Attenuation of Bacteria at a Riverbank Filtration Site in Rural India

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ABSTRACT: A riverbank filtration (RBF) system was installed in a rural village near the Kali River in southwestern India to evaluate its performance in attenuating total coliform bacteria and *Escherichia coli* loads in a monsoon-dominated climate in a developing country. A statistical analysis showed that RBF water was of higher microbial quality than other water sources in the study area. Based on the geometric mean of the data from the primary RBF well (MW3), the percent removal compared to the Kali River was 95.1% for total coliforms and 99.2% for *E. coli*. The maximum percent removals were 99.8% for total coliforms and 99.96% for *E. coli*. Bacteria concentrations were lower during the dry season than during the monsoon season when contaminants apparently infiltrated into the subsurface. The geometric mean of the annual removal efficiency translates to an approximately 1-log unit removal of *E. coli* per 26 m (≈75 ft) setback distance from the river. During the 1-year monitoring period, Indian water quality standards for total coliform bacteria were regularly exceeded, whereas *E. coli* standards were met for 29% of the dry season but only 7% of the monsoon season. The consistent problem of attaining local regulatory limits for bacteria show that, at this study site, (1) RBF needs to be considered a pre-treatment method and, (2) should be combined with conventional disinfection technology. Finally, although the bacteria data confirms that the setback distance of a RBF well from a river is an important factor determining the water quality, local conditions, such as influence of flood-irrigation of nearby rice paddies, presence of freely-roaming cattle and latrines, and outside defecation by residents, must be considered when establishing a RBF system in a monsoon climate in a developing country. *Water Environ. Res.*, **85,** 2164 (2013).

KEYWORDS: riverbank filtration (RBF), bacteria, total coliforms, *Escherichia coli*, water treatment, India, developing country, monsoon climate.

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Introduction

More than one billion people in the world—18% of the global population—do not have access to safe drinking water (United Nations, 2006). Common water-related diseases can cause gastrointestinal infections, which in sensitive populations such as the very young or those with compromised immune systems, can lead to death (CDC, 2003). Further, repeated diarrheal episodes can impair health through chronic malnutrition, increased infections, and reduced growth and development (Ejemot et al., 2009). The World Health Organization estimates that access to improved drinking water can reduce the occurrence of diarrhea by 25% (WHO, 2005). Additionally, a review of 38 studies by Fewtrell et al. (2005) reported a 15% to 43% reduction in diarrheal diseases as a result of hygiene, sanitation, water supply, and water quality interventions. For these reasons, low-cost water treatment systems are needed to improve drinking water quality in regions currently not served by adequately treated water.

Lack of access to safe water is a well-documented problem throughout India. A government report found water to be unsafe for drinking in 46% of all samples tested in the vicinity of this study (Dharwad District Health Laboratory, 2003). A more recent study in northwestern India in 2007 and 2008 found that 45.4% of taps, 29.2% of bore wells, and 72.0% of open wells were unsafe for human consumption (Malhotra et al., 2009).

Because surface water sources are often unreliable and unsafe for human consumption, as much as one-third of the global population relies on groundwater sources of drinking (Worldwatch Institute, 2000). Worldwide, groundwater is predominantly used for irrigation. For example, Schiermeir reported 95% of groundwater used in northern India is to irrigate crops. As a result of both agricultural and domestic uses, depletion of aquifers is an increasing threat to the drinking water supply, with predictions that the majority of the Indian subcontinent, as well as many other parts of the world, will experience water scarcity by 2025 (World Resources Institute, 2001).

Declining water tables can lead to well failure, changes in water chemistry, and other serious environmental problems. Excessive drawdown can also lead to land subsidence and irreversible compaction of the aquifer, both of which inhibit aquifer recharge. Groundwater withdrawal can also lower surface water levels such that they cannot provide adequate habitat for aquatic life. Over 25% of the farms in India are in danger of pumping their wells dry within the next few decades. In the southern Indian State of Tamil Nadu, 95% of small farmers' wells have already gone dry (Pearce, 2004). Furthermore, recent satellite imagery shows evidence of severe drawdown rates in northern India (Rodell et al., 2009). Beyond health and environmental effects, the cost associated with drilling deeper-and-deeper wells is an economic burden (Sengupta, 2006). High drilling and pumping costs can force

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subsistence farmers to rely on rainfall to irrigate their crops, which can lead to diminished crop returns.

Riverbank filtration (RBF) is a relatively simple, low-cost water treatment technology that can help address the combined problems of contaminated surface water supplies and aquifer depletion. Riverbank filtration technology reduces groundwater withdrawals by tapping into surface water. Typically, RBF wells are drilled within a few hundred meters of a surface water body (e.g., river) so that when the well is pumped, surface water is drawn through the underlying sediments. During transport toward the RBF well, the water quality is improved via microbial degradation and predation, ion exchange, precipitation, sorption, filtration, dispersion, and groundwater dilution (Hiscock and Grischeck, 2002; Kelly and Rydlund, 2006; Vogel, Barber, et al., 2005). Riverbank filtration wells are generally best-sited in sandy sediments such as alluvial aquifers (Hubbs et al., 2006). Much of the biological activity in an RBF well occurs at the surface/groundwater interface where biofilms comprising bacteria, fungi, algae, and protozoa embedded in a granular matrix form along the riverbed (Schmidt et al., 2003). Largely as a result of this biologically active layer (*schmutzdecke*), RBF greatly reduces levels of pathogens, particles, and biodegradable compounds (Ray, 2004; Tufenkji et al., 2002).

Riverbank filtration systems have been used throughout the temperate and cold climates of Germany, Holland, Hungary, France, Switzerland, and Finland for decades—and in some sites for over a century (Peel et al., 2007; Ray et al., 2002; Tufenkji et al., 2002). To date, RBF remains relatively untested in monsoon climates (i.e., locations dominated by strong seasonal rains followed by a prolonged dry season). Because of the limited number of studies on RBF performance in tropical settings (e.g., Kumar and Mehotra, 2009; Sandhu et al., 2011), municipalities and funding agencies in developing countries are typically reluctant to adopt this water treatment technology. To help combat extensive dysentery-related deaths (WHO, 2005) and groundwater demands from rising populations, the use of RBF is increasingly considered to be a suitable, low-cost, and sustainable approach for the production of safe drinking water in developing countries such as India.

Total and fecal coliforms are widely used bacterial indicators to monitor microbial water quality in developed and developing regions of the world. The total coliform group of bacteria can survive and grow in both aerobic and anaerobic settings within warm-blooded hosts as well as water and soil (WHO, 2006). The presence of total coliforms indicates incomplete treatment or potential contamination of drinking water (Feng et al., 1998); nonfecal sources include pulp and paper mill effluent (Doyle and Erickson, 2006). *Escherichia coli* are an important subset of total coliform populations that are adapted to the higher temperatures of human and animal intestines (WHO, 2006). For this reason, *E. coli* are widely used as indicators of recent fecal contamination. In temperate environments, their survival half-life outside of their host ranges from 1 day (in water) to 3 days (in soil). However, in moist, warm, high-nutrient settings in tropical environments, *E. coli* can maintain free-living populations (Winfield and Groisman, 2003). Fecal contamination of drinking water supplies is a public health concern because it can carry pathogens causing gastroenteritis, meningitis, and other waterborne diseases (WHO, 2006). Potential sources of fecal contamination include direct discharge of human and animal waste as well as nonpoint agricultural and storm runoff.

European and U.S. RBF systems have achieved bacterial removal percentages of 99.2% to 99.999% (2.1- to 5-logs) for total coliforms and 99.9% to 99.994% (3- to 4.2-log) for *E. coli* (Boving et al., 2010; Kelly and Rydlund, 2006; Kühn and Müller, 2000; Schubert, 2002; Tufenkji et al., 2002; Vogel, Harris et al., 2005). The percentage of co-extracted groundwater from these RBF wells ranged from 25% to 87% (Grischek et al., 2010; Hoppe-Jones et al., 2010; Kelly and Rydlund, 2006; Schmidt et al., 2003; Schubert, 2002).

This primary objective of this study was to evaluate the bacterial removal performance of a community-sized RBF system under monsoon conditions in a rural settlement of southwestern India. Although India has made steady progress toward developing its urban centers, much of rural India still lacks the services, including water treatment facilities, commonly found in developed nations. This paper describes the results of a year-long study of bacteria concentrations in RBF wells, local river water, and from other existing water sources to determine whether RBF treatment could meet the Bureau of Indian Standards (BIS) limits for drinking water during dry and wet (monsoon) seasons that characterize the climatic conditions of this region of India. This study contributes new bacteriological water quality information that was not addressed in previous studies of the Kali River and its tributaries (Bharati and Krishnamurthy, 1990; Bharati and Krishnamurthy, 1992; Chavadi and Gokhale, 1986; Krishnamurthy and Bharati, 1994; Krishnamurthy and Bharati, 1996; Manjunatha et al., 2001; Subramanian et al., 1987). Whereas the focus of this paper is on microbial parameters, a companion paper summarizes the results of concomitant hydraulic, geochemical, and hydrogeological site investigations (Boving et al., 2013).

Methodology

The RBF study site is located in the tropical monsoon climate of southwestern India (Figure 1). It is adjacent to the perennial Kali River and 4 km south of the town of Dandeli, Karnataka, India. The river receives polluted effluent from many sources, including municipal discharge and treated effluent from a large paper mill. Before project implementation, local residents relied on the polluted river water, unprotected and unimproved hand-dug (open) wells, or, when available, water diverted from upstream of the industrial and municipal inputs. Prior data (Dharwad District Health Laboratory, 2003) coupled with this project's field survey (Boving et al., 2012) confirm that these established water supply systems provide unsafe water and are unreliable, sometimes breaking down for months at a time (Patil, 2009). Drinking water quality in India is regulated by the BIS, which defines *desirable* (ideal) and, frequently, *permissible* (less than ideal) regulatory goals. The BIS standard for total coliform bacteria is 0 MPN/100 mL for 95% of samples collected throughout the year. Although the remaining 5% of samples cannot exceed 10 MPN/100 mL, two consecutive positive samples are not allowed. *Escherichia coli* levels are required to be 0 MPN/100 mL at all times (BIS, 1991).

The study site is in a meta-sedimentary basin that is rich in iron and manganese ore, and is overlain by lateritic soils up to 60 m thick (Radhakrishna and Vaidyanadhan, 1997). Laterites have naturally low fertility (Baligar et al., 2004). Alluvial soils are also found along river courses. An existing open well near the Village of Kariyampalli (KOW) was located 125 m away from the river. In addition, the bore well in the Village of Mainal (MBW) (1 km

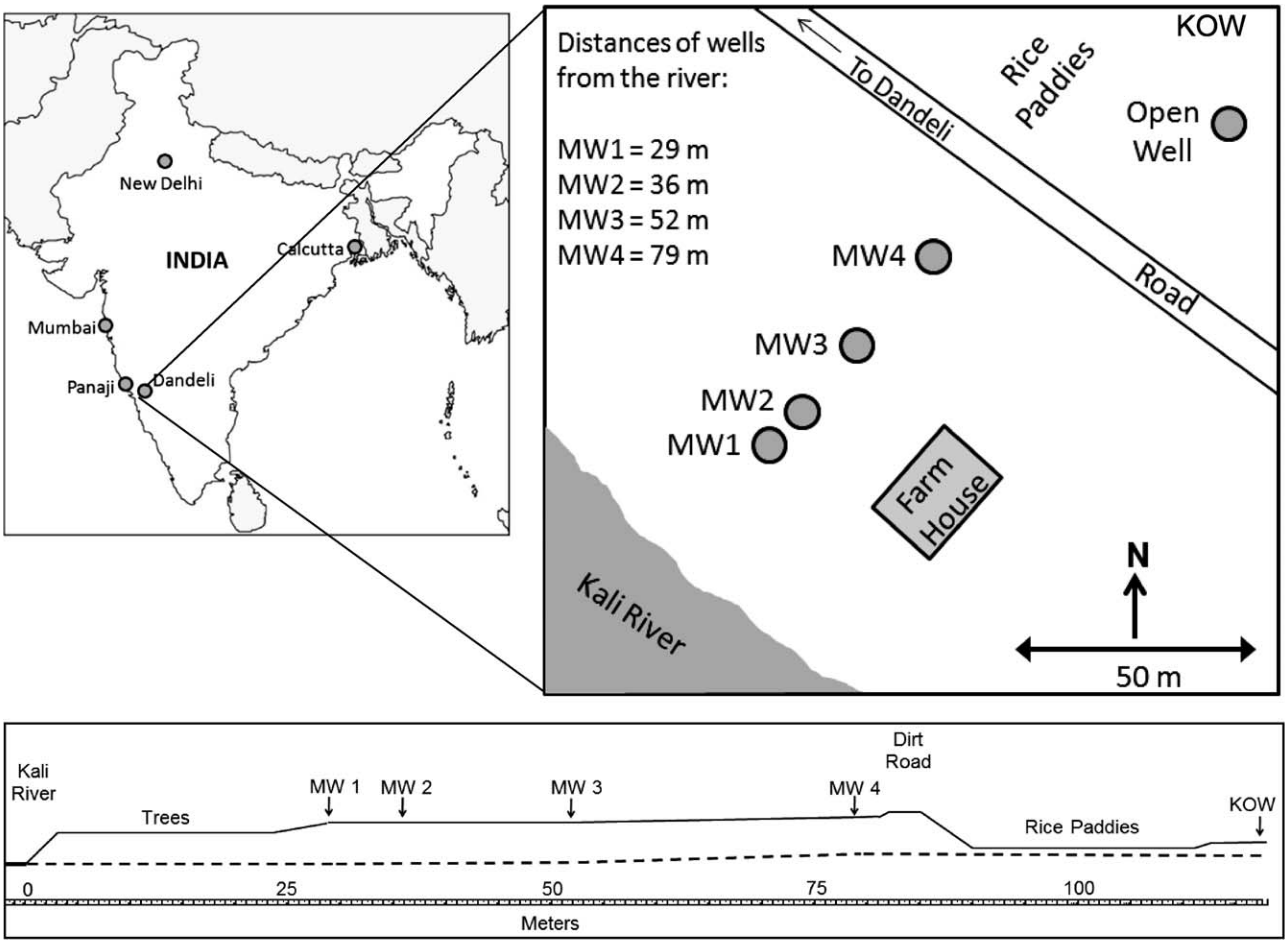

Figure 1—Map of study area and cross-section of the riverbank filtration (RBF) test site near the Town of Dandeli (MW = RBF wells 1 through 4; KOW = Kariyampalli open well). Note, KOW is surrounded by rice paddies irrigated with water from the Kali River. A bore well was located outside the map area. Horizontal scale as shown (m); vertical scale is about 10 times exaggerated (modified after Boving et al., 2013).

south of the RBF site; not shown in Figure 1) was occasionally sampled. Construction of the RBF wellfield and the hydraulic tests performed are described in detail in Boving et al. (2013). Briefly, four shallow RBF wells (20 to 25 m deep) were drilled 29 to 79 m away from the Kali River to study changes in RBF water quality with distance from the river (Figure 1). Construction of the RBF wells included a solid steel casing (diameter 0.15 m) that reached from 0.6 m above the surface to 6 m below. The steel well screen (welded holes) penetrated 6.9 m of unconfined aquifer and 0.5 m of solid bedrock. No casings or screens were used in the bedrock. The water levels were about 4 m belowground in all wells. The wellheads were encased in a 1 m^2 concrete slab for protection and covered by a steel cap. A submersible electric pump (CRI Pumps, Hubli, Karnataka, India) and calibrated class B CM/L water meters (Dasmesh India, Malerkotla, Punjab, India) were purchased locally. The single pulse 230-V pump was rated at 2 HP (1.49 kW). Prior to use, the pump and all wells were sanitized using a solution of 1 part 5% sodium hypochlorite bleach to 3 parts water. The solution was left in the well overnight and pumped out the next day (Minnesota Department of Health, 2006).

The yield of the principal RBF well (MW3) exceeded the capacity of the pump ($>$9.3 m^3/hr). The hydraulic conductivity (K) derived from an aquifer test was 6.3×10^{-5} m/s. The minimum travel time of the water from the Kali River to MW3 was about 45.2 days (Boving et al., 2012a).

Water was pumped from MW2 from mid-January to mid-March 2009. The pump was then moved to MW4 and operated through April. From May until the end of the study, MW3 was pumped again. The RBF wells were sampled periodically for total coliforms, *E. coli*, and other field parameters (Boving et. al., 2012a) from January to November 2009. Dedicated bailers were used in those wells not actively pumped. For total coliform and *E. coli* bacteria testing, raw unfiltered water samples were collected in 100 mL sterile bottles and kept in a cooler until analysis in the laboratory. The village well KOW and the Kali River were sampled using a plastic bucket.

Bacteria tests were performed using IDEXX (Westbrook, Maine) Colilert MPN (most probable number) defined substrate technique. Samples were incubated and analyzed at the Dandeli College Microbiology Laboratory. The detection range was $<$1 to $>$2 419.6 MPN/100 mL; minimum values were converted to 0.9 MPN/100 mL and maximum values to 2500 MPN/100 mL

(APHA et al., 2005; Costa, 2010; U.S. FDA, 2007). These altered endpoints were then used to plot and average data for each sampling site. Coliform data were averaged by water source, and these averages were compared across categories. Geometric means were used to minimize the effect of outliers in the data set (Costa, 2010). Positive (spiked with *E. coli*) and negative (distilled water) controls were run with each batch during the first month to verify handling procedures during training of field personnel.

Ideally, progressive dilutions would have been performed on samples from sites that routinely showed bacteria concentrations above the upper reporting limit, but limited supplies prevented such dilutions. By comparison, 2006 data on medium and small rivers in the States of Andhra Pradesh, Orissa, Pondicherry, Tamil Nadu, and Karnataka ranged from 11 to 37 000 MPN/100 mL total coliforms and from 3 to 5000 MPN/100 mL fecal coliforms. The highest bacteria levels in tributaries of the Krishna River Basin (which is adjacent to the Kali River Basin) in 2006 were 420 000 MPN/100 mL and 22 000 MPN/100 mL for total and fecal coliforms, respectively (CPCB, 2006). Notably, those upper levels are more than two orders of magnitude greater than the upper detection limit of the method used in this study. This implies that any removal percentages reported herein show minimum removals from the Kali River water, whereas the actual removal percentage was likely substantially greater.

The percentage change in bacteria concentration relative to the Kali River was calculated as follows (eq 1):

$$\%\ \text{Change} = \frac{[\text{River}] - [\text{Sample}]}{[\text{River}]} \times 100 \tag{1}$$

where [River] and [Sample] are the measured bacteria concentrations in the Kali River and the aqueous sample, respectively. From eq 1, log-removal values were calculated as follows (eq 2):

$$\text{Log}_{\text{removal}} = \text{Log}_{10} \frac{100}{(100 - \%\ \text{change})} \tag{2}$$

Additionally, average and maximum percent changes were calculated per eqs 3 and 4

$$\text{Average \% change} = \frac{\text{geometric mean of sample location}}{\text{geometric mean of Kali River}} \tag{3}$$

$$\text{Maximum \% change} = \frac{\text{minimum coliform level of sample location}}{\text{maximum coliform level of Kali River}} \tag{4}$$

Statistical significance testing with SPSS software (version 19, IBM, Armonk, New York) was performed on bacteria levels in RBF wells MW3 and MW4, the KOW, and the Kali River at the study site.

Total coliform and *E. coli* bacteria data are presented as both individual data points and as aggregate annual data (geometric means). The percent change for each of the sampling stations (RBF wells MW1 through MW4, KOW, Mainal Open Well [MOW], and Mainal Bore Well [MBW]) relates the (annual) mean bacteria concentrations in a water source to that of the Kali River at the field site (eq 1).

Bacteria data were also examined for possible seasonal changes during the dry (October to May) and monsoon (June to September) seasons. During the wet season, only the Kali River, KOW, and MW3 were tested.

A total of four data points were removed from the total coliform data set because of suspicion of sample contamination; however, their removal only negligibly affected the results. For similar reasons and consequences, seven *E. coli* data points were also removed.

Statistical significance testing was performed on bacteria concentration levels in RBF wells MW3 and MW4, the KOW, and the Kali River. All other sample stations had an insufficient number of data points to support meaningful statistical analyses. Of the samples from the continuously monitored wells, not all passed normality testing of skew $< |2|$ and kurtosis $< |4|$. Therefore, non-parametric Mann-Whitney U tests using two-tailed asymptotic significance test statistics were conducted.

Results

Total coliform bacteria concentrations for all samples ($n = 95$) ranged from 4.1 MPN/100 mL to exceeding the upper detection limit of the method (2500 MPN/100 mL) (Table 2). Figure 2a correlates total coliform data points with rainfall distribution. Of all total coliform samples, 25 (26%) were at or exceeded the upper detection limit. Most of these highly contaminated samples were taken from the Kali River, where total coliform concentrations were $\geq$2500 MPN/100 mL in 11 out of 15 samples (73%). A similarly high total coliform level was measured at the MBW ($\geq$2500 MPN/100 mL). The lowest total coliform level (4.1 MPN/100 mL) was measured at RBF well MW3 in late February 2009.

The Kali River's geometric mean total coliform concentration over the entire (1-year) sampling period was 1700 MPN/100 mL. Relative to the river, 44% higher concentrations were measured at KOW and MBW. This indicates that routinely used water sources are more polluted than the river. At the RBF well MW3, however, mean total coliform concentrations were 95% lower. Because the actual total coliform concentration in the river exceeded the upper detection limit in 11 of 15 samples, the actual removal percentage calculated based on the aggregate annual data likely underestimates the performance of the RBF system.

Examined by season (dry, $n = 75$; monsoon, $n = 20$) (Table 2), the Kali River's total coliform concentration during the dry season (2100 MPN/100 mL) was almost twice as high as during the monsoon (1200 MPN/100 mL). The total amount of rainfall in the study area during 2009 was 1550 mm, of which 1310 mm fell in the monsoon season between June and September. Increased river discharge during the monsoon diluted the total coliform load. However, the opposite effect was found at the RBF wellfield where the total coliform concentration at MW3 was less than half as much during the dry season relative to the monsoon (66 MPN/100 mL versus 140 MPN/100 mL). This indicates that contaminated water infiltrated from the surface during the rainy season. Nevertheless, MW3 was always found to be the least polluted source of water in the study area, and which was confirmed by significance tests (Table 1). Independent of the season, the KOW (the principal water supply for the villagers prior to RBF installation) was always equally or more polluted than the Kali River.

Table 1—Significance testing results for riverbank filtration (RBF) field site bacteria concentrations from Mann-Whitney U tests. Note that a water source to the left of $\ll$ is significantly less contaminated than that on the right, and a water source to the left of $<$ is less contaminated than that on the right, but not significantly so (MW3, MW4 = RBF wells 3 and 4; KR = Kali River at the RBF field site; KOW = Kariyampalli open well).

Parameter	Less contaminated → more contaminated
Total coliforms (all year)	MW3 $\ll$ MW4 $\ll$ KR $\ll$ KOW
Total coliforms (dry season)	MW3 $\ll$ MW4 $\ll$ KR $<$ KOW
Total coliforms (monsoon)	MW3 $\ll$ KR
E. coli (all year)	MW3 $<$ MW4 $\ll$ KOW $<$ KR
E. coli (dry season)	MW3 $\ll$ MW4 $\ll$ KOW $<$ KR
E. coli (monsoon)	MW3 $\ll$ KR

With regard to the *E. coli* data, concentrations for all samples ($n = 84$) ranged from below the lower detection limit (0.9 MPN/100 mL) to 1700 MPN/100 mL (Table 3). Unlike total coliforms, no *E. coli* samples were measured at or exceeding the upper detection limit of the method, whereas 10 (12%) samples—all from the RBF production well (MW3)—were below the minimum detection limit. Figure 2b correlates the data points with rainfall distribution.

Table 3 provides the geometric means for all six sampling sites on an annual basis. Relative to the Kali River (with an average of 460 MPN/100 mL), the water quality was better by 57% (KOW) to 99% (MW3). Based on seasonal means for *E. coli*, the water quality of the principal RBF well MW3 was always significantly better than any other water source in the study area (Table 1). However, more *E. coli* was detected in MW3 during the 4 months of the wet season than during the rest of the year (13 versus 1.8 MPN/100 mL). Table 3 summarizes the geometric means and removal percentages relative to the Kali River during the wet and dry seasons and over the entire monitoring period. Overall, the dry season means ($n = 64$) of *E. coli* concentration ranged from 1.8 MPN/100 mL in MW3 to 470 MPN/100 mL in the river. Relative to the river, mean removal of 58% (KOW) to >99% (MW3) were observed. With respect to the rainy season, means ($n = 20$) ranged from 13 MPN/100 mL (MW3) to 440 MPN/100 mL (Kali River) and removal percentages ranged from 55% in KOW to 97% in MW3. It is noteworthy that, unlike with total coliforms, the Kali River seasonal averages for *E. coli* remained almost unchanged (470 MPN/100 mL versus 440 MPN/100 mL). This might indicate a higher influx of *E. coli* that counteracts dilution in the river during the monsoon season.

Discussion

In a government study of eight local bore wells, five samples showed total coliform levels below the detection limit (not reported); in contrast, unsafe levels were found at KOW, MBW, and the Kali River (up to 46 MPN/100 mL) (Dharwad District Health Laboratory, 2003). Those previously reported total coliform bacteria concentrations were about two orders of magnitude lower than those observed in this study. Similarly, in 2006, India's Central Pollution Control Board (CPCB, 2006) reported the maximum total and fecal coliform levels in the Kali River downstream of Dandeli as 1800 MPN/100 mL and 560 MPN/100 mL, respectively. In contrast, this study repeatedly found total coliform levels in the river above the method

Table 2—Total coliform bacteria concentrations and removals. Presented data are all annualized and organized by dry and wet seasons. Note that wherever ≥2500 is used, the upper detection limit has been exceeded; as such, the geometric mean and maximum percent removals versus the river are underestimated (GM = geometric mean; MW = riverbank filtration well; KOW = Kariyampalli open well).

Site	*N*	Range[a]		GM[a]	Max. % change vs. Kali River	Avg. % change vs. Kali River	Log-removal of avg. % change
		Low	High				
All data (January to November 2009)							
Kali River	15	370	≥2500	1700	–	–	–
MW1	4	1300	≥2500	1800	48%	−6.1%	−0.026
MW2	4	170	520	360	93%	79%	0.7
MW3	43	4.1	920	85	>99%	95%	1.3
MW4	13	38	≥2500	230	99%	87%	0.87
KOW	7	n/a	≥2500	≥2500	−44%	−44%	−0.16
Dry season (January to May and October to November 2009)							
Kali River	10	400	≥2500	2100	–	–	–
MW1	4	1300	≥2500	1800	48%	11%	0.053
MW2	4	170	520	360	93%	83%	0.76
MW3	29	4.1	920	66	>99%	97%	1.5
MW4	13	38	≥2500	230	99%	89%	0.95
KOW	6	n/a	≥2500	≥2500	0%	−20%	−0.081
Rainy season (June to September 2009)							
Kali River	5	370	≥2500	1200	–	–	–
MW1					No data		
MW2					No data		
MW3	14	7.5	580	140	>99%	88%	0.93
MW4					No data		
KOW	1	–	≥2500	≥2500	0.0%	−110%	−0.32

[a] Most probable number (MPN)/L.

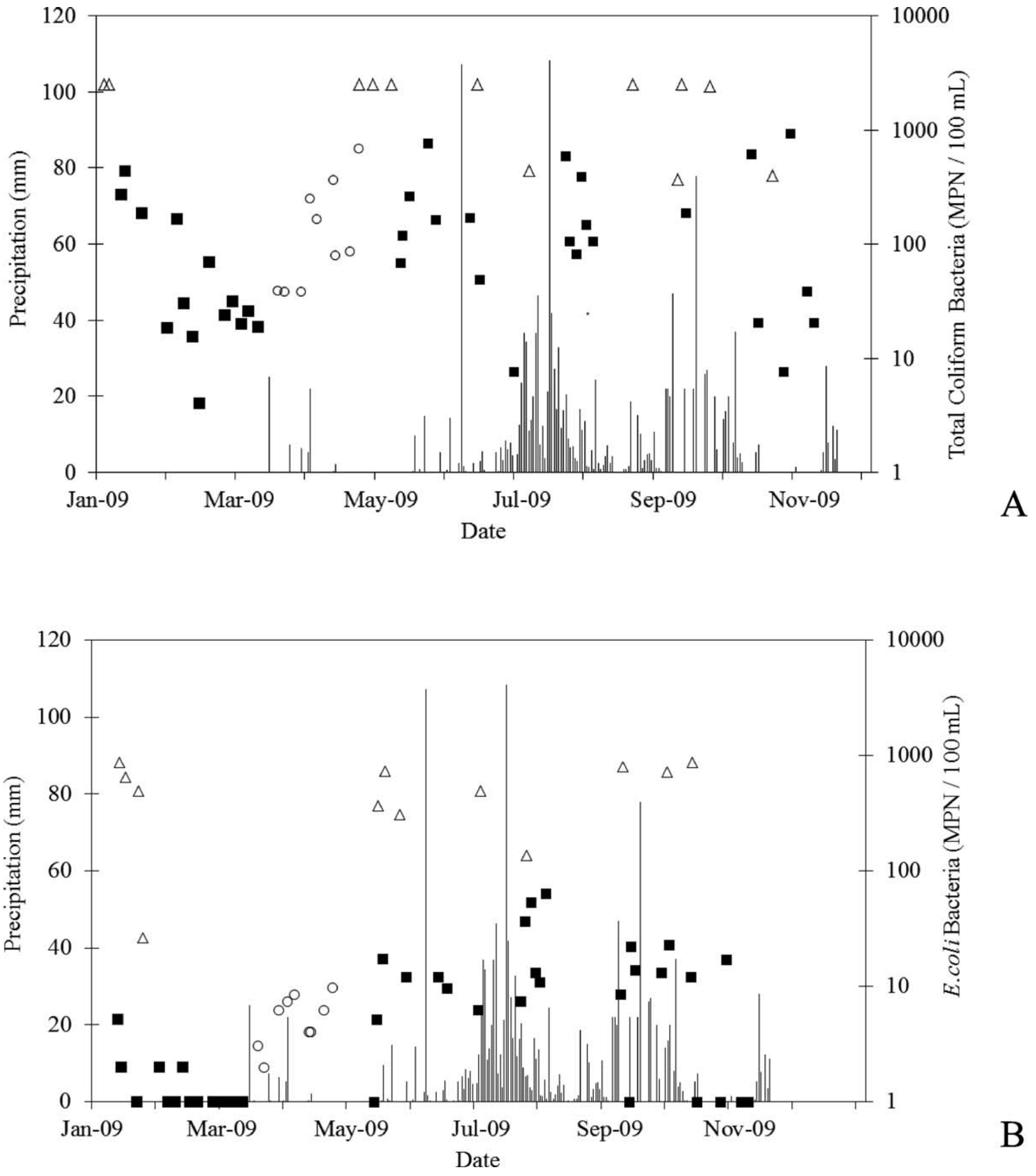

Figure 2—Total coliform bacteria (a) and *Escherichia coli* (b) levels (most probable number [MPN]/100 mL) and rainfall data (mm) over the 2009 monitoring period. Note that the heaviest rains occurred between early July and mid-October (squares = riverbank filtration [RBF] well MW3; circles = MW4; triangles = Kali River; bars = daily precipitation recordings). Solid diagonal trend lines show the similar rates of decline in total coliform concentrations at three stages during the 1-year sampling period.

detection limit of 2500 MPN/100 mL and maximum *E. coli* levels of 870 MPN/100 mL. Because the prior studies did not specify their test methods, it is possible that the differences in concentration are a result of how the fecal indicator bacteria were quantified. It is also possible that the Kali River water quality has declined following the earlier studies.

As shown in Figure 2a, total coliform bacteria concentrations at the RBF production well varied from 4.1 to 920 MPN/100 mL over the year. The average total coliform removal efficiency of MW3 was 97% during the dry season and decreased to 88% during the monsoon. While in operation, water produced from MW3 met BIS guidelines for *E. coli* bacteria in only 10 of the 46 sampling days (22% of the time)—mainly during the dry season (9 days or 29% of the time) and much less so during the monsoon season (1 day or 7% of the time). Total coliform BIS guidelines were never met during the study period; although levels did dip below 10 MPN/100 mL, they never did so on consecutive days.

Table 3—*Escherichia coli* concentrations and removals. Presented data are all annualized and organized by dry and wet seasons. Note that wherever 0.9 is used, the lower detection limit of the method has been exceeded (GM = geometric mean; MW = riverbank filtration well; KOW = Kariyampalli open well).

Site	*N*	Range		GM	Max. % change vs. Kali River	Avg. % change vs. Kali River	Log-removal of avg. % change
		Low	High				
All data (January to November 2009)							
Kali River	12	120	870	460	–	–	–
MW1	3	16	140	42	99%	91%	1.0
MW2	4	1.0	12	4.7	>99%	99%	2.0
MW3	44	0.9	64	3.6	>99%	99%	2.1
MW4	13	1.0	12	4.0	>99%	99%	2.1
KOW	7	27	1700	200	97%	57%	0.4
Dry season (January to May and October to November 2009)							
Kali River	8	120	870	470	–	–	–
MW1	3	16	140	42	98%	91%	1.2
MW2	4	1.0	12	4.7	>99%	99%	2.0
MW3	29	0.9	18	1.8	>99%	>99%	2.4
MW4	13	1.0	12	4.0	>99%	99%	2.1
KOW	6	27	1700	200	97%	58%	0.4
Rainy season (June to September 2009)							
Kali River	4	140	790	440	–	–	–
MW1					No data		
MW2					No data		
MW3	15	0.9	64	13	>99%	97%	1.5
MW4					No data		
KOW	1	–	200	200	75%	55%	0.35

[a] Most probable number (MPN)/L.

The operation of the wellfield over the course of the study revealed water quality differences between wells as well as between seasons. After pumping began in January 2009, bacteria levels in MW3 steadily decreased from 440 to 19 MPN/100 mL by mid-March. The pump was then moved to MW4 and total coliform levels began to increase (39 to almost 700 MPN/100 mL). Because both the pump and the wells were sanitized at the start of the study, the authors assume that the increase in bacteria in MW4 was related to surface inputs, particularly from nearby rice paddies that were irrigated with river water and plowed with the help of oxen. Stable isotopic data from the study site suggest that the irrigated rice paddies contributed water to MW4, but much less (if at all) to MW3 (Boving et al., 2012a). Thus, it appears that flood-irrigation with river water together with fecal waste from draft animals were the likely cause of increasing MW4 total coliform levels. This finding is corroborated by the water quality data from KOW that always exceeded the total coliform detection limit (Table 2). As shown in Figure 1, this well is located at the rice paddies and, in addition to direct contamination from lack of a cover and from lowering unclean buckets into the well, likely receives recharge from the surrounding fields that are irrigated with river water.

Because of worsening bacteria levels, the pump was moved from MW4 in May 2009 and reinstalled in MW3 where it remained for the remainder of the study. As before, bacteria levels trended lower after restarting MW3, reaching <10 MPN/100 mL just before the onset of the heaviest monsoon rains in early July. During the monsoon, total coliform concentrations were high (ranged from ≈100 to 900 MPN/100 mL). In the 2 months following the monsoon, levels dropped to as low as 8 MPN/100 mL.

Collectively, this data set indicates that the monsoon season rains influenced the RBF wellfield. As the river exhibited lower mean total coliform levels in the monsoon (Figure 2a and Table 2), the most likely pathway of bacterial contamination of the RBF well was direct recharge from the surface. Sources of bacteria within the study area include livestock waste as well as latrines and open defecation by residents. At this particular test site, although the owner of the cattle was advised to move the livestock away from the RBF wellfield, it did not occur until October 2009. A follow-up study would therefore be needed to verify whether removing cattle as a source of fecal indicator bacteria had any effect on the RBF water quality.

Figure 3 shows the annual mean percentage change of *E. coli* and total coliform concentrations in RBF wells MW1 through MW4, plus KOW, as a function of distance from the Kali River. The *E. coli* results indicate that water quality of all RBF wells was 91% to >99% greater than the river, whereas the open well KOW showed a lower improvement percentage (57%). In the case of total coliforms, the well water quality, with the exception of MW1, increased with distance from the river, and was highest in MW3. The water quality then declined in MW4 and toward the open well (KOW). This finding corroborates the previously stated possible influence of bacterial contamination (particularly total coliforms) originating from the influx of irrigation water from the rice paddies near KOW to the RBF wellfield. With regard to well MW1, the water quality relative to the river was 6.4% ($n = 4$) lower for total coliform bacteria, but 90.9% better for *E. coli*. That well was located a few meters from a concrete watering basin. The authors suspect that the difference between *E. coli* and total coliform bacteria in this well is related to seepage of contaminated water spilled during animal watering. Although the *E. coli* bacteria were removed during passage

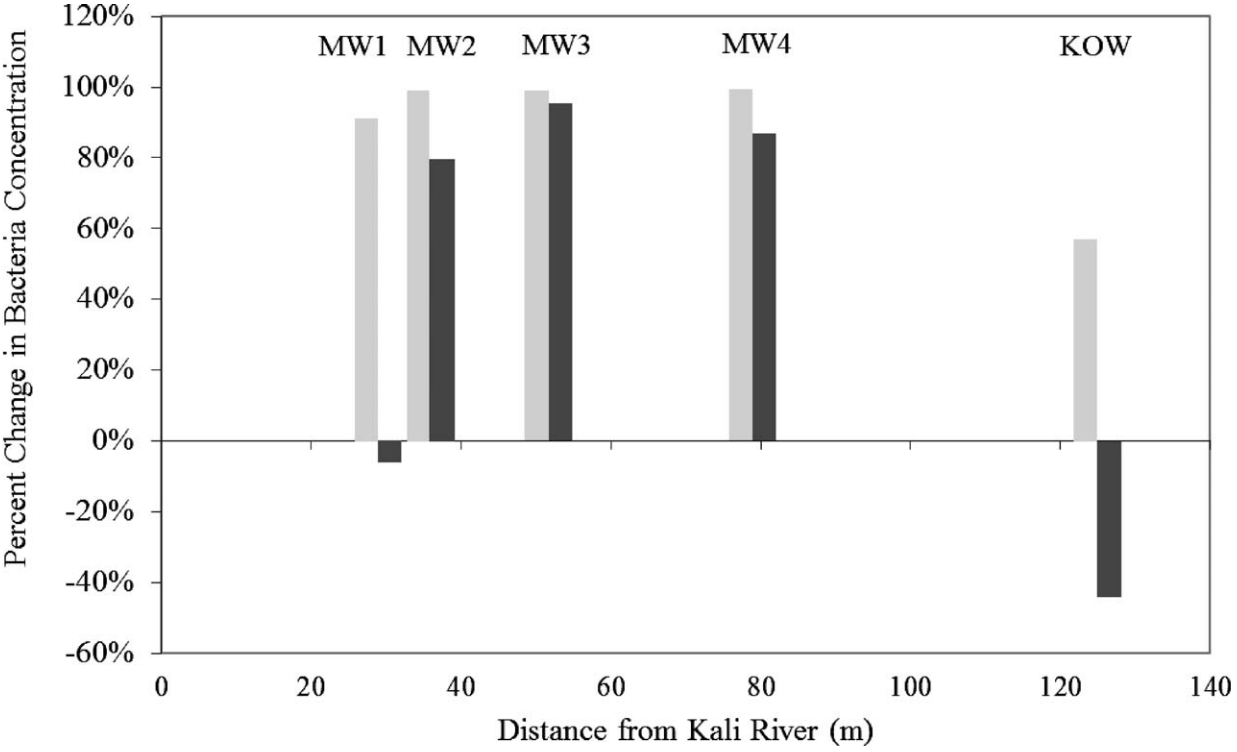

Figure 3—Percent change of *Escherichia coli* (gray) and total coliform (black) concentrations relative to the Kali River versus distance from the river. Note that negative values indicate average water quality that is worse than the Kali River. Presented are the annualized mean data (KOW = Kariyampalli open well; MW = riverbank filtration [RBF] wells 1 through 4).

through the soil, much of the total coliforms appeared to have percolated into the well. The water quality in the adjacent well, MW2, was 79.2% (total coliform) and 99.0% (*E. coli*) better than in the Kali River (Table 2), which suggests that pollution from the surface was a localized problem and only affected MW1 well water.

A similar pattern was evident for the *E. coli* data. As shown in Figure 2b, *E. coli* concentrations in MW3 dropped sharply below the detection limit after pumping began in January 2009. After the pump was transferred to MW4, *E. coli* concentrations trended higher, but never exceeded 10 MPN/100 mL. After pumping resumed in MW3 during the monsoon season, elevated *E. coli* levels were recorded. With one exception (October 2009), these levels declined again to below the detection limit after the rainy season. When the data for each RBF well are examined as a function of distance from the river (Figure 3), water quality increases with distance and is greatest at MW3, but then decreases toward MW4 and the open well (KOW) and rice paddies.

With regard to MW1,the water quality was significantly better (i.e., 90.9% mean removal of *E. coli* relative to the Kali River). However, total coliform concentrations were similar to the river. This result makes is unlikely that direct contamination of MW1 with fecal matter led to the increase in total coliform bacteria. Rather, it is likely that contaminated surface water or animal excrement seeped into the ground near the well and eventually reached MW1, but not until most *E. coli* had already been removed. Sporadic irrigation of a field of banana trees located between the river and the well could also have introduced contaminated water in the vicinity of that well (Figure 1). The best microbial water quality was consistently produced from MW3, which removed more than 99% (up to 2.4 logs) of *E. coli* relative to the river (Table 3). The removal efficiency translates to approximately 1-log unit of *E. coli* removal per 26 m (≈75 feet) of setback distance from the river.

Finally, Boving et al. (2013) used dissolved silica data to calculate the fraction of groundwater drawn in with the river water at each RBF well. At MW3, this mixing ratio was about one-quarter river water and three-quarters groundwater. This proportion was used in this study to predict the degree of attenuation of bacteria concentrations that results from the dilution of contaminated river water with (theoretically) bacteria-free groundwater. Figure 4 shows the annual geometric mean measured bacteria concentrations versus those predicted by the dilution model. According to these calculations, actual total coliform removal at MW3 was more than five times greater than that attributed to dilution alone, and 36 times greater in the case of *E. coli*. These results confirm that factors beyond dilution, such as biological activity and filtration (Schijven et al., 2002), are at work in removing bacteria in the RBF process at this test site. However, an investigation of these attenuation processes was beyond the scope of this study.

The persistent problems of attaining BIS regulatory limits for bacteria demonstrate that at this site RBF (1) needs to be considered as a pre-treatment method, and (2) should be combined with conventional disinfection technology such as chlorination or UV disinfection. Water with low bacterial counts (e.g., <10 MPN/100 mL) might increase in contamination level during storage (Schmidt et al., 2003). For this reason alone, some disinfection will be required to meet BIS standards. However,

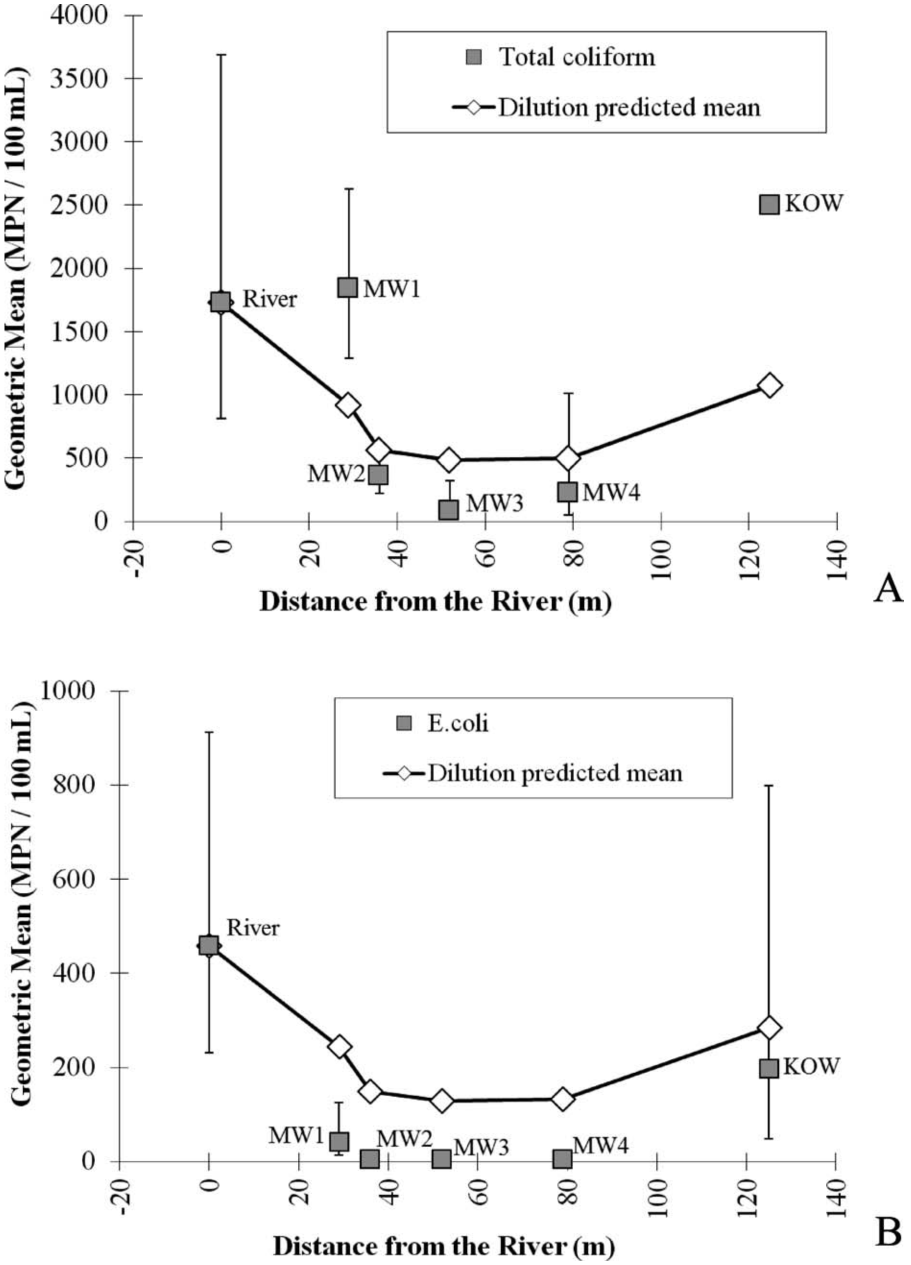

Figure 4—Measured and predicted annualized geometric mean total coliform bacteria (a) and *Escherichia coli* (b) concentrations compared to dilution model estimates from Boving et al. (2012a). Note that error bars show upper and lower range of geometric mean standard deviation of measured values.

achieving these standards will be much easier and less costly by using RBF-treated water rather than treating raw Kali River water (Kühn and Müller, 2000; Schmidt et al., 2003). In this regard, previous studies have shown that nanofiltration membranes had to be replaced every 8 days when used with conventionally pre-treated surface water compared to 62 to 75 days when used with water pre-treated via RBF (Ray et al., 2002).

Conclusions

Analysis of a RBF system in a rural village in monsoon-dominated southwestern India was conducted to investigate its performance during dry and wet seasons. The results of bacterial monitoring are summarized herein. A companion paper by Boving et al. (2013) summarizes the results of concomitant hydraulic, geochemical, and hydrogeological site investigations.

Statistical analysis shows significantly higher water quality at the primary RBF well (MW3) in comparison with pre-existing water sources in the study area. Based on the data from MW3, the mean percent removal compared to the Kali River was 95.1% for total coliforms and 99.2% for *E. coli*. The maximum percent removal was 99.8% for total coliforms and 99.96% for *E. coli*. Although greater removal of *E. coli* than total coliform bacteria was typically observed, an evaluation of the underlying causes was beyond the scope of this study. Bacteria concentrations in well water were lower during the dry season than during monsoon when rains apparently leached bacteria into the subsurface. Over the course of the 1-year monitoring period, Indian water quality standards for total coliforms were exceeded regularly, whereas *E. coli* standards were met 29% and 7% during the dry and monsoon seasons, respectively. The persistent problem of exceeding BIS regulatory limits for bacteria show that, for this study site, RBF should be considered a pre-treatment method and combined with conventional disinfection technologies.

Although total coliform and *E. coli* data sets confirm the importance of setback distance of a RBF well from a river in determining microbial water quality, local conditions, such as the proximity and influence of flood-irrigated rice paddies, the presence of freely roaming livestock and latrines, and outside defecation of residents, must be considered when establishing an RBF system in a monsoon climate in a developing country. For these reasons, technical and engineering support must be accompany farmer education about the importance of fencing-out livestock for wellhead protection, as well as behavioral changes with respect to personal sanitation and hygiene practices. Such modifications can be expected to reduce bacteria input from surface waters over time.

This study also provides strong evidence that siting an RBF well needs to account for surrounding land use; that is, in rural areas that rely on highly contaminated surface water for irrigation, RBF systems should be sited as far away from irrigated fields as possible.

In conclusion, this study demonstrates that RBF is a suitable pre-treatment technology for water in monsoon-dominated rural communities in developing countries.

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