followed by surface water and artificial infiltrate (22%), and bank filtrate (8%) (FSA, 2009).

In place of direct surface water abstraction, bank filtration with subsequent natural aquifer treatment has been used for water supply purposes since the 1870ies. One of the eldest exploited bank filtration sites are waterworks Duesseldorf-Flehe at the River Rhein and waterworks Dresden-Saloppe at the River Elbe. Both have been providing daily drinking water for several hundred thousand people since 1870 and 1875, respectively.

The water abstraction relies mostly on vertical wells, except for the waterworks along the River Rhine where also horizontal wells are installed. Typical characteristics for bank filtration sites in Germany are given in Table 1.

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Abstracted raw water is a mixture of bank filtrate and landside groundwater. Thus, raw water quality does not only depend on river water quality but also on landside groundwater quality. Due to the casually intensive agricultural use of the landside catchment, high portions of landside groundwater may result in increased concentrations of nitrate, sulphate, hardness and pesticides.

On the other hand, poor quality of river water in combination with high loads of suspended matter may result in river bed clogging. While the clogging layer comprises the biologically most active layer, it also strongly reduces water infiltration if the hydraulic conductivity decreases.

2 Bank filtration in Saxony

2.1 Water demand and bank filtrate abstraction

The Federal State of Saxony is located in the Southeast of Germany, bordered by the Czech Republic to the south and Poland to the east (Fig. 1). Bank filtrate as raw water source is used for both drinking water supply and process water. Bank filtration sites are concentrated in the lower lands at the rivers Mulde and Elbe and its tributaries, but also at the Lausitzer Neisse (Fig. 1).

Within a study, 19 bank filtration sites for the production of drinking water and 13 bank filtration sites for the production of process water were investigated. The bank filtration characteristics found in Saxony are typical for Germany, though no horizontal wells are operated. The abstraction rates of the waterworks producing drinking water range from 4000 m^3/a (Waterworks Koltzschen at the River Zwickauer Mulde) to 21 650 000 m^3/a (Waterworks Torgau at the River Elbe). Waterworks supplying process water abstract between 18 250 m^3/a to 2 453 000 m^3/a. The portion of bank filtrate in the pumped raw water accounts for 15 to 96%. For many waterworks used for drinking water production, travel times of bank filtrate have been determined using groundwater flow modelling, measurements of temperature and electrical conductivity and on the investigation of chloride and persistent trace organics.

Before 1990, the planning and construction of waterworks and well galleries was based on a predicted water demand of up to 200 litres per capita and day. Since 1990 many waterworks, especially in East Germany, have been facing drastic reductions in water consumption. Mean water abstraction rates for public water supply decreased due to political changes, the "water price shock" after re-unification of Germany, demographic changes but also changes in the consumption patterns (Fig. 2). While in Saxony in 1991 the production of raw water from bank filtrate relied on about 40×10^6 m^3/a, since 2001 the abstraction has been about 20×10^6 m^3/a only. In some regions, water use decreased by more than 50% within 10 years. Due to the expected demographic development, a further decrease in water consumption and thus water production is expected.

At many bank filtration sites, reduced water abstraction results in a lower portion of bank filtrate in the abstracted raw water. Thus, the quality of the landside groundwater becomes more important for the subsequent water treatment. To avoid this effect, a reduction in the number of wells seems reasonable. However, since peak demands still have to be met this option is not practicable.

In the following, the impact of a reduced mean water abstraction on bank filtrate portions and travel times will be presented for three waterworks in Saxony.

2.2 Bank filtration site Göttwitz

The bank filtration site Göttwitz ist located in the lowlands of northwest Saxony (Fig. 1) close to the stream Döllnitz in the east and Lake Göttwitz in the north (Fig. 3). In accordance to the general discussion, the water abstraction decreased between the early 1990ies and 2008 from about 1700 m^3/d to about 1000 m^3/d due to a lower water demand per capita and day (water savings) and reduction of leakage in the drinking water distribution systems. A sandy aquifer of low thickness (Table 2) is covered by a mighty clay layer limiting infiltration from the stream Döllnitz.

For an abstraction rate of 1700 m^3/d, the according bank filtration portion was determined to 13% based on groundwater flow modelling using Processing Modflow (Schwanke, 2008). The bank filtrate originates both from the Lake Göttwitz (12%) and the stream Döllnitz (1%). The low percentage of bank filtrate in the pumped raw water is caused by the morphology of the confining layer of the upper aquifer and management of lake water levels. Lake Göttwitz has a higher water level than Lake Döllnitz, which periodically is emptied.

A reduced water abstraction of about 1000 m^3/d results in a lower bank filtration portion of about 4%. The travel time between the lake and the northern well was calculated to >4 months for an abstraction rate of 1700 m^3/d and >20 months for 1000 m^3/d. The travel time for the infiltrating stream water (1–2% of abstracted water) has been calculated to 2–3 months for both scenarios. If the water demand will decrease further, the portion of bank filtrate will also further decrease, thus only groundwater is abstracted. This may cause problems in the future because nitrate and sulphate concentrations in the groundwater in the nearby agricultural area are high, whereas the nitrate concentration of bank filtrate is very low. Operation of only one well located nearest to the lake bank instead of all four wells would not have a noticeable effect on the bank filtrate portion if the total abstraction is low.

2.3 Waterworks Görlitz-Weinhübel

Waterworks Görlitz-Weinhübel is located in East Saxony, at the German-Polish border, in the floodplain of the River Lausitzer Neisse (Fig. 1). The waterworks supplies drinking water from bank filtrate and artificially recharged groundwater. The lake and the artificial infiltration basins are fed by River Neisse water to increase the available water quantity in the abstraction wells (Fig. 4). This handling was mainly practised during the 1980ies, when water demand and consumption were at a relatively high level. However, present investigations into the infiltration capacity of the lake proved that the bottom of the lake is almost completely clogged.

The main hydrogeological and technical information for the site are given in Table 3.

The shortest travel occurs between the river and the well north from the cross section (Fig. 4). Based on an analysis of seasonal temperature data for river water and groundwater as well as hydraulic gradients the travel time of bank filtrate was determined to 8 to 24 days depending on river stage. Lower abstraction from the siphon pipe system results in a longer travel time of bank filtrate. Originally, the impact of landside quality used to be low, considering that river water is infiltrated in the lakes and basins. However, due to significant clogging of the lake bed, the portion of landside groundwater abstracted is expected to increase.

2.4 Waterworks Meissen-Siebeneichen

The river bank filtration site Meissen-Siebeneichen is situated at the River Elbe, in a transverse valley between the Spaar Mountains and the Meissen granite bedrock (Fig. 5). The valley is filled with Pleistocene deposits to a depth of 5–20 m that comprise interfingered glaciofluviatile sediments ranging from fine sand to medium sand and gravel. The deposits are overlain by Holocene meadow loam (2–7 m thick). Along the monitoring cross-section, the thickness of the aquifer is about 18 m (Table 4).

The mean discharge of the River Elbe at Meissen is about 300 m^3/s. Groundwater recharge in the 200–300 m wide strip between the river and the bedrock is very low due to the meadow loam cover. Groundwater flow from faults in the bedrock and from the other side of the river beneath the river bed towards the production wells was assumed to be negligible. Thus, the only source of the pumped raw water was thought to be river water via bank filtration.

Groundwater samples were taken from the cross-section at a quarterly interval in 1995–1997 and on 12 May 2001 (Fig. 6). Groundwater was obtained using either a mobile submersible pump lowered into 120 mm diameter observation wells or from in situ membrane pumps used to sample from directly below the bed of the River Elbe. In the field, well head measurements included temperature, pH, alkalinity and O_2. In the laboratory, analyses included major ions, iron and manganese. Analyses were carried out according to German guidelines and DIN methods. Prior to analysis, water samples were filtered through a 0.45 μm cellulose-acetate filter. The anions Cl^-, NO_3^-,

SO_4^{2-} were determined using ion-chromatography.

The results of field investigations between 1993 and 1995 showed very high nitrate (up to 130 mg/L), chloride and sulphate concentrations at the bottom of the aquifer between the production well and the River Elbe (Fig. 7a). Whereas chloride and sulphate concentrations were also high landward of the production well, nitrate concentration was only about 50 mg/L. Only along the right-hand side of the river, the groundwater is highly polluted by nitrate (up to 170 mg/L) due to fertilizer applications at vineyards and greenhouses. It was thus assumed that the groundwater flows through the lower layer of the aquifer from the right side of the river beneath the river bed towards the production well. In the upper and middle layer of the aquifer, nitrate concentrations were lower than in river water due to denitrification processes along the flow path of bank filtrate.

The assumption of groundwater flow beneath the river bed was further supported by results of the determination of dissolved organic carbon (DOC) and ethylenediaminetetraacetate (EDTA). In the lower layer of the aquifer, low DOC and EDTA concentrations were found indicating mixing of groundwater and a small proportion of bank filtrate (Grischek et al., 1994). Low DOC values in this layer also suggested a high proportion of weakly or non-biodegradable organic matter resulting in a carbon limitation of the denitrification rate.

Since 1996, water abstraction from production wells has been reduced to only a few days per year. A groundwater sampling campaign in 2001 showed that as consequence the bank filtrate in the aquifer is slowly replaced by groundwater. However, there are still high nitrate concentrations in the lower layer of the aquifer and near the river, indicating a very slow process of replacement and the effects of occasional pumping (Fig. 7b). High sulphate and chloride concentrations, found at sampling points next to river indicated an up-coning of the groundwater from the lower layer and exfiltration into the river.

The geohydraulic assumptions based on hydrochemical investigations were verified by groundwater flow and transport modelling. The model area extended over

$1790 \times 800\,m^2$ and four layers of 5 m thickness each. The groundwater recharge from the River Elbe is controlled by the piezometric heads in the aquifer, the river water levels along the river course and the hydraulic conductance of the river bed. The horizontal conductivity value was set evenly to 1.4×10^{-3} m/s. The corresponding vertical hydraulic conductivities were chosen to be an order of magnitude smaller than the horizontal conductivities due to anisotropy (the ratio between horizontal and vertical hydraulic conductivity). This allowed the model validation using results from hydrochemical investigations in the four different layers in the cross-section.

The choice of model boundaries was based on the bedrock geomorphology, piezometric contour maps and results from hydrochemical investigations. Neumann type boundaries were used along groundwater flow lines taken from piezometric contour maps ($Q=0$), for groundwater flow into the model calculated from the related recharge areas and recharge rates, and for the three abstraction wells. Groundwater recharge from precipitation was set to 2.2 L/(s km^2). The river was not included as a fixed head boundary but as a Cauchy boundary with a clogging layer in the river bed of 0.1 m thickness and a hydraulic conductivity of 1×10^{-5} m/s.

Water head measurements from two sampling campaigns were used for model calibration. Hydraulic conductivities and proportions of pumped water from the production wells were altered slightly to achieve a better fit of measured and computed piezometric heads. Flow modelling was performed using Processing Modflow for Windows (Chiang and Kinzelbach, 2001). Tracer transport was calculated with MT3D using the finite difference method (Zhen, 1990). A value of 0.25 for the effective porosity is considered reasonable for the alluvial sediments. The longitudinal dispersivity was estimated from the scale length of the transport phenomenon. Values of 10 m for the longitudinal dispersivity and of 1 m for both the horizontal and the vertical transverse dispersivities were defined for the present transport model.

The results from groundwater flow and transport modelling reinforced the theory of groundwater flow beneath the river. Figure 8 shows examples for flow path lines of particles starting at the right side of the River Elbe in each model layer. Cross-sections

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A-A and B-B show that only particles starting in the upper layer of the aquifer are flowing into the river. All other particles turn away before they reach the river but flow towards the production well. Thus, high nitrate concentrations in the lower layer of the aquifer between the river and the production well can be explained by groundwater flow from the opposite side of the river.

Due to the small surface and subsurface catchment, the bank filtrate portion is very high. As function of the clogging intensity in the river bed, the bank filtrate portion varies between 86 and 96%.

Using the groundwater transport model, a time scale of several years for full replenishment of the bank filtrate and groundwater from the opposite side of the river was confirmed by non-steady state calculations. Thus, in 2001, no full replenishment of the nitrate rich water in the lower layer could be expected.

3 Managing bank filtration sites with respect to a fluctuating water demand

The management of waterworks depends on various limiting factors. Satisfying the fluctuating water demand is of prime importance which, however, is often opposed to the preferred continuous operation of wells to ensure stable flow conditions and removal rates. Another important factor is the mixing of river bank filtrate and groundwater to obtain an optimum quality with regard to raw water treatment. At most sites, the main aims of water quality management include reaching the maximum attenuation of organic compounds during aquifer passage and low concentrations of DOC, dissolved iron and nitrate in raw water. At all sites with long flow paths, mixing ratios of bank filtrate and groundwater were found to be of main importance for the concentration of DOC, nitrate, sulphate, dissolved iron and manganese in the abstracted raw water.

Figure 9 and Table 5 give an overview on options for management measures for bank filtration sites.

(I) Knowing the hydrogeologic conditions of a bank filtration site and facing raw water quality problems related to unfavourable flow or mixing conditions between river and

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groundwater, the most convincing way might be to replace wells. However, during a period of decreasing water demand and lower income of the waterworks investments to construct new wells – with location adapted to achieve the main aims in water pre-treatment – are limited and rare.

(II) Mostly, the frequently occurring seasonal floods in Saxon rivers erode the river bed and limit the clogging. Furthermore, by trend higher surface water quality and lower abstraction rates reduce river bed clogging. Consequently, technical measures in the river bed are not required.

(III) In short term, optimisation of production well operation is the most promising way to handle higher portions of landside groundwater and changes in raw water quality due to changing mixing ratios. It includes controlling the flow path length and travel time as well as the mixing by the selection of most suitable wells from a well field. For that, a detailed investigation of groundwater flow conditions and portions of bank filtrate in the raw water is very important to decide about most effective water quality management measures.

(IV) In Saxony, the water quality of many rivers improved after re-unification between 1989 to 1993 due to sanitation measures and closure of industries. Political activities, for example establishing the International Commission for Protection of the River Elbe and the recent EU Water Framework Directive, contributed to further improvement of surface water quality.

(V) Collaboration with farmers in the catchment area, agreements on compensation payments to limit the application of fertilizers (especially N) and pesticides or buying the land are appropriate measures on a long term basis to reduce nitrate, sulphate and pesticide concentrations in landside groundwater. Such measures have been practiced with different intensities and success. They may not be successful to balance the higher nitrate concentration of pumped raw water if the portion of landside water is increasing due to lower water abstraction.

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4 Summary

Bank filtration sites in Germany have been designed decades ago to replace direct abstraction of polluted surface water. Whereas from the 1970ies to the 1980ies, river water quality and removal of organic pollutants was the major concern in management of bank filtration sites, the situation has changed since 1990. The ongoing decrease in water demand in many regions in Germany, especially in Saxony, lead to lower portions of bank filtrate in the abstracted raw water. Landside groundwater quality becomes more important for the subsequent treatment for drinking water production. At some sites high nitrate and sulphate concentrations in landside groundwater demand specific mixing rations between bank filtrate and groundwater in the aquifer. Thus, optimisation of well operation to cover the lower mean demand and the remaining peak demand becomes a key issue in management of bank filtration sites.

Acknowledgements. The authors are grateful to the Ministry for Science and Art, Saxony, for financial support (grant no. 475316002512007), and to Mr. Deike (waterworks Görlitz), Mrs. Böhm (OEWA GmbH) and Mr. Fischer (DREWAG GmbH) for professional support.

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Table 1. Characteristics of bank filtration sites in Germany (Kühn and Müller, 2005).

Condition	Range
distance bank – well	20 to 860 m
well fields length along river	1 to 2 km
aquifer thickness	4 to 70 m
hydraulic conductivity	0.0001 to 0.05 m/s
travel times	3 days to 0.5 years

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Table 2. Geohydraulic conditions for the site Göttwitz.

Condition	Average value
aquifer thickness	10 m
hydraulic conductivity	2×10^{-4} m/s
distance between lake bank and abstraction wells	200 m
number of wells	4
maximum total abstraction rate	1700 m^3/d

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Table 3. Geohydraulic conditions for the site Görlitz-Weinhübel.

Condition	Average value
aquifer thickness	10 m
hydraulic conductivity	1×10^{-3} m/s
distance between river bank and abstraction wells	50 to 150 m
number of wells	32
maximum total abstraction rate	11 248 m^3/d

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Table 4. Geohydraulic conditions for the site Meissen-Siebeneichen.

Condition	Average value
aquifer thickness	18 m
hydraulic conductivity	1.2 to 1.4×10^{-3} m/s
distance between river bank and abstraction wells	100 m
number of wells	3
max. total abstraction rate	3800 m^3/d

Table 5. Management actions in catchments of bank filtration sites.

	Management action	Actors	Evaluation
I	new well construction (location, depth)	waterworks	expensive
II	technical measures in the riverbed	waterworks	continuous measure, expensive
III	optimisation of well operation	waterworks	short-term, high efficiency
IV	improvement of river water quality	politics	long-term measure
V	changes in land use in the catchment	politics, farmers	long-term measure

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Fig. 1. Bank filtration sites in Saxony.

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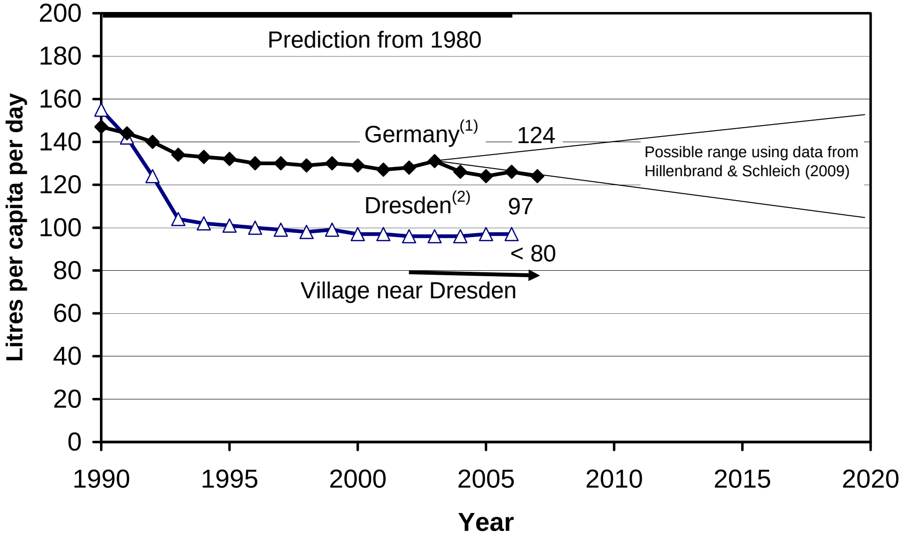

Fig. 2. Development of water demand per capita and day in Germany and Saxony. (1) BDEW (2009); (2) City of Dresden (2009).

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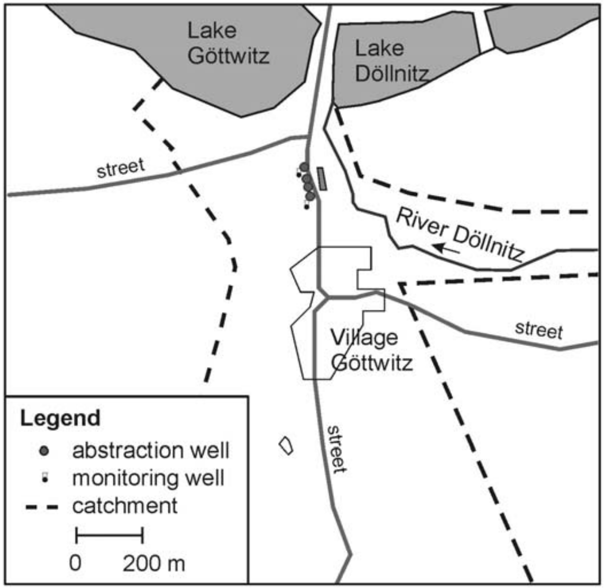

Fig. 3. Scheme of the bank filtration site Göttwitz.

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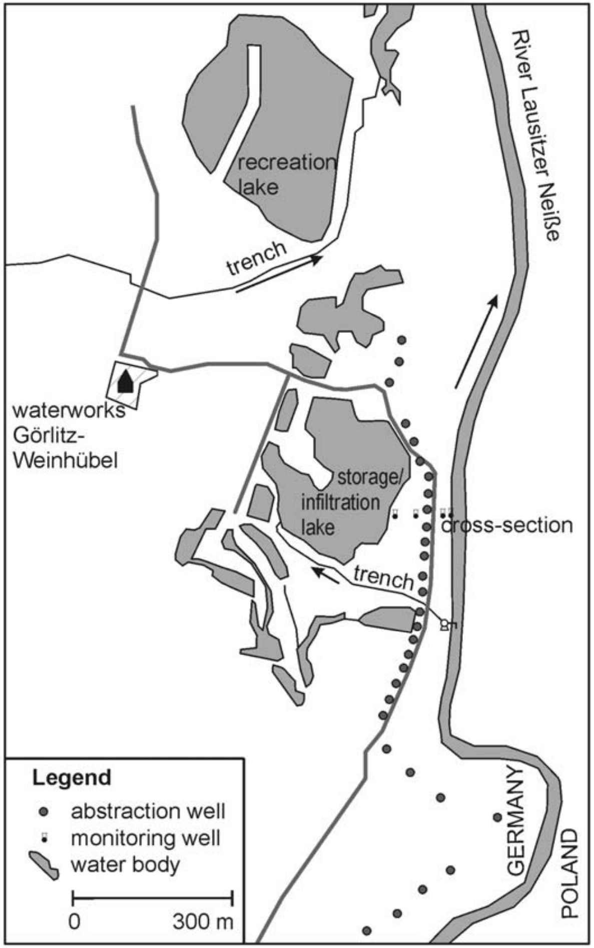

Fig. 4. Scheme of the bank filtration site waterworks Görlitz-Weinhübel.

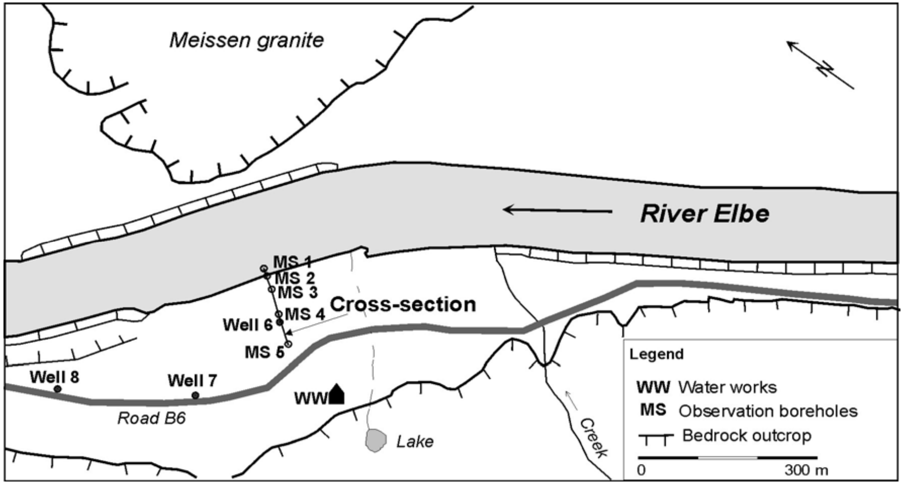

Fig. 5. Scheme of the bank filtration site Meissen-Siebeneichen.

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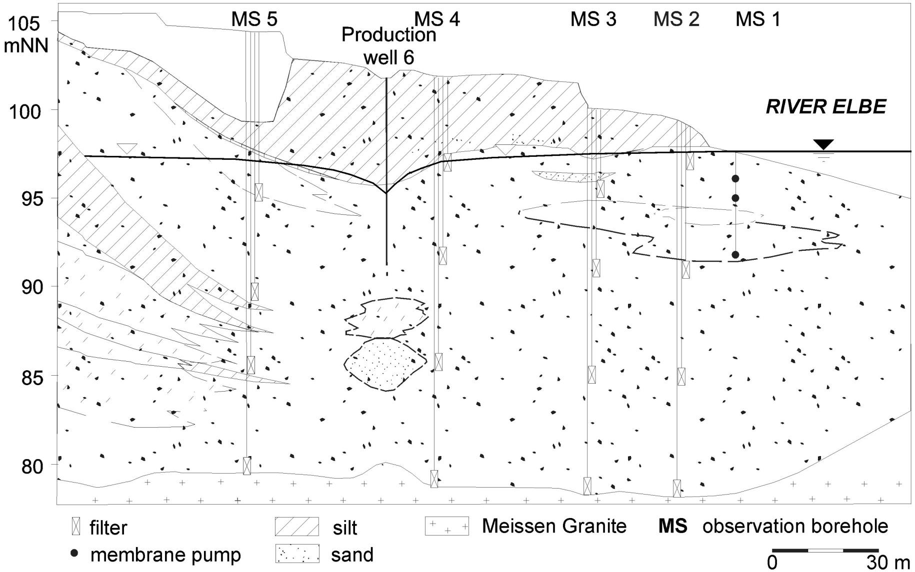

Fig. 6. Location of observation boreholes along the cross-section.

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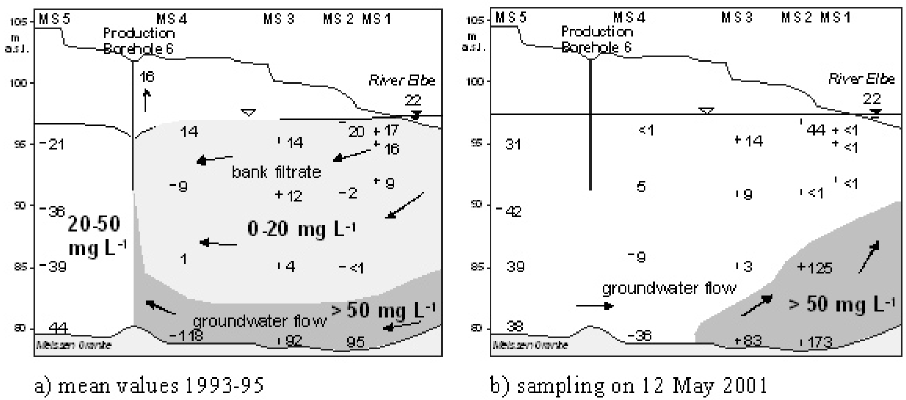

Fig. 7. Nitrate concentrations (mg/L) at observation points along the cross-section.

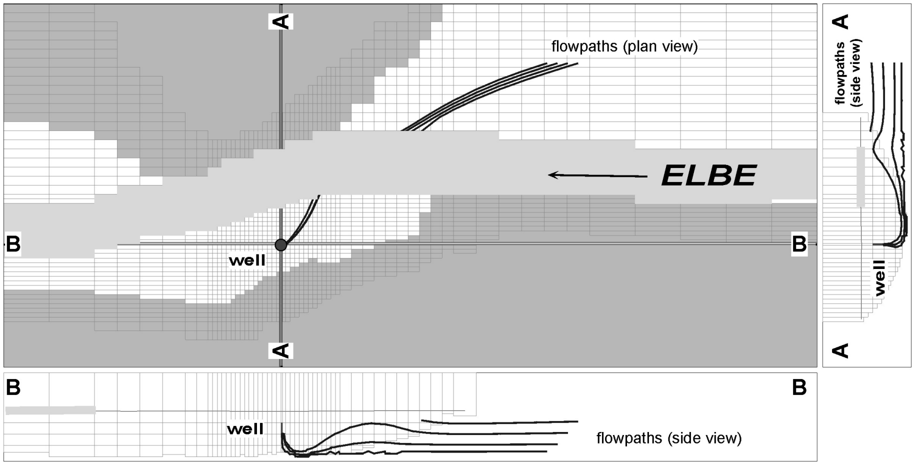

Fig. 8. Flow path lines of groundwater from the opposite side of the river.

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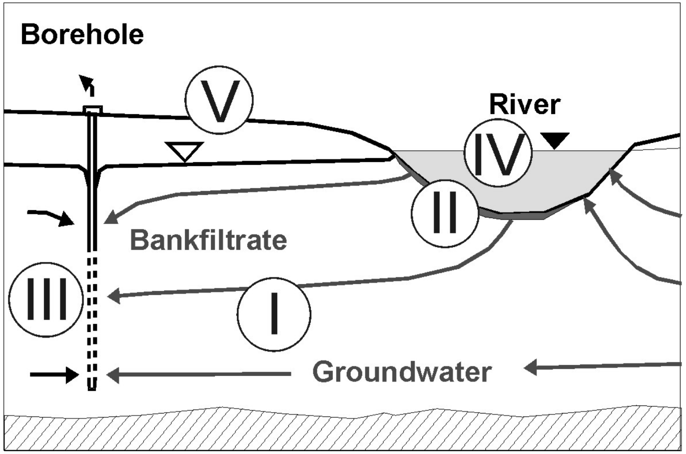

Fig. 9. Options for managing river bank filtration in quantity and quality.

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