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Assessment of saline–freshwater interface structure in the Indian coastal delta complexes

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Abstract The structure of the saline–freshwater interface is important in the context of estimating fresh groundwater reserves and sustainability, saline water intrusion processes and freshwater discharges into adjoining ocean basins. A method of investigating this structure using self potential and resistivity logs is presented and tested for the Mahanadi–Brahmini–Baitarni delta systems of Orissa on the Indian coast. The method involves establishing a graphical relationship between R_w (true water resistivity) and R_{we} (equivalent water resistivity) and the use of scatter trend diagrams between dissolved solids and other ions to derive and estimate ionic components for unknown zones at different depths. A three-dimensional saline–freshwater interface structure map of the study area has been derived and serves as an important tool for: (i) estimation of freshwater resources and withdrawal strategies for future well field development; (ii) understanding the processes and magnitude of saline water intrusion and developing appropriate mitigation strategies; and (iii) identifying areas with active subsurface fresh groundwater discharge channels into adjoining oceanic basins.

Key words freshwater sustainability; geophysical tool; interface/diffusion boundary; Mahanadi–Brahmini–Baitarni delta systems

INTRODUCTION

Fresh groundwater systems in the Indian coastal delta complexes constitute a very important resource for drinking, irrigation, agriculture and industrial sectors of the country and play a vital role in the growth and development of the rural base. These coastal systems are often interfaced with ocean basins on one side and upland regions with major river valleys on the other, and are subject to subsurface hydrodynamic and hydrochemical changes that cause saline water intrusion inland. Studying physico-chemical processes accompanying such intrusion, aquifer reservoir characteristics and palaeo-hydrogeological processes in different sub-systems of the deltas, would help to develop appropriate protective measures for sustained development of fresh groundwater resources.

Over the last two decades or so, the fresh groundwater resources in coastal deltas have been subjected to significant groundwater withdrawal resulting in reduction of water levels and freshwater storage potentials and causing saline water intrusion. This situation is being further threatened by possible sea-level rise due to global warming. It is therefore vital to obtain site-specific information about the existing fresh groundwater systems, their distribution and boundary conditions, and their inter-relationship with adjoining saline water bodies.

The fresh/saline water interface boundary is complex, sensitive and dynamic. This makes the strategies for well field development rather difficult and demands very accurate information in relation to: (a) the thickness of fresh/saline aquifers and their interface; (b) the nature of the interface or diffusion boundary; (c) estimates of saline/freshwater wedging and its geometrical variations; (d) depth levels for concrete plugging in the gravel packs to avoid vertical saline water inflows and mixing; (e) designing appropriate monitoring networks; and (f) assessment of possible vertical leakages through aquitards. Borehole geophysical techniques provide a reasonably powerful tool for estimation of interface/diffusion boundaries and water quality characteristics in multi-aquifer systems of coastal deltas (Jones & Buford, 1957; Radhakrishna. & Rao, 1990), and the present study applies this approach in the Mahanadi–Brahmini–Baitarni deltaic regions of the Orissa coast.

Indian coastal deltas and their groundwater potentials

Almost all of the major delta systems in India are located along the east coast, including the Ganges (West Bengal), Mahanadi–Brahmini–Baitarni (Orissa), Godavari, Krishna (Andhra Pradesh) and Cauvery (Tamil Nadu) with average rainfall and temperatures varying between 1100 and 1500 mm and 17–22°C, respectively. These delta systems are characterized by a high density canal networks and tube-well structures, and sustain as much as 60% of the irrigation and agricultural production of the country. Protection and sustainable development of fresh groundwater resources is therefore vital to economic growth.

Table 1 presents salinity and other data for different coastal delta systems in India.

Table 1 Salinity depth levels and groundwater potentials in different delta systems of the east coast of India.

S. no.	Name of the Delta	Region	Salinity depth levels (m)	Freshwater depth levels (m)	Transmissivity (m^2 day^{-1})	Usable fresh groundwater potentials (Mm^3 $Year^{-1}$)
1	Ganges (West Bengal)	Upper	Nil	0–80	800–1200	4388
		Middle & Lower	0–140	140–500	1500–3000	
2	Mahanadi–Baitarni-Brahmini (Orissa)	Upper	Nil	0–60	1000–1500	6817
		Middle & Lower	0-295	60–400	1200–2500	
3	Godavari , Krishna (Andhra Pradesh)	Upper	Nil	0–40	800–1500	8600
		Middle & Lower	0–300	0–40	1000–2500	
4	Cauvery (Tamil Nadu)	Upper	Nil	0–80	500–1200	2680
		Middle & Lower	0–150	150–300	1200–2000	

GEOPHYSICAL METHODOLOGY FOR ESTIMATION OF INTERFACE STRUCTURE

Estimation of saline water intrusion and subsurface fresh groundwater discharges into oceans are considered important in the context of sustainable development of groundwater resources systems.

Estimation of interface boundary and structure

The saline/freshwater interface or diffusion boundary can be demarcated broadly using surface geo-electrical methods and in detail from borehole geophysical logs of electrical resistivity. Estimation of true resistivity of a formation is most crucial and can be derived from an electrical resistivity log as follows:

$$R_t = F \times R_w \tag{1}$$

where R_t = true formation resistivity (Ω m^{-1}); R_w = saturated water resistivity (Ω m^{-1}); F = formation factor, which is inversely proportional to the porosity raised to an exponential power that represents void distribution.

The true resistivities of the formation and water saturated zone may be obtained if the data related to electrode spacing, mud resistivity, diameter of the borehole, apparent resistivity of the bed and formation factors are available. However, such estimations are rather complicated and could lead to several errors during the interpretational analysis. Alger (1966) demonstrated the usefulness of self potential (SP) logs for Gulf Coast aquifers and obtained good results, while Kwader (1986) estimated R_w values for Tertiary carbonate and granular formations by cross plotting saturated formation resistivity (R_0) against bulk porosity. These data, when plotted on Hingle porosity cross plots yielded graphical solutions for estimations of R_w values. The SP log profile in general is affected by several factors such as borehole diameter, bed thickness, shale/clay content of the formation, quality of the formational water, mud filtration invasion and temperature. The electrochemical potential generated in such logs is given by the formula:

$$sp = -K \log \frac{R_{mf}}{R_w} \tag{2}$$

where sp = log deflection (*mv*) against a zone ; k = a factor generally taken to be equal to 70 (but deviates marginally with borehole temperature (T) (°F) according to the relationship: 60 + 0.133 T); R_{mf} = resistivity of mud filtrate (Ω m^{-1}); R_w = resistivity of formation water (Ω m^{-1}).

The above equation is essentially based on the assumptions that: (a) both the borehole fluid and formation waters are sodium chloride solutions; (b) the shale formations are ideal ion selective membranes and the sand formations have no ion sieving properties; and (c) the borehole fluid has a much greater resistivity than the combined resistivity of the sand and shale. Although the relationship is used effectively in the oil industry, it cannot be applied directly in the water industry because the medium generally is not dominated by NaCl waters. To avoid this constraint, the following method is adopted to evaluate and quantify the water quality parameters for unknown zones at depths:

(1) A number of sites are selected for which water analyses and electrical log data are available. A linear relationship between R_w and total dissolved solids for the groundwater system under consideration is obtained.

(2) The $R_w - R_{we}$ interrelationship for NaCl and $NaHCO_3$ waters is plotted on a double log scale and the factor of deviation is obtained.

(3) Based on analytical results selected for a set of samples, scatter trend diagrams between TDS and different anions and cations are prepared. These graphical trends serve as standard diagrams for the area under consideration.

(4) R_w values for unknown zones are calculated and TDS and other ions are interpreted with the help of graphical trends. The resolution for interpretation of TDS values appears best for aquifers with R_w values between 50 ohm m^{-1} to 20 ohm m^{-1}. Beyond this boundary, data interpretation is made using the formula:

$$R_w = 10\,000/\text{Specific conductance} \tag{3}$$

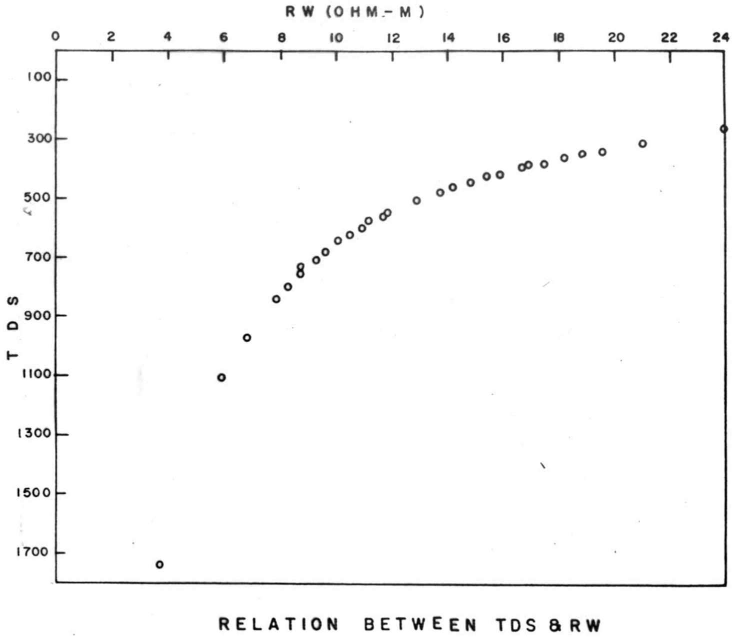

Fig. 1 Relationship between between R_w and R_{we} for the Mahanadi–Brahmini–Baitarni delta complex.

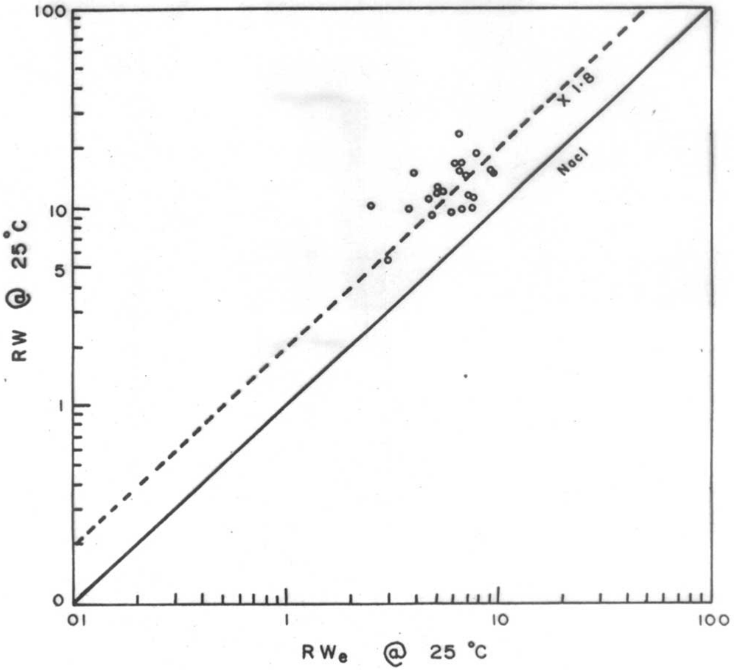

Fig. 2 Relationship between R_w and total dissolved solids for the Mahanadi–Brahmini–Baitarni delta complex.

Table 2 Results obtained from self potential log analyses.

Site and Location	Nature of aquifers	Zone depth (m)	Sp	R_{mf}	R_{we}	R_{mf}/R_{we}	R_w
South Mahanadi Delta Arilo (Long.86º13'38" Lat.20º12'15")	Fresh	0–60	+22.5	6.50	13.63	0.48	24.525
		60–96	+12.5	6.50	9.81	0.66	17.650
		96–107	–15.0	6.50	3.97	1.64	7.143
	Brackish	144–167	–15	6.50	4	1.625	3.8
		188–210	–25	6.50	2.890	2.249	2.8
		220–245	–40	6.50	1.778	3.656	1.8
Machagaon (Long.86º16'0" Lat.20º4'0")	Fresh	0–50	+22.5	5.00	10.48	0.48	18.865
		50–100	–25.0	5.00	2.20	2.27	3.954
	Brackish	108–146	–40	5.00	1.368	3.655	1.4
		172–193	–50	5.00	0.988	5.06	10.98
		196–222	–50	5.00	0.988	5.061	0.98
Patalia (Long.86º2'35" Lat.19º57'24")	Fresh	20–40	+10.0	6.00	8.34	0.72	15.006
		40–80	0.0	6.00	6.00	1.00	8.430
		80–110	– 7.5	6.00	4.69	1.28	8.430
	Brackish	122–138	– 45	6.00	1.394	4.304	2.509
		146–179	– 50	6.00	1.186	5.059	1.186
North Mahanadi Delta Jajang (Long.86º25'52"Lat.20º31'24")	Brackish	85–105	–47.5	5.90	1.24	4.76	2.226
	Fresh	105–250	–15.0	5.59	3.60		1.64
Masakani (Long.86º35'50" Lat.20º24'30")	Brackish	22–55	–20	3.15	1.646	1.914	2.692
		58–75	–15	3.15	1.937	1.626	3.487
		105–150	+20	3.15	6.029	0.522	0.852
		274–286	–20	3.15	1.646	1.914	2.692
	Fresh	290–310	–13	3.15	2.067	1.524	3.720
Adjhori (Long.86º45' Lat.20º34')	Brackish	36–44	–30	6.00	2.265	2.649	4.077
		52–62	–50	6.00	1.186	5.059	2.135
	Fresh	65–95	+10.0	6.00	8.34	0.72	15.006
		96–140	+14.6	6.00	9.63	0.62	17.330
		140–155	+29.0	6.00	15.37	0.39	27.760
		165–220	–7.5	6.00	4.69	1.28	8.430
Brahmini–Baitarni Delta Kherang (Long.86º45' Lat.20º59'30")	Brackish	120–140	–50.0	9.50	1.83	5.19	3.301
	Fresh	150–165	–25.0	9.50	4.17	2.28	7.513
		180–190	–20.0	9.50	4.92	1.93	8.356
		190–210	–20.0	9.50	4.96	1.91	8.900
		220–240	–30.0	9.50	3.54	2.68	6.374
Mandari (Long. 86º47' Lat.20º15')	Fresh	18–30	–30.0	13.00	4.9	2.642	8.82
		55–71	–35.0	13.00	4.17	3.112	7.51
		106–124	–15.0	13.00	8	1.625	14.4
		154–203	–15.0	13.00	8	1.625	14.4
Dakshinabad (Long. 20º54')	Fresh	43–53	–30.0	11.25	4.258	2.642	7.664
		89–107	–50.0	11.25	2.224	5.058	4.003
		165–198	–50.0	11.25	2.224	5.058	4.003
		199–217	–45.0	11.25	2.613	4.305	7.749
Musanga (Long.86º38' Lat.21º38')	Brackish	38–49	–50.0	3.50	0.692	5.058	1.246
		53–60	–50.0	3.50	0.692	5.058	1.246
	Fresh	110–148	–50.0	3.50	2.529	1.384	4.552
		155–214	–50.0	3.50	1.829	1.914	3.445
		278–287	–50.0	3.50	1.829	1.914	3.445

Sp, self potential; R_{mf}, resistivity of mud filtrate; R_{we}, equivalent water resistant; R_{mf}/R_{we}, ratio of mud filtrate and equivalent water resistivity; R_w, true water resistivity.

Analysis of the Mahanadi–Brahmini–Baitarni delta complex

Figure 1 depicts the relationship between R_w and total dissolved solids for the Mahanadi–Brahmini–Baitarni delta complex. The relationship between R_w and R_{we} for this delta complex is shown in Fig. 2 and the derived true resistivity (R_w) value is in the order of 1.8. Calculated interface depths are presented in Table 2.

The data have been further analysed and interpreted by constructing a set of graphical trends for TDS *vs* bicarbonates, chlorides and sulphates and also for TDS *vs* Na + K, hardness and Ca + Mg (Figs 3 and 4). The interpreted R_w values for different unknown deep zones could be further quantified in terms of TDS and different cations and anions. A comparative analysis of different hydrochemical parameters obtained from chemical analyses and interpreted *Sp* logs are presented for different well sites in Table 3.

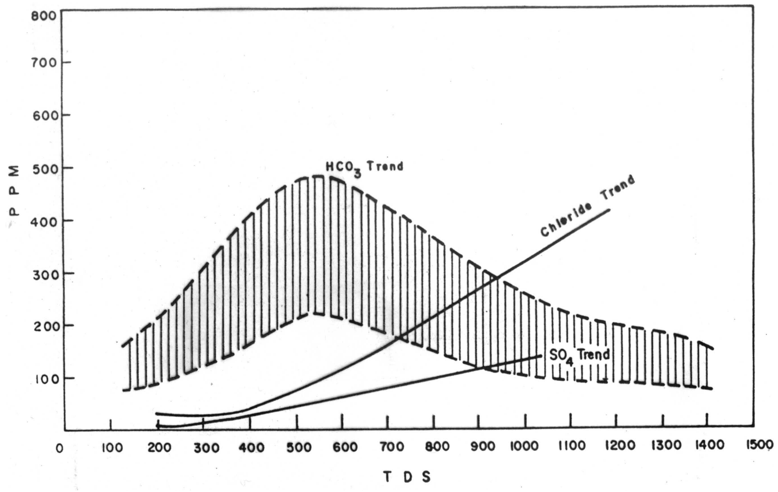

Fig. 3 Chemical activity of groundwater in the Orissa region.

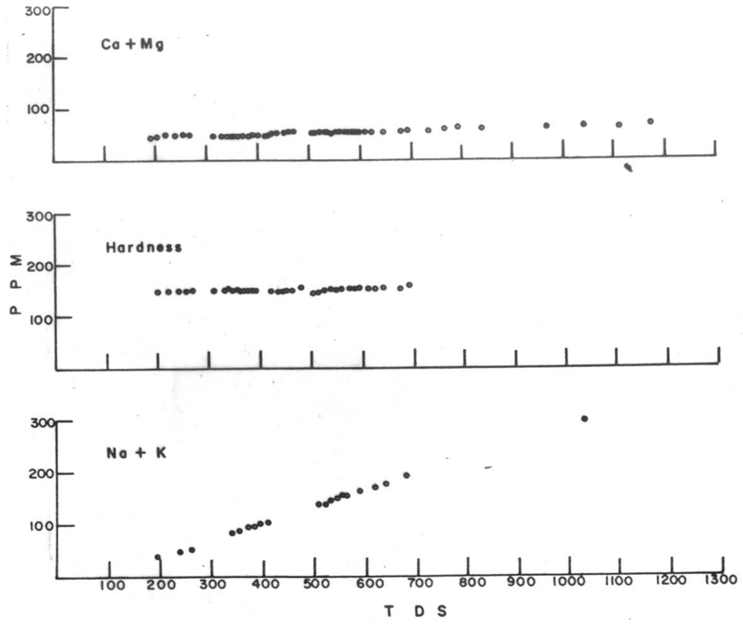

Fig. 4 Relationships between Ca & Mg, hardness and Na & K and TDS in the Orissa region.

Table 3 Hydrogeochemical parameters: laboratory and interpreted values.

Laboratory analysis of water samples (ppm)									Interpreted water qualities from sp logs (ppm)							
Well site and zone Depth(m)	Sp. Cond (μmhos cm^{-1})	TDS	Cl	SO_4	HCO_3	Ca+Mg	Na+K	TH	Sp. Cond. (μmhos cm^{-1})	TDS	Cl	SO_4	HCO_3	Ca+Mg	Na+K	TH
South Mahanadi Delta																
Arilo (69–90) F	725	471	44	–	232	45	–	135	560	365	38	20	150–372	50	70	153
(188–210) B	–	–	NDA	–	–	–	–	–	2640	1650	540	260	100–160	90	500	180
Patalia F (80–110)	1041	677	142	–	329	16	–	146	1200	780	200	95	60–387	60	220	160
(122–138) B	–	–	NDA	–	–	–	–	–	4160	2600	960	300	20–70	140	750	200
Machagoan (0–50) F	747	485	47	–	232	34	–	105	525	340	30	165	140–35	48	83	173
(108–146) B	–	–	NDA	–	–	–	–	–	3360	2100	730	340	40–100	110	800	198
North Mahanadi Delta																
Jaiang (115–200) F	1648	707	199	–	115	28	–	135	1570	1020	323	140	100–253	60	300	160
(85–105) B	–	–	NDA	–	–	–	–	–	4480	2800	1040	420	20–50	170	750	215
(290–310) F	–	–	NDA	–	–	–	–	–	2784	1740	570	260	50–125	80	560	180
Adhori (58–75) B	–	–	NDA	–	–	–	–	–	2912	1820	600	280	55–100	100	700	175
(165–220) F	983	639	180	–	165	31	–	205	1200	780	200	95	60–387	69	220	160
Brahmini–Baitarni Delta																
Kherang (120–140) B	–	–	NDA	–	–	–	–	–	3136	1960	670	280	40–100	110	700	180
(190–210) F	830	540	115	50	161	17	135	141	1015	660	150	77	195–450	52	190	160
Mandari (106–198) F	–	–	NDA	–	–	–	–	–	704	440	70	30	160–395	40	110	150
Dakshinabad (165–198) F	–	–	NDA	–	–	–	–	–	2892	1620	520	200	100–160	90	470	170
Musanga (236–272) F	–	–	NDA	–	–	–	–	–	3008	1880	640	310	58–100	110	580	192

Sp. Cond., specific conductance; TDS, Total dissolved solids; Cl chloride; SO_4, sulphate; HCO_3, bicarbonate; Ca + Mg, Calcium + Magnesium; Na + K, Sodium + Potassium; TH, total hardness; B, brackish water; F, freshwater; NDA, no data available

The above methodology has helped to define quantified water quality parameters for deeper aquifer zones in the complex coastal system of the Mahanadi–Brahmini–Baitarni delta in India. Based on these results, an interface configuration map for the entire region has been prepared and the saline water intrusion processes/mechanisms have been explained taking the flow dynamics into consideration. This methodology perhaps could be adopted in similar systems elsewhere in the world.

Saline freshwater interface structure in the Mahanadi–Brahmini–Baitarni Delta complex

The interface structure, nature of the interface and boundary conditions obviously become very important parameters in most coastal delta complexes of the world. This would form the basis for well field development and also facilitates understanding the mechanisms of saline water intrusion processes. Twelve representative well log sites have been selected where the interface boundaries are clearly identifiable (Fig. 5). The nature and characteristics of the interface at each well site are shown in Table 4.

An interface structure map based on the above data for the entire region is presented in Fig. 6. This suggests that the interface could be a hydraulic diffusion boundary with freshwater floating over saline water or a geological aquiclude/aquitard boundary with freshwater underneath the saline water. The nature of the interface and depths have to be carefully evaluated while designing the well field structures. The south Mahanadi delta region is characterized by a freshwater system sitting over a brackish water system with a diffusion boundary and with depths varying from 20 m to 100 m. The interface depth in general declines towards the coast but becomes greater

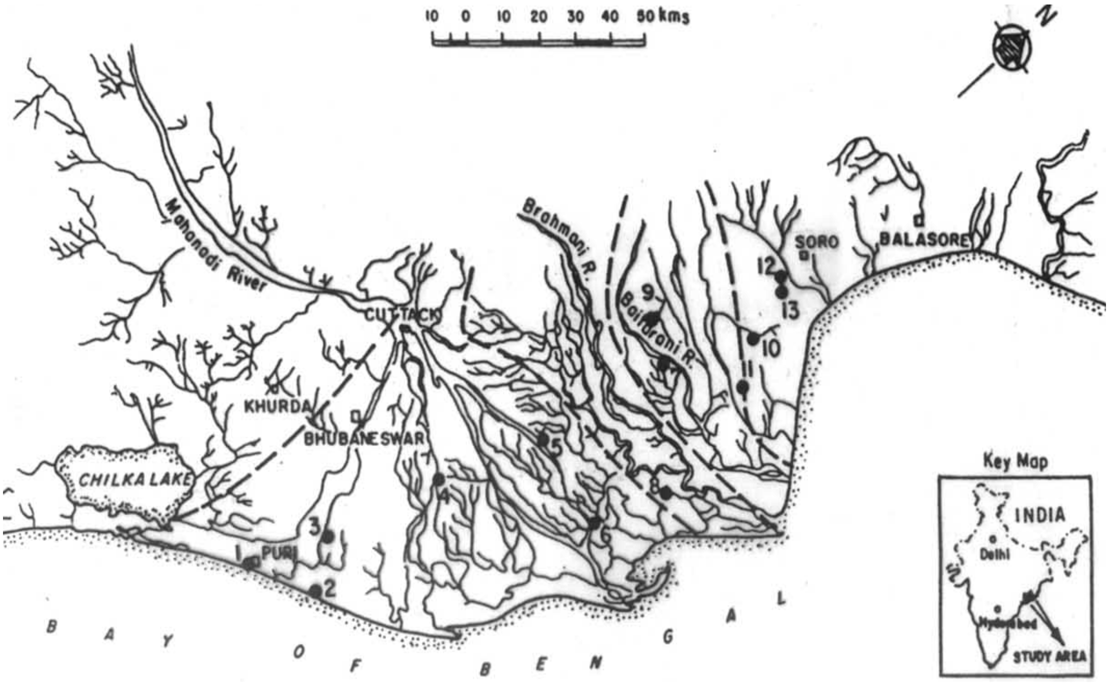

Fig. 5 Location of well log sites in the Mahanadi–Brahmini–Baitarni Delta complex, 1, Puri; 2, Konark; 3, Patalia; 4, Arilo; 5, Jajang; 6, Masakani; 7, Dubakona; 8, Madanpur; 9, Dakshinabad; 10, Musang; 11, Kherang; 12, Mandari.

Table 4 Saline–freshwater interface depths and characteristics.

Sl no.	Delta Region	Well site	Interface depth (*M*)	Nature of interface disposition
1	South Mahanadi Delta	Puri	28	Diffusion zone with freshwater overlying brackish water.
		Konark	30	
		Patalia	100	
		Arilo	100	
2	North Mahanadi Delta	Jajang	120	Aquiclude zone with brackish water overlying freshwater.
		Masakani	290	
		Dubakona	50	
		Madanpur	60	
3	Baitarni – Brahmini delta	Musanga	60	Aquiclude zone with brackish water overlying freshwater .
		Kherang	120	
		Dakshinabad	Nil	No interface—all through freshwater
		Mandari	Nil	

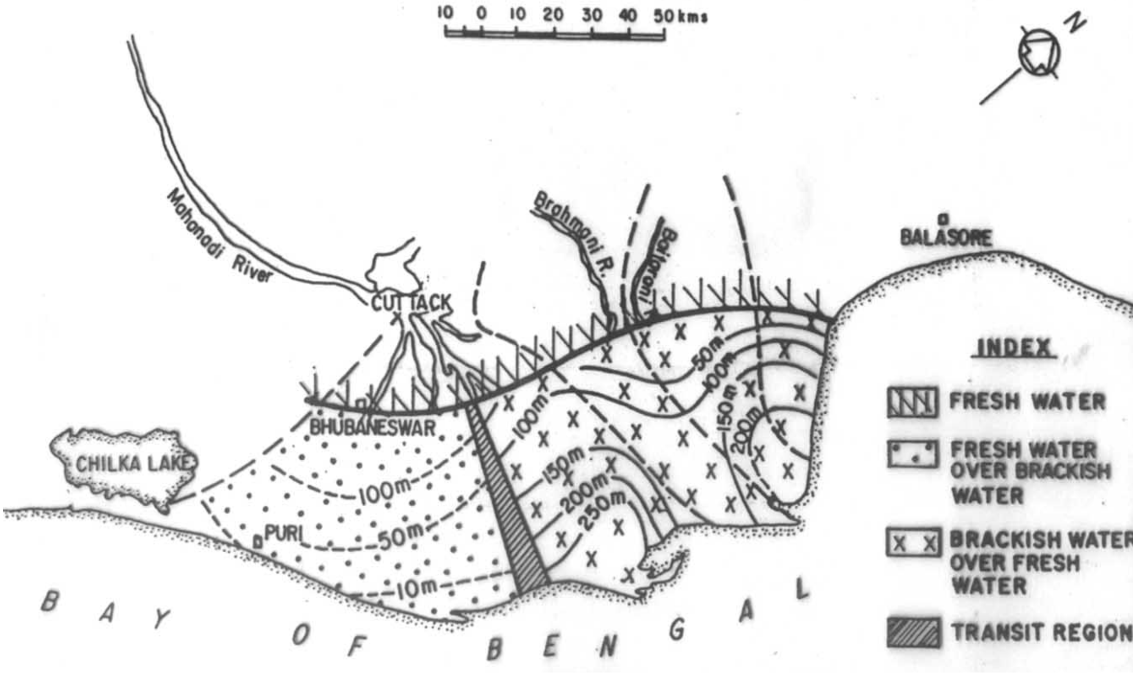

Fig. 6 The interface depth structure in the Mahanadi–Brahmini–Baitarni Delta complex.

inland. The north Mahanadi delta is represented by a brackish water system sitting over a freshwater system with aquicludes acting as an interface. This interface aquiclude is thicker towards the coast and thinner inland. It is therefore necessary in such systems to adopt cement plugging in the gravel pack area at different depths to avoid vertical migration of saline water while pumping. It is also necessary in such situations to estimate the lateral extension of aquiclude interface boundaries upstream where saline and freshwater systems come into juxtaposition, and to optimize and control the pumping without destabilizing the freshwater regime. The Brahmini–Baitarni region is also characterized by a similar disposition of the interface to that of north Mahanadi with depths varying from 60 m to 150 m. An exception is certain middle inter-stream areas where the aquifer systems are totally free from saline water at depths up to 300 m.

Saline freshwater interface/diffusion boundary—an indicator for sustainable development

Sustainable development is the most important and crucial aspect in freshwater resource systems development programmes, particularly in coastal systems where the freshwater systems are confronted by saline water intrusion problems. The sustainable development of freshwater in coastal groundwater systems is a factor related to: (a) upstream catchment hydrology, stage of groundwater development, stability of the river flow system and run off / infiltration / recharge rates; (b) the tidal impacts and sea level rise events; and (c) fresh groundwater withdrawal rates. The impacts of all these dynamic parameters could be measured through specially designed piezometers tapping both saline and freshwater aquifer systems at critical points. The reduction in recharge levels and overdraft situations would be reflected in the reduction of water levels in different piezometers in multilayered coastal systems and, at the same time, would facilitate intensification of saline water intrusion processes. Similarly, sea level rise events will endanger the near surface freshwater systems thereby reducing freshwater storage potentials. The dynamic hydrological changes described above would reflect on the vertical and lateral shifts/changes in respect of interface/diffusion boundaries and could act as a sensitive indicator for sustainable freshwater resource development programmes in coastal multi-aquifer systems.

CONCLUSIONS

(1) The self potential and resistivity logs, if obtained accurately, would help to estimate the bed boundaries and aquifer thicknesses and would facilitate quantification of ionic components in coastal multi-aquifer systems which will have immense bearing on the freshwater well field development programmes. Furthermore, they would aid the estimation of the mechanism and flow path configuration of saline water intrusion phenomenon.

(2) The interface structure map presented for Mahanadi–Brahmini–Baitrani delta region provides a useful tool for freshwater well field developmental programmes and well structure designs by minimizing failures on account of variations in water quality.

(3) The interface/diffusion boundaries, their space time variations, coupled with water level and quality changes in specially designed piezometer nests are relevant to the sustainability of freshwater resources and also to saline water intrusion phenomenon in the multi-layered coastal aquifer systems. This information may help to build the required strategies for protection and management of freshwater resource systems.

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