Chapter 12 Evaluation of Bank Filtration for Drinking Water Supply in Patna by the Ganga River, India

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Abstract Hydrogeological investigations in Patna by the Ganga River, together with water quality investigations were conducted in 2005–2006 to evaluate riverbank filtration (RBF) wells in the city. A groundwater flow model was used to obtain a better characterization of the groundwater flow conditions. The investigations showed that RBF is an efficient treatment technique for the removal of coliform bacteria (>4 log). The increase in Ganga water level during monsoon helps improve the surface water – groundwater interaction by scouring a 10 m thick sediment layer deposited on the river bed during the pre-monsoon. The dissolved organic carbon concentration was found to be low in Ganga water and groundwater (both <3 mgL^{-1}), except in monsoon the river water showed an increase (4.9 mgL^{-1}). The investigated RBF wells in Patna were found to provide sustainable drinking water in terms of quality and quantity throughout the year.

Keywords: Bank filtration, Ganga, Patna, drinking water, coliform removal

1. Introduction

Surface water bodies (mainly rivers) are the main source for drinking for most riparian urban areas in India. To cope with the large increase in water demand, especially for irrigation and drinking to serve the growing Indian economy, groundwater abstractions have also increased significantly. This has resulted in a

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widespread lowering of the groundwater table by more than 0.2 myear^{-1} from 1981–2000, especially in the regions to the south of the Ganga and Sutlej rivers (Indo-Gangetic alluvial plain) up to the southern margin of the hard-rock Deccan Plateau (Nagaraj et al. 1999, Jain et al. 2007). In the case of many cities along the Ganga River in India, the direct abstraction of surface water for drinking appears problematic during periods of low-flow or when the surface water receives large quantities of untreated or partially treated domestic sewage and industrial wastewater (Ray 2005). However, the hydrogeology of many riparian cities in India makes riverbank filtration (RBF) both feasible and attractive as an alternative to direct surface water abstraction, as it is possible to readily extract large quantities of water from river banks.

Patna, having a population of more than 1.7 million (Census of India 2001), is located along the Ganga River (Figure 12.1) and, by simple visual inspection, also appears to be a suitable RBF site. There, six wells of varying depths (150–200 m below ground level) are located 9–236 m from the river and supply water directly to the public distribution network. Analyses of river water and abstraction wells conducted in November 2005 and February 2006 indicated possible bank filtrate being abstracted (Sandhu et al. 2006), though its proportion and travel-time could not be determined then. Additionally, the presence of a confining clay layer and seasonal high sediment deposition interferes, to a varying extent, with the direct hydraulic connection between the aquifer beneath the city and the Ganga River (Sandhu and Thakur 2006). In conjunction with the previous studies, further field and laboratory investigations have been conducted on the water levels, water quality and potential of using bank filtration in Patna (Prasad et al. 2009).

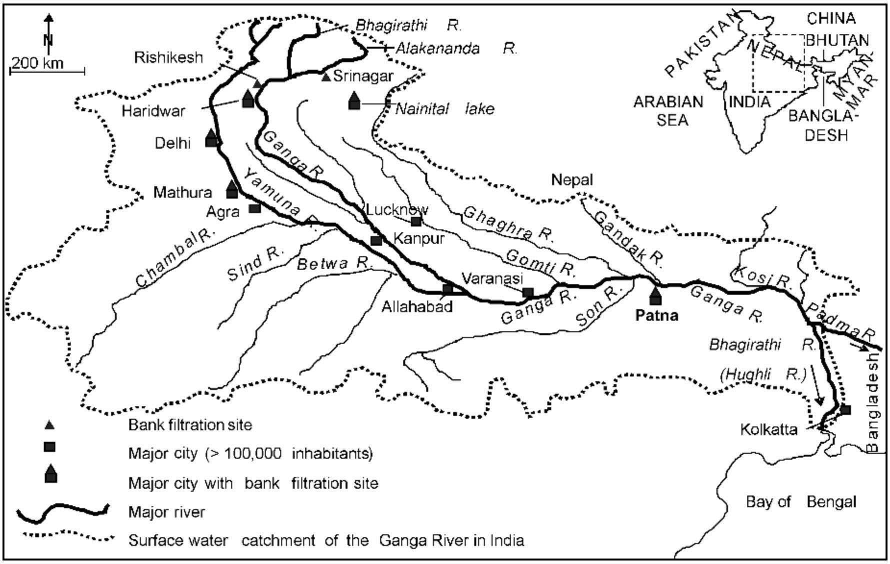

Figure 12.1. Ganga River catchment in India and major bank filtration sites.

In this study, results from field and laboratory investigations (2005–2006) and groundwater flow modeling are used to characterize some of the existing RBF wells in Patna. No investigations on these wells were conducted before 2005, and thus no knowledge about the RBF system in Patna was available. This study expands upon the previous work by Sandhu et al. (2006) and Prasad et al. (2009). An improved understanding of the hydrogeological boundary conditions by groundwater flow modeling is presented. Additionally, the effect of the high sediment deposition during the pre-monsoon and scouring by the Ganga during the monsoon season are discussed.

2. Study Area

2.1. Physiography and Hydrogeology

2.1.1. South Ganga Plain

The city of Patna lies at the northern edge of the South Ganga Plain (SGP) in the Indo-Gangetic Alluvial Plain (Figure 12.2). The SGP is a physiographic unit referring to the linear tract of land bounded by the Ganga in the north, the Rajmahal Hills in the east and the Precambrian Highlands in the south (Saha et al. 2007). The area of Patna city covers a 25 km stretch along the right (south) bank of the Ganga River, and is approximately 5 km in width. The elevation of the city from south to north varies between 48 and 54 m above mean sea level (MSL). According to Saha et al. (2007), the SGP varies from hilly and undulating topography in the south to flat monotonous terrain in the central part and in the north. The flat alluvial terrain in the centre and north displays an average regional slope of 0.63‰. More than 80% of the average annual rainfall (1,010 mm year^{-1}) from the SW monsoon occurs from June to September (Government of Bihar 1994).

The drainage of the SGP is controlled by the Ganga, flowing from west to east along its northern edge and a number of ephemeral streams originating from the Precambrian Highlands and flowing towards the Ganga in a NNE direction. Just upstream of Patna, a few large perennial rivers such as the Ghaghra, Son and Gandak join the Ganga. Thus the mean annual flow of the Ganga at Patna is significant around the year, and on an average is around 364×10^9 m^{3}a^{-1} (Jain et al. 2007). Even in the dry season (October–May) the flow of the river remains substantial.

A comprehensive description of the geology and hydrogeology of the SGP is provided by Saha et al. (2007). The alluvium deposited by the Ganga and ephemeral streams originating from the Precambrian highlands (Bisaria 1984) is underlain by the northerly sloping basement of crystalline rocks belonging to the Precambrian period (Mathur and Kohli 1963). Deep seismic refraction studies by Bose et al.

(1966) indicate an increase in thickness of the alluvium from south to north, with the maximum thickness of 500–550 m recorded along the course of the Ganga.

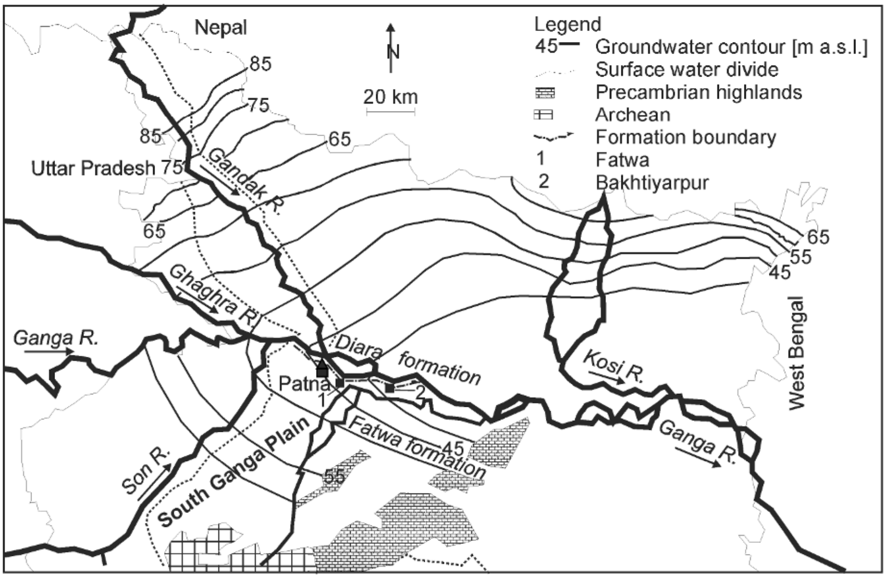

Figure 12.2. Geology and hydrogeology of the South Ganga Plain (after CGWB 1997 and Saha et al. 2007).

The alluvium in the SGP within the study area can be classified into two main formations, namely the Diara and Fatwa formations (Figure 12.2). The Diara formation of the late Holocene age covers the present course of the Ganga (adjacent to Patna) and consists of fine sand, silt and minor clay. The Fatwa formation of the middle to upper Holocene age forms a 10–25 km wide belt to the south of the Diara formation (including Patna and the area to the south). It consists of sand, silt, sandy clay and clay. In this formation, a clay layer is encountered immediately beneath the ground surface along the stretch from Patna to the east bordering the Diara formation. While in Patna the clay layer is usually 50 m thick, towards the east it reduces to 20–40 m. As presented by Saha et al. (2007), lithological information gathered by the Central Ground Water Board (CGWB 1990–1994) and Saha (1999) from three drinking water production wells at the towns of Fatwa, Bakhtiyarpur and Barh to the east of Patna along the Ganga indicate the presence of a 30–50 m thick upper clay layer followed by a 200–220 m thick sand aquifer. These wells are situated on the boundary of the Diara and Fatwa formations.

Within the Quaternary alluvium, the aquifers are semi-confined to confined and are made of unconsolidated, fine to coarse grained sands with occasional gravel beds. The groundwater level decreases from more than 60 m MSL to the south of the SGP to 45 m MSL along the south and north bank of the Ganga at Patna (Figure 12.2). The regional groundwater flow direction in the SGP is to the north with an average gradient of 0.77‰. The hydraulic parameters of the SGP as presented by Saha et al. (2007) were determined based on pumping test data of 19 deep tube wells (CGWB 1990–1994, Saha 1999). Accordingly, the transmissivity and storativity were determined by Jacob's Straight Line Method and by the Theis Curve Matching Method. In the SGP, the hydraulic conductivity (*K*) gradually increases towards the north, with the highest *K* ($>1.7 \times 10^{-3}$ ms^{-1}) observed along the Fatwa-Bakhtiarpur-Barh stretch on the northern edge of the Fatwa formation along the Ganga (Saha et al. 2007).

2.1.2. Patna

The aquifer geometry of an approximately 6 km long and 3 km wide stretch of Patna city located along the south bank of the Ganga (Figure 12.3) has been interpreted from borehole logs of the drinking water production wells situated in the study area (T3, T6 and T7), as well as from logs of boreholes drilled during the construction of the *Mahatma Gandhi Bridge* (Public Works Department 1966). These have enabled the construction of two cross-sections, ABC and DEF as shown in Figures 12.3 and 12.4, respectively.

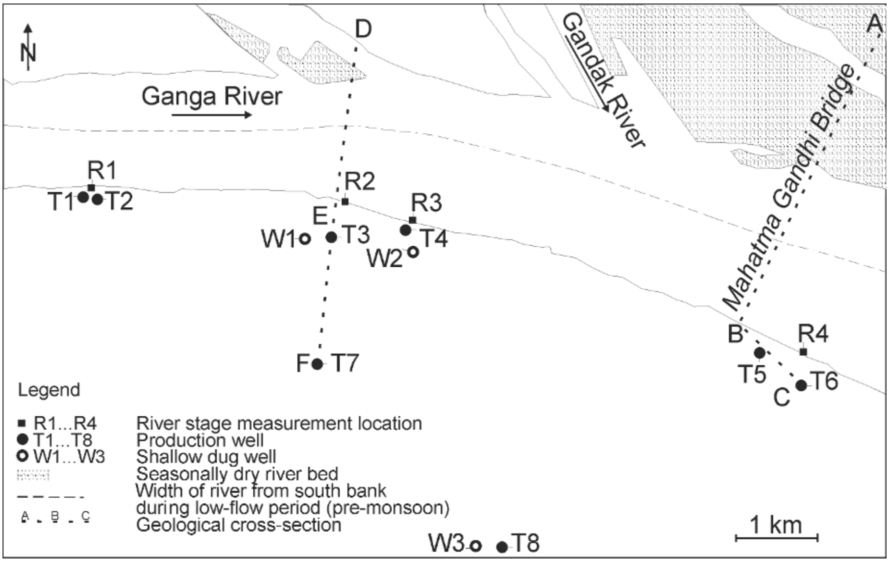

Figure 12.3. Study area in Patna city.

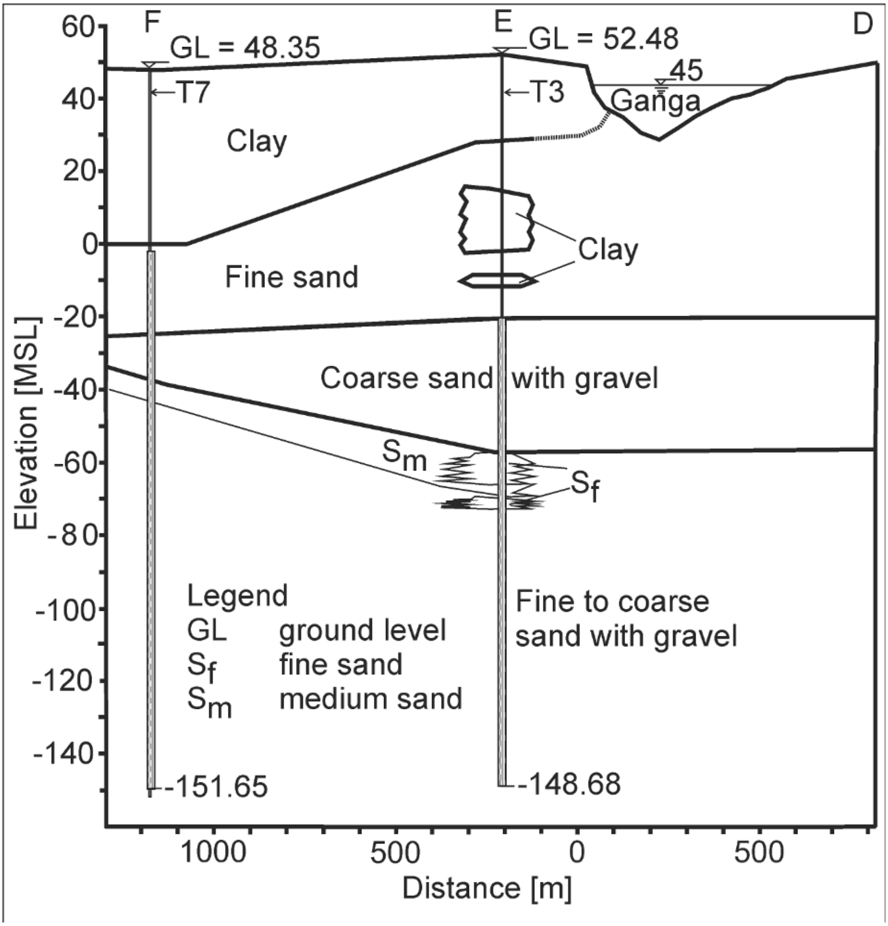

Figure 12.4. Aquifer cross-section DEF at Patna.

In general, the geometry of the aquifer corresponds to the description of Saha et al. (2007). The hydrogeology map of Bihar describes the aquifer below Patna as fairly thick and regionally extensive extending to a depth of 300 m (CGWB 1997). This aquifer depth is derived from the drilling depth of various wells in the city, and does not necessarily indicate the presence of an impermeable base. Hence, as described by Bose et al. (1966), it is probable that the aquifer is deeper (>500 m below ground level). The interpretations of the production well logs reveal a top confining clay layer below the city having a thickness of 24–59 m and extending from the ground level to a depth of 29 to −5 m MSL (Figures 12.4 and 12.5). However, the lateral extent of this confining clay beneath the Ganga is difficult to ascertain. Figure 12.5 indicates that the confining clay layer nearly extends beneath the entire width of the Ganga towards the north bank. However, it is not possible to reach the same conclusion from Figure 12.4 (cross-section DEF), since no boreholes exist in the river bed or across it on the north bank to indicate the extent of the confining clay layer beneath the Ganga. Below the clay layer, the aquifer comprises fine to coarse sand and gravel. However, a second clay layer separating an upper fine to medium sand layer from the main lower lying medium to coarse sand and gravel layer is visible at some locations. At these locations, where a double layered aquifer is visible, the well screens of the production wells are positioned only in the main lower fine to coarse sand and gravel layer at an elevation of −2 m MSL and below. In all the production wells, the groundwater levels rise above the base of the upper clay layer, thus exhibiting confining conditions.

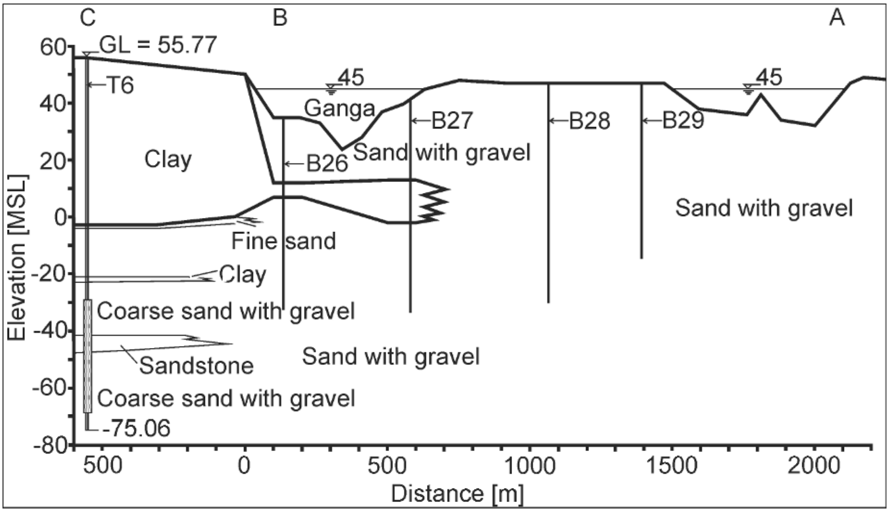

Figure 12.5. Aquifer cross-section ABC at Patna.

Aquifer transmissivities, and yields of existing drinking water production wells located more than 2 km to the south of the Ganga and parallel to it have been determined in previous studies conducted by the Central Ground Water Board (Maitra and Ghosh 1992). Transmissivities obtained from Jacob's straight line and Theis recovery methods were in the range of 5×10^{-2} to 2.2×10^{-1} m^2s^{-1} and 4.4×10^{-2} to 1.5×10^{-1} m^2s^{-1}, respectively. No indications of the saturated aquifer thickness for these wells on which the tests were conducted could be derived, and thus the same was assumed to be between 90 and 151 m (coinciding with the length of the filter-sections in the aquifer) in order to derive the hydraulic conductivity. This varied by an order of magnitude between 1.4×10^{-3} and 5.6×10^{-4} ms^{-1} depending on the aquifer thickness and presence of fine to coarse sand (and gravel).

2.2. Drinking Water Supply

The entire rural, and more than 90% of the urban water supplies of the SGP is met from the underlying Quaternary aquifers (Saha et al. 2007). In Patna, the drinking water is supplied by groundwater from 137 vertical production wells operated by the Patna Water Board (PWB) and Public Health Engineering Department (PHED) supplemented by numerous private production wells (Prasad et al. 2009). Each of these wells abstract 500–3,200 m^3day^{-1} from the fine to medium sand aquifer beneath the city. Each well operates discontinuously on an average for a total duration of around 12 hours per day. The wells are located throughout the city. The depth of these wells is 150–200 m. Ganga River water is not abstracted for domestic water supply. Ground water is preferred to surface water abstraction, as the cost of constructing, operating and maintaining a surface water treatment plant exceeds the financial resources available to the PWB (PWB 2005). Fifteen overhead reservoirs that were once used for storing drinking water are now not operational.

Prasad et al. (2009) report that the population of Patna has been increasing in recent years, necessitating increasing supply of drinking water mainly by the installation of deeper production wells. Out of 85 production wells operated by the PWB, more than 60% were installed from 2000 to 2004. The PHED (2006) reports that on an average the groundwater table declines at a rate of approximately 0.3 $myear^{-1}$, forcing them to install the impeller of the pumps at greater depths or even installing higher-capacity pumps. Many private production wells are installed by numerous housing cooperative societies and individual estate owners. These are not registered, and hence neither their production rates nor construction details are known. Within the city, many shallow dug wells exist in local aquitards within the top clay layer. Apart from irrigating small vegetable plots, these wells are also used for drinking and watering domestic animals.

3. Data and Methods

3.1. Field and Laboratory Investigations

The methodology used to investigate RBF in Patna consisted of field investigations, laboratory analyses and groundwater flow modeling (Figure 12.6). No previous site-specific data were available, and hence the investigation programme consisted of basic, but essential tasks. Geodetic surveys to determine the elevation of the ground surface and bench marking of the monitoring sites was carried out by the Integrated Hydro Development Forum Patna (IHDF) in 2005. A review of existing literature, including unpublished data and borehole logs was also done at Patna by the authors. Unpublished data on the Ganga River level and river bed-elevation was obtained by the authors from the river stage monitoring station of the Central Water Commission (CWC) in Patna.

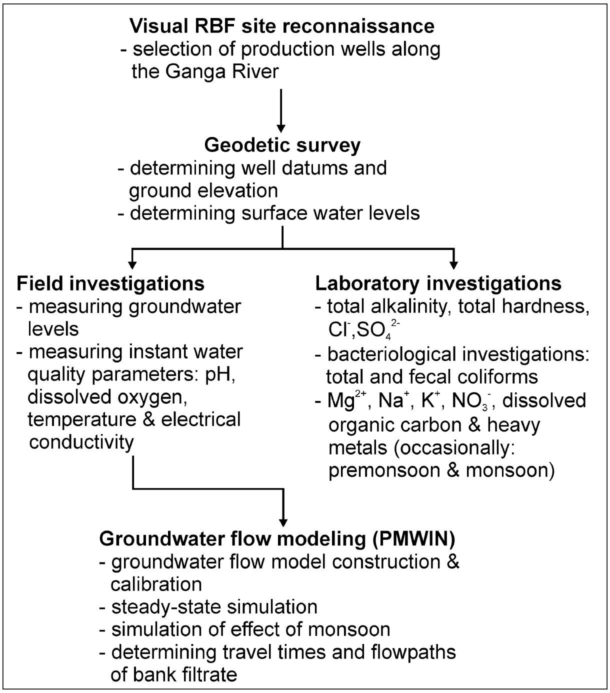

Figure 12.6. Methodology for investigating RBF at Patna.

The water levels and water quality of eight production wells (T1…T8), three dug-wells (W1…W3) and of the Ganga River at four sites (R1…R4) were investigated in this study (Figure 12.3) according to the methodology described by Prasad et al. (2009). Six wells (T1…T6), which abstract bank filtrate, are located within 10–236 m from the riverbank (Table 12.1). Two production wells are located further inland (T7 and T8), in the central part of the city. These were used to investigate the flow of groundwater from the south.

TABLE 12.1. Details of production wells used to investigate RBF in Patna.

Drinking water production well	Total production ($m^3 day^{-1}$)	Daily operation (h)	Distance from river bank (m)
T1	838	10.5	10
T2	1,094	12	70
T3	3,211	13	236
T4	2,736	12	40
T5	2,408	13	100
T6	503	11.5	92
T7	2,736	12	>1,000
T8	2,052	12	>2,000

Ground and surface water levels and water quality were investigated by IHDF at monthly intervals during the pre-monsoon (November 2005–May 2006) and at weekly intervals during the monsoon (June–October 2006). One set each of pre-monsoon and monsoon samples from all locations were analyzed at the laboratory of the water company Stadtwerke Duesseldorf AG (Germany) for dissolved organic carbon (DOC), major anions and cations and trace metals. The groundwater samples were taken from taps (for domestic use; i.e., drinking, bathing, washing) attached to the main supply pipe at each well. A plastic container (10 cm diameter) was used to collect the water from the taps to measure the instant field parameters for groundwater and collect samples for laboratory analyses. Samples to be analyzed for DOC were filtered into a sterilized glass bottle with a 45 μm one-way filter attached to a syringe. One drop of nitric acid was added with a pipette for preserving the sample. Two 100 mL bottles (one each for cation and anion analyses separately), were filled and three drops nitric acid were added as preservative to the sample for cation analyses. The groundwater for cation and anion analyses was not filtered as no suspended particles were visible and the water was clear, however surface water samples for cations, anions and DOC were always filtered. Additionally, one sample for isotope analyses was collected from each site in a glass bottle and sent to the University of East Anglia for analyses.

3.2. Groundwater Flow Model Geometry and Boundary Conditions

To get an improved understanding of the boundary conditions and the hydrogeological regime of the drinking water production wells, a two-layered groundwater flow model (Figure 12.7) using Processing Modflow Version 5.3.0 (Chiang and Kinzelbach 2001) was constructed from field observations of water levels, interpreting data and information provided in the borehole logs and hydrogeological map of Bihar (CGWB 1997 and Saha et al. 2007).

Model Geometry and Initial Conditions The two-layer groundwater flow model with a discretisation of 62 rows and 44 columns was constructed for the study area covering 30 km^2. A uniform thickness of 53 and 300 m was assigned to the upper and lower layers, respectively. A cell size of 200 × 200 m was used initially. The cell sizes of the production wells were refined to 20 × 50 m. An initial hydraulic head of 45 m MSL was used, which corresponds to the 45 m groundwater contour passing through Patna as shown in the hydrogeology map of Bihar (Figure 12.2). Although this resembles a fictive scenario considering the current high groundwater abstraction in Patna, it however would be a reasonably realistic scenario in case of no or limited groundwater abstraction. During the study period (2005–2006), the groundwater levels measured at rest in the production wells T1…T8, were in the range of 36–45 m MSL.

Boundary Conditions The Ganga River was simulated using the river boundary condition. The pre-monsoon surface water level (Ganga River) measured in April 2006 at the river stage measuring locations (R1, R2, R3, and R4) was interpolated

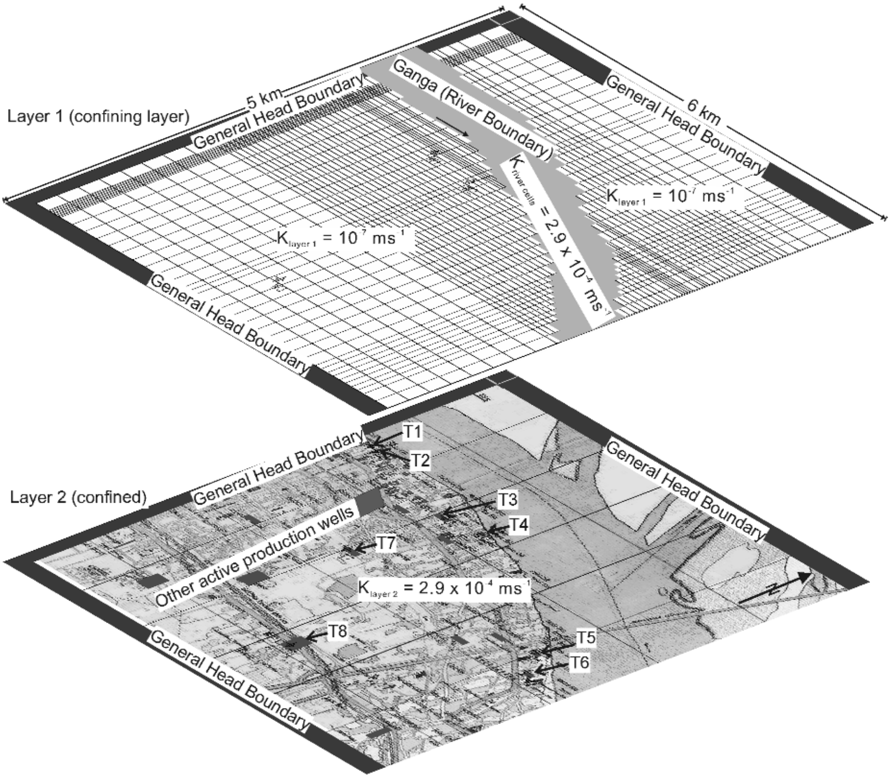

Figure 12.7. Numerical groundwater flow model (PMWIN) of Patna.

and assigned to the river cells. The hydraulic conductance of the river bed (leakage factor in m^2s^{-1}) was calculated for each river cell based on its dimensions and using a uniform hydraulic conductivity of 1×10^{-6} ms^{-1}. This conservative value is based on investigations by Grischek et al. (2002) that proposed a hydraulic conductivity of 10^{-6} ms^{-1} for application in groundwater flow modeling to simulate low surface flow conditions of the Elbe River. The current groundwater flow model for Patna also simulates a low discharge scenario for the Ganga. Grain size distribution analyzes the Ganga bedload sediments conducted by Singh et al. (2007) determined that fine to very fine sand having a grain size diameter between 63 and 500 µm (hydraulic conductivity ~10^{-5} ms^{-1}) are the dominant fractions (up to 80 %) of an approximately 300 km long stretch of the Ganga passing by Patna. Grischek et al. (2002) concluded that the hydraulic conductivity of the clogging layer was at least one order of magnitude lower than that of the bed sediments. Additionally, the thickness of the river bed bottom was taken to be equivalent to the difference between the pre- and post-monsoon elevations of the river bed. Thus the hydraulic conductance of the river cells ranged from 0.001 to 1 m^2s^{-1}. A general head boundary (GHB) condition was assigned to both layers in the north, south and west of the model domain. The hydraulic head of the GHB corresponds to the groundwater contour of 45 m (Figure 12.2) in the north, and to 50 m in the south and west of the model domain respectively. Initially only the eight production wells investigated during the study (T1…T8) were assigned to the lower model layer. However, with the current abstraction rates (Table 12.1) no significant drawdown occurred. In reality, a significant number of additional production wells (Figure 12.7, dark shaded rectangles in layer 2) exist within the 30 km^2 model domain, of which the location of at least 18 wells operated by the PWB could be identified. The total daily abstraction of these 18 wells (average operation of 12 h/day) is 34,300 m^3. In comparison, the total daily abstraction of the wells T1…T8 is 15,500 m^3 (45%). Hence the 18 wells operated by PWB were additionally assigned to the model domain. The production rates of all the wells are in the range 0.05–0.13 m^3s^{-1}.

4. Results and Discussion

4.1. Ground and Surface Water Levels

The water levels of all the production wells, and that of the Ganga River at the farthest downstream gauging site (R4), are shown in Figure 12.8. It is observed that the Ganga River level is higher than the production wells throughout most of the year. The pattern of groundwater levels resembles the Ganga River stage, indicative of a behavior for a confined aquifer. Thus, it can be inferred that the river is influent and in hydraulic contact with the aquifer. Due to the very high abstractions in Patna, a local groundwater trough is created, thus inducing surface water infiltration from the Ganga. However, this conclusion only applies at the local scale of Patna, and cannot be inferred from the regional hydrogeology map of Bihar in Figure 12.2.

4.2. Ganga River Morphology

The highest recorded Ganga River stage by the CWC field station in Patna (since 1965) is 50.27 m MSL in August 1994, which is nearly 2 m higher than observed in August 2006 (Figure 12.8). The corresponding channel width of the Ganga was 2520 m (measured approximately 200 m upstream of R2).

The data for the post-monsoon (December 2004) and the pre-monsoon (June 2005) river bed elevation profile have been combined with the lithological profile of production well T3 (Figure 12.9). Accordingly, the lowest post-monsoon elevation of the river bed was 29 m MSL In the pre-monsoon along the same profile, the lowest elevation measured was 34 m MSL, recorded 250 m from the bank. By the end of the pre-monsoon season in June 2005, the river bed elevation had risen up to 10 m.

Figure 12.9 indicates a dynamic change in the river bed morphology. Similar to the observation by Singh et al. (2007), an increase in the river bed elevation commences after the monsoon ends (post-monsoon) and continues up to the onset of the next monsoon the following year (pre-monsoon 2005) due to the maximum amount of deposition of bed load sediments with decreasing flow. By comparing the elevation of the sand layer in the adjacent aquifer to the south and the Ganga River bed, the extent of the hydraulic contact is increased due to scouring as a result of the monsoon. In the pre-monsoon (April–June), during the period when the Ganga water level is lowest up to when it rises as a result of increased snow melt, a 2–5 m thick sequence of bed load sediments deposits is formed that constitutes mainly fine sand (69–87%), medium and very fine sand with fractions (2%) of silt and clay (Singh et al. 2007).

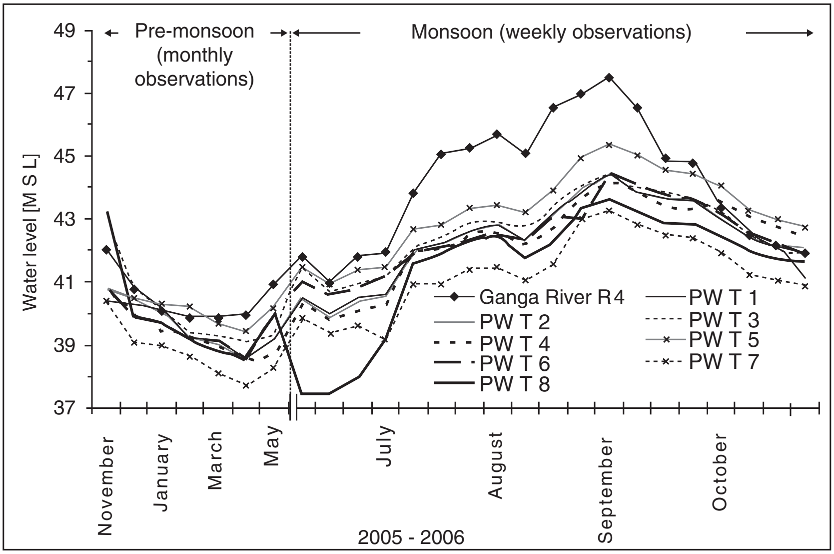

Figure 12.8. Water level observations for the Ganga River (R4) and production wells (T1…T8) at Patna.

4.3. Water Quality

The summary of the water quality data (Table 12.2) indicates that all physicochemical parameters from the production wells are within the maximum permissible limits set by the Bureau of Indian Standards (IS 10500-1991), and thus the abstracted water from the production wells is of good quality. It can be observed that the water in the shallow dug-wells exhibits greater mineralization than the deeper groundwater of the production wells. This is probably due to the much higher residence time of groundwater in the aquitards within the upper confining clay layer.

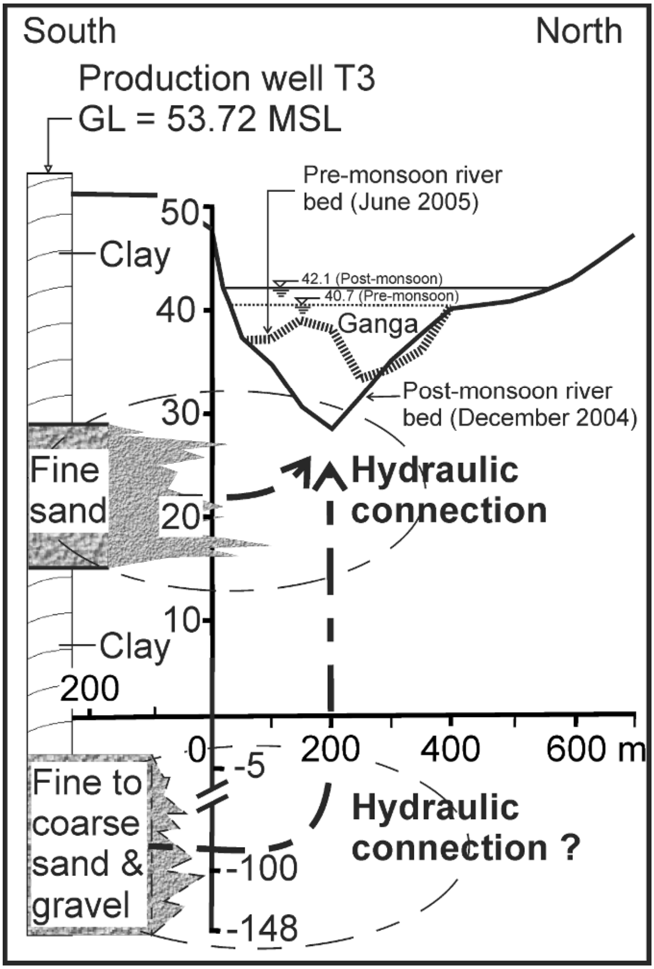

Figure 12.9. Aquifer cross-section of production well T3 and Ganga River in Patna.

The observed high total coliform count in the Ganga River (Table 12.2) is largely due to the discharge of untreated domestic sewage. The presence of total coliform in some of the production wells is most likely also due to the contamination of landward side groundwater from the south, as a result of many open unlined drains carrying domestic sewage. Nevertheless, the more than four log removal of total coliform is a considerable advantage of pre-treatment by RBF. The high total coliform count in the dug-wells can be attributed to the fact that these wells are open at the top, and only surrounded by a parapet. Additionally, the bathing of animals is also often undertaken adjacent to these wells. The wastewater is usually discharged into open unlined drains or septic tanks.

TABLE 12.2. Water quality during non-monsoon and monsoon periods.

Parameter	Ganga River (R1…R4)		Production wells (T1…T8)		Dug wells (W1…W3)	
	Pre-monsoon	Monsoon	Pre-monsoon	Monsoon	Pre-monsoon	Monsoon
pH	6.9–8.4	7.8–8.2	7.1–7.8	7.5–7.9	7.0–8.0	7.4–7.7
Water temperature (°C)	18.0–33.6	29.4–30.7	18.0–29.0	28.3–28.7	18.1–28.3	28.0–28.5
Electrical conductivity (μScm^{-1})	303–549	168–296	505–681	219–940	734–1547	210–1532
Dissolved oxygen (mgL^{-1})	4.8–9.0	2.9–5.6	0.7–7.4	0.0–6.6	1.8–6.9	3.5–5.5
Total alkalinity (mgL^{-1})	110–230	57–284	151–238	57–277	194–332	287–294
Total hardness (mgL^{-1} as $CaCO_3$)	105–506	90–123	84–364	142–218	148–503	356–446
Ca^{2+} (mgL^{-1})	43–46$^{3)}$	22$^{1)}$	67–84$^{9)}$	70–74$^{4)}$	97–104$^{3)}$	n. d.
Mg^{2+} (mgL^{-1})	13–18$^{3)}$	5$^{1)}$	16–20$^{9)}$	15–16$^{4)}$	26$^{1)}$	n. d.
Na^{+} (mgL^{-1})	17–29$^{3)}$	10$^{1)}$	25–35$^{9)}$	27–29$^{4)}$	83$^{1)}$	n. d.
K^{+} (mgL^{-1})	4–5$^{3)}$	3$^{1)}$	2–7$^{9)}$	3–5$^{4)}$	55$^{1)}$	n. d.
Cl^{-} (mgL^{-1})	3–21	4–9	3–69	3–41	39–83	52–114
SO_4^{2-} (mgL^{-1})	12–29	9–42	2–31	3–74	18–57	29–60
NO_3^{-} (mgL^{-1})	<1$^{2)}$	n. d.	0.7-7.7$^{5)}$	1–15$^{4)}$	55–83$^{2)}$	n. d.
DOC (mgL^{-1})	1.9–2.1$^{2)}$	4.9$^{1)}$	0.2–2.8$^{4)}$	0.6–1.6$^{4)}$	0.6$^{1)}$	n. d.
Total coliform (MPN/100 mL)	24,000–160,000	90,000–160,000	8–170	8–300	170–2200	800–5000

MPN most probable number, n = 180, $^{1)\dots9)}$ n = 1…9, n. d. = not determined

Some analyses in the pre-monsoon and monsoon, of iron and manganese, and certain trace metals were conducted in surface and groundwater. The analyses showed that the values were within the permissible limits in most cases. For a few exceptions, such as manganese, the values were within the tolerance limits (IS 10500-1991). While the concentration of iron and barium was <0.1 mgL^{-1} in all cases, that of manganese was in the range of 0.02–0.2 mgL^{-1}. Other heavy metals such as arsenic and copper were <0.01 mgL^{-1} in all samples. Nickel, lead and chromium were <2 μgL^{-1}. Cadmium was <0.5 μgL^{-1}. The concentration of zinc was <0.05 mgL^{-1} in all samples. The values of certain parameters such as the *pH* and concentrations of dissolved oxygen, total hardness, sodium, chloride, sulphate, nitrate, potassium, iron and the total coliform count of the river water (Table 12.2) corroborate well with results of the studies on the Ganga River water by Tiwary et al. (2005) and Ram and Singh (2007).

4.4. Groundwater Flow Modeling

A steady-state calibration of the groundwater flow model was done for two scenarios, one where all the production wells are inactive (Figure 12.10a) and the other where they are all active (Figure 12.10b).

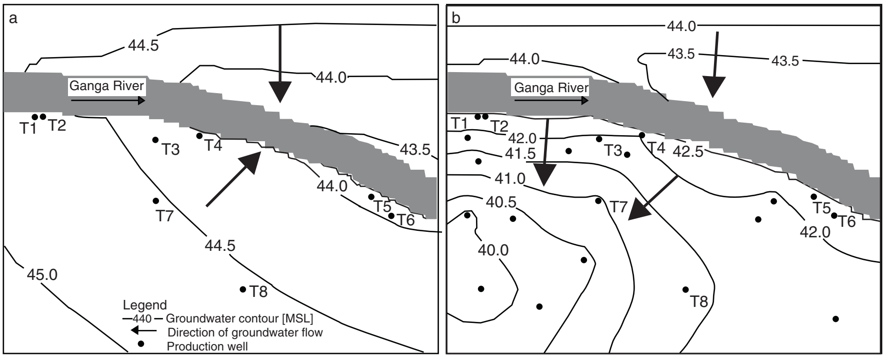

Figure 12.10. Direction of groundwater flow for (**a**) inactive production wells, and (**b**) active production wells in Patna.

For the fictive scenario where all the production wells are inactive (Figure 12.10a), the groundwater flow pattern and contours resemble the 45 m groundwater contour passing through Patna as seen in Figure 12.2. This is a logical scenario, considering that the Ganga is effluent for most of the year, except during monsoon when it becomes influent (Chaturvedi and Srivastava 1979, Saha et al. 2007). For the realistic scenario where all the production wells are active, the groundwater flow direction is reversed to the south of the Ganga (Figure 12.10b). To the immediate north of the Ganga, the groundwater flow direction remains unchanged, since there are no substantial groundwater abstractions in that area. The groundwater flow direction to the south corroborates with the results of the monthly groundwater level field measurements (Figure 12.8), where lower groundwater levels are observed throughout the year (compared to Ganga water levels), as a result of the high groundwater abstractions to meet the drinking water supply of Patna. Thus, as seen in Figure 12.2, the aquifer is effluent on a regional scale. At a local scale, it is reasonable to expect a groundwater trough in Patna resulting in an influent river as seen in Figure 12.10b.

Considering the significant aquifer thickness and storage, and the fact that most of the recharge to the aquifer occurs to the south of the SGP bordering the Precambrian highlands, the GHB to the south and west is a sensitive model parameter that affects the water balance and groundwater table of the model. With the current boundary conditions and model parameters, a good water balance with an error of −0.08% and −0.01% is achieved for both scenarios depicted in Figure 12.10a and b (Table 12.3). The discrepancy between the observed and simulated groundwater heads of the production wells was 0.13–0.62 m. Thus considering the scale of the model, a good calibration was achieved.

TABLE 12.3. Water balance for groundwater flow model for Patna.

Flow term	Production wells inactive		Production wells active	
	Inflow into model (m^3s^{-1})	Outflow from model (m^3s^{-1})	Inflow into model (m^3s^{-1})	Outflow from model (m^3s^{-1})
River leakage	0.003	0.32	0.53	0.002
GHB	0.31	0.0	0.62	0.0
Production wells	0.0	0.0	0.0	1.145
Sum	0.313	0.320	1.150	1.147

4.5. Isotope Analyses

One set of pre-monsoon samples of the Ganga River and groundwater was analyzed for the ^{18}O isotope, and one set of monsoon samples was analyzed for ^{18}O and ^{2}H isotopes (Table 12.4). The relative isotopic abundance (δ) indicates that in the pre-monsoon the $\delta^{18}O$ signature for the Ganga River (−6.35‰) is slightly greater than that of water from the production wells (−6.44 to −6.72‰). During monsoon the $\delta^{18}O$ signature of the Ganga water shows greater depletion (−8.70‰) compared to water from the production wells (−6.61 to −6.68‰). Likewise, the $\delta^{2}H$ signature of the Ganga River water is greater (−62.05‰) during the monsoon compared to production well water. The more depleted isotopic signature can be attributed to the very high proportion of precipitation in the Ganga River. The decrease in the $\delta^{18}O$ signature of the production well water during monsoon indicates a contribution of more depleted isotopic water (such as due to recharge) which could be due to mixing with bank filtrate.

TABLE 12.4. Relative isotopic abundance in Ganga River and groundwater in Patna (Hiscock 2006).

Relative isotopic abundance (‰)	Ganga River		Production wells	
	Pre-monsoon	Monsoon	Pre-monsoon	Monsoon
$\delta^{18}O$	-6.35^{b}	-8.70^{a}	-6.44 to -6.72^{c}	-6.61 to -6.78^{d}
$\delta^{2}H$	n.d.	-62.05^{a}	n.d.	-47.17 to -48.46^{d}

$^{a…d}$ n = 1…4, n.d. = not determined

5. Conclusion

The RBF wells investigated in this study in Patna were found to be efficient for the removal of coliform bacteria. Even during the monsoon, no turbidity was observed in the production wells. Water quality results show that the mineral content of the Ganga at Patna is low, but decreases further during the monsoon. Except for the dug wells, the mineral content of the bank filtrate wells and Ganga River water do not differ significantly. The organic carbon concentration in the river and well water is very low. The low presence of coliform bacteria in some wells is probably due to contamination from land side groundwater due to infiltration of waste water from open and unlined drains. Yet the sufficiently thick clay layer at the surface above the aquifer serves as an effective barrier against potential widespread contamination due to anthropogenic activities. Due to the confining nature of the aquifer, a sharp increase in water levels of the production wells is observed during monsoon which corresponds to the dynamic rise in the Ganga water levels indicating a good hydraulic connection.

The RBF wells in Patna provide significant quality improvements and are sustainable in terms of water quality throughout the year. Nevertheless, a final disinfection of the distributed water is recommended. Although a lowering of the observed groundwater levels in the production wells abstracting bank filtrate over a study period of one year is not observed, this observation cannot apply to all the production wells in the city. Thus, the RBF wells also appear to be sustainable in terms of water quantity abstracted. An abstraction strategy that incorporates the conjunctive operation of bank filtrate and groundwater production wells could arrest the declining groundwater levels in the city to some extent. This would be a useful tool in future.

According to Prasad et al. (2009), evidence from the records of the archives of the Bihar State suggest that the old course of the Son River passed parallel to the south of the Ganga River and through the city in 750 A.D., before joining the Ganga River near Fatwa approximately 10 km to the east of Patna (Public Works Department 1966). Currently the confluence of the Son with the Ganga is approximately 30 km to the west of Patna (Figure 12.2). The abandoned bed of the river in Patna city is characterized by an east-west aligned belt of coarse sand 2 m below ground level. The coarse sand is typical of the current river bed of the Son. Thus, at the points of confluence of the former course of the Son with the current course of the Ganga, the coarse sand aquifers found at a shallow depth would have a good hydraulic contact with the Ganga River. These could serve as potential RBF sites (Prasad et al. 2009).

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