

Aquifer system response to intensive pumping in urban areas of the Gangetic plains, India: the case study of Patna

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Abstract A significant component of domestic demand for water of urban areas located in the Gangetic plains is met by heavy pumping of groundwater. The present study is focused on the Patna municipal area, inhabited by 17 million people and spanning over 134 km², where entire urban water demand is catered from pumping by wells of various capacities and designs. The present study examines the nature of the aquifer system within the urban area, the temporal changes in the water/piezometric level and the recharge mechanism of the deeper aquifers. The aquifer system is made up of medium-to-coarse unconsolidated sand, lying under a ~40-m-thick predominantly argillaceous unit holding 8- to 13-m-thick localised sand layers and continues up to 220 m below ground. Groundwater occurs under semi-confined condition, with transmissivity of aquifers in 5,500–9,200 m² day⁻¹ range. Hydraulic head of the deeper aquifer remains in 9–19 m range below ground, in contrast to 1–9 m range of that of the upper aquitard zone. The estimated annual groundwater extraction from the deeper aquifer is ~212.0 million m³, which has created a decline of 3.9 m in the piezometric level of the deeper aquifer during the past 30 years. Unregulated construction of deep tube wells with mushrooming of apartment culture may further exacerbate the problem. The sand layers within the aquitard zone are experiencing an annual extraction of 14.5 million m³ and have exhibited stable water level trend for past one and half

decades. This unit is recharged from monsoon rainfall, besides contribution from water supply pipe line leakage and seepage from unlined storm water drains.

Keywords Gangetic plains · Urban water supply · Hydrogeology · Aquifers · Groundwater resource · Water level decline

Introduction

Groundwater plays a critical role in shaping up the economic and social health of many urban areas in the world. It is estimated that more than 1 billion urban dwellers in Asia and 1.5 billion in Latin America depend directly or indirectly on dug wells, springs and boreholes for their drinking water supply (World Bank 1998). In India, the aquifers underneath urban areas represent varied hydrogeological framework and plays a pivotal role in water supply. In hard rock areas, covering 70 % of the total geographical area of the country, aquifers have less potential and are unfit for large-scale development. Urban areas in this part exhibit greater dependence on external surface water sources. On the other hand dependence on groundwater is more in major parts of north India underlain by rich alluvial aquifers augmented by natural and canal recharge (Patel and Krishnan 2008). A study conducted in 304 cities and urban areas in India indicated that in the units located on hard rocks such as crystallines, basalts and limestones, 79, 92 and 95 % of total water supply, respectively, are surface water dependent (NIUA 2005). These cities derive their water supply from irrigation reservoirs or from other storages. However, the situation is reverse in the Gangetic plains, where the dependence on groundwater is ~70 %.

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India has presently ~285 million city dwellers constituting 28 % of its total population. By 2050, more than 50 % of India's population (projected as ~1.8 billion) will be living in urban centres, where delivering adequate potable water would be a major challenge (Londhe et al. 2004). Further, with shortage of suitable locations for constructing reservoirs and weirs, dependence on aquifers will increase significantly (Phansalkar et al. 2005).

Patna, the capital of Bihar state, is located in the central part of the Gangetic plains, referred to as the middle Gangetic plains. The state of Bihar is blessed with fertile soil, rich water resources and is known for its agrarian economy (Fig. 1). The city is amongst the oldest surviving urban centres of the world, with a continuous recorded history dating back to the fifth century BC and is symbolic of India's long urban heritage (Ramchandran 1999). The city (population 1.7 million) is one of the fastest growing urban centres in India. Despite the fact that the city is located on the banks of the River Ganga, the water supply is solely dependent on underneath aquifers, which also caters to the demand for vegetable farmlands in peri-urban

areas. However, as observed in other groundwater-dependent urban centres in the Gangetic plains, no management plan is in force for proper utilisation of this resource. Adoption of any sustainable management plan warrants thorough understanding of the aquifer systems of the area, which is lacking. The objective of the study was a detailed assessment of the aquifer system, its geometry and sub-regional continuity in Patna urban area. The spatial and temporal groundwater water level behaviour, attendant groundwater extraction and its relation to aquifer recharge and storage have been established for the first time.

Study area

Low ground elevations and the proximity to the Ganga and the Sone Rivers with its attendant risk of flooding have historically guided the expansion of the Patna city along the east–west aligned natural levee of the Ganga. The past two decades have witnessed industrial/commercial and residential development towards the south, invading the

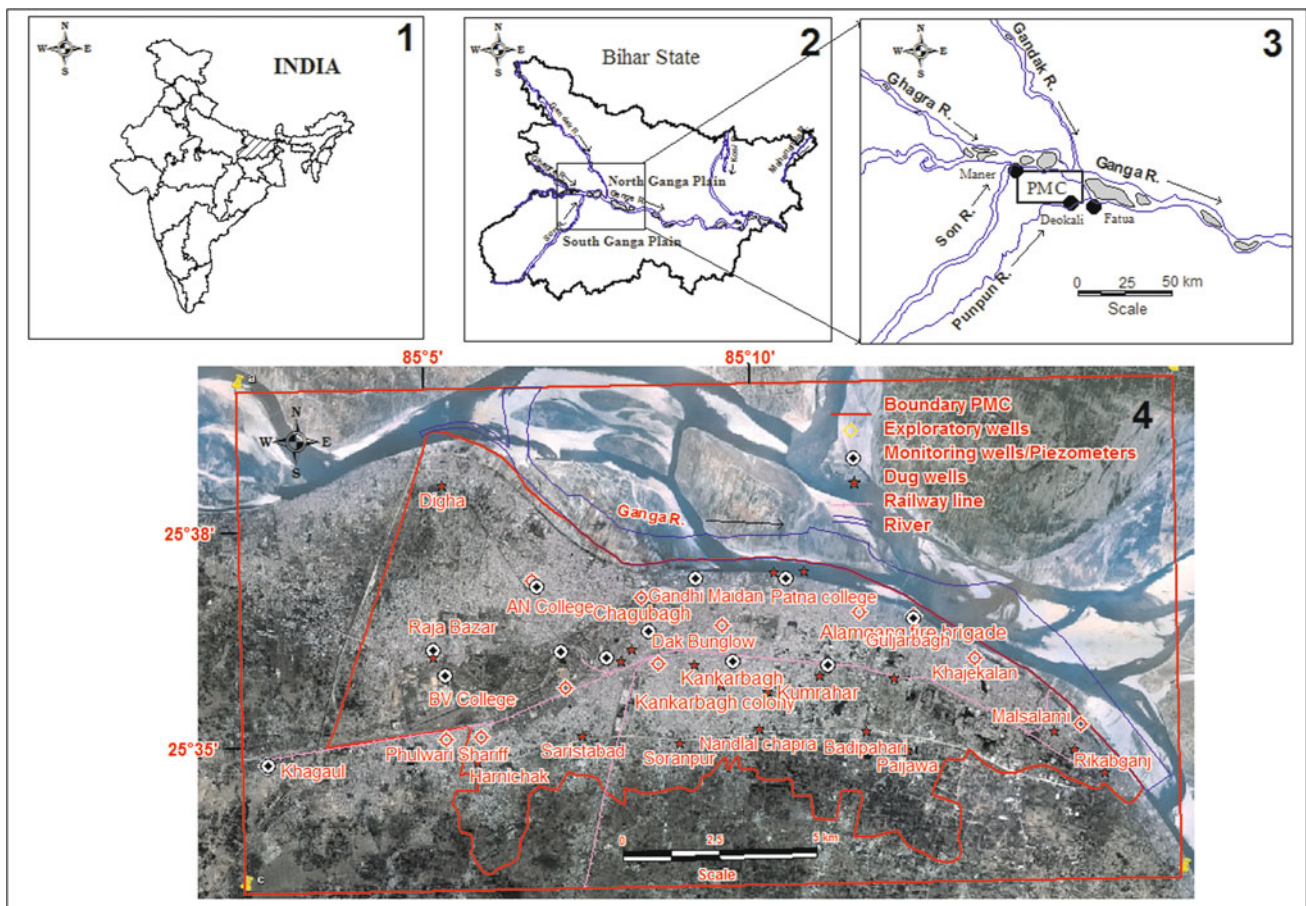


Fig. 1 Location map of the area. (1) Location of Bihar state in India, (2) WiFS image of Bihar showing the North and South Ganga Plains with major rivers, (3) Patna urban area located near the confluences of

three major rivers, the Ganga and the Gandak originate in Himalaya and the Sone flows from peninsular India. (4) Localities in Patna municipal area

back swamps between the Ganga and Punpun Rivers (Fig. 2). The potential aquifers have enabled water supply from intra-urban wells, without the need for complex water transfer systems from peri-urban well fields or surface-water sources. The present study covers 134 km² area of Patna Municipal Corporation (PMC), which is divided into 37 wards with a population density of ~16,000 persons km⁻². The most densely populated wards (>20,000 persons km⁻²) are located on the natural levee (Fig. 2) on the bank of the Ganga. The city has witnessed a population growth from 0.6 million in 1971 to 1.7 million at present, besides a floating population of about ~0.2 million, assembling during the office hours. Projected population for 2021 is 2.2 million. Sixty per cent of the study area is inhabited.

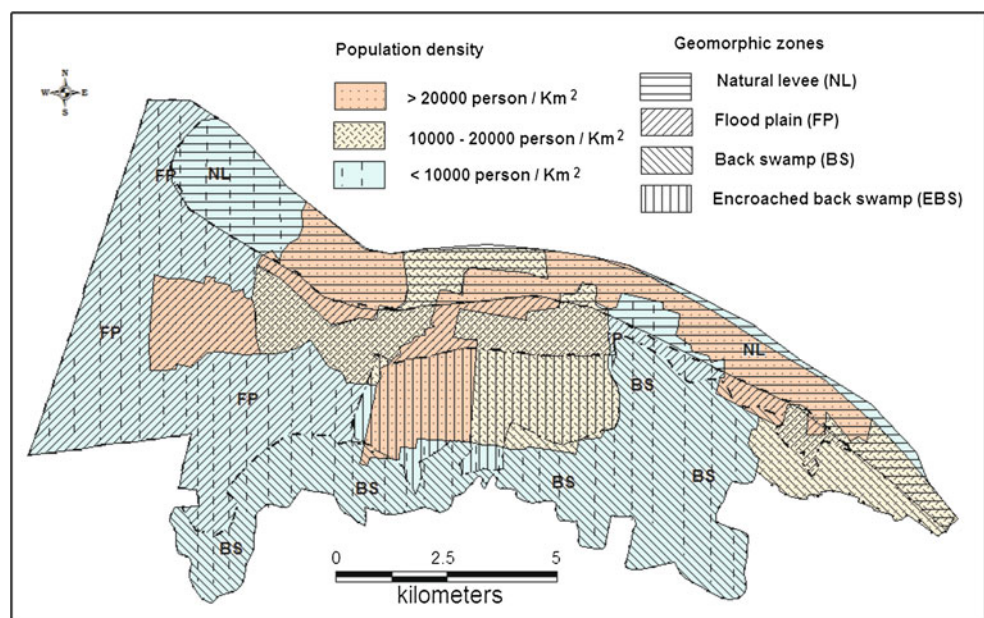
The middle Gangetic plains, which is the central part of the east–west elongated Gangetic Plains, represents monotonously flat topography, with altitude ranging from 46 to 54 m above mean sea level (msl) in Patna Urban area. Except the natural levee part, the elevation ranges from 46 to 49 m in southern and south eastern part, merging with the back swamps of the Punpun-Ganga system. The western part represents typical interfluvies between the Sone and the Ganga. Urbanisation has obliterated the minor drainages in the area. During high rainfall years, higher water levels in the course of the Ganga prevents the Punpun to debouch in its course, resulting in water logging in the back swamp areas, invading the southern part of the study area. Data of last 50 years reveal that flood water has also invaded the core urban area number of times by overtopping the embankment along the eastern bank of the Sone, though, less frequently than the Punpun in south.

The area is characterised by a sub-tropical to sub-humid climate with three distinct seasons ‘viz,’ monsoon (June–September), summer (March–May) and winter (December and January). The monsoon is brought in the area from south-west direction (known as south-west monsoon) from the Indian ocean as happens for the Indian landmass during the monsoon period. Average annual rainfall (1930–1980) of the area is 1,051 mm, 82 % of which is received during monsoon (Govt of Bihar 2010). However, the past decade has witnessed a higher annual rainfall (mean 1,116 mm). July and August are the rainiest months receiving 51 % of mean annual rainfall distributed in 26 rainy days. The average number of rainy days in a year is 53.

Materials and methods

The present study assembles details of deep tube wells, such as well design, discharge, drawdown and water level data from various agencies such as Patna Jal (Water) Board, Government of Bihar, Central Ground Water Board (CGWB), Government of India, State Ground Water Directorate, Government of Bihar and private drillers operating in PMC. Time-drawdown data of pumping tests conducted earlier by CGWB for 12 wells have been collected (CGWB 2009) and re-interpreted using Walton method (Walton 1962) to determine transmissivity (*T*) and storativity (*S*). Drill-cut sample of these 12 bore wells have been collected from CGWB and visually analysed to prepare sub-meter scale lithologs, which were further used for delineating aquifer configuration. Monthly measurements of water levels from bore wells tapping deeper sand zones (zones tapped 78–180 m bgl) were carried out at seven

Fig. 2 Geomorphic units and population distribution in Patna municipal area



locations during June 2008 to November 2010 and at another three locations for May 2009–November 2010. Additionally, 26 dug wells (depth 8–12 m, used for limited local use) tapping the sand layers within the aquitard zone were measured four times in a year for 2007–2010: during January, May (pre-monsoon), August (mid-monsoon) and November (post-monsoon). The water levels were used in preparing water level maps, referenced to both ground level and mean sea level. Water levels of four hydrograph network stations were collected (CGWB 2011) and trends were analysed for pre- (May) and post-monsoon (November) periods. In the absence of any authentic data on total number of wells operating in the area, field surveys were undertaken in five municipal wards to work out the number of tube wells in housing societies/apartments and private houses and their average discharge.

Groundwater extraction: history and status

Patna is one of the oldest urban areas in the Gangetic plains where water supply was taken up in a planned manner. Earliest systematic water supply scheme was introduced during the British rule in 1916–1918, around the High Court area, using steam-engine-run pump for drawing water from large-diameter gravel-packed dug well (Maitra and Ghose 1992). Three tube wells were initially constructed in 1920s (diameter 200 mm, depth 120 m) using brass strainer, with a reported discharge of 55–68 m³ h⁻¹ and drawdown of 3.66 m. Heavy-duty deep tube wells were first introduced in 1951, with 312 m long assembly, tapping 78 m granular zone with a reported discharge of 545 m³ h⁻¹ for 1.5 m drawdown (Maitra and Ghose 1992).

Until 1973, 18 public water supply deep tube wells were operational. By the year 1988, the number increased to 59, and presently 89 are working with an installed capacity of 2.97×10^4 m³ h⁻¹ (Table 1). In former times, water was lifted to overhead tanks for supply, which has been discontinued since 1957, when direct pumping into the distribution pipeline was initiated. The deep tube wells are presently connected through a web of ~500 km pipeline (dia. 75–300 mm), supported by 13 overhead tanks,

forming a complex interlinked delivery system with gate valves installed at strategic locations.

Inadequate availability of water in pipelines and limited coverage has compelled the housing societies (group of privately owned houses) and the apartment complex to have their own tube well-based supply. Since the past decade, with mushrooming of multi-storeyed apartments, there has been a phenomenal increase in number of such wells. These wells tap aquifer deeper than 80 m bgl, henceforth referred to as deep tube wells. No regulatory mechanism exist for drilling of new deep tube wells and in the absence of any monitoring mechanism by the water supply departments, precise data are not available on the number of such deep tube wells under operation. Based on field surveys conducted in five wards and available data from 'Patna Water Board', the number of such wells in the study area has been worked out as 3,250.

The water supply agencies have classified the deep tube wells into two categories: (1) *high yielding*—length of assembly 140–200 m, diameter 420 mm, production rate >200 m³ h⁻¹, housing diameter 460 mm, length of slotted pipe 55–60 m; (2) *medium yielding*—length of assembly 100 m, diameter 200 mm, production rate 125–250 m³ h⁻¹, housing diameter 420 mm length of slotted pipe 30–50 m. Medium-yielding deep tube wells are generally installed in low-pressure areas, between two high-yielding wells. Vertical turbine pumps of three different capacities are preferred for deep tube wells; 40 horse power (HP, 1 HP = 746 W) and 60 HP, mainly used for medium-yielding wells with a pump discharge of 110–170 m³ h⁻¹, and 100 HP pumps are used commonly (60 % of the total) for high-yielding wells with a discharge of 190–380 m³ h⁻¹. Historical data indicated a steady discharge since 1974 for 40 and 60 HP pumps, whereas a marginal increase is noted for 100 HP pumps, between the period 1976 and 2007. The reasons for this may be the use of slotted pipe with more open area and attention given towards the development of wells. Enquiry with the concerned officials also revealed an improvement in quality of gravel used as pack-material.

In apartments and housing societies, deep tube wells are fitted with submersible pumps with 20–30 m³ h⁻¹ capacity. Sample survey of 40 such wells indicated an average unit extraction of 35 m³ day⁻¹, which translates to a total extraction of 41.50 million m³ year⁻¹ from the apartments and housing societies. Currently, there is mushrooming of household bore wells. Such wells are less in number in the congested old city areas, but a common feature in the newly developed settlements in southern and western parts. In the absence of any accurate data base on number of household bore wells, an attempt has been made to estimate by conducting surveys in 80 households each, in five municipal wards with different population density.

Table 1 Progressive increase in number of water supply wells and annual extraction

Year	Total installed capacity (m ³ h ⁻¹)	Annual abstraction of water (million m ³)
1972	0.5×10^4	33.44
1980	1.40×10^4	81.76
1988	1.83×10^4	107.30
2008	2.97×10^4	136.87

The surveys revealed that an average 40 % of the 0.22 million households have their own bore wells. Out of 88,000 estimated units, 30 % ($n = 26,400$) are shallow wells (<30 m), drawing water from sand layers within the top predominantly argillaceous aquifer. Remaining wells are deep ($n = 61,600$) and extract water from sand layers at depth (>60 m). Considering an average extraction of household bore wells as $1.5 \text{ m}^3 \text{ day}^{-1}$, withdrawal by shallow wells is estimated at 14.45 and 33.72 million $\text{m}^3 \text{ year}^{-1}$ by deep wells.

Aquifer configuration and hydraulic parameters

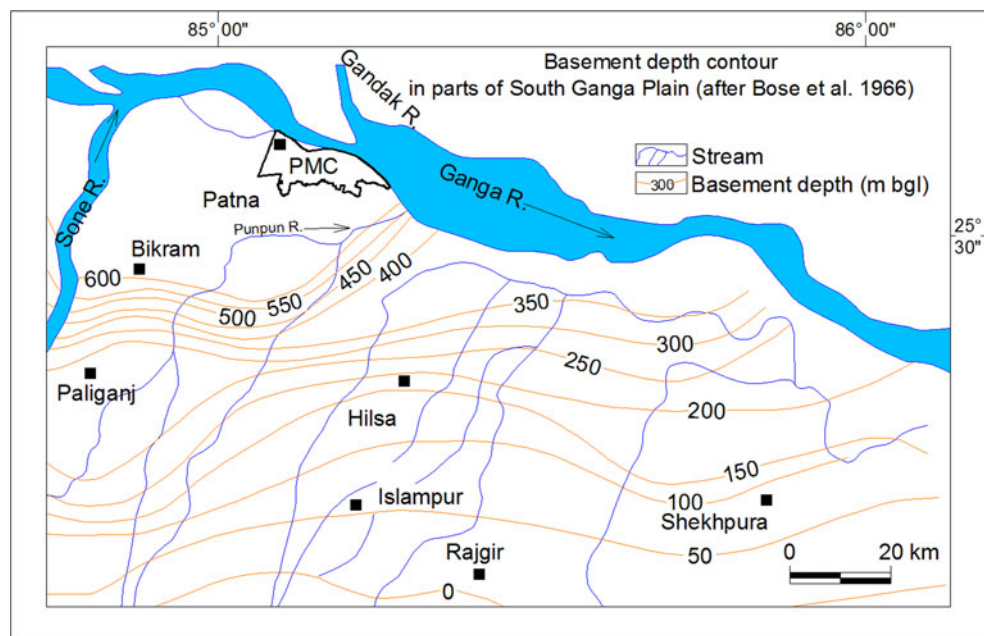
The Ganga basin is an active foreland basin formed in response to the uplift of the Himalaya’s due to collision of Indian and Asian plates (Dewey and Bird 1970). The middle Gangetic plains located in the central part of the vast Gangetic plains exhibit asymmetrical sediment wedging, with thickness varying from less than a meter towards basin margin areas with Peninsular craton, to more than 5 km near the Himalayan orogen (Rajagopalan et al. 1988). A seismic refraction study by Bose et al. (1966) revealed ~700 m thick Quaternary sediments in areas around PMC (Fig. 3), unconformably overlying Precambrian basement. Published work on lithological characteristics of the sediments is scanty. Departmental reports from CGWB (2009) and data collected from the State Government Departments (Maitra and Ghose 1992) have indicated alteration of sand, silt and sandy clay down to 310 m bgl. Hydraulically inter-connected aquifer groups are, however, yet to be established. In areas elsewhere in

middle Gangetic plains, with similar geology, a two-tier aquifer system made up of fine to coarse unconsolidated sand (with localised clay layers) has been established within 250 m bgl (Saha et al. 2010).

Sub-meter-scale lithologs prepared for 12 wells in the study area indicated multi-cyclic Quaternary deposits made up of sand, silt, clay and sandy clay up to ~260 m bgl. The top 30–50 m is predominantly argillaceous, with lithology of clay and sandy clay. The lithologs of wells at three locations, at Khagaul, Golghar and Sanatan Dharamsala are depicted in Fig. 4. The low-energy deposits in the upper slice of lithologs form Fatwa Formation of Middle–Upper Holocene age, akin to the ones observed in adjoining areas of the study region (Saha et al. 2007). An 8-to 13-m-thick fine sand layer is discernible within this unit in major part of the area. Hydrogeologically, the deposits from Fatwa Formation behave as a low potential argillaceous aquifer, henceforth referred as top aquitard zone.

The top aquitard zone is underlain by a thick medium to coarse sand layer forming potential aquifer system, henceforth referred to as deeper aquifer. This unit continues up to 220 m bgl followed by a clay layer (Fig. 5). In contrast to the grey-coloured aquitard zone, the sand layers forming the deeper aquifer are yellow to yellowish brown in colour, indicating its deposition under oxidising environment. This unit belongs to the Nawada Formation of Upper Holocene to Lower Pleistocene age and is exposed at 20 km south of the study area and beyond (Saha et al. 2008). The thickness of the deeper aquifer could not be ascertained in this study as the basal clay bed was not encountered for the area, except at isolated locations like at

Fig. 3 Basement depth contour (below ground in m) in parts of South Ganga Plain (after Bose et al. 1966)



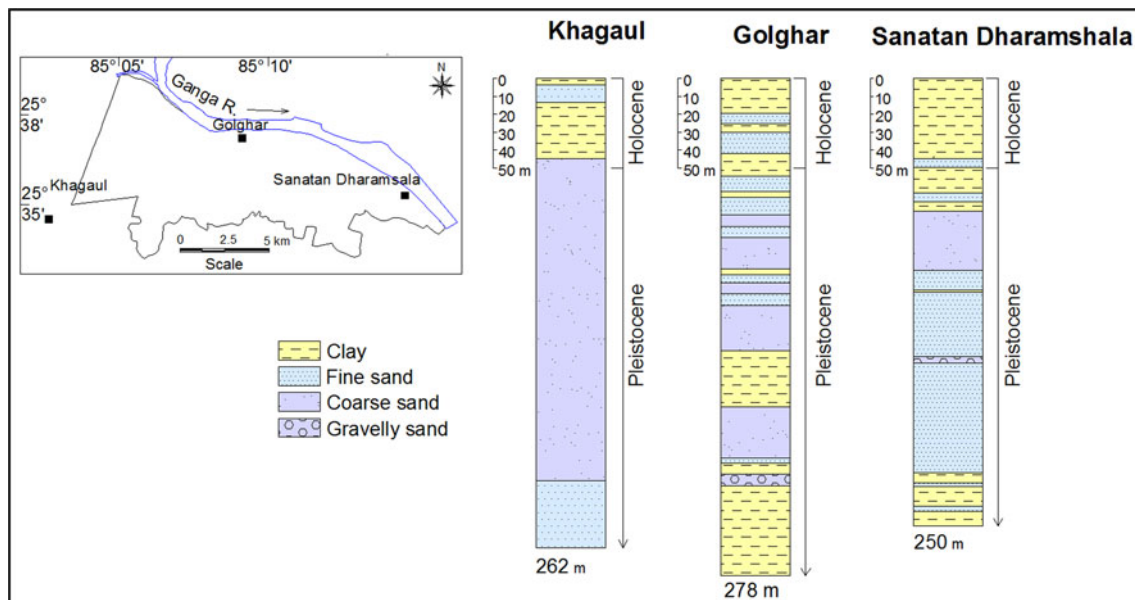


Fig. 4 Lithologies of three wells drilled in Patna municipal area

Gandhi Maidan and at Kadamkuan. Longitudinal continuity of the deeper aquifer is occasionally interrupted by 5- to 8-m-thick clay layers but they are not of any hydrogeological significance because of their localised extent.

Time-drawdown data of pumping tests available for 12 wells (CGWB 2009) indicate the pumping discharge in a range between 180 and 222 $\text{m}^3 \text{h}^{-1}$, with a drawdown variation of 2.21–4.09 m. The time drawdown data have been reinterpreted using Walton (1962) method for all the 12 wells. Transmissivity has been found to range between 5,470 and 9,229 $\text{m}^2 \text{day}^{-1}$ with a mean of 7,392 $\text{m}^2 \text{day}^{-1}$ (Table 2). Pumping tests conducted earlier (1980s) at four locations (Table 3) and interpreted using Jacob straight line method (Jacob 1950) indicated a transmissivity range of 3,796–13,165 $\text{m}^2 \text{day}^{-1}$ (Maitra and Ghose 1992). The specific capacity of the wells ranged from 56 to 100 $\text{m}^3 \text{h}^{-1} \text{m}^{-1}$ and the mean hydraulic conductivity (K) has been determined as 84 m day^{-1} . The determined K values correspond to those of coarse sand and coarse sand mixed with gravel in a worldwide compilation by Domenico and Schwartz (1997). In Bhojpur district, 60 km west of PMC, the deeper Pleistocene aquifers under similar hydrogeologic condition indicated K values in the range of 64–82 m day^{-1} (Saha et al. 2010). The Pleistocene aquifers around Sone-Ganga interfluvial region, including those underneath PMC, appear to be the most potential, considering the entire Gangetic plains, including the lower deltaic region of Bengal Basin (Ravenscroft et al. 2005; Umar 2006; Mukhejee et al. 2007). For two locations, A.N. College and Alamganj (Fig. 1), time-drawdown data from observation wells (at 7 and 9 m distances from main well)

were available. The interpretation of the data by the same method (Walton 1962) has indicated storativity as 5.2×10^{-2} and 3.0×10^{-3}

Behaviour of hydraulic heads

In spite of almost total dependence on deeper aquifers for water supply, no systematic records of piezometric level are available with 'Patna Water Board', the department mandated for water supply in PMC area, or with any other State Government agency. Maitra and Ghose (1992) have reported water levels measured during construction of deep tube wells for few locations during the period 1977–1987.

The water levels representing the top aquitard zone as well as the deeper aquifer follow the seasons, i.e. shallowest during August and deepest in May. Piezometric analysis of deeper aquifers for 2008, 2009 and 2010 reveals (1) wide variation in pre- and mid-monsoon water levels, however, (2) almost stable pre-monsoon level during the period. The pre- and mid-monsoon fluctuation in 2008 was recorded as 6.85 m primarily because of above-normal monsoon in that year. In years of 2009 and 2010 the mean fluctuation for the same period was recorded as 2.66 and 1.93 m (Fig. 6a). Both the years experienced sub-normal monsoon rainfall (–21.7 and –26.7 % less than normal). However, despite the low rainfall, the pre-monsoon piezometric level of the years remained almost stable. This indicates considerable recharge through the abandoned channel of Sone and possible recharge from north, stabilising the pre-monsoon piezometric level. The mean

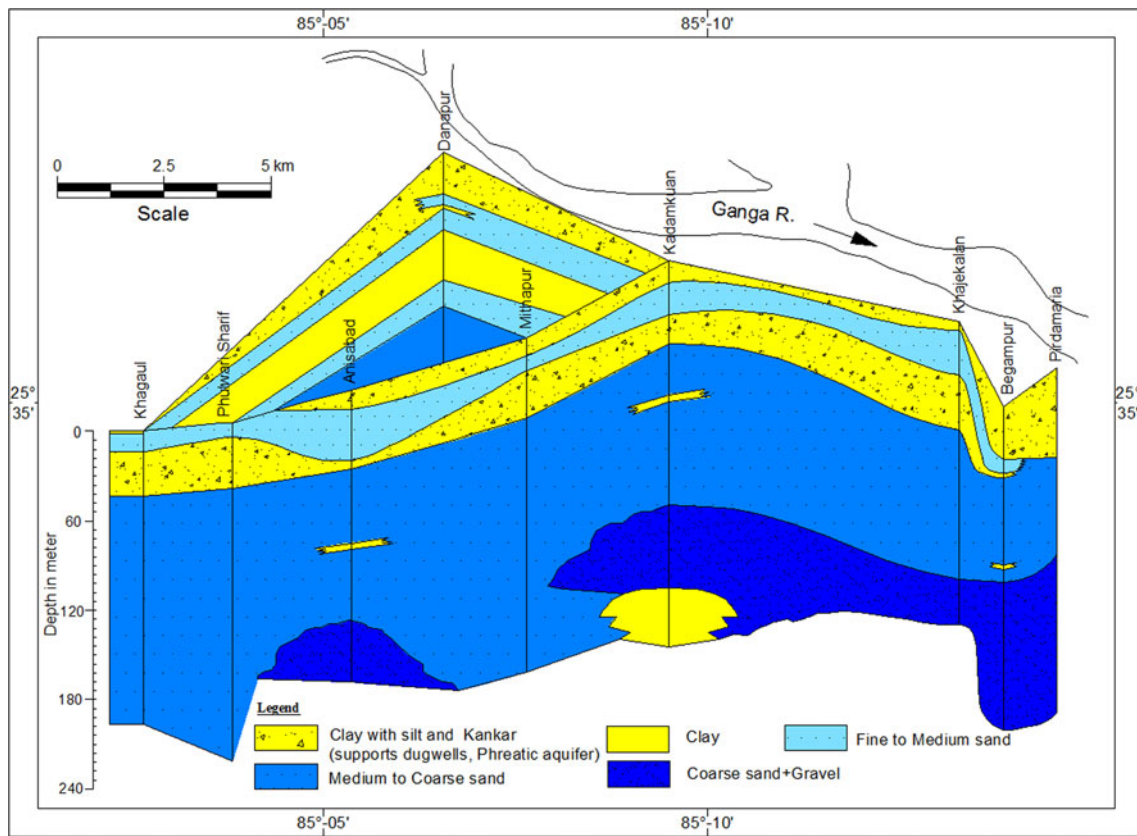


Fig. 5 Panel diagram showing aquifer geometry in Patna municipal area

Table 2 Details of 12 bore wells for which pumping tests data have been reinterpreted

Sl. no.	Location	Depth drilled (m bgl)	Depth range of tapped granular zones (m)	Discharge ($\text{m}^3 \text{h}^{-1}$)	Drawdown (m)	Transmissivity ($\text{m}^2 \text{day}^{-1}$)	Storativity	Specific capacity ($\text{m}^3 \text{h}^{-1} \text{m}^{-1}$)
1	Sanatan Dharamsala	250.12	078–173	209.0	2.22	5,876		94
2	Congress Maidan (Kadamkuan)	251.70	105–213	224.0	4.00	5,490		56
3	Fire Brigade (Patna city)	226.70	107–210	238.0	4.09	8,512		58
4	Karbigahiya	250.64	068–209	176.2	2.88	8,240		61
5	Khagaul	262.27	065–122	222.6	3.70	6,804		60
6	Anisabad	219.08	085–166	193.4	2.37	7,205		57
7	Khajekalan	202.80	088–154	199.8	3.16	8,890		63
8	Chajubagh	196.00	075–161	194.6	2.70	7,024		72
9	Harding Road	245.40	073–200	222.3	2.21	6,414		100
10	A.N. College (Pani Tanki)	225.00	093–181	208.9	2.15	7,126	6.9×10^{-2}	97
11	Phulwari Sharif	230.62	056–162	179.6	2.46	7,894		73
12	Alamganj	225.00	076–160	180.0	2.58	9,229	4.3×10^{-3}	70

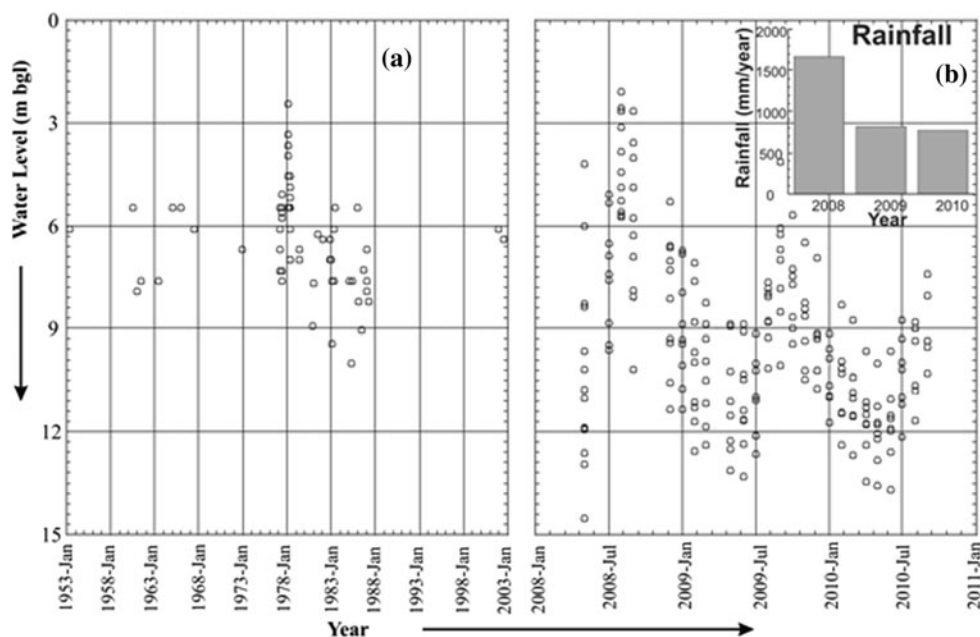
pre-monsoon water level of the top aquitard zone for 2008, 2009 and 2010 are 4.1, 3.38 and 4.09 m bgl, respectively, whereas the fluctuation between mid- and pre-monsoon remains ~ 2.5 m in about 60 % of the wells. The mean mid-monsoon water level of the top aquitard zone is 3.31 m bgl (Table 4).

The difference between the hydraulic heads of the top aquitard zone and the deeper aquifers is apparent year round. The hydrograph representing the top aquitard zone (Fig. 7) indicates that monsoon infiltration is the main source of recharge, whereas the deeper aquifer is mainly recharged from horizontal flow through the aquifers.

Table 3 Hydraulic details of deep tube wells drilled in 1980s

Location (year of construction)	Water level (m bgl)	Length of assembly (m)	Zone tapped (m bgl)	Total length of slotted zone (m)	Yield ($\text{m}^3 \text{h}^{-1}$)	Drawdown (m)	T ($\text{m}^2 \text{day}^{-1}$)
Danapur (1981)	6.25	136	61–106, 109–133	69	210	2.1	13,163
Raj Bhawan (1981)	7.69	152	76–102, 118–150	58	271	3.2	6,968
Kidwaipuri (1982)	Not available	138	69–78, 85–138	79	237	3.1	5,478
Kadamkuan (1980)	8.93	117	55–80, 82–107	50	112	1.4	3,796

Fig. 6 a Variation of piezometric levels in Patna municipal area (1953–2010). **b** Annual rainfall for the years 2008, 2009 and 2010



Possibly the deeper aquifers are also getting benefits of induced recharge from the Ganga. The top aquitard zone exhibits a gentler post-mid-monsoon recession limb, revealing its less exploitation in comparison with the deeper aquifers. The difference between the heads has been observed as ~ 5 m round the year (Fig. 7). In absence of historical data, a long-term analysis of the hydraulic head of the deeper aquifer was not possible. However, an overall comparison among data sets of 1960–1967, 1977–1986 and that of 2008–2010 reveals a decline in the range of 2–4 m. A location-specific comparison at Gandhi Maidan between 1988 and 2009 shows a decline of 2.5 m (Fig. 8).

Spatially, hydraulic head of the deeper aquifer remains at 12–14 m bgl over most of the study area during pre-monsoon 2010 (Fig. 9), while the ones representing the top aquitard zone remain mostly in 2–6 m bgl (Fig. 10). Infiltration from monsoon rainfall recharges the top aquitard zone, as evident from shallow water levels (0–2 m bgl), covering 80 % of the area during August 2010 (Fig. 11). The piezometric levels for the same period, however, remained in 10–12 m bgl along the densely populated part of the city (Fig. 12). Long-term (1996–2011) trend of

pre-monsoon water levels of a CGWB monitoring well (dug well, representing the aquitard zone) at Patna city (CGWB 2011; Fig. 13), established by least square technique has indicated a minor decline of 3.4 cm year^{-1} . The post-monsoon water levels for the same period have, however, exhibited a stable trend.

Response of deeper aquifer to heavy ground water extraction

The annual extraction by public deep tube well in PMC area has been determined as $137.0 \text{ million m}^3$. In addition, the wells at individual households and at apartments/housing societies extract additional 33.7 and $41.5 \text{ million m}^3 \text{ year}^{-1}$, respectively, yielding a total annual extraction from deeper aquifer in PMC area as $212.0 \text{ million m}^3$. The flow regimes in deeper aquifer during pre- and mid-monsoon, 2010 have been depicted in the piezometer contour maps prepared using natural neighbourhood technique (Figs. 14, 15). To understand the flow regime sub-regionally, the maps have been prepared for an

Table 4 Water levels of the aquitard and deeper aquifer zones (mean of 2008, 09, 10, in m bgl)

	Maximum		Minimum		Mean		SD	
	Pre-monsoon	Mid-monsoon	Pre-monsoon	Mid-monsoon	Pre-monsoon	Mid-monsoon	Pre-monsoon	Mid-monsoon
Aquitard zone (<i>n</i> = 26)	9.13	7.14	0.90	0.83	4.09	3.31	2.30	2.01
Deeper aquifer (<i>n</i> = 10)	19.20	11.67	15.67	8.81	12.18	10.38	1.15	1.09

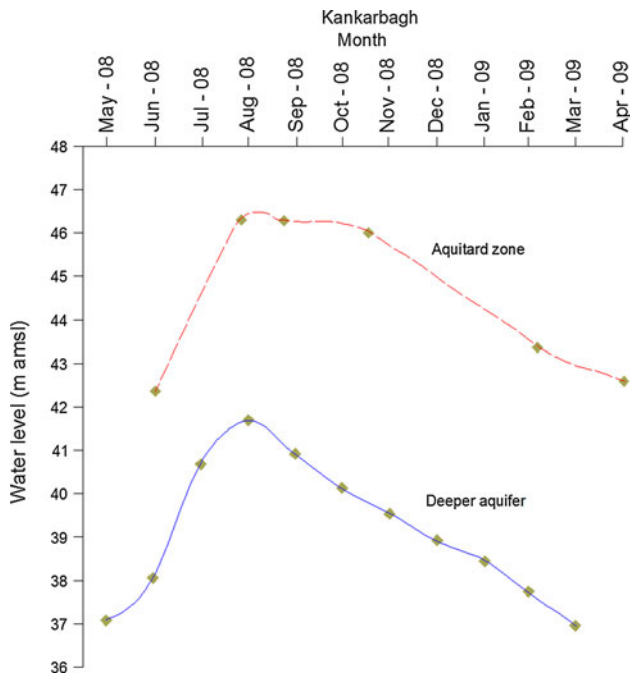


Fig. 7 Monthly hydrograph of a year (2008–2009) of wells at Kankarbagh tapping deeper aquifer and aquitard zone

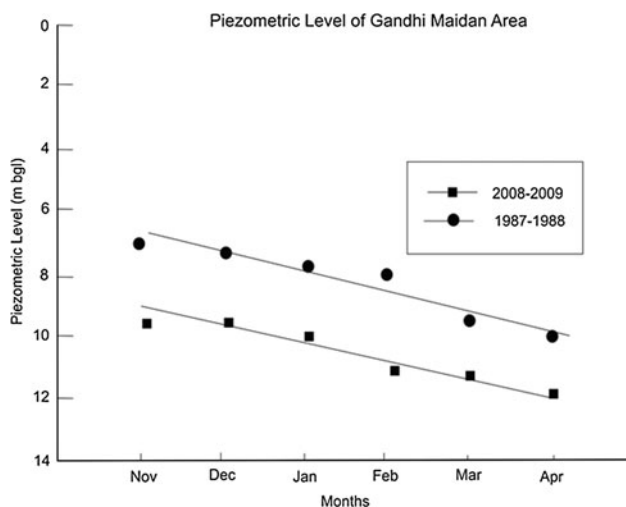


Fig. 8 Hydraulic head of deeper aquifer at Gandhi Maidan (1988–2009)

area extending beyond PMC, to an extent of 15 km in the south and 30 km in the west. Water level data of another 15 wells from the extended area, measured for a separate study, have been considered in preparing these maps. As can be seen, groundwater flow lines during both the periods reveal regional flow towards NNE, indicating that the Ganga is receiving groundwater in this region. The flow lines, however, in both the seasons, are found to be perturbed with a reverse flow direction, from north to south, for the stretch between Nooranibagh and Khajekalan (Figs. 14, 15). In this part, possibly, the Ganga is contributing to the deeper aquifer system. The other plausible reason may be inflow from the aquifers from North Ganga Plain, rich in groundwater resources (CGWB & GWD 2012). Detailed investigations tracing the effects of groundwater recharge event along the Bhabar belt bordering the North Ganga Plain can be taken up to elucidate the impacts of mountain front recharge on the Ganga Plain aquifer system (Carling et al. 2012). There are examples on aquifers in urban areas being recharged by the nearby rivers, like Dhaka city in Bangladesh which gets benefit from the Buri Ganga River (Ahmed et al. 1999). The NNE trending sub-regional flow alignment in the eastern and the southern parts of PMC is parallel to the alignment of the old paleo-channels of Sone River (Sahu et al. 2010), the mightiest peninsular tributary of the Ganga. These paleo-channels appear to be the main source of recharge in Patna urban area.

Despite significantly high transmissivity and significant source of recharge to the aquifers, a fall in piezometric head has been observed over the years. The difference of the mean pre-monsoon piezometric heads of 2008, 2009 and 2010 with the levels recorded in 1980–1981 at three locations, viz., Danapur, Raj Bhawan and Kadamkuan, reveals a decline of 3.9 m. An enquiry with private drilling companies revealed a decline of 3.0–6.0 m, particularly in the densely populated parts of PMC. The decline reflects extraction in excess of recharge to the deeper aquifers. The other reason is interference of cone of depression of numerous wells working simultaneously which fail to recoup due to the long transient period of water moving into the area (Custodio 2002). However, decline due to

Fig. 9 Pre-monsoon (2010) depth to water level map, representing deeper aquifer

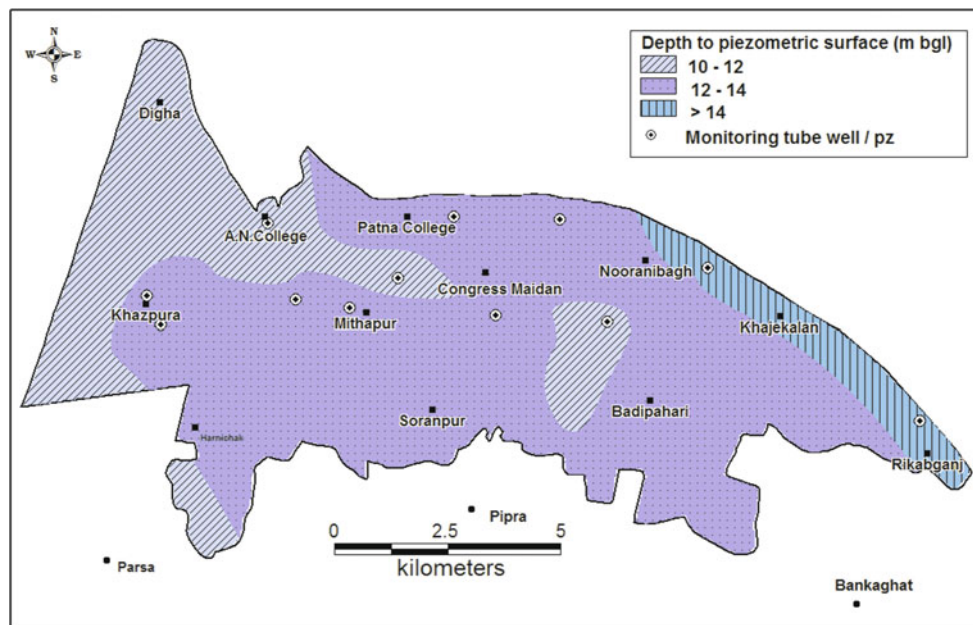
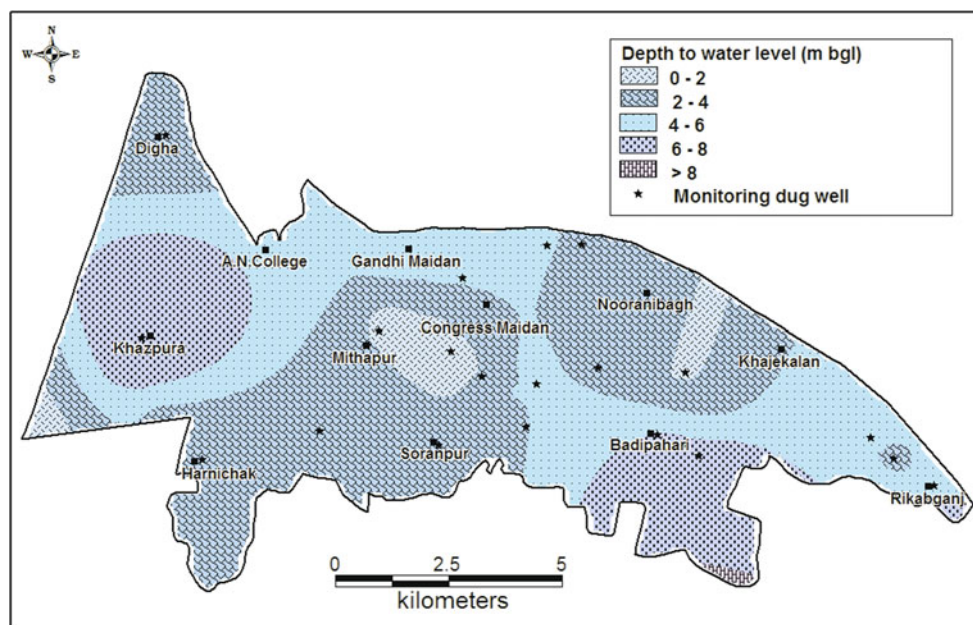


Fig. 10 Pre-monsoon (2010) depth to water level map representing top aquitard zone



interference of cone of depression will not be a significant component because of the high transmissivity and low drawdown (generally <3.0 m) observed in the area.

The modest fall in hydraulic heads between 1980 and 2010 is not yet alarming as the piezometric level still remains much above the base of the top aquitard zone. However, the expectation of a possible large-scale lowering of water level in near future results in a tendency to tap aquifers at greater depths. Such apprehension has got no scientific basis. A study on installed depth of the slotted pipe versus time of the public deep tube wells indicates

that during 1955–2004 periods the lowermost point of the slotted pipe has gone down >40.0 m. On the other hand the mid-point of the slotted pipe has gone down for only about 20.0 m, revealing that as the wells tapped deeper sand layers, the length of the installed slotted pipe has also increased over time. As already discussed, pumping yield of wells with 40 and 60 HP pumps remained same over the years, and a marginal increase has been observed for 100 HP pumps. Deep tube wells in certain parts of the Gangetic plains are affected by some performance-limiting processes, like encrustation and plugging in the slot

Fig. 11 Mid-monsoon (2010) depth to water level map representing top aquitard zone

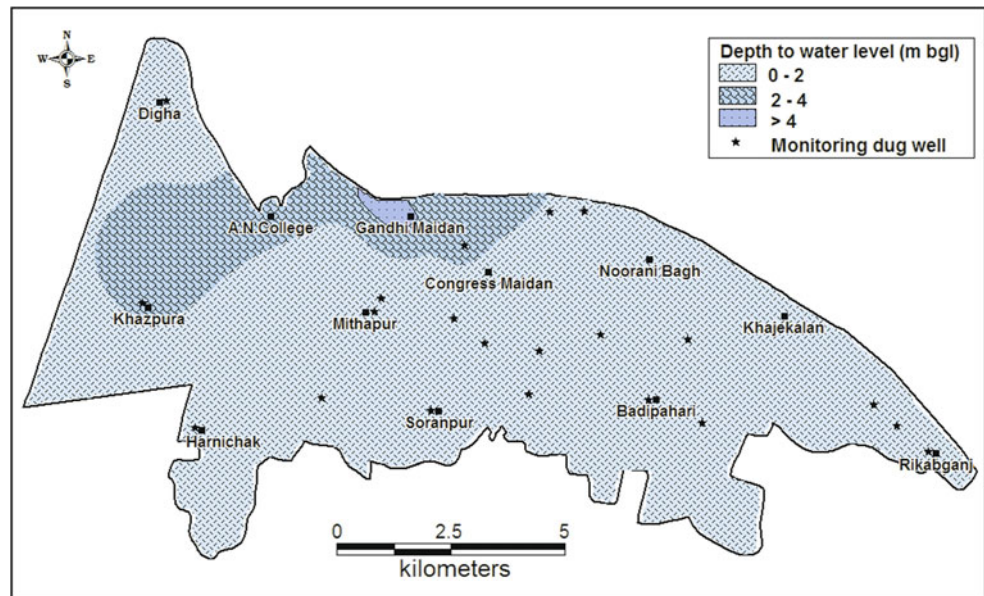
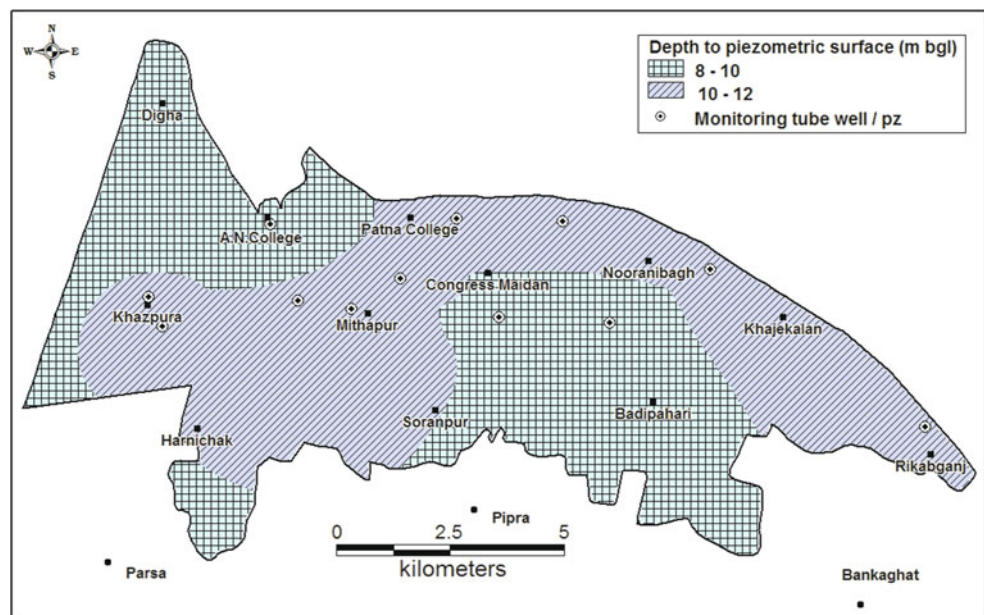


Fig. 12 Mid-monsoon (2010) depth to water level map representing deeper aquifer



(Karanth 1997). PMC area, however, is free from such processes because of low TDS of ground water (<1,000 mg l⁻¹).

The effective depletion of the deeper aquifer resource in the past 30 years has been determined based on the method outlined in Konikow and Kendy (2005);

$$\text{Storage depletion (m}^3\text{)} = S \times \text{area (m}^2\text{)} \times \text{decline in head (m)}$$

Considering an effective head decline of 3.9 m during the past 30 years and a mean storativity of 2.75×10^{-2} , the net depleted volume has been determined as 14.37 million m³.

Discussion of results

The present investigation reveals the disposition of aquifers, their hydraulic parameters and response to heavy pumping of groundwater in Patna urban area- a prominent city in the Gangetic plains with nearly 2 million inhabitants. During the present research an array of data on lithology of sub-surface strata, water levels, well design and construction history, discharge and drawdown of wells, hydraulic parameters of aquifers and long term water level trends has been compiled, to understand the effect of aquifer-based water supply on ground water regime and possible recharge mechanism.

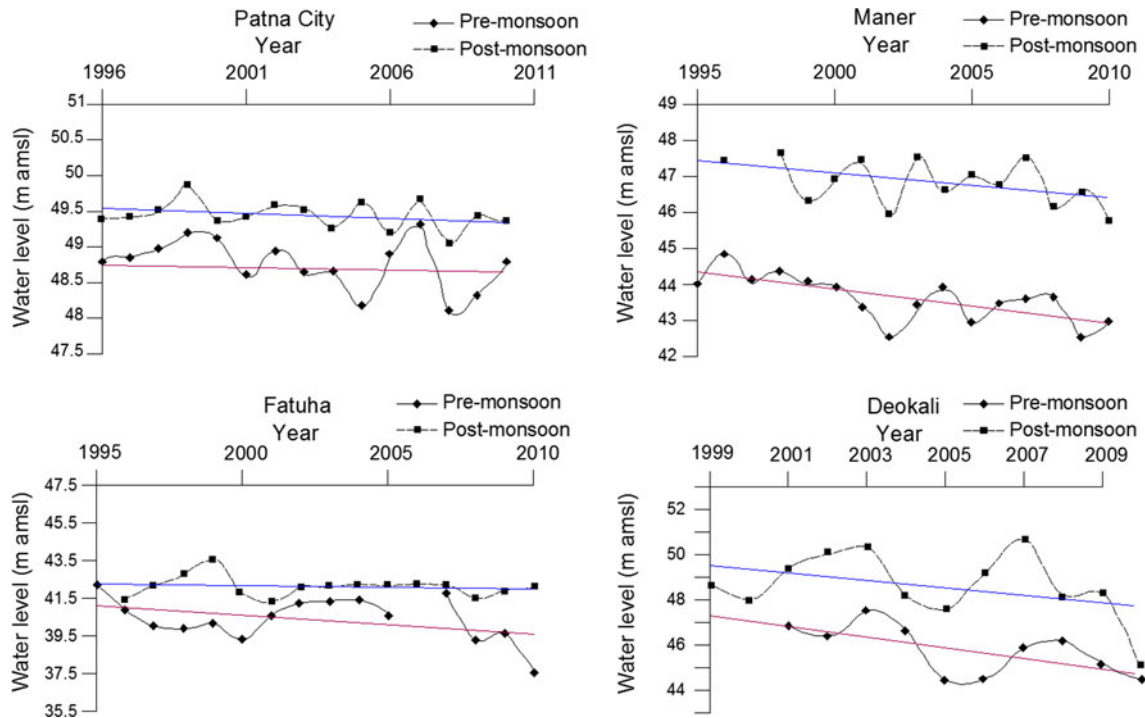
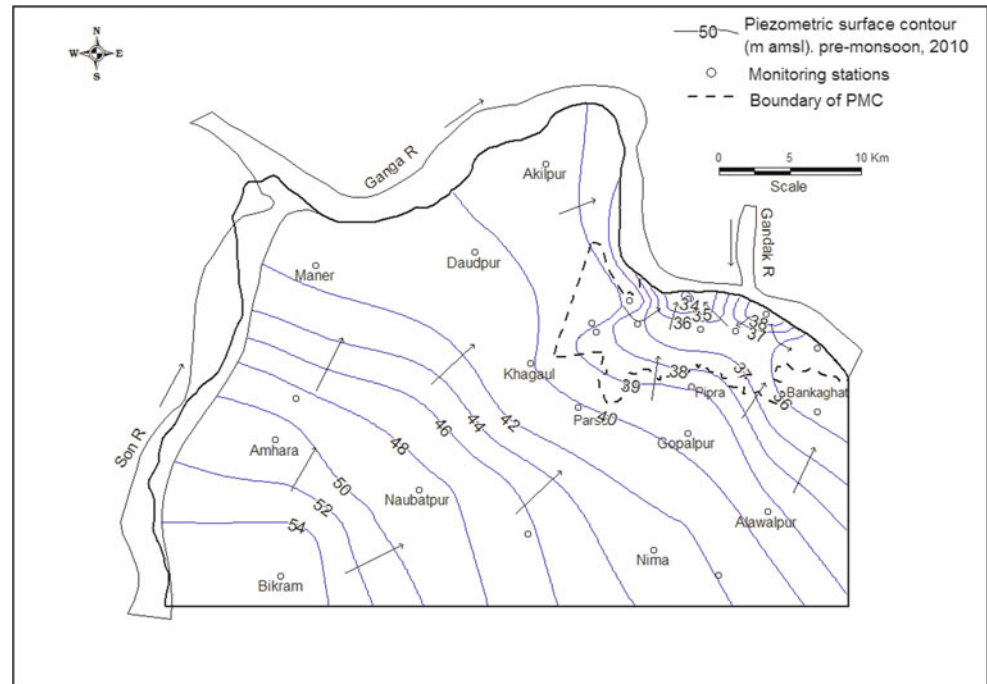


Fig. 13 Long-term water level trend from wells tapping top aquitard zone at Patna city (1996–2010), Maner (1995–2010), Fatuha (1995–2010) and Deokali (1999–2010)

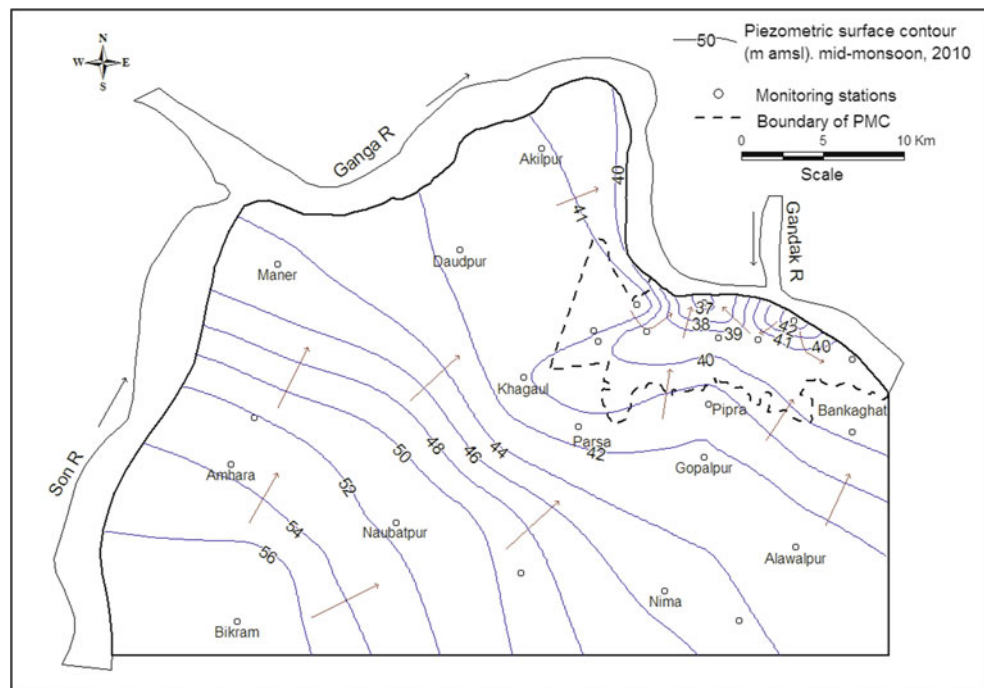
Fig. 14 Pre-monsoon (2010) piezometric surface contour, referenced to mean sea level, surrounding PMC area



The study reveals that in spite of $212.0 \text{ million m}^3 \text{ year}^{-1}$ groundwater extraction from the deeper aquifer, the decline in piezometric surface in the past 30 years is about 4.0 m, a significantly lower value than similarly located cities in south-eastern Asia, like Dhaka,

Kolkata, Bangkok and in other parts of the world (Holzer and Johnson 1985; Sahu and Sikdar 2008). The question is why the decline of piezometric surface is so low in PMC area? An immediate explanation that comes to mind is the recharge from the Ganga River or flow from aquifers of

Fig. 15 Mid-monsoon (2010) piezometric surface contour, referenced to mean sea level, surrounding PMC area



North Ganga Plain, underneath the course of the Ganga. As can be seen, the groundwater flow lines representing the deeper aquifer during pre- and mid-monsoon period, particularly in a stretch of about 6.0 km, around Khajekalan indicate this. The volume of water entering from north through this stretch has been determined using the equation $Q = TIL$,

where Q is volume in m^3 , T is transmissivity in $m^2 \text{ day}^{-1}$, I is hydraulic gradient and L is length of contour in m. Considering the values of Nooranibag (Alamganj) and Khajekala wells (Table 2), mean T has been considered as $9,000 \text{ m}^2 \text{ day}^{-1}$. Q has been determined as 27.2 million $m^3 \text{ year}^{-1}$, estimating the I and L values as 1:740 and 6,131.0 m, respectively. The substantial gap between this volume and the estimated groundwater extraction from the deeper aquifer ($212.0 \text{ million m}^3 \text{ year}^{-1}$), using the piezometric surface contour maps (Figs. 14, 15) indicate that a major component of the recharge is contributed by horizontal groundwater flow from the south and south-west. The abandoned channels of the Sone River continuing beneath the study area in NNE-SSW alignment (Sahu et al. 2010) are main conduits of recharge. These abandoned channels are connected to the present course of the Sone (source-water for recharge) in the south (Sahu et al. 2010). The bore well at Khagaul (Fig. 6) is located on one such abandoned channel. The drill-cut samples reveals a >150-m-thick coarse sand zone appearing at 42 m bgl. Transmissivity value of the aquifer, determined by interpretation of time-drawdown data of pumping tests available for Khagaul well, has been determined as $7,205 \text{ m}^2 \text{ day}^{-1}$.

The long-term (1995–2010) water levels of Patna city monitoring well (Fig. 13) show an almost stable trend, revealing no significant depletion of groundwater resource of the top aquitard zone. The hydraulic head of the deeper aquifer of the area, where groundwater remains under semi-confined condition, lies much above the base of the top aquitard. The localised sand layers within the top aquitard zone experiencing limited groundwater extraction are recharged by rainfall and also from other sources like leakage from pipe water supply. Studies on cities under various climatic regimes, fed by aquifer-based water supply (Foster 1990; Krothe et al. 2002), revealed that a component of recharge comes from leakage from city water supply and drainage infrastructure. Leakages are particularly higher when water is imported from peri-urban areas and other hinterland. In the study area, the leakage from pipe lines distributing water from Government-owned deep tube wells has been estimated at 20–30 % of total supply (JNNURUM 2006). A part of the leakage contributes to groundwater recharge. Thus a part of the extraction from deeper aquifer for water supply returns to the sand layers in the top aquitard zone. In addition, seepage from open drains, originally streamlets of the Ganga, also contributes to recharge of the aquitard zone. This is evident from the long-term water level trend of the Patna city monitoring well, which is a typical representative of the urban area. The other three dug wells (also representing the aquitard zone) where long-term water level trends (Maner-1995–2010, Deokali-1999–2010, Fatuha-1995–2010) have been analysed, represent peri-urban areas, beyond the limit of pipe-water supply. The analyses of pre- and

post-monsoon periods separately (Fig. 13) for all the three wells reveal a declining trend (range 2–24 cm year⁻¹). The sand layers within the top aquitard zone in peri-urban areas experience higher volume of extraction for drinking and irrigation needs in comparison with the core urban areas. Hand pumps are commonly sunk for drinking water, whereas low-capacity shallow tube wells (discharge <10 m³ h⁻¹) are used for irrigation in peri-urban areas.

In PMC area, though, the piezometric surface decline is not alarming; still, to be on safer side the water supply agencies and the users are tapping deeper and deeper sand layers. The mean depth of the slotted pipes of the public deep tube wells has gone down ~20 m over the past 50 years. An inquiry with the local drilling companies reveals that the mean depth of slotted pipes in household wells has increased at a rate of 2 m year⁻¹. The past 5 years, however, have witnessed a sudden increase in depth of wells by 30–40 m, owing to detection of arsenic (>0.05 mg l⁻¹) in shallow aquifers at <60 m bgl in adjoining areas of middle Ganga plains areas (Saha et al. 2009). In PMC area, however, groundwater up to the depth of investigation is low in arsenic load (Saha 2009).

Conclusions

As revealed during the course of present study in Patna urban area, the deeper aquifers (>60 m bgl), made up of medium-coarse sand of Pleistocene age, contribute >90 % of the water supply, have exhibited a decline of hydraulic head, though a modest 4.0 m in past 30 years. For sustainable water management of the area, a detailed study is needed for comprehensive understanding of the recharge mechanism and formulation of artificial recharge plan for the heavily exploited deeper aquifers. It is also recommended to strengthen the monitoring network for fine-tuned assessment of water level/piezometric level trend.

Groundwater extraction in PMC area is compensated mainly by groundwater flow through aquifers from south and south-west, primarily through the paleo-channels of the Sone River which are connected to its parent course at about 30 km south of the urban area. Further research can elucidate the volume of such flow in different seasons. The urban area is characterised by significant wastage of water through leakage of pipe water supply. Besides, household bore wells extract 20–30 % more than required because of easy availability and no regulation in force on groundwater extraction. Measures like limiting the pumping hours through regulation, imposition of higher electricity tariff for running pumps beyond a fixed limit or providing incentives for higher water use efficiency may be attempted by the Municipality to control the excess groundwater withdrawal in the urban area.

Many similar groundwater-dependent urban areas are located in the Gangetic plains, upstream of Garo-Rajmahal Gap, where detailed studies need to be taken up for sustainable development of the aquifers.

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