Hydraulic and Hydrogeochemical Characteristics of a Riverbank Filtration Site in Rural India

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ABSTRACT: A riverbank filtration (RBF) system was tested along the Kali River in rural part of the state of Karnataka in India. The polluted river and water from open wells served the local population as their principal irrigation water resource and some used it for drinking. Four RBF wells (up to 25 m deep) were installed. The mean hydraulic conductivity of the well field is 6.3×10^{-3} cm/s and, based on Darcy's law, the water travel time from the river to the principal RBF well (MW3) is 45.2 days. A mixing model based on dissolved silica concentrations indicated that, depending on the distance from the river and closeness to irrigated rice fields, approximately 27 to 73% of the well water originated from groundwater. Stable isotopic data indicates that a fraction of the water was drawn in from the nearby rice fields that were irrigated with river water. Relative to preexisting drinking water sources (Kali River and an open well), RBF well water showed lower concentration of dissolved metals (60.1% zinc, 27.8% cadmium, 83.9% lead, 75.5% copper, 100% chromium). This study demonstrates that RBF technology can produce high-quality water from low-quality surface water sources in a rural, tropical setting typical for many emerging economies. Further, in parts of the world where flood irrigation is common, RBF well water may draw in infiltrated irrigation water, which possibly alters its geochemical composition. A combination of more than one mixing model, silica together with stable isotopes, was shown to be useful explaining the origin of the RBF water at this study site. *Water Environ. Res.*, **86,** 636 (2014).

KEYWORDS: riverbank filtration, stable isotope, dissolved silica, heavy metals, water treatment, India, emerging economy, groundwater, flood irrigation, monsoon.

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Introduction

More than one billion people in the world—11% of the global population—do not have access to safe drinking water (UNICEF, 2012). And although in developing countries, like India, measurable progress has been made in supplying safe water, gross disparity exists in coverage between urban and rural areas. For instance, latrine usage is low in rural areas of India and only 14% of rural Indians have access to a latrine (Water.org, 2012). Quite often wastewater, together with industrial effluent and agricultural runoff, is discharged to rivers and lakes with little or no treatment. Yet microbial and chemical contamination of water resources can often be addressed with simple solutions, such as improvements in sanitation, hygiene, and treatment. One potential promising solution is riverbank filtration (RBF), which is a water treatment technique that has been used in Europe for over 100 years (Ray et al., 2002; Schmidt et al., 2003). For example, RBF supplies 75% of the water supply to the German capital of Berlin (Hiscock, 2005). In the Netherlands, RBF contributes about 7% (80 Mm^3/yr) of the national drinking water supply (Stuyfzand et al., 2004*)*.

In an RBF system, water is withdrawn from one or more wells near a river or lake. Wells may either be vertical or horizontal (Sandhu et al., 2011) and typically are installed more than 50 m away from the river (Grischek et al., 2002). By pumping an RBF well, the groundwater potential is lowered and river water (together with groundwater) is induced to flow through porous riverbed sediments (Hiscock and Grischek, 2002). As the raw surface water travels toward the RBF well, dissolved and suspended contaminants, as well as pathogens, are potentially removed or significantly reduced in numbers resulting from a combination of physical, chemical, and biological processes (Hubbs et al., 2004). Pathogen removal efficiencies of 3 to 4 log are quite common (Boving et al., 2010; Kelly and Rydlund, 2006; Kühn and Mueller, 2000; Kumar and Mehrotra, 2009). Similarly, Schmidt et al. (2003) demonstrated that RBF systems can reduce heavy metals concentrations of zinc (82%), copper (51%), lead (75%), chromium (94%), and cadmium (75%).

In general, the degree of pollutant removal depends largely on the properties of the materials through which the flow takes place. There is evidence that much of the contaminant removal occurs at the interface between the river and the sediments (Albrechtsen et al., 1998; Bellamy et al., 1985). This zone is known as the *colmation zone* or *schmutzdecke* and is characterized by high microbial activity and small grain size (Wang et al., 1995). It is thought that periodic scouring during flood events regenerates the treatment activity of the colmation layer (Gupta et al., 2009). Due to these auto-regenerative natural treatment processes, properly engineered RBF systems can maintain essentially unlimited treatment durations (Schubert, 2002).

Riverbank filtration offers an inexpensive means to remove large amounts of contaminants and improve the quality of the water delivered for domestic use (Schubert, 2002). Although typically considered a pretreatment technology preceding more

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advanced treatment operations (Ray, 2002; Schmidt et al., 2003; Speth et al., 2003), RBF may in some cases serve as the final step in providing drinking water (Dash et al., 2010). The advantages of using RBF for water treatment are removal of particles and turbidity (Dash et al., 2008, 2010; Dillon et al., 2002) and attenuation of bacteria, viruses, and parasite loads (Berger 2002; Boving et al., 2010; Dash et al., 2010; Gollnitz et al., 2003; Havelaar et al., 1995; Schijven et al., 1998, 1999; Tufenkji et al., 2002; Wang 2002; Weiss et al., 2003). Further, water treatment by RBF typically increases the degradation of micropollutants and lowers the concentration of pesticides and natural organic matter (Doussan et al., 1997; Kühn and Müller, 2000; Massmann et al., 2003; Miettinen et al., 1994; Ray et al., 2002; Verstraeten et al., 2002; Wang, 2002). Riverbank filtration also is known to attenuate the concentration of disinfection byproduct precursors (Weiss et al., 2002, 2003) and this technology is recognized for smoothing out temperature and concentration variations and compensating for peak pollution and shock loads (Ray, 2004).

Riverbed (alluvial) sediments are often highly permeable and the depth to groundwater in the vicinity of rivers is commonly relatively shallow. These attributes often make shallow RBF wells located near rivers highly productive, less costly to drill than typical groundwater resources (Schubert, 2002), and less prone to contamination than surface water resources (Ray et al., 2002). For these reasons, RBF technology is well suited for use in developing and industrial countries (Boving et al., 2010; Dash et al., 2010; Sandhu et al., 2011).

Historically, RBF has been used mostly along rivers in temperate and cold climates such as Germany (Schubert 2002). Until recently, RBF has been relatively untested in monsoonal climates, that is, locations dominated by strong seasonal rains followed by a prolonged dry season (Kumar and Mehrotra, 2009; Sandhu et al., 2011). Because of the limited number of studies on RBF's performance in these settings, municipalities in developing countries appear reluctant to adopt this water treatment technology (Cady et al., 2013). Using a field site in the heavily polluted Kali River in southern India as a showcase, the principal objective of this research was to evaluate the performance of RBF under the environmental conditions of a monsoon-influenced emerging economy, that is, a distinct dry and wet seasons with highly variable river stage elevations together with currently limited investments in water infrastructure. Another objective was to study possible effects on RBF wells resulting from farming practices that rely on flood irrigation using river water.

According to local health officials, the Kali River was the major source of drinking and irrigation water for more than 160,000 people in this part of rural Karnataka, India, in 2007. The river's water quality is compromised by industrial influent and untreated wastewater discharges in addition to monsoon season runoff. These conditions are all too common in India and other developing countries and could potentially affect the performance of an RBF system. To evaluate if a small community-sized RBF system is capable of producing high-quality water from the low-quality local river water for agricultural use and pretreatment for potable use, an RBF test site was installed along the Kali River.

This paper summarizes the RBF well field hydrogeology and hydraulics, including the results of a tracer test and the geochemical analysis of stable isotopic data and dissolved silica mixing model data. In a companion paper (Cady et al., 2013), the results of a yearlong water quality study of microbial contaminants at the RBF test site are described. Other elements of this study, such as testing the acceptance and economics of the RBF system and an assessment of possible changes in the health of the villagers served by RBF water have been summarized elsewhere (Boving and Choudry, 2010; Boving et al., 2012; Choudry and Boving, 2010).

Methodology

The study was conducted in a rural area along the Kali River in northwestern Karnataka, India (Figure 1a). The Kali River is a 185-km-long perennial river with a drainage basin of 3376 km^2 (Manjunatha, Balakrishna, Shankar, Mahalingam, 2001; Manjunatha, Balakrishna, Shankar, Sarin, 2001). This river flows west out of the Western Ghats and passes four dams en route to the Arabian Sea. The Kali River discharges at an average annual rate of 197 m^3/s at its lowest dam 35 km inland from the Arabian Sea (Radhakrishna and Vaidyanadhan, 1997). It originates near the Diggi village on the border of the states of Karnataka and Goa and joins the Arabian Sea near the Uttara Kannada District capital of Karwar. At the study site, the river's maximum depth was approximately 8 m and, according to local fishermen, varies by 4 m or more during the seasons.

The RBF well field was installed near the village of Kariyampalli (15°13′55.4" N, 74°39′55.6" E). This small village (population ≈1000) is located approximately 5 km downstream from the town of Dandeli (population 46,760). Dandeli is a major industrial city in Karnataka's Uttara Kannada district and is surrounded by several satellite villages. These villages commonly have a single dirt road bordered by simple houses, a small school, and perhaps a health clinic. The villages are surrounded by irrigated paddy fields and typically lack secure sources of safe drinking water. Industrial effluents released upstream from the study site appear to cause water pollution throughout the year. Resulting from the lack of other options and weak enforcement of existing water quality regulations, contaminated river water serves many uses, including drinking and flood irrigation of rice paddies.

Hydrogeology and Climate. The geology of the study area is characterized by the late Archaean Dharwar Schist Belt, which forms a plateau and ridge system west of the site. The Shimoga Basin of the Chitradurga Group, which encompasses the study site, consists of schists, conglomerates, limestones, greywackes, and cherts. Overlying these metasedimentary rocks are laterites up to 60 m thick (Radhakrishna and Vaidyanadhan, 1997). These clay-like, reddish laterites are structured soils that support the movement of water. Alluvial deposits along the Kali River, where present, are composed of partially rounded bedrock fragments of variable sizes. These deposits range in thickness from a few meters to 14 m and in the study area, the river fully penetrates the alluvial aquifer (PRE, 2006).

According to the local Panchayat Raj Engineering office in Haliyal, the mean depth to groundwater ranges from 3 to 30 m below ground surface (bgs). At the study site, groundwater was encountered at 3 to 4 m bgs. Main aquifers are formed in the weaker, weathered, and fractured bedrock and in laterites along with the alluvial patches found adjacent to major stream courses. Groundwater in the alluvial and lateritic aquifer materials occurs under unconfined, semiconfined, and confined conditions and is typically extracted by dug or bore wells. Dug wells in the area are 2 to 3 m in diameter with depths from 4 to 20 m. Bore wells vary

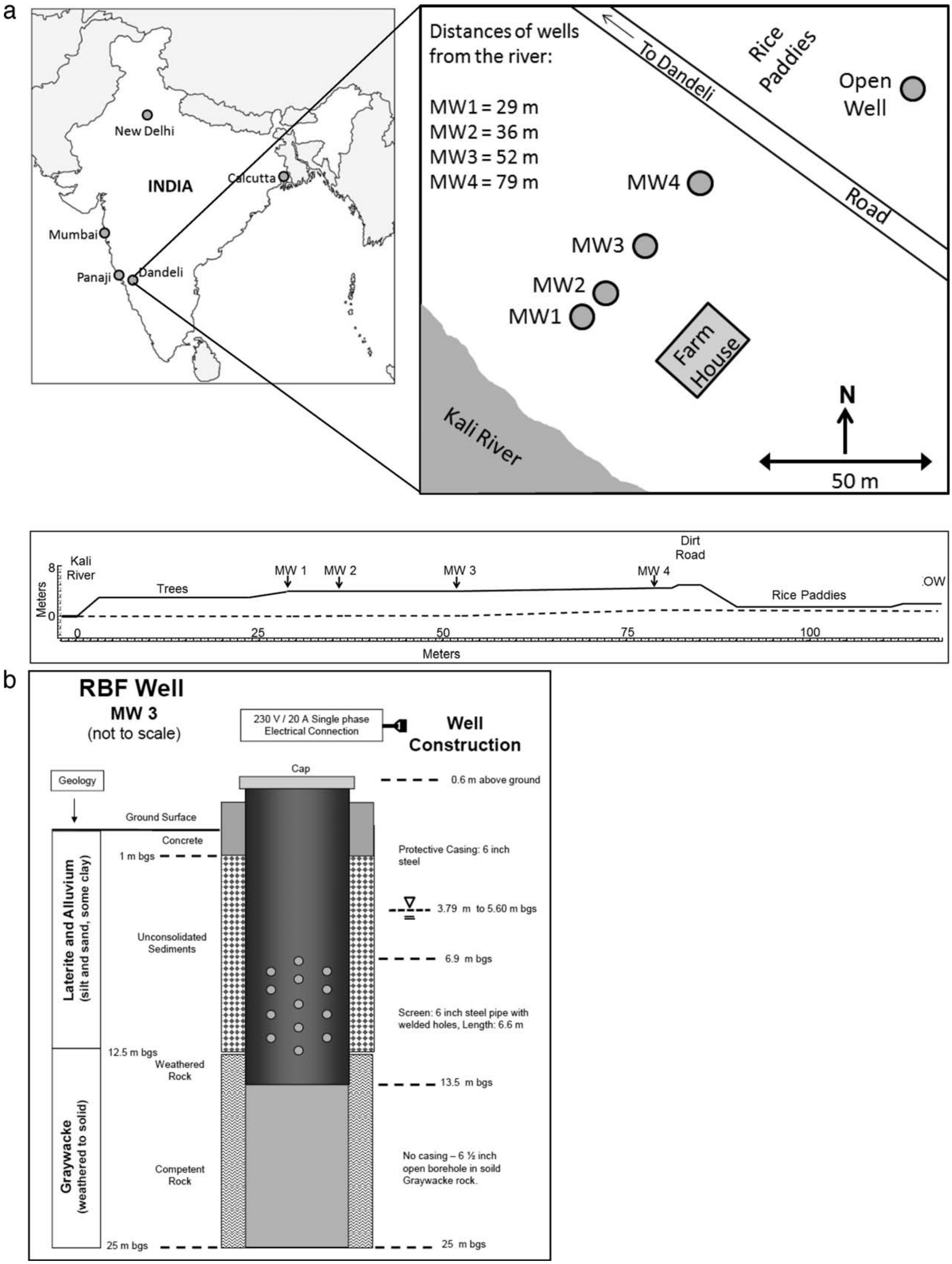

Figure 1a—Map of study area and cross-section of the riverbank filtration (RBF) test site near the town of Dandeli. MW = RBF wells 1 through 4. OW = open well serving the village of Kariyampalli. Note: Open well is surrounded by rice paddies irrigated with water from the Kali River. A bore well was located outside the map area. For cross-section: vertical and horizontal scale as shown (in meters)

from 40 to 80 m in depth with an average of 70 m. The yields of bore wells range from 50 to 250 m^3/d with a specific capacity between 15 to 95 m^2/d. Drawdown varies from 2 to 10 m. Dug well yields vary from 71 to 264 m^3/d and specific capacity ranges from 90 to 140 m^2/d. Eighty percent of the wells in the area yield 150 m^3/d (PRE, 2006).

The study area lies in the path of India's southwestern monsoon. The year may broadly be classified into two seasons. A dry season from October to May is followed by the humid monsoonal season, lasting from June to September. The total annual precipitation is 1500 mm. July is the wettest month with normal monthly rainfall in excess of 300 mm. Winds are predominantly southwesterly during the summer monsoon and northeasterly during the winter. Thunderstorms are common during the monsoon. Generally, the weather is hot throughout the year, peaking in May when the highest daytime temperatures can rise to 38 °C.

Field Methods. In January 2008, the search for a suitable RBF test site began with a hydrogeochemical survey of existing surface- and groundwater resources, including tap water, in the wider study area. Calibrated hand-held meters were employed to test each water source for pH, temperature (T), oxidation reduction potential (ORP) (tester HI98121; Hanna Instruments, Smithfield, Rhode Island), electrical conductivity, and total dissolved solids (TDS) (Hanna Instruments' HI98129). During the survey, test strips were used for estimating alkalinity (as $CaCO_3$) and hardness (Insta-Test5 pool and spa strips; LaMotte Co., Chesterton, Maryland), iron (Fe^{2+}/Fe^{3+}; Orion Research Aquafast; Thermo Fisher Scientific, Waltham, Massachusetts), nitrate/nitrite, chloride, free chlorine (Sensafe; Industrial Test Systems, Rock Hill, South Carolina), and total ammonia (Aquacheck; Hach Co., Loveland, Colorado). Free chlorine was included because of concern for the presence of bleach in the effluent from an upstream paper mill. Test strips have obvious limitations, but with reasonable accuracy they provide an indication of the general water quality characteristics at each location. All sample and survey locations were spatially referenced with a hand-held global positioning system (GPS) receiver (GPS 12 XL; Garmin, Ltd., Olathe, Kansas). The field survey data set was supplemented by water quality data from the literature and public records.

The principal water quality monitoring campaign lasted from January through December 2009. Ion, metal, and silica samples were collected in 100 mL HDPE plastic sample bottles. All samples were field filtered with glass 2-μm microfiber filter (Whatman, Inc., a division of GE Healthcare Bio-Sciences, Pittsburgh, Pennsylvania) followed by 0.45-μm filters (Whatman, Inc.). Metal samples were acidified with hydrochloric acid (Rankem, RFCL Ltd., New Delhi, India). Well water samples were collected under routine operating conditions of the RBF well field. The pump operated for about 6 hours every day, usually during the morning. Samples were collected at least once a week and after the pump had been running for at least 1 hour. Samples collected during 2009 were shipped to the University of Rhode Island (URI) and analyzed for anions and cations (Dionex ion DX-120 chromatograph; Dionex Corp., Sunnyvale, California) and heavy metal concentrations by ICP-MS (Thermo Electron Corporation [Waltham, Massachusetts] X-Series II Quadrapole). One in 10 samples tested were duplicates or standards for quality assurance and quality control. To study the relative contributions of river and groundwater to the RBF system, aqueous samples for naturally occurring silica and the stable isotopes of oxygen and hydrogen were collected. Silica samples were collected in 100-mL plastic bottles. The samples were field filtered with glass microfiber and 0.45-μm pore size filters (Whatman, Inc.). The samples were analyzed at the URI following the dissolved silica analysis after APHA molybdosilicate method #3113C on a Shimadzu UV-Visible 1601 Spectrophotometer (Shimadzu Corp., Kyoto, Japan). Stable isotope samples were collected in 50-mL plastic bottles with no field filtering or acidification. All isotope samples were sent to the Northern Arizona University's Colorado Plateau Stable Isotope Laboratory (CPSIL) for analysis on a Los Gatos Research Laser Mass Spectrometer. Samples were also analyzed for bacteria; results are discussed in the companion paper (Cady et al., 2013).

Riverbank Filtration Well Field. Based on the results from the 2008 survey, a site near the village of Kariyampalli was selected. The site sits on the eastern bank of the Kali River and is surrounded by rice fields and farm land (Figure 1). The site selection criteria were (1) accessibility of land next to the river and cooperation of the landowner, (2) need for safe water for drinking and agriculture, (3) presence of alluvial sediments, (4) degree of contamination of the Kali River, and (5) proximity of a village to the RBF well.

Visual inspections of outcrops within the study area, the examination of drill log data obtained from the local Panchayat Raj Engineering office in Haliyal, and observations made during the drilling of the RBF wells show that the geology in the study area is characterized by lateritic brownish-red silty loam and structured clay from the top to 8 to 10.5 m bgs, followed by a silty-sandy clay or light brown fine sand and silt layers of about 2 m, followed by 1 to 3 m of weathered greywacke or sandy-silty alluvium. The base of the strata is composed of solid greywacke.

In October 2008, four wells were drilled using the air hammer rotary method. Drill mud was removed by flushing the wells with pressurized water free of any additives. The wells were installed approximately perpendicular to the river with the farthest well (MW4) 79 m away from the riverbank (Figure 1a). An existing open well (KOW) is located 125 m away from the river and about 300 m from the village of Kariyampalli. The depth of this brick-constructed open well was approximately 7 m and its diameter 2.1 m. The well was uncovered and buckets were used to recover water for domestic uses. A small electric pump provided water for irrigation to the adjacent rice paddies.

Four wells were installed to systematically study the well field hydraulics and changes in RBF water quality with distance from the river. The elevation of the well field site was 454 m above sea level. A slight slope of the land surface toward the river was observed but could not be measured accurately with the available GPS equipment.

The thickness of the lateritic soil and the river bed sediments ranged from 12.5 to 14.0 m followed by bedrock beneath (Table

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(modified after Cady et al., 2013). Figure 1b—Riverbank filtration well construction diagram for well MW3 (RBF = riverbank filtration; bgs = below ground surface).

Table 1—Riverbank filtration well field installation data.

Parameters	MW1	MW2	MW3	MW4
Station name	Kariyampalli	Kariyampalli	Kariyampalli	Kariyampalli
Date installed	Oct. 26, 2008	Oct. 26, 2008	Oct. 26, 2008	Oct. 26, 2008
Land ownership	Private			
Location description	5 km ESE from Dandeli			
Latitude	15° 13′ 56.8″ N	15° 13′ 56.9″ N	15° 13′ 57.3″ N	15° 13′ 57.8″ N
Longitude	74° 39′ 54.8″ E	74° 39′ 55.0″ E	74° 39′ 55.4″ E	74° 39′ 56.1″ E
Above mean sea level (m)	454			
Distance from river (m)	29	36	52	79
Depth of well at time of drilling (m)	20	25	25	25
Depth to bedrock (m)	13.3	13.0	12.5	14.0
Width of well bore (in.)	7.5			
Length of casing (m)	12	12	11	12
Casing diameter	150 mm (6.0 in.)			
Slotted screening length (m)	No screen	7	7	7
Slotted screen diameter (in.)	NA	6	6	6
Static water level below surface (m)	4.29	4.42	3.79	3.84
Yield (m^3/hr)	2.16	3.60	>9.3	6.85
Slug test hydraulic conductivity (*K*; cm/s)	2.0×10^{-2}	1.8×10^{-2}	7.2×10^{-3}	6.4×10^{-3}

1). The construction of the well field is exemplified by well MW3 (Figure 1b). Solid steel 150-mm (6-in.) casing reached from approximately 0.6 m above ground to 13.5 m bgs. The well screen was manufactured at the site by cutting 10 mm wide and approximately 100-mm-long slots with a blow torch into the steel casing. The screen penetrated the unconfined aquifer from 6.9 m bgs down to the bedrock (Table 1). No casing or screen was used in the bedrock. At the surface, concrete was poured between the casing and the bore-hole to a depth of 1 m. The remainder of the space between the casing and the bore-hole was back-filled with collapsed natural sediment. The final depth of the well at the time of drilling was 25 m. The construction of the other three wells was similar except for MW1, which was drilled to just 20 m bgs and not screened. The static water levels were approximately 4 m bgs in all wells. Additional well field information is provided in Table 1. An electric submersible pump (CRI Pumps, Hubli, Karnataka) and calibrated class B CM/L water meters (Dasmesh India; Malerkotla, Punjab, India) were purchased locally. The 2 HP (1.49 kW) single phase 230-V pump had approximately 8 m^3/hr capacity at 100 m head.

All well heads were encased in a 1 m by 1 m concrete slab for protection and covered by a steel cap. The location of each well was documented with a hand-held GPS (Table 1). Prior to use, all wells were sanitized with a solution of 1 part 5% sodium hypochlorite (NaOCl) bleach to 3 parts water. The solution was left in the well overnight and then the wells were pumped continuously for at least 1 day.

Two aquifer tests were conducted on well MW3 (pumping rate: 9 m^3/hr). The pumping rate was about twice the anticipated production rate during well field operation. Water levels in the river, pumping well, and nearby wells were monitored electronically (In-Situ LevelTroll 500 and BaroTroll 500). Additionally, slug tests were conducted on all wells. The river stage was monitored electronically (LevelTroll; InSitu, Inc., Ft. Collins, Colorado) between January and April 2009.

The standard technique to determine the travel time from an injection point to a well is to inject a pulse of an easy-to-measure conservative tracer, such as a salt solution, and observe the breakthrough curve in the well (e.g., Davis et al., 1980; Lin et al., 2003). In this study, the tracer test was conducted to determine the time it takes for the tracer to be drawn from the injection well (MW2) to the pumping well (MW3). The test was performed in May 2009 by dissolving 3 kg of common table salt in 20 L of RBF water (150 g/L). The tracer solution was poured into MW2 at a rate of about 2 L/min. Using a plunger, the salt solution was mixed with the water within the injection well. The initial salt concentration in the well after mixing was 8 g/L, which was sufficiently low to deter density-driven flow of the tracer plume. The arrival of the tracer was measured by monitoring the electrical conductivity with a data logger (Levelogger; Solinst Canada Ltd., Georgetown, Ontario, Canada) installed in MW3. The pumping rate at well MW3 was 9 m^3/hr on average. The distance between both wells was 16 m (Figure 1). The tracer test ran for more than 6 days. Daily electric power outages, lasting from less than 1 hour to 12 hours, were common.

Results and Discussion

Hydrogeochemistry. During the initial water quality survey in 2008, river water and water samples from 22 different locations were tested (Table 2). All data, including pictures of each sampling location, was tabulated for linkage to Internet-accessible Google Earth maps (Google, Inc., Mountain View, California). The Kali River water ($n = 6$) was characterized by near neutral pH values, positive ORP values, and comparably low alkalinity, TDS, and electrical conductivity. These observations were similar to previous studies (Bharati and Krishnamurthy, 1990, 1992; Chavadi and Gokhale, 1984; Krishnamurthy and Bharati, 1994, 1996; Manjunatha, Balakrishna, Shankar, Mahalingam, 2001; Subramanian et al., 1987). Distinctly different measurements were recorded at an industrial wastewater confluence point downgradient from the town of Dandeli ($n = 1$; data not shown in Table 2), where the ORP was negative, the temperature of the effluent more than 6 °C higher, and electrical conductivity and TDS about 22 times higher than in the river.

The water quality of the open well (KOW; $n = 4$), relative to the river, is characterized by similar pH; lower ORP; and higher alkalinity, TDS, and electrical conductivity values. The lower

Table 2—2008 water quality survey data. Values in parentheses are averages.

Parameter	River ($n = 7$)	Open well ($n = 4$)	Hand pumps ($n = 6$)	Tap water ($n = 4$)
pH	7.3 to 7.6 (7.4)	6.9 to 7.4 (7.2)	6.3 to 7.2 (7.0)	7.3 to 7.5 (7.4)
Electrical conductivity (μS/cm)	34 to 168 (69)	235 to 922 (490)	243 to 2327 (1120)	42 to 557 (344)
Total dissolved solids (mg/L)	17 to 83 (34)	117 to 462 (247)	121 to 1162 (558)	20 to 278 (172)
Alkalinity (mg/L)	0 to 40	40 to 180	40 to >180	0 to >180
Oxydation reduction potential (mV)	207 to 284 (238)	150 to 233 (201)	–149 to 140 (35)	241 to 434 (298)

ORP values point to the degradation of dissolved organic matter during passage through the aquifer, while the higher alkalinity, TDS and electrical conductivity values suggest increased dissolution of mineral matter. Water from hand pumps ($n = 6$) had a low average pH and a comparably wide range of ORP values and very high electrical conductivity and TDS measurements. Outliers were more common in hand pumps that were used infrequently, if at all. Tap water ($n = 4$), available in Dandeli only, had TDS and electrical conductivity values ranging between that of the river and open wells. Alkalinity ranged widely.

Nitrate was 5 mg/L or less at all locations, except in one hand-pump water sample where 20 mg/L was detected. Sulfate concentrations ranged from 0 to 250 mg/L. The Indian drinking water quality standard for iron is 0.3 mg/L (as Fe; BIS, 1992; reaffirmed 1993) and was exceeded frequently, including in the Kali River. In general, compared to subsequent and more accurate ion chromatography measurements of nitrate, sulfate, and IC-PMS analysis of iron at the URI laboratories, the test strips tended to overestimate the concentrations of these ions. The BIS total hardness standard of 300 mg/L was exceeded only in hand-pump samples and the wastewater effluent sampling location. Total ammonia ranged from 0 to >6 mg/L and total chlorine was 1 mg/L or less in all samples. The absence of elevated chlorine concentrations indicated that any bleach that may have been discharged from industrial sources to the river upstream from the well field had been diluted or decayed. All bacteria data are discussed in Cady et al., 2013.

During the 2009 monitoring campaign, cation ($n = 80$) and anion ($n = 63$) samples were analyzed. Fewer anion samples were analyzed because of inadequate sample preservation. The average concentrations, including the range of major cations and anions collected from the RBF well field and samples from nearby wells and the Kali River, are shown in Figure 2. Overall, the RBF production well MW3 delivered water with a major cation and anion content that falls between the river and local shallow groundwater collected at KOW.

In addition to the major cations and anions, dissolved concentrations of noteworthy metals were determined from water sources in and around the RBF well field (Table 3). Relative to the Kali River (Figure 3), the water quality from well MW3 was improved, that is, the concentration of dissolved metals were lower by 27.8% cadmium, 60.1% zinc, 100% chromium, 83.9% lead, and 75.5% copper. Concentrations of manganese (–43.1%) and particularly iron (–2788%) were higher in the well water relative to the river. This was caused by initially high levels of iron- and manganese-rich particulates mobilized by pumping from newly installed wells in an iron/manganese-rich lateritic aquifer. Both iron and manganese concentrations decreased significantly after 1 year of pumping. Overall, the average RBF water quality is superior to the river water and all applicable drinking water standards for metals were met (BIS,

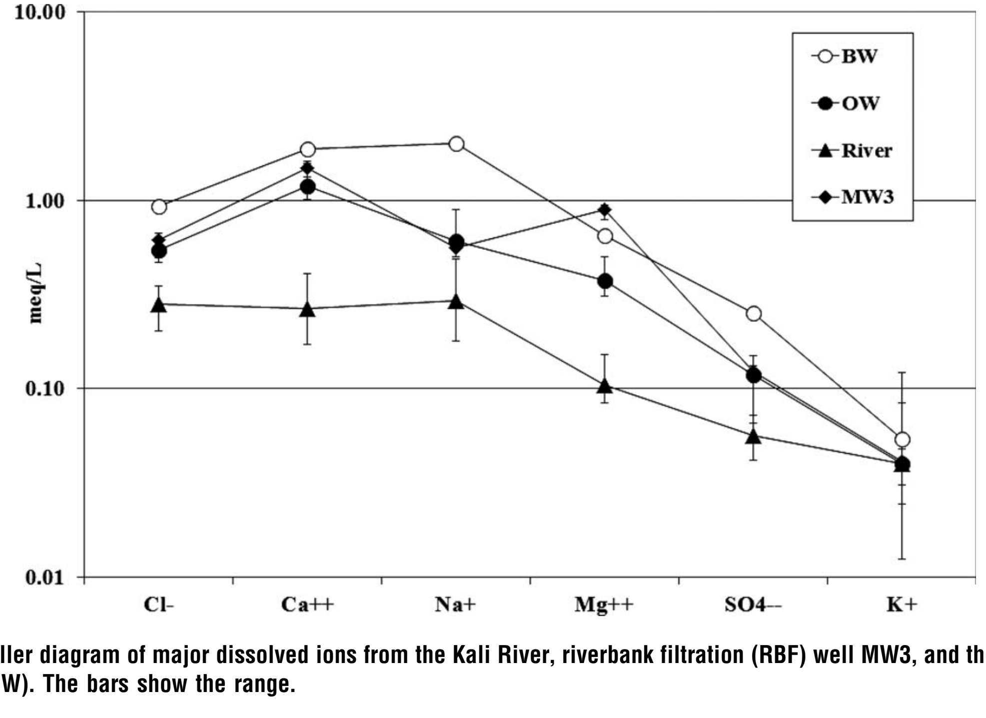


Figure 2—Schoeller diagram of major dissolved ions from the Kali River, riverbank filtration (RBF) well MW3, and the open well (OW) and bore well (BW). The bars show the range.

Table 3—Average dissolved metal concentrations including the percentage change in well MW3 relative to the river. Values in parentheses show range; asterisks (*) show statistical outlier concentrations using Dixon's Q test for outliers.

Parameter	River ($n = 14$)	MW3 ($n = 8$)	Open well ($n = 8$)	Hand pumps ($n = 6$)	Tap water ($n = 6$)	Δ%
Zinc (ppb)	31.6 (<0.1–225.7)	12.6 (<0.1–29.4)	20.5 (3.1–416.9)	228.6 (5.0–6004)	4.4 (<0.1–17.7)	60.1%
Lead (ppb)	1.37 (<0.09–8.01)	0.22 (<0.09–0.89)	1.11 (0.11–22.20)	3.58 (<0.09–13.62)	0.76 (<0.09–2.40)	83.9%
Copper (ppb)	1.43 (<0.1–5.31)	0.35 (<0.1–0.86)	1.58 (<0.1–27.5)	2.17 (<0.1–44.46)	0.14 (<0.1–0.57)	75.5%
Chromium (ppb)	0.40 (<0.07–3.28)	<0.07	0.75 (<0.07–1.96)	0.80 (<0.07–15.83*)	0.65 (<0.07–1.77)	100%
Cadmium (ppb)	0.18 (0.10–0.96*)	0.13 (<0.08–1.42*)	0.19 (<0.08–0.63)	0.39 (<0.08–1.37)	0.20 (<0.08–0.30)	27.8%
Manganese (ppm)	51 (0–336)	73 (0–267)	78 (1–1059)	538 (<1–2432)	109 (1–821)	–43.1%
Iron (ppm)	122 (0–1025)	3523 (490–14375)	166 (59–974)	166 (<1 - 25038)	144 (20–273)	–2788%

1992). Additionally, an independent laboratory (Shiva Analytical Lab, Bangalore) analyzed water from MW3 for dioxin, chlorinated phenols, and pesticides and did not find any concentrations above the method detection limits (0.01 ppm; gas chromatography–mass spectometry).

A total of 18 stable isotope samples were collected, including the RBF wellfield ($n = 11$) and the nearby open well ($n = 3$), the Kali River ($n = 3$), and a bore well ($n = 1$). The data are shown with the regional meteoric water line from Belgaum located 70 km to the NNW (Figure 4; Kumar et al., 2010). Most Kali River samples plot close to the meteoric line, indicating that the river is fed predominantly by precipitation. In contrast, data points from the open well ($n = 3$) show the effect of isotopic fractionation resulting from evaporation (Kendall and McDonnell, 1998). The isotopic signature of groundwater pumped from a 88-m-deep bore well was not distinctively different from that of the two RBF wells nearest the river (MW1 and MW2). Given that the riverbed is separated from the fractured bedrock aquifer by only a thin veneer of alluvial sediments, a hydraulic connection of the RBF wells to the deeper groundwater is therefore likely. Further, the isotopic signature of RBF water changed with distance away from the river from predominantly river-influenced to more evaporation-influenced water.

To determine the ratio of river to groundwater contribution to each RBF well, a two-end member mixing model was created using silica concentrations ($n = 46$). The model works on the assumption that, with time, more silica accumulates in groundwater resulting from dissolution of siliceous aquifer minerals (Hooper and Shoemaker, 1986; Hooper et al., 1990; Kennedy et al., 1986). As the river water is mainly fed by rain, its waters have even lower silica concentrations than the groundwater. The brief exposure time of river water in the bank sediments would not allow them to reach the same level of silica concentration seen in the groundwater as silica has a very slow dissolution rate. At the study site, dissolved silica data ($n = 46$) concentrations ranged from 8 mg/L (Kali River) to 46 mg/L (groundwater approximated by the 88-m-deep bore well in nearby Mainal village) (Average: 28 mg/L). As expected from increased groundwater contribution, silica concentrations in the RBF wells typically increased with distance from the river. The mixing model indicated that after 11 months of operation, 27% (MW4) to 73% (MW3) of RBF water originated from groundwater. Relatively less groundwater was drawn by MW4 even though it was located farther away from the river than MW3. This implies that some amount of river water that was used for irrigation on the rice paddies was drawn to MW4, while MW3 captured more groundwater. These mixing percentages fall within the range seen in other RBF studies, which showed 25 to 87% groundwater contributions (Grischek et al., 2010; Hoppe-Jones et al., 2010; Kelly and Rydlund, 2006; Schubert, 2002). The

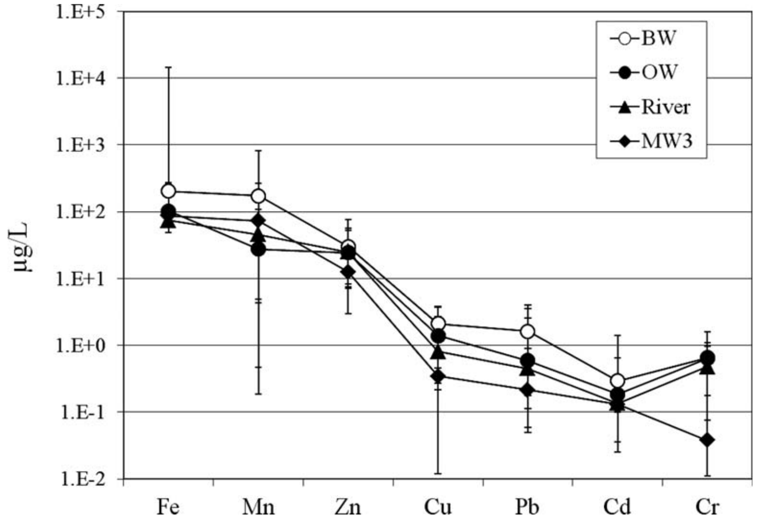


Figure 3—Schoeller diagram of average dissolved metals concentrations in water from the Kali River, riverbank filtration (RBF) well MW3, and the open well (OW) and bore well (BW). The RBF well had the lowest concentrations for all metals analyzed except iron and manganese. The bars show the range.

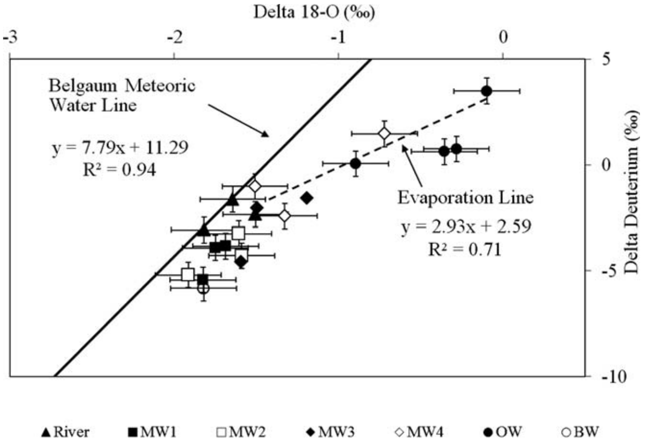


Figure 4—Stable isotope data from all four riverbank filtration (RBF) wells (MW1 through MW4), the Kali River, and a nearby open well (OW) and bore well (BW). Also shown is the regional Belgaum Meteoric Water Line (Kumar et al., 2010) and the evaporation trend line calculated from OW and MW4 data. The bars show the range.

interpretation of the silica data is limited by uncertainty about the local groundwater silica concentration. This is because the land-side groundwater silica concentration came from an 88-m-deep bore well and may therefore have a higher silica content than the fairly shallow RBF wells (25 m). In that case, the groundwater/river water mixing percentages at the RBF site would be skewed toward greater river water contributions.

When the dissolved silica data are combined with the stable isotope results, effects from both mixing and evaporation can be observed, which leads to a refinement of the RBF source water assessment. Evaporation shifts the isotopic signature toward less negative δO^{18} values (Hoefs, 2009), while mixing of river and groundwater is reflected in the dissolved silica concentrations. As shown in Figure 5, wells MW1 and MW2 fall on a mixing line between the river and groundwater, whereas wells MW3 and MW4 are trending towards the open well composition. The open well is farther away from the river than MW3 and MW4 (Figure 1a), yet has a silica signature that is closer to that of the river than the deep groundwater of the bore well. At the same time, the open well's isotopic signature has shifted toward less negative δO^{18} values, indicating evaporation. These observations can be explained by the fact that during the irrigation season (November through March), river water is applied to the rice fields surrounding the open well. Evaporation of standing water in the rice fields changes the isotopic fingerprint before the water recharges the shallow groundwater that feeds the open well. This explanation also resolves the observed isotopic shift in RBF wells MW3 and MW4 because a fraction of the RBF well water is likely drawn in from the nearby rice fields. This is further supported by the aforementioned lower percentage of groundwater contribution to MW4. Altogether, the irrigated rice fields appear to act as a secondary source of river water to the RBF system.

Well Field Hydraulics. Hydraulic tests were carried out to determine well yields, the aquifer response to pumping, and travel time of water from the river to the RBF wells. The yield of MW3 is sufficient to supply at least 4000 people with 55 L/d per capita as required by the Indian government. The average static hydraulic gradient along the one dimensional plane of the well-field was 0.011 and directed toward the river. This indicates that the natural conditions of this stretch of the river are of a gaining stream. During pumping from MW3, the overall well-field/river gradient reversed to 0.063 and increased to 0.206 between wells MW2 and MW3. Tests showed that well MW1 had the lowest yield (Table 1), while well MW3 exceeded the capacity of the

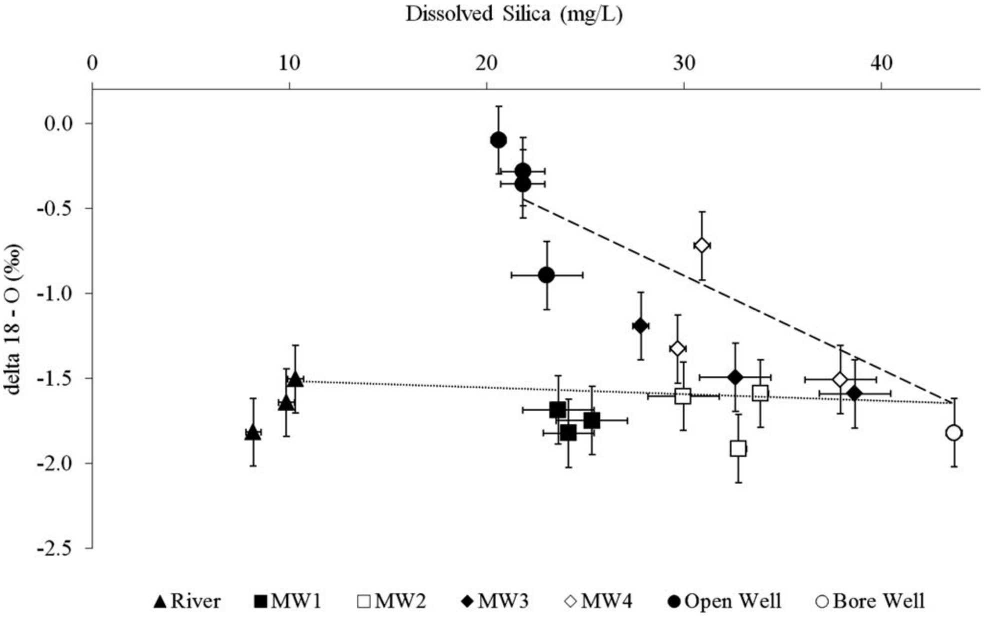


Figure 5—Dissolved silica concentrations (mg/L) versus $\delta^{18}O$ (‰) in riverbank filtration wells MW1 through MW4, the Kali River, the open well (OW), and the bore well (BW). Dotted: mixing line river—groundwater. Dashed: mixing line groundwater—open well.

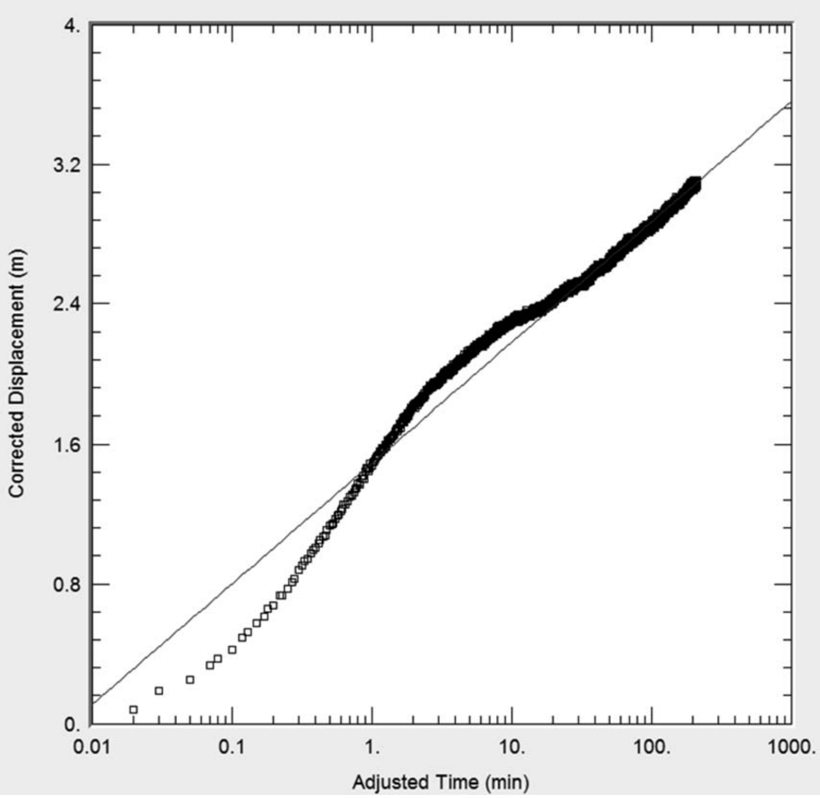


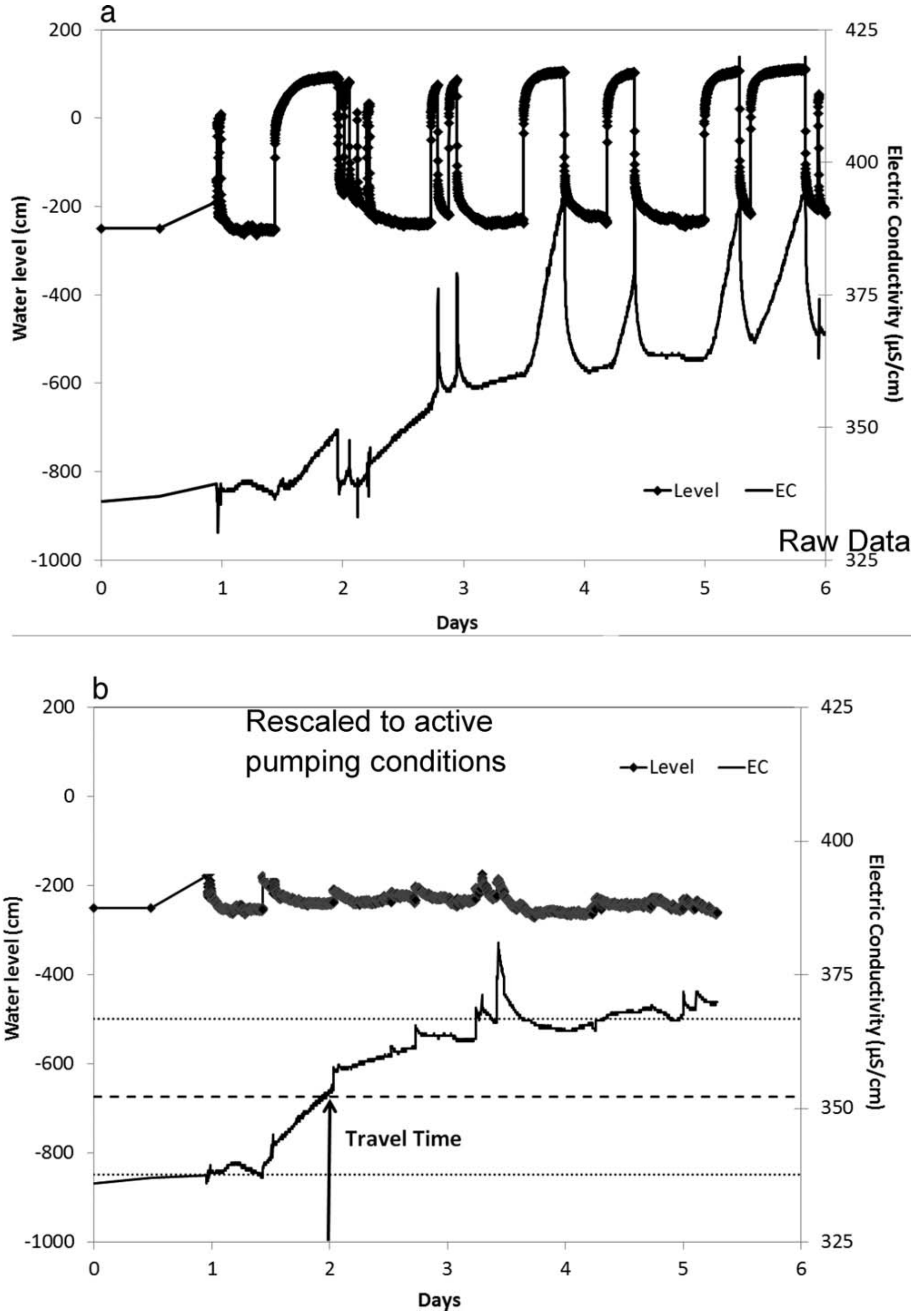
Figure 6—Time-drawdown data and graphical evaluations (Cooper–Jacob method for unconfined aquifers and partially penetrating wells) of the January 2009 aquifer test conducted on well MW3.

pump (9 m^3/hr). Examination of the drill logs indicate a greater presence of finer sediments (sandy silt) in the vicinity of the wells closer to the river (MW1 and MW2) versus those higher-yielding ones farther away (MW3 and MW4). The difference in geology is the likely explanation for the observed lower yields of the wells closer to the river (Table 1).

The hydraulic conductivity (*K*) was derived from two aquifer tests on MW3 conducted in January 2009. In general, for pumping tests near rivers, it is recommended to use steady state data, which can only be achieved by long-duration pumping (Shestakov and Nevecherya, 1998). Figure 6 depicts the drawdown data and graphical analysis of an aquifer test carried out on MW3 in January 2009. The examination of the time/draw-down data shows that the pumping test did not last long enough to have been directly influenced by the river, which would have caused the draw-down curve to plateau eventually. The emergence of a plateau would have indicated the presence of a constant head boundary (= river). The comparably low pumping rate of maximal 9 m^3/hr combined with the well's setback distance from the river (52 m) made it unlikely that any direct impact from the river would have been noticeable for weeks, if at all. In lieu of long-term time/draw-down data that clearly show the emergence of a plateau, aquifer properties can be estimated using standard methods of analysis for extensive aquifers (Duffield, 2013). Hence, hydraulic conductivities were estimated based on the Cooper–Jacob method for partially penetrating wells in unconfined aquifers using Aqtesolv software (HydroSolve, Inc., Reston, Virginia). The hydraulic conductivity (*K*) derived from two aquifer tests on MW3 ranged from 3.0×10^{-3} cm/s to 9.6×10^{-3} cm/s (mean: 6.3×10^{-3} cm/s). The mean *K* value is lower than the one of (nonlateritic) structured soils with horizontal and vertical fractures reported by Lilly (2000) but in line with typical values for lateritic sediments (Domenico and Mifflin, 1965). Although considered less reliable compared to the pumping test data, the slug test results were similar in magnitude and trended towards increasing *K* values with distance from the river (Table 1). The slug tests data were analyzed using the Bouwer–Rice solution for partially penetrating unconfined aquifers.

The analysis of the conservative racer test data was hampered by frequent power outages, lasting 5 to 8 hours on average (Figure 7a). Because of these outages, water levels during the test rebounded frequently. Even though these test conditions were not ideal, the tracer breakthrough time could still be estimated. For this, it was assumed that because of the shallow hydraulic gradient, the tracer movement during power outages (= nonpumping time) is insignificant. The data recordings during power outages were removed (66 hours in total) and the remaining electrical conductivity records during pumping were graphically corrected. The raw data and the breakthrough curve are shown in Figure 7a and 7b, respectively.

The mean travel time from the point of injection (MW2) to the point of extraction (MW3) was calculated by first assuming a homogeneous porous medium. Next, the background level of dissolved ions was subtracted. This was the preliminary electrical conductivity level from the MW3 (337 μS/cm). Finally, the travel



Figures 7a (top) and 7b (bottom)—Results of the conservative tracer test. The background electrical conductivity (EC) at MW3 before the tracer arrival was approximately 337 µS/cm. Repeated power outages caused flow interruptions and rebound in the water table elevation (7a). For the purpose of data analysis, major rebounds were removed (7b). The tracer travel time (45 days) was determined by taking the halfway point (dashed line) between the background EC at the start of the test and the EC after breakthrough (dotted lines).

time was estimated from the time at which the rise in electrical conductivity was at the halfway point relative to the full breakthrough electrical conductivity level (365 µS/cm). This approach is illustrated in Figure 7b, where the dotted lines represent the average background and post-breakthrough electrical conductivity values. The intersection of the dashed line with the electrical conductivity graph marks the tracer travel time, that is, tracer breakthrough after approximately 1.9 days (44.9 hours) of pumping. Given the 16-m separation between the injection well (MW2) and the extraction well (MW3), the average tracer travel velocity was 0.35 m/hr. Provided that this approach reflects the hydraulics of the entire well field under pumping conditions, it therefore takes at minimum 6.2 days and 9.4 days for the water to travel the distance between the river and the RBF wells MW3 and MW4, respectively. Longer mean travel times are likely as infiltration also occurs from the center of the river and not just from the riverbed closest to the well field or drawing-in water from along other, longer flow paths.

Travel times were also estimated on the basis of Darcy's law (eq 1) and the hydraulic conductivity values established by the aquifer tests on well MW3 (range: 3.0×10^{-3} cm/s to 9.6×10^{-3} cm/s).

$$T = \frac{dn}{Kgrad}. \tag{1}$$

where T is the travel time of a nonretarded solute, d is the distance between the river and the well (52 m in case of MW3), n is the porosity (30%), and $grad$ is the hydraulic gradient between the river and the well during pumping (0.063). The travel time calculated from the mean K (6.3×10^{-3} cm/s) value is 45.2 days, which is similar to the range reported in other RBF studies (Grischek et al., 2010; Hoppe-Jones et al., 2010; Kühn and Müller, 2000; Schmidt et al., 2003; Tufenkji et al., 2002), but approximately 5 to 7 times longer compared to the tracer test results. Because the tracer test results needed to be adjusted for the frequent power outages (Figures 7a and 7b) and it was assumed that homogenous conditions prevailed in the entire well field, that data set may be less reliable than the pump test data.

Conclusions

Conventional water treatment technologies employed in industrialized countries are often too costly and technically complex for effective use in emerging economies. This study focused on riverbank filtration technology, which has a proven record in Europe and the United States, but has only fairly recently garnered the attention of researchers and water managers in areas like India that have markedly different temperature and rainfall patterns than Europe and the United States.

A major objective of this study was to analyze and understand the performance of a small riverbank filtration system to determine its ability to supply treated water to a small rural community in southwestern India. The hydraulic testing and hydrogeochemical investigations over a 1-year period demonstrated that the RBF water quality and quantity meets and exceeds local standards of those parameters described in this study. The yield of the principal RBF well MW3 was sufficient to supply at least 4000 people with 55 L/d per capita as required by the Indian government.

A hydraulic analysis based on Darcy's law resulted in a mean travel time of 45.2 days, which is in line other RBF studies. Tracer test data indicated a comparatively high travel velocity of 0.35 m/d and minimum travel times from the river to the wells of up to 9.4 days. Besides being representative for the hydrogeological conditions between wells MW2 and MW3 only, one problem encountered during the tracer test were multiple power outages, which likely limit the value of these results. It would take additional aquifer tests in conjunction with tracer tests at other RBF wells and the river, together with numerical modeling of the field site, to further narrow the range of these travel time estimates.

Stable isotopic data indicated that the river was primarily precipitation fed and that the RBF wells farther from the river, including an existing open well in a nearby rice field, were influenced by evaporation. Dissolved silica concentrations indicated that 27% (MW4) to 73% (MW3) of RBF water originated from groundwater. Furthermore, it is evident that a fraction of the RBF well water, particularly in MW4, was drawn in from nearby rice paddies that were irrigated with river water. A comparison of Kali River water with MW3 well water showed that the well water heavy metal concentrations were lower by 60.1% zinc, 27.8% cadmium, 83.9% lead, 75.5% copper, and 100% chromium.

Overall, the findings reported herein support the suitability of RBF technology for water pretreatment in small rural communities, particularly in developing countries where more complex water treatment technologies are typically not affordable. Further studies are needed to investigate alternate hydrogeological settings. Even so, this study may help to convince water managers in emerging economies to seriously consider RBF technology for producing high quality water at sufficient quantity from low quality surface water sources.

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References

Albrechtsen, H. J.; Boe-Hansen, R.; Henze, M.; Mikkelsen, P. S. (1998) Microbial Growth and Clogging in Sand Column Experiments Simulating Artificial Recharge of Groundwater. In *Artificial Recharge of Groundwater*; Peters, J. H., et al., Eds; Balkema: Rotterdam, Netherlands; pp 73–77.

Bellamy, W. D.; Hendricks, D. W.; Logsdon, G. S. (1985) Slow Sand Filtration: Influences of Selected Process Variables. *J. Am. Water Works Assoc.,* **77** (12), 62–66.

Berger, P. (2002) Removal of Cryptosporidium Using Bank Filtration. *Proceedings of the NATO Advanced Research Workshop on Riverbank Filtration: Understanding Contaminant Biogeochemistry and Pathogen Removal*, Tihany, Hungary, September 2001; pp 85–121.

Bharati, S. G.; Krishnamurthy, S. R. (1990) Effect of Industrial Effluents on River Kali Around Dandeli, Karnataka; Part 1—Physico-Chemical Complexes. *Indian J. Environ. Health*, **32,** 167–171.

Bharati, S. G.; Krishnamurthy, S. R. (1992) Influence of Heavy Metals on the Distribution of Algae in the River Kali, Around Dandeli (North Kanara District) Karnataka State—India: *J. Karnataka Univ.–Sci.*, **36,** 1–12.

Boving, T. B.; Al-Ghazawi, Z.; Saadoun, I.; Schijven, J.; Al-Rashdan, J.; Shawaqfeh, M.; Blandford, W. (2010) River Bank Filtration for Protection of Jordanian Surface and Groundwater. Final Report Prepared for NATO Science for Peace and Security Program (Sfp), Project Sfp – 981454, Brussels, Belgium.

Boving, T. B.; Choudri, B. S. (2010) *Clean Water by Riverbank Filtration*; Final Report Prepared for World Bank, Development Marketplace Program, DM 2007, Grant No. 2447; Washington, D.C.

Boving, T. B.; Choudri, B. S.; Cady, P.; Davis, A.; Patil, K.; Reddy, V. (2012) Acceptance of a Riverbank Filtration System in Rural India. *J. Indian Water Works Assoc.,* Special Issue, December 2012, 33–41.

Bureau of Indian Standards (BIS) (1992) Indian Standard Specifications for Drinking Water; BIS-10500; (Reaffirmed 1993); BIS: New Delhi, India. http://hppcb.gov.in/eiasorang/spec.pdf (accessed June 6, 2013).

Cady, P.; Boving, T.; Choudri, B. S.; Davis, A.; Patil, K.; Reddy, V. (2013) Attenuation of Bacteria at a Riverbank Filtration Site in Rural India. *Water Environ. Res.*, **85,** 2164–2174.

Chavadi, V. C.; Gokhale, N. W. (1984) Preliminary Investigation on the Seasonal Variation of Water Quality in the Kali River, Uttara Kannada District, Karnataka. In *Ecodevelopment of Western Ghats*; Kerala Forest Research Institute, Peechi: Karala, India; pp 249–251.

Choudri, B. S.; Boving, T. B. (2010) Riverbank Filtration for Sustainable Water Supply in Underserved Areas: Field Studies Along the Kali River in Karnataka, India. *Proceedings of the ASCE–EWRI World Environmental & Water Resources Congress (Groundwater Council), the 8th Symposium on Groundwater Hydrology, Quality and Management*, Providence, Rhode Island, May 16–20, 2010.

Dash, R. R.; Bhanu Prakash, E. V.; Kumar, P.; Mehrotra, I.; Sandhu, C.; Grischek, T. (2010) River Bank Filtration in Haridwar, India: Removal of Turbidity, Organics, and Bacteria. *Hydrogeol. J.*, **18,** 973–983.

Dash, R. R.; Mehrotra, I.; Kumar, P.; Grischek, T. (2008) Lake Bank Filtration at Nainital, India: Water Quality Evaluation. *Hydrogeol J.*, **16** (6), 1089–1099.

Davis, S.; Thompson, G.; Bentley, H.; Stiles, G. (1980) Ground-Water Tracers—a Short Review. *Ground Water* **18** (1), 14–23.

Dillon, P. J.; Miller, M.; Fallowfield, H.; Hutson, J. (2002) The Potential of River Bank Filtration for Drinking Water Supplies in Relation to Microcystin Removal in Brackish Aquifers. *J Hydrol.*, **266** (3), 209–221.

Domenico, P. A.; Mifflin, M. D. (1965) Water from Low-Permeability Sediments and Land Subsidence. *Water Resour. Res.*, **1** (4), 563–576.

Doussan, C.; Poitevin, G.; Ledoux, E.; Detay, M. (1997) River Bank Filtration: Modeling of the Changes in Water Chemistry with Emphasis on Nitrogen Species. *J. Contam. Hydrol.*, **25** (1–2), 129–156.

Duffield, G. M. (2013) Pumping Tests in Bounded Aquifers. www.aqtesolv.com/pumping-tests/pumping-tests-in-bounded-aquifers.htm (accessed July 17, 2013).

Gollnitz, W. D.; Clancy, J. L.; Whitteberry, B. L.; Vogt, J. A. (2003) RBF as a Microbial Treatment Process. *J. Am. Water Works Assoc.*, **95** (12), 56–66.

Grischek, T.; Schoenheinz, D.; Ray, C. (2002) Siting and Design Issues for River Bank Filtration Schemes. In *Riverbank Filtration: Improving Source Water Quality*; Ray, C., et al., Eds.; Kluwer: Dordrecht, Netherlands; pp 291–302.

Grischek, T.; Schoenheinz, D.; Syhre, C.; Saupe, K. (2010) Impact of Decreasing Water Demand on Bank Filtration in Saxony, Germany. *Drinking Water Eng. Sci.*, **3,** 11–20.

Gupta, V.; Johnson, W. P.; Shafieian, P.; Ryu, H.; Alum, A.; Abbaszadegan, M.; Hubbs, S. A.; Rauch-Williams, T. (2009) Riverbank Filtration: Comparison of Pilot Scale Transport with Theory. *Environ. Sci. Technol.*, **43** (3), 669–676.

Havelaar, A. H.; van Olphen, M.; Schijven, J. F. (1995) Removal and Inactivation of Viruses by Drinking Water Treatment Processes under Full-Scale Conditions. *Water Sci. Technol.*, **31** (5–6), 55–62.

Hiscock, K. M.; (2005) *Hydrogeology—Principles and Practice*; Blackwell Publishing: Malden, Massachusetts.

Hiscock, K. M.; Grischek, T. 2002) Attenuation of Groundwater Pollution by Bank Filtration. *J. Hydrol.*, **266** (3–4), 139–144.

Hoefs J. (2009) *Stable Isotope Geochemistry*, 6th ed.; Springer Verlag: Berlin.

Hooper, R. P.; Christophersen, N.; Peters, N. E. (1990) Modeling Streamwater Chemistry as a Mixture of Soilwater End-Members—an Application to the Panola Mountain Catchment, Georgia, U.S.A. *J. Hydrol.*, **116,** 321–343.

Hooper, R. P.; Shoemaker, C. A. (1986) A comparison of Chemical and Isotopic Hydrogaph Separation. *Water Resour. Res.*, **22,** 1444–1454.

Hoppe-Jones, C.; Oldham, G.; Drewes, J. E. (2010) Attenuation of Total Organic Carbon and Unregulated Trace Organic Chemicals in the US Riverbank Filtration Systems. *Water Res.*, **44,** 4643–4659.

Hubbs, S.; Ray, C.; Mucha, I. (2004) Riverbank Filtration: Effect of Riverbed Clogging on Water Quality and System Capacity. In NATO Advanced Research Workshop: Clogging in Riverbank Filtration, Bratislava, Slovakia Republic, Sept 7–10, 2004. http://www.soulstatic.com/NATORBF (accessed June 12, 2013).

Kelly, B. P.; Rydlund, P. H. J. (2006) *Water-Quality Changes Caused by Riverbank Filtration Between the Missouri River and Three Pumping Wells of the Independence, Missouri, Well Field 2003-05*; USGS, Report Scientific Investigations Report 2006–5174; U.S. Geological Survey: Reston, Virginia; pp 1–48.

Kendall, C.; McDonnell, J. J., Eds. (1998) *Isotope Tracers in Catchment Hydrology;* Elsevier BV: Oxford, U.K.

Kennedy, V. C.; Kendall, C.; Zellweger, G. W.; Wyerman, T. A.; Avanzino, R. J. (1986) Determination of the Components of Stormflow Using Water Chemistry and Environmental Isotopes, Mattole River Basin, California. *J. Hydrol.*, **84,** 107–140.

Krishnamurthy, S. G.; Bharati, S. G. (1996) Distribution of Lead in the Surface Waters of the Polluted River Kali Around Dandeli Area, Karnataka, India. *Environ. Ecol.*, **14,** 390–393.

Krishnamurthy, S. R.; Bharati, S. G. (1994) Studies on the Metal Pollution of the River Kali around Dandeli (North Kanara District), Karnataka, India. *Pollut. Res.*, **13,** 249–252.

Kühn, W.; Mueller, U. (2000) Riverbank Filtration: An Overview. *J. Am. Water Works Assoc.*, **92** (12), 60–69.

Kumar, B.; Rai, S. P.; Kumar, U. S.; Verma, S. K.; Garg, P.; Kumar, S. V. V.; Jaiswal, R.; Purendra, B. K.; Kumar, S. R.; Pande, N. G. (2010) Isotopic Characteristics of Indian Precipitation. *Water Resour. Res.*, **46,** 1–15.

Kumar, P.; Mehrotra, I. (2009) Riverbank Filtration for Water Supply: Indian Experience. *Proceedings of the 2009 World Environmental and Water Resources Congress*, St. Louis, Missouri, May 17–21, 2009; American Society of Civil Engineers: Reston, Virginia; pp 1–9.

Lilly, A. (2000) the Relationship between Field-Saturated Hydraulic Conductivity and Soil Structure: Development of Class Pedotransfer Functions. *Soil Use Manage.*, **16** (1), 56–60.

Lin, A. Y. C.; Debroux, J. F.; Cunningham, J. A.; Reinhard, M. (2003) Comparison of Rhodamine WT and Bromide in the Determination of Hydraulic Characteristics of Constructed Wetlands. *Ecol. Eng.*, **20** (1), 75–88.

Manjunatha, B. R, Balakrishna, K.; Shankar, R.; Mahalingam, T. R. (2001) Geochemistry and Assessment of Metal Pollution in Soils and River Components of a Monsoon-Dominated Environment Near Karwar, Southwest Coast of India. *Environ. Geol.*, **40** (11–12), 1462–1470.

Manjunatha, B. R.; Balakrishna, K.; Shankar R.; Sarin M. M. (2001) Distribution of U–Th Nuclides in the Riverine and Coastal Environments of the Tropical Southwest Coast of India. *J. Environ. Radioact.*, **57** (1), 21–33.

Massmann, G.; Tichomirowa, M.; Merz, C.; Pekdeger, A. (2003) Sulfide Oxidation and Sulfate Reduction in a Shallow Groundwater System (Oderbruch Aquifer, Germany). *J. Hydrol.* **278** (1), 231–243.

Miettinen, I. T.; Martikainen, P. J.; Vartiainen, T. (1994) Humus Transformation at the Bank Filtration Water Plant. *Water Sci. Technol.*, **30** (10), 179–187.

Panchayat Raj Engineering (PRE) (2006) Water Quality Details of Observation Dug Well: Well #190304, Dandeli, India.

Radhakrishna, B.; Vaidyanadhan, R. (1997) Geology of Karnataka: Bangalor**e**. *Geol. Soc. India*, 353.

Ray, C. (2004) Modeling RBF Efficacy for Mitigating Chemical Shock Loads. *J. Am. Water Works. Assoc.*, **96** (5), 114–120.

Ray, C., Ed. (2002) *Riverbank Filtration: Understanding Contaminant Biogeochemistry and Pathogen Removal*; Kluwer Academic Publishers: Dordrecht, Netherlands.

Ray, C.; Schubert, J.; Linsky, R. B.; Melin, G. (2002) Introduction. In *Riverbank Filtration: Improving Source Water Quality*; Ray, C., Melin, G., Linsky, R.B., Eds.; Kluwer Academic Publishers and National Water Research Institute: Boston.

Sandhu, C.; Grischek, T.; Kumar, P.; Ray, C. (2011) Potential for Riverbank Filtration in India. *Clean Technol. Environ. Policy*, **13** (2), 295–316.

Schijven, J. F.; Hoogenboezem, W.; Hassanizadeh, S. M.; Peters, J. H. 1999) Modeling Removal of Bacteriophages MS2 and PRD1 by Dune Recharge at Castricum, Netherlands. *Water Resour. Res.*, **35,** 1101–1111.

Schijven, J. F.; Hoogenboezem, W.; Nobel, P. J.; Medema, G. J.; Stakelbeek, A. (1998) Reduction of FRNA Bacteriophage and Faecal Indicator Bacteria by Dune Infiltration and Estimation of Striking Efficiencies. *Water Sci. Technol.*, **38** (12), 127–131.

Schmidt, C. K.; Lange, F. T.; Brauch, H.-J.; Kühn, W. (2003) *Experiences with Riverbank Filtration and Infiltration in Germany*; DVGW-Water Technology Center (TZW): Karlsruhe, Germany. http://www.tzw.de/pdf/bankfiltration.pdf (accessed Jan 2, 2012).

Schubert, J. (2002) Hydraulic Aspects of Riverbank Filtration-Field Studies. *J. Hydrol.*, **266** (3), 145–161.

Shestakov, V.; Nevecherya, I. (1998) The Theory and Methods for Interpreting the Pumping Test Results. Moscow: MGU (in Russian). Cited in Ping, W.; Shestakov, V. M. (2008) Interpretation of Groundwater Pumping Testing near Rivers by Means of Numerical Simulation Methods. *Moscow Univ. Geol. Bull.*, **63** (4), 289–293.

Speth, T.; Merkel, T.; Gusses, A. (2003) Riverbank Filtration as a Pretreatment for Nanofiltration Membranes. Riverbank Filtration: Improving Source-Water Quality. *Water Sci. Technol. Libr.*, **43,** 261–265.

Stuyfzand, P. J.; Juhàsz-Holterman, M. H. A.; de Lange, W. J. (2004) *Clogging in Riverbank Filtration*. In NATO Advanced Research Workshop: Bratislava, Slovakia Republic, Sept 7–10, 2004. http://www.soulstatic.com/NATORBF (accessed June 12, 2013).

Subramanian, V.; Biksham, G.; Ramesh, R. (1987) Environmental geology of peninsular river basins of India. *J. Geol. Soc. India*, **30,** 393–402.

Tufenkji, N.; Ryan, J. N.; Elimelech, M. (2002) Bank Filtration. *Environ. Sci. Technol.*, **36** (21), 422A–428A.

UNICEF (2012) Progress on Sanitation and Drinking Water: 2012 Update. http://www.unicef.org/media/files/JMPreport2012.pdf (accessed July 22, 2013).

Wang, J., 2002. Riverbank Filtration Case Study at Louisville, Kentucky. In *Riverbank Filtration: Improving Source Water Quality*; Ray, C., et al., Eds.; Kluwer: Dordrecht, Netherlands; pp 117–146.

Wang, J.; Smith, J.; Dooley, L. (1995) Evaluation of Riverbank Infiltration as a Process for Removing Particles and DBP Precursors. *Proceedings of the Water Quality Technology Conference*, Nov 12–16, New Orleans; American Water Works Association: Denver, Colorado.

Water.org Home Page. http://water.org/country/india/ (accessed Jan 2, 2012).

Weiss, W. J.; Bouwer, E. J.; Ball, W. P.; O'Melia, C. R.; Arora, H.; Speth, T. F. (2002) Reduction in Disinfection Byproduct Precursors and Pathogens during Riverbank Filtration at Three Midwestern United States Drinking-Water Utilities. In *Riverbank Filtration: Improving Source Water Quality*; Ray, C., et al., Eds,; Kluwer: Dordrecht, Netherlands; pp 147–174.

Weiss, W. J.; Bouwer, E. J.; Ball, W. P.; O'Melia, C. R.; Arora, H.; Speth, T. F. (2003) Riverbank Filtration: Fate of DBP Precursors and Selected Microorganisms. *J. Am. Water Works Assoc.*, **95** (10), 68–81.