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REVIEW

Review on river bank filtration as an in situ water treatment process

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Abstract Surface and ground water are valuable sources for drinking water. Certain industrial, mining, and agricultural practices pollute these critical resources. Riverbank filtration (RBF) is a cost-effective in situ water treatment process, which removes suspended solids and organic and inorganic pollutants. The RBF process is defined as a natural filter of soils and aquifer sediments at the river site. In RBF, river water moves through the pores of the natural soils of the riverbed and riverbank. RBF improves several physical, chemical, and biological properties of the river water. Several treatment actions including, filtration, sorption, and biological degradation occur during this process. Under specific conditions, RBF could be used as a treatment or pretreatment process to remove or decrease pollutants in surface water. In this paper, the effectiveness of RBF in improving the river water quality is presented. RBF as a cost-effective water treatment process is also discussed. Furthermore, factors that affect the performance of the RBF process and its overall effectiveness for developing countries are also discussed.

Keywords Bank filtration efficiency · Natural water treatment process · Riverbank filtration · Water quality of bank filtration · Enhancement of river water quality

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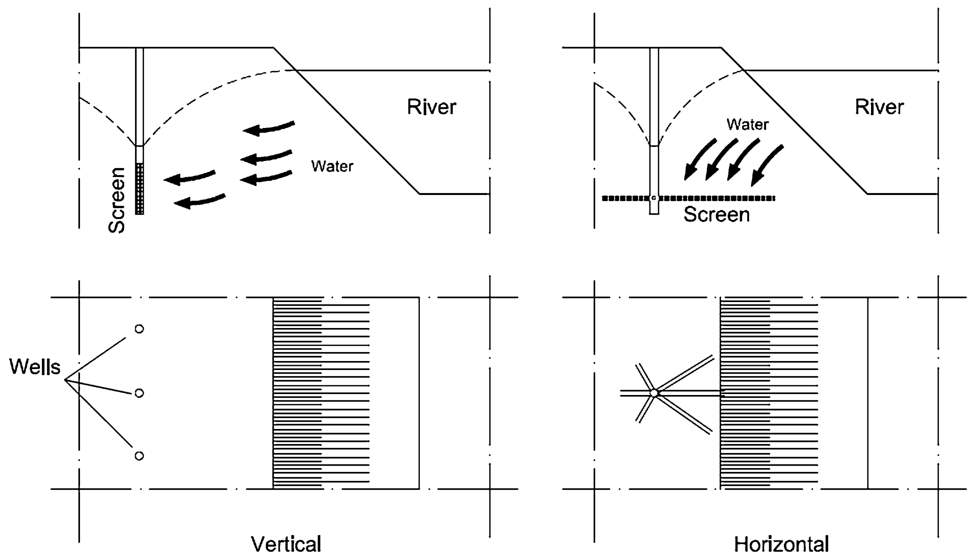
Introduction

Humanity faces numerous environmental problems due to increasing contaminants from point and non-point sources. Some of these compounds are toxic even at trace concentrations, especially when present as components of complex mixtures (Schwarzenbach et al. 2006). The demand for acceptable quality water increases with the population inflation and related activities including agriculture and manufacturing (Mahdizadeh Khasraghi et al. 2015; Valipour 2012a, b; Valipour et al. 2015 Yannopoulos et al. 2015). Several newly developed water treatment methods are being used to obtain higher quality water. However, the use of a simple, ancient, and natural method called river bank filtration (RBF) can easily be applied, due to its relatively low cost and sustainable means in improving the quality of surface waters (Thakur et al. 2012).

RBF is a water purification process, in which river water is naturally filtered to an aquifer through the riverbed or riverbanks. A series of biological, chemical, and physical actions take place during the underground passage that leads to the improvement of water quality (Sprenger et al. 2011). Under certain circumstances, conventional surface water treatments could be replaced with the RBF process to remove or decrease pollutants in surface water. RBF is a simple and natural process because it utilizes the natural soil as a filtration media. When a well is located in a permeable aquifer connected to a river, water begins pumping steadily, and the drawdown cone is created around the pumping well. The drawdown enforces a segment of the river water to penetrate the aquifer on the way to the pumping well. The pumping well can be a vertical or horizontal collector as shown in Fig. 1 (Ray 2011; Ray et al. 2002a).

Fig. 1 Horizontal and vertical wells in RBF systems (Ray 2011; Ray et al. 2002a)



During the river water passage through the aquifer media, several processes occur: filtration, adsorption, absorption, and degradation. These processes subsidize the removal/reduction of numerous dissolved and suspended contaminants including pathogens (Ray 2011). However, an evaluation of RBF's effectiveness is necessary before it can be applied in developing countries, where drinking water is in high demand. A closer look at the in situ RBF process weighs RBF's effectiveness and the subsequent benefits, including the removal of particulates, pathogens, dissolved organic matter (DOM), and disinfection-by-products (DBP) precursors.

Water quality of RBF process

During the RBF process, surface water is lead through the aquifer media, decreasing or eliminating turbidity, chemicals, pesticides, industrial contaminants, organic matter, and other pollutants.

Turbidity

Water turbidity is usually a good indicator of suspended matter, which in turn is a valid host of microbes and pathogens. In bank filtration, particles are removed through the combined efforts of straining, adsorption, and biodegradation (Ray et al. 2002a). Several researches proved that RBF is an efficient process for removing turbidity (Dash et al. 2008, 2010; Dillon et al. 2002).

Mikels (1992) studied RBF process through Columbia River and Kalama River at Washington State. Turbidity removal was approximately 1.9 and 1.1 log unit at RBF process through Columbia River and Kalama River, respectively, as presented in Fig. 2. The Kalama river turbidity varied between 1 and 5 ntu, whereas the turbidity of RBF water at Kalama varied between 0.3 and 0.4 ntu.

A study comparing the quality of water treated by the RBF process and river water was conducted during and after monsoon periods, in Haridwar (India). The water's source was production well adjoining surface water. This well is located in a sand–gravel unconfined aquifer with a thickness of 17 m. The water was filtered through this aquifer. Comparisons showed that the surface water turbidity was higher during monsoon periods than during non-monsoon periods. However, the quality of RBF-treated water was not significantly changed during monsoon or non-monsoon periods. In non-monsoon months, the water treated with the RBF process had a 1-log turbidity reduction. In monsoonal months, the turbidity log removal raised to be more than two logs. This study concluded that the RBF in Haridwar is a reliable process for the turbidity removal (Dash et al. 2010).

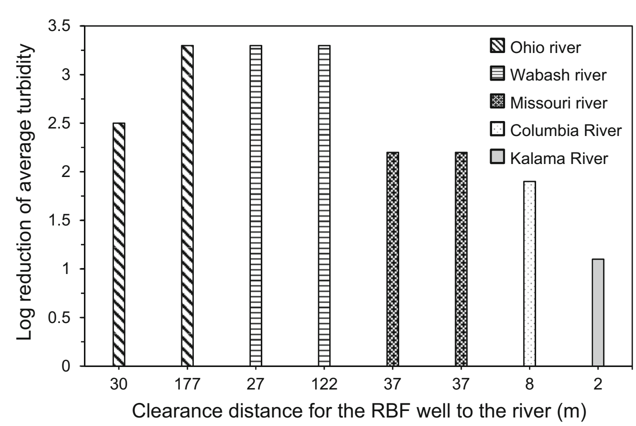


Fig. 2 Log reductions of average turbidity at different RBF systems (Mikels 1992; Weiss et al. 2005)

Weiss et al. (2005) examined the effect of RBF on the removal of turbidity by studying three rivers sites:

(1) Two wells, Well 9 and Well 2 were located at 30 and 177 m, respectively, from the Ohio River, Jeffersonville, Indiana.
(2) Two wells, the Collector Well with horizontal arms under the river and Well 3 were located at 27 and 122 m, respectively, from the Wabash River, Terre Haute, Indiana.
(3) Two wells Well 4 and Well 5 were located at 37 m apart from the Missouri River at Parkville, Missouri.

In this study, it was observed that RBF is an efficient process in the reduction of turbidity in surface water at all three sites as shown in Fig. 2.

Dissolved oxygen

Dissolved oxygen (DO) is a valuable indicator of water quality. The infiltration rate has a considerable influence on DO. Through the filtration of the water on riverbank and riverbed sediments, DO decreases frequently over the distance of a few meters (Diem et al. 2013). The RBF process faces new challenges due to its low infiltration rates, which cause high oxygen depletion, and subsequently causes high anoxic conditions (von Rohr et al. 2014).

During anoxic conditions, the reduction or the absence of oxygen leads to denitrification and the reduction of sulfate, Iron (III), and Manganese (VI). This causes undesirable dissolved matters including nitrite, sulfide, Iron (II), and Manganese (II) (Massmann et al. 2008). To help control undesired dissolved species, it is necessary to realize the dynamic consumption of oxygen during the RBF process. A new model to predict the DO during RBF was suggested by Diem et al. (2013). The model depends on the stochastic-convective reactive approach to develop the semi-analytical simulation for the dynamics of DO depletion upon RBF. The model is easy and quick and is considered a valuable tool when finding the DO values in different distances from the river, with respect to the related values in river water at different hydrologic and climatic conditions.

Dissolved organic matter

The presence of organic micropollutants (OMPs) in drinkable water is impacting public and environmental health. The United States Environmental Protection Agency (US EPA) and European framework directives place numerous OMPs on the priority list of contaminants. Nano-filtration, reverse osmosis, adsorption, and ozonation are the common recommendation treatment processes used to eliminate or reduce the OMPs. However, RBF is also efficient in removing the OMPs.

A study, based on a decision support system (DSS) and multi-criteria analysis (MCA) was performed to analyze different methods for the removal of OMPs. The examined methods included RBF, nano-filtration, reverse osmosis, adsorption, advanced oxidation, and ozonation. The following weighted criteria were considered: technical considerations, treatability, sustainability costs, and time. The study concluded that the RBF process was superior in OMPs removal over membrane and adsorption processes (Sudhakaran et al. 2013).

Miettinen et al. (1994) studied the quantity and quality changes of humic materials at a lake bank filtration site, in Finland. Significant reductions were observed in total organic carbon (TOC), chemical oxygen demand, and non-purgeable organic compounds. From UVA, it was found that the removal percentage of the high-molecular weight organic species is 87 %. However, this percentage was low for the low-molecular weight organic matters.

Ludwig et al. (1997) examined the effect of RBF on dissolved organic carbon (DOC) at the Elbe River, Germany. The authors addressed the reduction in the concentration of DOC during RBF. They also found that the most of this reduction is related to the high-molecular weight fraction.

Figure 3 shows the average total organic carbon (TOC) concentrations at and in the different distance of different rivers, located in the United States. These rivers are the Ohio River at Jeffersonville (Indiana), Missouri River at Parkville (Missouri), Wabash River at Terre Haute (Indiana), South Platte River at Brighton (Colorado), and Cedar River at Cedar Rapids (Iowa) (Hoppe-Jones et al. 2010; Weiss et al. 2005). It is obvious that TOC concentration decreases with increasing the distance to the river.

Research was performed to assess the benefits of the RBF process concerning control of DBP, precursor

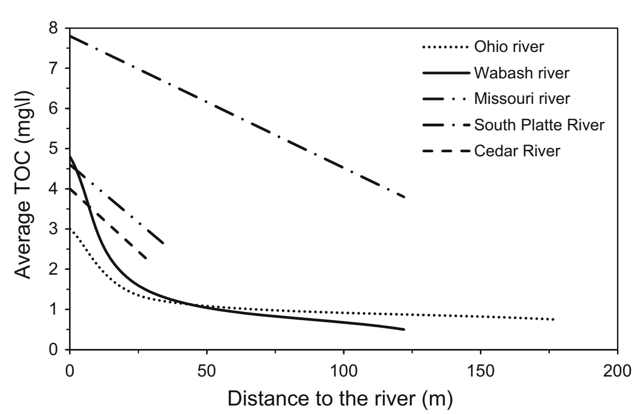


Fig. 3 Effect of RBF on TOC concentration (Hoppe-Jones et al. 2010; Weiss et al. 2005)

materials, and microorganisms at three mid-westerns United States (Ohio River, Wabash River, and Missouri River). Reductions in the concentrations of TOC, DOC, and DBP precursors upon bank filtration at all three sites were similar to or greater than those achieved by subjecting the river waters to a conventional treatment method. The conventional method was simulated with a bench scale line starting with coagulation, followed with flocculation, sedimentation, and glass fiber filtration. In RBF, TOC and DOC reductions at the closer wells of all three sites ranged from 35 to 67 %, and the trihalomethane and haloacetic acid precursor concentrations were decreased by 50–80 %. Reductions in precursors for haloketones, haloacetonitriles, chloropicrin, and chloral hydrate were between 30 and 100 % (Weiss 2005). Another research, performed at Elbe River, Germany, proved the effectiveness of RBF on the reduction of DOC (Clayton 1995), see Fig. 4.

Chemical properties

Numerous researchers studied the changes in dissolved inorganic pollutants during the subsurface filtration of the surface water (Doussan et al. 1997; von Gunten and Zobrist 1993). They concluded that the seepage velocity of the water through the pores of the river sediments and their content of organic matter are the most important parameters for the development of the filtration chemistry. Passage through the sediment–aquifer interface also allows numerous dissolved chemicals to undergo biogeochemical reactions and dilution, which ultimately decreases the concentration of parent species in bank-filtrated water (Ray 2004).

Lee et al. (2009) conducted research on the RBF process at the Daesan–Myeon area adjacent to the Nakdong River. They compared the qualities of the RBF-treated water and the river water using factor analysis. Chemical composition, water level, time series, and stable isotopes were considered in their research. The researchers concluded that river water was chemically less stable compared with RBF-treated water. Almost constant isotope compositions of hydrogen and oxygen were observed in RBF water, while noticeable variations of those appeared in river water. They also observed that the average Nitrate (NO_3) concentrations are 5.40 mg/l in the RBF water and 15.2 mg/l in the river. The overall conclusion showed that river water has higher chemical contaminants than RBF-treated water.

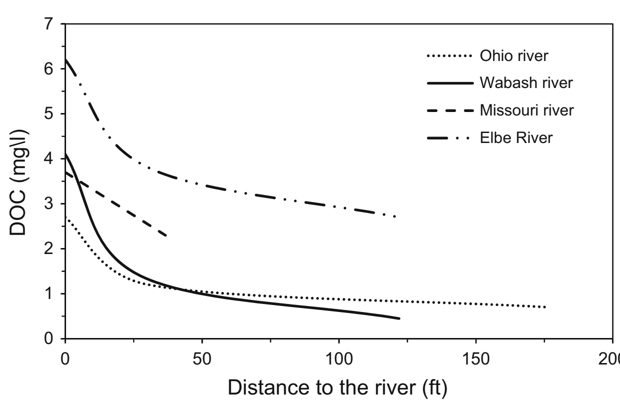


Fig. 4 Effect of RBF on DOC concentration (Clayton 1995; Weiss 2005)

Dash et al. (2008) studied the RBF process in Nainital Lake, Kumaun, State of Uttarakhand, India. They compared the quality of Nainital lake water and the natural treatment water from a tube well adjoining the lake. Studies of this water concluded that the concentration of ammonia and phosphorus in lake water was higher than those in tube-well water.

A study was conducted on Langat River (Selangor, Malaysia) to investigate the RBF water quality. The study showed valuable improvements in turbidity, COD, *E.coli*, and total dissolved solid. COD was 53.0 mg/l in the river water, and it was decreased to 8–18 mg/l after RBF process (Ibrahim et al. 2015). A field scale study in Korea showed that the BOD and COD of RBF water were reduced by 50 and 52 %, respectively (Kim et al. 2013). Another study on the Warta River (Poland) showed a decrease in COD removal as distance to the riverbank increases (e.g., decrease of 50 % as the distance increased from 30 to 250 m) (Górski 2010). A pilot RBF plant study was performed on Nakdong and Milyang rivers (Transom, Gimhae city of Gyeongsangnam-do, South Korea). The study showed a reduction in BOD and COD by 71 and 54 %, respectively (Kwon 2015).

Microbiological properties

RBF-treated water was presented by several researchers as an effective treatment process in decreasing or eliminating microorganisms. Table 1 shows the total coliform (TC) and fecal coliform (FC) in river and RBF waters in different countries (Dash et al. 2010; Ghodeif et al. 2016; Shamrukh and Abdel-Wahab 2011; Singh et al. 2010; Weiss et al. 2005). It is obvious that the RBF process is capable of reducing or removing TC and FC from river water.

Havelaar et al. (1995) studied the removal of enteroviruses and reoviruses at an RBF-treatment facility in the Netherlands. They compared the removal efficiency of the RBF process with that of other treatments, such as coagulation and flocculation and multiple interconnected reservoirs with a retention time of seven months. They found that the RBF process could provide 4-log removal of viruses and 5- to 6-log removal of F-RNA phages. They also found that fecal indicator bacteria and Aeromonas were decreased effectively and often not detectable in 1 l samples of RBF-treated water.

Table 1 Effect of RBF systems on total and fecal coliform removal

		Country	Total coliform	Units	Fecal coliform	Units	References
Ohio river	River	USA	1.3×10^6	[MPN/L]	Not determined		Weiss et al. (2005)
	RBF		0				
Wabash river	River		4.6×10^6				
	RBF		0				
Missouri river	River		7.5×10^5				
	RBF		0				
Nile river	River	Egypt	2.819	(MPN/100 ml)	290	(cfu/100 ml)	Ghodeif et al. (2016) and Shamrukh and Abdel-Wahab (2011)
	RBF		2		0		
Ganga river	River	India	23,000–93,000		1500–6400	(MPN/100 ml)	Dash et al. (2010)
	RBF		2–4		2		
Yamuna river	River		23×10^2–15×10^5		$15–23 \times 10^4$		Singh et al. (2010)
	RBF		$43–75 \times 10^3$		$43–93 \times 10^2$		

The RBF process was studied in Haridwar (India). The production well was apart from the surface water by 115 m, and the minimum travel time for the subsurface water path from the river to the well was 77 days in monsoon season and 84 days in non-monsoon period. For surface water, the bacterial count in the monsoon period increased ten times that in the non-monsoon period. However, RBF-treated water did not show this variation in the bacterial count with the changing seasons. In non-monsoon period, 3-log removal of coliforms was observed in RBF water. For monsoonal season, this increased to more than 4-log in coliforms reduction (Dash et al. 2010; Weiss et al. 2005). The RBF process can significantly reduce the risks of microbial contaminants in surface water. This also indicates that the RBF process can also decrease risks associated with DBP that might be composed through drinking water treatment processes (Wang 2005).

Dash et al. (2008) compared the RBF process with rapid sand filtration. They observed that the RBF process was more efficient in improving biological water quality than sand filters. Water from the RBF process achieved 5.2 and 4.2 log reduction of total and fecal coliform, respectively, whereas sand filters only achieved a 1.9 log removal in total and fecal coliform at the same sampling rate. In addition, the total coliform count in sand-filtered water was 2300 MPN/100 ml and chlorination is not advisable for this kind of water. However, none of coliforms were found in the samples of RBF-treated water and there is not a need for chlorination.

Factors affecting RBF efficiency

The complex geochemical, biological, and hydrologic factors, that influence the effectiveness of the RBF process, are complicated and connected. Only recently, researchers have begun to understand these factors.

Climate change

Climate change is a new challenge factor, which will have an obvious effect on RBF. It has a considerable effect on water quality and quantity, reduction–oxidation conditions, travel time, and removal efficiency. Water quantity and water quality are related and dependent upon river scenarios.

Evaluation and management of the river water relating to floods and droughts is necessary (Valipour 2016). Flooding and drought have an indirect effect on the efficiency of the RBF process. While flooding prevents clogging of the streambed by scouring, the opposite action occurs during drought conditions. Flooding results in a shear force called self-purification, but drought promotes sedimentation of suspend solids, leading to the clogging of the riverbed. The riverbed clogging can be both profitable and undesirable. On one hand, it promotes the biodegradation of contaminants. On the other, it reduces the hydraulic conductivity of the subsurface filtration zone (Hiscock and Grischek 2002). Droughts boost, encourage, and reinforce anaerobic conditions during the RBF path. Flooding decreases the travel time and causes the fast pass and penetration of undesirable micropollutants (Sprenger et al. 2011).

Temperature has vast changes in some rivers; it can play a noticeable role in the degradation rate through the RBF process. According to Van't Hoff theory, increased temperature is associated with an increased reaction speed of biological and chemical processes (Schijven and Hassanizadeh 2000). For RBF process, high water temperatures can stimulate degradation. However, the continuity of the stimulation is not preferable in the long term, as it leads to anoxic or anaerobic conditions, which in turn decreases the degradation rate (Sprenger et al. 2011).

Rudolf von Roher et al. (2014) investigated the effect of temperature and dissolved organic matter (DOM), as indirect climate change variables, on the degradation rate during the RBF process. Column studies were used in these investigations. The results indicated that temperature has a strong effect on the aerobic process accompanied with particulate organic matter degradation with activation energy of approx. 70 kJ mol^{-1}. The combined action of high temperatures (equal or more than 20 °C) and low infiltration rates (equal or less than 0.01 m/h), could cause anoxic conditions. The authors also mentioned that, the aerobic respiration led to the instant removal of biodegradable dissolved organic matter (BOM) at the column entrance, and an increase of microbe concentrations adjacent to the infiltration region. In addition, they found that DOM neither improved the aerobic conditions nor led to anoxic status in their column studies.

A study conducted in Lower Rhine Valley (Germany) assessed the influence of climate change on the drinking water purification system using the RBF process. It was found that low river water seasons were associated with an obvious reduction of the RBF well capacities. In addition, the reduction in river flow rate caused an increase in chemical pollutants. However, the research concluded that RBF has natural defense in overcoming the impact of climate change (Eckert et al. 2008).

Soil and water characteristics

During the RBF process, microbial cells and contaminants are decreased and/or eliminated by adsorption to the surface of the soil material. Shen (1999) studied the sorption of DOM into the natural soil, the results showed that the ability of soil sorption mostly returns to the ligand interchange between hydroxyl groups on the surface of the soil mineral and DOM. The ionic strength of the soil–water solution, the clay content, and pH has a positive effect on soil sorption capacity of DOM.

Soil type has an influence on microbial removal. The knowledge and realization of subsurface media efficiency on microbial removal is critical in evaluating the risk of water contamination. Volcanic soils, fine sand, pumice sand, and highly weathered aquifer rocks have notable microbial removal rates. However, poor removal rates have been observed in fractured rocks, structured stony soils, karsr limestone, and coarse gravel aquifers (Pang 2009). Natural composites in clay, montmorillonite, Bentonite, and the relevant clay minerals, are effective for use with the RBF process. The advantages of these minerals are high-specific surface area, and a valuable capacity to grasp exchangeable cations (Jiang et al. 2001). Using batch adsorption experiments, Ayala et al. (2008) studied the adsorption characteristics of the bentonite at Grau Region, Northern Peru. They examined the detention of some metals Cu, Ni, Zn, and Co in the bentonite, the effect of pH, concentration of organic compounds, and dissolved metals. The results showed that bentonite is a reliable adsorbent for these examined metals.

The soil median size affects the attachment, detachment, and straining of some microorganisms during the RBF process. Bradford and Bettahar (2005) used different grain sizes of Ottawa sand (Ottawa, IL) to investigate the effect of the grain size on the detention and transport of *Cryptosporidium* parvum oocysts. They performed saturated column studies with sand grain sizes of 150, 360, and 710 µm. The results indicated that the reduction in median sand size leads to more adsorption and less oocyst concentrations at the outflow.

Bertelkamp et al. (2014) studied sorption and biodegradation behavior of mixtures of 14 OMPs at concentrations representative oxic conditions during the RBF process. The study was processed by soil columns under oxic conditions in the laboratory. Although they observed trends between the biodegradation rate and the charge for charged compounds, they could not find a specific relationship between physicochemical properties such as hydrophobicity, charge, and molecular weight and the OMP mixtures. However, they obtained considerable relationship between the OMP functional groups and biological degradation rates.

Water level fluctuations

The variation in river/lake water level has a direct effect on the subsurface velocity of the infiltrated water. The fluctuations of the water level occur because of snow melting, floods, hurricane, or other climate changes (Shankar et al. 2009). This may lead to changes in quantity and quality of infiltrated water during the RBF process. Derx et al. (2010) indicated that there is a tight relation between the river–aquifer mixing zone and the fluctuations of river water level. They mentioned that the dilution of solute concentrations is due to the fluctuations of river water level. As a result, the transport of nutrients was highly affected. They also recommended that river water level fluctuations should be considered in the investigation of mixing zones.

The variations in river water level promote viruses to penetrate riverbanks with longer distance and higher concentrations when compared with those in steady water level. Increasing the water level between 1 and 5 m caused in increasing virus concentrations with 2–4-log and decreasing the travel time with 30 % (Derx et al. 2013).

Bank area uses

Land usage, such as agricultural expansion and urbanization within the surrounding valley of streams and rivers, has a strong influence on river biological diversity and ecosystem functions.

Land-use changes in river basins, can affect various characteristics of river ecosystem such as water quality, community structure, primary and secondary production, organic matter decomposition, ecosystem metabolism, and energy fluxes (Allan 2004; Young et al. 2008). Boechat et al. (2014) studied the Rio das Mortes River at the Brazilian Federal State, to investigate the influence of land use on the concentration and composition of fatty acid (FA) in suspended particle organic matter. They found high concentrations of palmitic, stearic acids, and sewage as a result of urbanization. They concluded that the main land-use sector has a dominant effect on both the FA concentrations and composition, along a 4th order of the Rio das Mortes River, was urbanization. The concentrations of FA in urbanized areas are high. This plays an obvious role in changing the energy and interactions of the food chains such as suspension feeder and bacterial production, leading to different behaviors of ecosystem actions, and affecting the water quality.

It could be concluded that land use has an indirect effect, due to changes in functional ecosystem characteristics, on the RBF process; but also it has a direct effect by dissolution of land uses' pollutants during water passage to the production well.

Aquifer design

The well arrangement is vital to obtain the desirable water quality and quantity. There are many different ways to construct wells with various spacing and distances from the riverbank. A feasibility study should be performed to choose the best design for the RBF process (Schijven and Hassanizadeh 2000).

There are two types of well design: vertical and horizontal. Both of them can be situated on one or each side of the riverbank. The horizontal well, is also called radial collector well (RCW), and is composed of some horizontal pipes connected readily to a larger vertical collector pipe. The horizontal pipes penetrate the aquifer to accumulate the water. Most of the time, the RCW is built adjacent to the river, allowing the placement of horizontal pipes under the riverbed, and motivating the river water to move toward the RCW as shown in Fig. 1. In RCW, water quantity can be increased with a suitable design of the well screen, the filter pack, the arrangement, and the length of the horizontal pipes of the RCW. The appropriate design could upgrade and optimize the RBF process (Lee et al. 2012). The RCW has a lower drawdown, a low velocity at entering pipes, and less cleaning operations. This results in lower operation costs; therefore, it is more efficient than the vertical well (Bakker et al. 2005).

pH

Sadeghi et al. (2011) performed sand columns studies to examine the influence of Ionic strength (IS) and pH on the sticking efficiency of PRD1 phage. The results showed that increasing IS and reducing pH were accompanied with improving the sticking efficiency, in adherence to DLVO theory (Hermansson 1999). They also provided an empirical equation to calculate the sticking efficiency of PRD1 phage in quartz sand, depending on the value of IS and pH. The equation is applicable in IS and pH ranges between 1 and 20 mM and 5–8, respectively.

Many studies showed that high pH increases the electrostatic repulsion, which in turn decreases the virus attachment (Grant et al. 1993; Hermansson 1999; Israelachvili 2011; Loveland et al. 1996). In addition, pH affects the adsorption of organic compounds. The adsorption of DOC compared to soil particles was dependent on the solution pH, and the maximum adsorption occurred at the pH 4.5 (Jardine et al. 1989).

Hydraulic conductivity and the travel distance

Travel times in the infiltration area between a river and pumping well(s) can be assessed using hydraulic-based or tracer-based approaches. Hydraulic methods rely on measuring the hydraulic conductivity, hydraulic gradients, and porosity of the sediments that are present between the riverbed and the well(s). Then, flow velocities and travel times are indirectly determined using Darcy's law calculations or numerical modeling of groundwater flow. Tracer-based methods may provide a more direct indication of flow velocity and travel time. Several researchers studied ^{222}Rn and water temperature as natural tracers (Bertin and Bourg 1994; Hoehn and Von Gunten 1989; Hoehn et al. 1992; Regli et al. 2003). Also, Water temperature could be applied as a heat tracer of the flow water (Stonestrom and Constantz 2003).

Travel time and distance between the river and RBF wells, a valued characteristics of the RBF process, have an important effect on subsurface filtration removals (Partinoudi and Collins 2007). Shorter travel times are not favorable for contaminant removal, whereas lower velocities and longer flow paths are more favorable (Wang et al. 2000).

The effect of travel distance on TOC and DOC removal can be developed from Figs. 3 and 4. It is clear that increased travel distance accompanies the reduction of TOC and DOC concentration. Figure 5 shows the effect of RBF travel distance at the Elbe River (Germany) and the Warta River (Poland) on several water quality parameters. At the Elbe River, as the travel distance increased, a decrease of the Nitrate (NO_3) and Ammonium (NH_4)

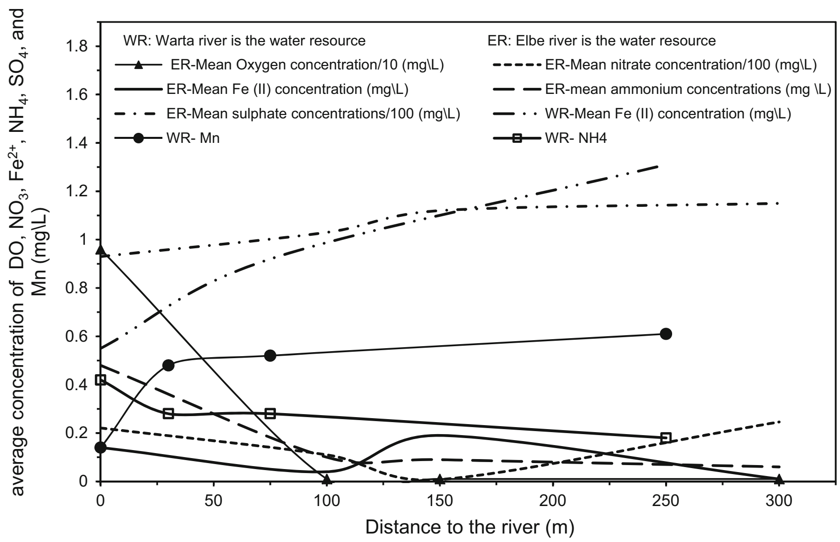


Fig. 5 Effect of the river–well distance on several water quality parameters at Warta and Elbe RBF systems (Górski 2010; Grischek et al. 1995)

concentrations was observed. Iron II (Fe^{2+}) concentration decreased to 0.01 mg/l at a 300-m travel distance. Sulfate (SO_4) concentration increased, with increasing of travel distance, to its maximum value (115 mg/l) at 300 m. This value is still less than the recommended SO_4 value (250 mg/l) by the US EPA national secondary drinking water regulation. The increase of SO_4 concentration was related to the agriculture activities. At the Warta River, Ammonium (NH_4) concentration decreased with the increase in the travel distance. However, Manganese (Mn) and Fe^{2+} concentrations increased as a result of mixing RBF water with groundwater. The RBF travel distance was recommended to be between 150 and 250 m for the Warta River in order to obtain a high quality water (Górski 2010; Grischek et al. 1995).

Mikels (1992) studied bank filtration site in Kalama, Washington, along the Columbia River. The collector well was relatively shallow, with the radials located only 6 m below the riverbed. Even with this shallow depth, the flow rate of riverbed infiltration was 0.022 m/d, which is still much less compared with it is value through slow sand filters (commonly 2.8 m/d).

During the RBF process, the precipitation of colloids, microorganisms, particles, calcium carbonate, and some metals lead to clog the riverbanks and riverbed, and form a clogging layer (Hiscock and Grischek 2002). The permeability of the clogged layer is not stable and depends on the hydrogeological changes. This should be considered in designing RBF sites (Schubert 2002). Ray et al. (2002b) mentioned that wells close to rivers with high hydraulic conductivity, yield RBF-treated water with high quantity and low quality, as the river water pollutants can easily pass to the production well. On the other hand, low hydraulic connection between wells and rivers diminish the quantity and improve the quality of RBF-treated water. This means that the best RBF site needs to be situated at the part of river with balanced hydraulic conductivity. The balanced hydraulic conductivity should provide an acceptable quality and quantity of RBF-treated water.

RBF cost

One of the important factors to be considered in selecting a water treatment process is the cost. This includes not only the construction cost but also operation and maintenance costs. Wang (2005) concluded that the RBF process, with adequate design and construction, is a very cost-effective water treatment process. Stauder et al. (2012) studied the cost of the RBF process as one of the water treatment processes alternatives in the Republic of Serbia. The maintenance and construction of RBF wells cost 0.15 €/m^3, and the RBF treatment process costs another 0.15 €/m^3. It was concluded that the RBF process was a valuable and cost-effective water treatment alternative process for the Tisa River in Serbia.

The cost of RBF as a pretreatment process was studied in the United States (Grooters 2007). Three different studies were conducted in Des Moines City-Iowa, Louisville City-Kentucky, and Kansas City-Kansas. These studies compared the cost of RBF as a pretreatment process to reverse osmosis with other traditional pretreatment processes. The comparison considered the capital, operational, and maintenance costs. It was concluded that using RBF, as the pretreatment to reverse osmosis, could reduce the treatment costs by 10–20 %.

Feasibility studies were performed on RBF as a pretreatment process for ultrafiltration. The study showed that 20–70 % of suspended solid could be removed by RBF depending on river water quality. This pretreatment stage minimizes the operation costs, enables cost-effective water treatment design, and reduces the capital costs (Chew et al. 2015).

Feasibility assessments in some African cities located in Kenya and Malawi, showed that RBF is worthwhile from the standpoints of water quality, water quantity, and cost considerations. It has been found that considerable savings, in both operation and maintenance, can be accomplished by switching from a conventional surface water treatment to the RBF process. In three water supply systems in Malawi, the switching to bank filtration could save over 80 % of the annual costs (energy and chemicals) when compared with the existing water treatment process (Sharma et al. 2012). RBF is often preferred to be used as a drinking water treatment process in cases where there is insufficient ground water and the treatment cost of RBF versus direct river water treatment is less (Grischek et al. 2002).

RBF process in developing countries

For the developing countries, the RBF process could be a valuable process in minimizing the risks associated with microbial contaminants, DBP that could be composed through the conventional drinking water purification processes, and chemical or oil spills that occur in source water (Wang 2005).

The RBF process is a dependable, attractive, and trustworthy water treatment process. Europe and the USA have used the RBF process; however, developing countries have only recently begun using it. UNESCO-IHE has shown a good method to predict the performance and efficiency of the RBF process. This method consists of four steps; (1) use MODFLOW to perform a hydraulic simulation of RBF; (2) determine the percentage of water coming from bank filtration, using NASRI bank filtration simulator; (3) anticipate RBF water quality; and (4) compare the effectiveness and efficiency of the RBF process with other conventional water treatment systems. This method has been used to perform feasibility studies in five cities on the African continent. From this study, it was concluded that the RBF process has high-quality performance, considerable cost efficiency, and less maintenance requirements (Sharma et al. 2012).

Egypt is one of the developing counties that face challenges in providing good quality water for its growing population. Surface water from River Nile and groundwater are the two drinking water resources (Shamrukh and Abdel-Wahab 2011). Researchers have studied the geology, characteristics, origin, and development of the Egyptian Nile valley (Ahmed 2009, 2013; Sestini 1989; Shamrukh et al. 2001). The Egyptian RBF processes were studied in sites where the vertical wells are located adjacent to River Nile/canal banks. These sites were proved as RBF sites using tracer studies (Ghodeif et al. 2016; Shamrukh and Abdel-Wahab 2011).

The RBF process was investigated in some Egyptian cities: Aswan, Naga Hamadi, Abu Tieg, Sidfa, Assiut (Abdalla and Shamrukh 2011; Hamdan et al. 2013; Shamrukh and Abdel-Wahab 2008, 2011). All of these studies concluded that the RBF process is an effective and economical process to produce a high-quality treated water. The RBF process that has been proved as a valuable Nile water treatment process in Egypt could be considered a good alternative to the conventional treatment process in some areas or a pretreatment process in others.

Conclusion and Recommendation

(i) Although sometimes viewed as a simple process, similar to slow sand filtration, the RBF process can be complex to understand because it is controlled by numerous factors including biological, biogeochemical, and hydrogeological. These factors can control the reduction/elimination of microbial, dissolved, and particulate pollutants.

(ii) The existing RBF comprehension mainly depends on practical understandings. No standards have been developed to guide the optimization of the RBF design.

(iii) The efficiency of the RBF process is diminished if the following characteristics exist in the system; short flow path, high gradients, very high percolation velocity, karst aquifer, and high levels of heterogeneity.

(iv) Quantification of water, travel time, and water pore velocity have a strong influence on the extracted RBF water quality.

(v) High temperatures lead to higher microbial activities, which in turn cause RBF anoxic conditions. Understanding the effect of temperature on the mechanism of oxygen consumption at RBF is crucial, in order to control the anoxic condition.

(vi) In order to access the operational performance of RBF, further analysis and research is needed to develop acceptable relationships.

(vii) Clogging of riverbank and riverbed is variable. More data are needed to understand the changes of their permeability upon the depending variables such as dynamic hydrology and water pollution.

(viii) RBF can be a very practical in situ water treatment technology for developing countries.

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