

Geophysical and Geochemical Approach for Seawater Intrusion Assessment in the Godavari Delta Basin, A.P., India

V. V. S. Gurunadha Rao · G. Tamma Rao ·
L. Surinaidu · R. Rajesh · J. Mahesh

Received: 8 January 2010 / Accepted: 11 August 2010 / Published online: 11 September 2010
© The Author(s) 2010. This article is published with open access at Springerlink.com

Abstract Coastal lands around Bay of Bengal in Central Godavari Delta are mainly agriculture fields and two times annually paddy crops putting in the study area. Canals of Godavari River are the main source of water for irrigation. Geophysical and geochemical investigations were carried out in the study area to decipher subsurface geologic formation and assessing seawater intrusion. Electrical resistivity tomographic surveys carried out in the watershed-indicated low resistivity formation in the upstream area due to the presence of thick marine clays up to thickness of 20–25 m from the surface. Secondly, the lowering of resistivity may be due to the encroachment of seawater in to freshwater zones and infiltration during tidal fluctuation through mainly the Pikaleru drain, and to some extent rarely through Kannvaram and Vasalatippa drains in the downstream area. Groundwater quality analyses were made for major ions revealed brackish nature of groundwater water at shallow depth. The in situ salinity of groundwater is around 5,000 mg/l and there is no groundwater withdrawal for irrigation or drinking purpose in this area except Cairn energy pumping wells which is using for inject brackish water into the oil wells for easy exploration of oil. Chemical analyses of groundwater

samples have indicated the range of salt concentrations and correlation of geophysical and borehole litholog data in the study area predicting seawater-contaminated zones and influence of in situ salinity in the upstream of study area. The article suggested further studies and research work that can lead to sustainable exploitation/use and management of groundwater resources in coastal areas.

Keywords Electrical resistivity tomography (ERT) · Groundwater quality · Bay of Bengal · In situ salinity

1 Introduction

Seawater intrusion into coastal aquifers leads to impairment of the quality of the freshwater aquifers. Excessive withdrawal of groundwater coupled by significant decrease in recharge contributes to the problem. The extent of saline water intrusion is influenced by nature of geological settings, hydraulic gradient, rate of groundwater withdrawal and its recharge (Choudhury et al. 2001). In studying the thickness and geometry of depositional systems, a common procedure is to make use of information from geological research, drilling, and exploitation boreholes. However, these methods are expensive and time consuming, preventing their use on a large scale. In contrast, geophysical measurements can provide a less expensive way to improve the knowledge of a set of boreholes (Maillet et al. 2005). For this reason, in many cases, geophysical prospecting techni-

V. V. S. Gurunadha Rao · G. T. Rao (✉) · L. Surinaidu ·
R. Rajesh · J. Mahesh
National Geophysical Research Institute,
Uppal Road,
Hyderabad 500007, India
e-mail: gopingri@gmail.com

ques can provide complementary data that enable geological correlation, even in sectors where there are no data from boreholes. Indirect geophysical methods (like electrical resistivity tomography (ERT) and VES surveys) generate continuous data throughout a given profile. It helps in understanding spatial relations between fresh, brackish, and saline water, which commonly coexist in coastal aquifers. The resistivity tomography tool has been successfully used to demarcate the saltwater–freshwater interface in different coastal settings worldwide (Bugg and Lloyd 1976; Urish and Frohlich 1990; Van Dam and Meulenkamp 1967; Zohdy 1969; Frohlich et al. 1994; Nowroozi et al. 1999; Choudhury et al. 2001). There are a variety of geophysical techniques for which it would be useful to know the subsurface resistivity in order to estimate the saline water intrusion. The large differences between the resistivity of saltwater saturated zones and the freshwater saturated zones have been used by number of investigations for determination of saltwater intrusion in many coastal areas. (Hodlur et al., 2010; Van Dam and Meulenkamp 1967; De Breuk and De Moor 1969; Zohdy 1969; Sabet 1975; Respond 1990; Ginsberg and Levanton 1976; Urish and Frohlich 1990; and Frohlich et al. 1994)

The study area forms a part of the river Godavari delta system in East Godavari District of Andhra Pradesh in India (Fig. 1). Groundwater quality analyses have been carried out for pre-monsoon and post-monsoons of 2006 from different pumping wells, open wells, and hand pumps in the area. Groundwater chemistry has been successfully employed to evaluate seawater intrusion in coastal aquifers by different authors (Pujari et al. 2009; Subba Rao. 2002; Naik et al. 2007; Saxena et al. 2002, 2004, 2005). High total dissolved solids (TDS), chloride, and sodium concentrations in the study area has prompted us to take up geophysical investigation for delineate high salinity zones through use of ERT and borehole litholog data for ascertaining the nature of subsurface geological formations. The present study was conceived to help reveal the extent and assess the seawater intrusion, if any into the coastal aquifer based on a combined analysis of geophysical and hydro-chemical data.

2 Study Area

The Central Godavari Delta is located between 16°25_ N to 16°55_ N latitude and 81°44_ E to

82°15_ E longitude with its hydrological boundaries as the river Gowthami Godavari in the East, the river Vainateyam Godavari in the west and the Bay of Bengal in the South. The study area covers about 250 km². Irrigation drainage flows to Bay of Bengal through three important drains, viz., Vasalatippa drain, Kunavaram Drain, and Pikaleru. The entire area is under the command of the Godavari Central Canal system and the canal system remains operational for 11 months during the year with a closure for 1 month for maintenance purposes. The temperature continuously increases from the end of February to the hottest month (May) to between 33°C and over 45°C in the interior. In the coldest month (January), 25°C is recorded in the coastal regions. The normal annual rainfall of the district is 1,137.6 mm distributed unevenly over 57 rainy days annually. Most of the rainfall occurs during the southwest monsoon season (June–September) contributing about 72% of annual rainfall.

3 Geology and Geomorphology

The area has rich alluvial plains formed by river Godavari and has a very gentle land slope of about 1 m/km (Bobba A. G 2002). Major part of the area consists of sandy loams and sandy clay loams (GSI 2006; Fig. 2). The quaternary sediments occupying along the coastal tract and inland river valleys include thick blankets of alluvium, gravel and colluvial deposits, beach sand, kankar, soils of various types. The fluvial deposits can be seen along Godavari River. Godavari River started discharging large amounts of sediments into the Bay of Bengal thus initiating the delta building processes during the quaternary. The upper deltaic sediments are essentially fluvial while those in the lower delta region are fluvio-marine. Three prominent lineament trends have been identified in Krishna–Godavari Deltas viz., NE–SW, ENE–WSW, and NW–SE. These lineaments are inferred to be pre-quaternary-comprising primordial weak zones that are subsequently reactivated by geotectonic movements. The NE–SW and ENE–WSW trends are rift related. A major NE–SW trending lineament from the west of Mogalturu to south of Amalapuram, which is the northern boundary of the area is interpreted to have caused a major shift in the distributaries of the Godavari River.

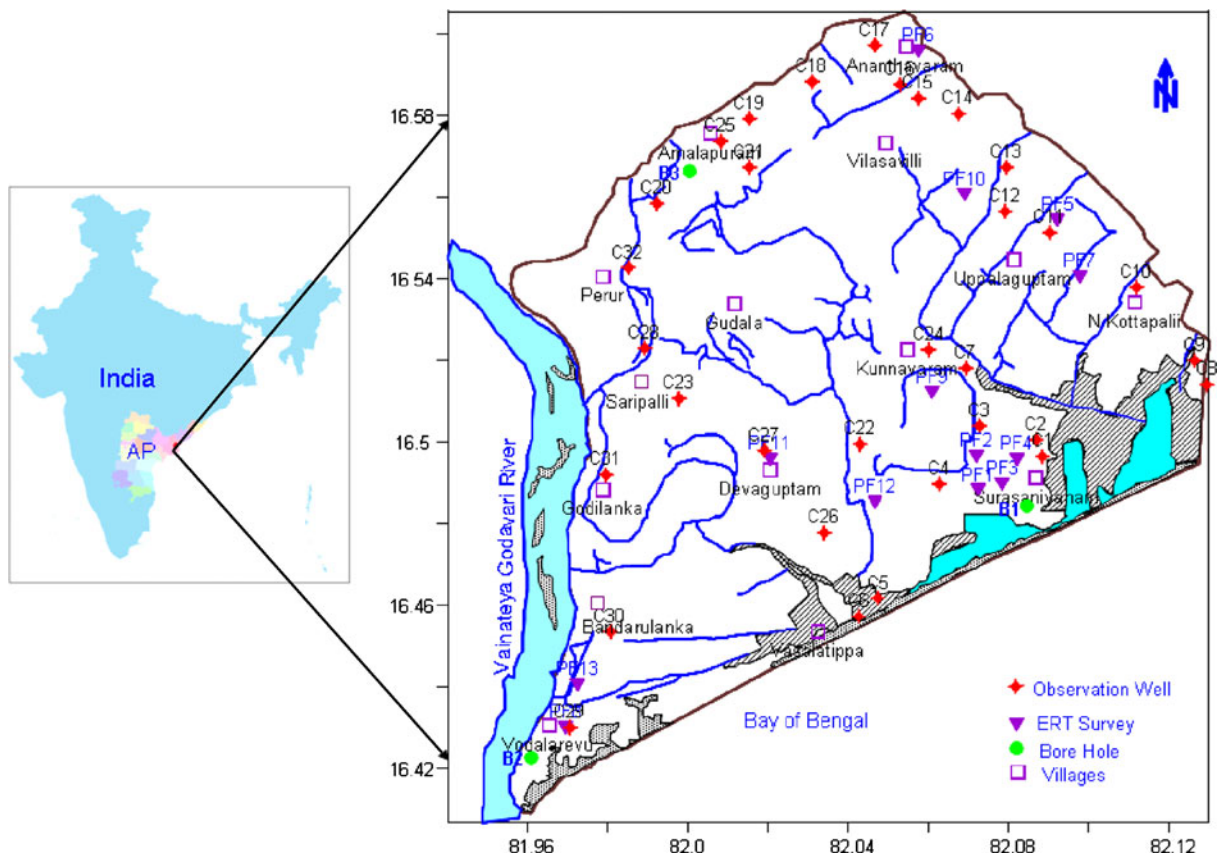


Fig. 1 Location of observation wells, ERT and bore well litholog in the study area

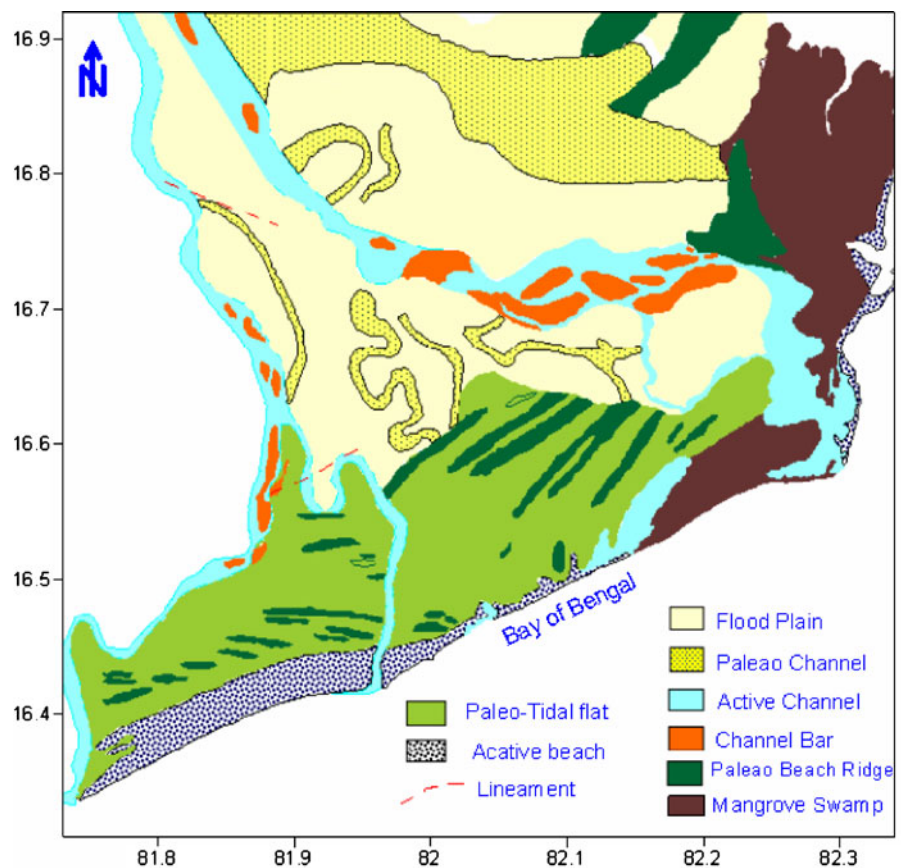
4 Materials and Methodology

A network of 32 observation wells were established in the area for monitoring water level and water quality assessment which includes pumping wells, open wells, and hand pumps. Groundwater samples were collected in 1,000 ml polythene bottles pre-cleaned with double-distilled water. The collected samples were filtered by Whatman filter paper prior to their analysis in the laboratory. The samples were analyzed for all major ions by following standard methods (APHA 2005). Water level monitoring as well as water quality analyses have been carried out for pre-monsoon and post-monsoon seasons of 2006. The groundwater quality database has been developed for analyzing groundwater conditions, if any, favorable for sea water intrusion.

The electrical geophysical prospecting method consists of determining the distribution of a physical parameter that is characteristics of the subsoil (the resistivity) on the basis of a very large number of

measurements of apparent resistivity made from the ground surface (Telford et al. 1990; Store et al. 2000). Multi-electrode resistivity survey is a combinational technique of profiling and sounding involving a number of electrodes with a fixed inter-electrode spacing. With the multi-electrode survey one can get lateral as well as the vertical information of the shallow subsurface. SYSCAL PRO-96, Incorporated Research Institutions for Seismology (IRIS)-made instrument is used to acquire resistivity data. It is a ten-channel multi-electrode automatic resistivity meter with high accuracy. Multi-core cable used with this equipment supports 5 m maximum inter-electrode spacing physically. In the data acquisition, one can use second and third spacing maximum up to nine times of physically allowed maximum spacing to acquire data from deeper levels. The measured apparent resistivity is converted in to true resistivity using RES2D.INV inversion program in order to produce the 2D resistivity cross-section image. The Multi-Electrode Resistivity Imaging system used for

Fig. 2 Geology and geomorphological features in the Godavari river delta



data acquisition was a modified version of ABEM Lund Imaging system known as IRIS Syscal Switch Resistivity meter. The data inversion was calculated with the least squares inversion method (Dahlin 1996). The output from the RES2DINV displays three sections, i.e., measured and calculated apparent resistivity pseudo-sections and the inverse model resistivity section. The pseudo-sections are a qualitative way of presenting spatial variation of the measured or calculated apparent resistivity along cross-section and do not reflect the true depth and true formation resistivity.

5 Groundwater Quality Analyses

Groundwater level and quality monitoring has been carried out by establishing 32 observation wells for pre-monsoon and post-monsoons of 2006 for providing input to the integrated data interpretation. The mean values of the parameters during post-monsoon and pre-monsoon periods for 32 wells were presented

(Table 1). The data presented shows that pre-monsoon values of most parameters elevated concentration as compared with the post-monsoon values. Most of groundwater samples indicated slightly alkaline nature with pH varying from 7.0 to 8.5. Elevated TDS concentration levels noticed around Surasaniyanam, Vodalarevu, Devaguptham, and N. Kottapalli villages. High values of sodium are also reported in the samples. Further, all the groundwater samples indicated chloride concentration exceeding permissible limit. High TDS, sodium, and chloride contents can be attributed to possible seawater intrusion in the area. High concentration of TDS, sodium, and chloride have been observed at Surasaniyanam (C2, C3, and C4), Vasalatippa (C5 and C6), N. Kottapalli (C8 and C9), Saripalli (near Gudala village) (C23), Vodalarevu (C29), Devaguptam (C22, C26, and C27) and Bandarulanka (adjacent to Vodalarevu village; C30). The elevated concentration of TDS, sodium, and chloride in samples mentioned above indicates brackishness of the groundwater. Further high TDS, chloride, and sodium concentration have been found

Table 1 Groundwater quality statistics of various chemical constituents

Parameter	Pre-monsoon (June 2006)			Post-monsoon (November 2006)		
	All values in mg/l, except pH			All values in mg/l, except pH		
	Min	Max	Average	Min	Max	Average
pH	7.4	8.9	8.1	7.5	8.8	8.0
TDS	274	12,768	5,262.4	572	8,858	3,310.1
Na	24	7,590	2,419.8	24	2,725	761.0
Ca	12	816	82.1	12	160	53.7
K	2	803	224.7	2	562	99.0
Mg	0	4	0.1	0	5	0.2
Cl	57	2,741	871.3	64	2,912	890.4
F	0.25	0.95	0.6	0.25	1.02	0.7
SO ₄	20	220	57.8	20	140	63.1
NO ₃	0.5	18	2.9	1.1	22	3.7
HCO ₃	37	220	109.2	61	1,037	238.4

in Amalapuram (C19, C20, C21, and C25), Anantavaram (C14, C15, C16, C17, C18) and Perur (C28 and C32) villages due to the in situ salinity of the overlying clay formations. In the area where canal irrigation is dominant, considerable leaching of clay minerals has taken place in the shallow aquifers (CGWB 1999). Among all the parameters potassium, magnesium, and fluoride have reported normal concentrations whereas HCO₃, Ca, and NO₃ (as N) are found with elevated levels. On other hand, considerable amount of HCO₃ and Ca reflect the contribution of from water–rock interaction, while the occurrence of relatively large amount of NO₃ in many samples also reflects influence of anthropogenic pollution. The statistical analysis of various constituents in groundwater estimating minimum, maximum, and average values generally reflected that most of the samples possess brackish water. Comparison of TDS, sodium, and chloride ionic concentrations during pre-monsoon and post-monsoon indicates a reduction during post-monsoon due to leaching action of rain water as well as return flow from irrigation. Reduction of sodium concentration in groundwater from pre-monsoon to post-monsoon also indicates influence of canal irrigation and rainwater recharge in the delta. There is a slight reduction reported as regards the chloride concentration during the same period. Depth to groundwater level is varying from 1 to 12 m below ground level. The fluctuation of groundwater level from pre-monsoon to post-monsoon is hardly <2 m only. The groundwater level contours from post-

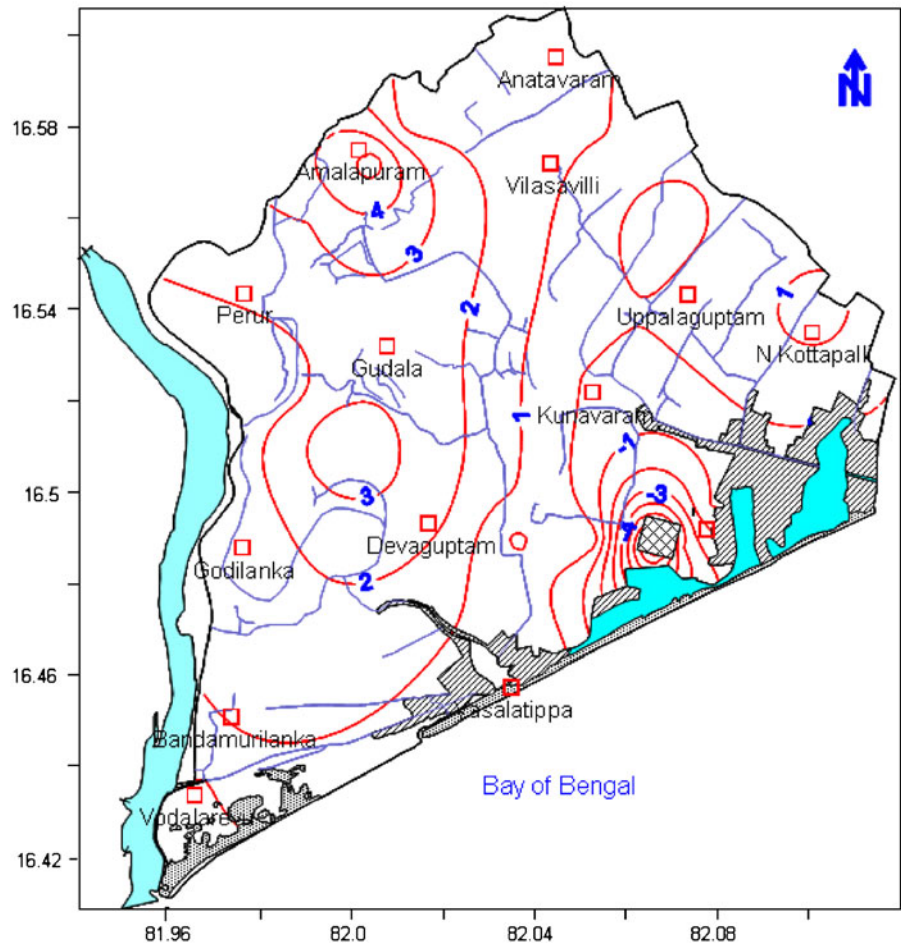
monsoon and pre-monsoon of 2006 indicated that the groundwater flow is predominantly towards the Bay of Bengal (Figs. 3 and 4).

6 Geophysical Investigations

Multi-electrode resistivity imaging surveys have been carried out at 13 locations in the study area (Fig. 1). Resistivity data was collected using the Wenner–Schlumberger array as the array represents adequate signal/noise ratio, an important parameter in low resistivity environments, while it also provides adequate resolution (Ward 1989). The RMS error computed for iterations of resistivity data has been found varying from 6.4% to 15.6% in the inverse model resistivity sections. Delineation of various subsurface layers like marine clays as well as in situ salinity of formations up to a depth of 45 m only has been inferred. In the coastal areas, the principal aquifers have formed in the unconsolidated alluvial formations, deposited under various sedimentary environments. The geoelectrical profiles (Fig. 5) shown resistivity values that varied laterally with depth, in the vertical aspect, two levels could be distinguished in accordance with the resistivity values obtained.

Regional picture of in situ salinity of marine clays in the area has been ascertained from the electrical resistivity images profile (PF)1, PF3, PF6, PF7, PF8, and PF11 (Fig. 5). The inter-electrode spacing of 5 m

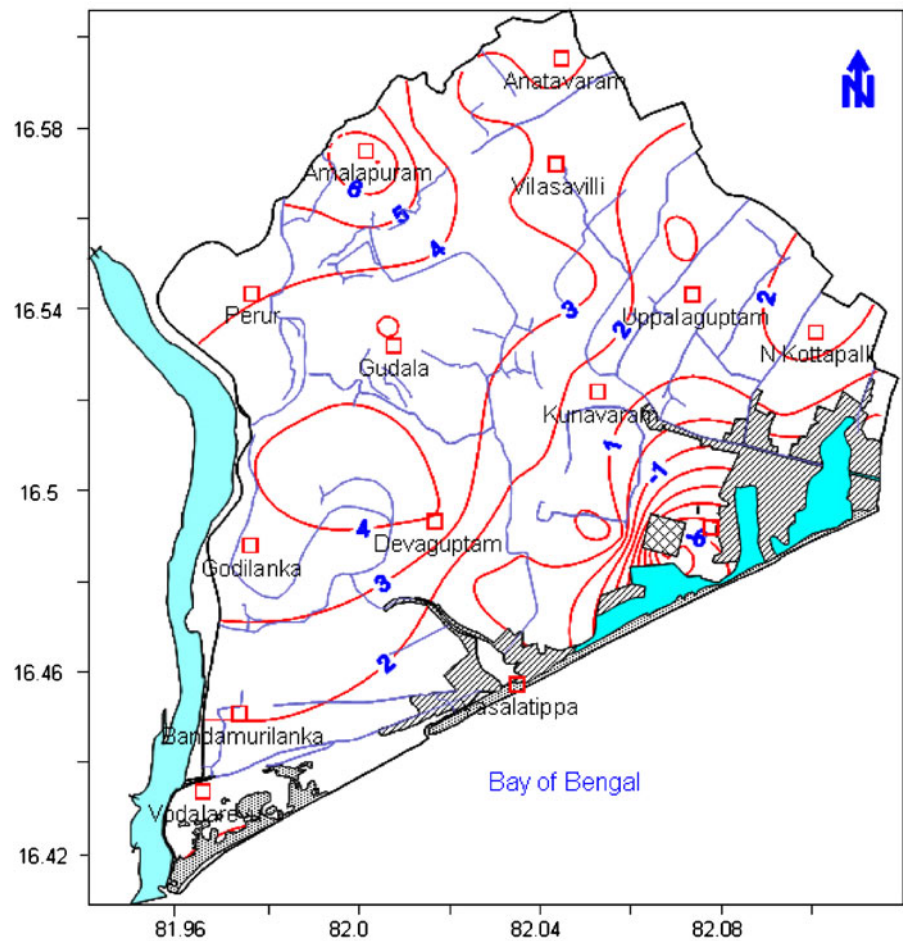
Fig. 3 Groundwater level contour (amsl)—pre-monsoon June 2006



was maintained throughout the profile of 280 m. PF1 is (E–W oriented) performed near Ravva Onshore terminal and in electrical resistivity image (PF1), the upper part was showing a low resistivity range $\sim 5\text{--}20 \Omega\text{m}$ up to 12 m depth. There was a second level with low resistivity values below $1 \Omega\text{m}$ between 12 and 28 m depth. This was indicating in situ salinity of marine clays around Ravva onshore terminal with resistivity $>1 \Omega\text{m}$ and at depth of the formation the image indicated slightly higher resistivity layer in the range of $1\text{--}4 \Omega\text{m}$, which may be indicating a clay formation. PF3 is (E–W oriented) also performed near Ravva Onshore terminal. Image PF3 is indicating very low resistivity $<1 \Omega\text{m}$ up to the depth of 19 m and second layer is having resistivity range of $1\text{--}4 \Omega\text{m}$ up to the depth of 22 m. Resistivity $>10 \Omega\text{m}$ in the underlying formations at the bottom represent unconsolidated sand with hard material or gravels. Profile 6 was carried out in Anantavaram village and oriented

in a NE–SW direction. The ERT image showing a very low resistivity $<1 \Omega\text{m}$ up to the depth of 45 m. This may be indicating thick deposition of marine clays in the area. PF7 was oriented in NE–SW direction and carried out in Uppalaguptam village. High resistivity $\sim 500 \Omega\text{m}$ was found in the top of the section of ERT extending up to the depth of 16 m. In the NE portion of the image, slight increase in the resistivity up to the depth of 30 m indicates the presence of consolidated sand with gravel. Further below a second layer with low resistivity of $<1 \Omega\text{m}$, representing sand with saturated clay formation up to the depth of 45 m was found in the ERT profile. The PF8 in Vodalarevu village and oriented in E–W direction indicated high resistivity ranging $5\text{--}20 \Omega\text{m}$ in the top may be that the top soil and sandy clay formation up to the depth of 10 m in East portion of the image and it is slightly decreasing depth towards west up to 5 m. Further underlying clay formation

Fig. 4 Groundwater level contours (amsl)—post-monsoon November 2006



with resistivity of $<1 \Omega\text{m}$ extends up to the depth of 45 m. ERT PF11 in Devaguptam village and oriented in NE–SW direction showing a very low resistivity $<1 \Omega\text{m}$ up to the depth of 20 m and the second layer has a resistivity of $\sim 1 \Omega\text{m}$ up to the depth of 35 m. The zone may be representing saturated sandy clay formations.

7 Correlation of Geoelectrical Imaging with Borewell Lithologs

Available three borehole litholog data presented here which were drilled at Amalapuram, Vodalarevu and Surasaniyanam by CGWB (Fig. 6). In general, in most cases the resistivity of saline water aquifers is very low ($<10 \text{ m}$). The major part of the study area consists of sandy loams and sandy clay loams (Bobba 2002). A complex situation could be seen due to presence of clay layers. The resistivity of marine clay

has been found to be $<1 \Omega\text{m}$. It becomes difficult for identification of saline water layers within the clayey formation which may contain fresh water. If both of them are present in the sub-surface, ambiguity increases. Resistivity data interpretation of freshwater and saline water aquifers can become more reliable if it is supported by better geophysical anomalies, which can resolve the two aquifers more efficiently. Comparative data analyses of borehole log data and geoelectrical profile data accomplishes the objective (Hodlur, et al. 2010). Comparison of the ERT image (PF1) and borehole lithology of B1 indicate that there is good agreement. The profile up to 12 m depth with a very low resistivity in range of 3–20 Ωm has been observed gives a representation of the top soil and sand within the clay formation. The second layer is encountered between 12 and 28 m was a clay formation saturated with saline water ($<1 \Omega\text{m}$). The third layer at depth up to 45 m is a medium grained sand and clay formation. Comparison of the Image

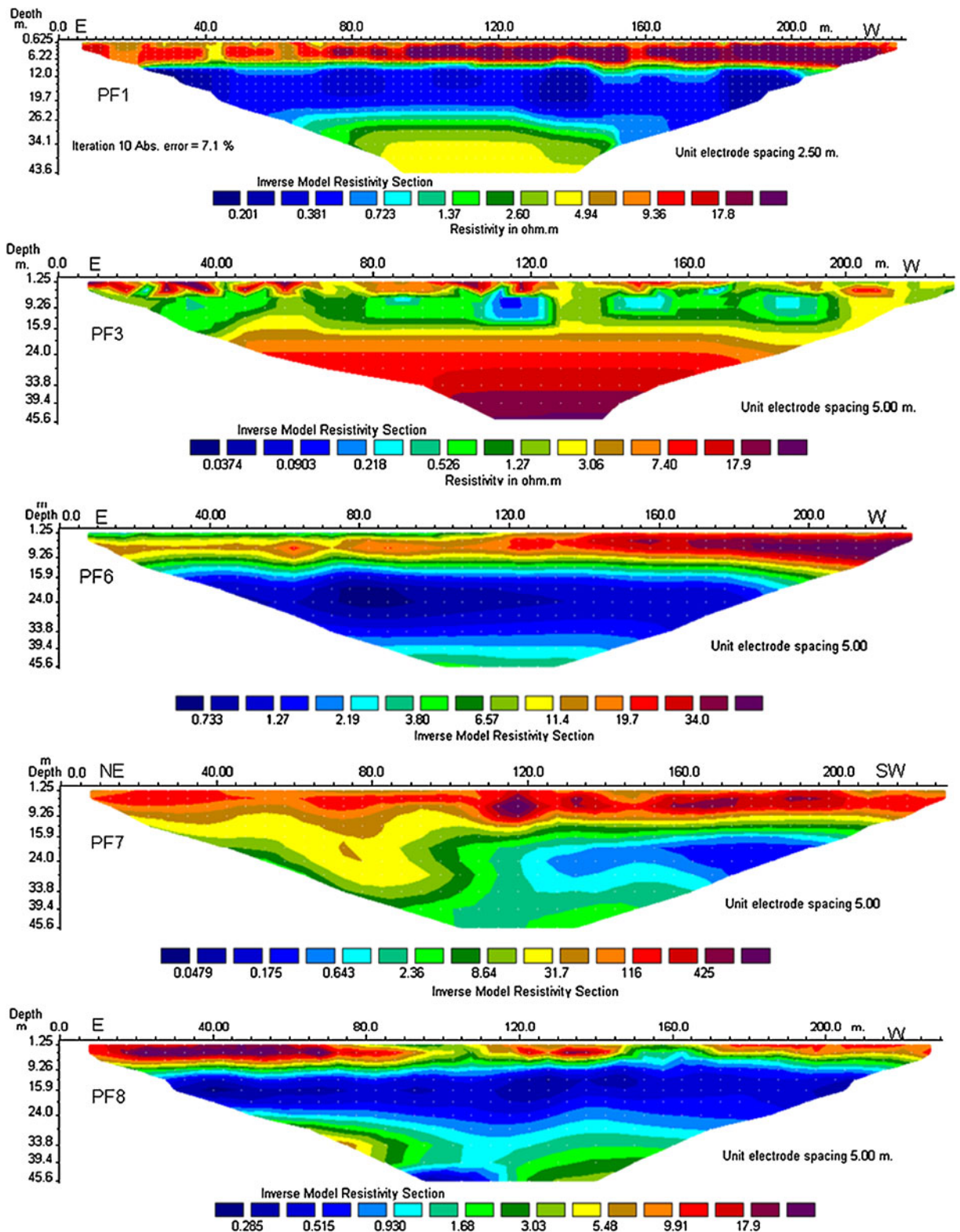


Fig. 5 Inverse model resistivity section of electrical resistivity tomographic profiles (PF1, PF3, PF6, PF7, PF8, and PF11)

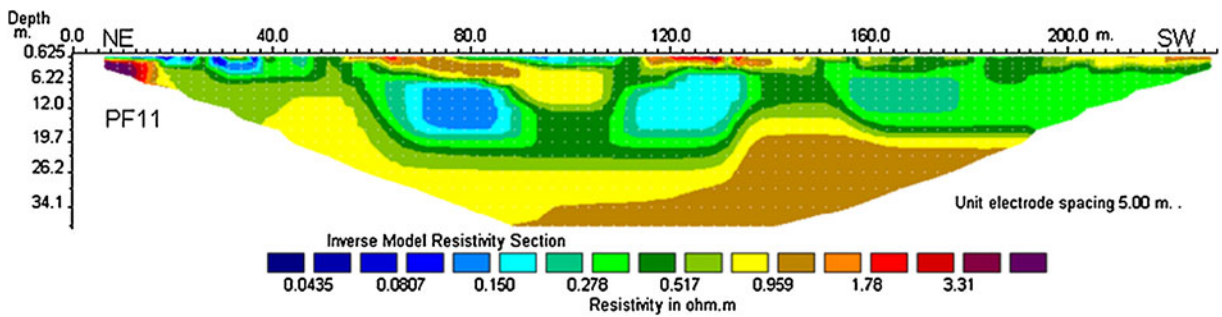


Fig. 5 (continued)

PF8 with the borehole litholog showed that the top layer has a high resistivity ranging 5–20 Ωm, it may be the top soil and sandy clay formation up to 10 m depth. Further below the underlying clay formation has reported resistivity <1 Ωm up to 45 m depth. Also the resistivity image PF11 correlated with the borehole litholog B1. In the image, the resistivity range indicated presence of top soil and sand within the clay formation. The underlying second layer is clay and medium-grained sand with clay up to the depth of 35 m.

8 Results and Discussions

In an alluvial formation the sand, clay and a fine-grained sand formation in the sub-surface has shown a minimum resistivity among all the aquifer materials. Thus, fine-grained sand formation may contain high TDS (>1,000 mg/l) water may be responsible for lower resistivity value of the aquifer in the area, and any formation having less than this optimum resistivity value may represent either clay or sand

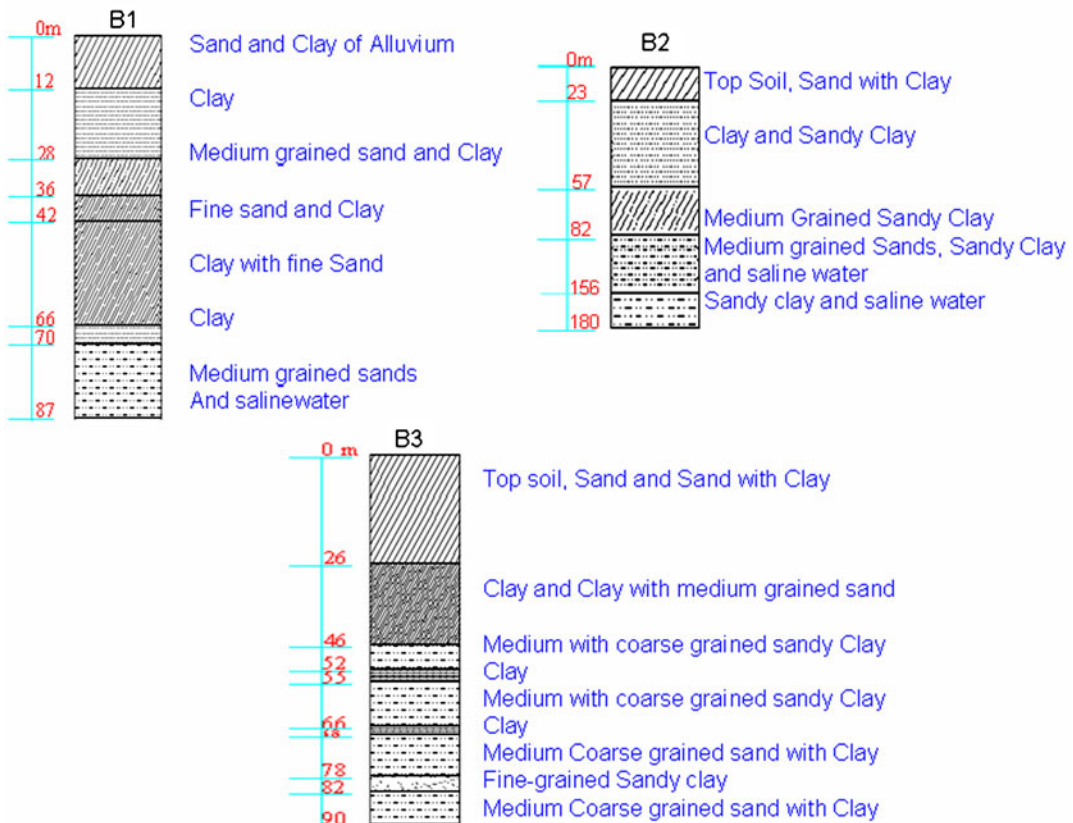


Fig. 6 Borehole lithologs in the area

formation, containing ground water of elevated TDS (>1,000 mg/l), which is unsuitable for human consumption. High TDS, chloride, and sodium concentrations are reported at Surasaniyanam, Vodalarevu, Devaguptham, Vasalatippa, and N. Kottapalli villages (Table 2). The higher concentrations may be due to infiltration of sea water from the high tides, which intrude in the Pikaleru, Kanavaram, and Vasalatippa drains. The lowering of resistivity resulted may be due to the encroachment of seawater into the freshwater zones in the area. ERT profiles and negative regional groundwater level contours during pre- and post-monsoon seasons and elevated chloride concentrations confirm brackish condition. The elevated TDS, chloride, and sodium concentrations reported in Amalapuram, Anantavaram, and Perur villages may be due to in situ salinity from the overlying clay formations. This was confirmed in the ERT profiles and well log interpretations.

The interpretation of ERT images indicated that sand and saline sands are mostly found near surface and saline water-saturated sand followed by saline water-saturated clay layer are present with a thickness of 20–25 m. The interpreted section across the area shows that the near surface thick marine clays are deposited near the shore and gradually becomes thicker away from the sea and same has been reflected in ERT profiles and bore well lithologs. This implies that clay might have been deposited below the sea water possibly during marine transgression. Absence

of any significant saline water intrusion at the deeper levels can be explained by the presence of impervious clay layers at depth and their possible extensions under the sea.

9 Conclusions

Integrated, geophysical survey and geochemical analysis methods were employed to assess the subsurface geologic formations, aquifer geometry and seawater intrusion, if any in the area. The area generally has a clay formation at shallow depth, which largely responsible for prevention of saline water intrusion into the underlying aquifers. Major ionic compositions effectively indicated effects of the seawater intrusion and particularly TDS and Chloride concentrations are the simplest indicators for assessment of salinization process. In this study, values of TDS and chloride concentrations are found to be very high indicated that the saltwater intrusion is due to in situ salinity of groundwater in the marine clays rather than lateral movement of sea water from Bay of Bengal in upstream areas of Amalapuram, Anantavaram, and Perur villages. The lowering of resistivity was due to the encroachment of seawater in to the freshwater zones and also infiltration of sea water from the high tides intruding into the Pikaleru, Kannvaram, and Vasalatippa drains in Surasaniyanam, Vodalarevu, Vasalatippa, Devaguptam,

Table 2 Range of high TDS, chloride and sodium concentrations in the villages

Village name	Pre Monsoon(mg/l)						Post Monsoon(mg/l)					
	TDS		Cl		Na		TDS		Cl		Na	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Surasaniyanam	2,611	11,925	243	1,156	161	3,818	2,758	8,858	206	973	137	2,725
Devaguptam	2,595	9,216	1,334	1,970	1,702	4,140	4,762	6,016	1,485	2,912	1,264	2,118
Vodalarevu	1,348	3,149	973	1,018	903	1,403	1,541	4,301	802	1,012	745	945
Vasalatippa	9,062	11,674	1,299	1,486	2,822	3,818	5,286	8,390	1,384	1,690	1,318	2,221
N. Kottapalli	7,496	12,788	299	1,578	1,403	6,670	4,928	1,108	398	1,796	408	1,473
Saripalli	1,447	3,821	291	927	736	2,528	1,472	3,741	192	831	138	1,524
Bandarulanka	1,328	5,825	512	2,749	621	3,624	3,341	4,926	912	1,963	978	2,215
Amalapuram	274	1,503	57	534	24	713	248	1,002	64	263	32	677
Anantavaram	1,061	3,917	156	668	506	1,702	598	3,780	149	767	98	429
Perur	1,328	3,249	391	1,315	621	1,403	1,419	3,341	462	1,012	442	1,128

and N. Kottapalli villages. Groundwater level contours show a predominant groundwater flow direction towards the Bay of Bengal from Amalapuram area. ERT surveys indicated that thick marine clays are present from the surface and have thickness of about 20–25 m and the marine clays possess the paleosalinity due to the recession of the sea level. Comparison of ERT data interpretation with more reliable interpretations, such as resolution from well litholog data, improves and increases the reliability, and reduces the ambiguity and uncertainty of the ERT data interpretation. Such a study enabled estimation of resistivity of two primary composite zones, the freshwater zone and the saline water zone. Regular monitoring of groundwater level and water quality for compliance, as well as environmental protection of groundwater resources to remove the public apprehensions of groundwater pumping from Ravva onshore wells is recommended.

Acknowledgment Authors are grateful to Director, N.G.R.I., Hyderabad for his continuous encouragement and kind permission to publish this paper. Author's are thankful to honourable reviewers and Editor for their encouragement and guidance for improvement of the manuscript.

Open Access This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

References

- APHA. (2005). *Standard methods for the examination of water and wastewater* (21st ed.). Washington: American Public Health Association.
- Bobba, A. G. (2002). Numerical modelling of salt-water intrusion due to human activities and sea-level change in the Godavari Delta, India. *Hydrological Sciences Journal*, 47, S67–S80.
- Bugg, S. F., & Lloyd, J. W. (1976). A study of freshwater lense configuration in the Cayman Islands using resistivity methods. *Quarterly Journal of Engineering Geology*, 9, 291–302. doi:10.1144/GSL.QJEG.1976.009.04.02.
- Choudhury, K., Saha, D. K., & Chakraborty, P. (2001). Geophysical study for saline water intrusion in a coastal alluvial terrain. *Journal of Geophysics*, 46, 189–200. doi:10.1016/S0926-9851(01)00038-6.
- CGWB. (1999). Groundwater Resources and Development Prospects in East Godavari District, Andhra Pradesh. Ministry of Water Resources, Government of India. Unpublished Report, 210 pp.
- De Breuk, W., & De Moor, G. (1969). The water table aquifer in the eastern coastal area of Belgium. *Bull. Assoc. Sci. Hydro.*, 14, 137–155.
- Dahlin, T. (1996). 2D resistivity surveying for environmental and engineering applications. *First Break*, 14, 275–284.
- Frohlich, R. K., Urish, D. W., Fuller, J., & Reilly, M. O. (1994). Use of geoelectrical method in groundwater pollution surveys in a coastal environment. *Journal of Applied Geophysics*, 32, 139–154.
- Hodlur, G. K., Dhakate, R., Sirisha, T., & Panaskar, D. B. (2010). Resolution of freshwater and saline water aquifers by composite geophysical data analysis methods. *Hydrological Sciences Journal*, 55(3), 414–434.
- Ginsberg, A., & Levanton, A. (1976). Determination of saltwater interface by electrical resistivity sounding. *Hydrological Science Bulletin*, 21, 561–568.
- GSI. (2006). Geology and Mineral Resources of Andhra Pradesh. GSI Miscellaneous Publication No.30 Part VII 2nd Revised Edition. 2006, pp.91.
- Maillet, G. M., Rizzo, E., Revil, A., & Vella, C. (2005). High resolution electrical resistivity tomography (ERT) in a transition zone environment: application for detailed internal architecture and infilling processes study of a Rhône River paleo-channel. *Marine Geophysical Researches*, 26, 317–328.
- Naik, P. K., Dehury, B. N., & Tiwary, A. N. (2007). Groundwater pollution around an industrial area in the coastal stretch of Maharashtra state, India. *Environmental Monitoring and Assessment*, 132, 207–233. doi:10.1007/s10661-006-9529-6.
- Nowroozi, A. A., Stephen, B. H., & Henderson, P. (1999). Saltwater intrusion into the freshwater aquifer in the eastern shore of Virginia: a reconnaissance electrical resistivity survey. *Journal of Applied Geophysics*, 42, 1–22. doi:10.1016/s0926-9851(99)00004-x.
- Pujari, P., Abhay, K., & Soni. (2009). Sea water intrusion studies near Kovaya limestone mine, Saurashtra coast, India. *Environmental Monitoring and Assessment*, 154, 93–109. doi:10.1007/s10661-008-0380-9.
- Sabet, M.A. (1975). Vertical electrical resistivity sounding locate groundwater resources: a feasibility study. Virginia Polytechnical Institute, Water Resources Bulletin 73, 63 pp.
- Subba Rao, N. (2002). Geochemistry of groundwater in parts of Guntur district, A.P. India. *Environmental Geology*, 41, 552–562.
- Saxena, V. K., Krishna, K. V. S. S., Singh, V. S., & Jain, S. C. (2002). *Hydro-chemical study for delineation of fresh groundwater region in the Potharlanka*. India: Krishna Delta.
- Saxena, V. K., Mondal, N. C., & Singh, V. S. (2004). Evaluation of hydrogeochemical parameters to delineate fresh groundwater zones in coastal aquifers. *Journal of Applied Geochemistry*, 6, 245–254.
- Saxena, V. K., Singh, V. S., Mondal, N. C., & Maurya, A. K. (2005). Quality of groundwater from Neil Island, Andaman & Nicobar, India. *Journal of Applied Geochemistry*, 7, 201–206.
- Store, H., Storz, W., & Jacobs, F. (2000). Electrical resistivity tomography to investigate geological structures of earth's upper crust. *Geophysical Prospecting*, 48, 455–471.

- Respond, H. (1990). Geoelektrische Untersuchungen zur Bestimmung der azwasserrSusswasser-Grenze im Gebiet zwischen Cuxhaven und Stade. *Geol. Jahrb. C*, 56, 3–37.
- Telford, W.M., Geldart, L.P., & Sheriff, R.E. (1990). *Applied Geophysics*. Cambridge University Press. 770 pp.
- Urish, D. W., & Frohlich, R. K. (1990). Surface electrical resistivity in coastal groundwater exploration. *Geoexploration*, 26, 267–289.
- Van Dam, J. C., & Meulenkaamp, J. J. (1967). Some results of the geo-electrical resistivity method in groundwater investigations in The Netherlands. *Geophysical Prospecting*, 15(1), 92–115.
- Ward, S. (1989). Resistivity and induced polarization methods. In S. Ward (Ed.), *Investigations in geophysics 5, geotechnical and environmental geophysics 1* (pp. 147–189). Tulsa: SEG.
- Zohdy, A. A. R. (1969). The use of Schlumberger and equatorial soundings on ground water investigations near El Paso, TX. *Geophysics*, 34, 713–728.