A New Focus on Groundwater–Seawater Interactions
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Geoelectric and geochemical studies for hydrological characterization of Sagar Island, South 24 Parganas, West Bengal, India

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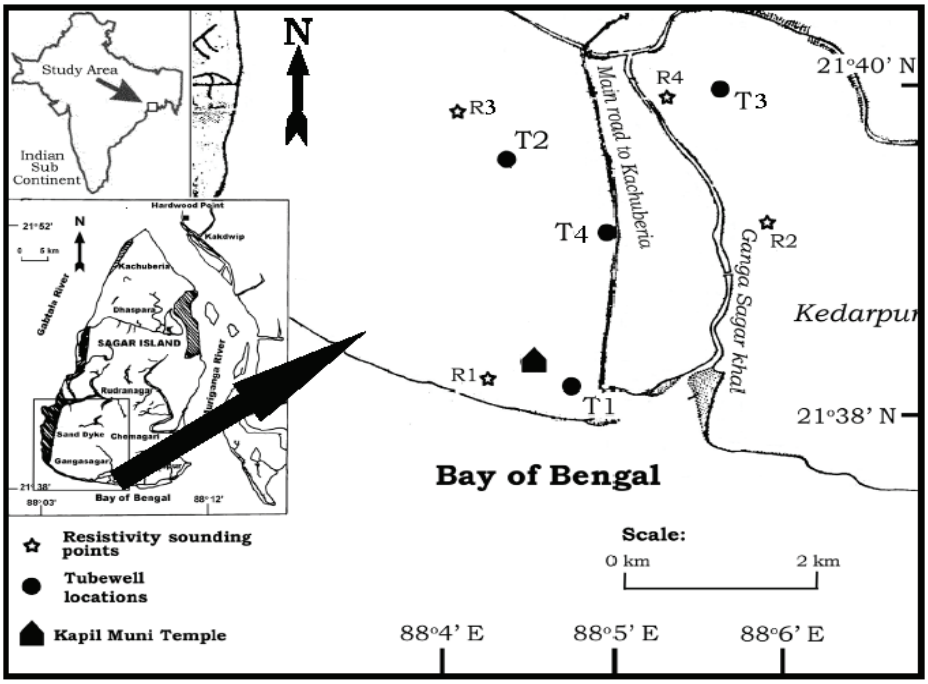
Abstract Integrated geoelectric and geochemical investigation were carried out in the Sagar Island region to assess the prevailing groundwater conditions and chemical quality of groundwater. Geologically, the area is constituted of alluvial and marine sediments of Quaternary age. Vertical electrical soundings (VES) in the area of investigation mostly show five layers consisting of topsoil, saline water, brackish water, a clay layer and freshwater-bearing zones. The VES findings show the potential freshwater-bearing zone to be of appreciable thickness at depths of 175.0 to 220.0 m under confined conditions. The surface true resistivity contour map shows the intrusion of saline water in the southern part of Sagar Island at shallower depths. The results of VES studies significantly correspond with the borehole data. Chemically, the fresh groundwater is Na-HCO_3 type with TDS ranging from 465 to 645 mg/L. The water is safe for drinking and domestic purposes but unsuitable for irrigation purposes. The concentrations of arsenic, iron, lead and mercury in the samples are below the recommended limit for drinking water of the World Health Organization (WHO).

Key words Sagar Island; Vertical Electric Sounding (VES); litho-resistivity relation; seawater contamination (SWC); freshwater aquifer

INTRODUCTION

Sagar Island, the largest island in the Ganga Delta (21°37′N to 21°57′N, 88°2′35″E to 88°11′E), is elongated in the N–S direction (~30 km) and has varying width in the E–W direction The southern portion of the Island widens to ~12 km (Fig. 1, insets). It is bordered to the north, west, east and south by the Hooghly, Gabtala and Muriganga rivers and the Bay of Bengal, respectively (Fig. 1). Sagar Island has a flat topography with no significant variation in elevation from mean sea level (~3 m). The island covers 235 km^2 and is home to 46 villages, a population of 0.20 million (Majumdar *et al*., 2002), and the "Kapil Muni" Hindu temple (near T1, in Fig. 1(a)). The village of Gangasagar has been selected as a tourist centre by the Government. For drinking water, the island is solely dependent upon the deeper aquifers at between 180 and 330 m below ground level (b.g.l.) (Das, 1991). Fresh groundwater in the deeper aquifers occurs under confined conditions and is tapped by means of small diameter tubewells fitted with hand pumps. Shallow dug wells in this area produce saline water. A geoelectric (resistivity) survey has been conducted to identify various lithological units, evaluate the groundwater condition, find potential aquifer zones, and determine the possibility of seawater contamination in and around the Gangasagar area.

(a)



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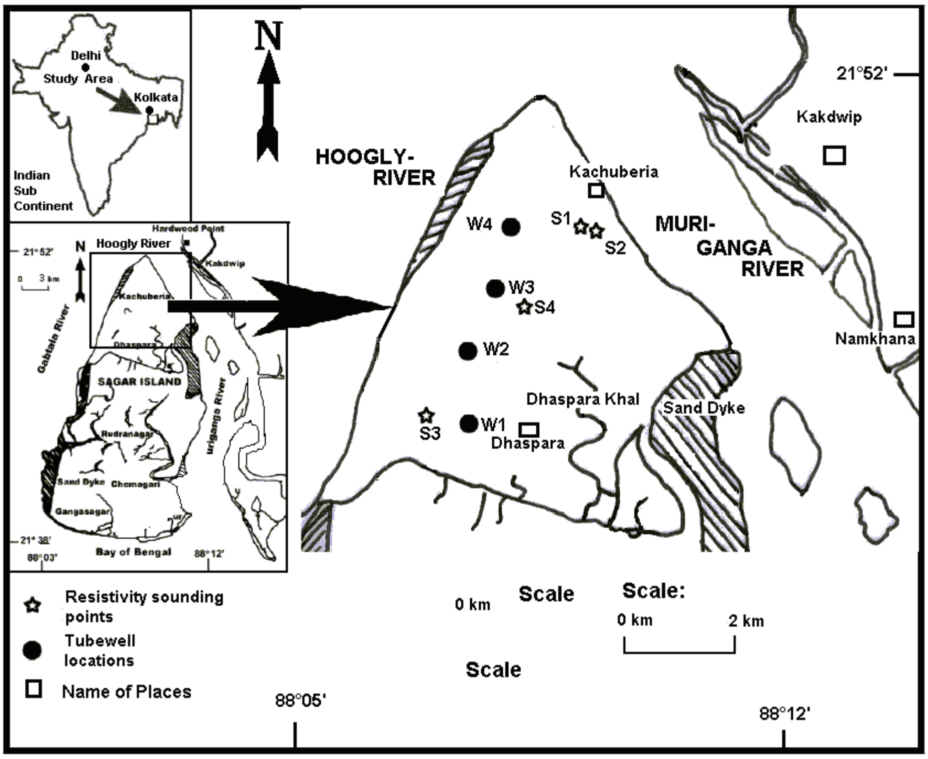


Fig. 1 (a) Southern Part of Sagar Island. Tubewell locations are as follows: T1—beside Hanuman Temple; T2—northern part of Paschim Nutungheri village; T3—Lalpur village; T4—beside Sridham Gangasagar High School. (b) (Northern Part of Sagar Island. Tubewell locations are as follows: W1—Eastern-Mandirtala; W2—inside Bamankhali Market; W3—Eastern part of Patharpratima village; W4—Pakhirala village beside main road.

GEOLOGY OF THE STUDY AREA

Sagar Island lies at the southernmost part of the Indo-Gangetic Plain, which is the largest alluvial tract in the world, and the Quaternary alluvial fill of this plain is carried and deposited by the River Ganga and its tributaries/distributaries. The Quaternary sediments of the Bengal Plain are composed of flood plain and deltaic deposits that are subdivided into two major groups (Roychoudhuri, 1974): younger Holocene and older Pleistocene alluvium. The southern extremity of the Bengal Plain is characterized by the presence of an extensive coastal belt, which Chakrabarti (1995) divided into two environmental zones. Sagar Island, being a part of this coastal belt, falls under the "macrotidal Hooghly estuary" zone. It has been established that Hooghly estuary is characterized by a broad expanse of syn-depositional fluviotidal and marine coastal sediments (viz. sand, silt and clay) deposited during the Flandrian Transgression around 6000 years BP (the on-lapping sequence) and subsequent delta progradation (the off-lapping sequence) (Chakrabarti, 1995). From the early part of this century, it underwent a destructive phase (Chakrabarti, 1992). The present day configuration of Sagar Island reveals that a number of small isolated islands, earlier separated by tidal creeks, are now welded almost into a single landmass due to gradual reduction of the width of the tidal creeks.

Coastal marshes, mangrove swamps, tidal flats, mudflats, sand dunes or ridges, marine terraces, and tidal inlets are all coastal features of this island (Paul & Bandyopadhyay, 1987).

Hydrogeology

Sagar Island is criss-crossed by numerous tidal creeks and man-made canals. These creeks, and tanks, are the main sources of surface water, which has a high hardness and salinity (Chakrabarti, 1995). In rainy seasons, the salinity of the water of the tanks decreases and becomes brackish. The average annual rainfall of Sagar Island is about 200 cm, with a mean temperature of 22°C. The area is characterized by the presence of fluvio-tidal and marine coastal facies deposits (Chakrabarti, 1991), where freshwater aquifers occur between the depths of 180 and 330 m. The upper aquifer zone contains saline water in its upper part and brackish water in its lower part. The lower aquifer zones are confined and separated from the overlying brackish aquifers by an impermeable clay layer of ~20 m thickness. The piezometric head in the freshwater zones varies from 1 to 4 m b.g.l. with the hydraulic gradient being generally towards the sea.

Geoelectric resistivity investigation

The geoelectric resistivity method has been extensively used for structural, hydrological and geothermal investigations (Stewart *et al*., 1983; Yadav & Abolfazli, 1998; Majumdar *et al*., 2000; Pal & Majumdar, 2001; Majumdar & Pal, 2005). Here, a Schlumberger vertical electrical sounding (VES) study was carried out in the southern and northern parts of the Sagar Island region to ascertain the vertical distribution of the water bearing zones within the aquifer system.

DATA ACQUISITION AND INTERPRETATION

The VES investigation was conducted at seven locations with a maximum electrode spacing of 1200 m (Fig. 1) using resistivity equipment DDR-4 manufactured by Integrated Geo Instruments and Services Pvt. Ltd, Hyderabad. The resistivity sounding curve is interpreted by a one dimensional (1-D) inversion technique using the "RESIST" software. Preliminary values of the model parameters are obtained by matching the VES field curves with the theoretical master curves and auxiliary point charts. These model parameters are subsequently used as input (starting model) in RESIST for further refinement of the results of the 1-D inversion algorithm. The resistivities of different layers and corresponding thicknesses are reproduced by a number of iterations until the model parameters of all VES curves are totally resolved with minimum RMS error. The 1-D inversion model parameters can serve as the starting model for 2-D and 3-D approaches to improve the approximation of the sub-surface geology. In such cases, 1-D interpretation is usually found to be fairly consistent with those observed in 2-D and 3-D inversions (Monteiro Santos *et al.*, 1997; Olayinka & Weller, 1997). The results of VES are interpreted in terms of the subsurface geology and aquifer characteristics under prevailing hydrodynamic conditions.

DISCUSSION OF RESULTS

Inversion results for all eight VES points were interpreted and subsequently correlated to resolve the lithological conditions. The nature and distribution of different litholog-ies along with the variation in resistivity reveals the presence of four to five layers in the region. The first layer is interpreted as alluvial clayey soil. The second and third layers represent saline and brackish water zones. Both these layers are composed of clay with silt and sand lenses. The fourth layer is impermeable clay. The most important layer is the lowermost, which is interpreted to be a sandy, freshwater zone. The freshwater zone is at a depth of 175–206 m at six sites and at 218–220 m at two sites. The freshwater zone has high resistivity values (41.0–57.3 Ωm) while the overlying saline and brackish layers have low values (0.4–1.0 Ωm, and 6.0–9.7 Ωm, respectively). Field samples have confirmed the presence of saline water within a few metres b.g.l.

A generalized borehole lithology prescribed by the Public Health Engineering Department (PHED, 1994) and Central Ground Water Board (CGWB, 1987) near Kapil Muni Temple (near VES R1) shows the presence of a clay layer with silt and sand lenses from the surface down to 204 m. Beyond 204–271 m, the formation is made up of medium to fine sand with clay intercalation, which is a potential freshwater zone. The layer para-meters interpreted from the VES studies correlate with the borehole data (Fig. 2). The true surface resistivity contour maps (Fig. 3(a)–(d)) show the intrusion of saline water in the southern part of Sagar Island at a shallow depth (20 m). Using the results of VES and borehole lithologs, a litho-resistivity relationship has been established (Table 1).

Hydrogeochemistry

A geochemical investigation was carried out to assess the suitability of the water for irrigation and drinking purposes and document any seawater/groundwater interaction.

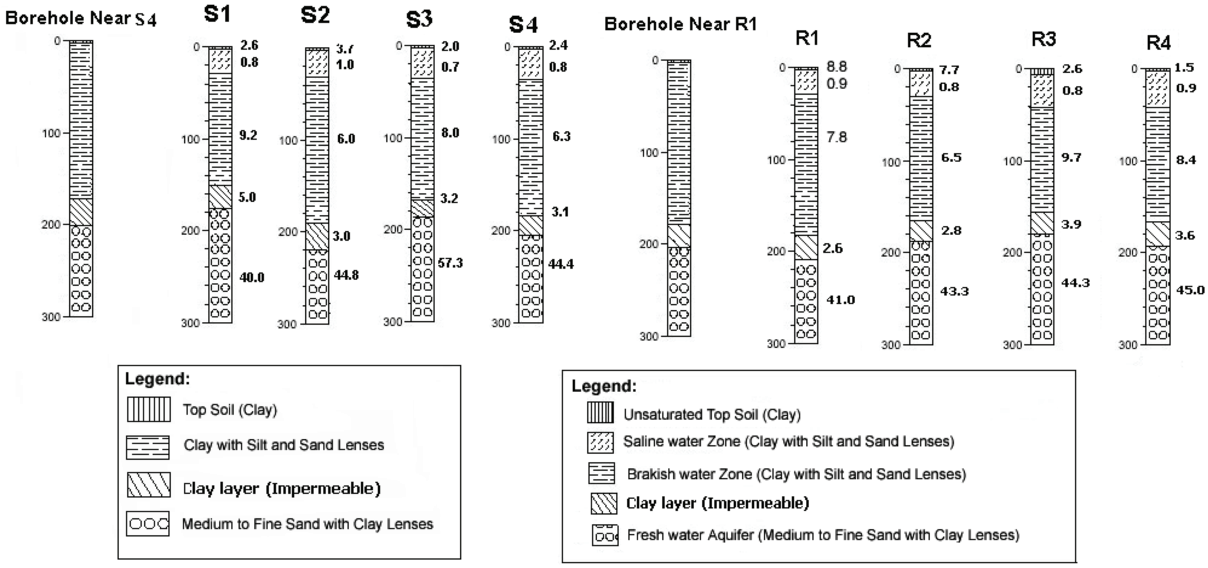


Fig. 2 Borehole lithology described by CGWB in Patharpratima Village (near to VES location S4 – northern part of Sagar Island) and combined borehole lithology by (CGWB & PHE) near Kapil Muni Ashram (near to VES location R1 – southern part of Sagar Island) and layer parameters depicting VES interpretation for different locations. Numbers on the left- and right-hand side of the logs show depth from ground level (m) and true resistivity values (Ωm), respectively.

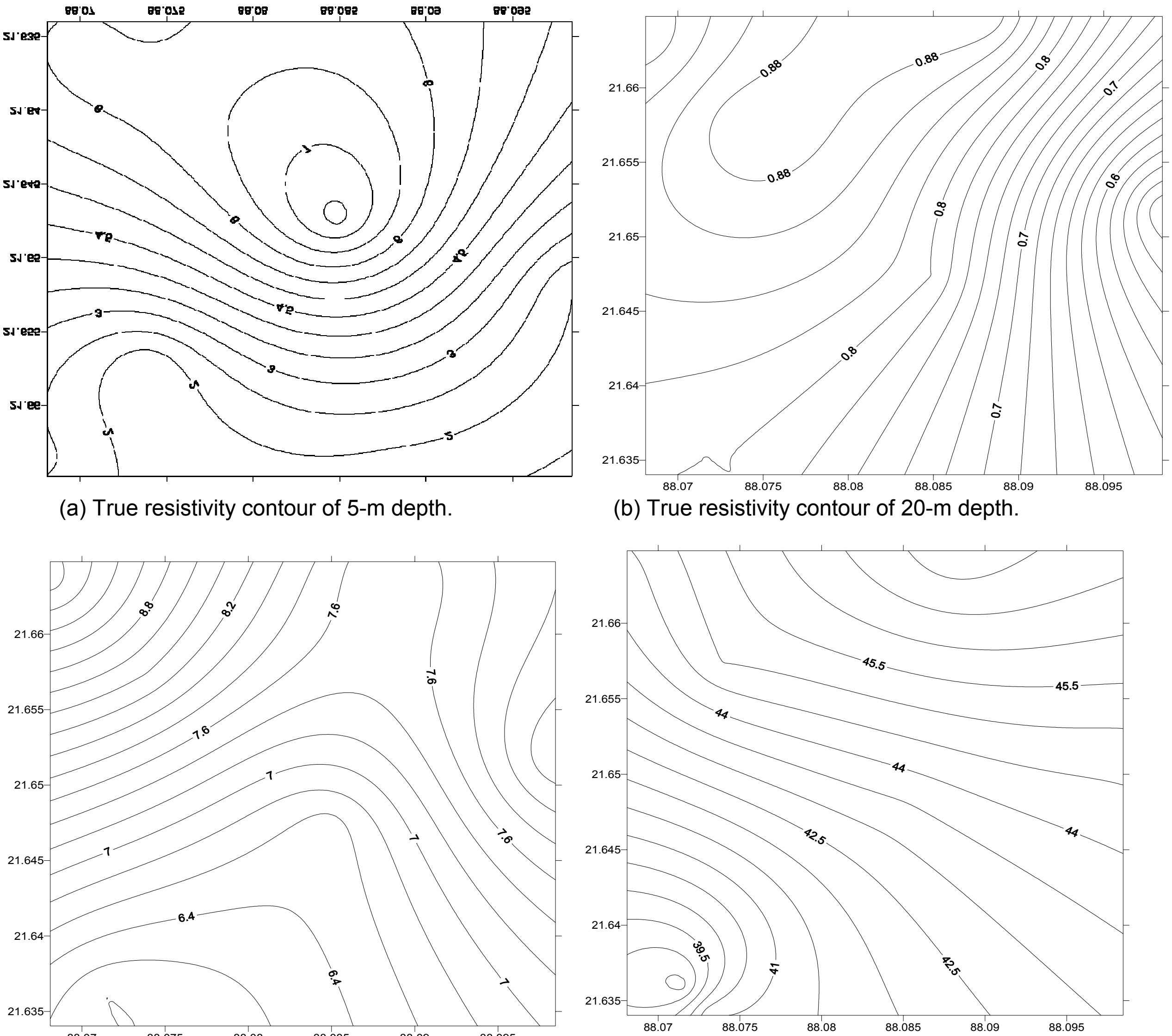
Table 1 Litho-resistivity relationship.

Probable lithology	Resistivity range
Unsaturated top soil (Clay)	1.5 to 7.7 Ωm
Saline water zone (Clay with silt and sand lenses)	0.7 to 1.0 Ωm
Brackish water zone (Clay with silt and sand lenses)	6.0 to 9.7 Ωm
Clay, grey, sticky layer (impermeable)	2.6 to 5.0 Ωm
Freshwater aquifer (Medium to fine sand with clay lenses)	41.0 to 57.3 Ωm

Eight groundwater samples were collected from tubewells from ~180 to ~330 m between 16 and 20 March 2005 (T1–T4) and 14 and 18 March 2006 (W1–W4). The water samples were collected in pre-cleaned transparent plastic bottles. Before collection of water samples, the bottles were thoroughly rinsed with the same. Concentrations of major cations, anions and some hazardous elements (present in Table 2) were measured in the chemical laboratory of the Center for Study of Man and Environment, Salt Lake, India.

DISCUSSION OF RESULTS

Total dissolved solids (TDS) contents (465–645 mg/L) clearly shows that all the samples are freshwater. TDS *vs* electrical conductivity (EC) plots show a linear trend (Fig. 4) with strong correlation (R^2 = 0.992). The ratio of TDS and EC is 0.603, which is close to the ratio (0.627) for water from sands of the Gangetic alluvium and Tarai-Bhabar (Chaterji & Karanth, 1963).



(a) True resistivity contour of 5-m depth.

(b) True resistivity contour of 20-m depth.

(c) True resistivity contour of 120-m depth.

(d) True resistivity contour of 200-m depth.

Fig. 3 True surface resistivity contour maps, Sagar Island.

Total hardness (2.497 Ca + 4.115 Mg) values indicate the waters are moderately soft (Sawyer & McCarty, 1967) and, according to WHO guidelines (2004), suitable for domestic use. The Sodium Adsorption Ratio (SAR) for all samples was calculated ($Na^+/\{(Ca^{++}+Mg^{++})/2\}^{1/2}$, all values are in meq/L) and plotted against EC (Richards, 1954) (Fig. 6) to determine the suitability of the water for irrigation purposes. The plots suggest the groundwater in the southern parts of Sagar Island are unsuitable for irrigation purpose in terms of the sodium (SAR) and salinity hazard (EC), but the groundwater from deep tube wells in the northern part of Sagar Island are suitable in terms of the SAR and Soluble Sodium Percentage (SSP).

The soluble sodium percentage [$\{(Na^+)/(Na^++K^++Ca^{++}+Mg^{++})\} \times 100$, all values are in meq/L] values (63.07–85.42) were also high, indicating the dominance of Na^+

Table 2 Chemical composition of groundwater in the Sagar Island.

Sample no.	Electrical conductivity at 25°C (μs/cm)	TDS (mg/L)	Carbonate (as $CaCO_3$, mg/L)	Bi-carbon-ate (as $CaCO_3$, mg/L)	Chloride (Cl, mg/L)	Sulphate (SO_4, mg/L)	Sodium (Na, mg/L)	Potassium (K, mg/L)	Calcium (Ca, mg/L)
T1	940.0	574.0	40	360.0	96.0	8.1	219.0	25.0	8.01
T2	1040.0	645.0	80	420.0	84.0	7.1	225.0	20.0	9.6
T3	810.0	498.0	30	385.0	44.0	0.4	190.0	16.0	11.2
T4	750.0	470.0	60	345.0	50.0	0.4	191.0	17.0	9.6
W1	820.0	502.0	0.0	353.5	76.0	0.20	155.0	20.0	22.5
W2	840.0	510.0	0.0	365.5	60.0	0.20	150.0	20.0	20.9
W3	920.0	560.0	0.0	295.8	120.0	12.1	145.0	22.0	25.7
W4	750.0	465.0	0.0	295.8	74.0	0.30	115.0	13.0	28.9

Sample no.	Magnes-ium (Mg, mg/L)	Arsenic (As, mg/L)	Iron (Fe, mg/L)	Lead (Pb, mg/L)	Mercury (Hg, mg/L)	Total hardness (mg/L, CaCO3)	SAR	Soluble sodium percent age	Residual sodium carbonate	Seawater contamina tion
T1	7.8	<0.01	0.72	<0.01	<0.001	150.0	13.2	84.29	2.75	0.72
T2	8.8	<0.01	0.38	<0.01	<0.001	60.0	12.62	85.42	3.93	0.46
T3	7.8	<0.01	0.39	<0.01	<0.001	60.0	10.67	84.44	2.59	0.33
T4	6.8	<0.01	0.35	<0.01	<0.001	52.0	11.53	85.11	3.05	0.34
W1	10.70	<0.01	0.40	<0.01	<0.001	100.0	6.74	78.44	3.79	0.36
W2	13.62	<0.01	0.35	<0.01	<0.001	108.0	6.27	76.49	3.83	0.28
W3	15.57	<0.01	0.42	<0.01	<0.001	128.0	5.56	72.85	2.29	0.69
W4	20.46	<0.01	0.33	<0.01	<0.001	156.0	4.00	63.07	1.73	0.43

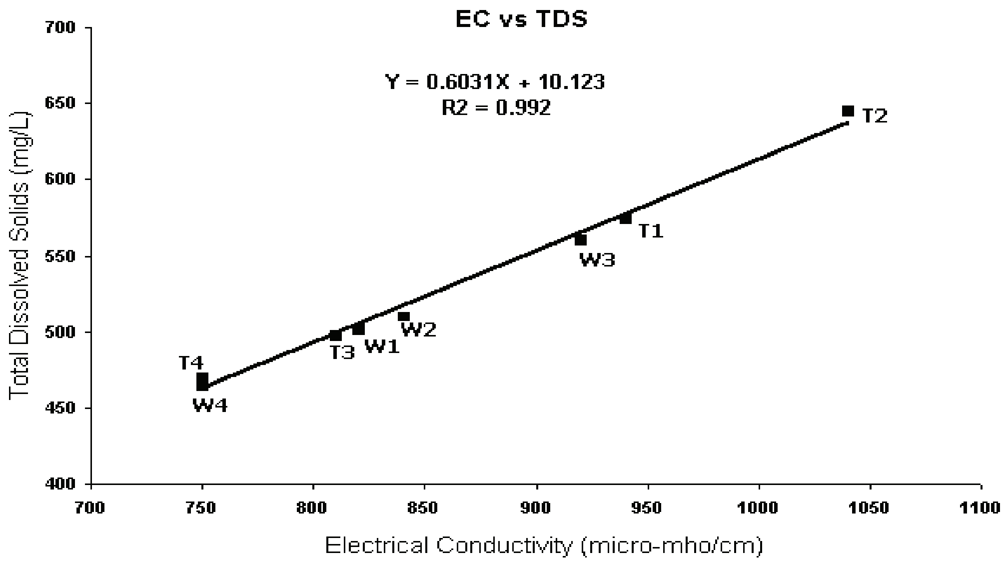


Fig. 4 Variations of TDS with electrical conductivity (EC) for groundwater samples. (at 25°C).

in the major cations. Residual sodium carbonate [$(HCO_3^-+CO_3^{--})$–$(Ca^{++}+Mg^{++})$, all values are in epm] values (1.73 to 3.93) suggest that only the groundwater in the northern part of Sagar Island is suitable for irrigation.

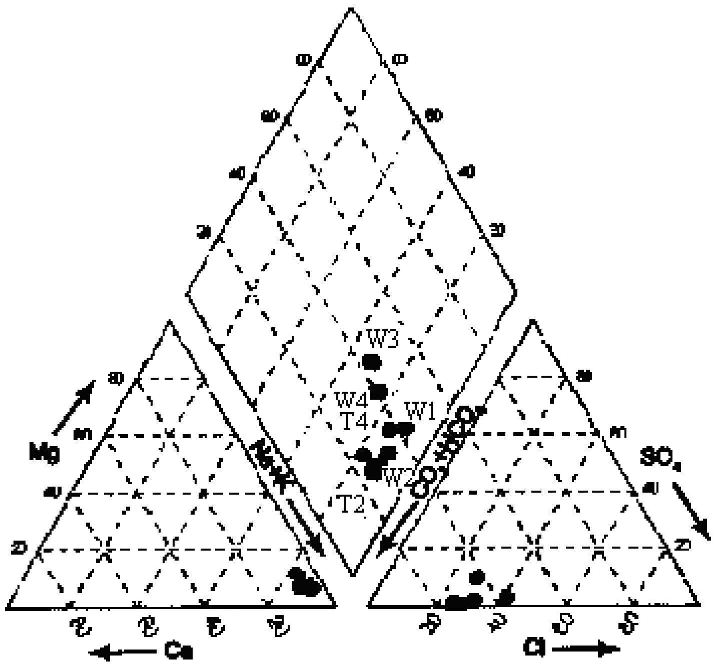


Fig. 5 Piper's trilinear diagram for groundwater samples.

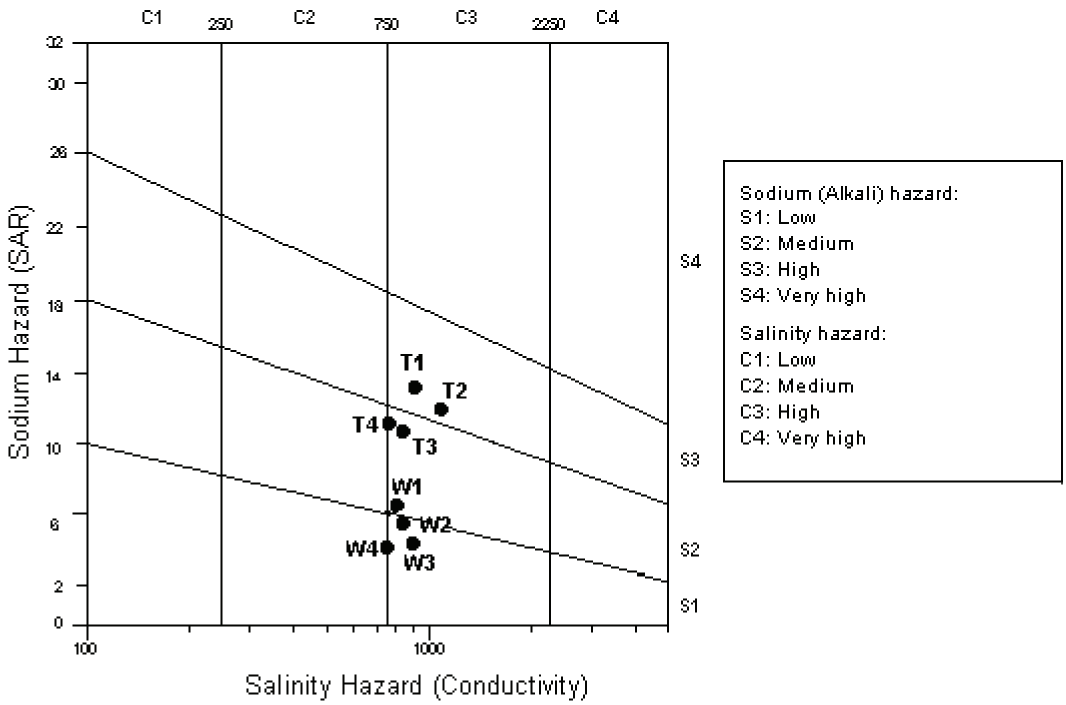


Fig. 6 Richard's diagram for classification of irrigation waters (EC *vs* SAR).

The possibility of seawater contamination is examined using the ratio $Cl^-/(CO_3^{--}+HCO_3^-)$ (all values are in epm), as suggested by Revelle (1941). The ratio is ~243 for seawater from Bay of Bengal and 0.5 for freshwater (Majumdar *et al.*, 2002).

The same ratio in the groundwater samples (0.28–0.72, with an average of 0.45). indicates that nearly all the samples are free of seawater contamination. Only the sample (T1, nearest to the sea) with a ratio of 0.72 represents slightly contaminated water. Concentrations of arsenic, iron, lead and mercury in the samples were found to be safe for drinking water purposes.

It is important to note that the Na content is higher than that generally found (20 mg/L) in groundwater (WHO, 2004). It ranges from 115–225 mg/L, with a mean of 173.7 mg/L. In two samples near the sea (T1 and T2), the Na content is higher than 200 mg/L, the acceptable limit for the drinking water recommended by the WHO (2004).

CONCLUSIONS

The following conclusions can be drawn from these integrated studies:

1. Vertical electrical soundings (VES) have delineated the topsoil, the saline/brackish groundwater zones, an impermeable clay layer and freshwater aquifers in sub-surface geological formations. The freshwater zones are at a depth of 175–206 m at six sites and 218–220 m at two sites.
2. VES findings suggest potable groundwater zones of appreciable thickness, which can be tapped for drinking water purposes. The potential groundwater-bearing zone is under confined conditions. The groundwater conditions of the region as interpreted from the VES study correlate well with the borehole data.
3. A litho-resistivity relationship was established that can be used for estimating lithologies in other unexplored areas under similar hydrodynamic conditions.
4. There is no evidence of seawater mixing with groundwater. Only one sample (T1), nearest to the sea, is slightly contaminated with seawater.
5. Groundwater of this area is of the Na-HCO_3 type.
6. The chemical quality of groundwater is safe for drinking, domestic purposes, and partly suitable for irrigation purposes.
7. Concentrations of arsenic, iron, lead and mercury in the samples are below the recommended limit for drinking water of WHO (2004).

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REFERENCES

Central Ground Water Board (CGWB) (1987) Unpublished borehole data.

Chakrabarti, P. (1991) Morphostratigraphy of coastal Quaternaries of West Bengal and Subarnarekha delta, Orissa. *Indian J. Earth Sci.* **18**(3-4), 219–225.

Chakrabarti, P. (1992) Geomorphology and Quaternary geology of Hooghly estuary, West Bengal, India. PhD Thesis, University of Calcutta, India.

Chakrabarti, P. (1995) Evolutionary history of the coastal Quaternaries of the Bengal plain, India. *Proc. Indian. Nat. Sci. Acad. A* **61**(5), 343–354.

Chaterji, G. C. & Karanth, K. R. (1963) A note on the relationship between resistivity and quality of ground water in sands of the Gangetic alluvium and Tarai-Bhabar formations in India. *Rec. Geol. Surv. India* **92**(2), 279–292.

Das, S. (1991) Hydrological features of Delta's of India. *Mem. Geol. Soc. India*. **22**, 183–225.

Majumdar, R. K. & Pal, S. K. (2005) Geoelectric and borehole lithology studies for groundwater investigation in alluvial aquifers of Munger District, Bihar. *J. Geol. Soc. India* **4**, 463–474.

Majumdar, R. K., Majumdar, N. & Mukharjee, A. L. (2000) Geoelectric investigations in Bakreswar geothermal area, West Bengal, India. *J. Appl. Geophys.* **45**, 187–202.

Majumdar, R. K., Mukharjee, A. L., Roy, N. G., Sarkar, K. & Das, S. (2002) Groundwater studies on south Sagar Island region, South 24-Parganas, West Bengal. In: *Analysis and Practice in Water Resources Engineering for Disaster Mitigation* (Proc. of International Conference on Water Related Disasters, ICWRD-2002, held at Kolkata, December 2002), vol. 1, 175–183. New Age International (P) Ltd, India.

Monteiro Santos, F. A., Andrade Afonso, A. R. & Mendes Victor, L. A. (1997) Study of the Chaves geothermal field using 3D resistivity modeling. *J. Appl. Geophys.* **37**, 85–102.

Olayinka, A. I. & Weller, A. (1997) The inversion of geoelectrical data for hydrological application in crystalline basement areas of Nigeria. *J. Appl. Geophys.* **37**, 103–115.

Paul, A. K. & Bhandyopadhyay, M. K. (1987) Morphology of Sagar Island, a part of Ganga delta. *J. Geol. Soc. India* **29**, 412–423.

Pal, S. K. & Majumdar, R. K. (2001) Determination of ground water potential zones using iso-resistivity maps in alluvial areas of Munger district, Bihar. *Indian J. Earth Sci.* **1-4,** 16–26.

Public Health and Engineering Department (PHED) (1994) Unpublished bore hole data.

Roychoudhuri. M. K. (1974) Geology and mineral resources of the States of India., Part I, West Bengal. *Geol Surv. India. Miscellaneous Publication* **30**, 1–30.

Revelle, R. (1941) Criteria for recognizing sea water in groundwater. *Am. Geophys. Union Trans*. **22**, 593–597.

Richards, L. A. (ed.) (1954) *Diagnosis and Improvement of Saline and Alkali Soils*. Hand Book 60, US Dept of Agriculture.

Sawyer, C. N. & McCarty, P. L. (1967) *Chemistry for Sanitary Engineers* (second edn). McGraw-Hill, New York, USA.

Stewart, M., Layton, M. & Lizanec, T. (1983) Application of resistivity surveys to regional hydrologic reconnaissance. *Ground Water* **21**(1), 42–48.

World Heath Organization (WHO) (2004) *Guidelines for Drinking-Water Quality, 1. Recommendations* (third edn). WHO, Geneva, Switzerland.

Yadav, G. S. & Abolfazli, H. (1998) Geoelectrical sounding and their relationship to hydraulic parameters in semiarid regions of Jalore, northwestern India. *J. Appl. Geophys*. **39**, 35–51.