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Development and Management of Base Flow of a Sand-dominated Alluvial Aquifer of a Large Ephemeral River for Drinking Water Supply in Semi-arid and Fluoride Affected Areas: Example of the River Mayurakshi, Birbhum District, West Bengal, India

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ABSTRACT

Semi-arid tropical regions in India and elsewhere face major challenges in the management of public water supply for drinking purpose. In such regions knowledge on base flow availability in major rivers is important in development of water management strategies and estimation of small to medium water supplies especially for semi-arid conditions where groundwater is contaminated with fluoride at variable depths.

This study focuses on identification, exploitation and utilization of the unexploited base flow of the river Mayurakshi between Md. Bazar in the west and Sainthia in the east in Birbhum district, West Bengal, by understanding the subsurface hydrogeology of the river as well as a proper knowledge of the water budget, water resources in storage, and water quality.

Exploratory drilling on the river bed revealed two aquifer settings: unconfined in the west, and semi-confined in the east. Water level is shallow occurring within 2 m below ground level. The sands of the unconfined aquifer are mostly coarse and that of the semi-confined aquifer are medium to coarse. The transmissivity values reveal that the potentiality of the aquifer in the western stretch of the river is higher than that of the eastern stretch. Water supply systems that can be constructed below the river are bed-mounted infiltration gallery and collector well with radials. Water quality does not exceed the permissible limit of Indian Drinking Water Standard except for manganese, iron and colliform bacteria. Therefore, the water needs to be treated for these parameters before supplying to the communities for drinking purpose.

INTRODUCTION

Semi-arid tropical regions in India and elsewhere face major challenges in the management of scarce freshwater resources under pressures of population, economic development, climate change, pollution and over-abstraction (Mathias and Wheater, 2010). Groundwater is commonly the most important water resource in these areas. In some areas excess fluoride in groundwater is also a growing concern. Therefore, an optimal use and management of the scarce groundwater resources is imperative. A precondition for this is a sound understanding of the particularities of the hydrogeology of semi-arid regions as well as a proper knowledge of the water budget, water resources in storage including base flow, and water quality. Base flow is an important component of the groundwater system. In this paper base flow is considered to be the component of streamflow that is attributed to shallow groundwater discharge. Reay et al. (1992) found that neglecting base flow as a source to streams leads to misinterpretation of data and mismanagement. Knowledge on base flow availability is important in development of water management strategies, and estimation of small to medium water supplies, especially for semi-arid conditions (McMahon and Mein, 1986). Estimating base flow contributions to streams are useful for watershed planners to determine water availability, water use allocations, assimilative capacity of streams and aquatic habitat needs (Stuckey, 2006). Base flow displays spatial and temporal variability due to climate, land use, soils, frequency and amount of recharge, vegetation, topography, and geology (Stuckey, 2006; Delin et al., 2007; Santhi et al., 2008).

Birbhum district in West Bengal, is one such semi-arid district where the groundwater at places contains high concentration of fluoride. The district lies in the western part of West Bengal and is situated between 23.54° and 24.58° north latitude and 87.09° and 88.03° east longitudes, and about 4,545 square kilometers in area and is triangular in shape (Fig. 1). River Ajay forms the southern base whereas the apex of the triangle points to the north. The river forms the boundary between the districts of Birbhum and Bardhaman. The district is bounded by Murshidabad district in the east and north-east, Bardhaman district in the south and south-east, and Sahebganj and Dumka districts of Jharkhand in the west.

Geographically, this area lies at the north eastern end of the Chota Nagpur plateau, as it slopes down and merges with the alluvial plains of the river Ganga. The climate on the western side is dry and extreme, but is relatively milder on the eastern side. During summer, the temperature can go up to 40°C and in winters it can drop to around 10°C. The hot weather condition lasts from middle of March to middle of June, the rainy season from middle of June to middle of October, and the winter from middle of October to middle of March. The average rainfall of the district is about 1289 mm, out of which 1009 mm occurs during the monsoon period and 280 mm during the non-monsoon period. Several rivers flow across Birbhum district. The three most important rivers are Ajay, Mayurakshi and Brambhani. The rivers originate in the Chota Nagpur plateau and flow across Birbhum in a west–east direction. These rivers are furious during the monsoon but shrink during the dry summer months. The cyclical rotation of drought and floods of the rivers cause misery to life and property.

River Mayurakshi has its source on Trikut hill; about 16 km from Deoghar in Jharkhand state and is about 250 km long. It flows through Jharkhand and then through the districts of Birbhum and Murshidabad in West Bengal before flowing into the river Bhagirathi near Kandi town in Murshidabad district. The drainage area is about 8,500 sq km and the important tributaries are the

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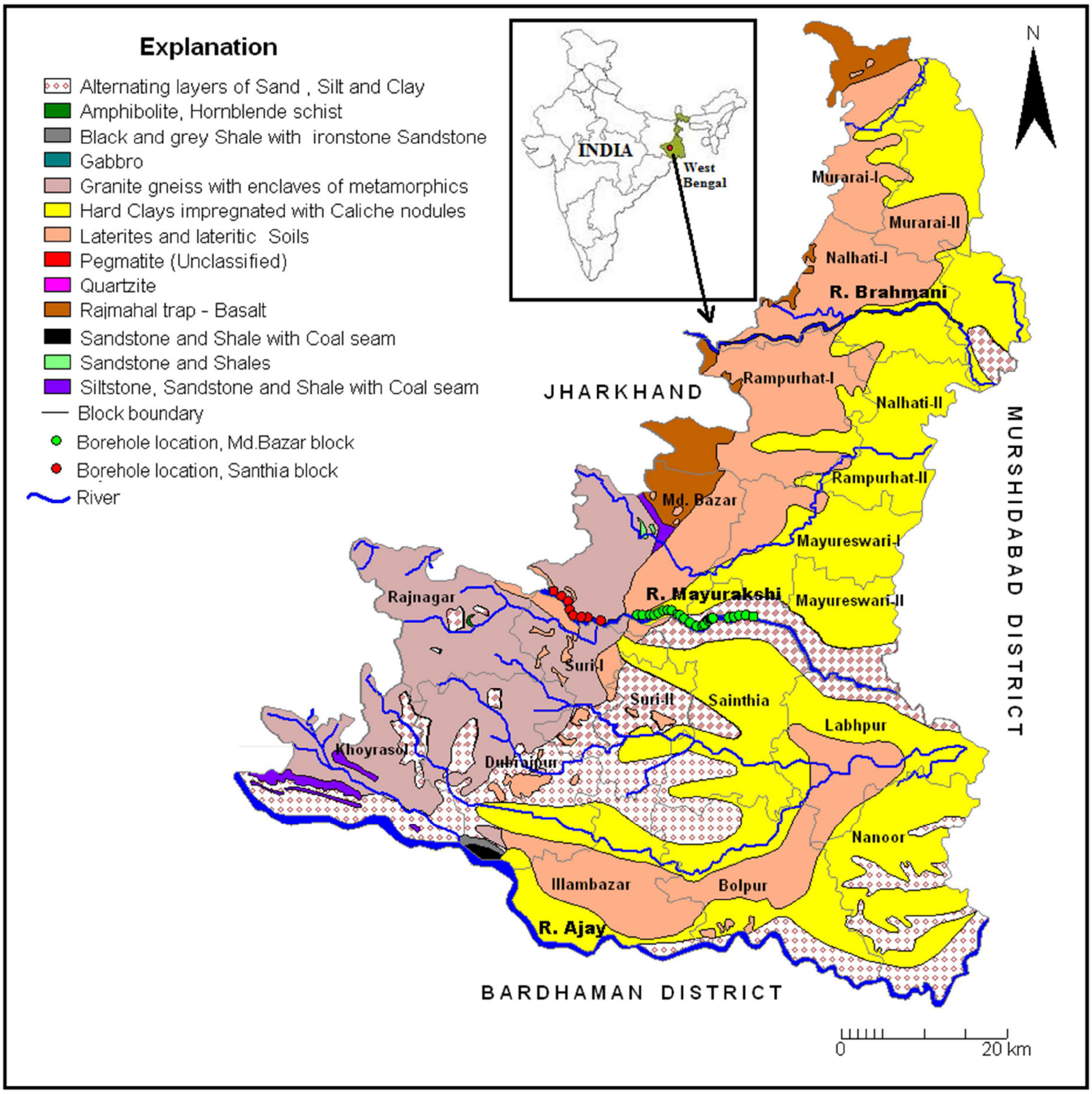

Fig. 1. Study area showing geology of Birbhum district and locations of borehole on River Mayurakshi. The geology is based on Dumka and Bardhaman Geological Quadrangle map of GSI, 2001.

Brambhani, the Dwarka, the Bakreswar and the Kopai. The Mayurakshi enters Birbhum from Jharkhand and flows through the centre of the district from west to east (Fig. 1). It leaves the district and joins river Dwarka in Murshidabad which itself is a tributary of the river Bhagirathi. The river is almost dry for seven or eight months in the year. During this time stagnant pools of water are seen at some places. But when the rain comes water flows with very high velocity swamping everything within reach. The Massanjore dam (also called Canada dam) near Dumka in the state of Jharkhand and Tilpara barrage near Suri, Birbhum district had been constructed on this river for hydel power, irrigation and flood-control purposes. The Massanjore dam is about 65 km upstream from Suri in Birbhum district, West Bengal. The dam is 660 m long and 47 m high and is supplemented by barrages at Tilpara on river Mayurakshi, Deocha on river Dwarka, Baidhara on river Brahmani, Kendisala on river Bakreswar and Kultare on river Kopai. The reservoir has an area of 67.4 km^2 when full and has a storage capacity of 620,000,000 m^3. The barrage, some 32 km downstream, at Tilpara, near Siuri is 309 m long. Major embankments also lie along the stretch of the river for flood protection. In monsoon the amount of maximum water-flow in this river is 57,000 m^3/sec, although in the dry months the water-flow is only 14 m^3/sec.

Geologically the district comprises diverse rock type ranging from Archaean to Quaternary in different geological settings and heterogeneous geological condition (GSI, 2001; Fig.1). The crystalline metamorphic rocks of Archaean to Proterozoic age comprising amphibolites, hornblende schists, and gneisses occupy the southwestern part of the district. The Gondwana Supergroup overlying this basement is represented by sandstone and shale with coal seams of Permian to Jurassic in age. The Gondwana is overlain by Rajmahal Trap (basalt) occurring in the northern and northwestern parts of the district. The north and central part of the area is occupied by laterite and lateritic soil. Hard clay impregnated with caliche nodules of late Pliestocene to early Holocene occupy the area in the north-east and east and is overlain by alternating layer of sand, silt and clays of middle to late Holocene.

The western part of the district underlain by Archaeans, Rajmahal Traps and Gondwanas suffers from water scarcity owing to poor groundwater potentiality of the formations. In these areas, groundwater occurs under unconfined condition in the weathered zones (6-12 m thick) as well as under semi-confined condition in the zone of secondary porosities below the weathered zone between 55 and 70 m below ground level (bgl). From the weathered zone groundwater is generally being developed through open wells and the available discharges can barely meet the domestic needs. During summer the wells generally go dry. Groundwater from the zone of secondary porosity is being developed through bore wells, yielding 60 – 150 litres per minute (lpm) of water and at places as high as 330 lpm. Therefore, these areas suffer from drinking water scarcity especially during the summer months. Moreover, Murari-I and Rajnagar blocks have been declared as drought prone areas by the Agriculture Department, Government of West Bengal. Four blocks, namely, Murari-II, Nalhati-II, Nanoor and Rampurhat–II have been declared as semi-critical by the Central Ground Water Board and State Water Investigation Directorate considering groundwater development with respect to the groundwater resources in the blocks (CGWB and SWID, 2011). Further, in 7 blocks, namely, Khoyrasol, Mayureswar-I, Nalhati-I, Rajnagar, Rampurhat-I, Sainthia and Suri-II the groundwater is fluoride contaminated. In Khoyrasol the fluoride concentration in groundwater varies from 0.44 to 7.60 mg/L and the screens of the wells are placed in Gondwana rocks where sediments were directly supplied from the Archaean terrain containing minerals with high fluoride at a depth of around 50 m bgl. In Nalhati-I block the fluoride concentration varies from 2.0 to 16.2 mg/L. The wells tap the weathered and fractured basaltic rocks and intertrappean beds. In Rajnagar block the fluoride concentration varies between 0.54 and 11.25 mg/L and the wells tap the aquifer at depths of 12-22 m bgl in fractured granite. In Rampurhat-I block the fluoride concentration varies between 1.31 and 14.75 mg/L and the screens of the wells are placed at depths of 30-80 m bgl in alluvium. In Suri-II block the fluoride concentration varies between 1.15 and 10.80 mg/L and the wells are placed at depths of 60-75 m bgl in fractured granite (Sinha Ray, 2008). These water scarce, drought prone and fluoride affected areas require special attention from the point of view of drinking water supply.

This paper therefore, focuses on identification, exploitation and utilization of the unexploited base flow of the river Mayurakshi by understanding the subsurface hydrogeology below the river bed at selected locations as well as a proper knowledge of the water budget, water resources in storage, and water quality.

FIELD AREA

The field area covers a length of 16 km on the river Mayurakshi in Sainthia block bounded by latitudes 23.93ºN to 23.96ºN and longitudes 87.56ºE to 87.71ºE and 5 km in Md. Bazar block bounded by latitude 23.95ºN to 23.98ºN and longitude 87.46ºE to 87.51ºE (Fig.1).

METHODS

Drilling

In order to understand the sub-surface geology of the river in the two blocks and the nature of the aquifer, 50 mm diameter boreholes were drilled on the river bed (Figs. 1 and 2) using hand sludging method (Ball and Danert, 1999; Ali, 2003). Drill cuttings were collected at 2 m intervals and logged, photographed, and sampled. The visualization package RockWorks® 15 was used to construct longitudinal and transverse sub-surface lithological cross-sections based on the logged boreholes.

Aquifer test

To calculate the aquifer parameters such as hydraulic conductivity, transmissivity and storage coefficient 72-hour aquifer test was conducted on five test wells (Fig. 2). Test wells and observation wells were constructed at suitable locations based on the drilling results. For construction of the 150 mm test wells manually-operated direct rotary drilling method was used and for the 50 mm diameter observation wells hand sludging drilling method was used.

After lowering of the casing assembly in the test wells and observation wells the annular space between the casing and the borehole was packed with clean, coarse sand from the bottom of the borehole to 5 m above the screen and above that the annular space was filled up with clay. After this the wells were developed by mechanical surging using a diesel operated submersible motor pump to remove the fine materials from the screen apertures and aquifer around the wells. Well discharge was measured by volumetric and 'V' notch methods.

For analysis of the pumping test data Jacob's straight line method (Cooper and Jacob, 1946) based on Theis (1935) equation for unsteady state flow condition in unconfined aquifer has been used. The 'third' segment of 'time-drawdown' curve of an observation well has been used to determine transmissivity (T) and specific yield (S_Y) values

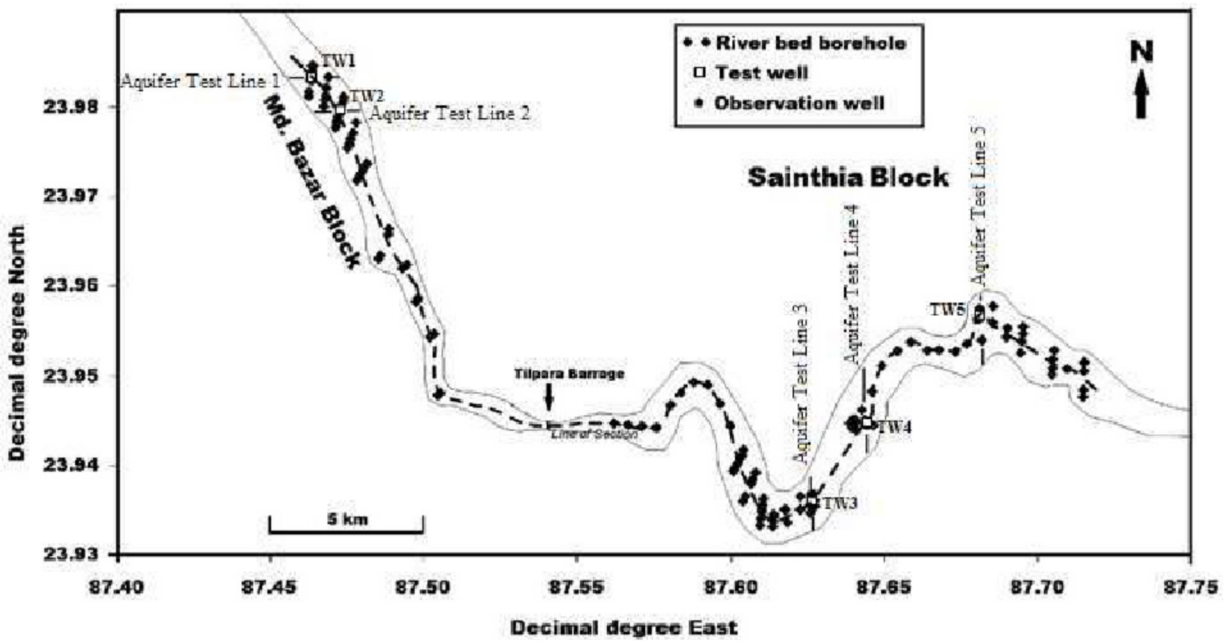

Fig. 2. Distribution of boreholes, test wells and observation wells on River Mayurakshi in Md. Bazar and Sainthia blocks, Birbhum district. Dashed line is the line of the cross section shown in Fig.6.

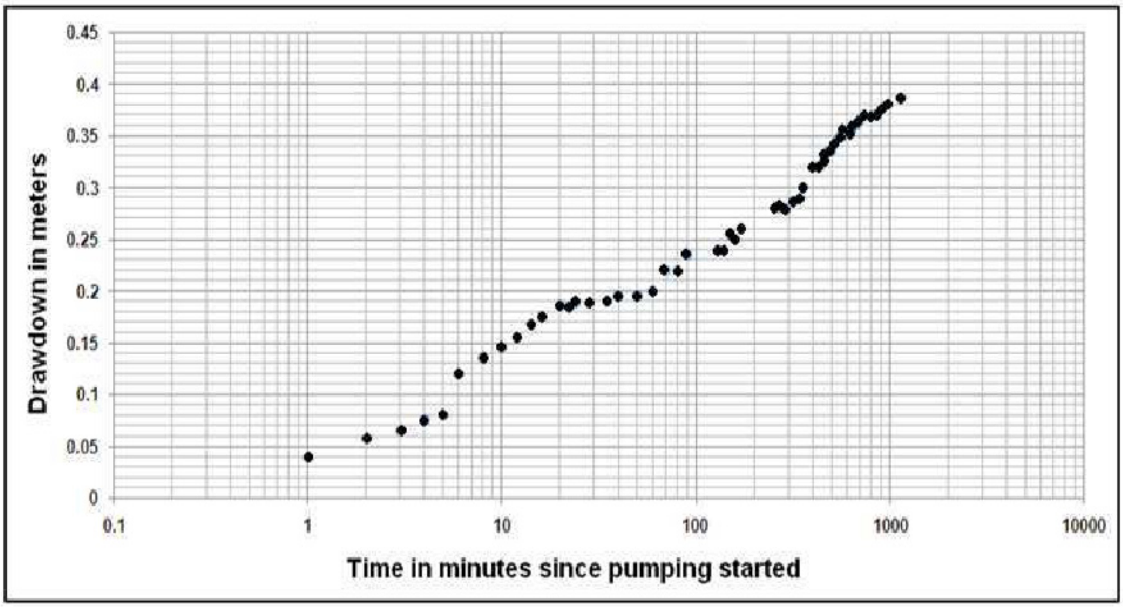

Fig. 3. Plots of drawdown against time of Observation well 4 of Test well 3 at Sainthia.

because an unconfined aquifer reacts initially in the same way as a confined aquifer. Gravity drainage is not immediate but water is released instantaneously from storage by compaction of aquifer material and by expansion of the water itself. This is the 'first' segment of the 'time-drawdown' curve. The second segment shows a decrease in slope because of the replenishment by gravity drainage from the interstices above the cone of depression and hence the flow is essentially vertical. The 'third' segment which starts after several minutes after pumping has started, represents the period during which the 'time-drawdown' curve conforms closely to the Theis type curve An example of the plots of drawdown against time during aquifer testing in observation well 4 of test well 3 is given in Fig. 3.

The safe distance ($2r_0$) is double the radius of the cone of depression and wells located at distances more than this will not interfere with each other when the two wells are pumped simultaneously. The safe distance has been determined using the non-steady relation of Theis (1935).

Water Level and Groundwater Flow

For water level measurements, steel tapes graduated up to 1 mm interval and 169 Solinst Model 101 water level meter were used. The quantity of groundwater flowing through the alluvial sediments across given cross-section of the river has been calculated using the Darcy's equation $Q = TiL$ where, Q = quantity of water flowing through a given cross-section; T = Transmissivity of the aquifer; i = Hydraulic gradient; L = Length of the cross-section.

Grain Size Analysis

The sediment samples of the test wells were subjected to mechanical analysis by sieving with sieves of the American Society for Testing Material (ASTM) standard sieve size 5 to 325 using 100 to 150 gm of samples (Folk, 1968). The grain size distribution curves (Fig. S12) were used to obtain the d_{10}, d_{40}, d_{60}, d_{70} and uniformity coefficient (UC) values. Based on these values, the screen slot size and recommendation for construction of natural-pack infiltration gallery or gravel-pack gallery were suggested.

Design of Abstraction Structure

In geological environments beneath the river where the aquifer is in an unconfined to semi confined condition infiltration galleries or collector wells with radials can be constructed. Infiltration gallery is a horizontal perforated or porous pipe with open joints surrounded by a gravel filter envelop laid in a permeable material with high water table and a continuous recharge. A schematic design of an infiltration gallery is shown in Fig. 4. The design requirements for infiltration gallery are grain size, sediment thickness, hydraulic conductivity, water table depth and radius of influence for specified discharge. The maximum length with 100% safety factor of the infiltration gallery is calculated using the following equation (Driscoll, 1986):

$$\frac{Q}{L} = q = \frac{K}{2r_0}\left(H^2 - h^2\right)$$

where, Q = discharge (m^3/day). q = discharge per unit length (m^3/day/m). K = hydraulic conductivity (m/day). r_0= radius of influence (m). H = height of static water level above gallery bottom (m). h = height of pumping water level above gallery bottom under steady state condition (m). L = calculated length of gallery (m).

The radius of the infiltration gallery is calculated using the following equation (Driscoll, 1986):

$$r^2 = \frac{1.16 \times 10^{-5}\, Q}{\pi V}$$

where, V= axial velocity inside the screen. Q = yield in m^3/day. r = radius in m

In case of semi-confined aquifer or where the water table is very deep in an unconfined aquifer infiltration gallery is not feasible. In such an environment collector well with radials may be placed. A collector well with radials is essentially a large diameter well from which horizontal strainers protrude radially near the bottom into the aquifer (Fig. 5). The design requirements for collector well are grain size and transmissivity of aquifer material below river bed, width of the river and non-monsoon time period. The length and number of radials can be calculated from Theis non-equilibrium equation (Theis, 1935) as given in Raghunath (2007)

$$u' = \frac{r'^2 S}{4Tt}$$

where, S = storage coefficient. T = transmissivity (m^2/day). r' = width of the river bed (m). t = non-monsoon time period (days)

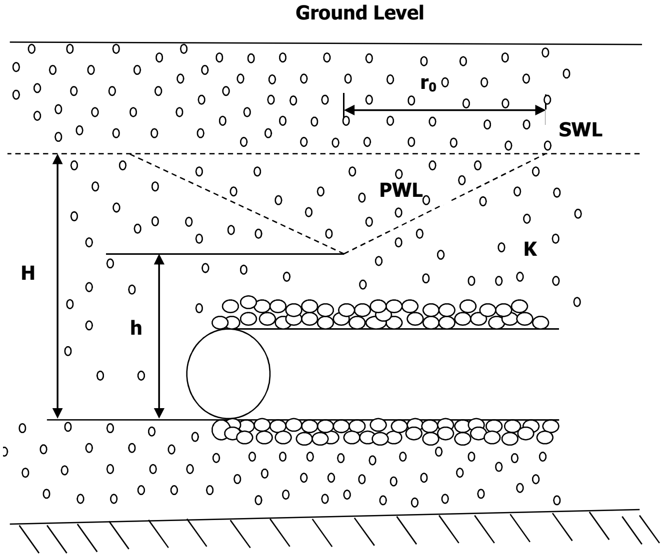

Fig. 4. Cross-section of an infiltration gallery showing parameters required for calculating length of gallery.

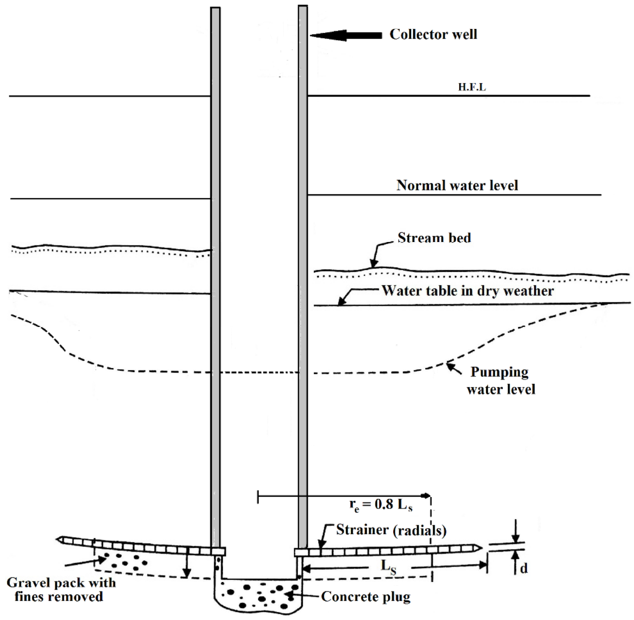

Fig. 5. Cross-section of a collector well with radials.

We get the value of W'(u) against the value u from Theis type curve to calculate drawdown 's'

$$s = \frac{Q}{4\pi T} * W'(u)$$

where, Q = Discharge (m^3/day). s = drawdown (m)

Since the river bed is a narrow stripped aquifer and the collector well will be located in the middle of the river bed with respect to both the banks, the drawdown due to both image wells located at a distance equal to the width of the river from the collector is included. The cumulative effect of both image wells is '2s'. Therefore, total drawdown allowable is

$$s_a = s_1 - 2s$$

where, s_1= maximum drawdown (m). s_a = allowable drawdown (m)

Now, from Theis Equation:

$$\frac{s}{s_a} = \frac{W'(u)}{W(u)}$$

For the value of W(u) we get corresponding value of 'u' for the real collector well from Theis type curve.

$$\text{Now,} \quad \frac{u'}{u} = \frac{r'^2}{r^2}$$

where r = effective radius of the collector well (m)

Since the 'r' of the collector well is equal to 75 to 85% of the individual L_s

$$0.8L_s = r$$

where, L_s= length of each radial (m)

The number of radials is calculated as follows:

$$n = \frac{Q}{\Pi d L_s p V_e}$$

where, d = diameter of radials (m). n = number of radials. p = effective percent open area. V_e= entrance velocity (m/sec).

Water Quality

Water samples were collected from the test wells and analyzed for chemical and bacteriological parameters, and pesticides. The samples were collected in clean polyethylene bottles. Prior to collection the sampling bottle was washed three times with the well water before filling with the sample water. The samples were taken to the laboratory within the shortest possible time and during transportation due care was taken to protect the water samples from direct sunlight. In the laboratory the samples were filtered using 0.45 mm Millipore filter paper and acidified with ultra-pure nitric acid for cation analyses. For anion analyses, these samples were refrigerated at 4°C. Each groundwater sample was analyzed in the laboratory for sixteen chemical parameters, two bacteriological parameters and three pesticide parameters as per the standard methods of APHA (1995). The analytical precision chemical analysis of water samples was checked by calculating the charge balance error (CBE) which is calculated using the following formula after Freeze and Cherry (1979)

$$\text{CBE} = \frac{\Sigma meq_c - \Sigma meq_a}{\Sigma meq_c + \Sigma meq_a} \times 100$$

where meq_c and meq_a represent the concentrations in millequivalents per litre of cations and anions respectively.

If the CBE is within ± 10%, the analysis is assumed to be good.

RESULTS

Lithology and Stratigraphy

One hundred thirty one slim holes were drilled on the bed of the river Mayurakshi in Md. Bazar and Sainthia blocks with depth ranging between 10 and 36 m (Figs. 1 and 2). The sub-surface lithological profile west of Tilpara Barrage (Fig. 6) reveals that 8 to 10 m thick sand occurs at the upper part of the lithological column followed at depth by thick clay with occasional sand lenses (Figs. 6, S1-S3). In borehole SH 6 (Figs. 6, S2) it is observed that the clay continues at least up to a depth of 30 m. The 8 to 10 m thick sand is the upper unconfined aquifer of the area through which the base flow takes place. Therefore, the pumping test well lines were selected at 6.8 km (Aquifer Test Line 1) and 5.8 km (Aquifer Test Line 2) west of Tilpara barrage (Figs. 2, S1-S3) with the test wells located in the middle of the river (Fig. 2) where the thickness of the sand is maximum.

The sub-surface lithological distribution east of Tilpara barrage in Sainthia block (Figs. 6, S4-S6) reveals that the present day river sand occurs at the upper 4 m of the lithological column. This sand rests on yellow to grey clay with occasional sand lens which occurs up to the drilling depth of 20 m. At places the clay occurs up to a depth of 12 m followed by sand with occasional clay lenses up to the maximum drilling depth of 30 m. These sections reveal that there is a thin unconfined near-surface aquifer of about 2-4 m thick in the upper part, through which the base flow of the river takes place, followed by an aquitard at depth. In the eastern part of the section the aquitard is followed by an aquifer. The second aquifer, which is overlain by an aquitard is semi-confined in nature and continues at least up to a depth of 36 m. Based on the subsurface lithological distribution aquifer test lines 3, 4 and 5 were selected (Figs. 2, S4-S6) east of Tilpara barrage.

Aquifer test

At Md. Bazar block two test wells and ten observation wells were constructed on the bed of the river, one test well on each of the aquifer test line 1 and 2. On test line 1 six observation wells and on test line 2 four observation wells (Fig. 7) were constructed. The subsurface lithology along each test line is shown in Figs. S7 and S8. At Sainthia three test wells and eighteen observation wells were constructed on the bed of the river, one test well on each of the aquifer test line 3, 4 and 5. Test line 3 has eight observation wells and, each of the test lines 4 and 5 has five observation wells. The distribution of the test well and the observation wells and the subsurface lithology on each of the test well line is shown in Figs. 8, S9-S11. The design aspect of the test wells and observation wells are given in Table S1.

Water level measurements were carried out in the test wells and observation wells prior to pumping. Repeat measurements of the water level in the available wells were carried out towards the end of the field work in the month of April 2012 to understand the lowest water level. The water level data are given in Table 1.

The test wells were pumped for 72 hours at a constant discharge. The rate of discharge of the pumping well, maximum drawdown of the test wells and the observation wells and specific capacity of the test wells are given in Table 2.

In Md. Bazar block the water level is very shallow and rests within 0.5 m below the bed of the river (Table 1; Figs. S7, S8). The storage coefficient of the aquifer ranges between 0.16 and 0.3 indicating that the aquifer is unconfined in nature (Table 3). The transmissivity of the aquifer in test line 1 is 1987 m^2/day and in test line 2 is 7878 m^2/day (Table 3), indicating that the potentiality of the aquifer is very high along test line 2. Therefore, an infiltration gallery may be constructed below the river bed along test line 2.

In Saithia block pumping tests on test well lines 3, 4 and 5 indicate that the observation wells with screen placed in the upper sand [1-3 m below river bed level (brl)] and underlying clay (6-9 m brl) response to pumping of the respective test well (Table 2). This indicates that there is leakage of water from the overlying clay and sand into the aquifer. Therefore, the semi-confined aquifer is receiving the base flow of the River Mayurakshi. The water level is very shallow and rests above the base of the upper confining bed within a depth of 2 m brl (Table 1; Figs. S9 - S11). In the month of April the water level is within 3 m (Table 1). The storage coefficient value of the aquifer ranges between 5.1×10^{-3} and 1.3×10^{-2} (Table 3), indicating that the aquifer is semi-confined in nature. The transmissivity of the aquifer varies from 394 to 1751 m^2/day, the highest being along the aquifer test line 3. Therefore, a collector well with radials may be constructed below a depth of 14 m below the river bed on test line 3.

The safe distance ($2r_0$) between two abstraction structures on river Mayurakshi ranges widely from 38 to 420 m depending upon transmissivity and storage coefficient values as well as the well discharge. The lowest value is obtained for test well 1 of Md. Bazaar block and the highest for test wells 3 and 4 of Sainthia block (Table 3).

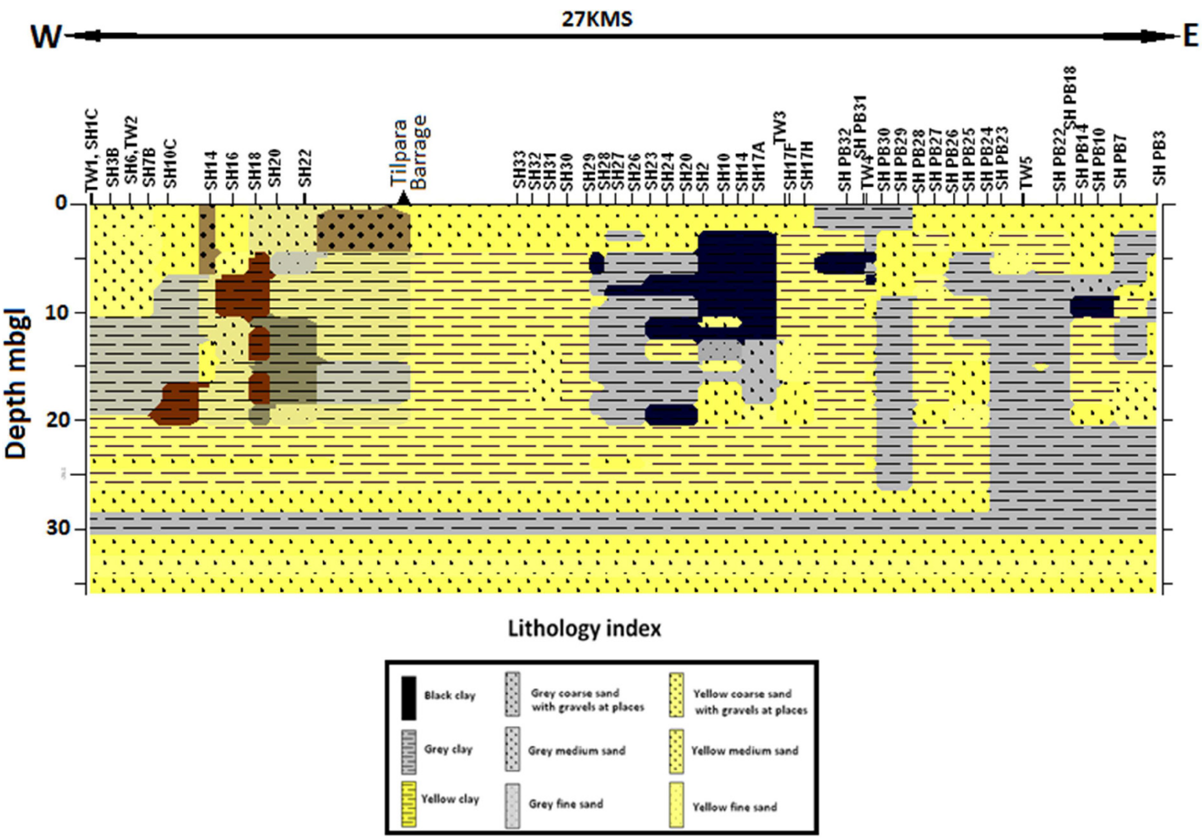

Fig. 6. Sedimentary sequences across the River Mayurakshi along the line of section shown in Fig. 2.

Table 1. Water level data in test wells and observation wells

River	Site	Well No.	MP (m)	WL BMP (m)	WL Below River Bed (m) January	February	March	April
Mayuraskhi	Md.Bazar	TW 1	0.58	1	-	0.42	-	-
		OW 1	0.26	0.52	-	0.26	-	-
		OW 2	0.33	0.775	-	0.445	-	-
		OW 3	0.33	0.7	-	0.37	-	-
		OW 4	0.3	0.695	-	0.395	-	-
		OW 5	0.3	0.74	-	0.44	-	-
		OW 6	0.3	0.4	-	0.1	-	-
		TW2	0.51	0.82	-	0.31	-	-
		OW 1	0.265	0.44	-	0.175	-	-
		OW 2	0.315	0.52	-	0.205	-	-
		OW 3	0.37	0.77	-	0.4	-	-
		OW 4	0.26	0.65	-	0.39	-	-
	Sainthia	TW 3	0.575	1.61	1.035	-	-	2.77
		OW 1	0.1	1.2	1.1	-	-	-
		OW 2	0.15	0.785	0.635	-	-	-
		OW 3	0.1	0.93	0.83	-	-	-
		OW 4	0.185	1.165	0.98	-	-	-
		OW 5	0.143	1.436	1.293	-	-	-
		OW 6	0.333	1.6515	1.3185	-	-	-
		OW 7	0.11	0.82	0.71	-	-	-
		OW 8	0.12	0.33	0.21	-	-	-
		TW 4	0.215	1.51	1.295	-	-	4.135
		OW 1	0.14	1.42	1.28	-	-	-
		OW 2	0.06	1.4	1.34	-	-	4.175
		OW 3	0.3	1.52	1.22	-	-	0.98
		OW 4	0.1	1.155	1.055	-	-	-
		OW 5	0.1	0.73	0.63	-	-	-
		TW 5	0.41	1.6	1.19	-	-	-
		OW 1	0.16	1.16	1	-	-	-
		OW 2	0.18	1.42	1.24	-	-	-
		OW 3	0.26	1.65	1.39	-	-	-
		OW 4	0.21	2	1.79	-	-	-
		OW 5	0.34	0.67	0.33	-	-	-

Note: Water level of April 2012 could not be measured in some wells since the wells were destroyed
MP – Measuring point; WL BMP – Water level below measuring point. The reference datum of measuring point is the river bed.

Table 2. Discharge – drawdown data of test wells and observation wells

River	Block	Test well no.	Discharge (m^3/day)	Max. Drawdown (m)	Specific Capacity (m^3/day/m)	Max. Drawdown in Observation wells (m) 1	2	3	4	5	6	7	8
Mayurakshi	Md. Bazar	TW1	1136	1.26	902	0.005	0.04	0.13	0.12	0.05	0	-	-
		TW2	1136	1.8	631	0.03	0.03	0.03	0	-	-	-	-
	Saithia	TW3	821	3.47	237	0.45	0.565	0.31	0.386	0.40	0.50	0.055	0.18
		TW 4	869	3.75	232	1.07	1.35	1.28	1.785	0.13	-	-	-
		TW 5	821	4.06	202	1.34	1.40	1.55	1.38	0.39	-	-	-

Table 3. Hydraulic parameters of aquifers below river bed

River	Blocks	Aquifer Test Line	Transmissivity (m^2/day)	Storage coefficient (m)	Safe distance	Remarks
	Md Bazar	1	1987	2.5×10^{-1}	38	Unconfined
		2	7878	1.65×10^{-1}	120	Unconfined
Mayurakshi	Sainthia	3	1751	1.15×10^{-2}	300	Semi-confined
		4	625	1.3×10^{-2}	420	Semi-confined
		5	394	5.1×10^{-3}	420	Semi-confined

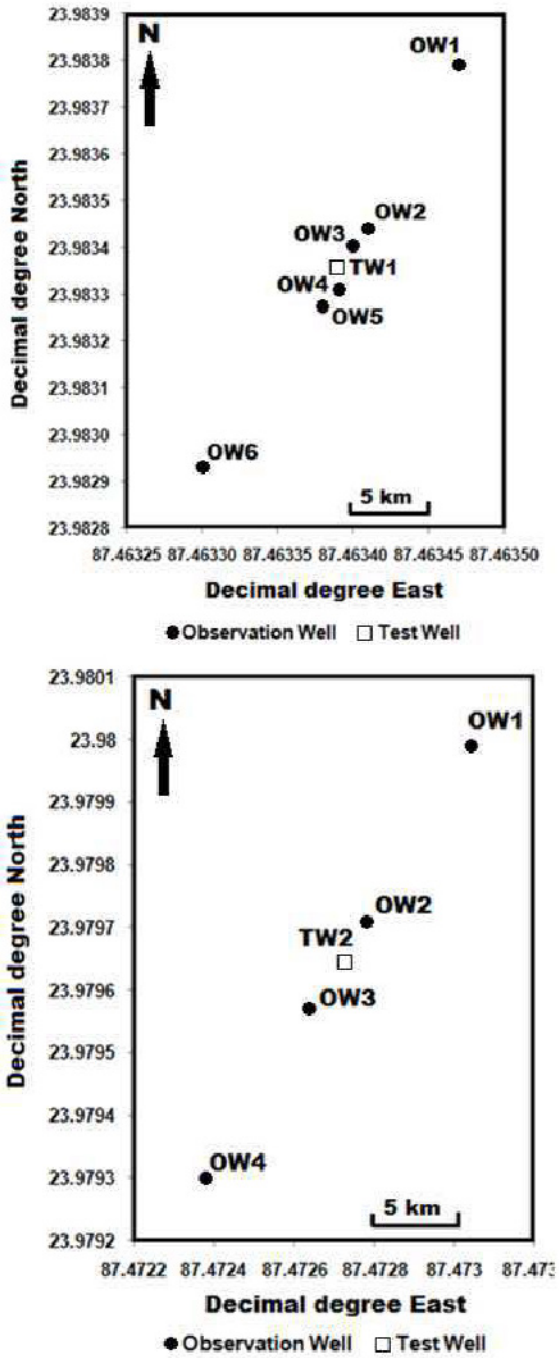

Fig. 7. Distribution of observation wells and test wells on aquifer test lines 1 and 2 on River Mayurakshi in Md. Bazar block.

Flow of Groundwater across Test Well Lines

The water table contour maps of pre-monsoon and post-monsoon seasons based on the water table measurements in 59 network stations in 2011 spread over the entire district suggest that the groundwater flow directions are towards the river. Hence the river is effluent in nature throughout the year.

The flow rates at the cross sections of the river along the test lines have been computed using Darcy's equation and given in Table 4. The groundwater flow varies between 8029 and 39164 m^3/day, being highest across aquifer test line 1.

Sediment Texture

The results of the grain size analysis of the five test wells are given in Tables S2 – S6. Cumulative frequency curves (Fig. S12) generated from grain size distribution data from mechanical analysis of sediment samples of the test wells were used to determine depth wise mean diameter, median, uniformity coefficient and slot size of screens of infiltration galleries/radials of collector wells.

The sediments which constitute the aquifer material of TW1 in Md. Bazar are largely sands which are variable in texture from fine to coarse up to a depth of 18 m brl and shows a coarsening upward sequence. The mean diameter of the sediments range between 0.25 (very coarse sand) and 2.45 ϕ (fine sand) with an average of 0.97 ϕ (coarse sand) (Table S2B). Infiltration gallery may be placed within a depth of 12 m brl as fine sand occurs below that depth. The sediments of TW2 are largely sands which are variable in texture from fine to coarse up to a depth of 16 m brl . The mean diameter of the sediments range between 0.15 (coarse sand) and 2.46 ϕ (fine sand) with an average of 0.80 ϕ (coarse sand) (Table S2B). Infiltration gallery may be also placed within a depth of 12 m brl as fine sand occurs below that depth.

The aquifer material of TW3 in Sainthia block are largely sands which are variable in texture from medium to coarse with a more or less coarsening upward sequence from a depth of 36 to 14 m brl. There is a thick clay bed from 4 to 14 m brl ruling out the possibility of an infiltration gallery. The median diameter of the sediment ranges between -0.29 (very coarse sand) and 1.47 ϕ (medium sand) with an average of 0.63 ϕ (coarse sand) (Table S4B). A collector well with radials may be constructed below 14 m brl in this location. In TW4 there is a clay bed at the upper part of the lithological column from 2 to 16 m brl ruling out the possibility of an infiltration gallery. The sands occur from a depth of 16 to 26 m brl and are variable in texture from medium to coarse. The mean diameter of the sands ranges between 0.34 (coarse sand) and 1.13 ô (medium sand) with an average of 0.81 ϕ (coarse sand) (Table S5B). Collector well with radials may be constructed below 16 m brl. In test well TW5 the sediments which constitute the aquifer material are sands which are variable in texture from fine to coarse from a depth of 4 to 22 m brl. There is clay bed of 4 m thickness at the upper part of the lithological sequence. The mean diameter of the sediments ranges between 0.26 (coarse sand) and 2.1 ϕ (fine sand) with an average of 0.94 ϕ (coarse sand) (Table S6B). An infiltration gallery may be placed within a depth of 4-12 m brl as fine sand occurs below that depth.

Hydrogeochemistry

The results of the chemical, bacteriological and pesticide analyses and the Indian drinking water standard BIS 10500 (2012) and CBE are given in Table 5. All the samples have CBE within the acceptable value of ±10%, indicating that the analytical results are reliable. The groundwater quality with respect to chemical parameters is generally within the desirable limit except for iron (TW3) and manganese (TW1, TW3 and TW4). Bacteriologically, the groundwater is contaminated with colliform bacteria. The major cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) and major anions (Cl^-, HCO_3^- and SO_4^{2-}) content in the groundwater samples (Table 5) indicate that the groundwater is dominated by alkaline earths and weak acids. Bicarbonate concentration varies from 50 to 164 mg/L, and it contributes 72% (mean) of the total anions in the groundwater.

DISCUSSION

Geology

River Mayurakshi drains through a variety of country rocks such as laterites, granite gneiss, hard clays impregnated with caliche nodules and middle to late Holocene sand, silt and clay from west to east respectively (Fig. 1). The modern day river sands rest on these lithological units. In the Precambrian granite gneiss terrain groundwater occurs in the upper weathered residuum and fractured, fissured and jointed rocks below under unconfined to semi-confined condition. Dug wells in the weathered zones can yield 4 – 5 m^3/day of water.

Table 4. Groundwater discharge across test well lines

River	Location	Test well no.	Transmissivity (m^2/day)	Width of river (m)	Hydraulic gradient	Groundwater flow rate	
						m^3/day	MGD
Mayurakshi	Md. Bazar	TW 1	1987	438	4.5 x 10^{-2}	39164	10.34
		TW 2	7878	507	1.3 x 10^{-2}	27307	7.21
	Sainthia	TW 3	1751	185	8 x 10^{-2}	25775	6.81
		TW 4	625	443	2.9 x 10^{-2}	8029	2.12
		TW 5	394	368	1.0 x 10^{-1}	14499	3.83

Bored wells tapping the potential fractures below the weathered mantle can yield up to 25 m^3/hr of water (CGWB and SWID, 2011). In the upper Tertiary to lower Quaternary lateritic areas groundwater occurs under unconfined condition and the aquifer does not permit large scale groundwater withdrawal. The Holocene alluvium are 30-50 m thick and rests on Pleistocene hard clays with yield of about 100-150 m^3/hr of water. Groundwater in many places has fluoride concentration > 1 mg/L and is unfit for drinking.

Geology below the river bed is very variable with rapid facies variation both in vertical and horizontal directions. The upper 10 m unconfined aquifer below the river bed in the stretch west of Tilpara Barrage gradually thins to about 4 m in the east through which the base flow takes place. In the eastern part the productive aquifer is overlain by a 20 m thick aquitard and is semi-confined and leaky in nature. This aquifer continues at least up to a depth of 36 m brl. The bed rocks in the entire section could not be determined because of the limitation of the depth of drilling.

Groundwater Chemistry

Bicarbonate in groundwater is generally derived from the weathering of silicate minerals (Stumm and Morgan, 1996). Processes related to anthropogenic activities can be understood by identifying pollution by Cl, NO_3, and SO_4 in groundwater (Sengupta *et al.,* 2008; BBS/UNICEF, 2011; McArthur et al., 2012). In the shallow alluvial sands of the Bengal basin, pristine groundwater should be dilute as the concentration of Cl in rain is typically less than 3 mg/L (Sengupta *et al.,* 2008). In Bengal basin most dilute groundwater contains < 5 mg/L Cl that are not affected by salt-water intrusion (McArthur et al., 2012). In Bangladesh, the typical concentration of Cl in drinking water is <10 mg/L (BBS/UNICEF, 2011) in those geographic regions that are not affected by salt-water intrusion. The natural baseline concentrations of both NO_3 and SO_4 in rainfall are very small. Groundwater in the Bengal basin is anoxic, so the small concentrations of natural NO_3 and SO_4 in recharge are rapidly removed, the latter into trace amounts of diagenetic pyrite (Nickson et al., 2000). As a consequence, unpolluted groundwater contains a concentration of NO_3 that is undetectable, and of sulfate that is detectable but typically < 0.1 mg/L (McArthur et al., 2012). The high chloride, nitrate and sulphate concentrations in sample TW 5 (Table 5) are indicative of anthropogenic pollution from waste water from pit latrines, septic tank and open defecation. The impact is also corroborated by high total and faecal colliform count in the test wells. The groundwater at places has also high concentration of iron and manganese (Table 5). Hence the water should be adequately treated before supplying to the local people for drinking purpose.

Table 5. Results of the chemical, bacteriological and pesticide analyses

Parameters	Concentration River Mayurakshi					Ground-water quality* Accept. Limit
	Md.Bazar		Sainthia			
	TW 1	TW 2	TW 3	TW 4	TW 5	
pH	7.72	7.93	8.33	8.16	8.20	6.5 to 8.5
TDS (mg/L)	72	78	152	96	218	500
Hardness (mg/L)	100	92	200	140	340	300
Bicarbonate(mg/L)	58.4	50	164	122	140	200
Chloride (mg/l)	11.60	10.60	13.50	9.60	88.70	250
Sulphate (mg/l)	2.5	2.8	7.25	3.1	6.25	200
Nitrate (mg/l)	0.61	0.3	1.45	0.25	19.40	45
Fluoride (mg/L)	0.67	0.66	0.53	0.44	0.19	1.0
Arsenic (mg/L)	0	2	0	0	0	10
Sodium (mg/L)	9.0	8.9	23	16	52	-
Potassium(mg/L)	1.40	1.40	0.90	1.30	4.40	-
Calcium (mg/L)	10.90	14.00	34.40	25.40	39.70	75
Magnesium(mg/L)	7.50	3.30	12.50	8.70	12.50	30
Manganese(mg/L)	0.18	<0.05	0.91	2.27	<0.05	0.1
Iron (mg/L)	0.1	0.2	1.2	0.5	0.1	1.0
Chromium (+3)	<0.05	<0.05	<0.05	<0.05	<0.05	0.05
Total Colliform (MPN/100ml)	1600	1600	9	7	23	0
FaecalColliform (MPN/100ml)	1600	1600	0	0	23	0
Lindane(g-BHC) (mg/L)	0	0	0	0	0	0
Endosulphan I (mg/L)	0	0	0	0	0	0
Aldrin(mg/L)	0	0	0	0	0	0
Charge Balance Error (%)	8.25	8.21	7.50	7.42	1.37	-

*with respect to BIS 10500:2012

Groundwater Abstraction Structures

In Md. Bazaar block along the test well line the sediments up to a depth of 16-18 m brl consists of fine to coarse sand. The water level is very shallow and rests within 0.5 m brl (Figs. S7, S8). The transmissivity of the aquifer varies between 1987 and 7878 m^2/day. Therefore, an infiltration gallery may be constructed in the river bed along the aquifer test line 2 (Fig. 9). In Saithia block the upper part of the stratigraphic column consists of clay. Below this clay the sediments are largely sand which is variable in texture from medium to coarse. Pumping tests in all the test wells indicate that the observation wells with screens placed in the upper sand (1-3 m brl) and underlying clay (6-9 m brl) response to pumping of the respective test well. This indicates that there is leakage of water from the overlying clay and sand into the aquifer. Therefore, the lower semi-confined aquifer is receiving the base flow of the river Mayurakshi. The water level is very shallow and rests above the base of the upper confining bed within a depth of 2 m brl. The transmissivity of the aquifer varies from 394 to 1751 m^2/day, the highest value recorded in test well 3. Therefore, a collector well with radials may be constructed on test line 3 (Fig. 9).

Infiltration galleries and collector wells have been designed (Tables 6 and 7) based on the assumptions that the total volume of water flowing across the cross-sections of the river cannot be abstracted because of sustainability and environmental factors. The safety factor has been assumed to be 30-40 % which means that only 60-70% of the water flowing across the particular section of the river can be abstracted.

The infiltration gallery of 300 mm along test line 2 at Md. Bazar diameter should be placed at a depth of 8 m below the river bed. The calculated length of the gallery based on the safe rate of abstraction of

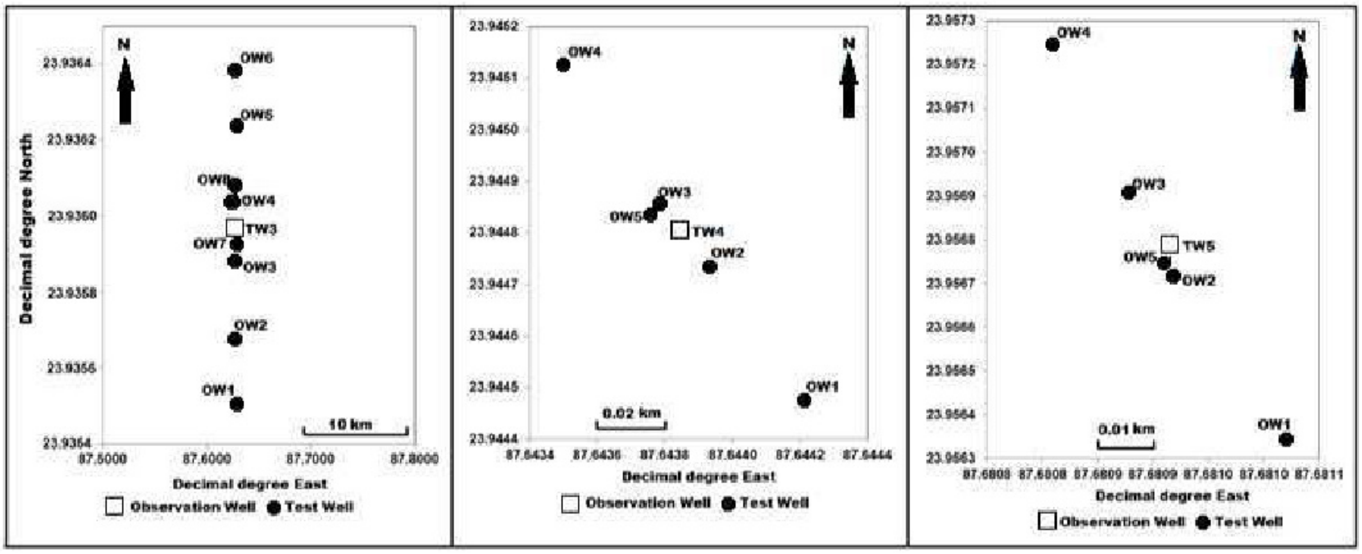

Fig. 8. Distribution of observation wells and test wells on aquifer test lines 3, 4 and 5 on River Mayurakshi in Sainthia block.

18927 m^3/day or 5 MGD is 190 m. The diameter of the gallery should be >557 mm to maintain the axial velocity inside the screen ≤ 0.9 m/sec so that the head loss is ≤ 0.3 m, and avoid turbulent flow and air entrainment.. The screen slot size should be 0.87 mm. The screens require artificial packing and the gravels for the pack should be 5-6 times the screen slot size (Table 6).

The collector well on test line 3 has been designed based on the assumption that the maximum drawdown will be 15 m and the discharge will be 15142 m^3/day or 4 MGD. The depth of the 4 m diameter well should be 26 m below the river bed with 8 radials each of 65 m length and 200 mm diameter (Table 7). Since it may be difficult to construct such a long radial, it is suggested to have 16 radials of 30 m length with a screen slot size of 0.45 mm (Table 7). Although sediment analysis suggests that artificial packing may not be required but it may be prudent to have artificially packed screens. Gravels for the pack should be 5-6 times the screen slot size of 0.45 mm.

Implications of the Design Yield

A cautious approach should be adopted before planning for construction of abstraction structures (infiltration gallery or collector well with radials) on river bed based on the overall economics of the withdrawal of water from the site. Infiltration gallery is always restricted to the total width of the river bed and depth to water table below the river bed. But at places where sustainability of water supply can be counterbalanced by higher drawdown and no other cheaper means for groundwater withdrawal are available, horizontal wells like collector wells with radials may have to be resorted to even if it is a costlier proposition.

River Mayurakshi is an effluent river throughout the year. The proposed infiltration gallery and collector well with radials will draw water principally from discharging groundwater. The net groundwater availability for future development in Mayurakshi basin comprising Md, Bazar, Sainthia, Labhpur, Mayureswar I and II, Siuri I and II blocks (Fig. 1) is 430 X 10^6 m^3/year (CGWB and SWID, 2011). The total groundwater that will be withdrawn though these river bed structures is 12.4 X 10^6 m^3/year. This means that <3% of the net groundwater availability will be abstracted through these structures. Hence the small amount of reduction in the baseflow of the river that will occur due to abstraction will not have any significant adverse effect on the river regime.

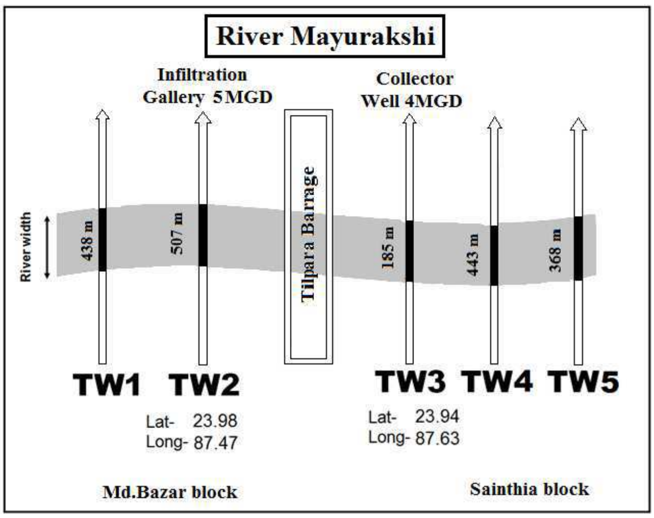

Fig. 9. Feasible groundwater abstraction structures that may be constructed on the bed of River Mayurakshi for future public-water supply. Figure not to scale.

Table 6. Design of the proposed infiltration gallery

Location	Latitude	23.98°
	Longitude	87.47°
Pre-pumping water level (PWL) (m below river bed)		0.31
Steady state water level (SWL) (m below river bed)		2.11
Bottom of infiltration gallery (m below river bed)		8
Height of pre-pumping water level above gallery bottom (H) (m)		7.69
Height of water level above gallery bottom under steady state condition (h) (m)		5.89
Safety factor		30%
Allowable Discharge (m^3/day)		18927 (5 MGD)
K= T/b (m/day)		502
Safe distance ($2r_o$)		120
Length of gallery (m)		190
Diameter of gallery (mm)		>557
Screen slot size (mm)		0.87
Gravel packing		Artificially packed screen. Gravels for the pack should be 5-6 times the screen slot size

Table 7. Design of the collector well

Discharge (m^3/day)	Latitude	Longitude	Width of the river bed (r') (m)	Maximum Drawdown assumed (m)	Well dimension		Radial dimension					Screen slot size	Gravel packing
					Depth (m)	Diameter (m)	Length (m)		Diameter (inch)	Number			
							Calculated	Field		Calculated (mm)	Field		
15142 (4MGD)	23.94	87.63	185	15	26	4	65	30	8	8	16	0.45	Naturally packed screen is required

CONCLUSIONS

Concerns about the current supplies of drinking water to the communities residing in semi-arid and fluoride affected blocks of Birbhum district of West Bengal led to the present systematic hydrogeologic investigation of river bed aquifer system to understand the quantity and quality of groundwater flowing below the bed of the River Mayurakshi. Based on the study, groundwater withdrawal points have been identified at the best possible location on the river bed and abstraction structures have been designed for supply of low fluoride drinking water. An infiltration gallery of 190 m length and > 557 mm diameter may be constructed in Md. Bazar block west of Tilpara Barrage to abstract 18927 m^3/day (5MGD) of water and a 4 m diameter collector well with 16 radials each 30 m length and 8 inch diameter at two levels with at least 4 m separation between them may be constructed in Saithia block east of Tilpara barrage to abstract 15142 m^3/day (4 MGD) of water. The water needs to be treated for iron, manganese and colliform bacteria before supplying to the villages for drinking purpose. This paper, therefore, illustrates the potentiality of river bed aquifer of ephemeral rivers of the semi-arid and fluoride affected areas for sustainable supply of drinking water to the vulnerable section of the community. The results would be useful to engineers and planners to plan for sustainable supply of safe drinking water in the conurbations adjacent to ephemeral rivers in other semi-arid areas of India and elsewhere.

Supplementary Material: Supplementary material containing figures and tables showing lithological sections, grain size distribution curves, design of test and observation wells, and grain size analysis is available on Society website: www.geosocindia.org

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References

Ali M. (2003) Review of drilling and tubewell technology for groundwater irrigation. *In*: Rahman A.A., Ravenscroft P., (Eds.), Groundwater resources and development in Bangladesh- background to be arsenic crisis, agricultural potential and the environment, Dhaka: Bangladesh Centre for Advanced Studies, University Press Ltd.

APHA (American Public Health Association) (1995) Standard Methods for the Examination of Water and Wastewater, 19th edition, American Public Health Association, American Water Works Association, and Water Pollution Control Federation: Washington, DC.

Ball, P. and Danert, K. (1999) Hand and Sludging: a Report from Northwest Bengal. Report of DFID KAR Project R7126 "Private Sector Participation in Low Cost Water Well Drilling", Cranfield University.

BBS/UNICEF. (2011) Bangladesh National Drinking Water Quality Survey 2009. Bangladesh Bureau of Statistics and UNICEF, Dhaka.

BIS 10500. (2012) Indian Standard Drinking Water - Specification (Second Revision). Bureau of Indian Standards, New Delhi, pp.1-11.

CGWB (Central Ground Water Board) and SWID (State Water Investigation Directorate). (2011) Report on the dynamic ground water resources of West Bengal as on 31.03.2009, Technical report series 'B' No. 234, 1-244.

Cooper, H.H. and Jacob, C.E. (1946) A generalized graphical method for evaluating formation constants and summarizing well field history. Amer. Geophys. Union Trans., v.27, pp.526-534.

Delin, G.N., Healy, R.W., Lorenz, D.L. and Nimmo, J.R. (2007) Comparison of local to regional scale estimates of ground-water recharge in Minnesota, USA. Jour. Hydrol., v.334, pp.231–249.

Driscoll, F.G. (1986) Groundwater and Wells. 2nd ed. Johnson Division, St. Paul, MN.

Folk, R.L. (1986) Petrology of Sedimentary Rocks: Austin, University of Texas Publication, 170p.

Freeze, R.A. and Cherry, J.A. (1979) Groundwater. Prentice Hall Inc., Englewood Cliffs, N.J., 604p.

GSI (Geological Survey of India) (2001) District Resource Map of Birbhum, West Bengal. www.portal.gsi.gov.in (accessed on 25.02. 2012).

Mathias, S.A. and Wheater, H.S. (2010). Groundwater modeling in arid and semi-arid areas: an introduction. *In*: Wheater H.S., Mathias S.A., Li, X. (Eds.), Groundwater modeling in arid and semi-arid areas: Cambridge University Press.

McArthur, J.M., Sikdar, P.K., Hoque, M.A. and Ghosal, U. (2012) Waste water impacts on groundwater: Cl/Br ratios and implications for arsenic pollution of groundwater in the Bengal Basin and Red River Basin, Vietnam. Science of the Total Environment, v.437, pp.390-402.

McMahon, T.A., & Mein, R.G. (1986) River and Reservoir Yield. Water Resources Publication, Littleton, CO, 368p.

Nickson, R., McArthur, J.M., Ravenscroft, P., Burges, W.G., & Ahmed, K.M. (2000) Mechanism of arsenic release to groundwater, Bangladesh and West Bengal. Appld. Geochem., v.15, pp.403-413.

Reay, W.G., Gallagher, D.L. and Simmons Jr., G.M. (1992) Groundwater discharge and its impact on surface water quality in a Chesapeake Bay inlet. Water Resources Bull., v.28(6), pp.1121–1133.

Raghunath, H.M. (2007) Ground Water. 3rd ed. New Age International (P) Limited, New Delhi.

Santhi, C., Allen P.M., Muttiah, R.S., Arnold, J.G. and Tuppad, P. (2008). Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. Jour. Hydrol., v.351, pp.139-153.

Sengupta, S., McArthur, J.M., Sarkar, A.K., Leng, M., Ravenscroft, P., & Howarth, R.J., et al. (2008) Do ponds cause arsenic-pollution of groundwater in the Bengal Basin? An answer from West Bengal. Environment Science and Technology, v.42, pp.5156-64.

Sinha Ray, S.P. (2008) Report on Studies of High Fluoride Groundwater in parts of Birbhum district with a view to find out cause of its mobilization and develop strategies for safe drinking water supply. Centre for Ground Water Studies. Kolkata, August 2008.

Stuckey, M.H. (2006) Low flow, base flow, and mean flow regression equations for Pennsylvania streams. US Geological Survey Scientific Investigations Report, 2006-5130.

Stumm, W. and Morgan, J.J. (1996) Aquatic Chemistry. Wiley-Interscience: New York.

Theis, C.V. (1935) The relation between the lowering of the piezometric surface and the rate and duration of discharge of well using groundwater storage. Amer. Geophys. Union Trans., v.16, pp.519-524.

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