Environ Geol (2008) 55:823–835
DOI 10.1007/s00254-007-1034-x

ORIGINAL ARTICLE

Hydrochemical framework of the aquifer in and around East Kolkata Wetlands, West Bengal, India

Paulami Sahu · P. K. Sikdar

Received: 6 February 2006 / Accepted: 10 September 2007 / Published online: 11 October 2007

Abstract The area lies between Hugli river in the northwest and Bidyadhari river in the east and includes the East Kolkata Wetlands. The East Kolkata Wetlands is included in the List of Wetlands of International Importance (“Ramsar List”), as per the Convention on Wetlands signed in Ramsar, Iran, in 1971. This wetland has been declared as a Ramsar site on the 19th August 2002 (Ramsar site no. 1208) and therefore has acquired an international status. The area is a part of the lower deltaic plain of the Bhagirathi–Ganga river system and is generally flat in nature. The sub-surface geology of the area is completely blanketed by the Quaternary fluviatile sediments comprising a succession of clay, silty clay, sand and sand mixed with occasional gravel. The Quaternary aquifer is sandwiched between two clay sequences. The confined aquifer is made up of moderately well sorted sand and reflects fluviatile environment of deposition. The regional groundwater flow direction is from east to west. Detailed geochemical investigations of 40 groundwater samples along with statistical analysis (for example, correlation and principal component analysis) on these chemical data reveal: (i) four types of groundwater quality, for example, good, poor, very poor and water unsuitable for drinking purpose, (ii) four hydrochemical facies which may be assigned to three broad types such as “fresh”, “blended”, and “brackish” waters, (iii) the evolution of the “blended” water is possibly due to hydraulic mixing of “fresh” and “brackish” waters within the aquifer matrix and/or in well mixing, and (iv) absence of Na–Cl facies indicates continuous flushing of the aquifer.

Keywords East Kolkata Wetlands · Piezometeric surface · Water quality index · Hydrochemical facies · Principal component analysis

Introduction

The area consisting of 333.50 km^2 is bounded by latitude 22°25′N to 22°40′N and longitudes 88°20′E to 88°35′E and lie between Hugli river in the northwest and Bidyadhari in the east. The area consists of Salt Lake City and Rajarhat block in the north, parts of Bhangar-I and Bhangar-II block in the east, parts of Sonarpur block in the south and Kolkata City in the west (Fig. 1). An important location within this area is the East Kolkata Wetlands, which occupy 125 km^2 area (Fig. 2). The East Kolkata Wetlands is included in the List of Wetlands of International Importance (“Ramsar List”), as per the Convention on Wetlands signed in Ramsar, Iran, in 1971. This Convention is an intergovernmental treaty which provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. There are presently 155 Contracting Parties to the Convention, with 1,675 wetland sites, totaling 150 million hectares, designated for inclusion in the Ramsar List of Wetlands of International Importance. The East Kolkata Wetlands has been declared as a Ramsar site on the 19th August 2002 (Ramsar site no. 1208) and therefore has acquired an international status.

P. Sahu
Department of Environment Management,
Indian Institute of Social Welfare and Business Management,
Kolkata 700 073, India

P. K. Sikdar (✉)
Department of Environment Management,
Indian Institute of Social Welfare and Business Management,
Management House, College Square (West),
Kolkata 700 073, India
e-mail: p_sikdar@hotmail.com

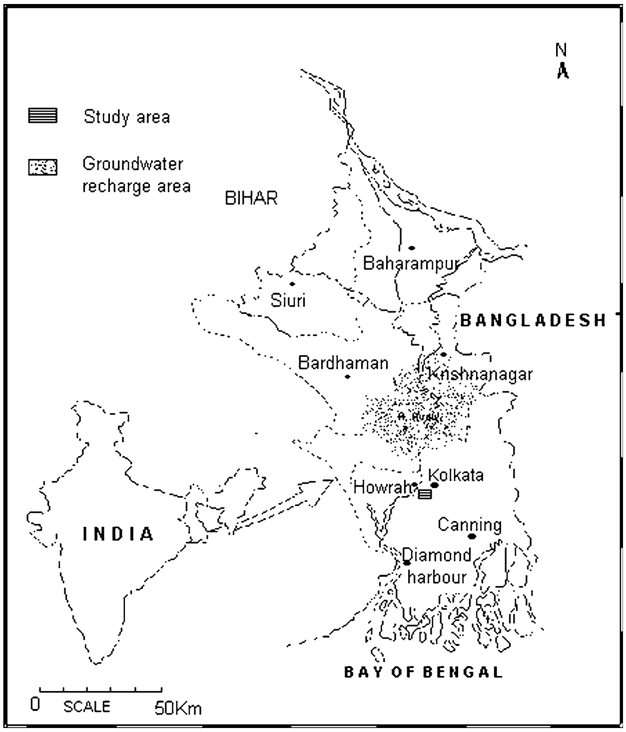

Fig. 1 Location of study area

This wetland acts as a sewage water treatment plant and treats about 800 million liters of wastewater flowing out daily from Kolkata. Wastewater of the city is a mixture of domestic and industrial effluent carrying high amounts of heavy metals. This wastewater is fed into the wetland locally known as “bheries”. But the outlet water from the “bheries” contains insignificant amounts of these heavy metals. Scientists have also shown that there is a very low flux of metals from the sewage water to the fish. Therefore, the heavy metals remain within the wetland system. These heavy metals can possibly leach from the soil and the bottom sediments of the “bheries” to the groundwater body. Leaching of pollutants will be accelerated due to over-withdrawal of groundwater for domestic, irrigation, industrial and commercial needs. Therefore, the aquifer below the East Kolkata Wetlands will be contaminated and the east to west groundwater flow will transport heavy metals from the wetland aquifer to Kolkata aquifer. Therefore, it is imperative to access the potentiality of the wetland aquifer in terms of quality.

Hydrogeological setting

The area is a part of the lower deltaic plain of the Ganga–Bhagirathi–Hugli river system. The land surface with its elevation of 3–6.5 m above mean sea level slopes gradually towards the south and southeast. This elevation differs locally because of palaeo-levees, palaeo-courses, channels, etc.

The climate of the study area is predominantly influenced by the northeast and southwest monsoons. Hot lengthy summer with occasional nor’westers, prolonged monsoon from June to October, mild winter and a brief spring are the characteristic features of the climate in the area. The average annual rainfall is about 1,650 mm, 80% of which occurs during June–October. The annual maximum and minimum temperatures are 42°C and 10°C, respectively.

River Hugli is the nearby dominant river of this area. Past drainage is marked by Bidyadhari river. There are many small palaeo-channels present in the area. Tali’s nala and Bidyadhari khal are the two important palaeo-channels. Two canals, namely, Krishnapur Canal and Bagjola Canal are present along the northern boundary of the study area. The wastewater flow of Kolkata city is carried by a system of canals and channels. Dry weather flow (DWF) and storm water flow (SWF) channels carries 75%, the Bagjola, Krishnapur and Beleghata canals in the north carries 15% and rest is carried by Talis Nala in the south. These canals are heavily silted and receive both untreated domestic wastewater and industrial wastewater. The DWF and SWF channels run parallel from west to east through the centre of the area and divide the area into two halves. These two canals join together near Bantala where it is known as Bhangar Canal (Fig. 2).

The occurrence of groundwater in the area is controlled by the geology. The Quaternary stratigraphy of the area (Table 1) has been compiled on the basis of lithological, floral, faunal and radiocarbon dating (Chaterji et al. 1959; Banerjee et al. 1984; Sen and Banerjee 1990; Barui and Chanda 1992; Hait et al. 1996). The sub-surface geology of the area is completely blanketed by the Quaternary fluviatile sediments comprising a succession of clay, silty clay, sand and sand mixed with occasional gravel. Lithologs of deeper exploratory boreholes, drilled by various agencies, suggests the existence of underlying Tertiary clay at an average depth of 296 m (Chaterji et al. 1959). This clay bed continues up to a depth of at least 614 m below the surface.

Lithologs also reveal that there is another clay layer of Upper Quaternary age at the top of the succession of 40 m thickness on an average. A perusal of an east–west cross section AA′ (Figs. 3a, 5a) reveals that the topmost clay layer, in general, thins out towards the east from 31 m to about 21 m. The north–south cross section BB′ (Figs. 3a, 5b) shows a gradual thickening of topmost clay layer from north to south from around 12 m to about 21 m.

The Quaternary aquifer is sandwiched between the clay sequences. These two clay beds are dark grey in colour, sticky and plastic to semi-plastic in character and contain

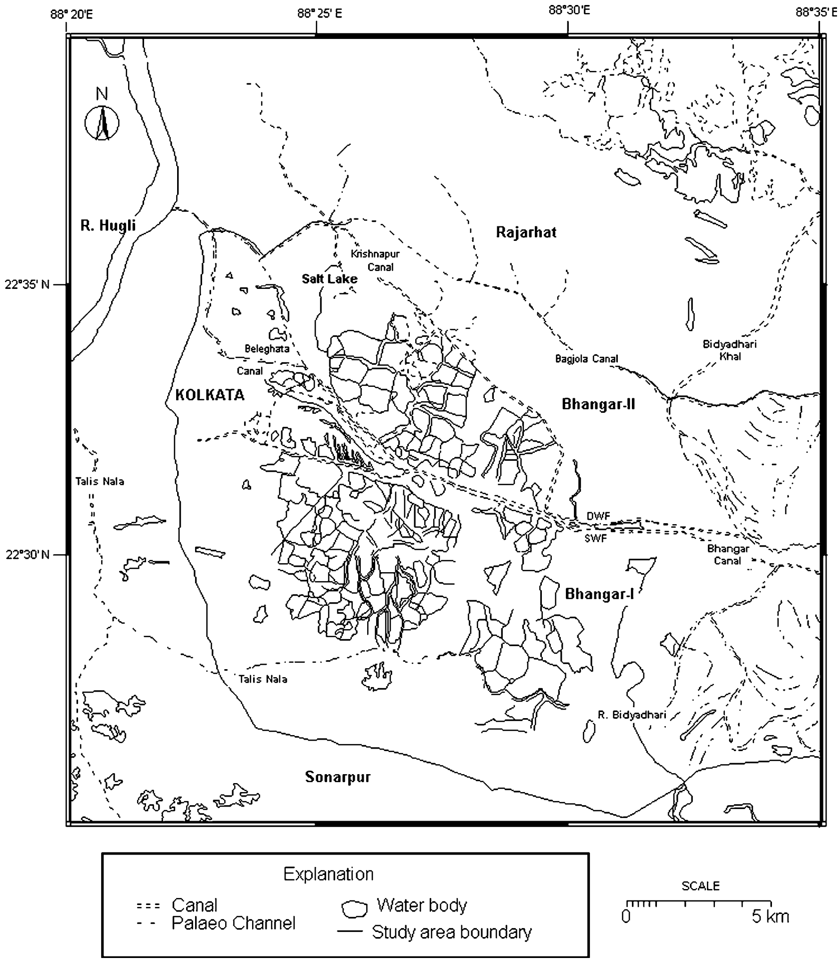

Fig. 2 Past and present drainage pattern

Table 1 Stratigraphy of the area of East Kolkata, India

System	Series	Lithology	Depth (m)
Quaternary	Holocene	Clay and silt, with peaty intercalation at two depth ranges from the surface	12.5
		(i) 2–5 m dated at 3,990 ± 70 years B.P.	
		(ii) 12–12.6 m dated at 7,030 ± 70 years B.P.	
	Pleistocene	Sand, fine to coarse with clay lenses, gravel and calcareous concretions	296
Tertiary	Pliocene	Clay, bluish grey, soft and sticky	To > 614

stringers of silt or fine sand. Clay beds are less plastic whenever they are admixed with silt or fine sand (Sikdar 2000; Sikdar et al. 2002). The top clay layer is underlain by a sequence of fine to coarse sand horizons mixed occasionally with gravel. The continuity of the sand layer that forms the aquifer material is broken by occasional clay lenses of limited lateral extent. The aquifer is often silty and highly micaceous.

The sands are moderately well sorted and have an average graphic inclusive standard deviation of 0.98 that reflects a fluvial environment of deposition. The fining upward sequence of the Quaternary sediments indicates a fluvio-deltaic depositional environment. Occurrence of peat in the upper horizons of the sediments and occurrence of marsh or salt lakes at the northern part of the area indicate that bog and marshy conditions prevailed during the close of sedimentation.

The yellow colour of the sand (at a depth range of 24–76 m) is thought to be due to oxidation of the sediments generated from the Archean terrain of the Chotonagpur Plateau and brought down by the rivers flowing from the west. The grey to light grey colour of overlying sediments

Table 2 Status of the piezometric surface of the present study area

	Piezometric surface below ground level (m)		Piezometric surface with respect to M.S.L. (m)	
	Post-monsoon 2004	Pre-monsoon 2005	Post-monsoon 2004	Pre-monsoon 2005
Maximum	16.70	17.63	+4.685	+2.69
Minimum	1.33	2.71	–12.90	–14.407
Average	7.15	8.95	–2.217	–3.17

indicates a reducing condition of deposition and brought down from the Himalayan domain during the late Quaternary period (Sikdar 2000).

The thick clay bed at the top of the stratigraphic column helps to confine water under pressure in the deeper sand sequence. During the present investigation, piezometric data were collected from 85 tubewells where strainers were placed at depths ranging between 40 and 220 m. Groundwater occurs in a confined condition within a sandy aquifer sandwiched between two clay beds. Summary of piezometric surface data is presented in Table 2.

Groundwater elevation contours of post-monsoon in 2004 (Fig. 3a) reveal that a groundwater trough exists within the wetland near Dhapa–Manpur region and the groundwater moves towards this depression from the surrounding region. Troughs are also observed at places such as Ghasiara and Arapanch, Ushpara of Bhangar-I block and near Entali and Bagbazar of Kolkata. Local groundwater mounds, from which groundwater moves away in all directions (Fig. 3a). Groundwater contours of pre-monsoon in 2005 (Fig. 3b) is more or less similar to that of post-monsoon in 2004 except for a general recession of the piezometric surface of 2–4 m. The striking difference between the contours of these two periods is the absence of two local groundwater mounds within Kolkata, one at Beleghata and the other near Ballygunja during pre-monsoon period of 2005.

Fourth degree trend surface map of pre-monsoon, 2005 (Fig. 4a) indicates that the regional flow of groundwater is from east to west. The map indicates that there is a groundwater mound near the south-eastern corner of area near Pratapnagar region. From this mound, groundwater flows in all directions. At northeastern corner of the study area, there is another groundwater mound near Hatisala region. From this high, groundwater moves towards southwest and near Gangapur region the flow direction takes a bend and flows towards west. This map also reveals that a depression of 13.7 m from mean sea level near Entali triggers groundwater flow from wetland in the east to Kolkata in the west. The trend surface map of post-monsoon

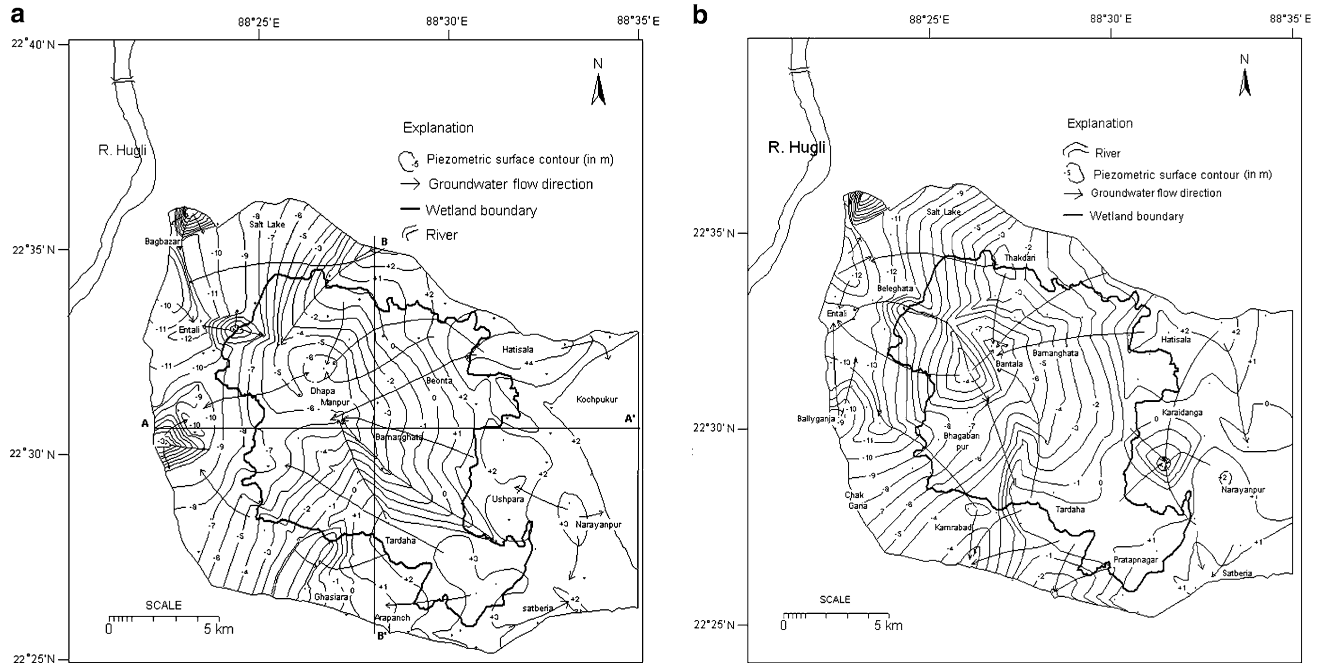

Fig. 3 **a** Contour map showing the elevation of piezometric surface (with respect to mean sea level) during post monsoon, 2004. **b** Contour map showing the elevation of piezometric surface (with respect to mean sea level) during pre-monsoon, 2005

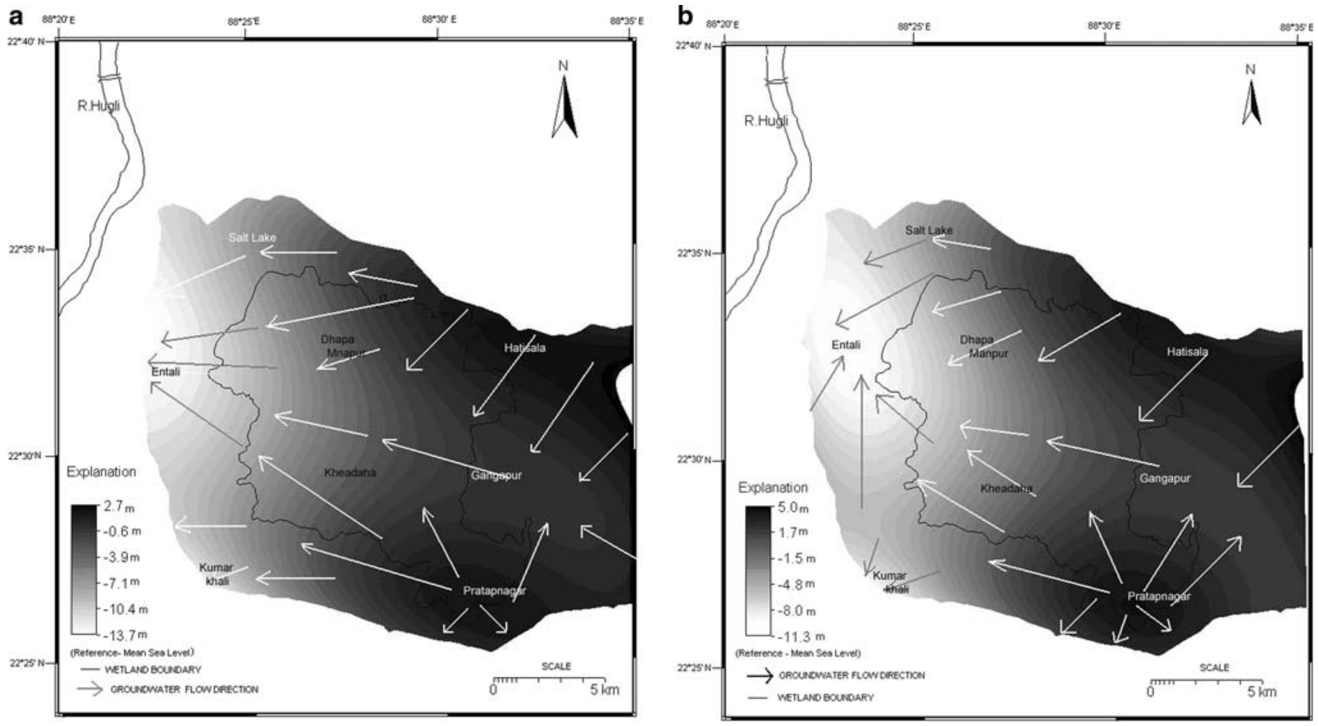

Fig. 4 **a** Fourth degree trend surface map of pre-monsoon, 2005. **b** Fourth degree trend surface map of post monsoon, 2004

in 2004 (Fig. 4b) is more or less similar to that of pre-monsoon period in 2005 except that the maximum depth of zone of depression was 11.3 m and is extended more towards south. Another trough is observed near the south-eastern corner of the area near Kumarkhali. This trough influences the groundwater flow locally and deviates the regional east–west flow to a local SSW flow.

The east–west cross section AA′ (Figs. 3a, 5a) shows the elevation of piezometric surface above mean sea level for post-monsoon in 2004 and pre-monsoon in 2005 periods. The section reveals that the groundwater occurs in a confined condition with the piezometric surface above the base of the top confining clay bed. In and around Bantala, the piezometric surface is only 0.6–1.0 m above the base of the confining bed. In this area groundwater abstraction should be restricted. Excessive groundwater withdrawal from this part of the aquifer will result in further decline of the piezometric surface. This condition may ultimately rest at a depth below the base of the confining bed and will lead to a change in the aquifer condition from a confined to an unconfined system. This will result in loss of water from the overlying aquiclude into the underlying aquifer. If this water contains toxic material then the freshwater aquifer will be polluted. Again loss of water from the aquiclude will result in volumetric compression of the aquiclude, which will be manifested at the surface in the form of land subsidence.

Another section BB′ from north to south (Figs. 3a, 5b) shows the elevation of piezometric surface above the mean sea level for post-monsoon in 2004 and pre-monsoon in 2005 periods. This section also reveals that the groundwater occurs in a confined condition with the piezometric surfaces above the base of the top confining clay bed. In and around Bamanghata, the depth of piezometric surface is 7.2–8.6 m below ground level (Fig. 5b). The piezometric surface is only 1.6 m above the base of the upper confining clay bed. Therefore, excessive withdrawal of groundwater in this area may lead to a similar condition.

Chemical quality of groundwater

Forty groundwater samples were collected from manually operated tubewells. The samples were collected in clean polyethylene bottles. Prior to collection, the sample bottles were rinsed thoroughly with the sample water. The samples were taken to the laboratory within 3 h of collection and during transportation due care was taken to protect the water samples from direct sunlight. Samples were refrigerated at 4°C and analyzed within 24 h to 3 days as per the standard methods of APHA (1985). Each of the groundwater samples were analyzed for 26 parameters such as pH, specific conductivity, TDS, total hardness, bicarbonate, carbonate, chloride, sulphate, phosphate, nitrate, fluoride, calcium, magnesium, sodium, potassium, iron, manganese, copper, arsenic, zinc, lead, total chromium, hexavalent chromium, cadmium, nickel and selenium. The chemical

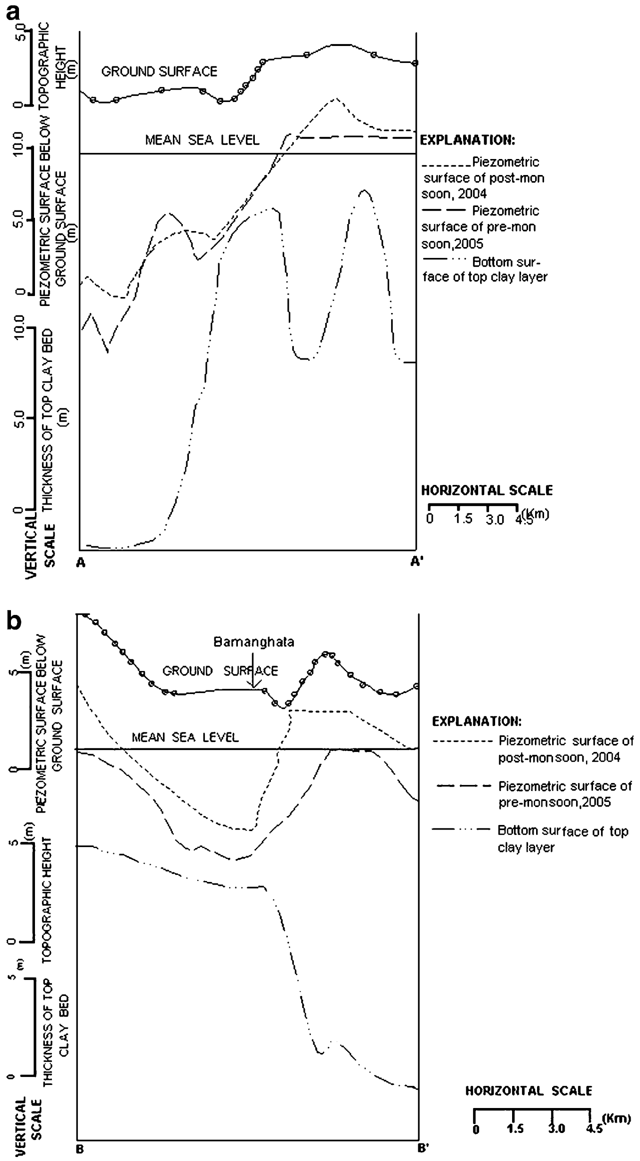

Fig. 5 **a** Graph showing east–west cross section. **b** Graph showing north–south cross section

analyses of the groundwater and the percent compliance with the Indian Standard (BIS 10500 1991) and WHO (1993) are summarized in Table 3.

To obtain a comprehensive picture of the quality of the groundwater, water quality index (WQI) is one of the most effective tools (Tiwari and Mishra 1985; Singh 1992; Subba Rao 1997; Mishra and Patel 2001; Naik and Purohit 2001). WQI is defined as a rating reflecting the composite influence of different water quality parameters. WQI is calculated from the point of view of the suitability of groundwater for human consumption.

For computing WQI three steps are followed. In the first step, each of the 19 parameters has been assigned a weight (w_i) according to its relative importance in the overall quality of water for drinking purposes (Table 4). The maximum weight of 5 has been assigned to the parameters like nitrate, arsenic, lead, chromium, cadmium and selenium due to their major importance in water quality assessment. Zinc is given the minimum weight of 1 as it plays an insignificant role in the water quality assessment. Other parameters have a weight between 1 and 5 depending on their importance in water quality determination. In the second step, the relative weight (W_i) is computed from the following equation:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}, \tag{1}$$

where W_i is the relative weight, w_i is the weight of each parameter and n is the number of parameters.

Calculated relative weight (W_i) values of each parameter are also given in Table 4.

In the third step, a quality rating scale (q_i) for each parameter is assigned by dividing its concentration in each water sample by its respective standard according to the guidelines laid down in the BIS 10500 (1991) and the result multiplied by 100:

$$q_i = (C_i/S_i) \times 100 \tag{2}$$

where q_i is the quality rating, C_i is the concentration of each chemical parameter in each water sample in mg/l, and S_i is the Indian drinking water standard for each chemical parameter in mg/l according to the guidelines of the BIS 10500, 1991.

For computing the WQI, the SI is first determined for each chemical parameter, which is then used to determine the WQI as per the following equation

$$\mathrm{SI}_i = W_i \cdot q_i \tag{3}$$

$$\mathrm{WQI} = \sum \mathrm{SI_i} \tag{4}$$

where SI_i is the subindex of ith parameter, q_i is the rating based on concentration of ith parameter and n is the number of parameters.

Water types, determined on the basis of the values of WQI, are given in Table 5.

The computed WQI values are classified into five categories as follows:

<50	excellent water
50–100	good water
100–200	poor water
200–300	very poor water
>300	Water unsuitable for drinking.

In this study, the computed WQI values ranges from 48.7 to 605.9 and therefore, can be categorized into five types,

Table 3 Comparison of groundwater quality with drinking water standards, Indian and WHO

Parameters	Range		Indian standard	Percent compliance	WHO limits	Percent compliance
	Maximum	Minimum				
pH	8.1	6.5	6.5–8.5	100	7.0–8.0	85
Sp. conductivity (micromhos/cm at 25°C)	4,500	670	–	–	–	–
Total dissolved solids	2,565	514	500	100	1,000	75
Total hardness as $CaCO_3$ (mg/l)	820	240	300	12.5	–	–
Carbonate (mg/l)	BDL	BDL	–	–	–	–
Bicarbonate (mg/l)	592	280	–	–	–	–
Chloride (mg/l)	1,550	50	250	30	250	30
Sulphate (mg/l)	117	<1.0	200	100	250	100
Phosphate (mg/l)	BDL	BDL	–	–	–	–
Nitrate (mg/l)	0.74	0.28	45	100	50	100
Fluoride (mg/l)	1.19	BDL	1	95	–	–
Calcium (mg/l)	416	71	75	15	75	15
Magnesium (mg/l)	174	31	30	0	30	0
Sodium (mg/l)	49	132	–	–	200	100
Potassium (mg/l)	12	35	–	–	–	–
Iron (mg/l)	11.7	0.18	0.3	7.5	0.3	7.5
Manganese (mg/l)	2.13	0.01	0.1	17.5	0.1	17.5
Copper (mg/l)	BDL	BDL	0.05	–	1.0	–
Arsenic (mg/l)	0.07	0.04	0.05	2.5	0.01	5
Zinc (mg/l)	7.11	0.004	5	97.5	3.0	95
Lead (mg/l)	2.28	BDL	0.05	97.5	0.01	97.5
Hexavalent chromium (mg/l)	BDL	BDL	0.05	100	0.05	100
Total chromium (mg/l)	BDL	BDL	–	–	–	–
Cadmium (mg/l)	BDL	BDL	0.01	100	0.003	100
Nickel (mg/l)	BDL	BDL	–	–	0.02	100
Selenium (mg/l)	BDL	BDL	0.01	100	0.01	100

Detection limit for copper 0.002, arsenic 0.003, lead 0.01, chromium 0.008, cadmium 0.001, phosphate 0.005, selenium 0.001, fluoride 0.005. All values in mg/l

BDL below detection limit

"excellent water" to "water, unsuitable for drinking". Although only 7.5% groundwater samples show "excellent" quality, a majority of the samples, about 52.5%, falls in the category of "good water"; 27.5% of the water samples are of the "poor" quality and "very poor" quality which is shown by 7.5% of the collected groundwater samples. Only 5% of the water samples fall in the category of "water, unsuitable for drinking". The spatial distribution of the water types is shown in Fig. 6. "Excellent water" covers only 1.8 km^2 of the total area. A majority of the area is occupied by "good water" and it covers about 153.5 km^2. The area covered by "poor water" and "very poor water" is 132.0 and 28.0 km^2, respectively. In about a 18.2-km^2 area the water is "unsuitable for drinking purpose".

In the northeastern and southeastern parts of the East Kolkata Wetlands, the groundwater is of "good" quality. In the northwestern part of the wetlands in and around Bantala the water is "unsuitable for drinking" to "very poor". In the rest of the wetland area the water is of "poor" quality.

Hydrochemical facies

Hydrochemical facies are water masses that have different geochemical attributes and are helpful for comparing the origins and distribution of groundwater. Hydrochemical facies are frequently delineated by trilinear diagram of Piper (1944) and have contributed to the understanding of flow and water quality (Back 1960; Ophori and Toth 1989; Sikdar et al. 1993; Sikdar and Bhattacharya 1999).

Based on 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 and plotting them in the trilinear

Table 4 Relative weight of chemical parameters

Chemical parameters	Indian Standards[a] (BIS 10500, 1991)	Weight (w_i)	Relative weight $W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$
Total dissolved solids (TDS)	500–2,000	4	0.0580
pH	6.5–8.5	4	0.0580
Total hardness (TH)	300–600	2	0.0289
Bicarbonate	244–732	3	0.0435
Chloride	250–1,000	3	0.0435
Sulphate	200–400	4	0.0580
Nitrate	45–100	5	0.0725
Fluoride	1–1.5	4	0.0580
Calcium	75–200	2	0.0289
Magnesium	30–100	2	0.0289
Iron	0.3–1.0	4	0.0580
Manganese	0.1–0.3	4	0.0580
Copper	0.05–1.5	2	0.0289
Arsenic	0.05	5	0.0725
Zinc	5–15	1	0.0200
Lead	0.05	5	0.0725
Chromium	0.05	5	0.0725
Cadmium	0.01	5	0.0725
Selenium	0.01	5	0.0725
		$\sum w_i = 69$	$\sum W_i = 1.000$

[a] For each parameter, lower value indicates desirable level and higher value indicates permissible level in the absence of alternate source as per BIS 10500, 1991

diagram four hydrochemical facies could be identified, for example:

Facies 1: Ca–Mg–HCO_3
Facies 2: Ca–Mg–HCO_3–Cl
Facies 3: Ca–Mg–Cl–HCO_3
Facies 4: Ca–Mg–Cl.

The relevant chemical parameters of these facies are given in Table 6. The plots of samples belonging to these facies are also shown in the Piper (1944) diagram (Fig. 7). The aerial distribution of these hydrochemical facies is depicted in Fig. 8.

These four hydrochemical facies may further be assigned to three broad types—“fresh”, “blended”, and “brackish” waters (Table 6) whose salient chemical properties are given below.

Freshwater

The “fresh”-type groundwater consists of Facies 1, which occupies 29.3 km^2 of the area. The water is relatively soft with an average hardness 348 mg/l. This type of water is relatively fresh with total dissolved solids (TDS) ranging between 514.5 and 1139.7 mg/l with an average of 737 mg/l. The bicarbonate content (average 499 mg/l) far exceeds the chloride content (average 194 mg/l).

Blended water

The water belonging to this type comprises Facies 2 (59.8 km^2) and Facies 3 (117.7 km^2) is inferior in quality compared to the freshwater type. The water is hard with an average hardness of 449 mg/l. The TDS concentration ranges from 641.7 to 1,127.2 mg/l with an average of 811 mg/l. The chloride content (average 273 mg/l) exceeds the desirable level of 250 mg/l for drinking water.

Brackish water

Groundwater of Facies 4 belongs to this “brackish” type and occupies 126.6 km^2 of area. The TDS concentration is very high ranging from 603.1 to 2,564.7 mg/l with an average of 1,159 mg/l. Chloride content (average 550 mg/l) is also very high with respect to bicarbonate concentration (average 393 mg/l). The water is very hard with a mean hardness of 621 mg/l.

Compositional structure and evolution of groundwater types

Groundwater quality is the composite of several interrelated parameters, which are subjected to local and temporal

Table 5 Calculation of WQI for individual water samples

Sample no.	$\mathrm{WQI} = \sum_{i=1}^{n} \mathrm{SI}_i$	Water type
1	157.4	Poor water
2	107.3	Poor water
3	66.5	Good water
4	49.9	Excellent water
5	75.2	Good water
6	76.5	Good water
7	310.5	Water unsuitable for drinking
8	135.3	Poor water
9	48.7	Excellent water
10	58.9	Good water
11	74.6	Good water
12	163.3	Poor water
13	180.3	Poor water
14	265.5	Very poor water
15	278.3	Very poor water
16	71.7	Good water
17	140.3	Poor water
18	605.9	Water unsuitable for drinking
19	87.5	Good water
20	231.2	Very poor water
21	89.1	Good water
22	68.9	Good water
23	45.4	Excellent water
24	65.1	Good water
25	51.9	Good water
26	83.7	Good water
27	86.8	Good water
28	104.3	Poor water
29	84.8	Good water
30	105.6	Poor water
31	97.9	Good water
32	154.8	Poor water
33	98.3	Good water
34	88.4	Good water
35	81.5	Good water
36	85.1	Good water
37	64.0	Good water
38	122.7	Poor water
39	99.6	Good water
40	126.7	Poor water

variation. Therefore, to understand the compositional data structure (in this case seven components, such as HCO_3^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+ and K^+) and to separate and estimate the relative importance of the factors controlling the chemical evolution of groundwater, Varimax-rotated R-mode factor analysis or principal component analysis (PCA) has been carried out (Usnoff and Guzman 1989; Sikdar et al. 1993, 2001). Principal components are the eigen vectors of a variance–covariance matrix. The methodology after Davis (1973) involves three steps: (i) standardization of the raw data in terms of a zero mean and a unit variance and computation of the variance–covariance matrix; (ii) computation of a set of mutually orthogonal principal component axes (the elements in each axis referred to as "loading") which are actually the eigen vectors of a variance–covariance matrix, the corresponding eigenvalues denote the proportion of variability accounted for by the respective PC axis, and (iii) computation of a set of PC scores for each of the varimax-roted factor PC axis, corresponding to individual samples. Each of the PC axis or factors (with high loadings on one or more variables) may be representing an independent source of variation in the data matrix and these may give some clues to genetic processes (Harman 1967).

Correlation coefficient matrix (Table 7) indicates the existence of several groups of significantly related parameters at 97.5% or more confidence level. Calcium, magnesium, sulphate and chloride are highly interrelated among themselves. This interrelationship indicates that the hardness of the groundwater is permanent in nature. Chloride and bicarbonate also form another group, but they are negatively related.

The PCA has been carried out using a set of data consisting of 40 groundwater samples collected from different locations of the study area. The first four factors are selected to represent the dominant hydrochemical processes, which have helped in the formation of the present groundwater chemistry without loosing significant information. The output of the PCA (Table 8) reveals that the first four eigenvalues together account for over 90% of the total variability of the combined population. PC-axes I indicate that the water-quality constituents are affected by process such as dissolution of minerals in the aquifer material, which provides calcium, magnesium, chloride and sulphate. The plots of PC-scores corresponding to PC-axes I (chloride, calcium and magnesium dependent) and II (bicarbonate dependent) (which together account for over 61% of the total variability) are shown in Fig. 9. A clear categorization of data could be made in this diagram namely "fresh", "blended", and "brackish" types.

Figure 9 shows that the "blended" water occupies an intermediate position between the "fresh" water and "brackish" water. The aerial distribution pattern (Fig. 8) of groundwater indicates that large pockets of blended water lie within the "fresh" water and "brackish" water zone. These observations indicate that the evolution of the "blended" water is possibly due to hydraulic mixing of "fresh" and "brackish" waters within the aquifer matrix and/ or in well mixing.

During the Late Quaternary period, the area of south Bengal, including the present study area, was below the sea

Fig. 6 Water quality index map

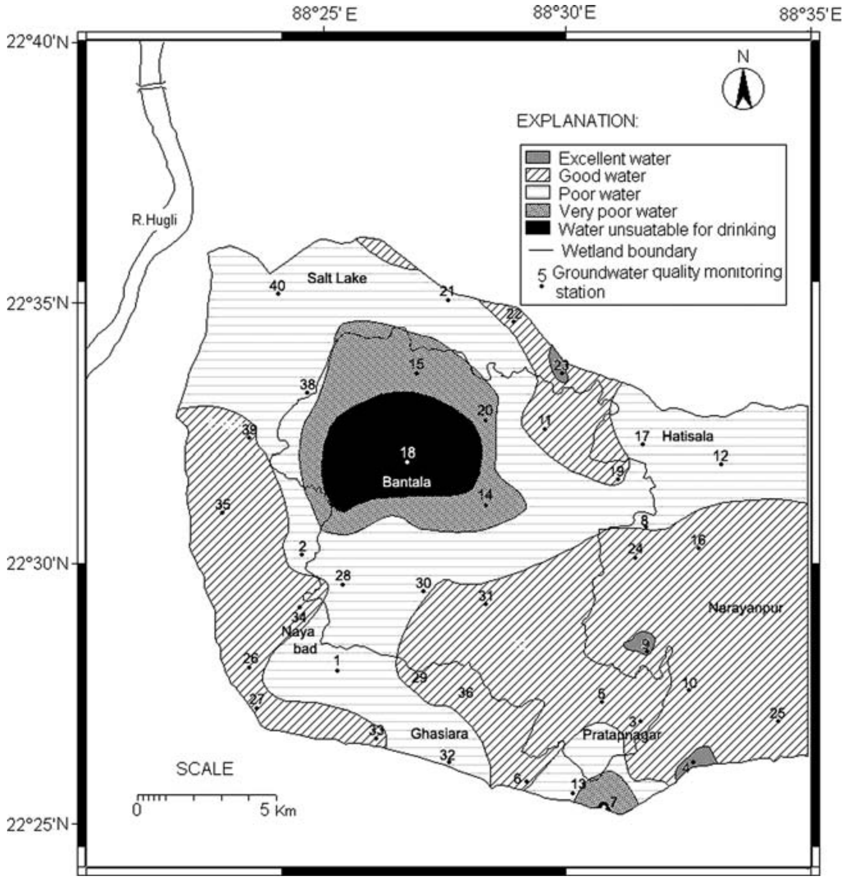

Table 6 Average composition of different hydrochemical facies

Hydrochemical facies	Cation (percent equivalent)			Anion (percent equivalent)		
	Calcium	Magnesium	Sodium + potassium	Chloride	Bicarbonate	Sulphate
Freshwater	36.2	28.4	35.4	34.6	64.4	1
Facies 1						
Ca–Mg–HCO_3						
Blended water	38.56	29.72	31.72	50.78	47.89	1.33
Facies 2						
Ca–Mg–HCO_3–Cl						
Facies 3						
Ca–Mg–Cl–HCO_3						
Brackish water	42.59	32.94	24.47	63.82	33.06	3.12
Facies 4						
Ca–Mg–Cl						

level under a marine environment (Sen and Banerjee 1990; Barui and Chanda 1992; Hait et al. 1994a, b, 1996; Sikdar et al. 2001). Later the seawater was trapped by sediments at the time of their deposition forming connate water. Later this connate water had undergone certain modification during its confinement and formed modified connate water (Sikdar et al. (2001). The modified connate water rich in chloride has been progressively diluted by influxes of freshwater. Therefore, the high chloride content of the groundwater of this area possibly represents a remnant of ocean water entrapped in the sediments during their deposition under marine conditions, which has later undergone some modification during its period of confinement (Sikdar et al. 2001). Later the confined ocean water was progressively diluted by influxes of freshwater from (i) the recharge area lying far north of the study area (Fig. 1), and (ii) infiltration of meteoric water through small pockets in the eastern region of study area where the

Fig. 7 Piper diagram showing fields of different hydrochemical facies

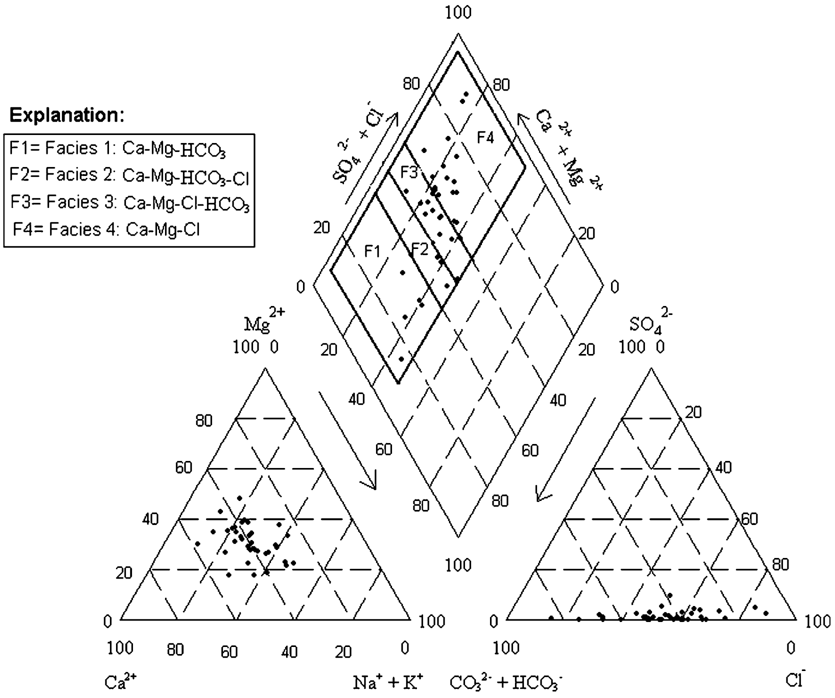

Fig. 8 Spatial distribution of different hydrochemical facies in the study area

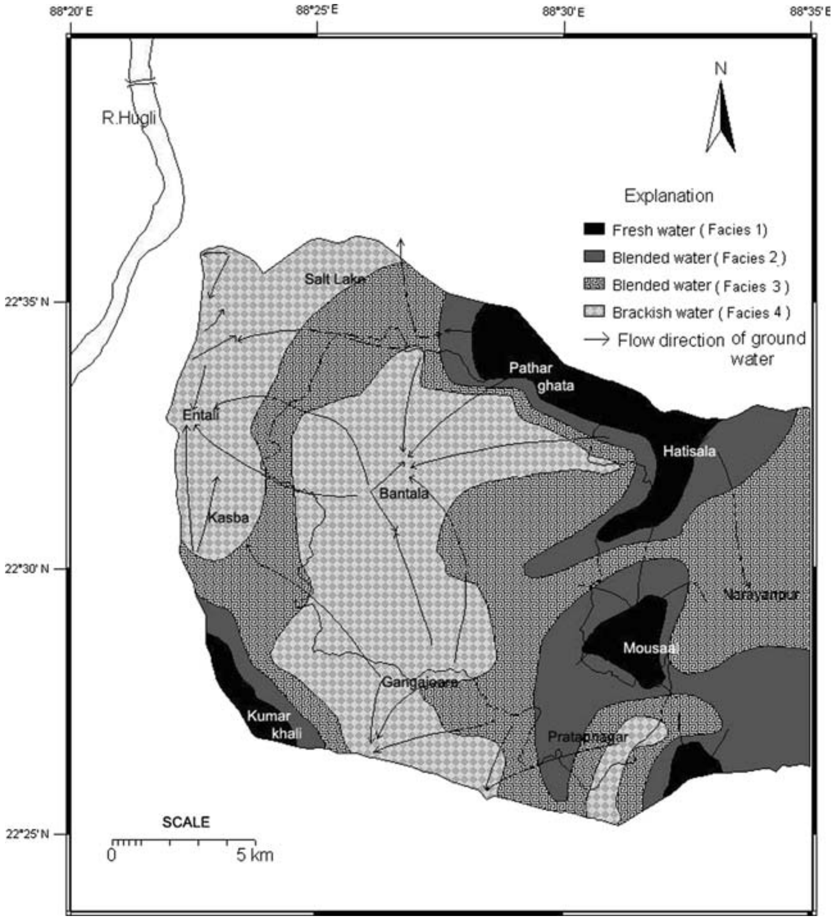

Table 7 Correlation coefficient matrix of chemical parameters of 40 groundwater samples

	HCO_3	Cl	SO_4^{2-}	Ca	Mg	Na	K
HCO_3	1.000						
Cl	–0.351**	1.000					
SO_4	–0.206	0.671*	1.000				
Ca	–0.023	0.864*	0.632*	1.000			
Mg	–0.093	0.869*	0.590*	0.836*	1.000		
Na	–0.035	0.177	0.016	0.094	0.002	1.000	
K	–0.189	0.019	–0.065	–0.095	–0.022	0.062	1.000

* Statistically significant correlation between variables at 99.9% confidence level

** Statistically significant correlation between variables at 97.5% confidence level

top clay bed is conspicuously absent or regions with "stratigraphic short cuts" where the thickness of confining clay bed is less than 10 m, resulting in the formation of the present "brackish" water. These "short cuts" and local unconfined conditions have developed due to the scouring action of several palaeo-channels of Bidyadhari river in the eastern region of this area (Fig. 2). The wide variation in chloride content in the "brackish" water indicates that the dilution process has not been uniform.

Sikdar et al. (2001) had shown greater variability in the hydrochemical facies distribution of Kolkata–Howrah aquifer, lying just west of the present study area. They identified eight hydrochemical facies, four of which are absent in the present study area. These facies are sodium dominated hydrochemical facies. Absence of these hydrochemical facies indicates medium flushing of the aquifer by freshwater. Hence, ion exchange of sodium in clay for calcium and magnesium in water by circulating water in the present study area as per the following equation is limited:

$$Ca^{2+} + Mg^{2+}(\text{water}) + Na_2\ \text{clay} \rightleftharpoons Ca + Mg\ \text{clay} + 2Na^{+}(\text{water})$$

Table 8 Principal component analysis using 40 groundwater samples

Variables	Loading on PC-axes			
	I	II	III	IV
HCO_3	–0.107	0.980[a]	–0.017	–0.105
Cl	0.931[a]	–0.243	0.144	0.0378
SO_4	0.770	–0.211	–0.046	–0.106
Ca	0.942[a]	0.099	0.070	–0.048
Mg	0.934[a]	0.0359	–0.039	0.041
Na	0.042	–0.016	0.997[a]	0.029
K	–0.037	–0.099	0.029	0.990[a]
Eigenvalue (%)	46.176	15.489	14.624	14.414
Cum (%)	46.176	61.664	76.289	90.703

[a] Variables with significant loading

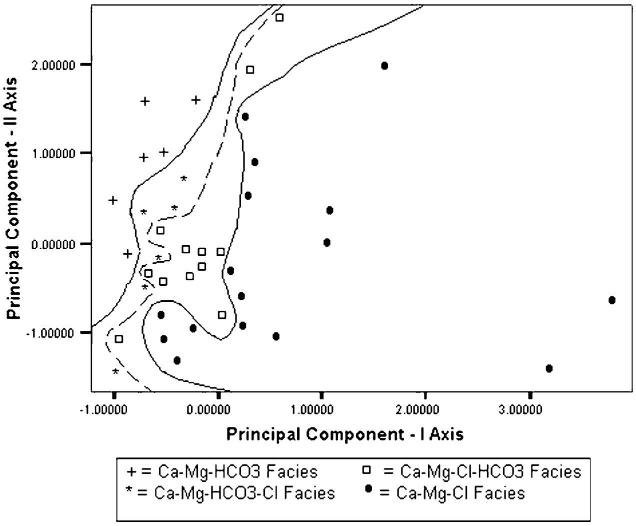

Fig. 9 Plots of PC scores for PC I versus PC II

The absence of Na–Cl facies indicates absence of zone of stagnation in the study area; therefore, groundwater movement is not restricted within the aquifer and there is a continuous flushing action by recharge which inhibits base exchange reaction between Na-ions present in clay and Ca and Mg-ions present in circulating groundwater.

Conclusion

Even though the regional topography of the area in and around East Kolkata Wetlands is more or less flat, due to various rates of groundwater withdrawal through groundwater abstraction structures at different places, local groundwater mounds and troughs have developed. These groundwater mounds and troughs determine the local groundwater flow pattern and also control the distribution of water quality of the area (Fig. 8). There is a striking resemblance between the aerial distribution of the WQI (Fig. 6) and that of hydrochemical facies (Fig. 8) within the area. All "excellent" and "good" quality water broadly coincides with freshwater (Facies 1) to blended water (Facies 2) facies, "poor" to "very poor" quality water coincides with blended water of Facies 3 type and 'water, unsuitable for drinking' matches with brackish water (Facies 4). Therefore, at the present rate of withdrawal, the groundwater in the western fringe of the area may deteriorate in quality because of flow of brackish/blended water, of "very poor" to unsuitable for human drinking quality towards freshwater zones of "good" quality. Near the southeastern boundary of the area the water type may change from excellent to good quality. In the central part, the groundwater quality may improve due to inflow of fresh/blended water of good quality towards the brackish water zone of "very poor" to "unsuitable for drinking" type.

Acknowledgments The authors convey thanks to Prof. Ashoke K Dutta, Director, Indian Institute of Social Welfare and Business Management for giving permission to publish this paper. The authors also acknowledge the help and encouragement rendered by Professor Swastik Misra, Head, Public Systems Management, Indian Institute of Social Welfare and Business Management, and for the help rendered by Mr. Surajit Chakraborty, JRF in preparation of the maps. The first author is thankful to Council of Scientific and Industrial Research (CSIR), India for their financial assistance.

References

APHA (American Public Health Association) (1985) Standard methods for the examination of water and waste water, 16th edn. APHA, AWWA, WPCF

Back W (1960) Origin of hydrochemical facies of groundwater in the Atlantic Coastal Plain. In: 22nd International Geological Congress, Copenhagen, pp 87–95

Banerjee M, Sen PK, Dastidar AG (1984) On the depositional condition of the Holocene sediments of Bengal basin with remarks on environmental condition of the soft grey clay deposition in Calcutta. Indian Geotech Conf 84(1):63–69

Barui NC, Chanda S (1992) Late Quaternary pollen analysis in relation to palaeoecology, biostratigraphy and dating of Calcutta peat. Indian Natl Sci Acad 58B(4):191–200

BIS (Bureau of Indian Standards) 10500 (1991) Indian Standard drinking water-specification. First revision, pp 1–8

Chaterji GC, Deshmukh DS, Sinha SC, Niyogi BN (1959) Some recent observations on the depth of sediment in the Ganga valley below Varanasi. Ganga Valley: a symposium. ONGC, Dehra Dun

Davis JC (1973) Statistics and data analysis in geology. Wiley, New York

Hait AK, Das HK, Chakrabarty S, Ray AK, Chanda S (1994a) Late Quaternary Palaeontological changes in coastal Digha: a note based on floral and faunal record. Indian J Earth Sci 16(2):192–198

Hait AK, Das HK, Ghosh S, Ray AK, Chanda S (1994b) On the occurrence of Mangrove biota and some faunal remains from the sediments of Haldia: West Bengal in relation to its past environment. J Palynol 30:73–78

Hait AK, Das HK, Ghosh S, Ray AK, Chanda S (1996) Environmental variations in Late Quaternary sequence of Kolaghat, West Bengal, India. Curr Sci 70(12):1089–1093

Harman HH (1967) Modern factor analysis. 2nd edn. University of Chicago Press, Chicago

Mishra PC, Patel RK (2001) Study of the pollution load in the drinking water of Rairangpur, a small tribal dominated town of North Orissa. Indian J Environ Ecoplan 5(2):293–298

Naik S, Purohit KM (2001) Studies on water quality of river Brahmani in Sundargarh district, Orissa. Indian J Environ Ecoplan 5(2):397–402

Ophori DU, Toth J (1989) Patterns of groundwater chemistry, Ross Creek Basin, Alberta, Canada. Groundwater 27(1):20–26

Piper AM (1944) A graphic procedure in the geochemical interpretation of water analysis. Am Geophys Union Trans 25:914–923

Sen PK, Banerjee M (1990) Palynoplankton stratigraphy and environmental changes during Holocene in Bengal basin, India. Rec Palaeobot Palynol 62:25–35

Sikdar PK (2000) Geology of the Quaternary Aquifers of the Twin City of Calcutta–Howrah. J Geol Soc India 56:169–181

Sikdar PK, Sarkar SS, Dasgupta S (1993) Compositional structure of groundwater in and around Gangajalhati, Bankura district,West Bengal. Indian J Earth Sci 20(1):17–27

Sikdar PK, Bhattacharya P (1999) Geochemistry of groundwater of Jhalda–II Block, Purulia district, West Bengal. J Appl Hydrol XII(2):10–22

Sikdar PK, Sarkar SS, Palchoudhury S (2001) Geochemical evolution of groundwater in the Quaternary Aquifers of Calcutta and Howrah, India. J Asian Earth Sci 19:579–594

Sikdar PK, Mondal S, Saha L, Sarkar SS, Banerjee S (2002) Environmental impact assessment of a proposed info-tech complex in East Calcutta wetlands. Environmentalist 22(4): 241–260

Singh DF (1992) Studies on the water quality index of some major rivers of Pune, Maharashtra. Proc Acad Environ Biol 1(1):61–66

Subba Rao N (1997) Studies on water quality index in hard rock terrain of Guntur district, Andhra Pradesh, India. National Seminar on Hydrology of Precambrian Terrains and hard rock areas, pp 129–134

Tiwari TN, Mishra MA (1985) A preliminary assignment of water quality index of major Indian rivers. Indian J Environ Proc 5:276–279

Usnoff EJ, Guzman A (1989) Multivariate analysis in hydrochemistry: an example of the use of factor and correspondence analysis. Groundwater 27(1):27–34

WHO (World Health Organization) (1993) Guideline for drinking water quality, 2nd edn, vol 1, p 188