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PAPER

Methodology for evaluation of potential sites for large-scale riverbank filtration

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Abstract

Despite being a simple and inexpensive pretreatment technology, the cost-effectiveness of riverbank filtration (RBF) depends on complex hydrogeological and hydrogeochemical variables. One of the most important issues for decision makers regarding RBF is optimal site selection. Therefore, a methodology for multicriteria site evaluation for large-scale RBF schemes is offered. The methodology is primarily designed as a prescreening method, applied over a wide area, but can also serve as a guide for evaluating individual RBF sites. To facilitate further discussion about improvements on the methodology, the reasoning behind each relevant factor and its weight in the evaluation is presented. The methodology is divided into three sequential steps through which a site can be assessed. The first step is to establish the existence of connectivity between the river and aquifer. This is termed the essential criterion, and is a binary determination of site suitability. If the site is determined to be suitable, it is then assessed via a set of quantity criteria, which measure the aquifer capacity and amount of bank filtrate that can be effectively abstracted. Lastly, water quality criteria are assessed by means of surface-water and groundwater quality. The quantity and quality criteria form a result expressed as the site suitability index (SSI), which ranges from 0 to 1, where higher scores represent increased suitability. Finally, the methodology is applied to evaluate existing sites of large-scale RBF application as a demonstration of its applicability. The success of these existing sites is compared to the calculated SSI value and discussed.

Keywords Groundwater management · Managed aquifer recharge · Riverbank filtration · Water supply · Site characterization

Introduction

Riverbank filtration (RBF) is a low-cost pretreatment technology that has been widely applied in Europe and in the USA for many decades (Grischek et al. 2002; Ray 2008; Dillon et al. 2019; Kruc et al. 2020) and more recently in countries such as India, China, and Egypt (Sandhu et al. 2011; Hu et al. 2016; Ghodeif et al. 2016). The main motivation for applying RBF is the removal of particles, organic compounds and pathogens at a low cost compared with conventional treatment of surface water via coagulation/flocculation and sedimentation/filtration. An additional motivation in some countries, such as China and Vietnam, is to avoid overexploitation of groundwater resources (Wang et al. 2016; Glass et al. 2018).

Riverbank filtration as induced infiltration of surface water into the adjacent aquifer uses natural processes such as filtration, biodegradation and adsorption, which frequently result in positive changes in the infiltrated water quality. Although it is a simple technology, a successful and cost-effective operation of large-scale RBF schemes depends on rigorous site investigation due to complex hydrogeological and hydrogeochemical variables particular to each site. Therefore, much of the research on RBF comprises the assessment of the feasibility of potential sites. Site investigation can be costly and limited to a small area, usually involving boring, borehole logging, pumping tests and hydrochemical sampling and analysis for several months (e.g. Sandhu 2015). For this reason, a methodology for preselecting and evaluating suitable sites in a wider area using large databases and multi-criteria analysis is critical, particularly in regions where RBF is

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not widely applied and can have a positive impact on the water supply system.

To date, there is no consensus on the optimal methodology to evaluate site suitability for RBF. Several works in the past have highlighted the relevant parameters for RBF application (Ray et al. 2002; Schubert 2002; Hubbs 2006a, b; Shamrukh 2011), but only a few researchers have offered quantitative methodologies to evaluate RBF sites (Lee and Lee 2010; Srisuk et al. 2012; Wang et al. 2016; Patil et al. 2020). However, in the view of the authors, the current methodologies still have many limitations (further discussed in section 'Method overview and review of previous methods'), including the overweighting of low relevance variables, the arbitrary assignment of parameters weights and the requirements of datasets that are impractical to obtain.

The objective of this article is to offer a new multicriteria evaluation of the suitability of RBF sites for large-scale application, but it also can serve as a rough guide for evaluating any single RBF site. To facilitate further discussion on improvements to the methodology, the rationale behind each relevant factor and its weight in the evaluation is presented. In addition, the data necessary for the evaluation is intended to be practical. Furthermore, the evaluation of existing sites using this method is presented to demonstrate the methodology's applicability. There are many site- or region-specific variables and many decisions which are directly linked with the goal of the RBF application; as a result, this methodology does not aim to be applied as a final site evaluation.

Methodology

Method overview and review of previous methods

Previous methods to evaluate and select RBF sites include those proposed by Lee and Lee (2010) from Korea, Srisuk et al. (2012) from Thailand, Wang et al. (2016) from China, and Patil et al. (2020) from India. The present method aims to preselect areas where large-scale RBF is feasible and grade them according to a site suitability index (SSI). The SSI is primarily based on the transmissivity of the site's aquifer, which will generate the site quantity index (I_Q). I_Q is then multiplied by factors related to the site's aquifer and river characteristics. The advantage of using factors is that it preserves the aquifer transmissivity as the deciding factor, while still penalizing sites which present other unfavorable conditions. All other methodologies adopted a system in which each criterion received a weight and was summed to form an index (Table 1). Thus, a site with very low transmissivity could achieve a high index, if all other conditions were favorable. However, a site with very low transmissivity is still undesirable for RBF application, despite other requirements being met, such as low clogging of the riverbed, good surface-water and groundwater quality and low gradient between river and aquifer.

Multiple variables affect the site suitability for RBF (Fig. 1); however, there is one essential criterion which must be fulfilled for any RBF application: The river must be hydraulically connected to the adjoining aquifer. Without this, any abstracted water will consist mostly (or exclusively) of groundwater and not bank filtrate (BF). This condition is indispensable for RBF and should be included in

Table 1 Percentage weights for the evaluation of RBF sites from published methods

Criterion	Lee and Lee 2010	Srisuk et al. 2012	Wang et al. 2016	Patil et al. 2020
Connection between river and aquifer	-	-	15%	-
Aquifer thickness	11.1%	20%	10%	20%
Aquifer hydraulic conductivity	5.6%	10%	10%	
Groundwater level	-	-	10%	12%
Permeability of the riverbed	-	-	10%	-
River shear stress/velocity	-	-	-	20%
Gradient between natural groundwater level and river water level	-	-	5%	-
River discharge	-	15%	10%	-
Surface-water quality	33.3%	5%	15%	24%
Groundwater quality	-	10%	15%	-
Land use	-	5%	-	8%
Soil cover	-	-	-	8%
Social aspects	50%	25%	-	8%
Sum	100%	100%	100%	100%

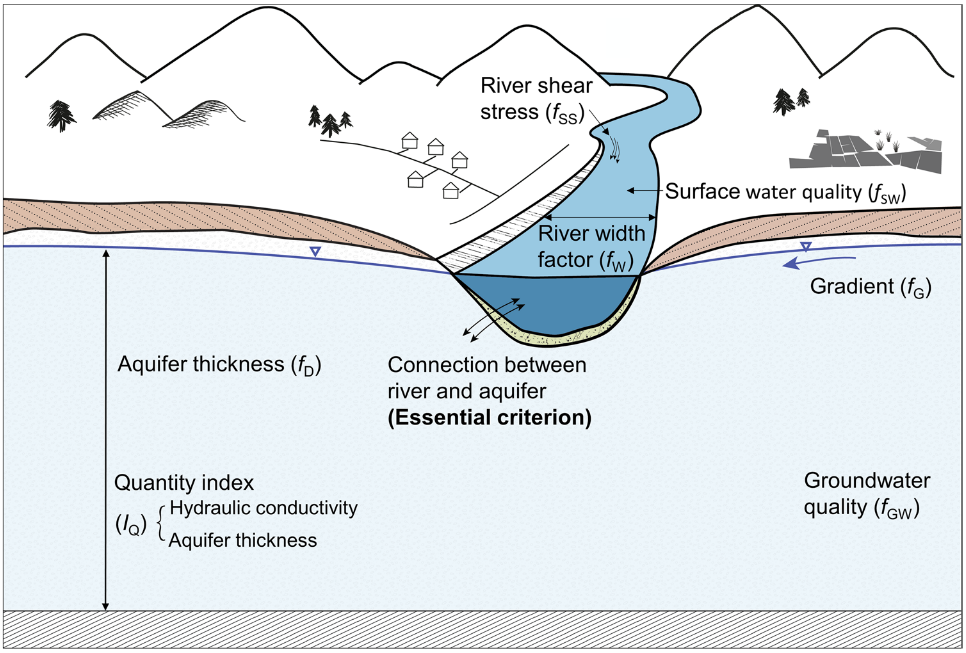

Fig. 1 Criteria for RBF site selection considered in the methodology proposed in this article

any methodology independently of region or goal, although this is not the case for most of the aforementioned methods, which simply assume connection is always present (Lee and Lee 2010; Srisuk et al. 2012; Patil et al. 2020). Wang et al. (2016) weight it equally with other criteria, which results in the potential for a high mark to be achieved for sites where RBF is not feasible. In the present methodology, the connection between river and aquifer is viewed as an essential criterion and if not fulfilled, the site is immediately rejected.

To draw general criteria for RBF site selection, a few assumptions about the goal of RBF are necessary. For the sake of this article, the site evaluation is made for the application of a large-scale operation, with an abstraction capacity >10,000 m^3/d. When searching for sites for small-scale RBF schemes, even size-limited pockets of alluvial sediment deposits may be feasible as shown for several sites in mountainous regions in India (Sandhu et al. 2011) and Switzerland (Diem et al. 2013). There, large-scale schemes cannot be operated.

Based on the principle that the goal of RBF is to abstract large quantities of water; a suitable site must have an aquifer which allows for large abstractions. This constitutes a vital criterion for RBF application. The main factors regarding the absolute quantity of water that can be abstracted are the aquifer thickness (D) and hydraulic conductivity (K), which together account for the aquifer transmissivity (T). Sites with high transmissivity aquifers allow for high abstraction rates, while sites with low transmissivity aquifers, high abstraction rates can only be managed by increasing the number of wells, which would require a larger area and higher costs, making the RBF application less favorable. In very low transmissivity aquifers, the establishment of a large-scale RBF scheme might become unfeasible due to the costs. In the previous methods, the site transmissivity has accounted for 17–30% of the analysis weight, which may result in a site with very unfavorable hydrogeological conditions receiving a high mark.

The second assumption made here is that the goal is to abstract as much BF and as little groundwater as possible. A proper site should be able to abstract at least 50% of the BF. The portion of BF being abstracted depends on several factors, including design choices and site characteristics. Design choices include the abstraction rate, the number of wells, distance between each well and distance between the wells and the riverbank. Site characteristics that influence the portion of abstracted BF include the aquifer thickness, the gradient between the groundwater and the river, the river course and the clogging of the riverbed. Strong clogging of the riverbed lowers the portion of BF, thus sites with high clogging potential are undesirable. However, obtaining information about riverbed clogging is time consuming and costly. There is no large database which can be used for a large-scale evaluation. Nonetheless good indicators that a site has low clogging potential are a high river shear stress, high area of infiltration in the river and high quality of infiltrated water (Schubert 2002; Hubbs 2006a, b; Grischek and Bartak 2016). Of the previous methods, only two have considered clogging in their evaluation (Wang et al. 2016; Patil et al. 2020).

Water quality is the main goal of most research on RBF sites. While assessing site suitability of a specific site it is crucial that surface water, groundwater and BF quality be taken into consideration. However, to take these factors into consideration in a general analysis for a wide area, it is necessary to consider the goals of RBF and the possible alternatives. RBF is a form of natural pretreatment generally seen as inexpensive compared to other methods. Site selection for RBF must weigh the benefits of RBF against the alternative treatment options; therefore, assuming that the most suitable RBF location is the one with the most pristine surface water for example, is far too simplistic. On the contrary, on a river stretch with particularly pristine water, direct surface abstraction might be preferable to RBF. If a site has poor surface-water quality, the quality of BF will possibly be subpar, despite the improvements from subsurface infiltration. However, if the alternative is abstracting surface water directly, RBF can lead to a much cheaper post-treatment, thus RBF application can be advantageous at such a site. Hence, disqualifying a site for poor surface-water quality can potentially rule out sites where RBF would be needed the most. Alternatively, if the goal of site selection is to find the site with best resulting water quality in a certain region and there is an alternative site upstream with better surface-water quality, there is reason to select one site over the other.

Previous methods give high weights for surface-water quality parameters (Lee and Lee 2010; Wang et al. 2016; Patil et al. 2020), which can at times disqualify a potentially suitable site where RBF application would be of great benefit. Furthermore, the choice of chemical parameters for grading has also been in the authors' opinions inadequate. Some of the methods use general water quality indexes which heavily favor parameters (such as nitrate and pathogens) which are not as relevant for RBF (Lee and Lee 2010; Srisuk et al. 2012; Wang et al. 2016), as they are mostly attenuated during bank filtration. Presence of pathogens in the surface water, for example, can be part of the argument in favor of the application of RBF and not against it. Nitrate is usually reduced during infiltration, but can also serve as a redox barrier for manganese and iron reduction and subsequent release, which are common problems during RBF (Grischek and Paufler 2017). Several parameters in surface water can be detrimental to RBF application, especially those that lead to strong reducing environments during infiltration—see section 'Surface-water quality (f_{SW}) and groundwater quality factors (f_{GW})'. Therefore, it is the view of the authors that water quality parameters as a general criterion for RBF site suitability must be used only according to specific local and goal dependent conditions and should not be heavily weighted.

Poor groundwater quality may be problematic for some sites due to mixing with groundwater during bank filtration will occur at most RBF sites. There are numerous constituents that may be present in groundwater (manganese, iron, heavy metals, arsenic, ammonium, organic compounds, etc), which should be taken into consideration. However, one must also consider that dilution with BF will occur, and that groundwater quality can be highly heterogeneous; thus, heavily weighting groundwater quality is also not recommended. For those reasons, in the present method, only general recommendations regarding the range of the factors and relevant parameters to surface-water and groundwater quality are given. To achieve higher accuracy, the exact factors must be determined on a case-by-case approach according to the region and goals of RBF application.

Depending on the site selection goals, social aspects can and have been taken into consideration in other studies (Lee and Lee 2010; Srisuk et al. 2012; Boving et al. 2019; Patil et al. 2020). This includes population density, availability of land, insufficient or low-quality water supply from other sources, availability of electricity, and proximity to villages/cities which may limit pipeline construction. None of those are considered in the present study because they are in large region dependent and hence the criteria would vary significantly according to the economic development and available water resources across different regions. Commonly, only sites having a need for improvement of water supply are covered in an RBF suitability assessment. The results then could be further downscaled and evaluated or adjusted taking into account land availability, pipeline construction costs, etc.

Criteria

General approach

The criteria for site selection are divided into three sequential steps (Fig. 2):

Step 1. Essential criterion: hydraulic connection between river and aquifer
Step 2. Quantity criteria: aquifer transmissivity (hydraulic conductivity and thickness), gradient between aquifer and river, river width (infiltration area), and river shear stress (relevant for riverbed clogging)
Step 3. Quality criteria: surface-water and groundwater quality

The *essential criterion* is fulfilled if the river cross section cuts into an aquifer layer. In various projects, sites proposed for RBF in the past were later rejected due to the existence of a thick clay cap preventing water exchange between the river and the aquifer. If the essential criterion is not fulfilled, RBF is not feasible and the area is considered unsuitable. The remaining sites are graded according to the other criteria and receive a site suitability index (SSI). The SSI ranges from 0 to 1, with higher scores representing suitability.

The *quantity criteria* define whether the aquifer has enough capacity for a cost-efficient large-scale abstraction. Transmissivity (*T*) is a product of the aquifer thickness (*D*) and the aquifer hydraulic conductivity (*K*). Together, those factors are the best indicators for the aquifer abstraction

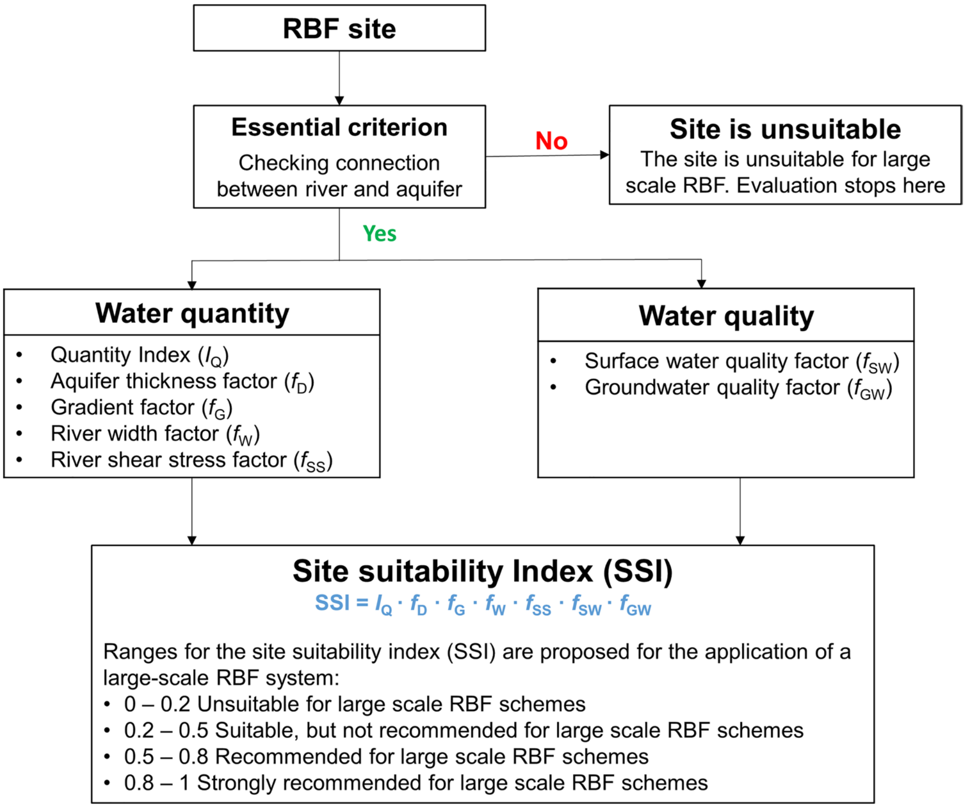

Fig. 2 Flow chart for the methodology application

capacity and form the basis of the quantity index (I_Q). For aquifers with low thicknesses (<10 m) design issues may be encountered, decreasing potential abstraction; therefore, the factor f_D is applied to correct for specific conditions. The other quantitative criteria can have positive or negative effects on the RBF application, although their impact is generally not as consequential as site transmissivity; thus, the other quantitative criteria are applied as multiplying factors (Table 2). These include the river width (f_W), the groundwater flow gradient towards the river (f_G), and the river shear stress (f_{SS}).

The *quality criteria,* at this stage, are also not decisive factors for RBF application, but they do carry some weight to the site suitability. Therefore, they are also used as multiplying factors, which include the surface-water quality (f_{SW}) and the groundwater quality (f_{GW}).

The SSI is calculated by multiplying the quantity index by the quantitative and qualitative criteria factors (Eq. 1).

Table 2 Quantity index and multiplying factors for the site suitability index (SSI)

Criteria	Symbol	Range	Remarks
Quantity index	I_Q	0–1	Based on the aquifer transmissivity, thickness and hydraulic conductivity. The higher the transmissivity, thickness and hydraulic conductivity, the higher the index
Aquifer thickness factor	f_D	0–1	Factor used to correct for sites with low aquifer thickness (<10 m)
Gradient factor	f_G	0.8–1	A low gradient of groundwater flow towards the river would be of advantage to receive a higher portion of BF. The lower the gradient, the higher the related factor
River width factor	f_W	0 - 1	A low river width decreases the amount of abstracted BF and increases the infiltration rate in the riverbed which increases the clogging potential. The higher the width, the higher the factor
River shear stress factor	f_{SS}	0.8–1.0	A low shear stress increases fine sediments and organic material deposition in the riverbed, increasing the clogging potential. The higher the shear stress, the higher the factor
Surface-water quality factor	f_{SW}	0.7–1.0	The presence of high amounts of biodegradable organic carbon and ammonium in the surface water leads to increased reducing conditions in the aquifer, which decreases the BF water quality, thus receiving a smaller factor
Groundwater quality factor	f_{GW}	0.7–1.0	Mixing with highly polluted groundwater decreases the abstracted water quality. Portions of the aquifer with very high arsenic, ammonium, manganese, iron, dissolved organic carbon (DOC) etc concentrations receive a smaller factor

$$\mathrm{SSI} = I_{\mathrm{Q}} \cdot f_{\mathrm{D}} \cdot f_{\mathrm{G}} \cdot f_{\mathrm{W}} \cdot f_{\mathrm{SS}} \cdot f_{\mathrm{SW}} \cdot f_{\mathrm{GW}} \tag{1}$$

The following ranges for the site suitability index (SSI) are proposed for the application of a large-scale RBF system:

0–0.2. Unsuitable for large-scale RBF schemes
0.2–0.5. Suitable, but not recommended for large-scale RBF schemes
0.5–0.8. Recommended for large-scale RBF schemes
0.8–1. Strongly recommended for large-scale RBF schemes

Essential criterion: Connection between river and aquifer

The simplest way to verify the connection between the river and aquifer is to check if the river cross section cuts into a layer with sufficient hydraulic conductivity, usually above 1×10^{-5} m/s, although higher values are preferred. This can be achieved by the interpolation of boreholes or cross sections in the region combined with information regarding the river depth. Depending on aquifer heterogeneity this may require a large number of data points, which may not be available for a particular region, and which would excuse the use as an essential criterion. Also, complex hydrogeological formations, such as hydraulic windows, may allow for hydraulic connection, despite a particular cross section not cutting into the aquifer. If this is suspected to be the case, the essential criteria can be overlooked, although a factor should be added due to the uncertainty of RBF feasibility. There are other possibilities to check for hydraulic connection, including river and borehole water level logging and chemical analysis but these methods rarely apply to wide areas.

Because most of the benefits from RBF come from infiltration through granular media, fissured and karst aquifers are also not considered suitable for RBF. Thus, connection with fissured/karst aquifers does not count, unless there is an underlying granular aquifer where the well filter screen can be placed.

Quantity index (I_{Q}) and aquifer thickness factor (f_{D})

Aquifers with low transmissivity yield low abstraction rates and thus need many wells in order to yield high abstracted volumes. This results in elevated costs for the construction and operation of large-scale RBF schemes. In contrast, aquifers with high transmissivity allow for high abstraction volumes and offer RBF at a lower cost. The quantity index was constructed based on the capacity of a vertical well to abstract groundwater. The estimated maximum theoretical abstraction (Q) of a vertical well is calculated based on Eq. (2) (e.g. Fetter 2014; Treskatis 2017) and is displayed in Fig. 3.

$$Q = \frac{\pi \cdot \left(D^2 - (D - s)^2\right)}{\ln\left(3000 \cdot s \cdot \sqrt{K}\right) - \ln\left(r_0\right)} \tag{2}$$

In Eq. (2), D is the saturated aquifer thickness (m), s is the drawdown (m), K is hydraulic conductivity (m/d) and r_0 is the wellbore radius (m). The calculations assume a well with radius of 0.3 m is used. The other necessary assumption is the maximum acceptable drawdown in the well. A widely agreed upon drawdown limit, which is adopted in this methodology, is one third of the saturated aquifer thickness as a technical threshold for sustainable well operation, up to a maximum of 5 m (Bezelgues et al. 2010). A similar approach was used by Böttcher et al. (2019), who developed a quantitative method to assess the potential for the thermal use of groundwater. High drawdowns (>1/3·D or 5 m) will increase operation costs.

Large-scale RBF schemes generally consist of several vertical wells whose cones of depression interfere with one another. Since Eq. (2) refers to a single vertical well, Q is overestimated, however this was considered an acceptable assumption for the purpose of this paper. For thick aquifers (>50 m), in most cases installation of the filter screen pipe below 50 m below ground level (bgl) would not be favorable for RBF, because the portion of abstracted BF would diminish and the portion of groundwater would increase. Therefore, abstraction capacity for aquifers >50 m thickness was considered the same as if they had 50 m and the hydraulic conductivity considered in the calculations is also limited to the first 50 m of aquifer.

The quantity index was estimated to be inversely proportional to the costs to build and operate a large-scale RBF scheme. A site with low transmissivity (e.g. 200 m^2/d) would require at least 20 wells to abstract ≥10,000 m^3/d leading to high construction and operation cost. While at a site with

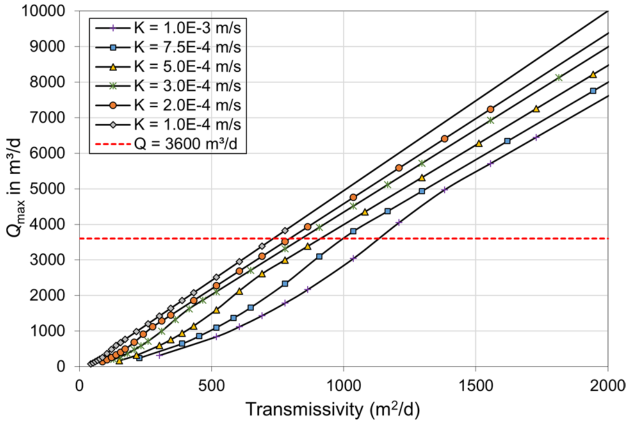

Fig. 3 Theoretical maximum abstraction rate (Q) considering a single abstraction well with a radius of 0.3 m. K = hydraulic conductivity

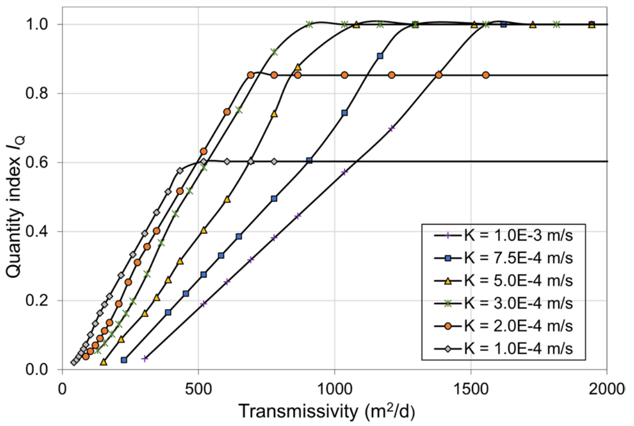

Fig. 4 Quantity index as a function of aquifer transmissivity and hydraulic conductivity affecting well yield

high transmissivity (e.g. 1,000 m^2/d) three or less wells may abstract more than 10,000 m^3/d, which markedly reduces the costs.

The quantity index (I_Q) (Fig. 4) is calculated according to Eq. (3). Although it is theoretically possible to abstract very large volumes from aquifers with very high transmissivity using a single well, the practical implications for the borehole diameter, screen length and the requirements for the pump make the abstraction of such high volumes decidedly less favorable. On the other hand, such sites are suitable for the installation of horizontal collector wells (HCWs). In several countries, e.g. Hungary, Germany, USA, and Malaysia, drilling companies offer construction of HCWs at different scales and acceptable costs. However, installation of HCWs is not taken into consideration in the presented methodology because in many countries vertical well construction is common and offers from experienced HCW drillers are rare or expensive. Thus, for vertical well schemes, sites with even higher transmissivities (e.g. 2,000 m^2/d) are considered equally suitable as sites with about 1,000 m^2/d. An abstraction of 3,600 m^3/d or 150 m^3/h per well, as in the large-scale RBF scheme in Torgau ($D = 50$ m, $K = 6 \times 10^{-4}$ m/s, $T = 2{,}592$ m^2/d; Grischek et al. 1998), is seen as a satisfactory abstraction rate at RBF sites with large transmissivities. Thus, aquifers which allow for abstractions higher than 3,600 m^3/d from a single well are not seen as significantly more suitable, therefore the maximum abstraction rate (Q_{max}) used in Eq. (3) is 3,600 m^3/d and sites which allow for abstraction ≥3,600 m^3/d receive $I_Q = 1$.

$$I_Q = \frac{Q}{Q_{max}} = \frac{Q}{3600} \tag{3}$$

In Eq. (3), Q is the maximum theoretical abstraction rate (m^3/d) as calculated by Eq. (2). If two aquifers lay on top of each other (not separated by an aquitard), their horizontal transmissivity can be added according to Eqs. (4)–(7).

$$T_1 = K_1 \cdot \ D_1 \tag{4}$$

$$T_2 = K_2 \cdot \ D_2 \tag{5}$$

$$K_{average} = K_{1/2} = \frac{\left(K_1 \cdot D_1 + K_2 \cdot D_2\right)}{\left(D_1 + D_2\right)} \tag{6}$$

$$T_{1/2} = K_{1/2} \cdot \left(D_1 + D_2\right) = K_1 \cdot D_1 + K_2 \cdot D_2 = T_1 + T_2 \tag{7}$$

A very low aquifer thickness (<10 m) is unfavorable for RBF application using vertical wells. At low thickness, a few meters of drawdown may become critical. Furthermore, the low thickness limits the filter screen length, potentially leading to high velocities in the filter screen which can cause operation problems in the long term. These design limitations make vertical wells in such aquifers less efficient as compared with thicker aquifers. One solution would be the use of horizontal collector wells, which are however much more expensive. An aquifer of less than 5 m is thus considered not suitable for large-scale schemes and the factor f_D is added for thickness below 10 m (Fig. 5).

Ambient groundwater flow gradient factor (f_G)

The natural gradient between the groundwater and the river is important for the potential portion of BF in the abstracted water. A large gradient can result in high portions of groundwater in the abstracted water, while gradients near 0 or negative (permanent losing river) would result in a very high portion or even 100% BF; thus, sites with lower gradients are preferred.

In addition to the groundwater flow gradient, there are several hydrogeological site characteristics and design choices which control the portion of abstracted BF. In

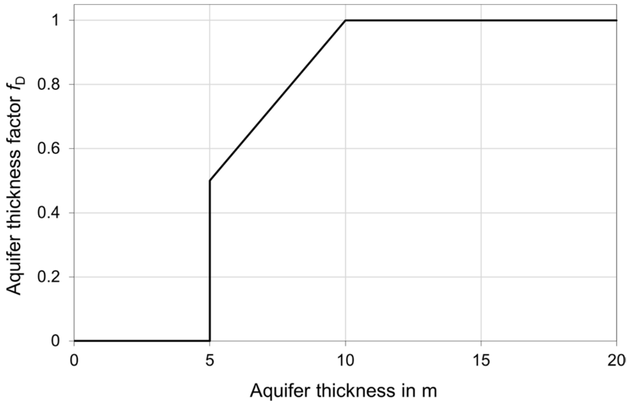

Fig. 5 Aquifer thickness factor (f_D)

principle, the induced drawdown caused by the pumping must be sufficient to overcome the gradient (if the gradient is not already negative) and revert the subsurface flow in the direction from the river to the well(s). Thus, higher pumping rates and wells closer to the river increase the portion of abstracted BF. Multiple wells close to each other increase drawdown, therefore also increasing the BF portion. Counterintuitively, a higher aquifer transmissivity can affect the amount of abstracted BF negatively due to reduced drawdowns considering the same abstraction rates. Clogging of the riverbed likewise decreases the amount of abstracted BF. Using Eq. (8) proposed by Holzbecher (2013), the portion of abstracted BF relative to total abstracted water can be estimated for a situation of a single well (Fig. 6).

$$\propto (\%) = \frac{Q_{\mathrm{bf}}}{Q} \cdot 100 = \frac{2}{\pi} \cdot \left(\arctan \sqrt{\beta} + \frac{\sqrt{\beta}}{\beta + 1} \right) \cdot 100 \qquad (8)$$

where $\propto$ is the portion of abstracted BF (0–100%), Q_{bf} is the abstraction rate of BF (L^3/T), Q is the total abstraction rate by the well (L^3/T), and β is a value representing the physical setting of the site which can be calculated by using Eq. (9).

$$\beta = \frac{1}{\pi x} \frac{Q}{Q_{x0}} - 1 \qquad (9)$$

where x is the distance of the well from the riverbank (L), Q_{x0} is ambient groundwater flow (L^2/T) which can be calculated from Eq. (10).

$$Q_{x0} = K \cdot \left(\frac{H_{\mathrm{GW}} - H_{\mathrm{River}}}{L} \right) \cdot D \qquad (10)$$

where H_{GW} is groundwater head (L), H_{River} is river stage (L), D is aquifer thickness (L), and L is the distance between river and groundwater head (L).

During an RBF site investigation, it is possible that the gradient becomes a relevant factor against the establishment of an RBF scheme. The gradient might be too large for the desired abstraction rate at the required distance of the river to the wells and result in a very low portion of BF in the abstracted water. As seen in Fig. 6, a high gradient (e.g. 5‰) can lead to less than 10% of abstracted BF at one RBF site, but still lead to >50% at others. As multiple variables, including design choices (distance between river and wells, abstraction rate, number of wells) can overcome high gradients, the gradient is frequently not a deciding factor for large-scale RBF application. In addition, the gradient between river and well(s) is variable through time, potentially varying significantly according to seasons and recent rainfall events. Since the gradient used for this evaluation might be a snapshot of a single point in time including one groundwater level measurement and one river water level measurement, it may not be entirely representative. For those reasons, the gradient factor (f_G) is not a deciding factor on the SSI, varying only between 0.8 and 1. For a gradient of 0.5‰ or less $f_G = 1$ and for a gradient of 5‰ or more $f_G = 0.8$, with the factor changing linearly between those values (Fig. 7). This approach also results in $f_G = 1$ for sites along a losing river, where the surface water naturally infiltrates into the aquifer without pumping, but does not favor those sites. This might be seen as a limitation and adjusted for losing river stretches or meanders.

Width factor (f_W)

High-capacity RBF schemes are mainly found at rivers having a width of >100 m, e.g. along the Rhine River and Elbe River (Germany), Danube River (Slovak Republic, Hungary) and Ganga River (India; Grischek et al. 2002; Sandhu et al. 2011). An infiltration rate of ≤0.2 $m^3/(m^2 \bullet d)$ was found at

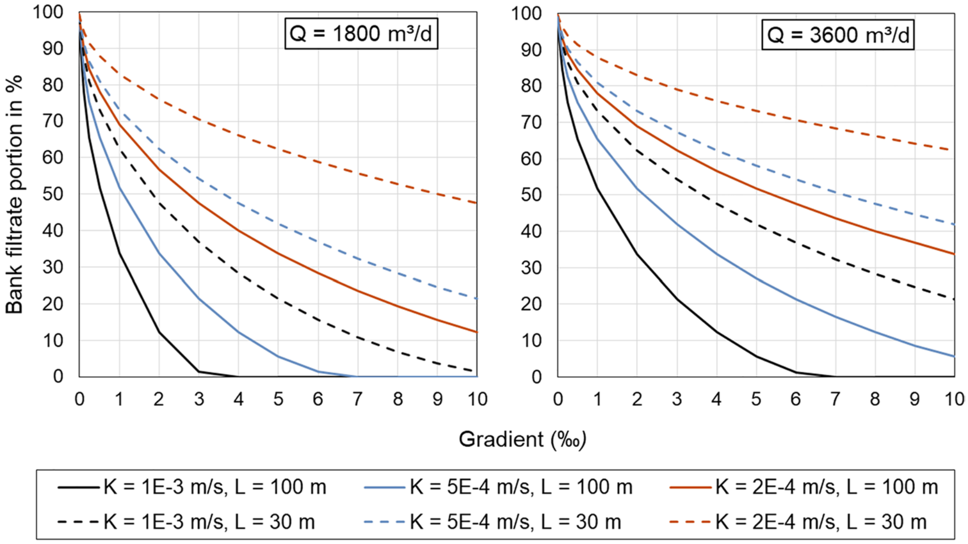

Fig. 6 Portion of abstracted BF in total abstracted water using Eq. (8), considering a single well, an aquifer depth of 20 m, no clogging of the riverbed and varying aquifer hydraulic conductivities ($K = 2 \times 10^{-4}$ – 1×10^{-3} m/s), distance between the river and wells (L = 30 and 100 m), abstraction rates (Q = 1,800 and 3,600 m^3/d) and gradients (0–10‰)

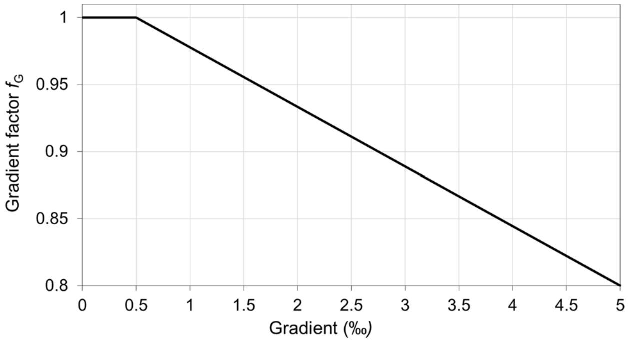

Fig. 7 Gradient factor (f_G) to include the gradient of ambient groundwater flow towards the river

RBF sites that have been in operation for several decades without severe riverbed clogging problems limiting abstraction rates in the long term (Grischek and Ray 2009). If the river is wide, a large infiltration area is available and a low infiltration rate is expected (Fig. 8a). If a large amount of water is pumped near a river with a low width, the infiltration area is low compared to the volume of infiltrating river water. This increases the risk of clogging and reduces the amount of abstracted BF. Low river widths also lead to reduced BF% in the abstracted water, as more groundwater from the opposite side of the river is abstracted. The relation between river width and BF% is displayed in Fig. 8b. The calculation was done with the analytical solution for a partially penetrating stream with streambed resistance (Eq. 11) from Hunt (1999) for an exemplified site with typical characteristics (unconfined aquifer, $D = 30$ m, $K = 5 \times 10^{-4}$ m/s, $Q = 3{,}600$ m^3/d, distance between the well and the river = 30 m). Although the results will vary for different aquifer characteristics, a similar pattern remains. Similar results are also achieved with numerical solutions.

$$\frac{\Delta Q}{Q_w} = \operatorname{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda d}{2T}\right)\operatorname{erfc}\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{Sd^2}{4Tt}}\right) \quad (11)$$

where ΔQ is river depletion flow rate [L^3/T], Q_w is the constant well pumping rate [L^3/T], S is aquifer storage coefficient, specific yield or effective porosity [-], T is aquifer transmissivity [L^2/T], t is pumping time [T], d is shortest distance between well and river edge [L], λ is riverbed conductance term [L/T] which can be calculated from $\lambda = \frac{K'W}{b'}$, where K' is permeability of the semipervious layer [L/T], b' is thickness of the semipervious layer [L], and W is river width [L].

The width factor is added to correct for lower BF% and increased clogging potential, penalizing rivers with low width. An adequate site ($f_W = 1$) is considered one which can maintain low infiltration rates and high BF%. According to the analytical solution, BF% increases sharply according to width, reaching an inflection point at about 15 m and remaining mostly stable after 50 m. Therefore, the width factor was constructed to mimic this behavior, where a low width (e.g. 5 m) receives a low factor ($f_W = 0.43$), while an intermediate width (e.g. 25 m) already receives a high factor ($f_W = 0.89$), and widths ≥50 m receive $f_W = 1$.

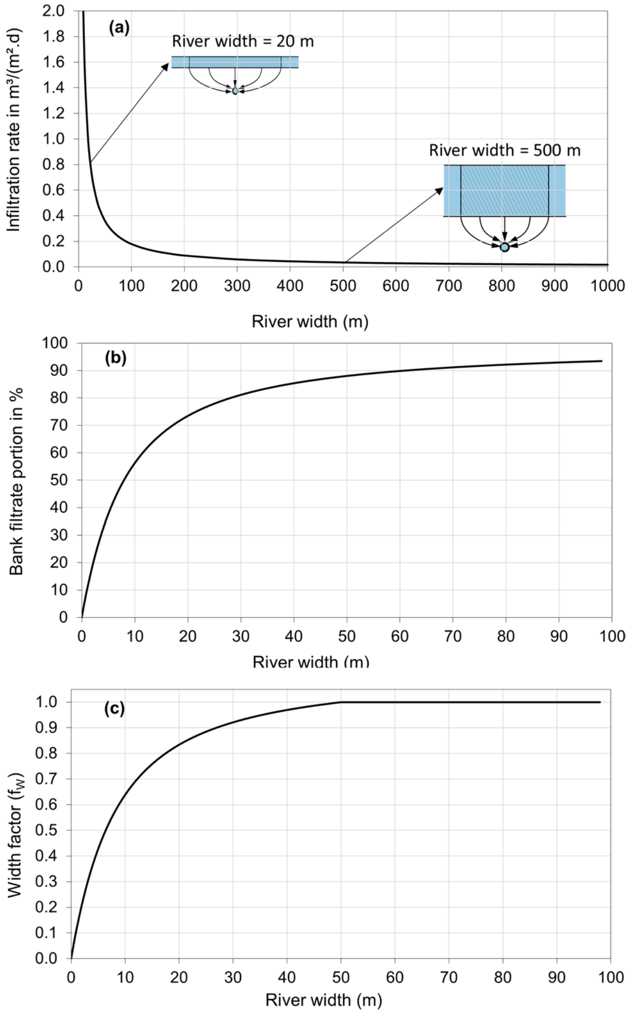

Fig. 8 **a** Theoretical infiltration rates at an RBF site where 3,600 m^3/d are being abstracted, 50% of which consists of BF, from a 100-m stretch of river; **b** changes in BF% according to variations in the river width of a typical RBF setting; and **c** width factor according to river width

Shear stress factor (f_{SS})

Clogging of the riverbed is an often underestimated problem at RBF sites and issues related to clogging may only appear years after start of the operation (Grischek and Bartak 2016). Clogging is a complex issue which is costly to measure in the field and hard to predict with easily available information. Sufficient shear stress in the river is one parameter that indicates the capacity to remove this clogging layer, making the site less susceptible to clogging. Shear stress as a factor includes river flow velocity and river depth, which are parameters which can be somewhat easily obtained. The river flow velocity correlates to the river gradient, hydraulic radius and roughness coefficient. River slope, depths and velocities may be available from databases of river authorities. River depth (h_R) can be taken also from cross sections, river width from aerial photographs, satellite images and Landsat maps. Shear stress can be estimated for rivers with a width of >100 m using Eq. (12), although more precise equations exist for smaller rivers.

$$\tau = 10{,}000 \cdot h_R \cdot i_R \tag{12}$$

where τ is shear stress in N/m^2, h_R is river depth in m, and i_R is river slope (m/m).

The DIN 19961 (2000) provides data indicating the threshold shear stress (critical shear stress, $\tau_{cr)}$ required to move sediments of different sizes on the riverbed (Table 3). Sites with mean flows sufficient to move coarser sediments (steeper rivers) are theoretically less predisposed to clogging effects. Thus, sites with a shear stress incapable of moving fine sands ($\tau \leq 1$ N/m^2) receive the smallest factor (f_{ss}) of 0.8, while sites capable of moving gravel-sand mixtures and strongly colloidal sediments ($\tau \leq 12$ N/m^2) or show a frequent flow variation with at least 12 N/m^2 during high water flow (cleaning effect limiting riverbed clogging), receive the maximum factor of 1. Sites in-between vary as displayed in Table 3.

This approximation is seen as fitting for a wide prescreening selection; however, the issue of clogging is much more complicated. The grain size distribution of the riverbed material also plays a significant role in the shear stress capacity to remove the clogging layer. As observed by Stuyfzand et al. (2006), counterintuitively, riverbeds consisting of gravel are more at risk of clogging than sandy riverbeds, despite the latter having lower hydraulic conductivity. The reason for this, is that in gravel riverbeds a clogging layer can form below the coarser sediments and in turn those sediments serve as a shield for the clogging layer, effectively blocking its removal despite a sufficient shear stress. Also, Schubert (2002) discussed an armoring of the riverbed at the RBF site Flehe at the Rhine River and better conditions for RBF in the inner bends of a meander (deposition zone). However, such effects have not been included in the proposed method to keep it simple, but should be considered during detailed site investigation

Table 3 Approximate amount of shear stress necessary to move granular media of different particle sizes according to the DIN 19661 (2000)

Particle size classification	Particle size diameter (mm)	Critical shear stress τ_{cr} (N/m^2)	Shear stress factor f_{ss}
Coarse gravels	20–63	45	1
Medium gravels	6.3–20	15	1
Loam/clay (strongly colloidal)	-	12	1
Gravel sand	0.63–6.3	12	1
Coarse sands	0.63–2	3–6	0.9
Medium sands	0.2–0.63	1–2	0.85
Fine sands	0.063–0.2	1	0.8
Silt	0.002–0.063	0.2	0.8

Surface-water quality (f_{SW}) and groundwater quality factors (f_{GW})

In this paper, only rough recommendations regarding the range of the factors and relevant parameters of surface-water and groundwater quality are given, because the relevance of each parameter varies according to the region and goals of RBF application. Although surface and groundwater quality can be decisive in the decision to use a particular site for RBF application, the authors recommend not to overvalue the water quality parameters in a wide preselecting site screening. Also, general drinking water quality indexes should not be used for grading because the water quality requirements are not the same for drinking water as for an effective RBF scheme.

For surface water, what is considered critical for an RBF scheme are water constituents which consume oxygen (leading to stronger reducing conditions in the aquifer) and parameters which increase the riverbed clogging potential. Unfortunately, the parameter biochemical oxygen demand (BOD) does not have a sufficiently low limit of detection to assess the oxygen consumption during the flow path of the BF. The most common constituents responsible for large oxygen consumption in surface water are ammonium (Covatti and Grischek 2021) and organic compounds determined as biodegradable dissolved organic carbon (BDOC; Schoenheinz 2011); 1 mg/L of ammonium leads to the consumption of about 3.6 mg/L of dissolved oxygen (DO), while 1 mg/L of BDOC consumes about 4.5 mg/L of DO. BDOC is rarely analyzed or reported, but total organic carbon (TOC) and/or dissolved organic carbon (DOC) concentrations are more widely available. While the amount of BDOC in DOC varies, the assumption that BDOC represents about 30% of total DOC is seen as valid for many rivers in continental climate. The determination of assimilable organic carbon (AOC) is tricky, expensive and not widely available. The particulate organic matter, included by TOC measurements, can also be partly oxidisable and therefore contribute to oxygen consumption, especially in riverbeds. If there is a high concentration of algae, a higher risk of clogging and reducing conditions are expected to occur in the riverbed and aquifer, but this does not exclude the applicability of RBF.

High loads of suspended solids (mechanical clogging) and biodegradable substances (biological clogging) in the river water also increase the clogging potential (Schubert 2002). Highly turbid rivers (>100 NTU) have been shown to be more susceptible to clogging (Pholkern et al. 2015; Gutiérrez et al. 2018); although, exact turbidity ranges for increased clogging risk have not yet been established and likely depend on riverbed composition. It is advisable to add a small factor (e.g. 0.95) for highly turbid rivers if other options are available.

At bank filtration sites, mixing with groundwater almost always occurs; thus, at sites with polluted groundwater or strong reducing conditions, posttreatment costs become much higher. The most relevant pollutants will vary according to the region. Strong reducing conditions in the aquifer can lead to high manganese, iron, ammonium and arsenic (in certain regions only) concentrations, while high concentrations of DOC, chloride, nitrate, pesticides, organic halogens, phenols, etc. can also be prejudicial and lead to high post-treatment costs. However, evaluating the wide range of possible groundwater quality conditions is beyond the scope of this article. If data are available, it is constructive to introduce a factor for groundwater quality; however, it must be taken into account which pollutants are present, in what ranges they lie, viable water supply alternatives, post-treatment options and the relative importance of quantity and quality of water for the goals of RBF. In most cases, it is useful to separate the site suitability index into a quantitative part and qualitative part, which can be evaluated separately.

It is important to consider that RBF sites can sometimes abstract >90% of BF which can dilute groundwater pollutants considerably. Consequently, low quality groundwater may not be overly detrimental. Aquifer pollution can also be fairly heterogeneous, meaning that concentrations of ammonium, manganese, iron and arsenic can vary significantly in small spatial distances. This means that water quality from one borehole does not translate perfectly to adjacent areas and there is a degree of uncertainty regarding the representativeness of the collected data. Caution is advised when applying a factor based on a few data points to a large area. Thus, for a region-wide prescreening analysis, it is suggested that the groundwater and surface-water quality factors lie in the range from 0.7 to 1 and are not significantly lower. For the evaluation of specific sites, where the exact contaminant concentrations are determined, lower factors can be applied. What can usually be achieved from groundwater quality from several boreholes in a wide area is to identify hotspot areas, which have higher risk of containing high levels of certain pollutants, therefore deserving a slight downgrade to the site suitability index. If there is high evidence of strong pollution in one area (e.g. anthropogenic pollution source), lower factors can be applied. The same can be applied to different river stretches.

A few suggestions for factors according to some parameters are given in Table 4. If concentrations in surface water and in groundwater are higher than the ones displayed on the table, the corresponding factor is suggested. As previously stated, factors can be region dependent—for example, arsenic is not a problem in groundwater in Germany, but in Vietnam concentrations above 800 µg/L can be found in groundwater (Winkel et al. 2011). In Vietnam, a range of factors might be set for different ranges of arsenic concentration, while this does not make sense in Germany. Extreme concentrations of one parameter can warrant higher factors—for example, ammonium concentrations in groundwater above 20 mg/L are rare, but have been observed in diverse places such as Germany, The Netherlands and Vietnam (Rössner et al. 2000; de Vet et al. 2010; Winkel et al. 2011). At these sites, smaller factors (e.g. 0.8) can be used.

Examples of method application

To demonstrate its applicability, this methodology was applied to 20 existing sites (see Table 5 and the Appendix). Considering most are already operational sites, the essential criterion or hydraulic connection between river and aquifer is implied. Also, since most of these sites have been in

Table 4 Suggestions for utilizing factors for surface-water (f_{SW}) and groundwater (f_{GW}) quality for site selection

Parameter	Recommended limit in drinking water (WHO 2006)	Groundwater	Surface water	Factor
Ammonium	0.5 mg/L	≥2.5 mg/L	≥2.5 mg/L	0.9
Arsenic	10 µg/L	≥20 µg/L	-	0.9
Chloride	250 mg/L	≥500 mg/L	≥250 mg/L	0.9
DOC	-	≥5 mg/L	≥10 mg/L	0.9
Iron	0.2 mg/L	≥10 mg/L	-	0.95
Manganese	0.05 mg/L	≥1 mg/L	-	0.95
Nitrate	50 mg/L	≥100 mg/L	≥50 mg/L	0.9
Pesticides (total)	0.5 µg/L	≥1 µg/L	≥2 µg/L	0.9
Turbidity	5 NTU	-	100 NTU	0.95

operation for a long time, information about the original gradient of ambient groundwater flow towards the river has not been documented in publications, only the gradient resulting from the pumping, which will self-evidently be flowing from the river to the aquifer (negative gradient); thus, f_G cannot be considered in this evaluation. Finally, since the quality criteria depend on RBF goals and regional alternatives, it does not make sense to compare the water quality of different parts of the world. Thus, the quality criteria are not evaluated and only the quantity criteria are weighted.

Of the 20 evaluated sites, 13 were considered very good sites (0.8–1). At 10 of those sites, large-scale RBF systems are indeed present; however, one site with lower grade also has a large RBF system in place. The RBF site in Karany, Czech Republic, abstracts about 59,000 m^3/d but has only gained an SSI of 0.25. According to the feasibility assessment this site is not suitable for large-scale application, but it is able to produce a sufficient quantity through a high number of wells (497) and additional infiltration basins (Bruthans et al. 2019). Because the well scheme is operated as a siphon system, it can be managed at comparably low maintenance cost (no individual well pumps) and low energy cost. For comparison, the same abstraction could be achieved with 17 vertical wells if abstraction rates were equal to those present at Torgau (Elbe, Germany) or Embaba (Nile, Egypt), which have average abstraction rates per well of 3,600 m^3/s (Grischek et al. 2002; Paufler et al. 2018a). Other sites such as those at the Beberibe River in Brazil or at the Enns River in Austria, are viable sites for RBF application, however not suitable for large-scale application. This shows that a low SSI does not completely eliminate a site for RBF application. There are and will be sites that are built and successfully operated under those conditions. Despite this, the authors maintain that the SSI is a strong indicator of a site cost efficiency for large-scale application. (Table 6).

The five sites from China (points 1–5) are sites which have been evaluated by Wang et al. (2016) in their RBF site selection methodology. Their scoring varied from 0 to 100, whereby points 1–5 received a score of 92, 83, 77, 69 and 9, respectively. The largest discrepancy relative to the current methodology is for point 4, which received a grade that indicates the site is suitable for RBF according to Wang et al. (2016), but an SSI of only 0.02 (unsuitable), according to this methodology. The poor index score is a result of low aquifer thickness (5 m) and low transmissivity (150 m^2/d), which allow for low abstraction rates only. The previous methodology highly weighted other less important parameters, thus giving it a higher score.

Limitations and further recommendations

The cost-effectiveness of RBF depends on complex hydrogeological and hydrogeochemical variables. Therefore, it is of utmost relevance that researchers engage in the discussion of finding concrete ways to evaluate potential sites and regions for RBF application. This article does not intend to offer a final solution to this important problem, but rather to advance the discussion on site selection methodology. Due to the many variables and particularities present in each region, a single uniform methodology is likely not feasible. However, key takeaways for further site selection methodologies can be drawn:

- There is one essential criterion for RBF: the river must be hydraulically connected to the aquifer.
- Aquifer capacity is vital for the application of RBF; thus, aquifer characteristics such as hydraulic conductivity and aquifer thickness should be heavily weighted.
- Factors which affect the amount of BF in relation to groundwater such as gradient and clogging of the riverbed should be accounted for. These types of data are usually not readily available. Data quality and availability should be taken into consideration when weighting these parameters.
- The impact of water quality on site selection depends on the goals of RBF application, and therefore should be scored separately from quantity criteria.
- Many surface-water quality parameters relevant for drinking water, such as pathogens and nitrate, are frequently not relevant to RBF as they will be partly or fully removed during subsurface flow; thus, general water quality indexes are not suitable for evaluating surface-water quality for RBF.

This study strives to highlight the most relevant variables and make recommendations accordingly. However, there are still gaps in RBF research that need to be filled in order to optimize site selection methodologies:

- Sustainable infiltration rates for an RBF site in relation to clogging effects
- Ranges of turbidity and suspended solids in the river that can significantly affect clogging
- The impact of riverbed composition on the aforementioned issues
- Surface-water parameters and ranges indicating the cost-effectiveness of RBF as opposed to direct surface-water abstraction combined with different post-treatment strategies

The proposed RBF site selection methodology can be used to score individual sites and compare them as seen in section ‘Examples of method application’. However, this methodology is recommended for use as a prescreening method in a wide area/region. A natural next step would be its application using geographic information systems (GIS), where the data can be interpolated, converted into factors and overlaid for an entire region.

Table 5 Application of the methodology for 20 RBF sites around the world

Site	Aquifer thickness (m)	Hydraulic conductivity (m/s)	I_Q	f_D	River width (m)	f_W	Shear stress (N/m^2)	f_{SS}	SSI	Reference
Enns River (Austria)	5	3.7×10^{-3}	0.58	0.5	80	1	90	1	0.29	Caldwell 2006
Beberibe River (Brazil)	15	3.0×10^{-4}	0.44	1	5	0.41	-	1	0.18	Bertrand et al. 2021
Songhua River, point 1 (China)	18	6.9×10^{-4}	1	1	200	1	-	1	1	Wang et al. 2016
Songhua River, point 2 (China)	20	6.9×10^{-4}	1	1	600	1	-	1	1	Wang et al. 2016
Songhua River, point 3 (China)	22	6.9×10^{-4}	1	1	500	1	-	1	1	Wang et al. 2016
Yinma River, point 4 (China)	5	1.4×10^{-4}	0.03	0.5	90	1	-	1	0.02	Wang et al. 2016
Yitong River, point 5 (China)	12	1.4×10^{-4}	0.15	1	35	0.94	-	1	0.14	Wang et al. 2016
Jizera River, Karany (Czech Republic)	10	4.0×10^{-4}	0.27	1	30	0.92	-	1	0.25	Bruthans et al. 2019; Grischek et al. 2002
Nile River, Embaba (Egypt)	60	6.0×10^{-4}	1	1	300	1	-	1	1	Ghodeif et al. 2018
Ognon River, Genuille (France)	5	1.0×10^{-3}	0.18	0.5	35	0.94	-	1	0.08	Grischek et al. 2002
Elbe River, Tolkewitz (Germany)	10	1.5×10^{-3}	0.91	1	120	1	5-20	1	0.91	Grischek et al. 2002; Paufler et al. 2018a, 2018b
Elbe River, Torgau (Germany)	50	6.0×10^{-4}	1	1	130	1	5-20	1	1	Grischek et al. 1998
Rhine River, Grind (Germany)	15	3.0×10^{-3}	1	1	400	1	24	1	1	Caldwell 2006
Yamuna River, Delhi (India)	16	2.9×10^{-4}	0.46	1	300	1	-	1	0.46	Groeschke et al. 2017
Warta River, Mosina-Krajkowo (Poland)	40	6.0×10^{-4}	1	1	70	1	29	1	1	Kruc et al. 2020
Nakdong River, Daesan-Myeon (South Korea)	46	1.2×10^{-2}	1	1	400	1	-	1	1	Lee et al. 2012; Lee and Lee 2010
Great Miami River, Bolton (USA)	50	1.3×10^{-3}	1	1	60	1	14	1	1	Caldwell 2006
Platte River, Ashland (USA)	20	1.8×10^{-3}	1	1	300	1	2	0.9	0.90	Caldwell 2006
Ohio River, BE Payne (USA)	20	1.4×10^{-3}	1	1	610	1	4	0.95	0.95	Caldwell 2006
Russian River, Wohler (USA)	15	8.2×10^{-3}	1	1	60	1	8	0.95	0.95	Caldwell 2006

Although this methodology can be used as presented, it is encouraged to tailor it to the investigated region based on specific goals related to RBF application, taking into account data availability. Finally, prior to the establishment of an RBF site, an individual site investigation including boring, borehole logging, pumping tests and hydrochemical sampling and analysis is still considered indispensable.

Appendix

Table 6 Additional information regarding the RBF sites evaluated using the current methodology

Site	Transmissivity (m^2/d)	River slope (m/m)	River depth (m)	No. of wells	Total capacity (m^3/d)	Average capacity/well (m^3/d)
Enns River (Austria)	1,600	0.0018	5	1	2,000	2,000
Beberibe River (Brazil)	389	-	-	-	-	-
Songhua River, point 1 (China)	1,080	-	-	-	-	-
Songhua River, point 2 (China)	1,200	-	-	-	-	-
Songhua River, point 3 (China)	1,320	-	-	-	-	-
Yinma River, point 4 (China)	63	-	-	-	-	-
Yitong River, point 5 (China)	150	-	-	-	-	-
Jizera River, Karany (Czech Republic)	346	-	-	497	59,000	120
Nile River, Embaba (Egypt)	3,110	-	-	6	21,600	3,600
Ognon River, Genuille (France)	432	-	-	-	2,000	-
Elbe River, Tolkewitz (Germany)	1,296	0.0003	1.5–5	72	36,000	500
Elbe River, Torgau (Germany)	2,592	0.0003	2–5	42	150,000	3,600
Rhine River, Grind (Germany)	3,900	0.0002	12	7[a]	106,000	15,140
Yamuna River, Delhi (India)	400	-	-	-	-	-
Warta River, Mosina-Krajkowo (Poland)	2,074	0.0018	1.6	-	-	-
Nakdong River, Daesan-Myeon (South Korea)	48,000	-	-	43 + 1[a]	65,000	-
Great Miami River, Bolton (USA)	5,700	0.0007	2	10	60,000	6,000
Platte River, Ashland (USA)	3,100	0.0002	1	2[a]	76,000	38,000
Ohio River, BE Payne (USA)	2,500	0.00004	10	1[a]	64,000	64,000
Russian River, Wohler (USA)	10,600	0.0008	1	5[a]	142,000	28,400

[a] Radial collector wells

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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