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A Water Quality Appraisal of Some Existing and Potential Riverbank Filtration Sites in India

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Abstract: There is a nationwide need among policy and decision makers and drinking water supply engineers in India to obtain an initial assessment of water quality parameters for the selection and subsequent development of new riverbank filtration (RBF) sites. Consequently, a snapshot screening of organic and inorganic water quality parameters, including major ions, inorganic trace elements, dissolved organic carbon (DOC), and 49 mainly polar organic micropollutants (OMPs) was conducted at 21 different locations across India during the monsoon in June–July 2013 and the dry non-monsoon period in May–June 2014. At most existing RBF sites in Uttarakhand, Jammu, Jharkhand, Andhra Pradesh, and Bihar, surface and RBF water quality was generally good with respect to most inorganic parameters and organic parameters when compared to Indian and World Health Organization drinking water standards. Although the surface water quality of the Yamuna River in and downstream of Delhi was poor, removals of DOC and OMPs of 50% and 13%–99%, respectively, were observed by RBF, thereby rendering it a vital pre-treatment step for drinking water production. The data provided a forecast of the water quality for subsequent investigations, expected environmental and human health risks, and the planning of new RBF systems in India.

Keywords: bank filtration; drinking water treatment; inorganic chemicals; organic micropollutants; Ganga; Yamuna; Damodar

1. Introduction

The substantial discharge of untreated to partially treated industrial and domestic wastewater into surface water (SW) in India, accompanied by the very high turbidity during monsoon, frequently interrupt the production of drinking water by conventional plants. These plants directly abstract surface water and treat it by flocculation, sedimentation, rapid sand filtration, and disinfection. By using wells installed in the banks of flowing rivers, riverbank filtration (RBF) combines the advantage of easy access to large volumes of SW with the benefit of natural filtration during aquifer passage. Field investigations conducted mainly on urban drinking water production systems at various locations across India have confirmed that there is a large potential to use RBF as an alternative or a supplement to directly abstracted SW for drinking water production [1]. The main advantage of using RBF is that it provides an ecosystem service by effectively removing pathogens and turbidity, especially during the monsoon [2]. A significant removal of total coliforms, *Escherichia coli* (*E. coli*), turbidity, adenoviruses, and noroviruses by up to 90%–99.99% (≥4 Log_{10} removal) is attained at RBF sites in northern India [2–7]. This is due to the superior surface water quality in Uttarakhand in contrast to the extremely polluted (with domestic sewage and industrial wastewater) stretch of the Yamuna river in the central part of Delhi (downstream of Uttarakhand). Other key water quality benefits of RBF are the removal of dissolved organic carbon (DOC) and organic contaminants, which are often responsible for the color of water. High concentrations of DOC and organic contaminants require high doses of chlorine and thereby create a greater risk for formation of carcinogenic disinfection byproducts, as reported for an RBF site in Mathura by the Yamuna, 150 km downstream of Delhi [8,9]. Furthermore, the use of RBF for rural water supply in the southwest Indian state of Karnataka has demonstrated a removal of total coliforms and *E. coli* of 1–3 Log_{10} and 2–4 Log_{10}, respectively [10,11].

However, RBF does not present an absolute barrier to other substances of concern (e.g., ammonium), and some inorganic elements (e.g., arsenic) may even be mobilized, as has been observed in central Delhi. There, infiltrating sewage-contaminated river water is the primary source of the ammonium contamination in the aquifer (35 mg/L), leading to reducing conditions that probably trigger the release of geogenic arsenic (0.146 mg/L) [12]. In light of the growing concern of emerging pollutants in the environment, recent studies on the occurrence of organic micropollutants (OMPs) in SW and their removal by RBF in Delhi [13–16] and Mathura [15,16], and potentially by RBF in Agra [16], have confirmed that the compounds with the highest relevance at these sites are diuron (37%–91% removal by RBF with respect to source river water concentration), 1H-benzotriazole (77%–98%), acesulfame, theophylline (56%–99%), diclofenac (37%–80%), gabapentin (91%–100%), and paracetamol (46%–50%) [16]. Overall, most studies have concluded that RBF is advantageous as a pretreatment step that improves water quality compared to directly abstracted and conventionally treated SW.

The water quality of only a few RBF sites (e.g., Uttarakhand, Delhi, Mathura, Agra, and rural Karnataka) have been monitored for periods long enough to include seasonal effects (≥1 year). Other than these sites, very limited holistic and systematic water quality information, especially for concentrations of inorganic and organic substances (including OMPs), is available for existing and potential RBF sites in other locations in India. Field visits to some conventional drinking water treatment plants, which directly abstract surface water, have shown that the main quality parameters that are usually and routinely determined are physical field parameters, total hardness and total alkalinity, major anions, and often only the presence or absence of bacteriological coliform indicators. Moreover, bacteriological indicators are only occasionally quantified as counts/100 mL of sample. These limited number of parameters do not cover the entire list of parameters in the Indian drinking water standards [17]. Moreover, despite the advantages of being a sustainable natural process, an element of integrated water resources management, and a component of managed aquifer recharge [18,19], RBF is intentionally used for pretreatment only at some places in India, resulting in a low portion (<0.1%) of drinking water produced therefrom [20].

In order to effectively implement RBF by starting with a suitable site for an exploratory well and to subsequently make an informed decision to expand it into a full-scale RBF system, knowledge of site-specific geohydraulic and water quality parameters is essential. Therefore, the objective of this article was to obtain an initial assessment of water quality parameters for the selection and subsequent development of new riverbank filtration sites in India. Post-treatment options have been discussed for sites where inorganic parameters exceed the Indian Standard or WHO guideline value for drinking water [17,21]. Mostly urban, but also some rural sites located in countrywide diverse hydroclimatic conditions, were investigated. The design parameters of these RBF systems and a summary of their hydrogeological settings were presented in a previous publication [22] and are thus not repeated here. Present post-treatment conducted and future post-treatment requirements at these sites supplement this information.

2. Materials and Methods

2.1. General Sampling Strategy

A random snapshot screening of water quality parameters (as specified subsequently), including instant physical field parameters, major ions, inorganic elements, DOC, and 49 mainly polar OMPs (those of environmental relevance in Europe) was conducted at a total of 21 different locations across India during the monsoon in June–July 2013 and the dry non-monsoon period in May–June 2014 (Figure 1). In 2013, 49 samples from 17 locations were collected (Figure 1, green circles/squares). In 2014, 75 samples from 11 locations were taken (Figure 1, red circles/squares). Out of the 21 locations sampled, 7 locations were sampled both during wet (monsoon, 2013) and dry (non-monsoon, 2014) seasons (Figure 1, orange circles).

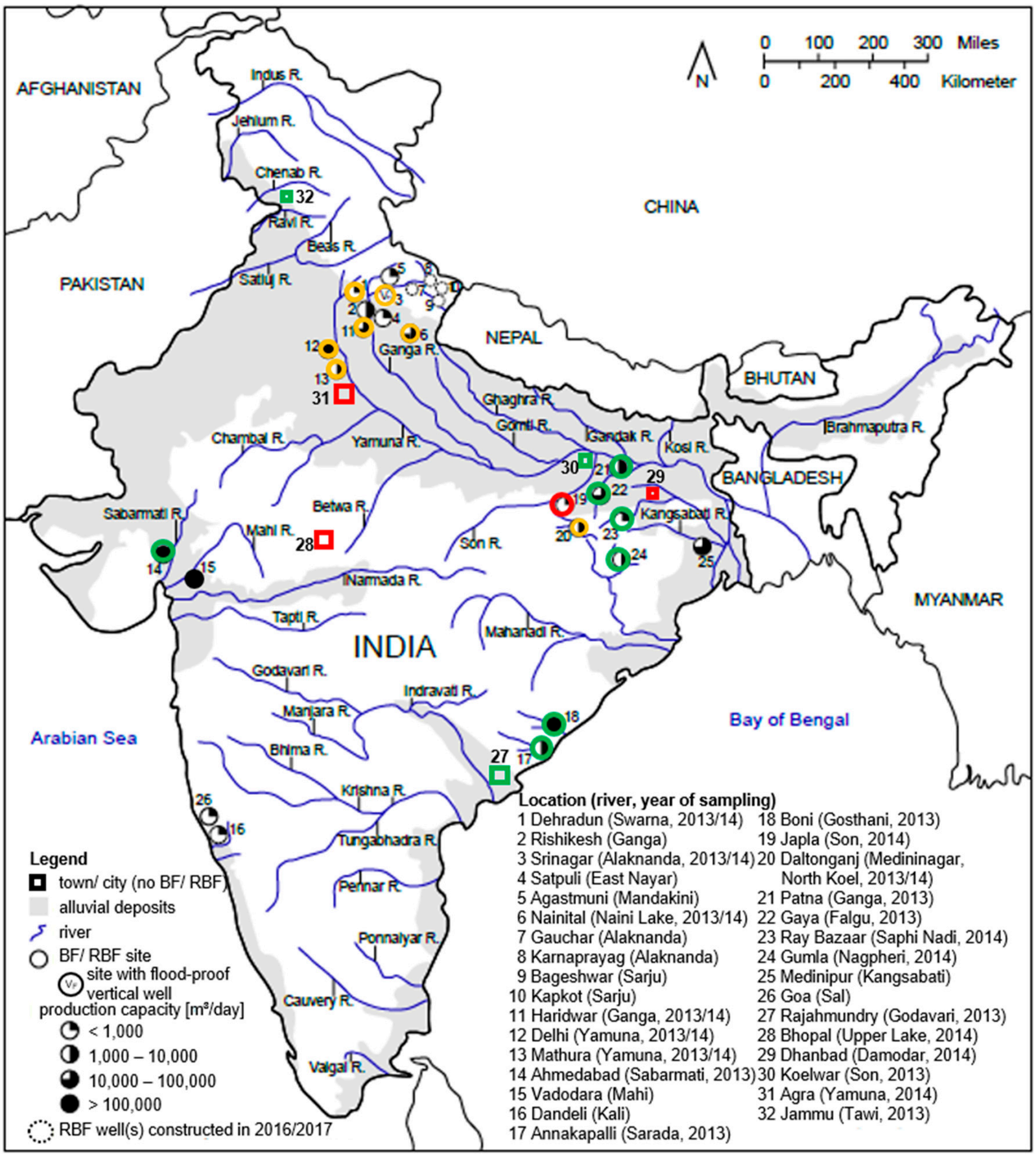

Figure 1. Locations having riverbank filtration (RBF) wells in India and those sampled in 2013 (monsoon, green circles), 2014 (non-monsoon, red circles), and both in 2013 and 2014 (orange circles), including six locations where it was not conclusively established that the existing wells abstract bank filtrate (squares) (modified from [22]).

A "random snapshot screening" means that in each case a single (random) sample was taken, but not a composite sample over a certain time period, from different sites or water depths, which were screened for a set of different parameters and different single compounds (targeted screening for higher numbers of OMPs). The sampling locations were selected using a four-stage methodology derived for the investigation of potential and existing RBF sites, for which no or only limited data exist in the public domain [20]. Accordingly, the sampling locations were selected within the first stage "initial site assessment" and with the support of the National Institute of Hydrology in Roorkee and its regional centers across India (see "Acknowledgements"). This included site visits and a visual assessment, interaction with the local water supply and research organizations, the subsequent documentation of verbal and onsite archived information, and finally the random snapshot water quality sampling. Sampling from rural areas was conducted to take into account potential non-point pollution of SW [23], especially as a result of monsoon runoff.

In earlier field investigations [20], no health-relevant organic trace compounds were detected using non-target screening analysis with gas chromatography–mass spectrometry (GC/MS) of Ganga River water in Haridwar in 2005. Consequently, a mobile solid-phase extraction (SPE) unit was developed to enrich the sample onsite for subsequent analyses in the laboratory. The mobile SPE unit was developed in order to mitigate the effects of long transport times of the samples to the laboratory, which usually occur between sampling and subsequent laboratory enrichment and analysis in India. Furthermore, enrichment of the sample is very important because of the low concentrations of OMPs found in the environment [24]. Thus, while volumes of up to 500 mL per sample suffice for the enrichment of OMPs from moderately to highly polluted waters, nearly 1 L is required per sample for waters expected to have a low pollution. Additionally, the (air) transport of such large-volume samples to distant laboratories is extremely limited. Depending on the group of parameters sampled for (inorganic chemical parameters, DOC, and OMPs), around 130 samples in total were collected from SW bodies, RBF wells, and in some case ambient groundwater (GW) from sites in the states of Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, Andhra Pradesh, Madhya Pradesh, Gujarat, and the cities of Jammu and Delhi during both sampling campaigns in 2013 and 2014.

2.2. Sampling and Analysis of Water for Inorganic Chemical Parameters and DOC

The temperature, pH, dissolved oxygen, and electrical conductivity (EC) of the water samples were determined onsite using a WTW multi 3430 instrument (Wissenschaftlich-Technische Werkstätten GmbH (WTW), Weilheim, Germany). Two 100-mL water samples were collected from each source of water at the sampling location, for DOC and for ions (including inorganic trace elements). All samples were filtered with a 0.45-µm Whatman syringe filter. Subsequently, the samples for the determination of DOC were conserved with nitric acid. The analyses for anions and trace metals were conducted using inductively coupled plasma optical emission spectrometry (ICP-OES, Spektrometer Optima 4300 DV, PerkinElmer) in a radial viewing configuration in the Division of General and Inorganic Chemistry at the Faculty of Agriculture, Environment & Chemistry in the University of Applied Sciences Dresden. DOC analyses were conducted by the Institute for Water Chemistry (IWC) at the TU Dresden.

A spectrum of 18 inorganic (trace) elements, including trace metals and radionuclides, were determined, which comprised iron (Fe), manganese (Mn), strontium (Sr), barium (Ba), zinc (Zn), silicon (Si), chromium (Cr), cobalt (Co), nickel (Ni), copper (Cu), aluminum (Al), selenium (Se), lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), silver (Ag), and nickel (Ni). The objective was to determine if the concentrations of these elements exceeded the guideline value [17,21] or if the concentrations were unusually high, thereby indicating a possible contamination.

2.3. Water Sampling and Analyses of Organic Micropollutants

The enrichment of OMPs was conducted onsite by the mobile SPE unit from 0.5 L–1 L filtered water samples with an enrichment factor of 1000 [25]. One-hundred and twenty-four water samples were collected and enriched in total (in 2013 and 2014). Cartridges (OASIS, Waters, Milford, MA, USA) were used for the enrichment. Subsequently, a target screening analysis using RP-HPLC (Agilent, 1100, Santa Clara, CA, USA) and ESI-MS/MS (QTRAP®, Q3200, Sciex, Framingham, MA, USA) was conducted for 49 polar organic compounds (pharmaceuticals, pesticides and transformation products, antibiotics, medical contrast media, corrosion inhibitors, and stimulants such as caffeine that are not micropollutants). The analyses for the OMPs were conducted by the IWC [26].

3. Results and Discussion

3.1. Inorganic Chemical Parameters

The concentrations of major ions and 18 other inorganic elements in surface water analyzed at most RBF locations in Uttarakhand, Jharkhand, Andhra Pradesh, and Bihar did not exceed the Indian drinking water guideline values [17] and thus the surface water quality is generally suitable for RBF in terms of these parameters (Table 1). However, the extremely high salinity of Yamuna river (R.) water (EC 1665–1700 µS/cm) and adjacent GW (EC 1455–3400 µS/cm) between Delhi and Agra gives the drinking water derived from the waterworks a brackish taste.

The concentrations of mainly Fe, Mn, and As exceeded the Indian drinking water guideline requirement (acceptable limit, [17]) only in some source waters and occasionally in drinking water, and in some cases the permissible limit in the absence of an alternate source (Table 2). Mn is naturally occurring in many surface water and groundwater sources, particularly in anaerobic or low oxidation conditions [21]. This explains its comparatively high concentration, especially in the Yamuna R. in Delhi, because of the very high input of wastewater (industrial and domestic) and correspondingly very low dissolved oxygen concentrations of 0.1–0.3 mg/L in river and groundwater (hand pumps). The Indian standard for drinking water [17] requires an acceptable limit of 0.1 mg/L and a permissible limit in the absence of an alternate source of 0.3 mg/L for Mn. Mn can be removed by chlorination followed by filtration [21], as is practiced in Jharkhand, where the bank filtrate subsequently undergoes post-treatment comprising aeration, flocculation, rapid sand filtration, and disinfection. Similarly, the water from a radial collector well (RCW) supplying raw water for drinking to the township of the oil refinery in Mathura also undergoes similar conventional post-treatment [8,9].

Arsenic exceeded the required acceptable limit of 10 µg/L for drinking water [17,21] in groundwater (hand pumps) near the Yamuna riverbank in central Delhi and Mathura (Table 2). The As concentrations of 44–66 µg/L found in the water from hand pumps in central Delhi (Table 2) were consistent in magnitude to concentrations of 27–56 µg/L that were determined by Lorenzen et al. [27] for shallow depths (6–13 m below ground level) in the same area.

In the RBF RCW constructed within the riverbed in Mathura, the acceptable limit was exceeded only during the non-monsoon 2014 (32 µg/L), but not in monsoon 2013. However, the concentration was a <50 µg/L limit in the absence of an alternate source [17]. This indicates a decrease in concentration by mixing with a greater portion of bank filtrate abstracted on account of a higher hydraulic head in monsoon. This is a positive effect of RBF, as was also observed for the Palla RBF site in Delhi where As was found to be <10 µg/L due to a high portion of bank filtrate abstracted from the high-capacity vertical well field [27]. In contrast, ambient groundwater in different areas in Delhi was found to have high As concentrations (range 17–100 µg/L, mean 40 µg/L), as determined by Lalwani et al. [28]. For all other sites, the arsenic concentration was a <10 µg/L detectable limit.

Table 1. Field parameters and major ions of source water, RBF well water, and drinking water at various locations sampled in 2013 and 2014 (n = 1 for each source at each location).

Location (State) Season	Source of Water Sample	Name of SW Body	T_W	pH	EC	DO	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	NO_3^-	SO_4^{2-}
		Treatment	°C	-	µS/cm	mg/L							
Dehradun (UK) non-mon. 2014	SW	Song & Asan	25.0	7.8	n.d.	n.d.	92	38	3.0	1.4	3.4	4.9	301
	DW	SWA	26.0	7.7	n.d.	n.d.	96	40	3.4	1.5	5.2	2.7	343
Jammu (JK) mon. 2013	SW	Tawi	27.0	8.5	539	n.d.	26	5.2	3.9	1.9	<5	<1	<10
	Potentially RBF from Tawi		21.9	8.3	591	4.0	25	6.7	2.7	0.8	n.d.	<5	<10
Mathura (UP) non-mon. 2014	SW	Yamuna	30.8	7.9	**1700**	6.3	76	34	199	21	280	14	97
	RBF	Yamuna	34.7	7.3	**1455**	0.1	69	29	161	17	215	4.4	69
	DW (RBF, small RO)		38.2	**6.4**	150	1.1	2	0.6	17	1.7	15	<1	<5
Agra (UP) non-mon. 2014	SW	Yamuna	29.6	**8.8**	**1665**	18.5	77	35	206	21	290	22	92
	DW	SWA	30	7.5	**1645**	0.1	73	33	199	20	279	13	97
	GW (private well)		28.5	6.8	**3400**	3.3	121	**116**	372	5.1	661	**74**	353
Bhopal (MP) non-mon. 2014	SW	Bhopal L.	29.6	8.1	337	7.1	19	7.6	11	2.8	0.2	n.d.	<5
	DW	SWA	30.4	8.1	257	7.2	22	8.2	12	2.5	12	<1	7.2
Daltonganj (JH) non-mon. 2014	SW	N. Koel	27.7	7.6	251	5.0	22	6.7	17	2.2	5.3	<1	6.8
	RBF	N. Koel	31.2	7.6	272	5.2	22	5.9	15	2.0	5.9	<1	8.0
	DW	RBF-CT	30.3	7.9	255	6.9	23	6.9	18	2.5	7.1	<1	9.1
Japla (JH) non-mon. 2014	SW	Son	32.8	**8.6**	172	8.1	16	5.1	9.0	2.1	5.9	<1	11
	RBF	Son	32.0	8.5	177	7.5	17	5.2	9.7	7.2	9.5	<1	13
	DW	RBF-CT	30.6	8.3	193	7.0	17	4.9	9.3	2.1	5.3	<1	10
Ray Bazaar (JH) non-mon. 2014	SW	Saphi	37.6	**8.6**	253	8.8	23	6.9	17	2.4	8.8	<1	14
	RBF	Saphi	26.8	7.2	313	4.4	29	8.1	19	3.4	11	1.2	14
	DW	RBF-CT	29.2	7.9	325	7.1	30	7.8	19	3.8	12	1.1	17
Gumla (JH) non-mon. 2014	SW	Nagpheri	31.0	8.2	131	8.1	12	3.0	9.5	1.8	5.5	<1	<5
	RBF	Nagpheri	30.5	7.5	135	5.6	12	3.0	9.6	2.0	5.5	<1	<5
	DW	RBF-CT	30.3	7.3	141	6.9	14	2.7	8.5	2.3	5.2	1.3	8.4

Table 1. *Cont.*

Location (State) Season	Source of Water Sample	Name of SW Body	T_W	pH	EC	DO	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	NO_3^-	SO_4^{2-}
		Treatment	°C	-	µS/cm	mg/L							
Dhanbad/ Jamadoba (JH) non-mon. 2014	SW	Damodar	34.6	**8.9**	347	11.8	27	12	20	6.3	15	2.1	60
	DW	SWA	34.6	8.1	371	7.9	26	13	20	6.3	15	3.0	61
Gaya (B) mon. 2013	SW	Falgu	36.0	**9.2**	185	8.1	18	5.3	7.8	2.9	6.2	<1	<10
	RBF	Falgu	32.0	7.9	155	n.d.	62	17	11	1.9	<5	<1	<10
Anakapalli (AP) mon. 2013	SW	Sarada	31.5	**9.0**	398	12.5	20	18	35	4.5	35	<1	17
	RBF	Sarada	30.7	8.1	540	7.1	25	17	29	5.6	33	<1	17
Ahmedabad (GJ) mon. 2013	SW	Sabarmati	30.1	**9.2**	558	9.6	20	8	6.5	1	6.1	<1	<10
	DW	CT- RBF/DIS	29.8	**9.1**	611	12.7	21	7.6	6.2	1	6.4	< 1	<10

Values highlighted in bold font: Values exceeding the permissible limit in the absence of an alternate source [17] or exceptionally high values for electrical conductivity (EC) resulting in a noticeable saline taste. Abbreviations: RBF: Bank filtration well water; DW: Drinking water (after post-treatment/disinfection); GW: Groundwater; SW: Surface water; SWA: Surface water abstraction followed by conventional treatment; RBF-CT: Bank filtration followed by conventional treatment; DIS: Only disinfection by chlorination as post-treatment; RO: Reverse osmosis; states: UP: Uttar Pradesh; UK: Uttarakhand; JH: Jharkhand; B: Bihar; AP: Andhra Pradesh; GJ: Gujarat; seasons: non-mon. 2014: Non-monsoon (May–June 2014); mon. 2013: Monsoon (June–July 2013); n.d.: Not determined.

Table 2. Summary of inorganic parameters exceeding acceptable limits [17] determined in 2013 and 2014.

Element	Source Water	Dissolved Concentration (mg/L) *	Location and Description
Fe	GW	0.7–11	Delhi (central), handpumps on Yamuna River east bank
	RBF	2	Mathura (only in monsoon 2013)
	SW	0.3–1.4	Agra, Keetham Lake water intake for Mathura and Yamuna River
Mn	SW, RBF, GW	0.2–0.6	Delhi (central), Yamuna River, handpumps on river east bank and 5 RBF RCW
	RBF	0.6–1	Mathura, in monsoon 2013 and non-monsoon 2014
	GW	0.3	Mathura, hand pump near RBF well, in monsoon 2013
	GW	1.3	Gaya, mixed sample from various vertical wells within Falgu riverbed downstream of city possibly also receiving wastewater, in monsoon 2013
	RBF and DW	0.4–0.9	Ray Bazaar, RBF RCW (0.9 mg/L) within riverbed and subsequently conventionally treated DW (0.4 mg/L), in non-monsoon 2014
	SW	0.2	Chas (Bokaro–Dhanbad area, Jharkhand), Garga River at confluence with Damodar River, receiving substantial amount of wastewater from Bokaro Steel City
	RBF	0.2–0.3	Nainital, vertical wells numbers 2 and 4
As	SW	30 μg/L	Koelwar, Son River water near sand mining site within riverbed
	GW	44–66 μg/L	Delhi, hand pumps on Yamuna riverbank
	GW	20 μg/L	Mathura, hand pumps on Yamuna riverbank near RBF well, in monsoon 2013
	RBF	32 μg/L	Mathura, RBF RCW within Yamuna riverbed, in non-monsoon 2014 only
Al	SW	30–40 μg/L	Coastal Andhra Pradesh, Godavari, Sarada and Thatpudi rivers
	DW	278 μg/L	Bhopal, conventionally treated drinking water from PHED DW plant

* Except for As and Al; RBF: Bank filtration well water; DW: Drinking water; GW: Groundwater; SW: Surface water; RBF RCW: Riverbank filtration radial collector well; PHED: Public Health and Engineering Department.

Aluminum was found above the detectable limit of 10 µg/L mainly in surface waters, and substantially exceeded (up to 278 µg/L) the acceptable required drinking water guideline value of 30 µg/L [17] only in one drinking water sample from the water treatment plant in Bhopal that conventionally treats surface water (from Bhopal Upper Lake) using aluminum-based coagulants (Table 2). While the Indian Drinking Water Standard permissible limit [17] in the absence of an alternate source is 200 µg/L, the WHO guideline [21] advocates a practicable concentration of ≤100 µg/L for large water treatment facilities using aluminum-based coagulation processes. Otherwise, Al concentrations ≥30 µg/L were mainly found in the sampled rivers of Andhra Pradesh in monsoon 2013 (Table 2). The detectable naturally occurring Al in surface water in Andhra Pradesh was attributed to the surface runoff from the substantial bauxite deposits found in the Eastern Ghats (hills) through which these rivers flow. Al concentrations were below the detectable limit of 10 µg/L in most other samples from RBF and groundwater production wells and in drinking water.

At all sites sampled in Figure 1, barium (0.04–0.49 mg/L), cadmium (<1 µg/L), chromium (<2 µg/L), copper (<15 µg/L), nickel (<4 µg/L), and selenium (<40 µg/L) were below the WHO guideline limits [21] of 1.3 mg/L, 3 µg/L, 50 µg/L (provisional), 2 mg/L, 70 µg/L, and 40 µg/L (provisional), respectively, in all samples. In all samples, cobalt was <2 µg/L (detection limit), and zinc ranged from <4 µg/L up to 0.71 mg/L. As there are no guideline limits for cobalt and zinc in drinking water, these two parameters, as well as Ba, Cd, Cr, Cu, Ni, and Se, are not of concern to human health at the sampled sites.

3.2. Dissolved Organic Carbon

Of all the surface waters sampled, it was found that the stretch of the Yamuna River starting in central Delhi (ITO Bridge) up to ~200 km downstream in Agra, had the highest DOC concentration of around 12 mg/L (Figure 2). In Figure 2, it can be observed that the DOC concentrations in the Yamuna River at Delhi and Mathura were significantly lower during the monsoon in 2013 compared to the non-monsoon in 2014. The annual monsoon thus had a positive effect on highly polluted surface waters (e.g., in Delhi and Mathura) in terms of lowering the DOC concentration by dilution. On the other hand, for surface waters already having a relatively low ambient or background DOC concentration, such as that observed in Uttarakhand (Haridwar and Nainital in Figure 2) and Jharkhand (Daltonganj in Figure 2 and Dhanbad in Figure 3), it may even increase during monsoon, probably due to surface runoff.

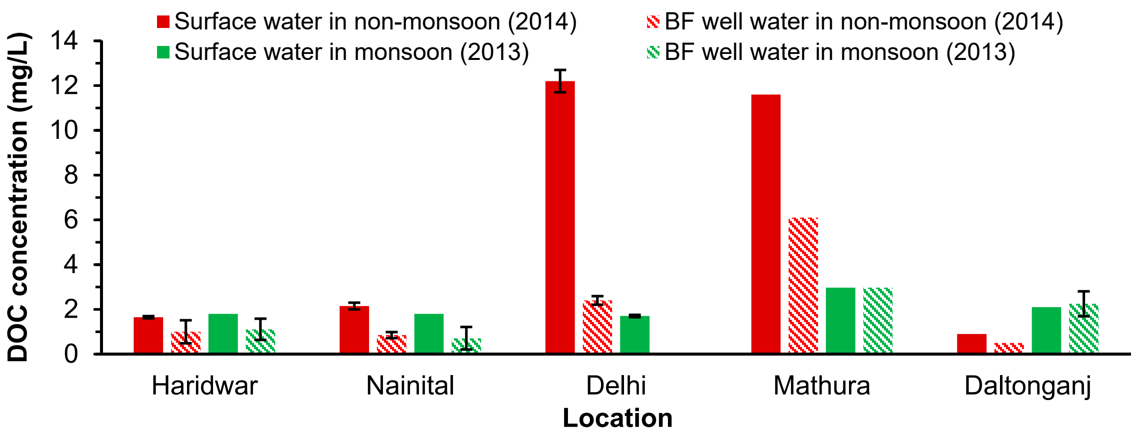

Figure 2. Median dissolved organic carbon (DOC) concentrations in surface water and bank filtration wells at selected sites, except for the RBF wells in Delhi, where no samples were collected in monsoon (2013). Error bars indicate the standard deviation for numbers of samples (n_m: Monsoon; n_{nm}: Non-monsoon) ≥ 2. Haridwar: Ganga, n_m = 1, n_{nm} = 2; RBF, n_m = 9, n_{nm} = 13; Nainital: Naini Lake, n_m = 1, n_{nm} = 2; BF, n_m = 3, n_{nm} = 6; Delhi: Yamuna, n_m = 2, n_{nm} = 2; RBF, n_{nm} = 5; Mathura: Yamuna, n_m = 1, n_{nm} = 1; RBF, n_m = 1, n_{nm} = 1; Daltonganj: North Koel, n_m = 1, n_{nm} = 1; RBF, n_m = 2, n_{nm} = 1.

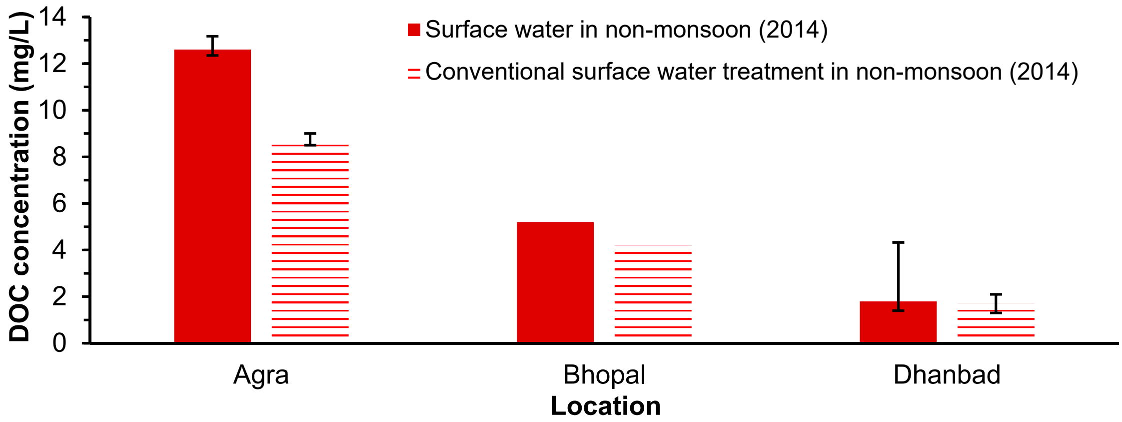

Figure 3. Median DOC concentrations in surface water and conventionally treated drinking water derived from direct surface water abstraction at selected sites in non-monsoon 2014. Error bars indicate the standard deviation for number of samples (n) $\geq$ 2. Agra: Yamuna, n = 3, n_{CT} = 2; Bhopal: Upper Lake, n = 1, n_{CT} = 1; Dhanbad: Damodar, n = 3, n_{CT} = 2.

In Figure 2, the DOC concentration was observed to be slightly lower in the bank filtration wells in Haridwar and Nainital, which have a caisson and vertical well design, respectively, when compared to surface water concentrations. At these locations, the travel time of the bank filtrate was longer (weeks to months) compared to Daltonganj (Figure 2). In Daltonganj, the travel time was only in the range of minutes to hours on account of the radial collector wells being installed within the riverbed at a shallow depth (1–6 m, [22]), and consequently no significant removal of DOC was observed. As the RBF well in Mathura also has a radial collector design, albeit with longer travel time (1.5–3 days, [8]) compared to Daltonganj, the DOC concentration in well water was similar to the river water during monsoon. Nevertheless, the advantage of RBF in Mathura is visible in Figure 2 during non-monsoon conditions, when nearly 50% DOC removal occurred.

The DOC concentration in directly abstracted surface water and drinking water derived thereof by conventional treatment in non-monsoon (2014) was compared for the cities of Agra, Bhopal, and Dhanbad (Figure 3). It was observed that at least for highly polluted surface waters with a high DOC concentration (e.g., Yamuna River in Agra), the removal of DOC by conventional treatment systems (which do not use activated carbon) was lower than that observed for RBF systems with similar source water quality, such as by the RBF wells in Delhi and Mathura upstream of Agra (in Figure 2).

The DOC concentration in surface water at the RBF sites of Haridwar (Ganga River and Upper Ganga Canal), Srinagar (Alaknanda River), and Nainital (Nainital Lake) in Uttarakhand, and in the Asan River that flows past the industrial area in Dehradun city, was relatively low at 1.1–2.4 mg/L, with only a minor difference between the non-monsoon and monsoon seasons. In the corresponding RBF wells, the DOC concentrations were 0.4–2.3 mg/L and generally lower than the respective surface water, except for one RBF well in Haridwar and Srinagar that had slightly higher DOC concentrations (compared to their surface water sources) of 2.5 and 2.7 mg/L, respectively. The higher DOC concentration in the RBF well in Haridwar could be attributed to human activities, such as washing and bathing, that take place at the well.

At the RBF sites of Daltonganj (North Koel R.), Gumla (Nagpheri R.), Ray Bazaar (Saphi Nadi R.), and Japla (Son R.) in Jharkhand, the surface water and water from the RBF wells contained DOC in the range of 0.9–3 mg/L and mostly 0.5–1.7 mg/L, respectively, with higher DOC observed in monsoon (Figure 2, location Daltonganj). The water from two wells showed exceptionally higher DOC of 2.7 and 3 mg/L. However, while these RBF sites are generally affected by low surface water pollution on account of them being located mostly in the upstream areas of the towns, and the impact of anthropogenic activities (agricultural and industrial activities) is low, the observed DOC removal was generally low due to the very short travel time of the bank filtrate to the wells [22].

In the river water sampled in coastal Andhra Pradesh (Figure 1, locations 17, 18, and 27), DOC in monsoon (June 2013) was 3–4.6 mg/L. In the RBF well water in Annakapalli (Figure 1, location 17), DOC was 3 mg/L. The RBF well in Annakapalli is similar in design to that in Daltonganj (Figure 1, location 20, [22]), and thus was expected to have short travel times of bank filtrate in the range of hours. Therefore, a large removal of DOC was not expected.

In monsoon 2013 at other locations in India, the DOC in surface water in Gaya (Falgu R.), Patna (Ganga R.), Koelwar (Son R.), and Ahmedabad (Sabarmati R.) was 1.9–2.3 mg/L and 3.2–3.8 mg/L upstream and downstream, respectively, of the Tawi R. in Jammu, with lower concentrations of 0.9–1.5 mg/L in the RBF and groundwater abstraction wells. In these towns, the RBF systems are also located in the upstream areas, and consequently a lower anthropogenic impact is noticeable.

However, two different RBF site examples to those discussed previously are in Daltonganj and Gaya, where the RBF wells have been inappropriately sited within the riverbed and downstream of the towns such that they are directly impacted by wastewater discharged locally or upstream. Consequently, not only was the DOC concentration in the surface water higher, but due to the discharge and accumulation of domestic wastewater directly at and around the wells, which can also be potentially contaminated by flood water, the DOC concentration in the abstracted well water was nearly 4 mg/L.

3.3. Organic Micropollutants

Out of 49 mainly polar OMPs screened, only 22 could be detected (Table 3). Although not regarded an OMP, caffeine was detected in nearly all surface water samples and in many groundwater, RBF well water, and treated water samples in concentrations ranging from <10 ng/L up to 400 ng/L (ubiquitous presence, hence not in Table 3). The occurrence of these 22 OMPs and caffeine is summarized in Table A1. Overall, 26 OMPs were not detected (Table A2).

Similar to the highest DOC concentrations found in the Yamuna R. water between Delhi and Agra, the highest occurrence and also nearly the highest concentrations of OMPs comprising pharmaceutical, medical contrast media, personal care product, corrosion inhibitor, insecticide, and herbicide compounds were also found along this stretch in the river water and also partly in the RBF RCW in Mathura and handpumps located near the river (groundwater, Table 3). The removal efficiency of OMPs by RBF can be demonstrated by taking the Mathura RBF site as an example, where the Yamuna R. had comparably (to Delhi and Agra) high concentrations of OMPs (Figure 4).

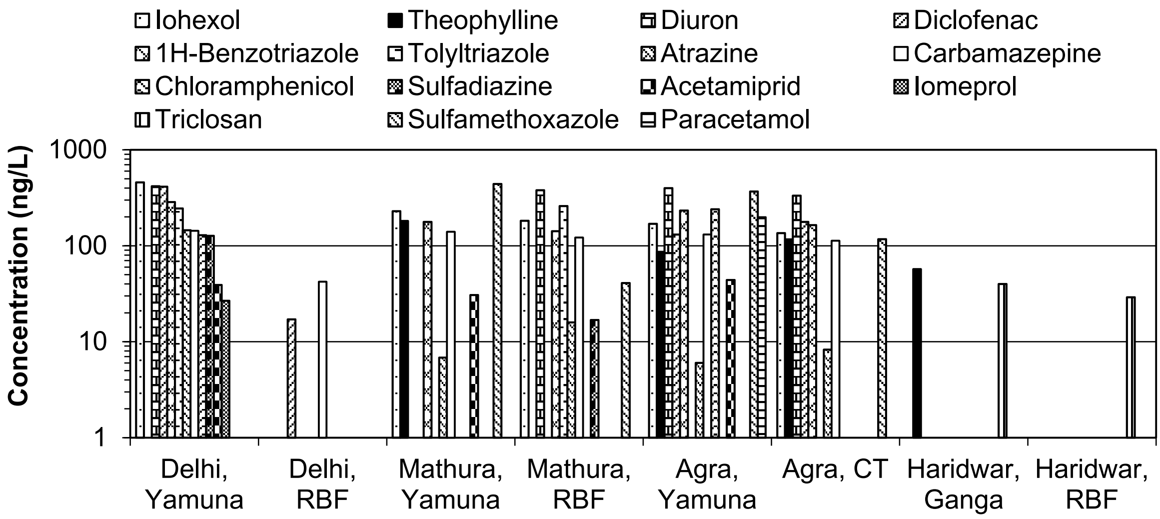

Figure 4. Median concentrations (except for Mathura) of organic micropollutants (OMPs) in surface water, RBF well water (RBF), and conventionally treated (CT) drinking water at selected sites sampled in non-monsoon 2014. Number of samples (n): Delhi: Yamuna, n = 2, n_{RBF} = 5; Mathura: Yamuna, n = 1, n_{RBF} = 1; Agra: Yamuna, n = 3, n_{CT} = 2.

Table 3. Concentrations of OMPs at selected sites where their presence was detected in non-monsoon 2014, given as median and maximum (separated by /) values in ng/L. Values in parentheses () indicate the number of samples these values are based on (if $\neq n$ in column 2), or the number of samples wherein the OMP was not detected (n.d.).

Location, River	**Source of Sample/*n***	**1H-Benzotriazole**	**Acetamiprid**	**Atrazine**	**Carbamazepine**	**Chloramphenicol**	**Cotinine**	**Diclofenac**	**Diuron**	**Ibuprofen**	**Iohexol**	**Iomeprol**	**Iopromide**	**Naproxen**	**Paracetamol**	**Phenazone**	**Phenobarbital**	**Simazine**	**Sulfadiazine**	**Sulfamethoxazole**	**Theophylline**	**Tolyltriazole**	**Triclosan**
Limit of detection		**30**	**10**	**10**	**30**	**30**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**30**
Delhi (central), Yamuna	SW/2	285/ 320	39.0/ 49.9	145/ 153	143/ 145	129 (1)	**d.**	413 (1)	418 (1)	**d.**	457/ 465	26.7/ 30.8	52.3/ 54.9	n.d.	**d.**	**d.** & 12.2	220/ 371	10.5/ 10.8	127/ 179	**d.**	**d.**	245/ 253	**d.**
	GW/2	n.d.	n.d.	n.d.	64.7/ 78.8	n.d.	n.d.	307/ 382	n.d.	n.d.	n.d.	n.d.	n.d.	161 (1)	n.d.	**d.**	133/ 177	n.d.	28.5/ 44.1	n.d.	34.8 (1)	n.d	n.d.
	RBF/5	n.d.	n.d.	n.d.	42.3 (2)	n.d.	n.d.	17.1/ 24.8 (3)	n.d.	25.9 (1)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**d.**	n.d.	n.d.	n.d.
Mathura, Yamuna	SW/1	177	30.7	**d.**	140	n.d.	46.2	**d.**	**d.**	n.d.	229	**d.**	12.4	n.d.	n.d.	158	39.0	n.d.	**d.**	440	182	**d.**	n.d.
	RBF/1	142	n.d.	15.9	122	n.d.	14.4	**d.**	379	n.d.	182	**d.**	15.5	n.d.	n.d.	40.0	n.d.	n.d.	16.8	40.9	n.d.	259	n.d.
	RO/1	36.8	n.d.	n.d.	n.d.	n.d.	n.d.	43.9	23.7	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**d.**	n.d.	43.2	n.d.
Agra, Yamuna	SW/3	226/ 240	43.9/ 72.5	**d.** (2) & 23.3	131/ 186	240 & n.d.(2)	44.9/ 69.8	131/ 246	398/ 463	**d.**	169/ 256	**d.**	**d.** (2) & 16.8	94.2 (1)	198 (1)	235/ 446	67.5/ 69.8	**d.** & n.d.(2)	n.d.	368/ 400	86.7/ 448	**d.**	**d.**
	CT/2	164/ 190	n.d.	**d.**	113/ 124	n.d.	20.6/ 23.2	177 (1)	333/ 418	n.d.	136/ 162	**d.**	**d.**	n.d.	n.d.	54.3 (1)	33.8/ 56.2	n.d.	n.d.	117/ 196	**d.** & 33.5	**d.**	n.d.
Japla (Jh.), Sone	SW/1	n.d.	n.d.	13.2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**d.**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	42.7
	RBF/1	n.d.	n.d.	13.6	n.d.	n.d.	18.8	n.d.	n.d.	108	n.d.	n.d.	n.d.	n.d.	76.2	n.d.	n.d.	n.d.	n.d.	n.d.	140	n.d.	n.d.
	CT/1	n.d.	n.d.	13.6	n.d.	n.d.	**d.**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**d.**	n.d.	n.d.	n.d.	n.d.	**d.**	n.d.	n.d.	n.d.
DTJ (Jh.), N. Koel	SW/1	n.d.	n.d.	n.d.	n.d.	n.d.	13.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**d.**	n.d.	n.d.	41.4
	RBF/1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**d.**	n.d.	n.d.	n.d.
	CT/1	n.d.	n.d.	n.d.	n.d.	n.d.	21.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	341	n.d.	n.d.	**d.**	17.8	n.d.	30.1
Dhanbad, Damodar	SW/4	n.d.	n.d.	n.d.	58.2 & n.d.(3)	n.d.	126 & n.d.(3)	46.9 & n.d.(3)	72.5 & n.d.(3)	n.d.	10/ 100	n.d.	n.d.	n.d.	50.5/ 146	59.7 & n.d.(3)	25.8 & n.d.(3)	n.d.	n.d.	39.6 & n.d.(3)	94.3 & n.d.(3)	88.9/ 102	n.d.
	CT/1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**d.**	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**d.**	n.d.	67.0	n.d.
Nainital	SW/2	n.d.	n.d.	n.d.	n.d.	n.d.	**d.** & 13.0	n.d.	89.5/112	n.d.	n.d.	n.d.	n.d.	n.d.	**d.** & 105	n.d.	n.d.	n.d.	n.d.	**d.**	**d.** & 35.1	n.d.	n.d.
	BF/6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	**d.**	n.d.	n.d.	n.d.

Abbreviations: n.d.: Not detected; **d.**: Detected but not quantifiable (qualitative result only); SW: Surface water; GW: Groundwater; BF/RBF: bank filtration (lake)/riverbank filtration; RO: Household reverse osmosis unit; CT: Conventional treatment; DTJ: Daltonganj (Medininagar, Jharkhand); Dhanbad (Jharkhand).

In Figure 4, it is observed that the concentrations of some OMPs in the RBF well water were 13%–99% lower than river water (RCW design, fast travel time), whereas others were not present in well water or else detectable in very low concentrations that were not quantifiable. Although this observation was made from the interpretation of a limited number of samples (Figure 4) in this study (collected once during non-monsoon 2014), similar ranges for removal of OMPs by RBF were observed for the same locations in a subsequent study (September 2015 to June 2018) [16]. The higher concentrations of atrazine, diuron, iopromide, sulfadiazine, and tolyltriazole in RBF water (and diuron after reverse osmosis) in Mathura compared to river water could be attributed to the possible effect of high concentrations of these substances in landside groundwater [16]. Thus, in general, dilution effects (groundwater, monsoon) cannot yet be ruled out. Among the herbicides, atrazine was found in the Yamuna R. water at all the sampled locations, with the highest concentration of 153 ng/L being found in Delhi (Table 3). Although atrazine was found in Mathura and Agra, its concentration in the Yamuna R. water was very low and could not be quantified.

Cotinine, diuron, paracetamol, triclosan, theophylline, and sulfamethoxazole were present or only detectable in very low concentrations (but not quantifiable) in the surface water in Haridwar (Figure 4), Srinagar, and Nainital (Table 3) in Uttarakhand. Of these OMPs, only sulfamethoxazole was detectable in nearly all RBF water samples, albeit in unquantifiable amounts (<10 ng/L), and triclosan was present in Haridwar (29 ng/L) and in Srinagar (38 ng/L, only one out of three samples). No other OMPs were detectable in the RBF wells at these sites.

In the state of Jharkhand at the RBF site of the town of Japla, surrounded by predominantly rural and agricultural areas, atrazine was found in surface water, bank filtrate (RCW), and subsequently conventionally treated water with a concentration of 13–14 ng/L, indicating no removal, most likely also on account of the very short travel time of the bank filtrate due to the shallow RCW design of the wells. However, in the more industrialized and densely populated coal mining city of Dhanbad, a wide range of pharmaceutical compounds (paracetamol, sulfamethoxazole, phenazone, diclofenac, theophylline, tolyltriazole, and carbamazepine), contrast media (iohexol), and the herbicide diuron were found in concentrations ranging from 10 to 126 ng/L in the adjacent Damodar R. (Table 3). The Damodar R. receives wastewater from the industrial cities of Dhanbad and Bokaro. In the conventionally treated drinking water derived by direct abstraction from the Damodar, sulfamethoxazole and iohexol were found in unquantifiable amounts (<10 ng/L). Tolyltriazole was found in drinking water (67 ng/L) slightly below the concentration in surface water (88–102 ng/L, Table 3). This indicates on one hand not much removal by conventional treatment, but on the other hand also indicates a natural removal of the other compounds within the river water by degradation and/or dilution and low effect of mixing with landside groundwater.

4. Summary and Conclusions

The Yamuna R. water quality between Delhi and Agra was observed to have the highest organic pollution (concentration of DOC and OMPs), and the surface as well as the groundwater was characterized by a high salinity, giving the drinking water derived therefrom a brackish taste. However, the concentrations of some OMPs in the RBF well water were 13%–99%, and DOC was 50% lower than in river water. The removal of DOC and some OMPs by RBF was considerably greater compared to direct surface water abstraction and subsequent conventional treatment (e.g., in Agra).

At most RBF locations in Jharkhand, Andhra Pradesh, Bihar, and Jammu, surface water quality was generally good with respect to all inorganic parameters. The design and location of the radial collector wells (RCWs) in Jharkhand and Andhra Pradesh within the riverbed ensures the year-round abstraction of water, even during the non-monsoon, when very low to negligible surface water flow is observed. However, the travel time of bank filtrate for such riverbed RCW systems is too short, and thus the removal of organics is lower, and breakthroughs of pathogens and turbidity are likely to occur. One advantage at these locations is that the surface water itself has relatively low concentrations of DOC and OMPs. Iron and manganese can also occur in the abstracted water from such systems.

Thus, the bank filtrate subsequently undergoes post-treatment comprising aeration, flocculation, rapid sand filtration, and disinfection. In some coastal and peninsular (hard rock) areas of India (Jharkhand, Odisha, Andhra Pradesh, and Tamil Nadu), RBF is the only viable means of obtaining water compared to direct surface water or even groundwater, and in this context, RBF buffers the quantity of water required through bank or bed storage and can thus be considered to be an element of managed aquifer recharge and integrated water resources management.

This is the first country-wide overview of critical water quality parameters for some existing and potential RBF sites in India. Although this study was based on limited data for some locations, the data were well supported by results from recent investigations [16,29]. The data were insufficient to describe the hydrogeochemical and attenuation processes of inorganic parameters and organic substances in detail, but it nevertheless reiterated the fact that where in use, RBF at least serves as an effective pre-treatment step. For RBF sites at extremely polluted surface waters (such as in Delhi, Mathura, and potentially Agra by the Yamuna River), post-treatment should be made mandatory, e.g., by using activated carbon or advanced oxidation, which is less costly and easier to maintain if RBF is used for pre-treatment [16]. Moreover, the study provides a forecast within an initial site assessment of the water quality to be expected for subsequent investigations ranging from long-term monitoring and hydrogeological process description to environmental and human health risk assessments, and eventually the planning of new full-scale RBF systems in India. The water quality knowledge base generated in this study and the spatial distribution of the investigated sites, both with existing RBF systems and those with potential to develop new systems, forms the basis to develop a master plan for RBF water supply in India [30].

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Summary of occurrence of organic micropollutants.

OMP	Number of Samples Wherein Detected	Source Water
Iomeprol	2	Yamuna R.
Naproxen	2	Delhi groundwater, Keetham Lake Agra
Simazine	2	Yamuna R.
Chloramphenicol	3	Yamuna R.
Iopromid	5	Yamuna R. and RBF wells along Yamuna
Sulfadiazine	5	Yamuna R. and RBF wells along Yamuna
Ibuprofen	6	Scattered locations
Acetamiprid	7	Mainly Yamuna region
Atrazine	7	Yamuna region and Japla (Jharkhand)
Phenazone	8	Yamuna and Damodar river regions
1H-Benzotriazole	11	Mainly Yamuna region
Paracetamol	11	Scattered locations
Phenobarbital	11	Mainly Yamuna region
Iohexol	12	Mainly Yamuna region
Diuron	13	Mainly Yamuna region and Nainital Lake
Diclofenac	14	Yamuna and Damodar river regions
Sulfamethoxazole	14	Scattered locations
Cotinine	15	Mainly Yamuna region, Jharkhand and Nainital
Tolyltriazole	15	Mainly Yamuna region and Jharkhand
Carbamazepine	16	Yamuna and Damodar river regions
Theophylline	17	Scattered locations
Triclosan	23	Scattered locations
Caffeine	41	Ubiquitously present nearly everywhere

Table A2. List of organic micropollutants not detected in any sample.

Ametryne	Clofibric acid	Linuron	Atenolol
Atrazine-desethyl	Clothianidine	Loratadine	Ciprofloxacin Ditrizoate
Atrazine-desisopropyl	Diazepam	Primidone	Gabapentin
Bentazone	Gemfibrozil	Propanil	Metformin
Carbofuran	Iopamidol	Terbutryn	Metoprolol
Chlorothiazide	Isoproturon	Trimethoprim	*N*,*N*-Dimethylsulfamide Ranitidin

References

1. Sandhu, C.; Grischek, T.; Kumar, P.; Ray, C. Potential for Riverbank filtration in India. *Clean Technol. Environ. Policy* **2011**, *13*, 295–316. [CrossRef]
2. Sandhu, C.; Grischek, T. Riverbank filtration in India—Using ecosystem services to safeguard human health. *Water Sci. Technol. Water Supply* **2012**, *12*, 783–790. [CrossRef]
3. Dash, R.R.; Mehrotra, I.; Kumar, P.; Grischek, T. Lake bank filtration at Nainital, India: Water-quality evaluation. *Hydrogeol. J.* **2008**, *16*, 1089–1099. [CrossRef]
4. Dash, R.R.; Bhanu Prakash, E.V.P.; Kumar, P.; Mehrotra, I.; Sandhu, C.; Grischek, T. River bank filtration in Haridwar, India: Removal of turbidity, organics and bacteria. *Hydrogeol. J.* **2010**, *18*, 973–983. [CrossRef]
5. Gupta, A.; Singh, H.; Ahmed, F.; Mehrotra, I.; Kumar, P.; Kumar, S.; Grischek, T.; Sandhu, C. Lake bank filtration in landslide debris: Irregular hydrology with effective filtration. *Sustain. Water Resour. Manag.* **2015**, *1*, 15–26. [CrossRef]
6. Ronghang, M.; Gupta, A.; Mehrotra, I.; Kumar, P.; Patwal, P.; Kumar, S.; Grischek, T.; Sandhu, C. Riverbank filtration: A case study of four sites in the hilly regions of Uttarakhand, India. *Sustain. Water Resour. Manag.* **2018**. [CrossRef]
7. Sprenger, C.; Lorenzen, G.; Grunert, A.; Ronghang, M.; Dizer, H.; Selinka, H.-C.; Girones, R.; Lopez-Pila, J.M.; Mittal, A.K.; Szewzyk, R. Removal of indigenous coliphages and enteric viruses during riverbank filtration from highly polluted river water in Delhi (India). *J. Water Health* **2014**, *12*, 332–342. [CrossRef] [PubMed]

8. Singh, P.; Kumar, P.; Mehrotra, I.; Grischek, T. Impact of riverbank filtration on treatment of polluted river water. *Environ. Manag.* **2010**, *91*, 1055–1062. [CrossRef] [PubMed]
9. Kumar, P.; Mehrotra, I.; Boernick, H.; Schmalz, V.; Worch, E.; Schmidt, W.; Grischek, T. Riverbank Filtration: An Alternative to Pre-chlorination. *J. Indian Water Works Assoc.* **2012**, 50–58.
10. Cady, P.; Boving, T.B.; Choudri, B.S.; Cording, A.; Patil, K.; Reddy, V. Attenuation of Bacteria at a Riverbank Filtration Site in Rural India. *Water Environ. Res.* **2013**, *85*, 2164–2175. [CrossRef]
11. Boving, T.B.; Choudri, B.S.; Cady, P.; Cording, A.; Patil, K.; Reddy, V. Hydraulic and Hydrogeochemical Characteristics of a Riverbank Filtration Site in Rural India. *Water Environ. Res.* **2014**, *86*, 636–649. [CrossRef] [PubMed]
12. Groeschke, M.; Frommen, T.; Taute, T.; Schneider, M. The impact of sewage-contaminated river water on groundwater ammonium and arsenic concentrations at a riverbank filtration site in central Delhi, India. *Hydrogeol. J.* **2017**, *25*, 2185–2198. [CrossRef]
13. Mutiyar, P.K.; Mittal, A.K.; Pekdeger, A. Status of organochlorine pesticides in the drinking water well-field located in the Delhi region of the flood plains of river Yamuna. *Drink. Water Eng. Sci.* **2011**, *4*, 51–60. [CrossRef]
14. Kumar, P.; Mehrotra, I.; Gupta, A.; Kumari, S. Riverbank Filtration: A sustainable process to attenuate contaminants during drinking water production. *J. Sustain. Dev. Energy Water Environ. Syst.* **2018**, *6*, 150–161. [CrossRef]
15. Krishan, G.; Singh, S.; Sharma, A.; Sandhu, C.; Grischek, T.; Gosh, N.C.; Gurjar, S.; Kumar, S.; Singh, R.P.; Glorian, H.; et al. Assessment of water quality for river bank filtration along Yamuna river in Agra and Mathura. *Int. J. Environ. Sci.* **2016**, *7*, 56–67.
16. Glorian, H.; Börnick, H.; Sandhu, C.; Grischek, T. Water quality monitoring in northern India for an evaluation of the efficiency of bank filtration sites. *Water* **2018**, *10*, 1804. [CrossRef]
17. IS 10500. *Drinking Water—Specification*; Indian Standard (Second Revision); Bureau of Indian Standards: New Delhi, India, 2012.
18. Grischek, T.; Ray, C. Bank filtration as managed surface—Groundwater interaction. *Int. J. Water* **2009**, *5*, 125–139. [CrossRef]
19. Grischek, T.; Schoenheinz, D.; Sandhu, C. Water Resources Management and Riverbank Filtration. In *Drinking Water—Source, Treatment and Distribution*; Dobhal, R., Grischek, T., Uniyal, H.P., Uniyal, D.P., Sandhu, C., Eds.; Uttarakhand State Council for Science and Technology (UCOST): Dehradun, India, 2011; pp. 1–7.
20. Sandhu, C. A Concept for the Investigation of Riverbank Filtration Sites for Potable Water Supply in India. Ph.D. Thesis, TU Dresden, Faculty of Environmental Sciences, HTW Dresden, Division of Water Sciences, Dresden, Germany, 2015.
21. WHO. *Guidelines for Drinking-Water Quality*, 4th ed.; Incorporating 1st Addendum; World Health Organization: Geneva, Switzerland, 2017; ISBN 978-9241548151.
22. Sandhu, C.; Grischek, T.; Ronghang, M.; Mehrotra, I.; Kumar, P.; Ghosh, N.C.; Rao, Y.R.S.; Chakraborty, B.; Patwal, P.S.; Kimothi, P.C. Overview of bank filtration in India and the need for flood-proof RBF systems. In *Natural Water Treatment Systems for Safe and Sustainable Water Supply in the Indian Context—Saph Pani*; Wintgens, T., Nättorp, A., Lakshmanan, E., Asolekar, S., Eds.; IWA Publishing: London, UK, 2016; pp. 17–38, ISBN 9781780407104.
23. Mutiyar, P.K.; Mittal, A.K. Status of organochlorine pesticides in Ganga river basin: Anthropogenic or glacial? *Drink. Water Eng. Sci. Discuss.* **2012**, *5*, 1–30. [CrossRef]
24. Huntscha, S.; Singer, H.P.; McArdell, C.S.; Frank, C.E.; Hollender, J. Multiresidue analysis of 88 polar organic micropollutants in ground, surface and wastewater using online mixed-bed multilayer solid-phase. *J. Chromatogr. A* **2012**, *1268*, 74–83. [CrossRef]
25. Ullmann, M. Untersuchung zu Arzneimittelwirkstoffen bei der Uferfiltration in Indien (Investigation of Pharmaceutical Compounds during Riverbank Filtration in India). Master's Thesis, HTW Dresden, Dresden, Germany, 2013.
26. Schnitzler, H.; Börnick, H.; Ullmann, M.; Sandhu, C.; Grischek, T. Bestimmung von polaren organischen Spurenstoffen in Gewässern in Indien mittels vor-Ort-Anreicherung und LC-MS/MS (Determination of polar organic micropollutants in waters in India by on-site enrichment and LCMS/MS). In Proceedings of the Jahrestagung der Wasserchemischen Gesellschaft, Wasser, Haltern am See, Germany, 26–28 May 2014; pp. 479–483, ISBN 978-3-936028-83-6.

27. Lorenzen, G.; Sprenger, C.; Taute, T.; Pekdeger, A.; Mittal, A.; Massmann, G. Assessment of the potential for bank filtration in a water-stressed megacity (Delhi, India). *Environ. Earth Sci.* **2010**, *61*, 1419–1434. [CrossRef]
28. Lalwani, S.; Dogra, T.D.; Bhardwaj, D.N.; Sharma, R.K.; Murty, O.P.; Vij, A. Study on arsenic level in ground water of Delhi using hydride generator accessory coupled with atomic absorption spectrophotometer. *Indian J. Clin. Biochem.* **2004**, *19*, 135–140. [CrossRef] [PubMed]
29. Lapworth, D.J.; Das, P.; Shaw, A.; Mukherjee, A.; Civil, W.; Petersen, J.O.; Gooddy, D.C.; Wakefield, O.; Finlayson, A.; Krishan, G.; et al. Deep urban groundwater vulnerability in India revealed through the use of emerging organic contaminants and residence time tracers. *Environ. Pollut.* **2018**, *240*, 938–949. [CrossRef] [PubMed]
30. Grischek, T.; Sandhu, C.; Ghosh, N.C.; Kimothi, P.C. A Conceptual Master Plan for RBF Water Supply in India—Science, Policy & Implementation Aspects. In Proceedings of the Indo-German Conference on Sustainability, Chennai, India, 27–28 February 2016; pp. 118–123.