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HEAVY METALS CONCENTRATION IN RIVER AND PUMPING WELL WATER FOR RIVER BANK FILTRATION (RBF) SYSTEM: CASE STUDY IN SUNGAI KERIAN

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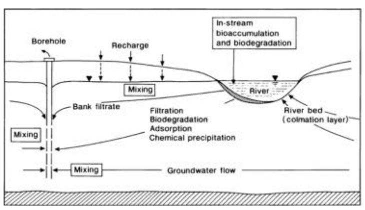
Graphical abstract



Abstract

Riverbank filtration (RBF) provides an alternative to extract raw water by removing pollutants such as suspended solids, organic carbon, and pathogenic bacteria/microbes in the water. However, the main issue with this system is the occurrence of high concentrations of arsenic (As), iron (Fe), and manganese (Mn) in the production well. Therefore, this study was conducted to compare the presence of heavy metals in river water and pumping well water for an RBF system. Water samples were collected from Sungai Kerian (Kerian River) and a pumping well during a three-day pumping test. The heavy metal concentration in both samples was analyzed for 21 elements using ICP-OES. A total of 12 elements were detected in the water samples from either the river or the pumping well. Among the detected elements, As and Fe had concentrations that exceeded the standard values set by the Ministry of Health, Malaysia. Results also suggested that the Fe concentration in the pumping well water was higher than that in the river water. Conversely, As was more frequently detected in the river water than in the pumping well water. These results imply that the As concentration in the river water was derived from external sources, while the presence of As and Fe in the pumping well water was influenced by geochemical and hydrochemical processes in the aquifer.

Keywords: Heavy metals, river water, pumping well water, river bank filtration, ICP-OES

Abstrak

Penurasan tebing sungai menawarkan kaedah alternatif untuk mendapatkan bekalan air mentah yang mampu menyingkirkan pencemar seperti pepejal terampai, karbon organic dan bakteria yang terdapat di dalam air. Walaubagaimanapun, kehadiran Arsenik, Besi dan Manganese berkepekatan tinggi di dalam telaga pengeluaran menjadi factor yang dibimbangi berkaitan kaedah ini. Oleh sebab itu kajian ini dijalankan untuk membandingkan kehadiran logam berat di dalam air sungai dan telaga menggunakan system RBF. Sampel air diambil daripada Sungai Kerian dan telaga yang terletak di tebing Sungai Kerian selama tiga hari. Kepekatan21 jenis logam berat di dalam kedua-dua sampel air dianalisa menggunakan ICP-OES. Sejumlah 12 elemen dikesan di dalam sampel air sungai dan air telaga. Diantara elemen yang dikesan, kepekatan As dan Fe melepasi kadar standard yang ditetapkan oleh Kementerian Kesihatan Malaysia. Hasil kajian mencadangkan kepekatan Fe di dalam air telaga adalah lebih tinggi daripada di dalam air sungai. Sebaliknya, kehadiran As di dalam air sungai adalah lebih kerap berbanding di dalam air telaga. Keputusan ini menggambarkan kepekatan As di dalam air sungai berpunca daripada luaran manakala kehadiran As dan Fe di dalam air telaga dipengaruhi oleh proses geokimia dan hidrokimia di dalam akuifer.

Kata kunci: Logam berat, air sungai, air telaga, penurasan tebing sungai, ICP-OES

1.0 INTRODUCTION

Surface water is commonly used as a source of drinking water in Malaysia. However, anthropogenic pressures from urbanization and expansion of agricultural areas have degraded the quality of surface water. The effect of climate change may also expose the population to high levels of water-security threats if proper action is not taken in water resource management or treatment. For example, extremely dry weather conditions in Malaysia at the beginning of 2014 caused the water level in several dams to decrease to critical levels, thereby reducing the amount of water supplied to approximately 6.7 million people. This situation suggests that existing large-scale dams may not be able to provide adequate water resources, especially during the dry season. Therefore, an alternative method of water management is necessary to ensure safe and stable supply of drinking water while coping with the increase in water demand.

Among available alternative treatment and management methods for drinking water, riverbank/bed filtration (RBF) is a technology that has gained attention [1]. In Switzerland, the management scheme for water resources focuses on two possible alternatives, which are aquifer recharge and underground storage [2]. Meanwhile, the Republic of Korea switched to RBF to obtain higher quality of water starting in early 2000 when the quality of local water sources deteriorated [3]. Basically, RBF relies on natural filtration of river water through an aquifer to remove pollutants such as suspended solids, organic carbon, and pathogenic bacteria/microbes in the water. Several processes are involved during filtration in the alluvium, including dilution, ion exchange, sorption, and biodegradation by microorganisms, which produce high-quality drinking water [4]. This RBF treatment has been applied in Germany for over a century [1].

To date, this treatment process has been implemented in many other countries around the world with different designs and operations to suit the objectives of water authorities. However, recent studies showed that high concentrations of iron (Fe) and manganese (Mn) were detected in wells in various locations [2]. Typically, Fe and Mn can be removed by using simple processes such as aeration and sand filtering [5][6], but continuous loading of these elements can lead to screen clogging in wells [6]. In addition, toxic elements such as arsenic (As), chromium (Cr), barium (Ba), and copper (Cu) were discovered in production wells [7]. The occurrence of these elements can be related to transient redox condition in aquifers.

Four important geochemical processes are involved in determining the efficiency of the treatment process and the quality of water extracted from production wells [2]. These processes include reduction near the riverbank, oxidation near the well, dissolution of carbonate minerals in the aquifer, and sorption–desorption to alluvial material, as shown in Figure 1. Reduced state near the bank is usually influenced by biodegradation activities in the colmation layer, which exhaust dissolved oxygen in the filtrate water. Furthermore, oxidation of organic carbon in aquifer sediments along the path further reduces the oxygen concentration. At the same time, oxygen deficiency promotes the reduction of nitrate as well as Mn and Fe oxides in the aquifer sediments. Nevertheless, metal ions carried by Fe and Mn oxide solids along the flow path are also released into the water during this reduction state [8].

Oxic conditions near the production well significantly benefit the RBF process in which dissolved Mn and Fe can precipitate into oxides with the presence of oxygen. The oxidation process affects other trace elements. For example, reduced species such as As(III) can be directly oxidized by Mn(III/IV) oxides, while Co(II) and Cr(III) are indirectly oxidized by oxidizing microbes. However, several factors may affect the oxidation process near the production well and cause a breakthrough of dissolved metals. These factors are 1) slow oxidation kinetics, 2) nearby reduction zone, and 3) clogging by clayey sand layer or elevated dissolved ions from mixing of oxic and anoxic groundwater.

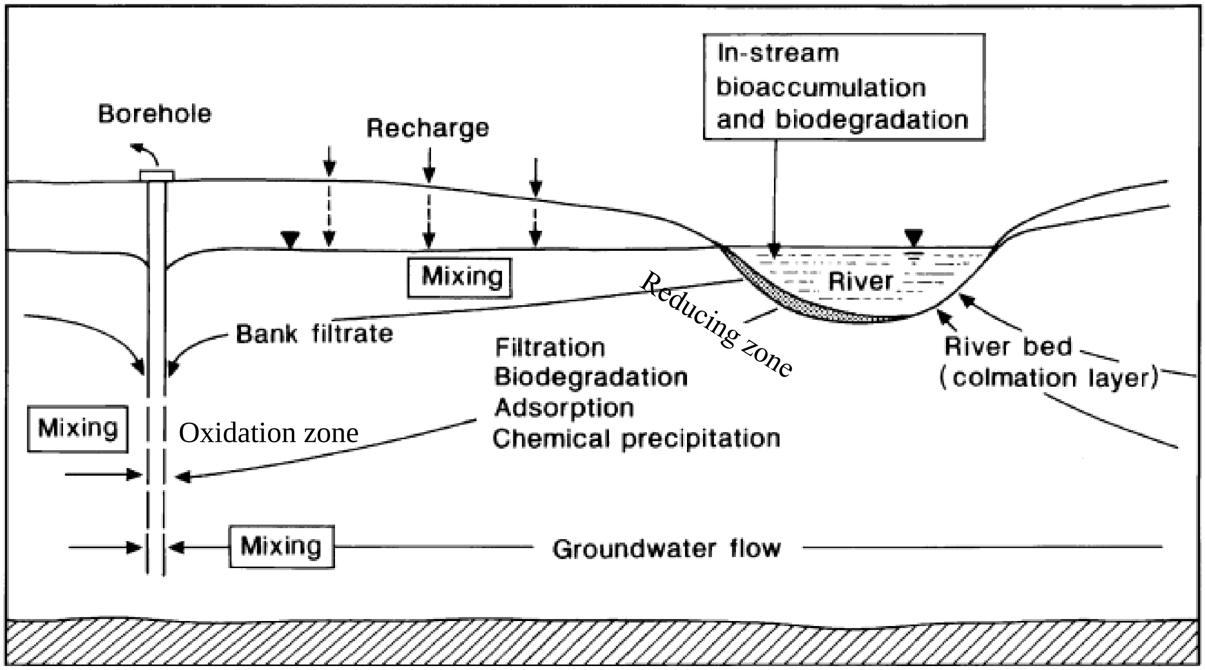


Figure 1 The illustration show mechanisms of natural RBF system. (Edited from Hiscock and Grischek,[9]

Besides the occurrence of redox-sensitive minerals, the quality of water from RBF is also subjected to dissolution or precipitation of carbonate minerals (e.g., $CaCO_3$ and $MgCO_3$) in water passages. A filtration process with low alkalinity and pH of water compared with groundwater may lead to $CaCO_3$ dissolution. In the case where minerals within infiltrate are similar to the groundwater, CO_2 and H+ produced during the oxidation of organic carbons may cause disequilibrium between the infiltrate and groundwater. The dissolution of carbonate mineral usually increases the hardness of water in production wells. Normally, with a low concentration of metals attached to carbonate minerals at high alkalinity, carbonate minerals can control the concentration of dissolved cationic metals [2].

Among the processes involved in the RBF system, adsorption and ion exchange also play an important role that determines the concentration of trace elements in production wells. The adsorption process along the flow path occurs through desorption of ions from aquifer sediments, which are adsorbed by ions from the bank infiltrate. Therefore, ion desorption from contaminated aquifer sediment causes problems such as metal contamination and indicates that the site may be unsuitable for water abstraction without further treatment. Thus, this type of site is usually avoided for application of the RBF system. In a positive way, sorption is the main retardation process for dissolved elements during filtration. Trace elements that are released in the reduction zone are adsorbed onto the organic matter surface or ions such as Al, Fe(III), and Mn(III/IV) oxides [10] [11].

Although the RBF system has been used for more than a decade in Europe, this treatment process remains unfamiliar in Malaysia and requires better understanding before it can be implemented. As mentioned, high concentrations of heavy metals in production wells are among the main concerns related to the abstraction of water from the RBF system. The presence of heavy metals in wells is closely related to the geochemical process in aquifers. This process depends on the infiltrate water, sediments in aquifer, and groundwater characteristics. Thus, the present study aims to determine the quality of river water and pumping well (bank filtration) in terms of heavy metal content. The possible geochemical process that may occur along the pathway of the RBF process according to the soil profile of the selected area is also discussed. The results obtained can be used as baseline data to determine the potential of the selected site for RBF system application.

2.0 METHODOLOGY

2.1 Study Area

Sungai Kerian is one of main tributaries of Kerian river basin. Thus, the river provides potable water for residents of this area. This river originates from the hilly headwaters in Mahang, Kedah, and flows through Lubok Buntar area and down to Kerian Valley in Parit Buntar, Perak, then continues westward to Malacca Strait [12]. This river is also the main body of water that acts as a boundary between the states of Kedah, Perak, and Penang. The study area was situated in Lubok Buntar, Kedah. The area is surrounded by oil palm plantations. Housing communities and villages are also located near this area. Figure 2 shows the location of the study area. For research purposes, pumping wells with a total depth of 31 m were drilled in September 2013. The wells were installed with 10-inch stainless steel screens at 24–30 m and a 1-m sand trap at 30–31 m. The upper part (ground level to 24 m depth) of the well was installed with a 10-inch-diameter PVC blank and a 1-m steel wellhead protector.

Figure 2 Site location

2.2 Soil Profile

Only layers that consist of coarse-grained and permeable water-bearing deposits are suitable for use as an aquifer in RBF systems [13]. Thus, site investigation was conducted to determine the type of soil in the selected area. The first assessment of soil profile for Lubok Buntar was conducted using ground resistivity technique. However, the process and other details of the site investigation are not discussed in this paper. Resistivity analysis was conducted to visualize the soil profile of the study area. Such analysis revealed that the soil in this area was generally divided into three main layers: silty clay (0–17 m), silty sand (17–32 m), and bedrock (>32 m). However, this result was slightly different from the borehole log data that showed coarse sand and gravel at a depth of 17–32 m. According to the contractor report, a layer of alluvium in Lubok Buntar consisted of gray stiff clay (0–2 m), light brown stiff clay (2–4 m), reddish stiff clay (4–5 m), white sandy clay (5–16 m), coarse sand (16–22 m), and gravel (22–31 m). These results are consistent with a soil characteristic study conducted at the Universiti Sains Malaysia laboratory using samples collected during the drilling process. According to the analysis, the Lubok Buntar aquifer is covered by clay from the ground level to a depth of 16 m, and has 1 m of gravely sand and 6 m of sandy gravel. The remaining 8 m consist of gravely sand. The presence of a coarse sand and gravel layer show the possibility for this site to abstract clean water from the river through an RBF system. At the same time, soil properties play an important role in geochemical reaction during the RBF process.

2.3 Sampling, Sample Preparation and Analytical Testing

Sampling: Water samples from Sungai Kerian and a pumping well were collected throughout the 72 hours of a pumping test from 0900 AM on April 9, 2014 to 0900 AM on April 12, 2014. The sample was collected at 8-hour intervals, which make a total of 10 samples for each sample of river water and pumping well. All samples for the testing were collected in clean polyethylene bottles. These samples were preserved in accordance with water and wastewater standards and then stored at a temperature of less than 4 °C [14]. The laboratory apparatus used in this study were pre-washed with 5% nitric acid (HNO_3) and rinsed with deionized water prior to testing.

Sample Preparation and analysis: Parameters for water quality monitoring, such as pH, dissolved oxygen (DO), and total dissolved solid (TDS), were analyzed in situ using a YSI Professional Plus multiparameter instrument. This instrument consisted of four probes, namely, temperature/conductivity, DO, pH, and ORP, which allowed direct measurement of the parameters on site. The samples collected for trace metal analysis were filtered and acidified with HNO3 to obtain pH less than 2. Trace elements were analyzed by Varian ICP-OES model 715-ES with auto sampler. Calibration standards were prepared using a multiple-element stock calibration solution with an initial concentration of

100 mg/L (Merck, Darmstadt, Germany). The collected samples were analyzed for 21 trace elements, namely, As, Be, Ca, Cd, Co, Cr, Cu, Fe, Li, Mg, Mn, Mo, Ni, Pb, Sb, Se, Sr, Ti, Tl, V, and Zn. The solvent used in solution preparation, dilution, and analytical procedures was prepared using deionized water from Milli-Q (Millipore) water purification system. Prior to the analysis, the instruments underwent approximately 30 minutes of conditioning and optimization. The results are reported in mg/L.

3.0 RESULTS AND DISCUSSION

General physico-chemical characteristics of Sungai Kerian and pumping well water samples are listed in Table 1. pH value is an important parameter of ion exchange or adsorption process between aqueous and solid phases. The pH values for both river (5.43) and pumping well (5.15) water are acidic and beyond the permissible limit of 5.5–9.0 and 6.5–9.0 set by the Ministry of Health (MOH), Malaysia for raw and drinking water quality. Lower pH in pumping well water is likely to occur because of reductive condition with a low concentration of oxygen. This low pH is a concern because leaching of toxic elements may increase as a result of acidic condition. The low pH also causes protons to chemisorb onto the minerals in soil and become positively charged, whereas high pH causes the minerals to be negatively charged [15], thereby affecting adsorption and ion exchange in the aquifer.

Total dissolved ion in water was estimated based on electrical conductivity. The results indicate that average conductivity for river water was 56.1 µS/cm, whereas pumping well conductivity was 82.9 µS/cm. The difference in concentrations of conductivity is subjected to the variation of Cl^- and HCO_3^- ion concentration [16]. Typically, conductivity less than 1000 µS/cm is mainly attributed to HCO_3^- ions that are commonly observed in shallow-depth (<35 m) wells. Another characteristic of shallow-depth well is low concentration of DO. However, in the present study, the average concentration of DO measured in the pumping well was 3.67 mg/L, which indicated a high concentration of O_2 in the water. Thus, we can conclude that the area near the pumping well was in oxic condition. The concentration of dissolved O_2 detected was reflected in high-redox potential data recorded during the study, as shown in Table 1. High concentration of O_2 also described low organic carbon loading from recharge resources/aquifer sediment that induced a degradation process along the flow path. Low concentration of TDS was measured in water samples from both the river and pumping well. The water sample from Sungai Kerian recorded an average of 34.7 mg/L while the sample from the pumping well recorded 51.1 mg/L. This result suggested that groundwater in the pumping well was not under the influence of seawater intrusion. Alternatively, low TDS values indicated the availability of fresh groundwater aquifers or effect of dilution from recharge resources.

The data obtained from heavy-metal assessment of the water samples from Sungai Kerian and the pumping well are presented in Tables 2 and 3. According to these results, As, Ca, Fe, Mg, Mn, Ni, Sb, Sr, Tl, and Zn were detected in either river water or pumping well samples. Among the 21 elements tested, As and Fe posed the most serious concern. The concentration of As in river water was surprisingly high with values of 0.064–0.220 mg/L, which were approximately 6 to 22 times higher than the permissible limit (0.01 mg/L) set by MOH Malaysia.

Table 1 General physico-chemical characteristics of water samples

Characteristics	Sungai Kerian	Pumping Well
Temperature (°C)	27.6	27.8
pH	5.43	5.15
DO (mg/L)	5.22	3.67
Conductivity (µS/cm)	56.1	82.9
TDS (mg/L)	34.7	51.1
Redox (mV)	222.8	238.2
Salinity (ppt)	0.02	0.03

The rubber and oil palm plantations in the river area can be the major contributors to the As contaminant in river water [17]. Thus, the high concentration of As in Sungai Kerian was mainly attributed to the oil palm plantations around the area. Meanwhile, the concentration of As in the pumping well water varied between 0.177 mg/L and 0.189 mg/L. These values are considered as hazardous for human consumption. The frequency of As discovered in the pumping well water was less than that in the river water, as shown in Tables 2 and 3. As was detected in the pumping well water only twice, that is, after 40 and 72 hours of continuous pumping. However, the detection time was not synchronized with As detected in the river water. In this case, the As content in the pumping well was presumably released from aquifer sediments in anoxic condition. Several studies have noted that high concentrations of As commonly occur in reduced condition in groundwater in Southeast Asian countries [7] [8].

Furthermore, the area with holocene alluvial lowland sediments face higher risk of As reduction in the absence of oxygen. Basically, flat areas in Peninsular Malaysia are either marine or reverie in origin and consist of unconsolidated deposits of sand, gravel, clay, and peat (holocene alluvial) [18]. Similar types of soil were analyzed in this study, as mentioned in the soil profile section. Therefore, we can say that As in the pumping well was affected by naturally high As contamination in the alluvial sediments and anoxic condition of groundwater. In addition, acidic pH (<6.5) of the pumping well water, as shown in Table 1, may have enhanced the mobility of As, especially As(III) species in the aquifer. No increase in As concentration was observed when the data from the river water and pumping well were compared.

Iron (Fe) concentration in the river and pumping well water also exceeded the permissible limit set by the MOH for raw (1 mg/L) and drinking (0.3 mg/L) water. The concentration of Fe in the river water was in the 0.397–3.179 mg/L range. The minimum concentration recorded for the pumping well sample was 3.75 mg/L and the maximum value was 6.22 mg/L. These values are considered as high, thereby making the water unsuitable for direct consumption.

Based on secondary drinking water regulations set by the United States Environmental Protection Agency, Fe concentration higher than the standard is not hazardous to humans, but it induces corrosion that leads to rusty color and metallic taste of the water, as well as scaling/sedimentation inside the distribution system.

Generally, Fe has two oxidation states in the environment, which are +II and +III. Fe (II) is very soluble at low pH and can precipitate into $Fe(OH)_2$ [2]. By contrast, Fe(III) is usually in the form of insoluble oxides and oxyhydroxides. As shown in Tables 2 and 3, the concentration of dissolved Fe is higher in the river water than in the pumping well water. These results indicated that Fe oxides were dissolved during the filtration process in the aquifer. The precipitation of Fe oxides could be related to the low pH (5.15) of the pumping well water examined in this study. Additionally, low oxygen concentration in the aquifer may have converted Fe oxides to more soluble ions and dissolved them in the water, which consequently increased the concentration of this metal in the water.

In this study, other trace elements were also discovered but in low concentrations. The maximum concentrations of Mn, Ni, Sb, Tl, and Zn monitored within 72 hours of pumping test were 0.113, 0.026, 0.057, 0.023, and 0.293 mg/L, respectively. Mn is another mineral that was easily affected by reduction and oxidation conditions in the aquifer. It changed into oxyhydroxide (MnOOH), $MnCO_3$, MnO_2, and Mn_3O_4 form in an oxygen-rich environment while it occurred in the form of dissolved ions in the reducing environment of the aquifer [3]. However, the Mn concentration observed in this study was lower than that of Mn reported in other Southeast Asian countries such as Laos and Cambodia [7]; [8]. Other metals (Ni, Sb, Sr, Tl, and Zn) were typically desorbed from contaminated sediment during the filtration process and were carried by opposite charge ions in the infiltrate. Consequently, these elements were detected in the pumping well. The results showed that the aquifer sediments in the study area were not contaminated by toxic metals such as Cd, Cu, and Pb.

Despite our findings, there is no guarantee that the area is not exposed to anthropogenic pollution caused by agricultural or urban development activities. Several recent studies have reported that anthropogenic factors such as mining, urbanization, and agriculture cause contamination of river water and soil [17];[19]. Therefore, precautions are necessary to prevent the infiltration of these metals into recharge resources and pumping wells.

Table 2 Trace metals detected in Sungai Kerian samples

Time	Cond	pH	DO	TDS	As	Ca	Fe	Mg	Mn	Ni	Sb	Sr	Tl	Zn
0	66.2	5.55	4.5	41.0	0.119	5.931	3.179	1.208	0.004	nd	0.032	nd	nd	0.048
8	62.5	5.50	5.3	38.3	nd	5.269	1.090	1.141	nd	nd	nd	nd	0.061	0.100
16	58.5	5.58	6.0	35.7	0.219	3.569	1.444	0.853	nd	nd	0.028	nd	nd	0.069
24	61.2	5.52	4.6	37.9	0.101	>8.000	0.826	0.945	nd	nd	nd	0.081	0.018	0.042
32	54.1	5.56	5.3	33.8	nd	4.533	0.397	0.923	nd	nd	nd	nd	nd	0.021
40	50.4	5.32	5.3	31.2	nd	3.127	1.066	0.694	nd	nd	nd	nd	nd	0.036
48	50.2	5.43	5.2	31.2	nd	3.624	1.187	0.736	nd	nd	nd	nd	nd	0.031
56	51.3	5.21	5.2	31.9	0.064	2.762	1.669	0.736	nd	nd	0.055	nd	nd	0.038
64	54.3	5.48	5.4	33.8	0.220	>8.000	1.569	0.858	nd	nd	0.025	0.028	nd	0.123
72	51.9	5.14	5.4	32.5	nd	3.944	0.478	0.975	nd	nd	0.055	nd	nd	0.035
MOH[a]	na	5.5-9.0	na	1500	0.010	na	1.000	150.000	0.200	na	na	na	na	3.000

Table 3 Trace metals detected in pumping well samples

Time	Cond	pH	DO	TDS	As	Ca	Fe	Mg	Mn	Ni	Sb	Sr	Tl	Zn
0	101.5	5.37	3.9	62.4	nd	4.456	3.749	0.927	0.023	nd	0.052	nd	0.023	0.293
8	91.2	5.2	3.9	56.5	nd	3.564	6.484	0.821	nd	nd	0.028	nd	nd	0.090
16	84.9	5.31	3.7	52.7	nd	4.863	3.957	0.898	nd	nd	0.023	nd	nd	0.073
24	84.2	5.01	3.8	52.0	nd	37.110	4.066	0.969	0.021	nd	nd	nd	nd	0.078
32	81.7	5.17	3.7	50.2	nd	4.232	4.590	0.938	nd	nd	nd	nd	nd	0.051
40	79.5	5.03	3.1	49.0	0.189	3.184	5.858	0.778	nd	0.010	0.039	nd	nd	0.044
48	78.4	5.17	3.4	48.1	nd	4.580	5.459	0.978	nd	nd	nd	nd	nd	0.075
56	81.2	5.21	3.6	50.0	nd	3.741	4.674	0.857	nd	nd	0.057	nd	nd	0.035
64	73.4	4.95	3.2	45.2	nd	4.283	4.532	0.929	0.113	0.026	0.050	nd	nd	0.093
72	72.6	5.06	4.4	44.8	0.177	3.262	6.217	0.817	nd	nd	nd	nd	nd	0.128
MOH[b]	na	6.5-9.0	na	1000	0.010	na	0.300	150.000	0.100	0.020	na	na	na	3.000

Time was set in hours. Cond (Conductivity) was measured in µS/cm meanwhile DO, TDS and traces metals are expressed in mg/L unit. nd stand for not detected and na indicated not available.
MOH (Ministry of Health), Malaysia guidelines for [a]raw water and [b]for drinking water.

Continuous consumption of water containing metal that exceeds the permissible limit set by authorities has negative effects on human health. Table 4 lists the possible toxicity implications of the metals observed in this study. Arsenic is known to be hazardous to humans even in small amounts. Additionally, As(III) is more acutely toxic than As(V) [5]. As mentioned, high Fe concentration does not have adverse effects on humans except on hemochromatosis patients; accumulation of Fe in the body from continuous consumption is poisonous to such patients. Mn is another mineral needed by the human body within certain limits, but large amounts of it may cause neurological disorders. Sb also has its own side effects, as shown in Table 4.

Table 4 Possible health risk when the concentration of listed elements exceed the maximum permissible limit set by authorities

Element	Potential health effects from long term exposure above the maximum concentration level	References
As	Skin damage, circulatory systems problems, neurological disorder and may have increased risk of getting cancer	[19-20]
Fe	Fe intoxication may occur among a number of people with genetic and metabolic diseases, such as hemochromatosis	[21]
Mn	Mn poisoning may lead to hallucinations, forgetfulness, nerve damage, respiratory and reproductive system failure.	[21-22]
Sb	Increase in blood cholesterol; decrease in blood sugar	[19]

4.0 CONCLUSION

The quality of water abstracted from the RBF system depends on the alluvium and groundwater characteristics of the site. Therefore, investigating soil and water characteristics has an important role in determining the suitability of the selected area for RBF system implementation. The presence of coarse sand and gravel layer in this area indicate the potential of water abstraction using the RBF system. However, higher concentrations of As and Fe were detected in the pumping well water than in the river water. The average concentrations of As and Fe in the pumping well water were 0.183 mg/L and 4.959 mg/L, while those for the river water were 0.145 mg/L and 1.291 mg/L, respectively. These values are higher than the standard limits of 0.01 mg/L and 0.3 mg/L set for drinking water by the MOH Malaysia. Therefore, the water obtained from the study area is not suitable for human consumption without further treatment. Low pH (5.15) caused by reductive condition in the aquifer is a possible factor that enhanced the leaching of toxic elements from aquifer sediments into the pumping well water. Other trace elements, such as Mn, Ni, Sb, Tl, and Zn, were detected in low concentrations. The results of this study suggest that heavy metal concentration in pumping well water is influenced by geochemical or hydrochemical processes along the water flow path. The low quality of water in terms of heavy metal content indicated that the study area is less suitable for clean water abstraction using the RBF system. However, further treatment can be proposed to solve this problem.

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