GEOPHYSICAL INVESTIGATIONS FOR GROUNDWATER IN COASTAL TRACTS

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ABSTRACT *Surface geophysical studies and borehole logging have been carried out in the coastal tracts of India with varied objectives. Electrical resistivity measurements, surface as well as borehole, have been the most widely used techniques. The groundwater quality interface and the spatial disposition of freshwater aquifers upto 300 m depth have been successfully identified. Case studies from the coastal tracts manifest the applications and limitations of the resistivity technique and the essentiality of integrating other geophysical techniques to remove ambiguities. The interpretation of geophysical data being contextual, a variety of problems related to exploration, development and conservation of groundwater can be geophysically addressed and solutions achieved economically.*

Key words Geophysical techniques; borehole logging; coastal tract; electrical resistivity measurements; freshwater/saltwater interface.

INTRODUCTION

The coastal tract of India extends over 5400 kms on mainland and 7500 km including the group of islands. Mainland coastal tract is densely populated. Anthropogenic activities have increased the demand of water and stressed the limited fresh groundwater resources. The coastal tract - the east coast stretching from Sunderban to the southern tip of Kanya Kumari, the Kerala and Gujarat coasts - is rimmed by coastal and deltaic sediments. Though they have enormous groundwater potentiality, in general, the availability of limited fresh groundwater all along the coastal stripe has always been a constraint. The shallow freshwater aquifers with limited lateral extents are mostly exploited. At places, because of increasing abstraction and consequent disturbed hydrodynamic equilibrium, the seawater has intruded inland contaminating the fresh groundwater. With the growing demand while there is a need for searching freshwater aquifers within an economically feasible depth of abstraction which may or may not be present at the point of demand, it is essential to have adequate and precise subsurface details, identifying the fresh/saline interface and changes therein as a prerequisite in preventing the intrusion through controlled abstraction or artificial recharge.

Along the east coast, deposition of sediments commenced during late Jurassic period under marine conditions. The trend of the Eastern Ghats and the basement topography over which the sediments were deposited, produced depressions and ridges forming a number of sub-basins further filled in during marine transgressions and regressions and successive delta formations through geological ages. The structural controls, depositional environment, complexities in sedimentation pattern, entrapped seawater in coastal lagoon deposits, flushing of permeable zones by recharging water at later stages etc., governed the quantity and *insitu* extent and intensity of groundwater quality. Aquifers occur over a large depth range extending inland for a few kilometers to hundreds of kilometers. The 10 to 15 km wide tract from the coast line, in general, holds brackish to saline groundwater (electrical conductivity more than 3000 μS/cm) with varied disposition even within the unconfined aquifers. Depth wise, while at places, the top aquifer may hold saline groundwater, at other places the deeper or intermediate aquifer is saline. Also, some of the aquifers may be in direct contact with the sea, either discharging freshwater into it or allowing seawater to intrude inland. Along the coastal tract there is, in general, a decline in the ground water level in freshwater aquifers, whether it is water table in the top unconfined aquifer or the piezometric surface of the deep confined aquifer that may trigger the ingress of seawater or upconing of saltwater. In parts of the coastal tracts of Gujarat and Tamil Nadu present day seawater intrusion in freshwater unconfined aquifers is observed. In most of the confined freshwater aquifers the fresh/saline interface may be located off-shore at present, but are prone to seawater intrusion as the interface advances landward due to overexploitation and reduced recharge. The vulnerability to seawater intrusion is aggravated further by tidal water in low-lying topography, natural hazards like catastrophic cyclones and tsunami, and global climatic changes which may cause sea level to rise (Thambi *et al.*, 2005).

Since the relation between available fresh groundwater and the level of development is not adequately known, management would primarily require an assessment of the aquifer geometry and water quality. The objective would be to select areas, locations and zones suitable for sustained development. Also, for reclamation of a seawater intruded aquifer, where fresh/saline groundwater interface is to be pushed towards the sea by recharging the aquifer artificially, it is necessary to locate the interface and its position with time for locating the recharge wells, as well as the artificial and natural lithological barriers.

NEED OF GEOPHYSICAL INVESTIGATION

Geophysical investigations with contextual interpretations are effective in making assessments for coastal tract groundwater development. Also, prior to drilling a borehole, information on aquifer disposition and water quality is desired. While surface geophysical techniques help define the negative and positive areas and zones before taking up the drilling, the post drilling borehole logging technique identifies precisely the zone to be tapped. So far the surface geophysical techniques got limited exposure and there is much potential in their applicability in the studies and monitoring of seawater intrusion and remedial measures through artificial recharge. Stewart (1999) has discussed the applications of geophysical techniques in coastal tracts in detail. Success and durability of wells drilled depend on the optimum well-design and construction for which multi-parametric borehole logging is essential. It identifies depth-wise micro-level changes in lithological and hydrochemical characters for tapping or recharging the suitable zones, position the cement seals either to prevent contamination or stop mixing of water from poor quality groundwater zones and monitor the variations.

GEOPHYSICAL TECHNIQUE AND APPROACH

Surface geophysical investigation particularly through electrical resistivity techniques has been widely successful in assessing the quality of groundwater at varied depths. Electrical resistivity of sediments is controlled by the resistivity of the interstitial water and the lithologic character. Effect of the former is more pronounced in coastal sediments where high concentration of dissolved solids in the interstitial water increases its conductivity. Resistivity of sediments decreases with increase in conductivity of water in it. But the variation is complex. It can be easily estimated for clean sands with uniform intergranular porosity, while it is not so for sands mixed with clays, because addition of clay also reduces the bulk resistivity. Since the reduction in resistivity by clay mixing is masked by that due to highly conductive interstitial water, the quality interface is generally delineated better than the lithologic interface by resistivity measurements in such an environment. This is what makes the resistivity technique practically effective in coastal tracts.

The coastal and deltaic sediments except a few thick sand/sandstone or clay units are of mixed nature. Either sands or clays mix in different proportions or numerous interbeds of clay separate the sands presenting overlapping resistivity ranges. Therefore the absolute value of interpreted layer/bed resistivity is seldom diagnostic. In coastal groundwater exploration and development, since the reduction in resistivity either due to clay or due to the presence of saline water is undesirable, the main objective remains the delineation of comparatively resistive layers/beds. However, in the aforesaid management aspects where impermeable clay barriers are also to be identified, the resistivity technique is to be integrated with other geophysical techniques such as induced polarization. Integration of surface geophysical techniques viz., seismic and electromagnetic (Stewart, 1982) is also essential at places where resistivity technique faces limitations of non-uniqueness in identifying deeper thin targets due to the presence of conductive, thick overburden, transitional variation in resistivity with depth and equivalence in response of intermediate layers.

The basic geophysical approach would be to conduct resistivity sounding near the existing borewell to standardize the range of the resistivity values locally with the water quality and lithology that could be recalibrated through the boreholes drilled and their multi-parametric geophysical logs and quality of water at different depths. Generally one has to be cautious with layer resistivities around 10 ohm-m and less. Very low resistivity values of the order of 1.5 to 2 ohm-m represent water quality deterioration.

CASE STUDIES

The significant findings of selected case studies from the coastal tracts of different states in India are described here manifesting the achievements, scope, limitations and the future prospects of geophysical investigations.

West Bengal

The coastal tract of Midnapur district, West Bengal encompasses a 90 km long stripe between Haldia and Digha in the out fall area of the rivers Kasai and Subarnarekha. The area is occupied by more than 2000 m thick column of Quaternary and Tertiary sediments comprising alternations of graded sand, silt and clay sequence. The Quaternary sediment is about 120 to 150 m thick. The Quaternaries are separated from the Tertiaries by 'Grey Clay' marker horizon. Towards the coast there exists a near surface brackish/saline water saturated zone of thickness varying from 20 to 130 m in the Quaternary sediments. The aquifers in the underlying Tertiaries upto about 300 m hold fresh groundwater.

The objective of the geophysical investigation was to map the saline/fresh interface and delineate the deeper fresh groundwater zones. Geophysically, the area presents a thick, highly conductive (1 to 3 ohm-m) geoelectrical layer capping the sequence of comparatively resistive layers upto 300 m depth, followed again by conductive layers. Resistivity sounding results were standardized through borehole lithologs, electrical resistivity and natural gamma radioactivity logs and quality of groundwater. Based on this, the quality interface was identified (Fig. 1). The group of freshwater aquifers in the Tertiaries occurring within a depth span of 150 to 360 m sandwiched between saline water aquifers was delineated. No seawater intrusion was identified. A significant finding was the thickening of the shallow brackish water zone to 300 m around Contai (Kanthi) located 10 km inland (Fig. 2). Towards the coast the thickness of the brackish water zone reduces to 40 m at a place 4 km inland and to about 135 m on the coast line. It was confirmed through drilling of boreholes at Contai and Junput on the coast line. Interpretation of shallow seismic reflection data from ONGC (Oil and Natural Gas Commission) indicated the presence of palaeo-channel around Contai in the depth range of 400 to 1000 m. In this coastal tract combination of surface resistivity measurements along with electrical and gamma logging of boreholes were effectively employed in delineating the fresh groundwater zones and their regional geometry. The hydraulic conductivity values obtained from pumping test data were correlated with the natural gamma radioactivity of the zones tapped to generate synthetic hydraulic conductivity log of the boreholes. Correlation of such synthetic logs of the boreholes (Fig. 3) located on the coast line gave hydraulic conductivity stratification and thus helped identify the permeable windows that are prone to seawater intrusion (Chandra *et al.*, 1994; Chandra and Singh, 1994; Chandra *et al.*, 2001).

Orissa

The coastal tract of Orissa occupied by sediments is about 330 km long. Resting on the Archaean gneisses, the Gondwanas and Tertiaries are overlain by recent to sub-recent sediments. The thickness of the alluvial capping on an average ranges from 50 to 150 m. The saline groundwater zone has a minimum width of 15 km in the extreme northeast and maximum of 75 km in the central part of the Mahanadi delta (Das *et al.*, 2004). To delineate the fresh/saline groundwater interface and

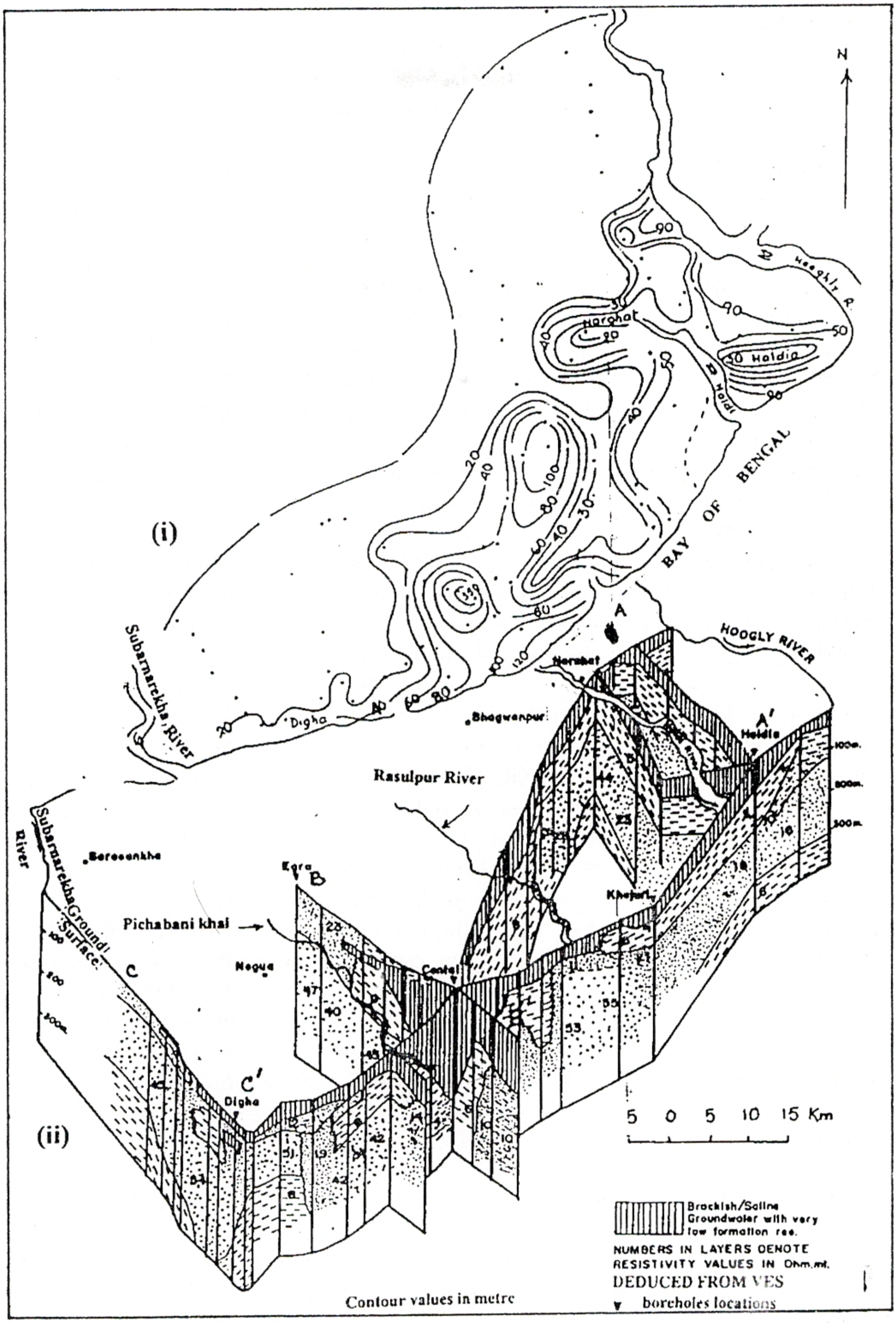

Fig. 1 (i) Depth to saline/fresh groundwater interface, and (ii) subsurface hydrogeological conditions inferred from vertical electrical soundings, coastal tracts of Midnapur district, West Bengal.

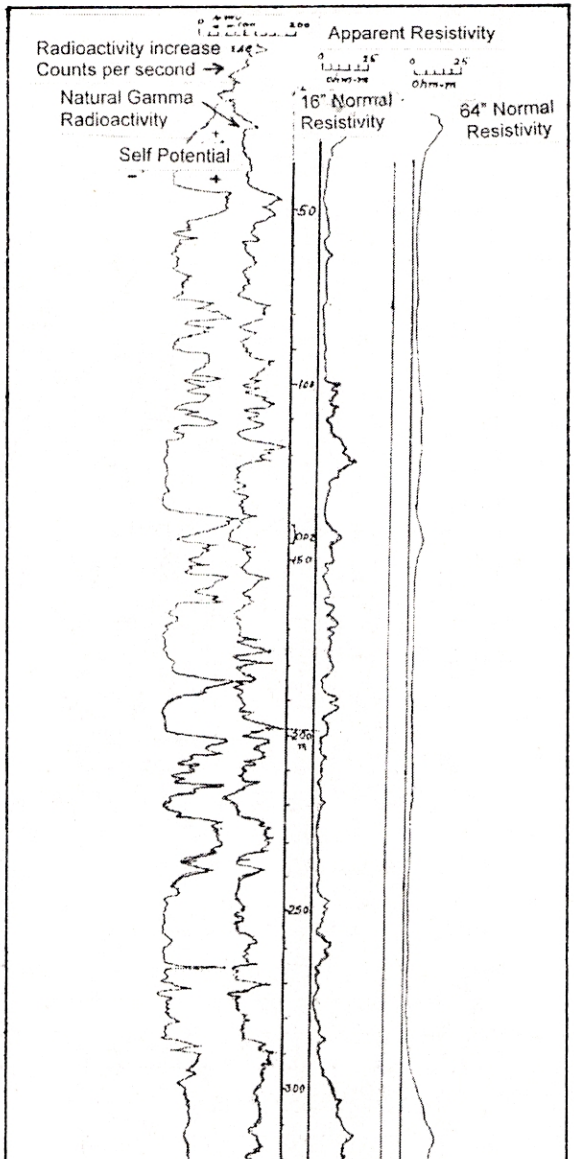

Fig. 2 Geophysical log of Contai (Kanthi) exploratory borehole Midnapur district, West Bengal.

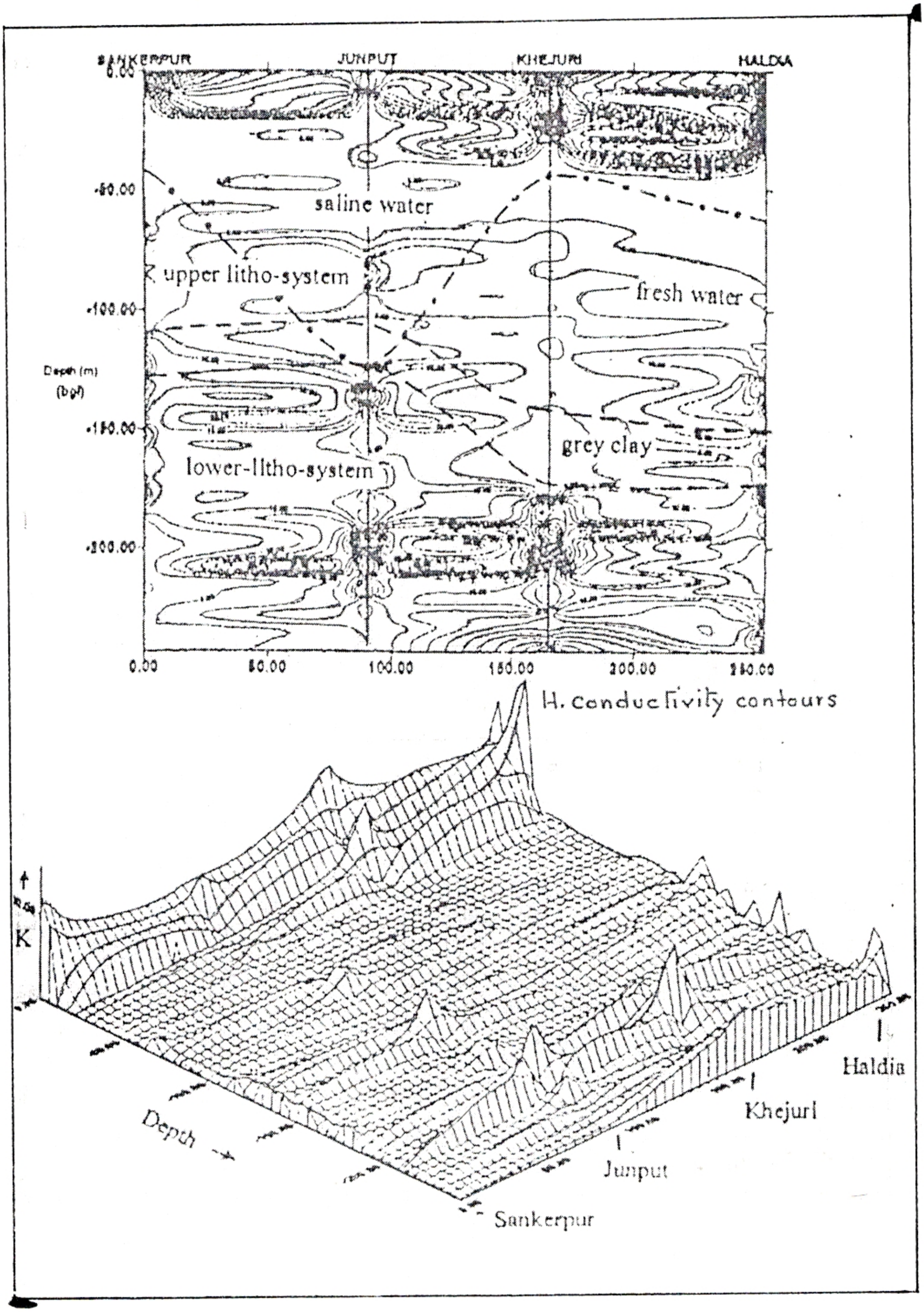

Fig. 3 Hydraulic conductivity stratification along Digha-Haldia coast line, based on synthetic hydraulic conductivity logs.

freshwater aquifers, geophysical investigations including surface surveys and borehole logging were carried out in parts of the coastal tract by Central Ground Water Board, National Geophysical Research Institute, DANIDA and State Agencies (Fig. 4). Four types of fresh/saline groundwater dispositions were identified, viz., freshwater overlying saline water, saline water overlying freshwater, alternate fresh and saline water zones, and saline water throughout, the depth explored being about 300 m. Near Puri coast two freshwater zones were delineated, the near surface one in the coastal sand dunes which is about 35 to 40 m thick and the other in the depth range of 160 to 240 m in the Tertiaries (Satpathy *et al.*, 1976; Shukla and Ramakrishna, 1988).

Andhra Pradesh

In the coastal tract of East Godavari district, Andhra Pradesh, towards east of Gautami Godavari river the subsurface geological sequence is of Tirupati sandstones, basaltic Traps and the Tertiaries – the Rajahmundry sandstones capped by alluvium. The depth to the top of Trap in the southern most coastal tract is about 800 to 900 m (Murthi and Ramakrishna, 1980). The maximum thickness of alluvium and underlying Rajahmundry sandstone and clays is about 300 m and 500 m, respectively. The Tertiaries and the Traps are exposed towards north of Bikkavolu. The sedimentary sequence in the coastal tract though holds numerous potential aquifers, they are mostly saturated with brackish to saline water (Raju *et al.*, 1982; 1983). The resistivity surveys were carried out for the delineation of fresh groundwater zones and the quality interface (Chandra *et al.*, 1982) (Fig. 5). The resistivity sounding curves were of two typical trends, viz., ascending and descending as shown in the last segment obtained along Bikkavolu-Tallarevu and Bikkavolu-Alamuru, respectively. Accordingly, these two sections present different depthwise groundwater quality profile. Like Bikkavolu-Alamuru there is no occurrence of near surface fresh groundwater zone along Bikkavolu-Tallarevu section. It was inferred that formation resistivity less than 5 ohm-m indicated the presence of brackish/saline groundwater, while that above 15 ohm-m indicated freshwater. Formation resistivities in the range of 5 to 15 ohm-m were attributed to clay mixing as well as marginal deterioration in ground water quality. The alluvium capping the Rajahmundrys which is about 120 m thick has very low resistivity. The upper part of the thick Rajahmundrys is also associated with resistivity less than 10 ohm-m. The lower part however has resistivity upto 30 ohm-m and may contain freshwater. The results of the resistivity soundings and ONGC seismic data reveals the possibility of encountering a fresh groundwater bearing granular zone immediately overlying the basaltic Trap along Bikkavolu-Tallarevu.

Tamil Nadu

Along Tamil Nadu coast, the sedimentary formations of Mesozoic to recent ages overlie the crystalline basement. Groundwater exploration has brought out the occurrences of deeper freshwater aquifers in the Tertiaries and Cretaceous, overlain by thick inherent saline water zone in South Arcot, Pudukkottai and Thanjavur

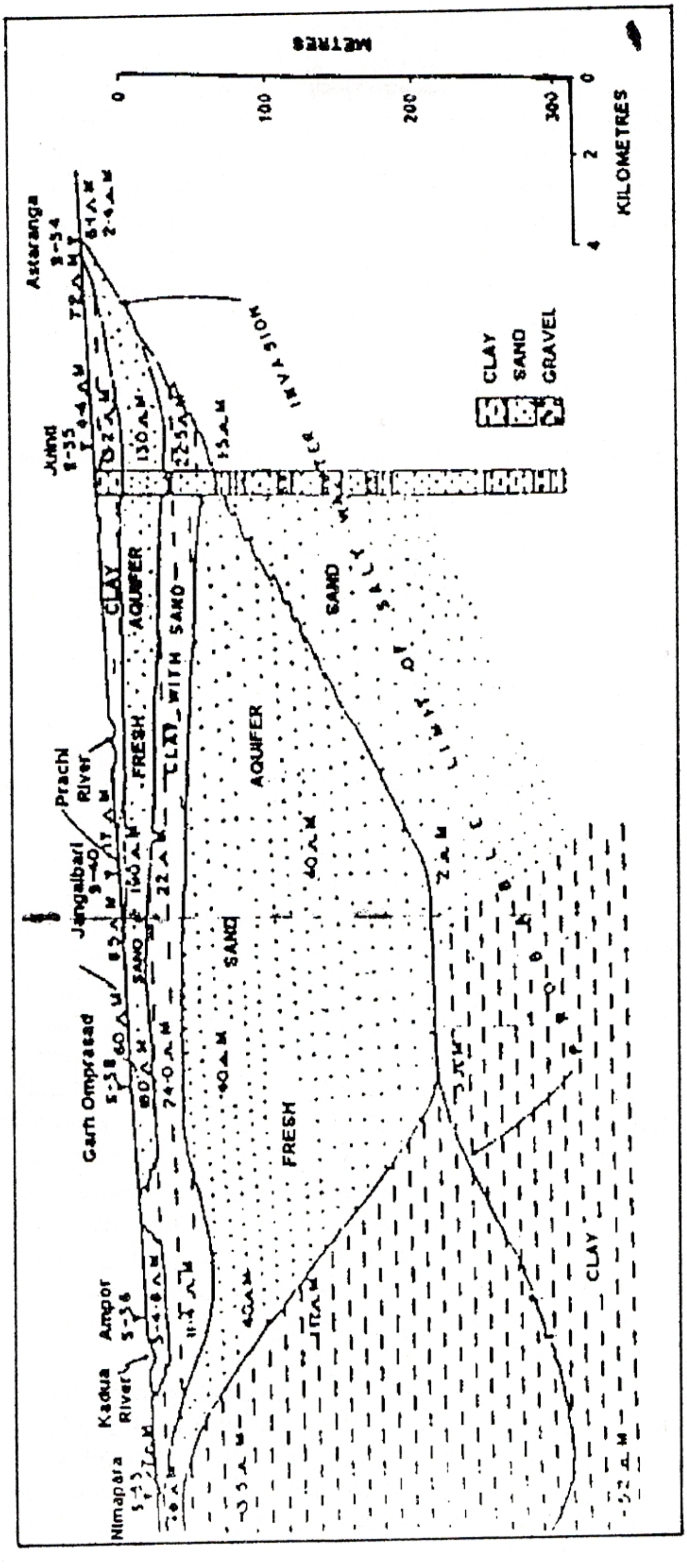

Fig. 4 Geoelectrical section showing coastal groundwater salinity, parts of Puri district, Orissa (Satpathy *et al.*, 1976)

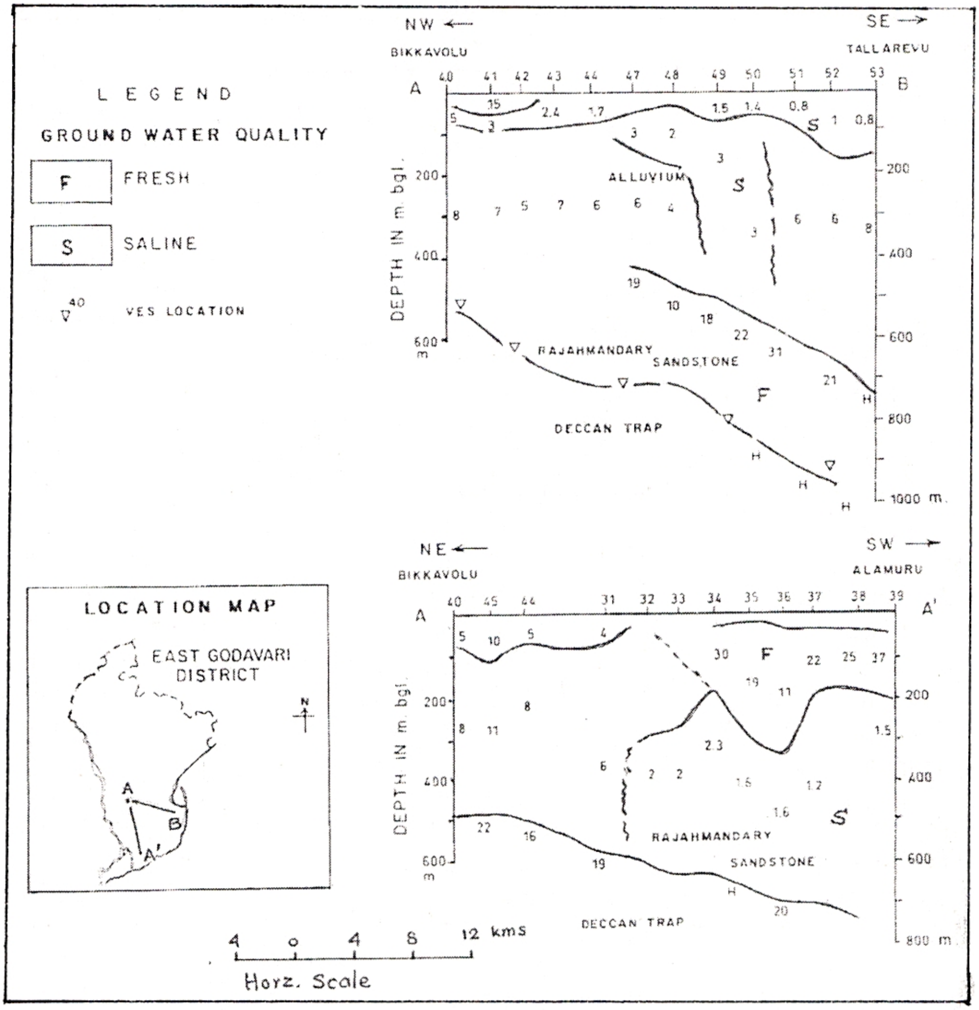

Fig. 5 Geoelectrical cross-sections from coastal tracts of East Godavari district, A.P.

districts. Also in Pondicherry and Karaikal the deeper aquifers in Tertiaries hold freshwater. In the costal tracts of Pudukkottai district, Tamil Nadu, freshwater aquifers occur at depths around 250 to 300 m in the Cretaceous formations overlying the Archaean crystalline basement. The overlying Tertiary and Quaternary formations are mostly saturated with brackish to saline groundwater of electrical conductivity (EC) around 3000 to 4000 µS/cm. A number of resistivity soundings were observed in the coastal tract of Pudukkottai district (Chandra and Ramakrishna, 1979). The resistivity sounding curve of 1000 m half-current electrode separation was of double ascending (AA) type (Fig. 6). The interpreted resistivity value (25 ohm-m) of the last layer was non-diagnostic due to the presence of the crystalline basement. The lithologic character of the resistive last layer occurring at a depth of around 240 m could not be ascertained as to whether the resistivity was due to the presence of thick freshwater zone or due to the resistive crystalline basement. To remove the ambiguity, a seismic study carried out by

Kailasam (1966) was utilized, which proved to be significant in revealing the depth of occurrence of the crystalline basement. Accordingly the ascending last segment of the resistivity sounding curve was attributed to the presence of resistive crystallines if occurring in the expected depth range. The shallow occurrence of resistive last layer (last segment of the resistivity sounding curve) was identified as thick freshwater bearing zone overlying the crystallines. With this approach, at Pandipattiram, Manamelkudi (located right on the coast), Karuvur and Villanur (Fig. 6), the occurrence of deeper freshwater zone associated with resistivity of 25 to 60 ohm-m was successfully inferred and confirmed through subsequent drilling of boreholes and their geophysical logging. At Kattumavadi and Ambalavananendal the resistive last layer was attributed to the presence of the crystallines. The moderately resistive and thick (50 to 100 m) freshwater zone got prominently reflected in the resistivity sounding curve because of the underlying presence of highly resistive crystalline basement. The technique would have faced limitations had the formation underlying the freshwater zone been highly conductive saturated with saline water. A point to be noted here is that the depth to the basement inferred through seismic study (Kailasam, 1966) matched nicely with the drilling results. The freshwater deeper aquifers in the coastal tracts of Pudukkottai district was under free-flowing condition with a maximum hydrostatic head of about 13 m above ground level at Manamelkudi in the year 1980 (CGWB, 1998). Excessive withdrawal of groundwater from these deeper aquifers would reduce groundwater discharge to the sea and the interface located offshore may get advanced towards the land.

In the coastal tracts of South Arcot district, Tamil Nadu, mainly occupied by thick Cuddalore sandstones of Tertiary age, the site at Porto Novo right on the coast line is located south of a fault zone. Here the crystalline basement is quite deep, around 2000 m as estimated by seismic studies. The ascending type resistivity sounding curve (Fig. 7) obtained here with appropriate resistivity range revealed the presence of fresh ground water beyond 160 m depth (Chandra and Adil, 1983). Range of resistivity values for the coastal sediments widely overlaps and local calibration is essential. For example at Auroville, located towards north of Pondicherry the Cretaceous formations are although associated with resistivities in the range of 6 to 10 ohm-m, these hold potable quality groundwater (Jayakumar *et al.*, 1984).

Further south, in Ramanathapuram district of Tamil Nadu, the resistivity survey was carried out in the coastal tract. Having almost similar coastal hydrogeological condition as Pudukkottai, the objective was to delineate the fresh groundwater zones overlying the crystalline basement occurring at depths around 400 to 500 m towards west of Pondikkonomoy (Fig. 8). The resistivity sounding curves at Ariyanendal and Palangulam picked up the resistive crystalline basement at a depth of around 400 m and also reflected feebly an increase in resistivity from 2 ohm-m to 8 ohm-m for the layer immediately overlying it (Chandra *et al.*, 1982). The depth to the basement was though confirmed by drilling, the overlying layer yielded brackish to saline water only. Possibly the subsurface structural control manifested as lineament along the river Vaigai towards north of the sites affected the hydrogeological conditions. Towards north of the lineament freshwater aquifers

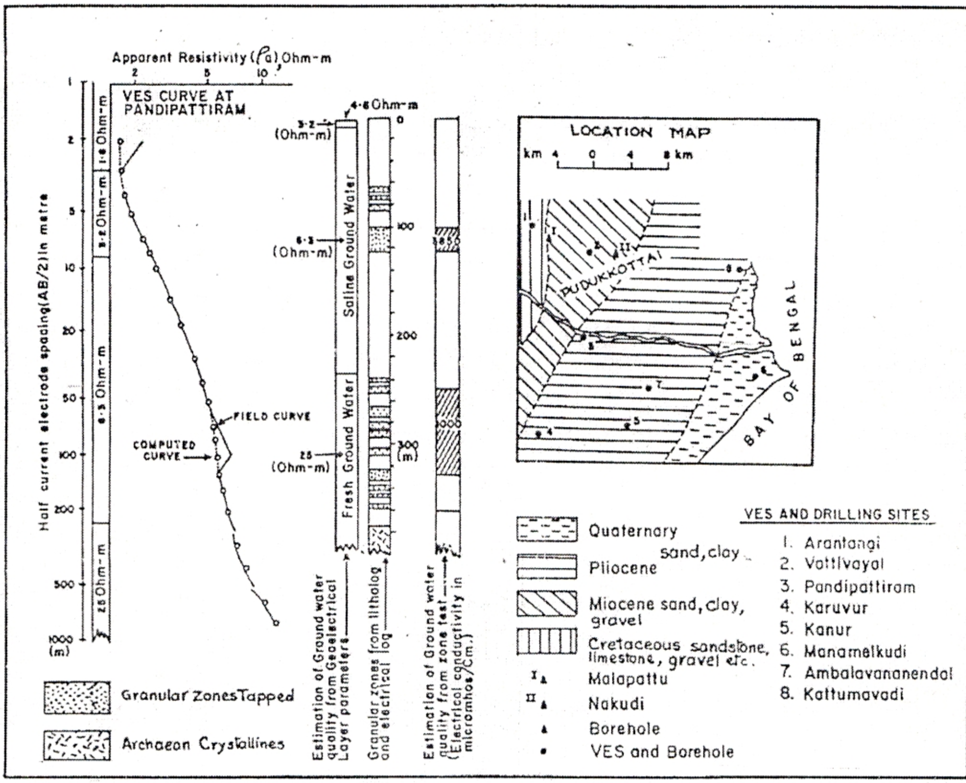

Fig. 6 Representative vertical electrical sounding curve, coastal tract, Pudukkottai district, Tamil Nadu.

overlying the basement were delineated and tapped at Tiruvadnai. Boreholes that did not touch the basement viz., at RS Mangalam and Salaigramam produced only brackish to saline water. Resistivity survey was thus found to be useful in minimizing the number of borehole drilling to confirm the hydrogeological condition.

Kerala

Along Kerala coast the thick shallow aquifers in the alluvium are generally fresh with isolated pockets of saline water developed during summer near backwater channels and tidal rivers. The underlying aquifers in Tertiary formations, viz., Alleppey, Vaikom, Quilon and Warkali hold freshwater with limited brackish water zones. These aquifers extend westward upto the Arabian sea (Thambi *et al.*, 2005). The geophysical logs of boreholes helped identify the granular zones, assess salinity of interstitial water and define the hydrostratigraphy.

Resistivity measurements carried out in the coastal tract of Kasaragod taluk, Cannanore district, Kerala occupied by laterite capped crystallines with a thin stripe of coastal sand and alluvium picked up the effect of saline tidal water 3 to 4 km inland in the rivers, viz., Uppala, Shiriya and Chandragiri joining the Lakshadweep

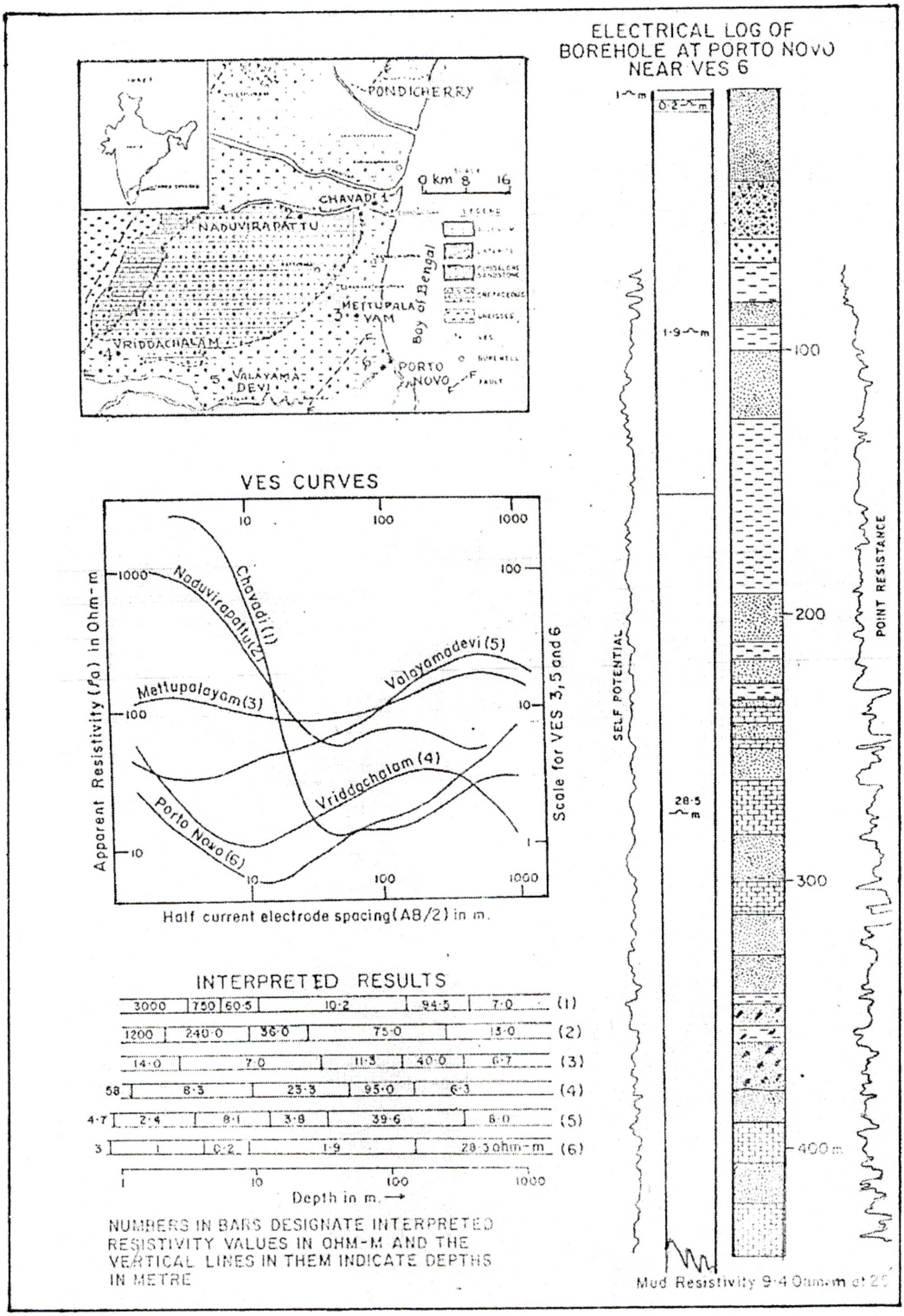

Fig. 7 Vertical electrical sounding curves and electrical log of exploratory borehole at Porto Novo, South Arcot district, Tamil Nadu.

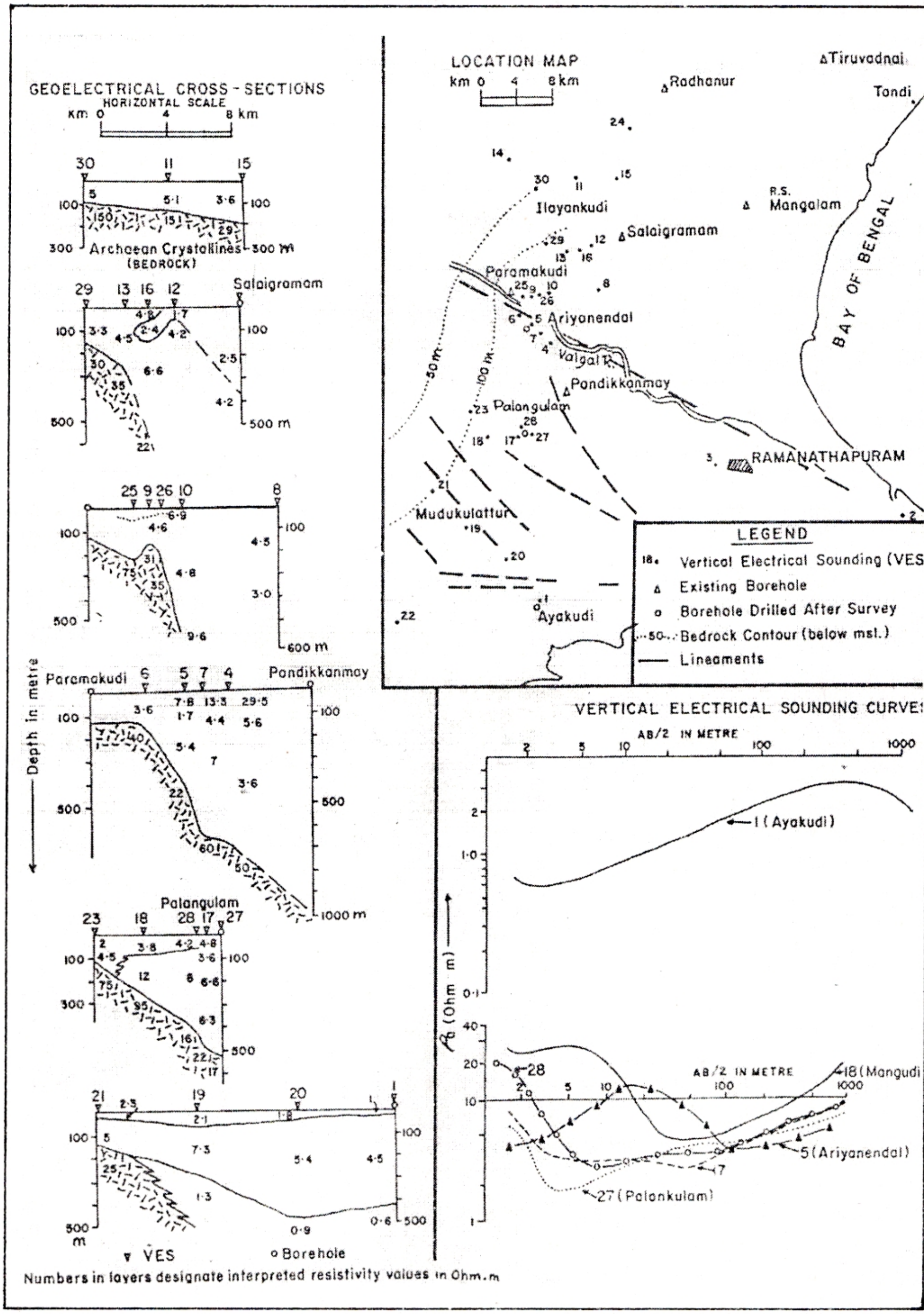

Fig. 8 VES curves and geoelectrical cross-section, coastal tracts of Ramanathapuram district, Tamil Nadu.

sea (Chandra and Ramakrishna, 1983). The quality of groundwater deteriorates upto about 20 m depth with layer resistivities ranging from 1.6 to 4.4 ohm-m.

Gujarat

Gujarat has about 1600 km long coast line from Lakhpat in Kuchchh district passing through Saurashtra and finally terminating at Umbergaon in Valsad district in the main land. The coastal tract of Kachchh and Saurashtra comprises a narrow stripe of 200-300 m thick Tertiary and Quaternary formations forming the aquifer. The sequence rests over the Deccan Trap basalt. Out of these, the Milliolite limestone of 5 to 50 m thickness forms the most prominent unconfined freshwater aquifer at the top. While the deeper aquifers in Gaj formation mostly hold inherent saline water, the top freshwater aquifer in the highly cavernous Milliolite limestone in some parts of Saurashtra coast, is affected by seasonal seawater intrusion where exploitation of groundwater is high due to industries and agriculture.

Electrical resistivity mapping by Bhowmick *et al.* (1980) established the fresh/saline groundwater interface in Mangrol-Chorwad tract of coastal Saurashtra. The areas of seawater ingress along the coastal tract of Kachchh and Saurashtra was identified by repeat surface geophysical measurements along coast-perpendicular profiles (GWRDC, 1998). Trivedi (2005) correlated the electrical logs of boreholes drilled in this coastal tract and identified the regional geometry of the freshwater aquifer along the coast line based on geophysical log inferred aquifer characteristics and the quality of interstitial water of the aquifers/formations encountered.

The case studies mentioned above manifest the effectiveness as well as the limitations of the geophysical investigations in identifying freshwater aquifers in the coastal tracts. The interpretation of geophysical data being contextual, a variety of problems related to exploration, development and conservation of groundwater can be geophysically addressed and solutions achieved economically. Coastal tracts being mostly capped either by highly conductive saline water saturated surface layer or highly resistive coast parallel sand dunes, resistivity measurements are quite tedious warranting experience and endurance.

CONCLUSIONS

Coastal tracts of India though endowed with prolific aquifers in thick sediments extending inland for kilometers, suffer from *insitu* groundwater quality deterioration and at places by seawater intrusion. The top aquifers may be saline or the deeper or moderately deep aquifers are found to be saline in nature. Scarcity of fresh groundwater is a constraint. Geophysical investigations mainly the surface electrical resistivity measurements are necessary to delineate the freshwater aquifers, differentiate the brackish ones, demarcate fresh/saline interface spatially, identify the lithology, and help locate zones that could be revitalized. Coastal high permeability windows prone to seawater intrusion can be identified by integrating the inferences drawn from surface and borehole geophysical, hydrogeological and hydrochemical investigations. Also, the groundwater developmental activities along the coast possibly triggering sub-surface hydrochemical changes could be monitored and cut to desired dimension by utilizing the surface and borehole geophysical findings. Surface geophysical investigation is non-invasive. It is an economic alternative to drilling for generating adequate subsurface information at close grid. The investigations carried out in the coastal tracts of West Bengal, Orissa, Andhra Pradesh, Tamil Nadu, Kerala and Gujarat revealed occurrences of shallow and deep freshwater aquifers upto about 300 m depth and the spatial disposition of the quality interface. Application of appropriate combination geophysical techniques such as resistivity and seismic and standardization through multi-parametric borehole geophysical logging, overcome the technique limitations and yield desired information adequately with precision.

Acknowledgements Author is indebted to Dr. Saleem Romani, Chairman, CGWB, for his valuable guidance and the opportunity to review the coastal hydrogeophysical studies. Author is grateful to Sri B.M. Jha, Member (SAM), CGWB, for his enthusiastic encouragement, and to Dr. K.D. Sharma, Director, NIH, Roorkee, for the opportunity to present the field experience. Author is extremely thankful to the Scientists of CGWB with whom he worked in the coastal tracts of different states.

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