

# Hydro-geophysical techniques for safe exploitation of the fresh groundwater resources in coastal area

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**Abstract** Vertical disposition of the freshwater aquifer lens and their progressive change on lateral scale are relevant to understand the short circuiting of fresh and saline water at coastal areas. Since, half of the world population dwells within 50 km of coast line, the freshwater aquifers at coast are deteriorating at alarming rate. There are well-defined water well construction plans for coastal aquifer management, but mostly fails while execution due to lack of precise knowledge of subsurface lithological layer setup. In the present study, an attempt has been made to investigate such precise information about subsurface lithological layer setup to protect the freshwater resources at coastal area, applying noninvasive hydro-geophysical technique. Integrated electrical parameters, hydrochemistry, topography, and water table assessment have been applied to decipher the geometry of freshwater lens at Cuddalore coast, India. Results show in this study (1) the electrical resistivity ( $\rho$ ) 1–10  $\Omega$ -m of subsurface formation, electrical conductivity ( $\sigma$ ) 30,891  $\mu$ S/cm of groundwater, and water table 1.55 m above mean sea level (MSL) confirms the zone of effluent contamination; (2) the zone showing  $\rho = 1\text{--}10 \Omega\text{-m}$ ,  $\sigma = 6172 \mu\text{S/cm}$ , water table 6.46 m below MSL is attributed to the saline water intrusion; (3) freshwater formations are identified in beach ridges underlain by clay layers with  $\rho = 30\text{--}60 \Omega\text{-m}$ ,  $\sigma = 453 \mu\text{S/cm}$  and water table above MSL; and (4) water well design is proposed to tap the freshwater aquifers avoiding vertical short circuiting of saline and freshwater.

**Keywords** Coastal aquifers · Hydro-geophysics · Freshwater protection · Water well design · India

## Introduction

Aquifers situated along the coast, however, add significant additional complications to the process of aquifer management: the potential for saline water intrusion to eventually render portions of the coastal aquifer unsuitable as a source of drinking water. Inappropriate management of coastal aquifers can lead to irreversible damages resulting in the deterioration of freshwater resources. Half of the world's population dwells within 50 km of the coastline (Hodges et al. 1993; Von and Turner 2001). Many industries settled in the coastal belts on worldwide for the reasons such as inexpensive availability of water resources, proximity of coast for ocean dumping of effluents, and ease of transportation through sea ways (Sonkamble 2012). Hence, the coastal aquifers are experiencing great stress and drinking water availability has become a major environmental concern to be addressed (Khair et al. 1994).

To avoid the vertical contamination of salinity in freshwater lens, the information about the aquifer geometry plays a key role in designing the water wells. The literature survey (Shamir et al. 1984; Ahlfeld and Heidari 1994; Cheng and Ouazar 2004; Dhar and Datta 2009; Kaleris and Ziogas 2013) of coastal belts around the world shows, majority of the water wells gets salinity intrusion due to the lack of precise mapping of the subsurface multi-layer aquifer systems, their disposition and saturated formation salinity. The coastal aquifers are fragile in nature and easily depleted due to overexploitation of groundwater resources in many parts of the world (Khair et al. 1994; Gossling 2001; Vengosh et al. 2005; Chidambaram et al. 2008). Due

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to high permeability of the formation, the coastal aquifers are sensitive to the rapid spread of the pollutants in case of heavy pumping (Rezaei et al. 2005). It causes potential salinization of groundwater and their sources are diverse including natural saline groundwater (Falgas et al. 2009); halite dissolution (Hidalgo and Cruz-Sanjulian 2001); seawater intrusion (Sanford and Pope 2010); anthropogenic contamination (Westbrook et al. 2005); etc. Among these sources, seawater intrusion is the most common and widespread problems in coastal areas, and forces the abandonment of water wells in many instances (Giordana and Montginoul 2006).

At coastal belts of developing nations, the present scenario of well construction is based on water striking depth which encourages the intermixing of the saline water into freshwater. This practice forces the abandonment of water wells in many a times. The literature (Gorelick et al. 1984; Bolster et al. 2007; Mantoglou and Papantoniou 2008) survey shows that the aquifer systems in many coastal belts of the world have already been deteriorated due to over exploitation of freshwater resources and unscientific construction of the water wells at coast, since the wells penetrate the multiple aquifers indiscriminately considering saline and freshwater layers.

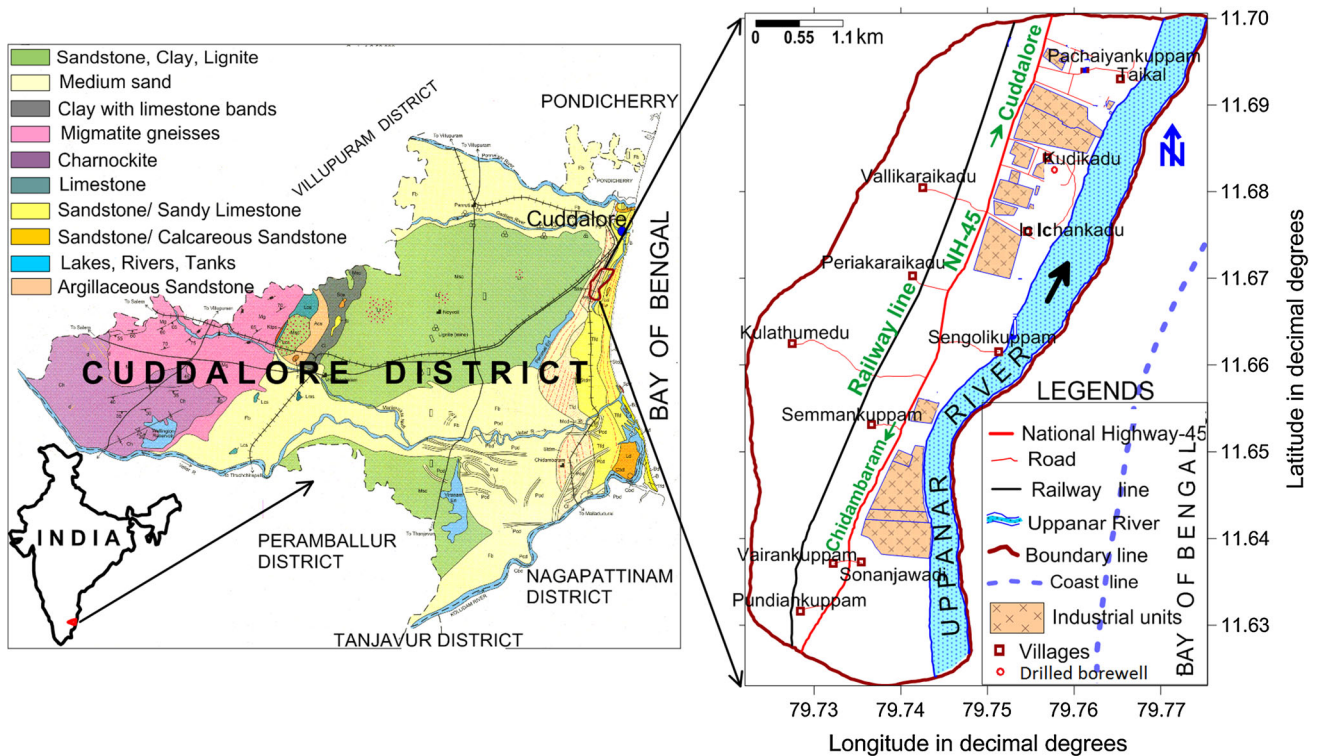
To control the salinity intrusion in coastal areas, Park and Aral (2003) have answered various questions such the safe pumping rate for existing wells, number of wells needed to supply the required freshwater to a community, where should these wells be placed and what should their pumping rates be, how close can these wells be placed to the coast with maximum withdrawal rates, through the mathematical models. Kaleris and Ziogas (2013) have demonstrated that the development of subsurface barriers is best alternative countermeasure to saltwater intrusion. When assessing the literature study on freshwater lens protection at coastal belts, the implementation of the freshwater wells were found practically failed in many cases due to target position errors of subsurface litho-layers and the corresponding hydro-geochemical characteristics. This hydrogeological complexity upon drilling a bore well induces salinity in the wells and forces abandonment of many freshwater wells. Similar trend of coastal aquifer degradation was identified in patches along the coastal belt (7517 km) of Peninsular India. This is the time to be aware of the threat to living beings and to intensify the saltwater intrusion monitoring and prevention projects, and increase coastal aquifer planning and management effort. The identification and protection of fresh groundwater resources in coastal area has become top priority for coastal community and government authorities. It has become a challenge for water resources authorities to establish the appropriate strategies for coastal aquifer management. Hence, safe exploitation of freshwater resources in coastal

areas is utmost important practice to meet the real meaning of sustainability.

To meet the thrust community demands in a complex coastal aquifers affected by industrial pollution and salinity intrusion from marine sources, a genuine practical approach has been attempted in the present study. This study provides a practical solution for resolving the intermixing of salinity into freshwater formation and strategies to protect the freshwater resources using the systematic hydro-geophysical investigations in a test site of 25 km<sup>2</sup> at coastal area of Cuddalore in India (Fig. 1). In this study, we emphasize the precise mapping of subsurface litho-layers and their salinity variations to tap freshwater lens in unconfined Quaternary aquifers at a coastal area in India. Thus the main objectives of this paper are to (1) decipher the freshwater lens precisely, in multi layer aquifer systems, and (2) propose a design of water well as practical solution for protecting fresh groundwater resources by tapping only freshwater, rejecting salinity intrusion. This approach has provided a conclusive comprehensive picture about the fresh groundwater sources and can be replicated as a practical long run solution for protecting freshwater resources in coastal areas.

## Study area

The present study area is situated in the industrial complex of 'State Industries Promotion Corporation of Tamil Nadu' (SIPCOT), coastal belt of Cuddalore district, Southern India (Fig. 1). The geology map and district resource map of Cuddalore has been obtained from Geological Society of India, Hyderabad (India). SIPCOT is a civic body oriented to provide infrastructure for the industrial units. Geographically it covers 25 km<sup>2</sup> area between latitudes 11°37'22"–11°42'02"N and longitudes 79°43'19"–79°46'31"E. Cuddalore is a port town from ancient times with historical trade ties to the occident and orient. Agriculture is the mainstay of the district and is dependent on availability of quality sub-surface water harvested through open dug wells, tube wells and bore wells. The primary crops are paddy, sugarcane, groundnut, coconut and millets; pulses like red gram, green gram and black gram; and fruits like bananas, cashew, mango and jackfruit. Uppanar River, also known as the Buckingham canal (Fig. 1) flows parallel to the coast in the study area, with high salinity (mean total dissolved solid: 28,870 mg/l) due to back waters from Bay of Bengal as well as discharge of industrial and domestic effluents (Sankaran et al. 2012). The over exploitation of groundwater resources for agriculture purposes has generated the reversal of hydraulic gradient towards inland aquifers enhancing saline water intrusion from Uppanar River. Some of the closed industries in the



**Fig. 1** Location map of the study area (25 km<sup>2</sup>), Cuddalore, Southern India

recent past have continuously dumped scrap and chemicals like gypsum, sulfuric acid, sulfur, lime, pesticides and other raw materials, which were the prime sources of subsurface pollution in the northern part. The effluent generation from all the functioning industries of SIPCOT is about 800 m<sup>3</sup>/day. In the absence of treatment, storage and disposal facility (TSDF), hazardous wastes has been dumped on the adjoining lands and in open pits within the SIPCOT area in the recent past. These hazardous waste upon prolonged storage on open land, have leached into the groundwater and contaminated the water resources (Sonkamble et al. 2014c).

**Geomorphic units and hydrogeology of the study area**

Geomorphologically the study area shows unconsolidated sediments such as beach sands, alluvium clay, silts, and gravel pebbles. These formations make this area suitable for groundwater development by shallow dug wells and tube wells in view of their high porosity and permeability. In the study area, the sedimentary rocks hold three aquifers at different depth i.e. (1) up to 30 m depth, (2) within the lignite zone at 120–140 m depth, and (3) with alternate sand and clay layers at between 170 and 300 m depth. Total quantity of water requirement for the industries is reported to 20,000 m<sup>3</sup>/day which is met by

groundwater below lignite zone of about 200 m depth. The annual draft including domestic and agriculture need of Cuddalore district is reported as 1105 million cubic meter (MCM) (CGWB 2009). Some industrial units of major water consumers have their own bore wells, and their combined water requirements could add substantially to the total water stress on the local groundwater reserves.

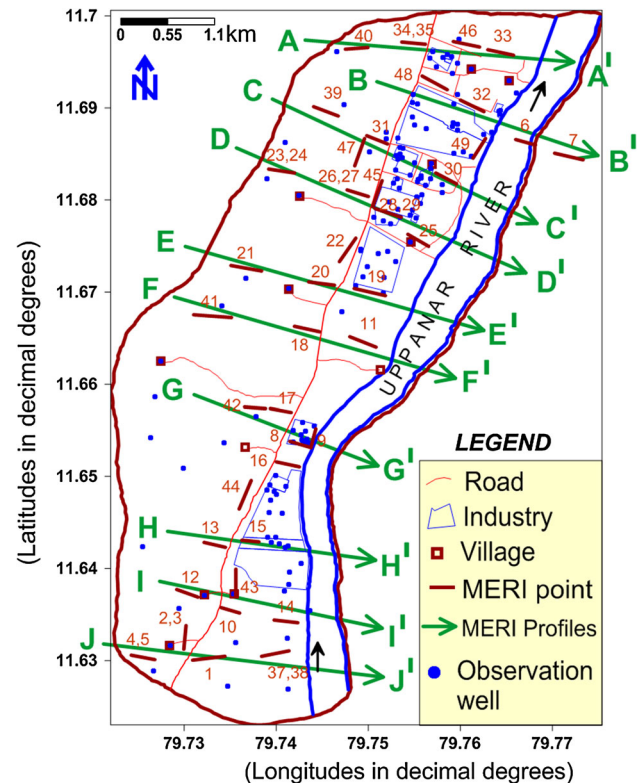
**Materials and methods**

Geophysical approach has been utilized in a number of studies for coastal freshwater lenses (Bugg and Lloyd 1976; Jacobson and Hill 1980; Ayers and Vacher 1986; Urish and Frohlich 1990; Anthony 1997). There are several advantages to geophysical surveys over estimations of lens dimensions based on hydrochemistry, topography and water table elevations. Geophysical methods are non-invasive and allow for rapid coverage of large areas in relatively lesser time. The theory and practice of electrical resistivity methods for groundwater investigations is well documented by Bhattacharya and Patra (1968), and Parasinis (1973). The interpretation of resistivity data and its applications to groundwater studies have been given in detail by Zohdy (1965). DC resistivity techniques may be used in the profiling mode (Wenner surveys) to map lateral changes and identify

near-vertical features or they may be used in the sounding mode (Schlumberger array) to determine depths to geoelectric horizons (e.g. depth to saline groundwater). The development in the resistivity technique as multi-electrode resistivity imaging (MERI) facilitate to map 2D and 3D resistivity distributions of subsurface bodies reliably and require less time (Barker 1978; Griffiths et al. 1990; Loke and Barker 1996; Barker et al. 2001; Sankaran et al. 2010; Sonkamble et al. 2014a, b).

To decipher the subsurface horizontal layers precisely, the systematic field surveys, comprising non-invasive multi-electrode resistivity imaging (MERI) at 49 locations, measurements of insitu groundwater quality and static groundwater head from a network of 80 observation wells, and topographic survey at 150 locations with grid size of 0.167 km<sup>2</sup>, were carried out in a test site of 25 km<sup>2</sup> Cuddalore coast, India (Fig. 1).

MERI profiling was carried out using the Wenner-Schlumberger configuration with a maximum of 48 electrodes and 5 m unit electrode spacing. Syscal Junior multi-node computer-controlled imaging system (IRIS Instruments, Model-Syscal Pro Switch-48) together with a remote control module was used. The survey lines were 240 m to give an effective maximum depth of investigation of around 45 m. The apparent resistivity data collected by MERI were inverted using the standard RES2DINV program through finite difference numerical code by Dey and Morrison (1979) modified by Loke and Barker (1996), to produce the subsurface true resistivity distributions, which were finally transformed into lithological set up. The MERI surveys were further validated by borehole lithologs, insitu groundwater quality (electrical conductivity) and water table measurements from a network of 80 observation wells (Fig. 2). Based on the 2D images of MERI, various geo-electric cross sections along different profiles are prepared which represents the subsurface lithology. These cross sections of MERI profiles are named from A–A' to J–J' and the orientation is east–west direction (Fig. 2). The profiles are derived projecting the nearby MERI points. The maximum length of the profile is up to 3000 m. Since, the profile depth varies from 20 to 45 m below ground level for different MERI points, the interpretation extended below the penetration depth considering its trend in the next immediate MERI point. The depth to groundwater was measured using water level indicator (OTT Contact Gauges, Model-OTT KL 010) and referenced to mean sea level (MSL). Topographic surveys using differential global positioning system (Model-Trimble R3) were employed for precise measurement of surface elevation. The insitu EC of groundwater was measured using multi-parameter meter (HQd portable meters, Model-HQ40d).



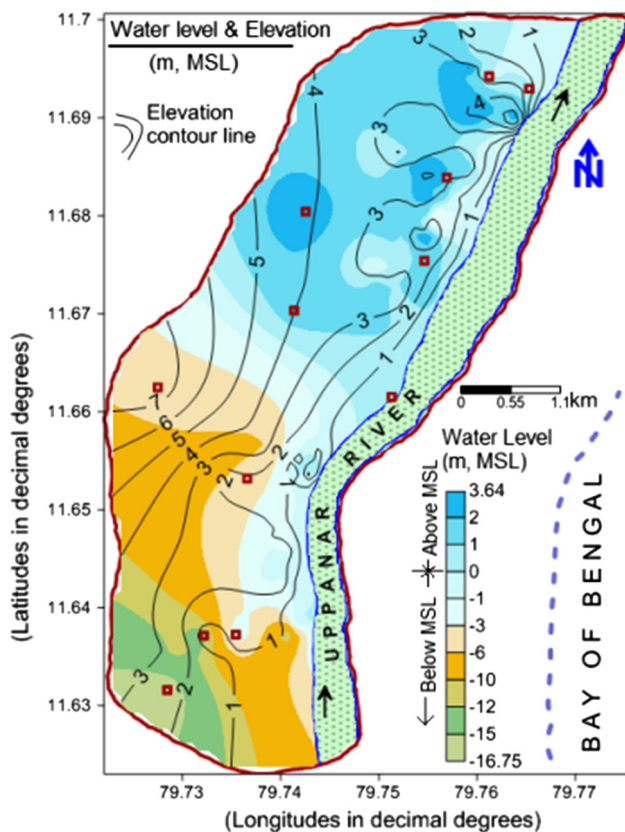
**Fig. 2** Locations of MERI survey points and MERI profiles from A–A' to J–J'

## Results and discussions

The topographic survey reveals that the elevation of the study area varies from 0.182 to 7.703 m MSL (Fig. 3) with a gentle slope from west to east. The EC of the groundwater samples from 80 key wells varies from 453 to 30,891  $\mu\text{S}/\text{cm}$ . The depth to water level varies from 3.64 to  $-16.75$  m MSL (Fig. 3). The negative sign indicates water level below MSL. Water level is found above MSL in northern part, whereas it is below mean sea level in the southern part (Fig. 3). The overexploitation of groundwater for agriculture purposes created reversal of hydraulic gradient in the south enhancing saline water intrusion.

The field observations show the top soil is followed by fine silt, clay and sand mostly of brown to white color. The lithologs of the exploratory well at Kudikadu village in the study area (Fig. 1) shows top soil (silty sand of fine to medium grain) up to 4 m depth, sand (fine to medium grain) at 4–10 m, clay with sand 10–17 m, clay at 17–25 m, sand (first aquifer) at 25–35 m, clay with sand lenses 35–95 m, sandstone with shale intercalation (second aquifer) at 95–142 m depths. Clay with sand and clay layers are found as alternate layers in beach ridges. Prior to interpretation of the profile sections of MERI, the





**Fig. 3** Contour maps of depth to water level (m, MSL) and topographic elevation (m, MSL) of the study area

resistivity ranges have been calibrated with the bore hole lithologs of exploratory well at Kudikadu village. These calibrated values of resistivity ranges have been applied for the interpretation of all the profile sections projecting MERI points.

Among the ten MERI sections (A–A’ to J–J’) carried out in the test site, three profiles A–A’, G–G’ and J–J’ (Fig. 2) have been presented in this article which can illustrate the industrial pollution, seawater intrusion and fresh groundwater sources covering the study area uniformly.

**MERI profile A–A’**

Profile A–A’ covers the MERI points 40, 34, 46 and 33 (Fig. 4). The maximum length of the profile is up to 2200 m. In this profile, the top layer is noted as silty sand (wet). The resistivity of the wet silty sand ranges from 10 to 25 Ω-m, with increasing thickness from 5 to 7 m in the west to about 34 m in the middle (Fig. 5). In the east, the dry silt resistivity range 400–1500 Ω-m is noted up to a depth of 4 m up to Uppanar River. The top silty sand layer is followed by clay with sand layer (25–50 Ω-m) in the west up to 10–11 m depth further it followed by the clay layer (30–60 Ω-m) extends up to 24–27 m depth. The bore

well at MERI 40 shows EC value 453 μS/cm and its converted resistivity value 22.07 Ω-m is falling close to the resistivity range (25–50 Ω-m) which is reported for the clay with sand layer (freshwater aquifer) shown in Fig. 5. In the east of the profile, top silt layer is followed by fine to medium sand (15–60 Ω-m) increasing the layer thickness from 35 m and below. The coarse sand layer (15–25 Ω-m) is observed as the bottom layer of the entire profile. The low resistivity (1–10 Ω-m) of the silty sand and high electrical conductivity (30,891 μS/cm) of groundwater sample and its converted resistivity value 0.32 Ω-m evidenced to confirm the plume of contamination (Fig. 5). The full scanning of chemical parameters of groundwater sample from the well located at the MERI 46 shows, sodium: 3751 mg/l; potassium: 671 mg/l; calcium: 2041 mg/l; magnesium: 286 mg/l; chloride: 3648 mg/l; sulfate: 9480 mg/l and bicarbonate: 260 mg/l. At this well the depth to water level was recorded as 1.55 m above MSL (Fig. 3). The low electrical resistivity, elevated concentrations of sodium, calcium, sulfate and chloride ions and water table above MSL corroborate the sources as industrial waste such as gypsum (CaSO<sub>4</sub>), sodium salts, etc. which had been dumped by the non-functioning industrial units.

**MERI profile G–G’**

The G–G’ profile is prepared using MERI numbers 42 and 8 passing the locations at east of Semmankuppam village and inside the industrial premises, in the central part of the study area (Fig. 2). This area is predominantly sandy zone (fine to medium) having resistivity values 1–15 Ω-m with some patches of wet silty sand (1–4 Ω-m) in the west from surface to about 32 m depth and dry silt patch in the top shallow zone (60–320 Ω-m) in the middle to east of the profile underlain by thin clay layer of resistivity 25–60 Ω-m (Figs. 6, 7). The major ion chemistry of the groundwater from the observation well located in the east of the profile (close to MERI 8) shows EC value of 5492 μS/cm; sodium: 596 mg/l; potassium: 126 mg/l; calcium: 133 mg/l; magnesium: 226 mg/l; chloride: 1087 mg/l; sulfate: 804 mg/l and bicarbonate: 189 mg/l. To determine the seawater contribution to freshwater aquifer, the Cl<sup>-</sup> concentration of seawater is used as natural tracer which shows 566 milli moles per liter (mmol/l) when there is no other source of chloride (Appelo and Postma 2005). Similarly, Uppanar River (flows with back waters from sea) water Cl<sup>-</sup> concentration recorded 391.6 mmol/l (13,902 mg/l) was considered as cent percent (100 %) salinity and then its mixing percentage in the groundwater sample is calculated based on Cl<sup>-</sup> concentration. The water samples of well shows Cl<sup>-</sup> concentration 30.6 mmol/l (1087 mg/l) and the calculated mixing percentage of Uppanar River water to the

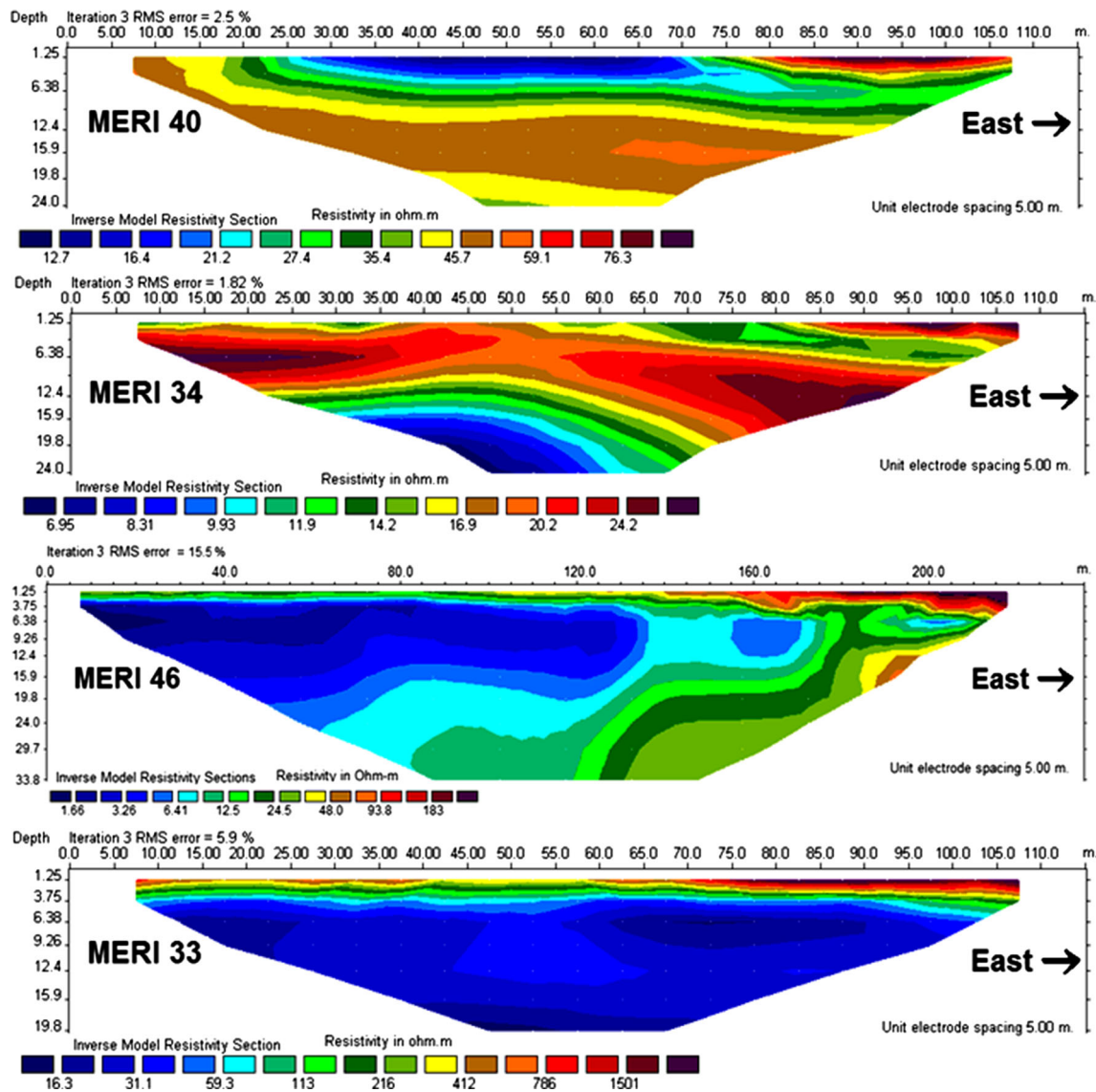


Fig. 4 MERI images of A–A’ MERI profile

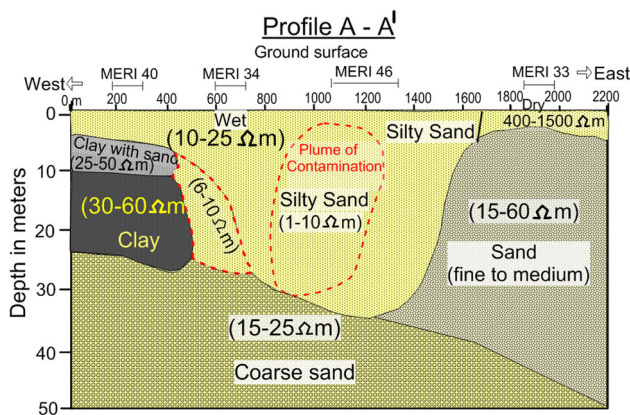


Fig. 5 Geo-electric sections of MERI Profile A–A’ in the northern part

well was 7.8 % indicating salinity from marine source in the central part of the study area. Thus the salinity from seawater intrusion corroborate with relative low resistivity range of 1–15 Ω.m.

### MERI profile J–J’

The profile J–J’ is prepared using MERI points 4, 1 and 37 located in the southern part of the study area near Pundi-ankuppam village (Figs. 1, 2). In this profile, the top layer up to 28–35 m depth is identified as wet sand (fine to medium), 0.5–10 Ω-m layer for the entire length of the profile except a patch of wet silty sand (10–15 Ω-m) at the top, up to 7–10 m depth at 0–500 m surface distance (Figs. 8, 9) of the profile. The wet sand layer is underlain

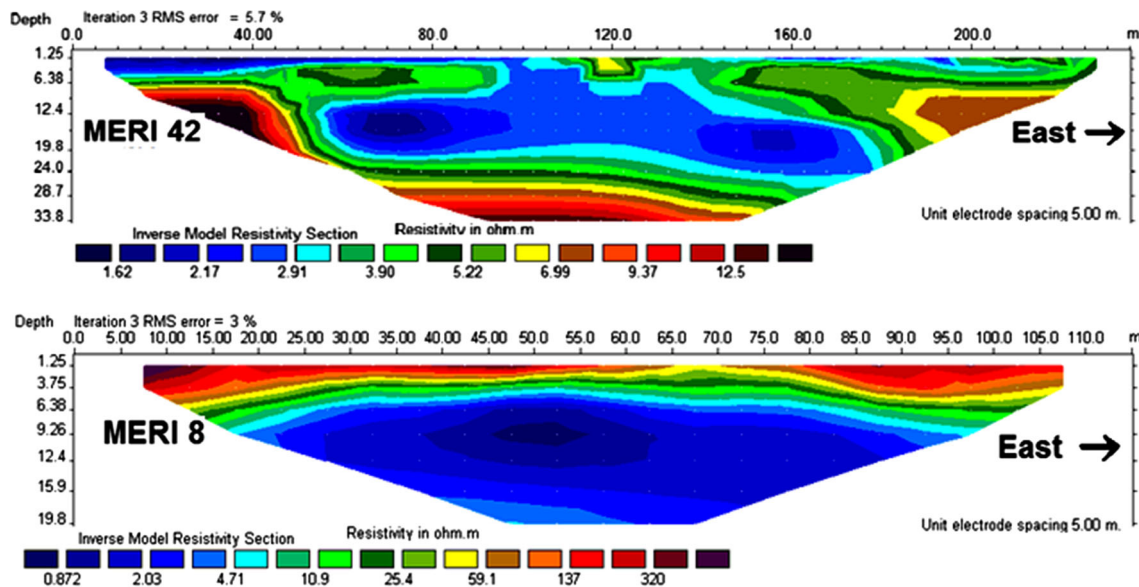


Fig. 6 MERI images of G–G' MERI profile

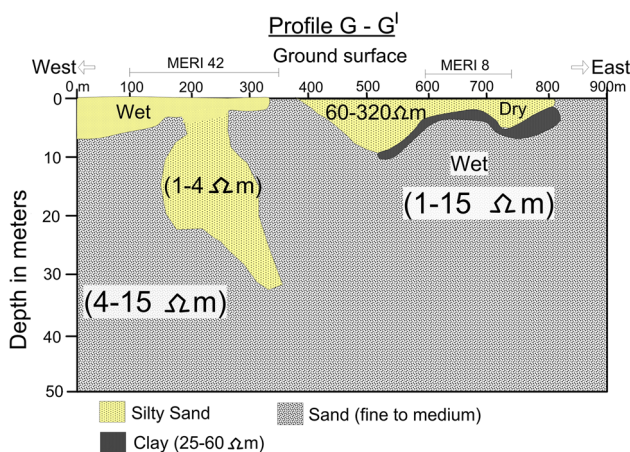


Fig. 7 Geo-electric sections of MERI Profile G–G' in the central part

by coarse sand layer (10–20 Ω-m) with a patch of clay with sand (25–35 Ω-m) occurred in the MERI 37 below 38 m depth between 1000 and 1800 m surface distances in the profile. The top soil low resistivity (0.5–10 Ω-m) is due to the saline water intrusion from Uppanar River which is further verified with the hydrochemical results from nearby observation well. The detailed chemical scanning at the nearby well shows EC value 6172 μS/cm, sodium: 657 mg/l (28.6 epm, equivalent per million); potassium: 151 mg/l (3.9 epm); calcium: 187 mg/l (9.4 epm); magnesium: 235 mg/l (19.6 epm); chloride: 1252 mg/l (35.3 epm); sulfate: 803 mg/l (8.3 epm) and bicarbonate: 226 mg/l (3.7 epm) noted in the well tapping the groundwater from 6.5 m below MSL (Fig. 3). The direct indication of saline intrusion can be determined if the ratio of  $Mg^{2+}/Ca^{2+}$  in epm is

greater than 5; if it is 1–5, it indicates upcoming of brines and salinity (CAMP 2000). At this well, the ionic ratio of  $Mg^{2+}/Ca^{2+}$  in epm was noted as 2.08 confirming salinity from the marine source. The high value of EC,  $Mg^{2+}/Ca^{2+}$  epm ratio > 2 and low resistivity range are well correlated and accessed the pathways for salinity from Uppanar River (Fig. 9). The measured depth to water level in the well was 6.46 m below MSL (Fig. 3). This water table (6.46 m, below MSL) has generated cone of depression which subsequently enhanced the reversal of hydraulic gradient towards western side. The salinity intrusion is due to overexploitation of the groundwater resources since the shallow sandy aquifers are characterized with good lateral hydraulic conductivity.

Geo-electric sections of MERI profiles from A–A' to J–J' helped to determine the resistivity ranges of distinct geological medium existing in the study area. The electrical resistivity of the geological medium are calibrated and validated with the available bore hole lithologs in the study area. Based on this correlation, the common ranges of electrical resistivities for various geo-formations have been established and shown in Table 1. Further, it is observed that the resistivity of a geological medium is not unique to it and there is considerable overlapping of resistivity ranges of few formation types, depending on moisture content, percentage of clay, porosity, formation compactness, grain size and matrix material, quality of water/salinity, and degree of anthropogenic contaminations. However, the order of resistivity range has provided the basic information which is enhanced by integrated hydro-geophysical parameters such as depth to water table (below or above MSL) and salinity level by measuring EC of groundwater.



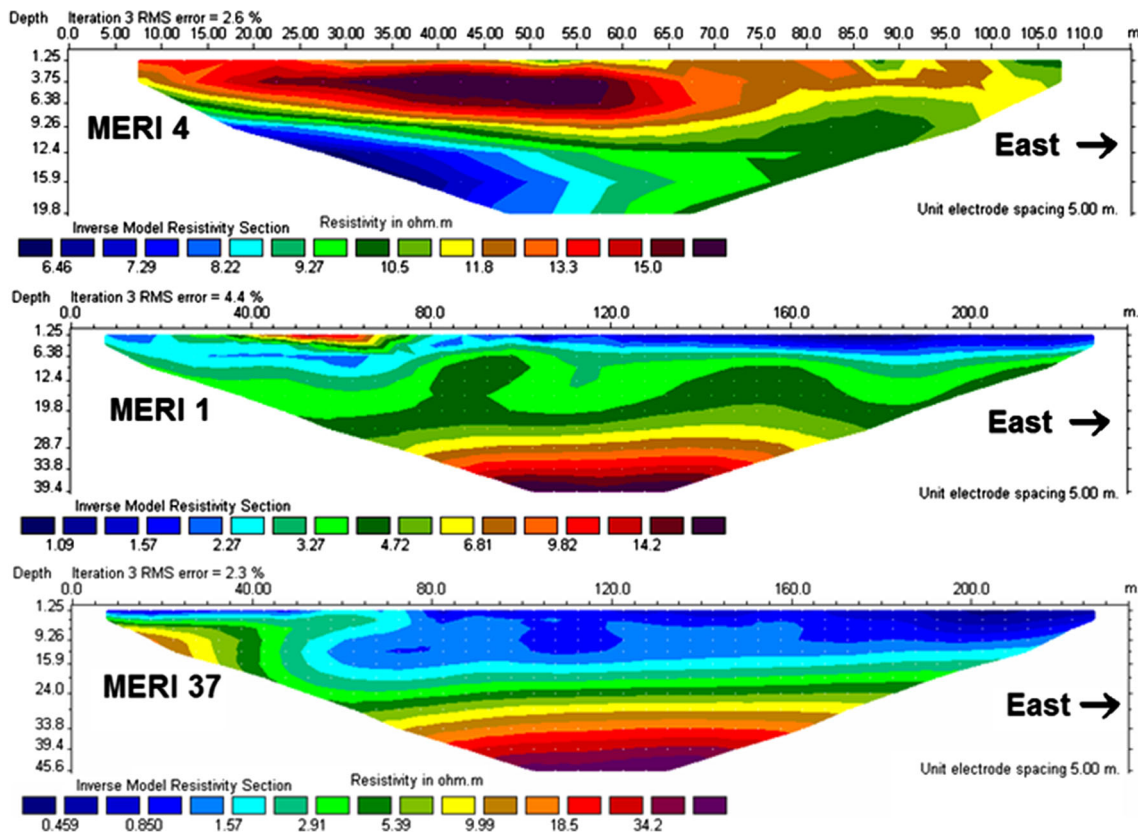


Fig. 8 MERI images of J–J' MERI profile

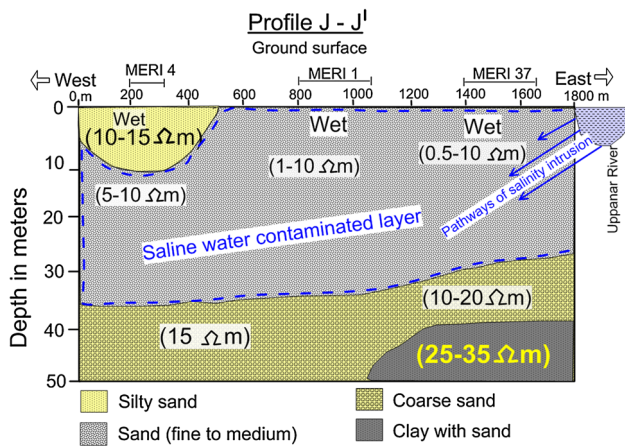


Fig. 9 Geo-electric sections of MERI Profile J–J' in the southern part

Thus the integrated hydro-geophysical study provides new insights for shallow subsurface geophysics in protecting freshwater lens in coastal belt. In general, the geoelectrical sections indicates the silty sand as top layer with varying resistivity ranges depending upon the moisture content and degree of contamination. The insitu EC of groundwaters ranges from 5469 to 30,891  $\mu\text{S}/\text{cm}$  from silty aquifers is caused to the anthropogenic pollution. Further, the EC

Table 1 Resistivity ranges of geological medium obtained from MERI correlating with well logs, in the coastal area of Cuddalore, India

S. no	Geological medium	Resistivity range (in $\Omega\text{-m}$ )
1	Silt (dry)	100–2000
2	Silt (wet)	5–30
3	Sand (fine to medium)	1–20
4	Silty clay (with sand)	25–50
5	Silty clay	30–80
6	Laterite (weathered saturated)	30–60
7	Laterite (hard dry)	100–2000

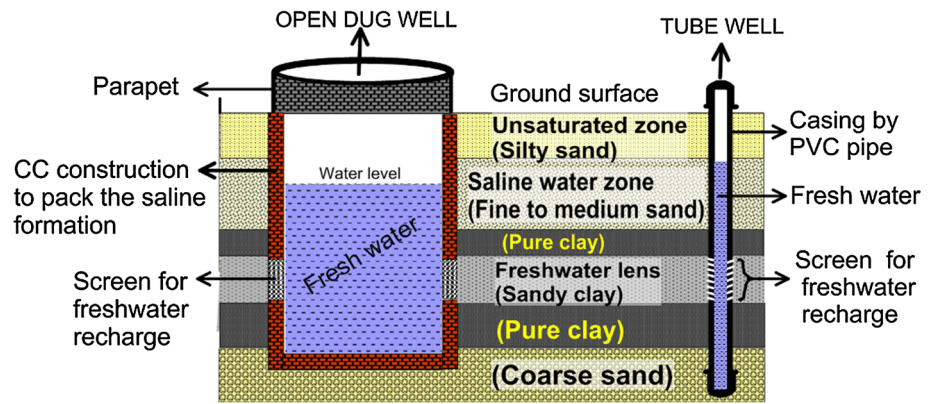
value of the groundwater samples close to MERI points has good agreement with the electrical resistivity. Also, the depth to water level (Fig. 3) measured in the observation wells matches with the depth of relative low resistivity (for saturated layer) in the MERI section.

### Strategies for safe exploitation of fresh aquifer

Since the coastal aquifers are highly porous in nature and always tend to reach chemical equilibrium transporting the



**Fig. 10** Schematic diagram of water well design to resolve intermixing of freshwater and saline water zones at coastal area



dissolved chemical constituents in vertical and lateral path (Sonkamble et al. 2012). In the coastal plain, an aquifer is typically composed of one to several layers with varying thickness and permeable sands or clay-rich materials. Confining units, consisting of clay-rich sediments, exist above and below an aquifer. These confining units are more continuous clay layers and separate the aquifers. The vertical variations in salinity are commonly found in coastal aquifers due to its multi layer system of quaternary formations. Hence, scientific and technical considerations are mandatory to design the water well and to avoid vertical contaminations of salinity in coastal belts. This is possible only, if the depth and thickness of freshwater lens are pre known.

*Well depth*

Several factors like position and potential of aquifers, salinity of groundwater, discharge, method of drilling and well construction, besides economic consideration, may determine the depth of well. Information pertaining to the depth zones of the aquifers and their productivities will be helpful in deciding how much of the aquifer has to be tapped to obtain a sustainable yield. Depending on the yield factor and the desired drawdown, the thickness of the aquifer that has to be screened to obtain a specified discharge may be estimated.

*Screen length and position*

The length of the screen to be installed is selected on the basis of the thickness of the aquifer to be tapped, anticipated drawdown and decline in the water levels, and stratification of the aquifer. In homogeneous aquifer, the lower one-third portion is screened since the upper portion gets desaturated during pumping. If the aquifer is heterogeneous, the most permeable portion of the lower part of the aquifer is tapped. When aquifers characterized by

salinity zoning in a vertical profile, the upper portion of the aquifer should be tapped.

*Screen size*

The most important part of the tube well is the screened or slotted section through which the water enters the well. The screen length, screen diameter and dimensions of perforations in the screen taken together determine the open area available for the water to enter the tube well. The maximum open area is obtained by providing V-shaped slots that widen towards the inside of the screen so that grains do not get lodged in the slots.

*Sealing of undesirable zones*

Zones which contain undesirable qualities of water should be efficiently sealed to prevent contamination of freshwater zones. If such zones are present in the lowest part of the hole, they should be back filled with clay or cement grout. If they occur in intermediate positions, the annular space against such zones should be sealed by cement grout. When surface contamination is suspected and salinity protection is to be provided to the well, the annular space between the casing and the drilled hole should be sealed from the top, down to safe level of about 10 m.

The present study forms the base for finding freshwater lens and also demarcated the zones of saline water ingress and industrial pollution. The communities have been informed about the zones of freshwater lens and advised to design the open wells of large diameter as per the schematic diagram shown in Fig. 10. The large diameter (~5 m) wells are therefore recommended that hold high storage capacity to sustain high discharge. The schematic diagram of water well design in Fig. 10 illustrates the construction method for the open well and tube well penetrating through the various formations of coastal sediments. For example, consider the freshwater bearing clay

lens (sand mixed) is overlain and underlain by porous formation of saline water (Fig. 10). To avoid vertical contamination of freshwater lens in open dug well, the overlain saline formation should be sealed with cement concrete (CC) construction from inside and the bottom of the well as well (Fig. 10). But for tube well, the casing has to be made a screen at the freshwater column to get recharged and the bottom of the casing is required to be sealed to avoid any leakage from saline formation (Fig. 10). Due care needs to be taken in CC construction and during installation of the casing to avoid leakage.

This idea has been adapted by the communities successfully, resolving the freshwater scarcity in the study area. Also, they are advised to withdraw the groundwater as minimal usage so that the stress on freshwater aquifer can be reduced. The communities have perception about the shortage of fresh groundwater and therefore they made optimal pumping rates as a regulation to be applied for their future generation.

## Conclusions

The conclusions are based on the integrated results of the parameters such as electrical resistivity of subsurface layers, electrical conductivity of groundwater sample, hydrochemical data, and water table referenced to mean sea level and topographic survey. The integrated geophysical scanning, hydrochemistry, topography, and water table have assisted to decipher the freshwater lens at coastal area of Cuddalore resolving the problem of intermixing of the saline and fresh groundwater resources. Based on the findings of the hydrogeophysical investigations the concluding points are drawn and summarized as (1) the low range of electrical resistivity (1–10  $\Omega$ -m), high electrical conductivity (30,891  $\mu$ S/cm) of groundwater and water table (1.55 m) above MSL has confirmed the zone of subsurface contamination by effluent but the zone showing  $\rho = 1\text{--}10\ \Omega\text{-m}$ , EC: 6172  $\mu$ S/cm, water table 6.46 m below mean sea level confirms the saline water intrusion, (2) freshwater formations are mostly identified in beach ridges (sandy clay) underlain by clay layers of electrical resistivity range 30–60  $\Omega$ -m, electrical conductivity of groundwater 453  $\mu$ S/cm and water table above MSL, and (3) design of well construction has been helpful in tapping the fresh groundwater, avoiding the vertical short circuit of saline and freshwater.

This study forms the basic tool and established the strategies for sustainable groundwater management in coastal area. The strategies are (1) construction of a subsurface dyke along either side of the Highway covering SIPCOT area, (2) optimal withdrawal rates (establish by aquifer modelling) of groundwater from shallow

unconfined aquifers, (3) increase the rain water harvesting through infiltration galleries to washout the salinity, (4) prevention of open dumping of untreated industrial effluent, municipal waste, washing waste of chemical barrels, and (5) establishment of common effluent treatment plant (CETP) in the industrial cluster.

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