Framework for feasibility assessment and performance analysis of riverbank filtration systems for water treatment

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ABSTRACT

Bank filtration (BF) is an attractive, robust and reliable water treatment technology. It has been used in Europe and USA for a long time; however experience with this technology so far is site specific. There are no guidelines or tools for transfer of this technology to other locations, specifically to developing countries. A four-step methodology was developed at UNESCO-IHE to analyse feasibility and to predict the performance of BF for water treatment. This included (i) hydraulic simulation using MODFLOW; (ii) determination of share of bank filtrate using NASRI BF simulator; (iii) prediction of water quality from a BF system using the water quality guidelines developed and (iv) comparison of the costs of BF systems and existing conventional surface water treatment systems for water treatment. The methodology was then applied to assess feasibility of BF in five cities in Africa. It was found that in most of the cities studied BF is a feasible and attractive option from hydraulic, water quality as well as operational cost considerations. Considerable operational and maintenance costs saving can be achieved and water quality can be further improved by switching from conventional chemical-based surface water treatment to BF or at least by replacing some of the treatment units with BF systems.

Key words | design, developing countries, framework, performance, riverbank filtration, water treatment

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INTRODUCTION

Bank filtration (BF), is a reliable and proven natural water treatment technology, in which surface water contaminants are removed or degraded as water moves through the soil/aquifer to a recovery well(s). Extraction of water is accomplished by an infiltration gallery or line of wells (horizontal, vertical or at an angle) located at a short to intermediate distance from the bank of a river or lake. Because of its ability to remove even the most persistent contaminants and microbes, BF can support or even replace other treatment processes in a water treatment scheme (Maeng *et al*. 2010; Sharma & Amy 2010). Furthermore, it also dampens temperature peaks and concentration peaks associated with spills. River bank filtration (RBF) is a traditional, efficient and well-accepted method of surface water treatment in Europe. For over 100 years, RBF has been used in Europe for the public and industrial water supply along the Rhine, Elbe and Danube rivers (Grischek *et al*. 2002; Irmscher & Teermann 2002; Hiemstra *et al*. 2003). RBF systems have also been supplying drinking water to several communities in the USA for nearly half a century (Ray 2008). Several mechanisms are responsible for improvement of water quality during BF. During infiltration and travel through the soil and aquifer sediments, surface water is subjected to a combination of physical, chemical and biological processes, such as: (i) filtration; (ii) dissolution and precipitation; (iii) ion-exchange;

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(iv) sorption-desorption; (v) complexation; (vi) redox reactions; (vii) microbial biodegradation, and (viii) dilution that significantly improve water quality.

RBF systems are relatively simple to operate and robust, therefore they have a high potential for application in developing countries (Ray 2008). However, this attractive technology has not been fully utilized in the developing countries. Furthermore, the experience with BF technology so far is site specific and requires extensive site investigations and pilot studies to assess its feasibility based on local conditions. In some countries, wells have been constructed next to a river or pond by local communities in order to improve water quality without adequate design considerations; however, BF systems have not been used as water treatment step by water supply companies. There are no guidelines or tools available for feasibility assessment, performance analysis or design of BF systems for water treatment. Therefore, the transfer of this viable and attractive multi-component removal technology is limited. In an attempt to promote this sustainable technology in developing countries, the main objective of this study was to develop a framework or methodology to assess the feasibility of a BF system for water treatment under given local (site-specific) conditions.

DEVELOPMENT OF GUIDELINES FOR WATER QUALITY PREDICTION

The design of a BF system includes determination of the following: (i) number of wells and production capacity per well; (ii) spacing between the wells; (iii) distance of the wells from the bank (and their alignment with respect to river/lake); (iv) share (%) of river/lake water and native groundwater; (v) quality of water obtained from the BF system production wells; (vi) post-treatment requirements (if any), and (vii) capital and operation and maintenance (O&M) costs. The design or performance assessment of a BF system requires analysis of hydraulic (water quantity) as well as water quality aspects of the system. There are some hydraulic models (e.g. MODFLOW, FEFLOW) available for estimation of production capacity and drawdown from a well under given hydrogeological conditions (Chiang 2005; USGS 2008). Some researchers have also presented models for estimation of removal of dissolved organic carbon (DOC) or organic micropollutants during soil passage (Skark et al. 2006; Maeng et al. 2011). However, there are no guidelines or methodology available to predict water quality improvements (removal of pathogens, nitrogen, phosphorus, organic matter and organic micropollutants) during BF. Therefore, firstly, literature reviews of BF systems were conducted to compile the removal rates of four main water quality parameters: (i) bulk organic matter; (ii) trace organic compounds; (iii) nitrogen species (ammonium, nitrate), and (iv) microbes. Data from 33 literature sources (32 field studies and one laboratory-scale study) on BF systems were analysed for removal of organic matter, nitrogen species, trace organic compounds and microbes for different travel or residence times and travel distances.

The data collected from literature review on contaminant removal by BF technology at various sites were arranged in a spreadsheet according to the classification together with the site conditions. The main parameters considered for removal were the travel time and the travel distance. Scatter plots of removal efficiency against the travel time or travel distance for each contaminant was then drawn for all the main water quality parameters (suspended solids, microbes, DOC, ammonium and nitrate, as well as different classes of organic micropollutants). Typical scatter plots for DOC and microbe removal during BF versus residence time are presented in Figures 1 and 2 respectively.

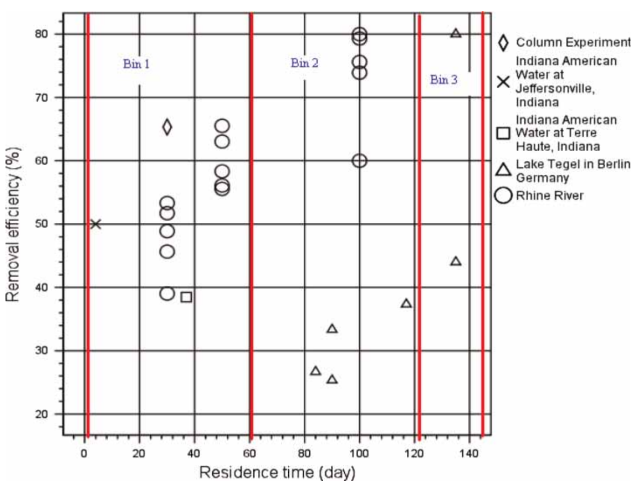

Figure 1 | Scatter plot of DOC removal efficiency versus residence time for BF systems.

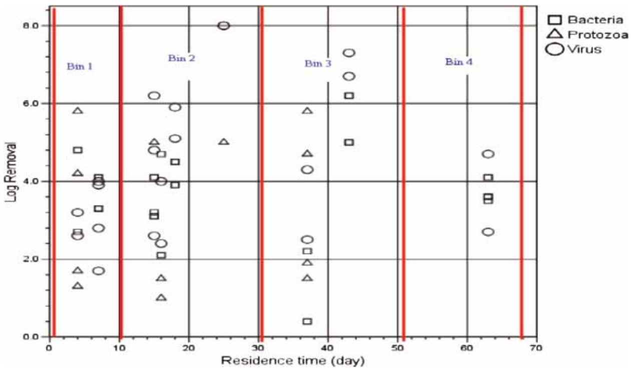

Figure 2 | Scatter plot of microbes removal efficiency versus residence time for BF systems.

The wide variation in removal efficiency at a particular residence time or travel distance is due to differences in site conditions. Despite the wide variation in removal efficiencies under given conditions, we attempted to devise guidelines for prediction of water quality by using the statistical analysis of data from the literature on removal efficiencies. From the scatter-plots data were grouped in different bins depending on the range of travel time or travel distance versus the removal efficiency. This step was necessary as the data were obtained from various sites and need to be normalized by calculating averages (means) and standard deviations. For the data sets falling in each bin, means and standard deviations were calculated so as to achieve lower and upper limits of removal efficiency for that particular range of travel distance or travel time. Based on these values and looking at general trends, the guideline for removal efficiency for each contaminant versus residence times and/or travel distance was defined.

It should be noted that the guidelines for removal of a contaminant in a given range residence times are rather conservative and may be lower than the maximum value that is found in the scatter plot as the guidelines recommends removal efficiency values with 90% confidence level. In general, the travel or residence time has significantly greater effect on removal efficiency than travel distance as there could be different residence times for the same travel distance depending on the hydrogeological conditions at the site and hydraulic conditions applied in the BF system. Therefore, when travel time can be determined or estimated, it should be used for prediction of water quality. In the absence of residence time data, using travel distance is an alternative approach for making a rough estimate of removal efficiency of a contaminant.

Table 1 | Typical DOC removal guideline for BF system

Influent range (mg/L)	Effluent range (mg/L)	Residence time (day)	Predicted removal efficiency (%)
1.0–7.5	0.5–5.6	1–60	44–62
		60–120	62–77
		120–145	77–87

A typical guideline for DOC removal during BF based on residence time is presented in Table 1. Details of the development of guidelines for removal of other contaminants are presented in Chaweza (2006) and Bosuben (2007). A specific framework developed for assessment of the removal of organic micropollutants during BF, following the same methodology, is presented in Maeng *et al.* (2011).

FOUR-STEP METHODOLOGY FOR FEASIBILITY ASSESSMENT OF BANK FILTRATION FOR WATER TREATMENT

The general framework for assessment of feasibility of BF technology for water treatment at a particular location is presented in Figure 3.

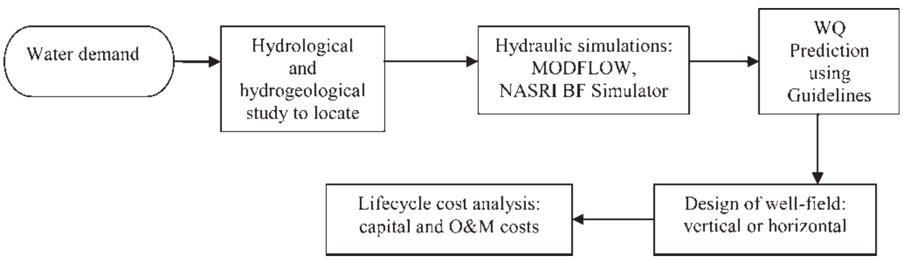

Figure 3 | General framework for assessment of feasibility of BF technology at a particular location.

After collecting the data on water demand, water quality and hydrological and hydrogeological aspects of given site, the feasibility of BF could be assessed. The four-step methodology developed at UNESCO-IHE for feasibility assessment of BF under given conditions consists of the following steps:

(i) Hydraulic simulation using MODFLOW
(ii) Determination of share of bank filtrate and local groundwater using NASRI BF Simulator
(iii) Prediction of the water quality using algorithm/guidelines developed based on literature review
(iv) Comparison of the capital and O&M costs of BF systems with that of existing conventional treatment systems.

Hydraulic simulation using MODFLOW

Hydraulic analysis software MODFLOW Pro (PMWIN Pro) was used to determine the pumping yield and drawdown under steady-state conditions corresponding to given locations of extraction wells. MODFLOW requires input of hydrological and hydrogeological data including river flow, groundwater table, ground layers, aquifer depth and type, hydraulic conductivities and porosities (Chiang 2005; USGS 2008). For the given allowable drawdown under steady-state conditions, the number of wells required for given production capacity and their spacing and corresponding travel times were determined using MODFLOW.

Table 2 shows a typical example of hydraulic analysis using MODFLOW for one of the sites for the vertical wells with the spacing of 50 m centre to centre. It was found that the required production capacity of 38,800 m^3/day could be achieved with different combination of number of vertical wells and distance of wells from water source for different residence times. From this type of theoretical analysis and practical considerations on number and production capacity of the wells, the number of wells required meeting the given criteria of drawdown in the well and minimum residence time can be determined. For example, for the given site if the maximum allowable drawdown is 1 m and if minimum required residence time is 40 days (from water quality considerations), the appropriate option would be using 10 wells at distance of 100 m from the source.

Determination of the share of bank filtrate and local groundwater

NASRI Bank Filtration Simulator (version 1.3a) developed during NASRI (Natural Systems for Recharge and Infiltration) Project of Germany was used to determine the share (%) of bank filtrate and local groundwater for given well arrangements (Holzbecher 2006; Holzbecher *et al.* 2006; TECHNEAU 2010). This simulator calculates the share of bank filtrate for given location of well based on: (i) number of wells; (ii) well spacing; (iii) distance of the wells from river bank; (iv) pumping rates; (v) base flow, and (vi) hydraulic conductivities. Figure 4 lists input and output parameters for NASRI BF simulator and Figure 5 shows an example of NASRI BF simulator output display.

The information obtained from this model is then used to decide upon the number and location of the production wells and for water quality predictions when the quality of surface water, contaminant removal rates and quality of

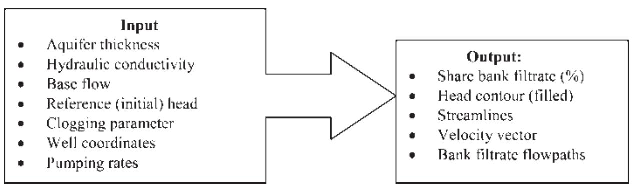

Figure 4 | NASRI BF simulator data input and output parameters.

Table 2 | Effect of number of wells and distance of wells from source on travel time and drawdown

No. of wells	Pump rate per well (m^3/d)	Distance of well from source = 50 m: Time (days)	Distance of well from source = 50 m: Drawdown (m)	Distance of well from source = 100 m: Time (days)	Distance of well from source = 100 m: Drawdown (m)	Distance of well from source = 150 m: Time (days)	Distance of well from source = 150 m: Drawdown (m)
4	9,700	9	2.8	18	2.5	36	2.7
10	3,880	26	0.78	46	0.5	68	0.2
20	1,940	41	0.7	70	0.18	120	0.01

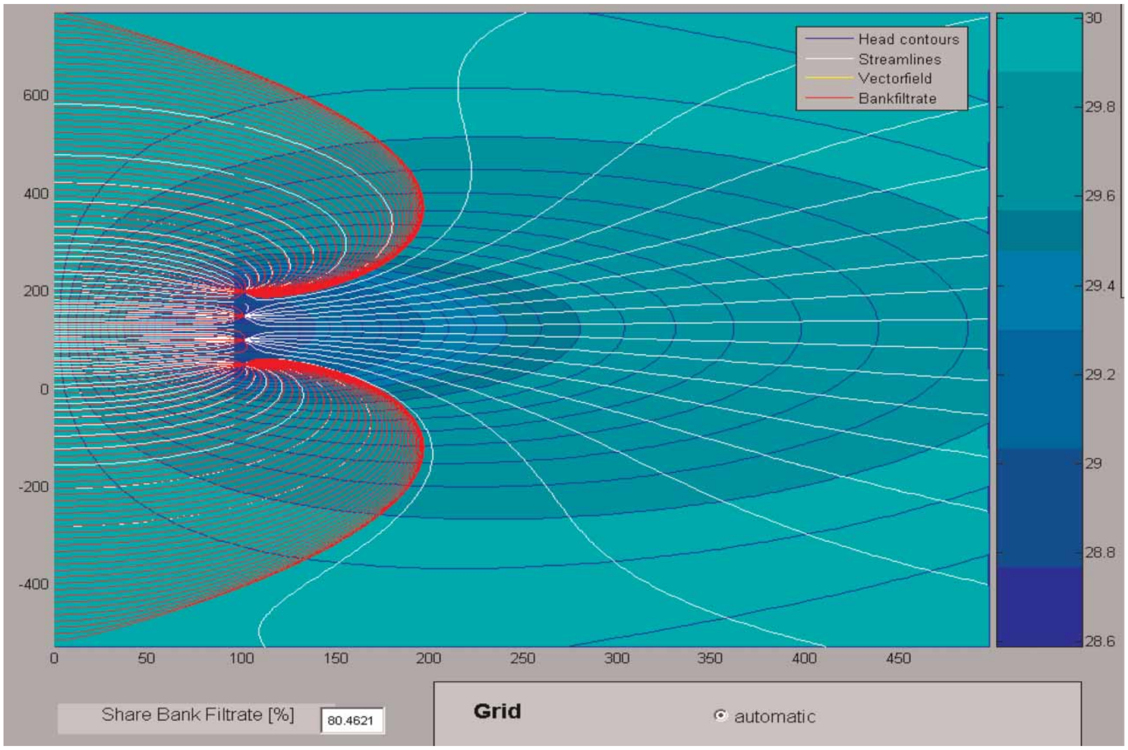

Figure 5 | Sample NASRI BF Simulator output display (4 wells 100 m from bank 50 m well spacing C/C, hydraulic conductivity 0.006 m/s).

native groundwater are known. Both of the hydraulic models used, MODFLOW and NASRI-BF Simulator can be employed to assess different hydraulic scenarios with respect to number, spacing, location and alignment of production wells.

Prediction of water quality

After hydraulic simulations with MODFLOW and NASRI BF Simulator and development of guidelines for water quality prediction (of different contaminants), the next step was to predict the quality of final bank filtrate. Removal efficiency of a BF system depends on residence times/travel distances from the bank to the well. The final water quality from a BF system was determined by the combined effect of: (i) the removal of given contaminant during soil passage, and (ii) dilution or mixing effect of local groundwater. For the given well arrangements, the final water quality can be predicted using the mass balance equation below:

$$C = C_{\text{river}} * P_{\text{RBF}} * (1 - R_{\text{RBF}}) + C_{\text{GW}} * (1 - P_{\text{RBF}})$$

where, C = concentration of a contaminant in product water from the BF system, C_{river} = concentration of a contaminant in surface water, R_{BF} = removal efficiency of BF for the given contaminant (based on the guidelines developed), P_{RBF} = % share of bank filtrate, C_{GW} = concentration of a contaminant in native groundwater.

A typical example of prediction of water quality from a BF system is presented in Table 3. The bank filtrate quality is predicted corresponding to minimum, average and maximum water quality parameter values to check if the final bank filtrate meets the applicable water quality guidelines and/or standards for all possible cases. The outcome of the prediction of different water quality parameters of bank filtrate is used to determine the best location for the wells. This step is carried out for various distances of wells from the bank (50–200 m) with varying percentage share of bank filtrate. Water quality is predicted for all hydraulically feasible options and the option meeting the local water quality guidelines of standard is selected. It should be noted that the greater the distance of the wells from the bank, the higher will be

Table 3 | An example of prediction of water quality from a RBF system using the algorithm developed (Distance of wells from the bank = 50 m; Bank filtrate share = 94.1%, Travel time = 26–38 days)

Parameter	Unit	Groundwater quality			Surface water quality			Average BF removal based on guidelines (%)	Final quality of bank filtrate (average)
		Min.	Avg.	Max.	Min.	Avg.	Max.		
DOC	mg/L	0.9	1	1.2	1	2.7	4.5	53	1.25
NH_4^+	mg/L	0.63	0.63	0.63	0.0	0.0	0.0	74	0.04
Faecal coliforms	/100 mL	0	0	0	10	384	1,600	100	0
Herbicides	μg/L	9.0	11.0	13.0	15	22	29	53.2	10.34

the removal efficiency and the greater will be the contribution from local groundwater. So the choice is between (a) few wells near the bank producing relatively lower quality water, which may require some treatment, or (b) more wells farther from the bank producing relatively good quality water.

Cost calculations and comparison

After selecting the design which meets both hydraulic and water quality requirements, capital and O&M costs of BF system are estimated. Finally, cost comparisons were done between BF technologies and existing conventional water treatment plants in terms of capital cost as well as O&M costs (labour, power and chemicals). For successful technology transfer of BF to developing countries, cost is important for its sustainability. Decisions can then be made regarding selection or further detailed analysis of the suitable water treatment method for given conditions.

The costs for establishing BF systems depend on many factors, including aquifer characteristics, type of well-screen installation, facility design and distance to the population served. BF systems are valued by both the utility and consumers. The value of BF is not just found in reduced treatment and delivery costs, but also in the many invaluable services it provides to the consumer, environment and future generations (Ray *et al.* 2002). Furthermore, O&M needs vary due to size of the BF facility, types of wells employed, continuous or intermittent operation of wells, materials used for well construction, geological environment and river conditions (Hunt *et al.* 2002).

APPLICATION OF ASSESSMENT METHODOLOGIES IN MALAWI AND KENYA

The assessment methodology developed was then applied for feasibility assessment of BF in five cities in Africa: three in Malawi – Blantyre, Lilongwe and Mzuzu; and two in Kenya – Eldoret and Nakuru. A summary of the hydrogeological data of these sites used for MODFLOW simulations is presented in Table 4. Details of these case studies are presented elsewhere (Chaweza 2006; Bosuben 2007). In most of these water supply systems, surface water (rivers) is the main source of water and conventional surface water treatment (sedimentation, chemical coagulation/flocculation, clarification and chlorination) is used. Water demand, water quality and treatment as well as hydrogeological data were collected from each of these sites to provide input for different models. The pumping rates for the vertical wells in different cities ranged from 0.024 to 0.2 m^3/s depending upon the hydraulic conductivities at the site, water demand and number of wells proposed. The distance of the wells from water source (river or lake) and the spacing between the wells both ranged from 50 to 100 m. Feasibility studies revealed that in all five cities, the hydrogeological conditions are favourable for BF and with the proper design of the production wells, existing water demand can be met with BF systems. Furthermore, it was found that the quality of water produced by the proposed BF systems is comparable to that produced by existing treatment plants, and meets local drinking water standards and WHO water quality guidelines.

Table 5 summarizes the salient features of the five water supply systems analysed for BF. Analysis of three water supply systems in Malawi showed that by switching from

Table 4 | Summary of hydro-geological data used for MODFLOW simulations

Description	Blantyre	Lilongwe	Mzuzu	Eldoret	Nakuru
Mesh size (m)	$5{,}000 \times 5{,}000$	$5{,}000 \times 5{,}000$	$5{,}000 \times 5{,}000$	$7{,}500 \times 6{,}000$	$5{,}000 \times 5{,}000$
Number of rows	200	200	200	250	200
Number of columns	200	200	200	300	200
Aquifer type	Unconfined	Unconfined	Unconfined	Unconfined	Unconfined
Main aquifer material	Silty gravelly sands	Gravelly clayey sands	Clayey silty sands	Coarse gravel and silty clay	Sandy sediments
Aquifer thickness (m)	30	50	40	50	60
Average hydraulic conductivity (m/s)	5.7×10^{-5}	3.9×10^{-5}	2.9×10^{-5}	6.0×10^{-4}	1.66×10^{-3}
Average porosity	0.29	0.28	0.24	0.28	0.28
Recharge rate (m/s)	5×10^{-10}	2×10^{-9}	2.7×10^{-9}	4.1×10^{-9}	3.2×10^{-8}

Table 5 | Salient features of the water supply systems analysed for feasibility of BF

	Blantyre	Lilongwe	Mzuzu	Eldoret	Nakuru
Population	700,000	670,000	135,000	217,000	285,000
Water sources	Shire river, Mudi dam	Lilongwe river	Lunyangwa river	Ellegirini, Endoroto and Moiben rivers	Lake water (31%); Groundwater (69%)
Existing water treatment plant capacity (m^3/day)	110,000	75,000	15,000	22,000	35,950
Operational costs of existing treatment system (US$/$m^3$)	0.120	0.030	0.009	0.043	0.029
Distance of the wells from the bank (m)	50	50	50	100	50
Well spacing centre to centre (m)	100	100	100	50	50
Share of bank filtrate in proposed BF system (%)	83	88	89	95	91
Estimated operational costs of BF system (US$/$m^3$)	0.098	0.014	0.009	0.036	0.020

existing conventional treatment to BF, savings of over 80% on existing annual treatment costs (chemical and energy only) are likely for Blantyre and Lilongwe cities, but for Mzuzu the annual operational costs of the BF system and existing conventional water treatment system are comparable. In Eldoret and Nakuru cities in Kenya, annual operational costs savings of about 16 and 32%, respectively, could be achieved by switching from conventional surface water treatment to a BF system. Furthermore, these operational cost calculations exclude the relative ease to the plant operators in O&M of BF systems compared with conventional surface water treatment plants in which they need to adjust the coagulant dose regularly. This analysis shows that the proposed four-step methodology can be used as a preliminary screening tool to assess the feasibility of a BF system for water treatment at a given site.

This framework uses MODFLOW and NASRI BF Simulator for the design or analysis of the well-fields and to estimate the share of bank filtrate in the water extracted from the wells. Any other hydrological models, if easily available and applicable, can also be used for this purpose. Furthermore, the water quality prediction step in the framework developed relies on the average removal range for a particular contaminant (based on literature review) and the dilution or mixing effect of local groundwater for estimation of the final concentration. It does not take into account the effect of redox conditions and potential leaching of the minerals underground and consequent increase in concentration of metals like iron and manganese or hardness in the product water. The guidelines for prediction of water quality from BF systems can be further updated and refined by including data on removal of different contaminants during soil passage from other literature sources.

It should be noted that this framework is only the very first step and will only serve as a tool or an approach, in cases where limited water quality and hydrogeological data are available, for quick assessment of feasibility of BF system as an option for water treatment. When BF is found feasible for a given site from this approach, then further detailed site investigations (hydrological and hydrogeological) and pilot studies should be conducted to verify the preliminary predictions. It is expected that application of this simplified assessment or feasibility methodology will help to promote the application of BF systems for water supply and treatment in developing countries.

CONCLUSIONS

Based on the literature review, framework for assessment of BF systems and its application in Malawi and Kenya, the following conclusions can be drawn:

- BF is a robust natural water treatment system which has high potential for application in developing countries, as the main treatment step or as the pre-treatment.
- A guideline for estimation of water quality of BF system for given travel time and/or travel distance was developed based on literature review. Guidelines for water quality prediction developed in this research could be used as a quick screening tool to make preliminary estimation of water quality. However, detailed design of the wells and pilot studies will be required to make more accurate predictions or estimation of water quality for a specific BF site.
- A four-step methodology, using existing hydraulic software and the water quality guidelines developed, was proposed for assessing feasibility of BF for water treatment. This methodology can be used for preliminary design of BF and to compare it with other above-the-ground conventional surface water treatment systems in terms of water quantity, quality and costs.
- Spacing between the wells and distance of the wells from the bank can be varied to get the required water quality and quantity from the wells for given allowable drawdown and production capacity.
- Application of the feasibility assessment methodology developed in selected cities in Malawi and Kenya showed that BF is feasible and attractive in these cities from hydraulic and water quality, as well as cost, considerations. It was found that considerable O&M costs savings can be achieved by switching from conventional chemical-based surface water treatment to BF.

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