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Application of bank filtration technology for water quality improvement in a warm climate: a case study at Beberibe River in Brazil

D. A. Freitas, J. J. S. P. Cabral, A. L. R. Paiva and R. J. R. Molica

ABSTRACT

Use of bank filtration (BF) to improve water quality is of great importance for public water supply. The BF technique consists of the use of wells situated near riverbanks with sediment materials from the banks and bed as a natural filter, which significantly reduces pollutant concentration found in surface water. The objective of this study was to analyse the ability of the BF technique to improve water quality in a study performed on the Beberibe River, Pernambuco State, Brazil. At a pilot scale, physical structure in the experimental module comprises one production well and seven observation wells. Groundwater levels and physical–chemical monitoring were conducted both at the Beberibe River and a production well, to evaluate the effectiveness of the BF technique. In addition, coliforms group and cyanobacteria removal were also analysed. The BF technique at the Beberibe River effectively improved water quality in terms of physical–chemical and bacteriological parameters and pumped water complies with potability standards required by Brazilian law and the rules of the World Health Organization.

Key words | bank filtration, Beberibe River, ground water, water quality, water supply, water treatment

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INTRODUCTION

In the last few decades, with economic development and population growth, supply of potable water has been strongly affected due to the growing demand for water, climate change and an increasing degree of surface water pollution. Spatial and temporal allocation of potable water has been decreased due to a decrease in the availability of quality raw water. Therefore, management of water resources for a sustainable potable water supply should consider not only the amount of available water but also its quality (Kubeck *et al.* 2009).

Use of alternative techniques such as bank filtration (BF) to improve water quality is of great importance for public supply. The BF technique uses wells situated near riverbanks with sediment materials from the banks and bed as a natural filter, which significantly reduces the pollutant concentration found in surface water (Lorenzen *et al.* 2010; Hoffmann & Gunkel 2011b; Stauder *et al.* 2012).

A number of European countries including Germany, the Netherlands, France, Switzerland, Hungary (Kim *et al.* 2003), the Slovak Republic (Schubert 2002) and Finland (Dash *et al.* 2008) have been using BF as an important source for the production of water for human consumption.

In Germany, BF has been of great importance for drinking water supply with large capacity waterworks located at lakes Müggelsee, Tegel and Wannsee (Kohfahl *et al.* 2009; Hoffmann & Gunkel 2011a; 2011b). Cities such as Düsseldorf and Basel receive potable water from BF systems (Kubeck *et al.* 2009). In Berlin, approximately 75% of the water supply comes from BF with improvements using artificial groundwater recharge (Kuehn & Mueller 2000). In Lake Tegel, BF for Berlin's water supply is achieved through several galleries with 116 wells pumping 260,000 m^3 day^{-1} to supply drinking water for 700,000 inhabitants (Hoffmann & Gunkel 2011a).

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Moreover, in Germany, BF researches are well advanced and there are many programs such as the NASRI project (Natural and Artificial Systems for Recharge and Infiltration) that include a large cooperation project for BF and artificial groundwater recharge. In Germany, the NASRI project has been investigating BF hydrochemistry and hydrogeology (Greskowiak *et al.* 2006), dissolved organic carbon removal (Grünheid *et al.* 2005), cyanotoxins (Grützmacher *et al.* 2010) and pharmaceutical residues (Heberer *et al.* 2004). Other NASRI project research themes include biological function characterization in first infiltration stretch of littoral interstices (Hoffmann & Gunkel 2011a, b), particulate organic matter (POM) retention (Gunkel *et al.* 2009), clogging processes (Hoffmann & Gunkel 2011b), as well as temperature effects on BF (Groß-Wittke *et al.* 2010).

Other countries such as India (Ray 2008), China (Wu *et al.* 2006), Korea (Lee *et al.* 2009) and Egypt (Shamrukh & Abdel-Wahab 2008) have also used BF for water supply. In India, the NASRI project has applied BF as a low-cost water treatment method. In northern India at Lake Nainital, in the Kumaon region at Uttarakhand state, BF has been used for more than 15 years (Dash *et al.* 2008). In the city of Haridwar, the BF system was installed at the banks of the Ganga River, which supplies more than 35% of the city (Dash *et al.* 2010).

In the United States, the water supply 'industry' classifies and adopts a regulatory concept that water originating from BF is 'groundwater under the direct influence of surface water' (GWUDI), and this variable is defined and executed as a response to local conditions of each state or regulatory agent (Hiscock & Grischek 2002). The United States started using this technique due to its low cost and its ability to remove several pathogenic microorganisms, such as *Cryptosporidium* and *Giardia* (Ray *et al.* 2002).

In Brazil, BF scientific studies have been started by Sens *et al.* (2006) and a pilot research has been applied in Peri Lake, Florianópolis city (Santa Catarina State, Southern Brazil). This research evaluated BF as a pre-treatment for removing cyanobacteria with good results. In Ituporanga (Santa Catarina State), Michelan *et al.* (2011) applied the BF system followed by backwashed slow sand filtration for supply to rural communities. In Northeast Brazil, the BF system at the Beberibe River in the Recife Metropolitan Region (RMR) (Pernambuco State) has been applied experimentally to evaluate this technique under geological and hydrological local conditions (Paiva *et al.* 2010).

For BF systems, it is necessary that the subsurface environment has specific hydrogeological characteristics. Sediment layers of the region should be examined because it is fundamental to establish an infiltration stretch between the surface water and the production well. Moreover, it is necessary to evaluate the heterogeneity and hydraulic conductivity of sediments (Fleckenstein *et al.* 2006), seasonality of river flow, stability of river channel, speed of flow, availability of river water during dry and rainy seasons and river water and groundwater quality (Hunt *et al.* 2002; Grischek *et al.* 2010). Additionally, pumped raw water is a mixture of bank filtrate and landside groundwater. Thus, the raw water quality of BF depends not only on river water quality but also on groundwater quality (Grischek *et al.* 2010).

The quality of water bank filtrate is influenced during passage through the river bank and aquifer sediments (surface and groundwater interface). Transition between streams and groundwater is very important for the BF process as well as the hyporheic zone and meiofauna interstices (Gunkel *et al.* 2009; Hoffmann & Gunkel 2011b). During water infiltration, microorganism metabolism occurs in the water–sand transition zone cross-linked with input and turnover of natural organic matter (NOM) as well as physical–chemical processes that act in self-purification processes in the bank filtrate (Gunkel & Hoffmann 2009; Maeng *et al.* 2010).

The clogging process during BF may reduce the permeability of the riverbed, due to the deposition of fine particles or the formation of biofilms (Goldschneider *et al.* 2007; Gunkel & Hoffmann 2009). Reduced infiltration rates may constitute a disadvantage with regard to productivity, but the formation of a clogging zone may also have many advantages, such as it is potentially more effective in removing contaminants than unclogged sands of aquifer because the adsorption and reduction capacities are larger owing to higher proportions of organic and/or fine-grained material (Goldschneider *et al.* 2007; Massmann *et al.* 2008; Hoffmann & Gunkel 2011a, b).

Surface water quality is improved during BF due to natural attenuation processes, such as filtration, adsorption, acid-base reaction, oxidation, reduction, hydrolysis and biochemical reactions. BF is able to reduce potential pollutant levels, such as pesticides, pharmaceutical residues, NOM and pathogenic microorganisms (Metge *et al.* 2010; Hoffmann & Gunkel 2011b). Moreover, studies have demonstrated that BF is a highly efficient method for the significant removal of turbidity (Dash *et al.* 2008; Thakur & Ojha 2010).

BF systems have the potential to provide a significant barrier against microorganisms, which has been observed by a number of researchers. The barrier is effective during passage through riverbed material and aquifer sediment to a production well (Göllnitz *et al.* 2005; Weiss *et al.* 2005; Faulkner *et al.* 2010), and it can reduce the presence of *Giardia* and *Cryptosporidium* protozoa (Weiss *et al.* 2005; Metge *et al.* 2010). However, there is still much uncertainty surrounding the capacity of BF to remove *Giardia* and *Cryptosporidium:* due to the low and variable concentrations of *Cryptosporidium* and *Giardia* present in the river waters, accurate log reductions for these pathogens could not directly be determined. Additionally, further research is necessary in order to assess the transport character and removal rates for pathogen surrogates and indicator organisms during passage through BF systems (Weiss *et al.* 2005).

The effectiveness of BF in removing microorganisms such as coliform groups, including *Escherichia coli*, has also been investigated (Wang 2002; Dash *et al.* 2010). Thakur & Ojha (2005) analysed at five wells located near the river bank at Ganga River, India, and it was observed that the BF system was effective in removing *E. coli*. Analysis of the BF system at the Nile River, Egypt, showed positive results in water bank filtrate for *E. coli* removal (Shamrukh & Abdel-Wahab 2008).

Some studies highlight the use of BF to remove cyanobacteria and their cyanotoxins (Chorus & Bartram 1999; Sens *et al.* 2006; Grützmacher *et al.* 2010). Abundant growth of cyanobacteria in water reservoirs creates severe practical problems for water supplies. The development of strains containing toxins is a common experience in polluted water systems all over the world (Chorus & Bartram 1999). Cyanobacterial blooms are very frequent events in Brazilian drinking water supplies as a consequence of eutrophication processes. In the reservoirs northeast from Brazil many toxic species of cyanobacteria have been reported (Bouvy *et al.* 2003; Molica *et al.* 2005).

The objective of the present study was to analyse the ability of the BF technique to improve water quality in a study performed on the Beberibe River, in Pernambuco State, Brazil. Physical, chemical and microbiological parameters related to the Beberibe River and the production well were monitored to analyse the ability of BF to improve water quality and compare it to potability standards required by Brazilian law and the World Health Organization (WHO).

EXPERIMENTAL PROJECT

Project location

The experimental area of the present research includes the Beberibe River basin in the RMR, state of Pernambuco, Brazil. The BF pilot project was developed on the Beberibe riverbanks, in the neighbourhood of Caixa d'Água in the RMR (Figure 1).

The Beberibe River basin belongs to the first group of coastal watersheds (GL-1) located in the north shore of the state of Pernambuco, with an area of 75.45 km^2 and includes 54 km^2 of the Recife municipalities, including Olinda City with 14 km^2 and Camaragibe City with 7.45 km^2.

The experimental area is situated in the Beberibe aquifer with semi-confined formations and average thickness of 100 m of sandstones with intercalations of mudstone. The Beberibe aquifer is considered the most important formation in terms of water storage (Cabral *et al.* 2008).

The Beberibe River is characterized as a polluted river and hypereutrophic by the State Environmental Agency of Pernambuco (CPRH 2011) in some sites, including the area of the experiment station. Anthropic activities in the Beberibe River basin that directly affect water quality include industrial activities, farming activities, urban activities with sewage input, riparian deforestation, construction and maintenance of roads and open landfills with leakage.

Assembly of pilot project

To obtain more detailed information on the sediment layers, standard penetration test (SPT) percussion boreholes were drilled both perpendicular (cross-section 1) and parallel

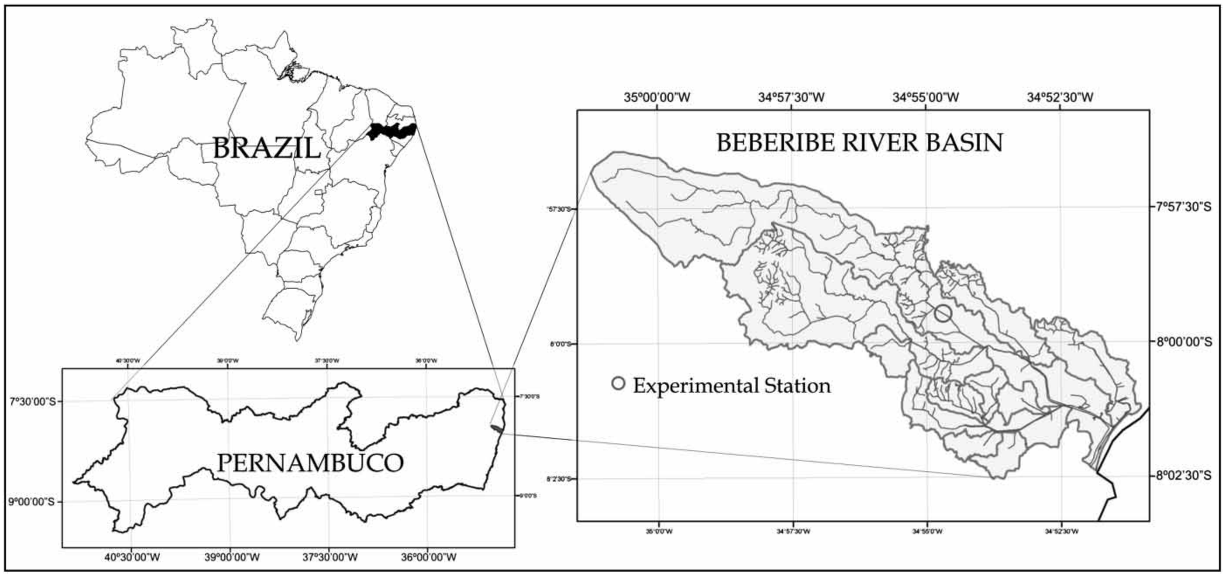

Figure 1 | Location of bank filtration experimental station in the Beberibe River basin.

(cross-section 2) to the Beberibe River (Figure 2). The boreholes were later transformed into observation wells (SP).

The production well project was developed after information from the boreholes. It was built with a depth of 15 m, a diameter of 15 cm and a screened interval between 7 and 13 m. The distance between the production well and the Beberibe River is about 65 m by groundwater flow direction. The production well built on the banks of the Beberibe River supplies an average flow of 12.6 m^3/h, i.e. 3.5 l/s, and it is operated for 24 h without interruption.

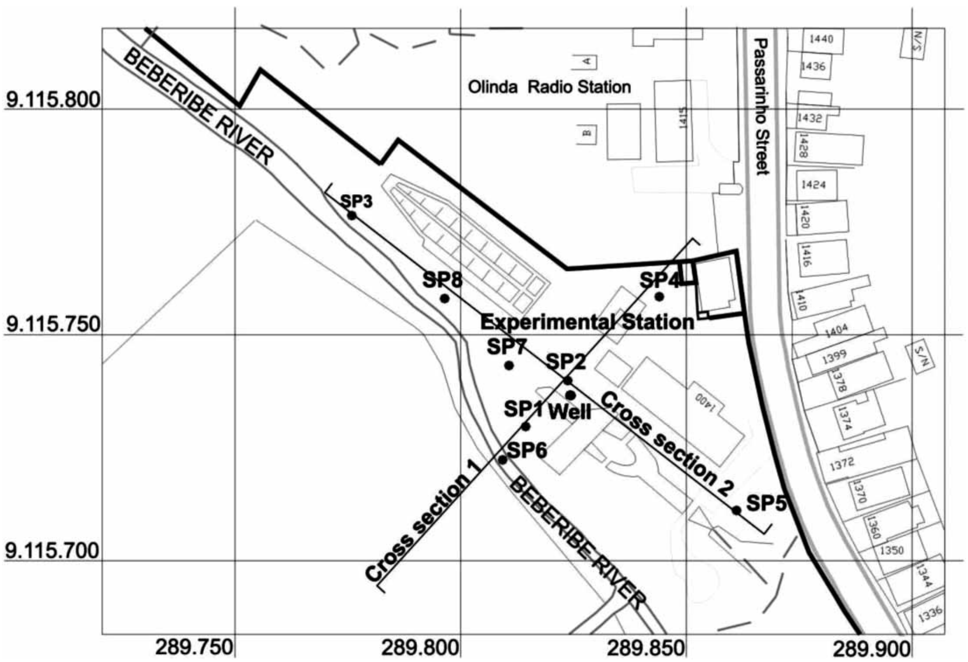

Figure 2 | Location of production well (Well) and observation wells (SP1, SP2, SP3, SP4, SP5, SP7 and SP8) at the Beberibe River banks, Olinda, PE.

On a pilot scale, the experimental module consisted of one production well (Well) and seven observation wells: SP1, SP2, SP3, SP4, SP5, SP7 and SP8 (Figure 2).

Piezometric monitoring

Piezometric monitoring was used to obtain readings of water levels of the production well, observation wells and the Beberibe River surface from March to December 2009. By monitoring groundwater level variations with the pumping action of the production well it is possible to produce a map of the tendency of potentiometric curves and evaluated hydraulic connection in the BF system in the Beberibe River.

Before starting piezometric monitoring, the positions of the observation wells and the production well were surveyed using a geodetic GPS. Furthermore, a common measurement reference level has been chosen for all the piezometers, assuming that the main building floor level is 0.00 m.

Groundwater levels of observation wells and production well were obtained with an analogue level meter for piezometric monitoring. Furthermore, the water levels of the Beberibe River were monitored through a limnimetric ruler, and depth values obtained were converted to the reference level.

Physical–chemical and bacteriological characteristics

Physical–chemical monitoring was conducted from March to December 2009, both at the Beberibe River and at the production well, to evaluate the effectiveness of the BF technique to treat water naturally.

All the analyses were performed according to the Standard Methods for Examining Water and Wastewater (APHA 2005) according to Table 1.

Analyses of total coliforms and faecal coliforms present in the Beberibe River and the production well water were conducted in November and December 2009 with dilution of 10^{-4} using the Colilert method (APHA 2005).

Cyanobacteria monitoring

To monitor cyanobacteria, seven samples of Beberibe river water and production well water with 1.0 l of river and well water were collected in sterilized bottles from November 2009 to January 2010. Analyses of cyanotoxins were not made in this research.

Samples were fixed with acetic Lugol's solution and cyanobacteria were counted according to the Utermöhl method (1958). Sediment chambers were taken to an inverted microscope and the number of cells per cyanobacteria species were counted in transects.

RESULTS AND DISCUSSION

Granulometric analysis of boreholes created two transversal sections of sediment layers characteristics, one

Table 1 | Physical–chemical parameters analysed, method and instruments used and numbers of samples considerating the Beberibe River and production well

Parameters	Method/instrument	Numbers of samples river and well
pH	SM 4500-H+ B/Homis Mod.108	20
Turbidity (NTU)	SM 2130 B/PoliControl AP2000	20
Conductivity (μS cm^{-1})	Cole Parmer Mod. 1481–61	19
Total hardness (mg l^{-1})	SM 2340 C/Titrimetric method with EDTA	19
Ammonia (mg l^{-1})	SM 4500- NO3- C/Titrimetric method	20
Nitrite-N (mg l^{-1})	SM 4500- NO2- C/Colorimetric method	20
Nitrate-N (mg l^{-1})	SM 4500 NO3- E/Hydrazine reduction method	20
BOD (mg l^{-1})	Titulometric method	20
COD (mg l^{-1})	Titulometric method	20
Total iron (mg l^{-1})	SM 3500-Fe B/Phenanthroline method	18
Total manganese (mg l^{-1})	SM 3500-Mn B/Persulfate method	18

perpendicular (Figure 3) and one parallel to the Beberibe River (Figure 4).

Parallel and perpendicular transversal sections of Beberibe River sediment layers are composed of layers of fine-grained material (silt and clay), followed by a strip of sand between 7 and 19 metres deep. This layer is an important zone to the production well and for the BF technique with a hydraulic connection between river and well production. For infiltration, a connection between river water and aquifer trough riverbed material is needed, which means hydraulic resistance must be low, and this is determined by the layer of fine particles, in most cases, at the water sediment transition zone, hyporheic zone (Gunkel & Hoffmann 2006).

Piezometric monitoring

Results of piezometric monitoring were important for monitoring variations in groundwater with the pumping action of the production well and results indicate that water coming from the production well is a mixture of groundwater from the phreatic aquifer and from surface water induced by the pumping through the sediment layers (Grischek *et al.* 2010).

Maps of potentiometric curves and flow lines (Figure 5) tend to go towards the production well, which is characteristic of the aquifer–river connection. In the winter period, the Beberibe River water level and piezometric heads production well and observations well were about 40 cm higher than in the summer period.

Correlating Beberibe River depths with piezometric levels of production well and observation wells, it was possible to evaluate seasonal variations: the rainy season had higher piezometric levels, possibly due to a greater charge of water table in this period, which includes the months from March to August 2009 (Figure 6).

Comparing the behaviour of Beberibe River depth and water level of production well and observation wells, similar components are observed, which define the interaction between the river and the production well, i.e. there is a hydraulic connection between the river and the aquifer (Figure 6).

This hydraulic connection associated with information of the piezometric head (Figure 5) and similar behaviour of the Beberibe River and the water level of the production well and observation wells (Figure 6) implies that there is flux from the river to the well. Lee *et al.* (2009) observed similar results in a riverbank filtration site in the Republic

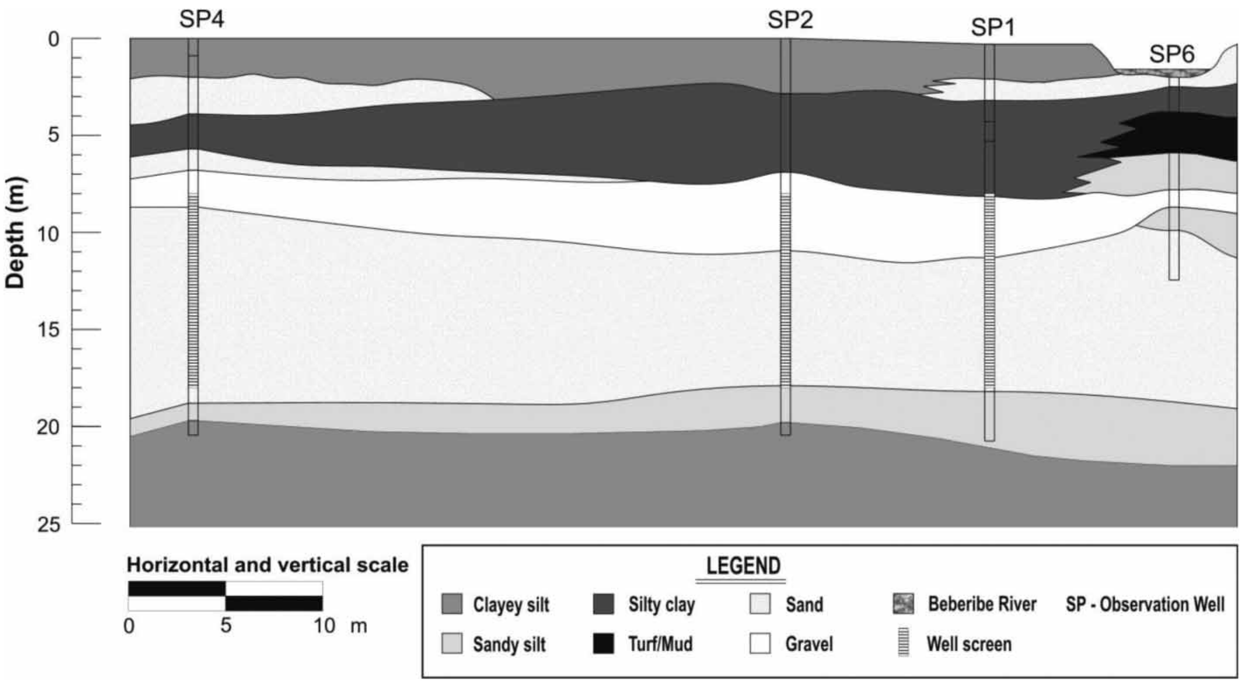

Figure 3 | Transversal section of sediment layers perpendicular to the Beberibe River in Caixa d'Água Experimental Station, Olinda, PE, Brazil.

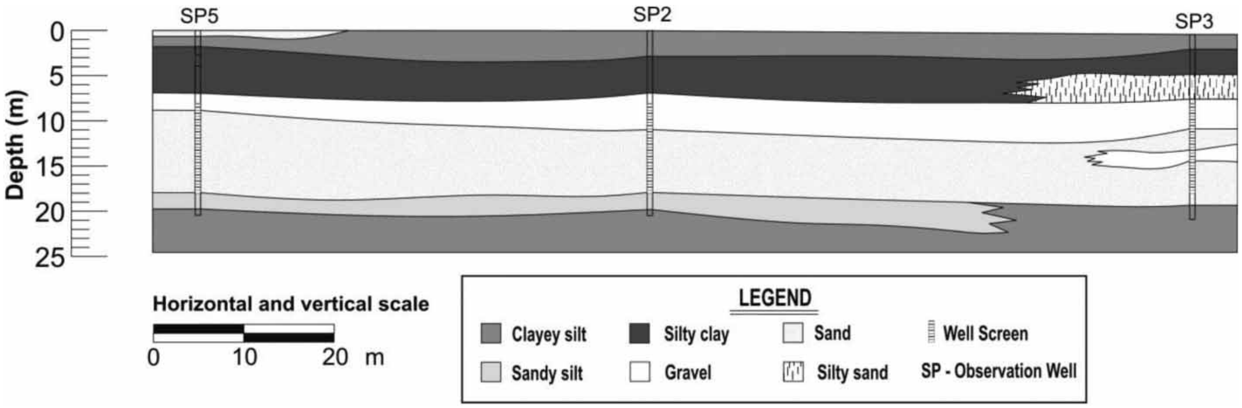

Figure 4 | Transversal section of sediment layers parallel to the Beberibe River in Caixa d'Água Experimental Station, Olinda, PE, Brazil.

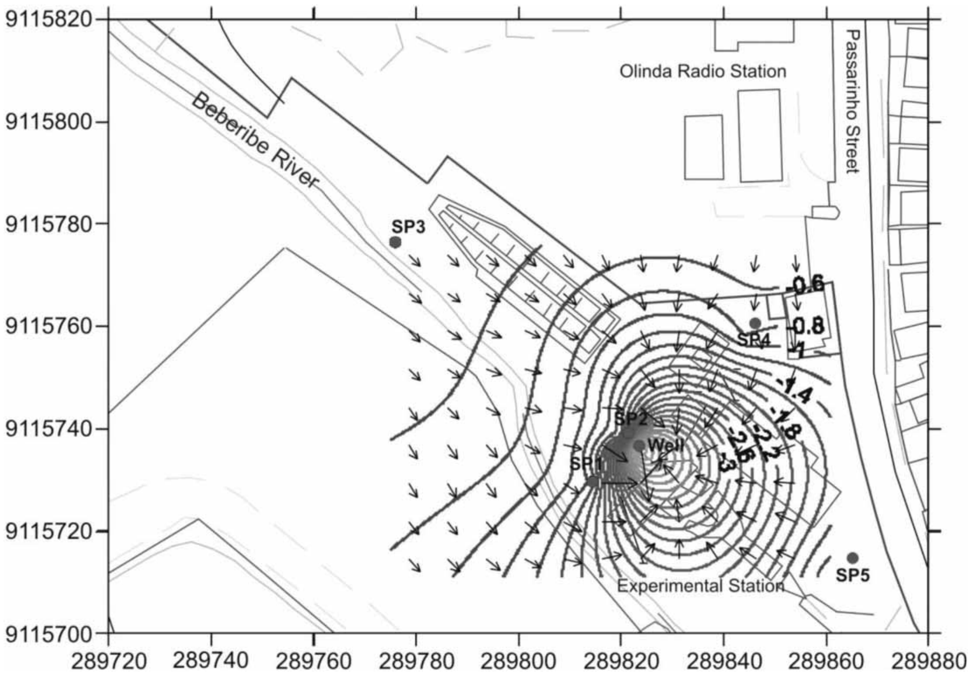

Figure 5 | Map of potentiometric curves and flow lines of production well pumping to the Beberibe River in Caixa d'Água Experimental Station, Olinda, PE, Brazil.

of Korea, adjacent to Nakdong River; the groundwater level rapidly responded to the river level and this finding was consistent with the irregular variation of the river level due to precipitation.

Physical–chemical and bacteriological monitoring

Production well water was within the potability standards established by Decree n. 518/2004 (Ministério da Saúde, Portaria 2005) of the Brazilian Health Department and World Health Organization (WHO 2008) for all physical–chemical parameters analysed (pH, turbidity, electric conductivity, ammonia in NH_3, nitrite in N, nitrate in N, total hardness in $CaCO_3$, biochemical oxygen demand ($BOD_{5.20}$), chemical oxygen demand (COD), total iron and total manganese). Likewise, water originating from BF did not have coliforms or faecal coliforms according to bacteriological parameters (Table 2).

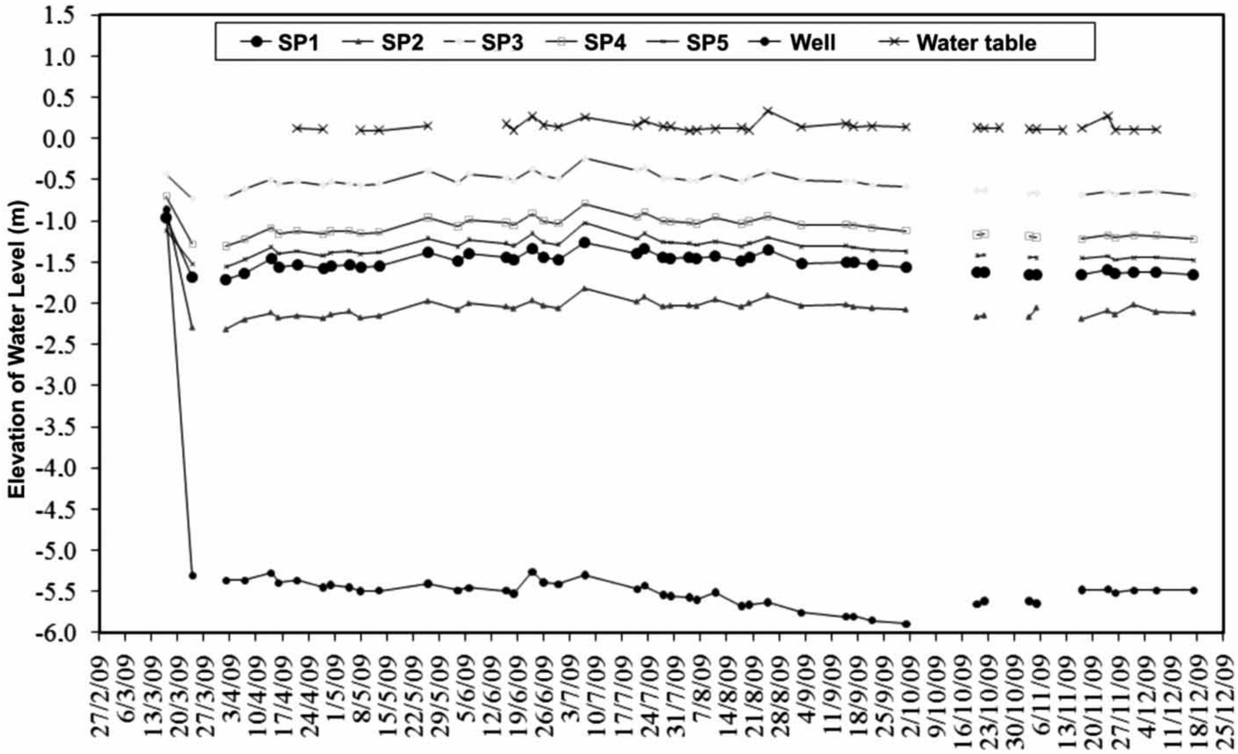

Figure 6 | Piezometric monitoring of production well, observation wells and Beberibe River surface level, in Caixa d'Água Experimental Station, March to December 2009.

Table 2 | Results of parameters analysed according to the maximum allowed values (MAV) by Decree n. 518/2004 of the Brazilian Health Department and by the World Health Organization (2008) which indicate the effectiveness of the BF technique

Parameters	Average concentrations: River	Average concentrations: Well	Brazilian law – Decree (HD) 518/2004	World Health Organization (2008)	BF performance
pH	7.0	6.5	6–9.5	6.5–8	Reduced
Turbidity (NTU)	34.03	0.76	5.0	5.0	Reduced
Conductivity (μS cm^{-1})	196.6	210.9	–	–	Increased
Total hardness (mg l^{-1})	30.7	33.87	500.0	500.0	Increased
Ammonia (mg l^{-1})	4.144	0.448	1.5	1.5	Reduced
Nitrite-N (mg l^{-1})	0.461	0.005	1.0	–	Reduced
Nitrate-N (mg l^{-1})	1.306	0.489	10.0	–	Reduced
BOD (mg l^{-1})	6.17	1.65	–	–	Reduced
COD (mg l^{-1})	26.8	9.2	–	–	Reduced
Total iron (mg l^{-1})	1.988	0.085	0.3	0.3	Reduced
Total manganese (mg l^{-1})	0.057	0.038	0.1	0.1	Reduced
Total coliforms (NMP/100 ml)	1,516–30,804	Absence	Absence	Absence	Eliminated
Faecal coliforms (NMP/100 ml)	300–3,428	Absence	Absence	Absence	Eliminated

It is noted that water coming from the BF technique decreases 97.7% of turbidity. The average concentration of Beberibe River water was 34.03 NTU and of production well water was 0.8 NTU. Many authors refer to BF as an effective system for reducing turbidity (Kuehn & Mueller 2000; Dash *et al*. 2008; Lee *et al*. 2009). According to Hoffmann & Gunkel (2011a), suspended particles are attenuated during the passage of river water through porous media. Thakur & Ojha (2010) evaluated BF for turbidity removal of the Ganga River in Uttrakhand, India; the variation of suspended sediment in Ganga River water is observed from 17 to 1,745 NTU, whereas in abstracted water variation of suspended sediment is observed from 1.02 to 0.2 NTU.

Nitrate removal at the BF system of the Beberibe River presented nitrate concentrations higher than at the production well. Lee *et al*. (2009) observed similar results in the Daesan-Myeon area, Republic of Korea, with nitrate concentrations lower in riverbank filtrate water than in Nakdong River water.

Results for iron and manganese showed a lower concentration in the production well than in the Beberibe River. Iron and manganese are indicators for oxygen consumption, It can be observed at BOD oxygen budget. In this case, in bank filtrate BOD was 1.65 mg l^{-1} whereas in the Beberibe River it was 6.17 mg l^{-1}.

Electric conductivity and hardness parameters analysed for the production well were higher than those of the Beberibe River, but keep within standard water quality ranges (Ministério da Saúde, Portaria 2005; WHO 2008). Similar results were also reported by Dash *et al*. (2010) at the Ganga River, Haridwar city, India, where hardness and electrical conductivity increased during BF. Thakur *et al.* (2011) analysed the same river and found that alkalinity and electrical conductivity increased after the passage of water through a porous medium. According to Thakur *et al.* (2011), this occurs when water passing through the sediment of the bank and riverbed dissolves some precipitation that causes an increase in alkalinity and electrical conductivity or because of changes in redox conditions (Hiscock & Grischek 2002).

The concentration of total coliforms for the Beberibe River ranged from 1,500 to 31,000 NMP/100 ml, and for faecal coliforms the concentration ranged from 300 to 3,400 NMP/100 ml. In the production well the coliform group was absent, thus data indicate that BF provides a substantial barrier to microbial contaminants under study conditions. Positive results for coliform removal for BF systems were reported (Wang 2002; Dash *et al*. 2008, 2010). Singh *et al.* (2010) observed at Yamuna River, India, a reduced number of coliform bacteria by around 50% in the bank filtrate.

The Beberibe's BF system showed an improvement in water quality for all parameters, which suggests effective water treatment or at least a substantial pre-treatment step for water supply (Ray *et al*. 2002). Results of physical–chemical and bacteriological parameters showed that all are within the Guidelines for Drinking Water ranges for the Brazilian Health Department (Decree 518/2004) and the World Health Organization (WHO 2008).

Cyanobacteria monitoring

In the Beberibe River, five cyanobacteria species were found: *Limnothrix redekei*, *Oscillatoria subbrevis*, *Pseudanabaena catenata*, *Aphanizomenon* sp. and *Spirulina* sp. Cyanobacteria concentrations evaluated at the Beberibe River ranged from 1,678 to 15,059 cells ml^{-1}. In an analysis of cyanobacteria removal using the BF technique in the samples of production well water, no cyanobacteria species were found, and 100% removal was achieved.

Removal of cyanobacteria is of great importance, particularly in drinking-water treatment; cyanobacteria are associated with the production of potent toxins that may intoxicate animals and human beings (Chorus & Bartram 1999). Studies have demonstrated the potential of the BF technique in the removal of cyanobacteria and cyanotoxins (Miller *et al*. 2001; Dillon *et al*. 2002; Sens *et al*. 2006). Chorus *et al*. (2003) studied the removal of algae and cyanobacterial toxins during slow sand filtration and BF. Results of these experiments suggest that sediment filtration methods are secure treatment methods for water sources contaminated by cyanotoxins under most conditions. According to Chorus *et al*. (2003), the main elimination processes are physical filtration of mostly cell-bound toxins and biodegradation of released, dissolved toxins.

CONCLUSIONS

The BF technique was applied to the Beberibe River banks and was demonstrated to effectively improve water quality in terms of both physical–chemical and bacteriological parameters and to be compliant with the potability standards required by Brazilian law (Decree 518/2004) and the rules of the World Health Organization (2008).

Electric conductivity and hardness increased in the BF system in the Beberibe River. This occurs during water passing through sediment layers, probably because bank filtrate absorbs many solutes.

The Beberibe River had five species of cyanobacteria, and these could be eliminated by the BF process; samples of the production well did not carry any cyanobacteria, with 100% cells removal.

Finally, the BF technique was an effective method for water treatment in local climate and sediment conditions of the RMR in the Beberibe River, improving water quality. BF systems seem to be a good technique for the developing world, thus it is important that other countries in the developing world set up similar experimental research to analyse BF effectiveness for water pollution characteristics and soil and climate conditions.

The water company in Pernambuco State has supported this research and has an interest in following up in the future, before incorporating the system into the full-time water supply.

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