ORIGINAL PAPER

An integrated approach to investigate saline water intrusion and to identify the salinity sources in the Central Godavari delta, Andhra Pradesh, India

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Abstract The Central Godavari delta is located along the Bay of Bengal Coast, Andhra Pradesh, India, and is drained by Pikaleru, Kunavaram and Vasalatippa drains. There is no groundwater pumping for agriculture as wells as for domestic purpose due to the brackish nature of the groundwater at shallow depths. The groundwater table depths vary from 0.8 to 3.4 m and in the Ravva Onshore wells, 4.5 to 13.3 m. Electrical Resistivity Tomography (ERT) surveys were carried out at several locations in the delta to delineate the aquifer geometry and to identify saline water aquifer zones. Groundwater samples collected and analyzed for major ions for assessing the saline water intrusion and to identify the salinity origin in the delta region. The results derived from ERT indicated low resistivity values in the area, which can be attributed to the existence of thick marine clays from ground surface to 12–15 m below ground level near the coast and high resistivity values are due to the presence of coarse sand with freshwater away from the coast. The resistivity values similar to saline water <0.01 Ω m is attributed to the mixing of the saline water along surface water drains. In the Ravva Onshore Terminal low resistivity values indicated up coning of saline water and mixing of saline water from Pikaleru drain. The SO_4^{-2}/Cl^- and Na^{+2}/Cl^- ratios did not indicate saline water intrusion and the salinity is due to marine palaeosalinity, dilution of marine clays and dissolution of evaporites.

Keywords Central Godavari delta · Groundwater · Groundwater Salinity · Evaporites · Ionic ratios

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Introduction

The high population density along the banks of major rivers and coastal areas is attributed to the easy availability of water. The search for groundwater also began along the alluvial tracts of rivers and coastal areas. The semi consolidated and unconsolidated sediments along the coastline helped mankind to go in for deeper groundwater exploration during the first half of the last century. As the exploration advanced towards deeper horizons, problems like salinity hazard, salt water intrusion, and land subsidence were encountered, which made the situation quite complex. The high population and the modern living standards demand more water, which has put the coastal aquifers under stress. Most of the coastal aquifers are sedimentary in nature, with a few out crops of hard rocks along the coast. One of the important features of coastal deposits is the occurrence of multilayered aquifers formed under freshwater, marine, and estuarine depositional environments. Coarse sediments are found to occur along the coast where youthful rivers discharge. Generally due to the differential compaction and

the nature of the bedrock topography, the coastal sediments attain a seaward dip. All these factors have a control on the quality of the formation water. The shorelines can be straight or irregular depending upon the structural features and wave energy. The delta formation along the river mouths has also an important role in the coastal hydrogeologic scenario. The distribution of freshwater aquifers is controlled by the dynamic equilibrium between hydrostatic heads in the fresh and saline water zones, influx of seawater into the streams and lagoons. Hence, the coastal aquifers are highly vulnerable to seawater intrusion and the shallow aquifers are easily depleted due to overexploitation of groundwater in many parts of India and worldwide (Khair et al. 1994; Gossling 2001; Vengosh et al. 2005; Lambrakis 2006; Sarwade et al. 2007; Chidambaram et al. 2008; Alpar 2009; Carreira et al. 2010; Mondal et al. 2011). It causes potential salinization of groundwater and their sources are diverse including natural saline groundwater (Vengosh et al. 1999; Trefry et al. 2007; Falgas et al. 2009); halite dissolution (Hidalgo and Cruz-Sanjulian 2001); presence of palaeo-brackish water, seawater intrusion (Kouzana et al. 2010; Abdollahi-Nasab et al. 2010; Sanford and Pope 2010); domestic, agricultural, and industrial effluents (Danielopol et al. 2003; Custodio 2010; Mondal et al. 2011). Among these sources, seawater intrusion is the most common and widespread in coastal areas, and forces the abandonment of water wells in many instances (Giordana and Montginoul 2006). Groundwater contamination due to saline water, industrial effluents or delineation of thickness and geometry of aquifer 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 boreholes data to understand the subsurface depositional features (Maillet 1947). The traditional resistivity measurements are carried out on the earth surface with a specified array, so that one obtained apparent resistivity sounding curves, apparent resistivity profile data or apparent resistivity pseudo-sections, all of which in a qualitative way reflect the horizontal or vertical variations in subsurface resistivity. Geophysical prospecting techniques can provide complementary data that enable geological correlation, even in sectors where there are no data from boreholes. Indirect geophysical methods (like ERT/HERT 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). 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; Frohlich et al. 1994).

The study area comes under Central Godavari canal command, which is called the food basket of India. Paddy crop were grown successively for three times in this region and there is no groundwater withdrawal for irrigation and also for domestic purpose. The groundwater at shallow depth is brackish in nature. The area experiences floods in every other year, and the lower reaches of the delta is affected by saline water mixing during tidal fluctuations. In the present study, we made an attempt to demarcate the saline water zones and to identify salinity origin in the delta region using Geophysical and hydrochemical investigations.

Description of the study area

The Central Godavari Delta, forming part of Godavari delta, is situated in East Godavari district of Andhra Pradesh in East coast of India. The study area covers about 295 km^2 located in the southern part of Godavari delta and is bounded by Bay of Bengal in the Eastern side and Vainateya River in the west, and plain lands of alluvial nature in the northern side (Fig. 1). The average annual rainfall in the study area of East Godavari District is about 1,137 mm distributed unevenly over 57 rainy days. In this area about 72 % rainfall occurs during the southwest monsoon season (June–September). During the northeast monsoon (October–December) the rainfall varies from 226 to 456 mm. July is the wettest month contributing to about 26 % of the annual rainfall and nearly 57 % of the SW monsoon rainfall. The central Godavari delta region provides an excellent opportunity for irrigated agriculture due to availability of vast stretches of arable fertile land created by river and coastal deltas. The majority of the Indian major river systems end up in the Bay of Bengal in the east coast thereby providing ample surface water potential for use for irrigation. Water is available in the canals throughout the year except between the last week of April and the second week of June. Three crops are grown successively in a year. The use of fertilizers and pesticides is very high in this region. As ample surface water is made available to irrigate the delta, there has been little or no effort to use groundwater in the delta. The area experiences seasonal floods in every alternate year. Godavari irrigation canal network is well spread out in the area and provides perennial source of irrigation in all seasons. Irrigation Canals in the area flows towards the Bay of Bengal through three important drains: Vasalastippa, Kunavaram and Pikaleru drains. Large network of Godavari canals are providing perennial irrigation as well as drinking water needs in the delta. These canals

Fig. 1 Location map of the Central Godavari delta, East Godavari district, A.P., India
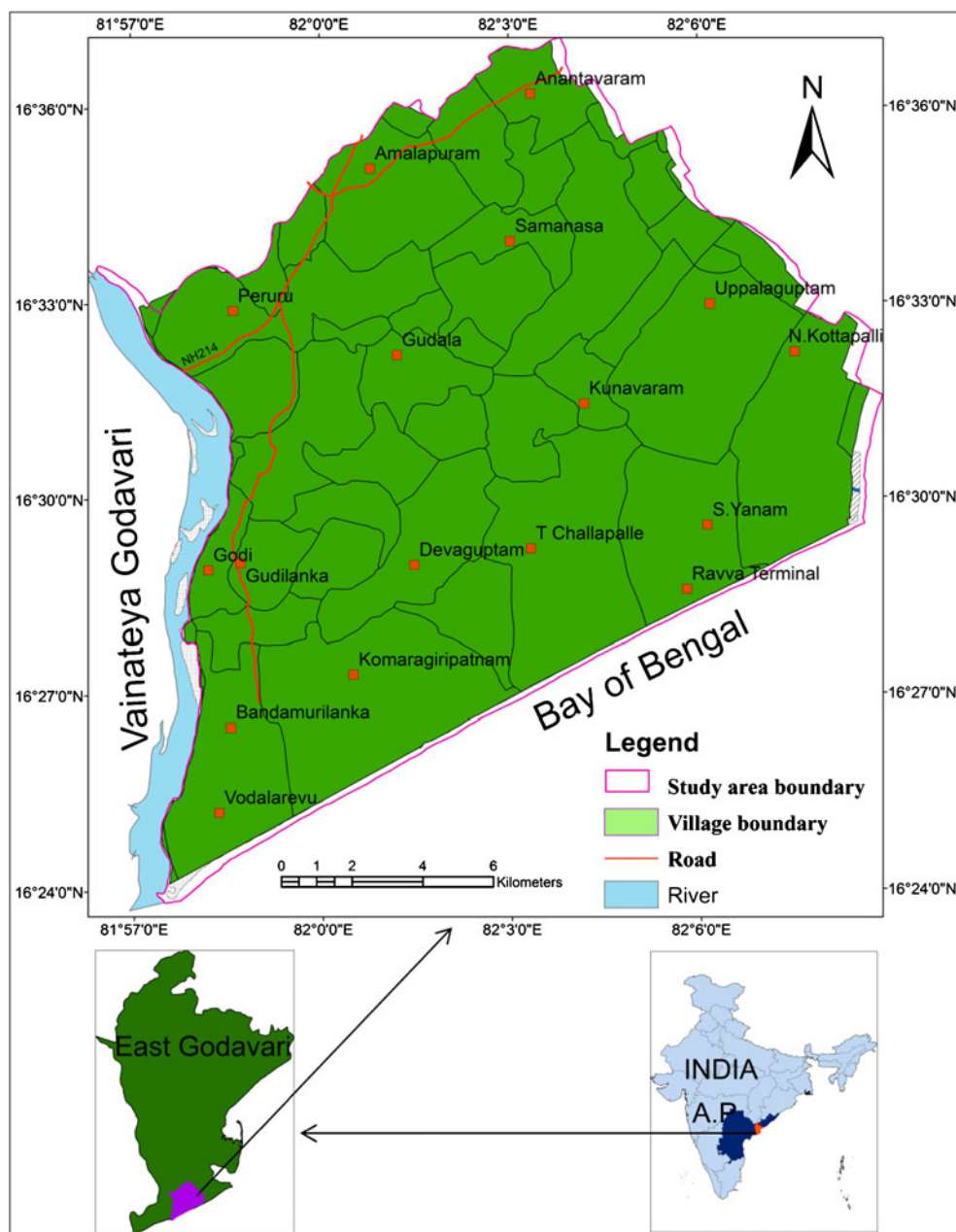
significantly help in reducing the native salinity of underlying marine clays due to recession of sea from inland to shore. The canals are in operation during last century and had been contributing for groundwater recharge, which impacted the improvement of groundwater quality in the area.

Geology and hydrogeology

The area is underlain by deltaic alluvium of recent age consisting of clay, silt, sand and gravel in varying proportions. Groundwater occurs under water table conditions, but semi-confined and confined conditions tend to develop in the area where impervious beds like clay overlie the saturated granular

zones. The groundwater is being tapped by shallow open wells ranging in depth from 3 to 8 m and filterpoint wells with a depth ranging up to 20 m. A series of marine transgressions and regressions in the past have greatly influenced the depositional environments of the delta. Four strand lines have been delineated on the basis of disposition of ancient channels and beach ridges, which indicate the successive stages in progradation of coastline in the evolution of delta (Rengamannar and Pradhan 1991). The study area includes both fluvial and marine landforms. The marine landforms are tidal flats, beach ridge complexes, mangrove swamps, etc. The fluvial landforms are palaeo channels, levees, back swamps, and flood plain. The Godavari delta area is a flat alluvial terrain and ground elevations vary from ~2 m at Ravva onshore terminal near the coast

to a maximum elevation of 7.8 m from mean sea level at Amalapuram in the western side. The area is represented by tidal flat inlets which receives seawater during high tides. The area has rich in Quaternary alluvial formed by river Godavari and topography is having a gentle slope towards the coast with a value of 0.0001 km^{-1} (Bobba 2002). A major part of the area consists of sandy loams and sandy clay loams. 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. Godavari River started discharging large amounts of sediments into the Bay of Bengal, thus initiating the delta building processes during the quaternary period. The upper deltaic sediments are essentially fluvial while those in the lower delta region are fluvio-marine sediments (Fig. 2; GSI 2006; Gurunadha Rao et al. 2011). The thickness of granular zones in the alluvium ranges from 18 to 258 m within the explored depths (CGWB 1999; Bobba 2002).

## Methodology and field equipment

Major ions

For the assessment of groundwater quality, 42 groundwater samples were collected from the shallow dug wells, bore wells and hand pumps in the pre-monsoon (June) and post-monsoon (November) seasons in the year 2006 from the represented dug wells, bore wells and hand pumps distributed throughout the study area. Samples were analyzed for major and minor ions (pH, electrical conductivity [EC], Ca^{+2}, Mg^{+2}, Na^+, HCO_3^-, Cl^-, SO_4^{-2}, NO_3^- and Br^-) by following standard methods suggested by APHA (2005). These samples were collected in 1-l polythene bottles. Prior to collection the bottles were thoroughly washed with diluted HNO_3^- acid, and then with distilled water in the laboratory before filling the bottle with the sample. The bottle is rinsed to avoid any possible contamination in bottling and every other precautionary measure has been taken. The chemical parameters analyzed include Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^- and Cl^- by volumetric method, Na^+ and K^+ were analyzed by flame photometer; F was analyzed by ion metric methods, NO_3^- by double beam spectrophotometer, SO_4^{-2} by turbidity, pH by a pH meter, total dissolved salt by gravimetric method and conductivity by conductivity meter.

Electrical Resistivity Tomography (ERT)

The resistivity was collected using SYSCAL PRO-96, IRIS-make instrument. 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

Fig. 2 Geology of the study area
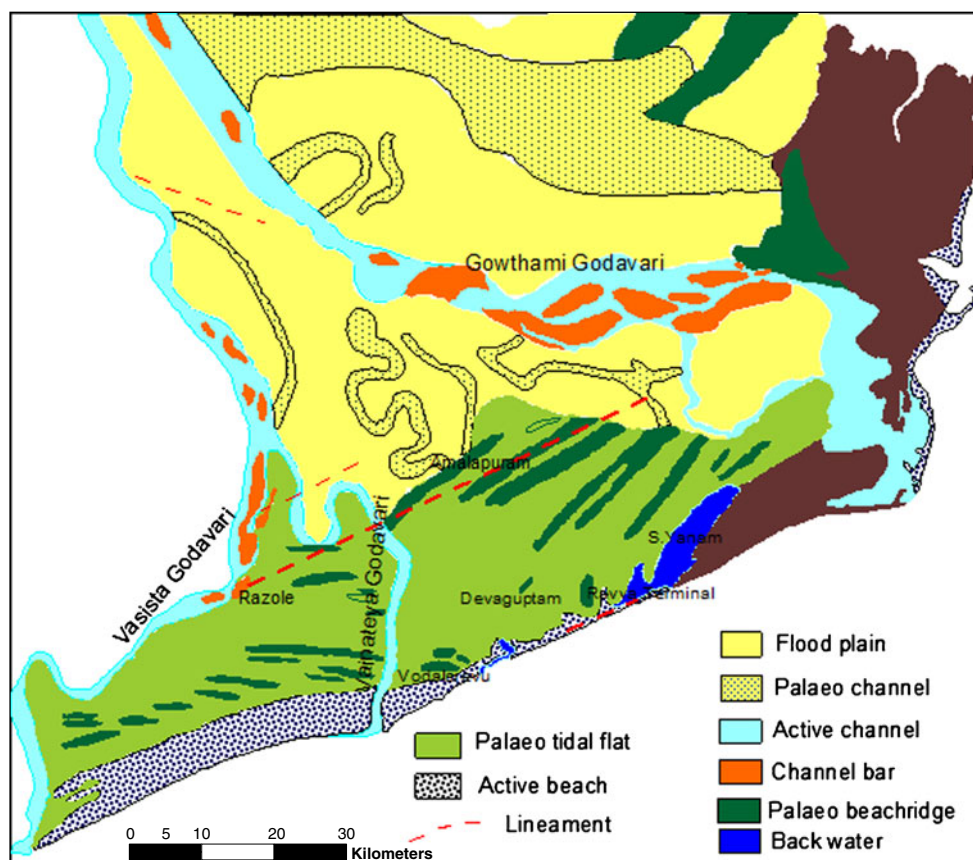
can use second and third spacing maximum up to nine times of physically allowed maximum spacing to acquire data from deeper levels. The measured apparent resistivity is converted into true resistivity using RES2D.INV inversion program in order to produce the 2D resistivity cross-section image. The Multi-Electrode Resistivity Imaging system used for 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.

In electrical resistivity method, the subsurface was energized by pumping with known amount of current (I) in to the sub-surface and measure the response on the ground surface in the form of voltage (V). Current electrodes are used for exciting the subsurface and potential electrodes for measuring the response on the surface. Electrical resistance

[R] is calculated (V/I), and apparent resistivities are computed for each electrode configuration taking into account the geometrical factor of the array, which varies from array to array and finally an apparent resistivity section can be obtained. In the present study, 2D Wenner–Schlumberger array was used to investigate subsurface of aquifer system. To tackle the 2D and 3D problems, we need more intensive data which is possible with multi-electrode systems (Griffiths et al. 1990; Griffiths and Barker 1993) and resistivity surveying instruments (Griffiths et al. 1990) and fast computer inversion software (Loke 1994). In a 2D subsurface model, the distribution of resistivity is both in vertical and horizontal directions, along with the traverse line. In this, we assume that there is no resistivity variation in the direction perpendicular to the traverse line. For carrying out 2D/3D imaging survey, the electrodes are to be planted along with the traverse in selected array type and measurements are done in a sequential pattern changing the interelectrode spacing in a systematic way, so that the subsurface is scanned depending upon the penetration of current lines. This entire measurement procedure will be carried out by the system and the data is stored in the system itself.

Fig. 3 Location maps of observation wells and ERT in the Central Godavari delta, A.P., India
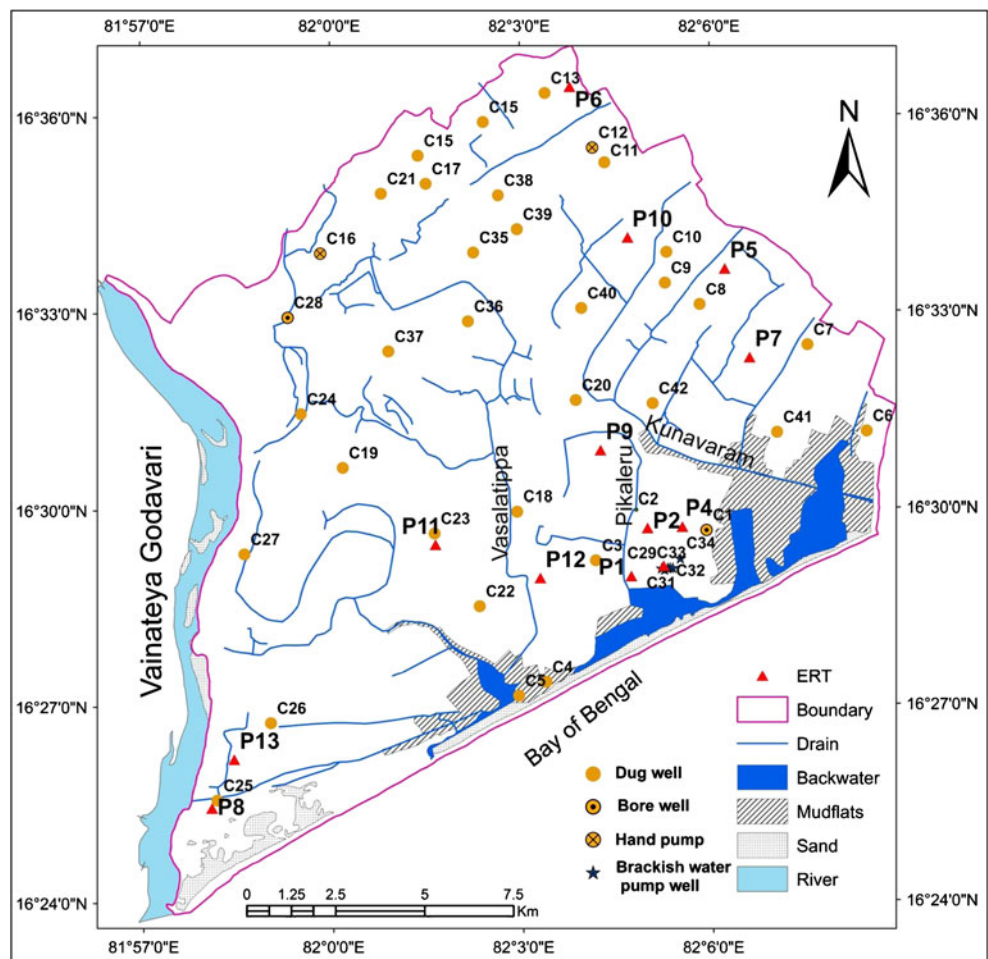
Data presentation and interpretation

2D resistivity/IP data is interpreted using 2D-Forward modeling software. Apparent resistivity values are calculated using finite-difference (Dey and Morrison 1979) or finite-element (Silvester and Ferrari 1990) method. RES2DINV inversion program can be applied and useful in studying the model resolution that can be obtained over different structures using various electrode configurations. RES2DINV will automatically determine a 2D resistivity model for the
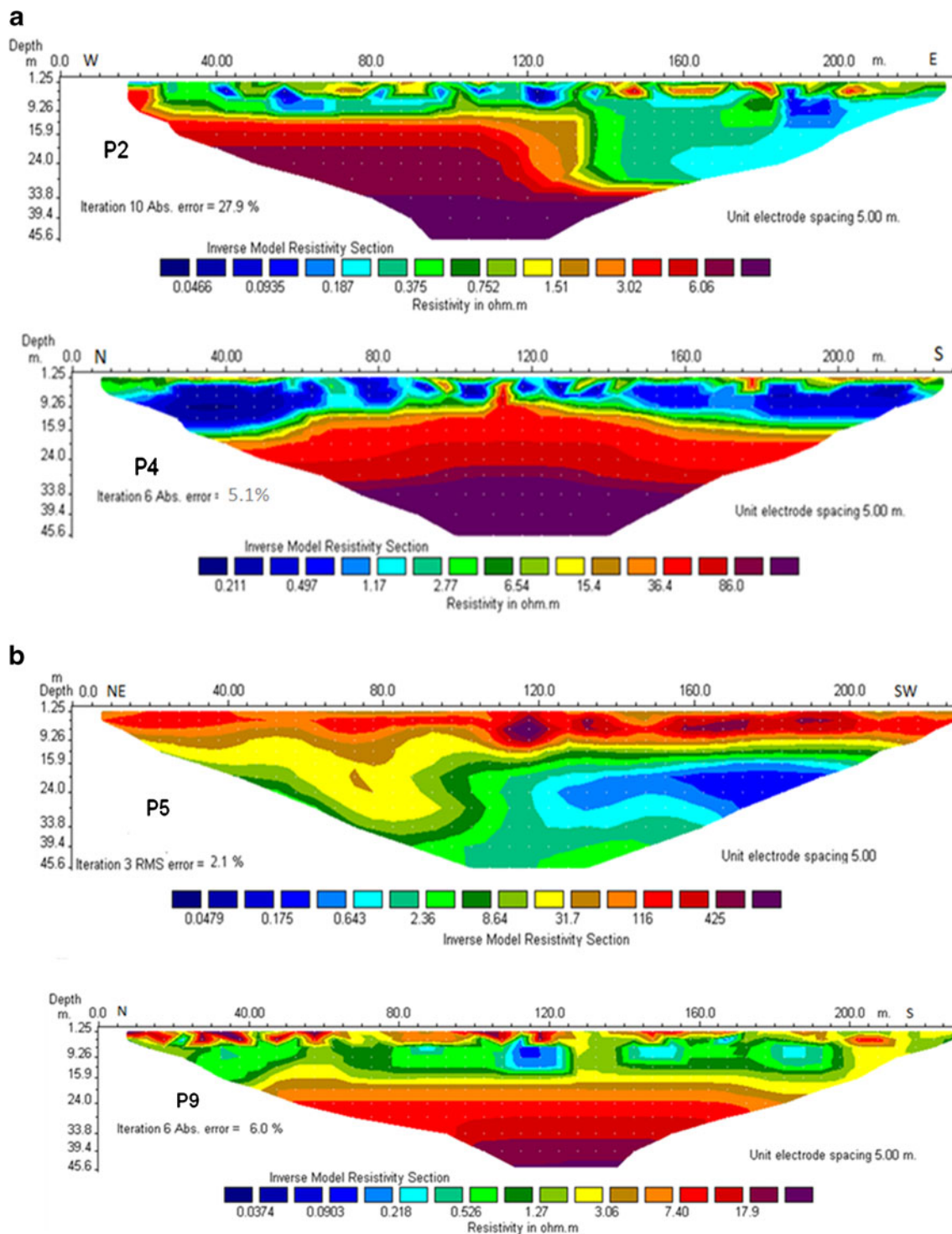

Fig. 4 a Electrical Resistivity Tomography (ERT) images in the Central Godavari delta, A.P., India. **b** ERT images in the Central Godavari delta, A.P., India. **c** ERT images in the Central Godavari delta, A.P., India
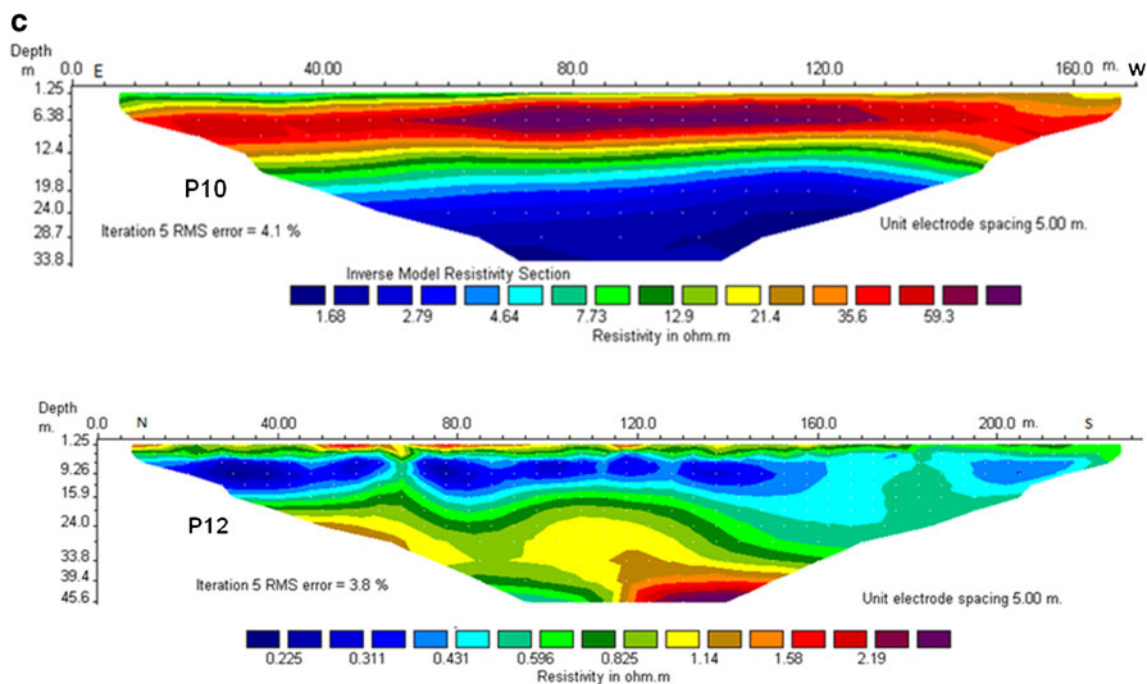
Fig. 4 (continued)

subsurface for the data obtained from electrical imaging surveys (Griffiths and Barker 1993). Software is also available for carrying out 3D interpretation where one can get overall subsurface structure with full precision and accuracy. Further, whenever the zones are identified, a soft ware 'slicer–dicer' is applied for interpreting the data so that an in-depth understanding of the sub-surface is possible.

2D imaging data is generally presented in the form of pseudo-depth sections. The location of the plotting point for any symmetric array is the midpoint of the system where as it lies between the current and the next potential electrode for an asymmetric array like three-electrode. Roy and Apparao (1971) proposed depth of investigation characteristic values for electrode arrays taking into account 'maximum contribution concept' after rigorous mathematic treatment. Edwards (1977) proposed another method of data presentation as an empirical approach plotting a vertical depth point at the median depth of investigation. Before presenting the data in the form of pseudo-section, all the individual profiles are to be observed for eliminating the 'bad data' points. The pseudo-section plot obtained by contouring apparent resistivity values is a convenient means for data presentation. However, pseudo-section gives an approximate picture of the sub-surface resistivity distribution and works as an initial guide for further quantitative interpretation. Inversion procedure can be applied for getting an almost true resistivity/IP subsurface geological setting. This is possible for obtaining 2D/3D section depending on the software.

Results and discussion

The electrical resistivity of a geological formation is physical characteristic, determines the flow of electric current in the formation. Resistivity varies with texture of the rock, nature of mineralization and conductivity of electrolyte contained within the rock (Parkhomenko 1967). Resistivity not only changes from formation to formation but even within a particular formation (Sharma 1997). Resistivity increases with grain size and tends to maximum when the grains are coarse (Sharma and Rao 1962), and also when the rock is fine-grained and compact. The resistivity drastically reduces with increase in clay content and which are commonly dispersed throughout as coatings on grains or disseminated masses or as thin layers or lenses. In saturated rocks low resistivity can be due to increased clay content or salinity. Hence, resistivity surveys are the best suited for delineation of clay or saline zone.

Geophysical Investigations using ERT surveys have been carried out at 13 locations in the Godavari delta and the locations were shown in (Fig. 3). The Wenner–Schluberger array with 5-m electrode spacing was used to collect resistivity data as the array can adequately represents signal/noise ratio and also provides adequate resolution, which is an important parameter in low resistivity. The computed RMS error of resistivity data was varying from 2.1 % to 27.9 % in the inverse model resistivity sections. The depth of investigation of about 45 m and various subsurface geological formations like marine clays and saline water mixing areas were inferred

Fig. 5 Groundwater contours in m (asl) and groundwater flow direction in the study area, June 2007.
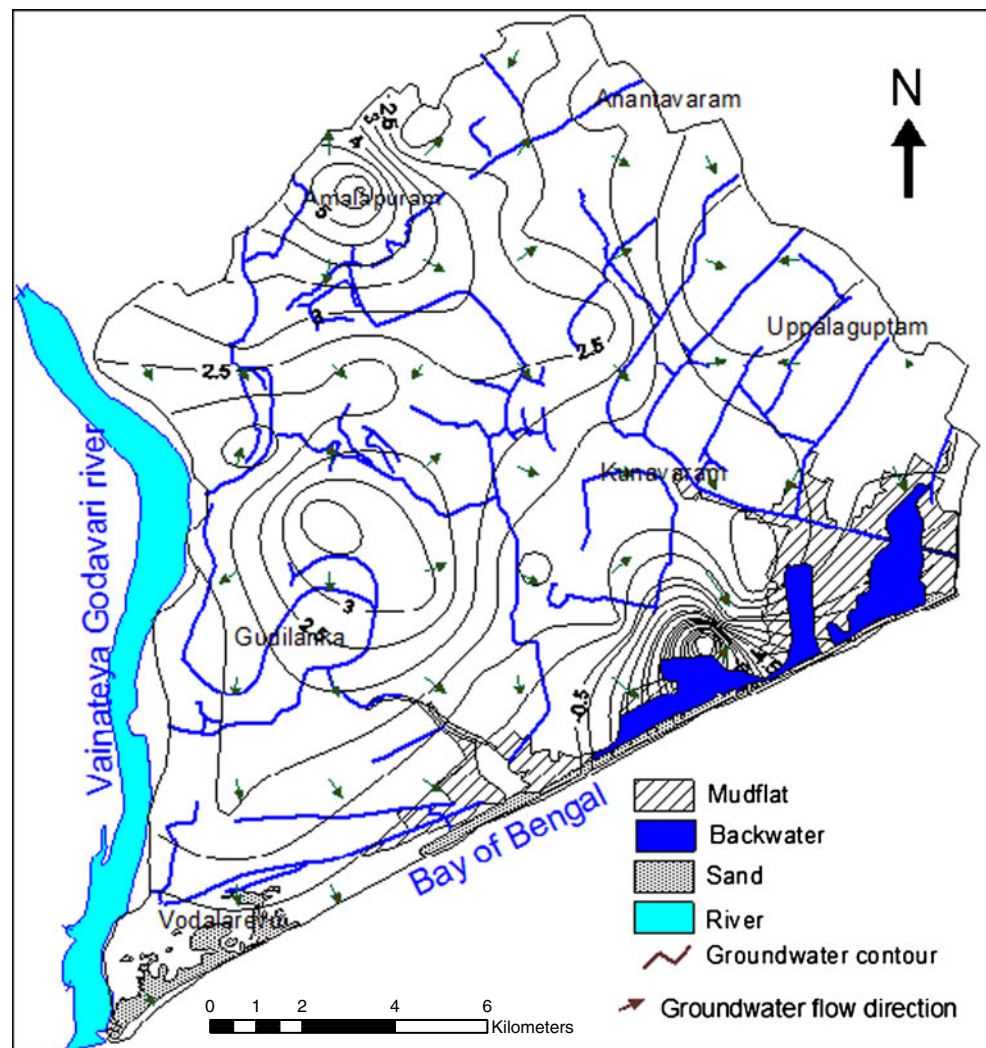
from the resistivity contrast up to a depth of 45 m only. In the coastal areas, the principal aquifers were formed in the

unconsolidated alluvial formations, deposited under various sedimentary environments. The geoelectrical profiles shown

Table 1 Groundwater quality status in the Central Godavari delta, East Godavari district, India

			June 2007				October 2007			
	Code	Village	TDS	Cl	SO4	Na	TDS	Cl	SO4	Na
Min	C38	Pedda Reddy palli	256	43	30	12	141	19	11	6
Max	C32	Ravva Onshore	25088	13490	365	7898	33536	16221	1870	8019
Average			5036	2056	107	1247	6343	2899	356	1473
	C10	Gollavalli	851	270	75	58	947	189	47	160
	C8	Uppalgupatam	1018	270	80	94	666	160	22	80
	C21	Amalapuram	3744	1420	135	699	3354	1490	41	932
	C22	Samanthakuru	4691	1764	110	848	2278	773	121	631
	C25	Odalarevu	3021	1079	95	518	2061	556	143	450
	C26	Bandamulanka	992	298	80	242	1978	698	67	479
	C32	Ravva Onshore	25088	11218	290	7626	32384	16033	1870	7436

All values are expressed in mg/l

Fig. 6 TDS (mg/l) in groundwater of Central Godavari district, East Godavari district, A.P. India
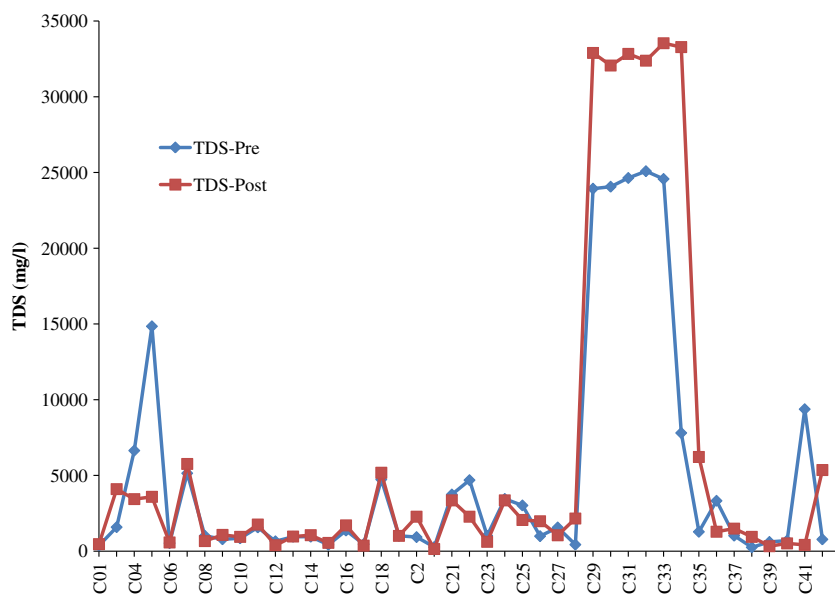
resistivity values that varied laterally with depth and also in the vertical aspect, two levels could be distinguished in accordance with the resistivity signatures obtained from ERT sections. The aquifer geometry and in situ salinity of marine clays in the area was ascertained from the electrical resistivity profile/images (P2, P4, P5, P9, P10 and P12; Fig. 4).

The profile P2 (W–E oriented) was carried towards the North direction near Ravva Onshore Terminal about 300 m distance from Surasani Yanam village. The image depicts that upper layer as a very low resistivity formation with resistivity of <1 Ω m up to a depth of 12 m along profile spreads up to 130 m; the low resistivity formation extended with depth about 30 m along the profile from 130 to 240 m

towards eastern direction. It may be indicative of saline water mixing with the freshwater or representation of extension marine clays to the sea in the East direction. The second layer from 12 to 45 m depth with slight higher resistivity, it is may be due to the presence of coarse sand with clay.

The profile P4 (N–S orientated) has been carried out near Ravva Onshore Terminal in Surasana Yanam village. The image deciphers that existence of threes subsurface conditions. Top layer exhibits very low resistivity value of <1 Ω m and extended up to 15 m depth from the surface, it is due to infiltration of saline water because close proximity to the backwater/wetland or saturated clay with saline water. Second layer represent the slight higher resistivity formation

Fig. 7 Na (mg/l) in groundwater of Central Godavari district, East Godavari district, A.P. India
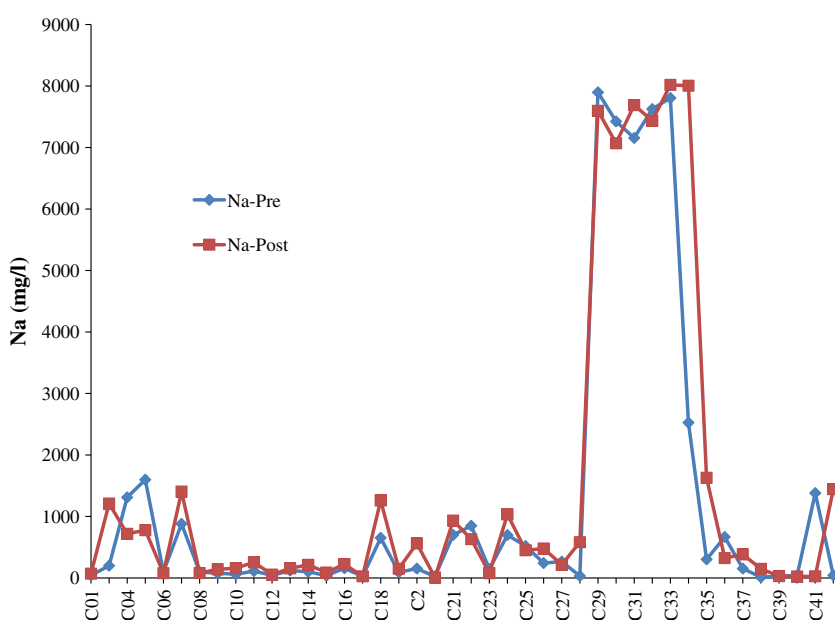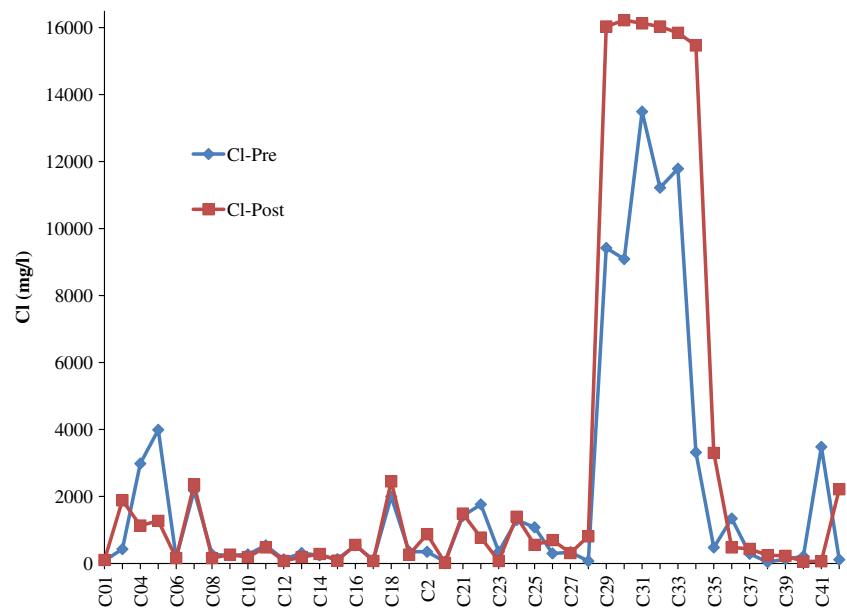
**Fig. 8** Cl Na (mg/l) in groundwater of Central Godavari district, East Godavari district, A.P. India

with ~80 Ω m, it may be because of consolidated sand formation or sand with gravel. The third layer has a higher resistivity with >80 Ω m up to a depth of 45 m, as the thickness of alluvium in that part of delta is very high and country rock is not expected at 45 m.

The profile P5 was carried out in upstream of Uppalaguptham Village and laid on the NE–SW direction. The top layer exhibits high resistivity >90 Ω m from the surface and extended up to 10 m depth; this would be due to the presence of consolidated material mostly with coarse sand and clay, further underlain by low resistivity formation with resistivity of <1 Ω m along the profile of 120 to 240 m at depth of 10–28 m in the NE

direction. This could be the deposition of marine clays in the area. The thickness of this marine clays gradually decreases towards the landward direction and increases towards the seaward direction. The resistivity values were in accordance with those in the ERT images.

The profile P9 was carried out in the Kunavaram Village, laid in the direction of N–S. The resistivity of the area indicates the existence of discrete formation material on the top. The resistivity varying from <1 to 3 Ω m, from surface to 15 m depth, indicates that the marine clays with contaminated soils with saline water existed in the subsurface. The second layer indicates a slightly higher resistivity

Fig. 9 SO₄ (mg/l) in groundwater of Central Godavari district, East Godavari district, A.P. India
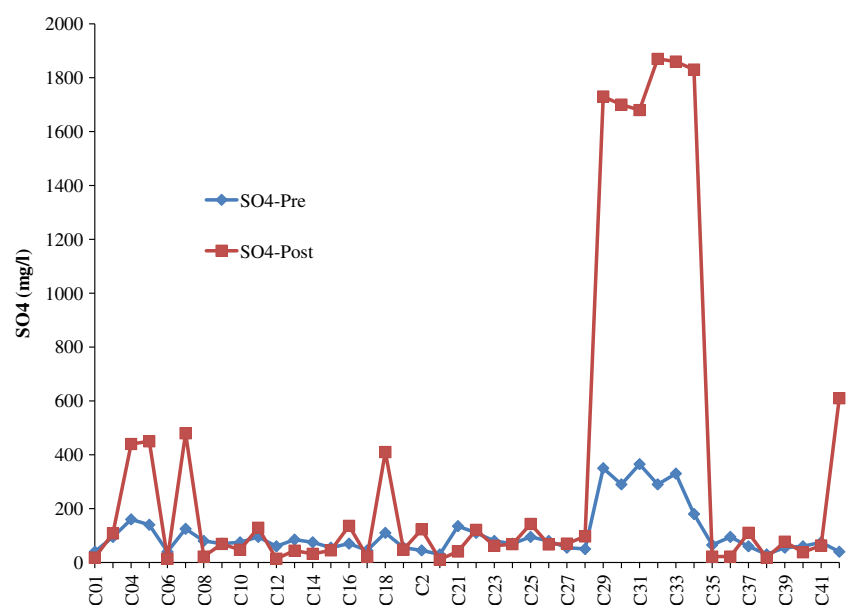
of about 3 to <20 Ω m up to 45 m depth. This layer could represent the contaminated soils with sand and gravel formation in bottom layers.

The Profile P10 has been carried out in near Vilasavilli village, in the E–W direction. The top portion of the image indicates higher resistivity in the area with a resistivity of >50 Ω m up to a depth of 12.5 m; this represents the existence of compacted sandy layer dominated with coarse sand. Furthermore, it is underlain by low resistivity formation with resistivity of 4–20 Ω m up the depth of 23 m. This formation was underlain by very low resistivity formation with resistivity of <2 Ω m up to the depth of 38 m, which could be indicating the marine clays deposition in the delta.

Profile P12 was carried out downstream of Kunavaram village in a N–S direction. The top of the image indicates very low resistivity of <1 Ω m up to the depth of 15 m; this may be due to infiltration of saline water drained from Kunavaram drain during the high tides. This formation was underlined with clay lenses, and this was reflected in

the ERT image with a resistivity of 0.5 to <1.5 Ω m. It was further underlain by slight higher resistivity formation in the bottom layers at the depth of 39–45 m, which may be due to the presence of coarse-grained sand with clay.

Major ion chemistry and groundwater levels

Groundwater occurs at shallow depths in the Godavari delta; groundwater levels in the dug wells are varying from 0.8 to 3.4 m in the delta. In the Ravva Onshore Terminal wells, it varies from 4.5 to 13.2 m. The total depth of dug wells varied from 1.2 to 4.5 m, and in bore wells located in the Ravva Terminal it varied from 18 to 160 m. The established groundwater flow direction is towards the Bay of Bengal from Amalapuram (Fig. 5). Groundwater samples were analyzed for major ions in the Godavari delta region before (June) and after monsoon (October) periods of 2007. The descriptive statistics for TDS, Na^{+2}, Cl^- and SO_4^{-2} are presented in Table 1. The average groundwater salinity

Fig. 10 **a** Spatial distribution of Na/Cl ratios (meq/l) >0.86 may represent presence of water. **b** Spatial distribution of Na/Cl ratios (meq/l) >0.86 may represent presence of water
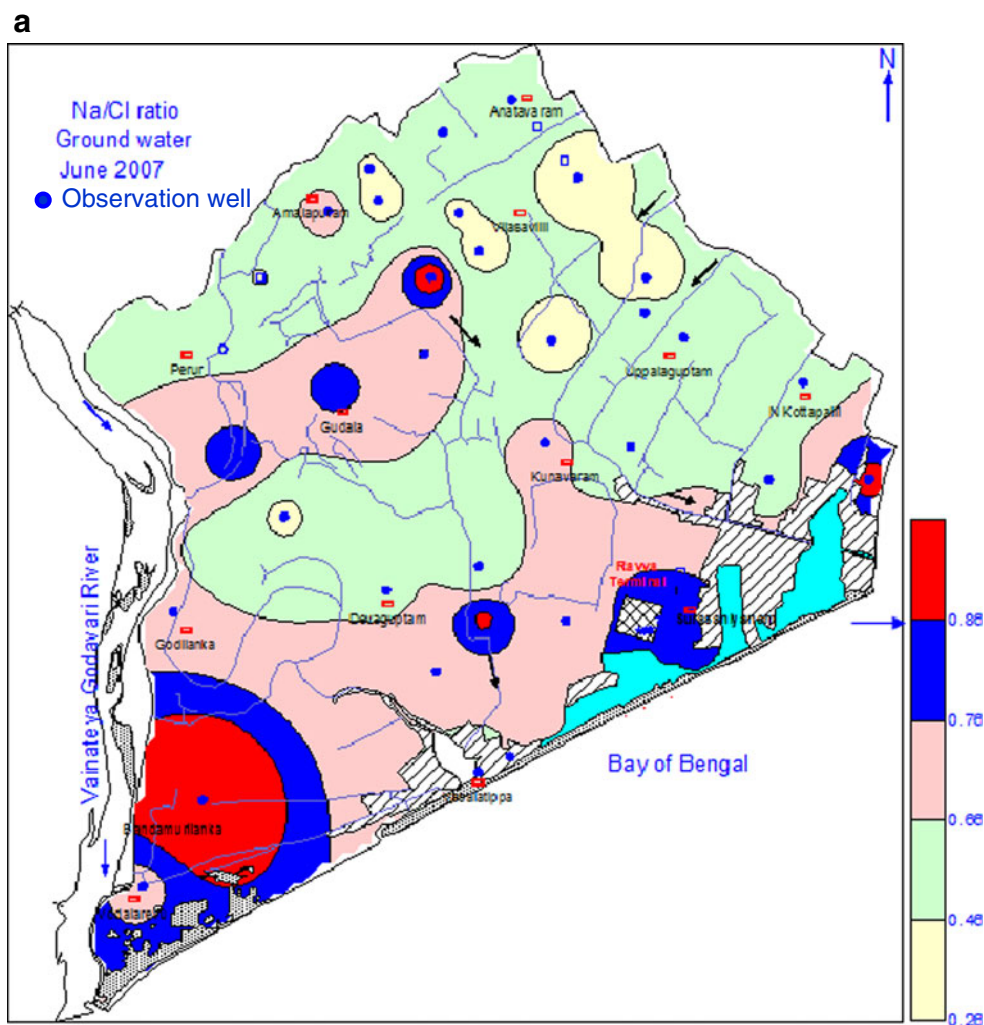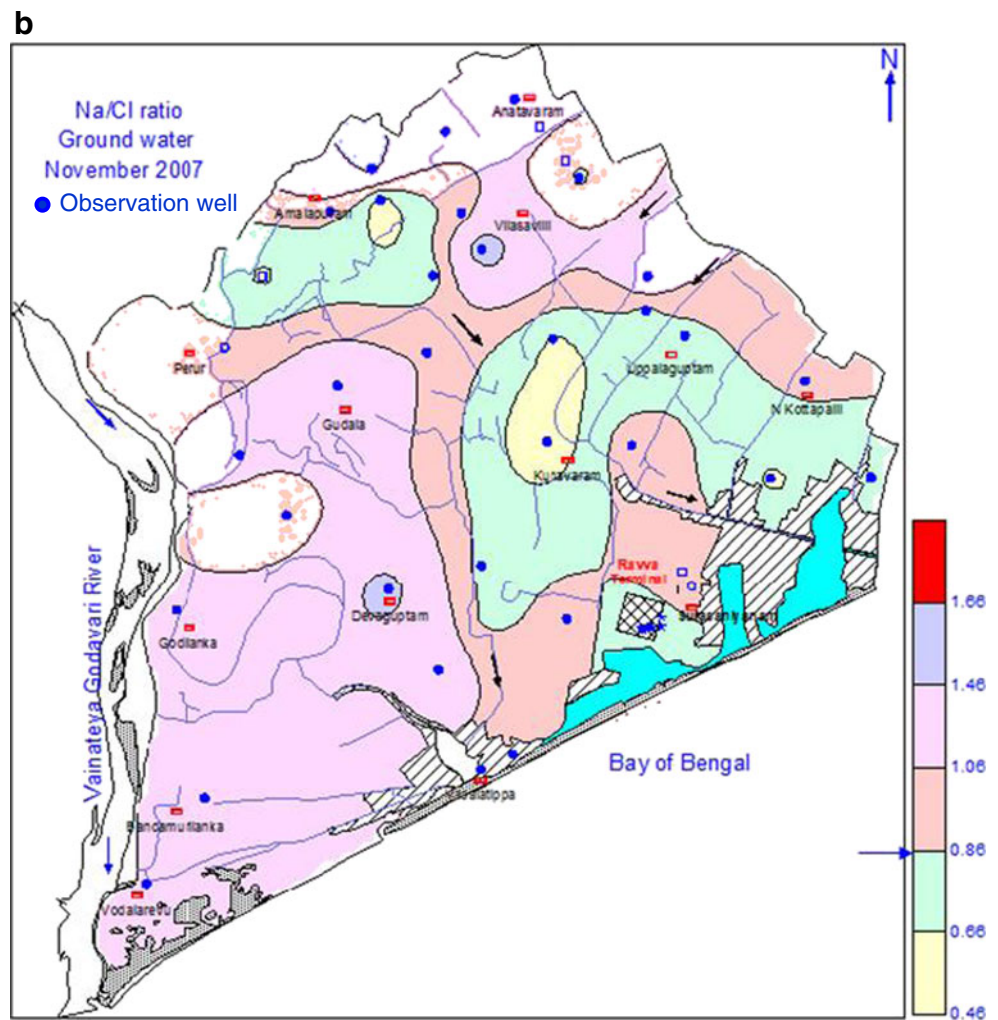
Fig. 10 (continued)

(TDS) varies from 5,036 to 6,343 mgl^{-1} from pre-monsoon to post-monsoon, indicating that in the post monsoon the groundwater salinity is increased due to dilution of aquifer material in groundwater. The maximum TDS was observed in the Ravva Onshore Terminal, and the minimum was in Pedda Reddy palli village. The TDS variations in groundwater from pre- to post-monsoon are shown in Fig. 6. In the post-monsoon, sodium content in groundwater was increased; it is due to dilution of clay minerals rich in sodium. The average sodium was 1,247 mg l^{-1} in pre-monsoon and 1,473 mg l^{-1} in post-monsoon. The temporal variation of sodium is shown in Fig. 7. Chloride and sulphate variations from pre monsoon to post monsoon was shown in Figs. 8 and 9. The average chloride varies from pre- to post-monsoon, from 107 to 356 mg l^{-1}. In pre-monsoon the chlorides are being increased in the wells near drains and coast (C4, C5 and C1); this is due to infiltration of seawater during high tides. There is no considerable change in sulphates in groundwater in the wells away from the coast from pre to post monsoon, whereas a drastic decrease was observed in the pre-monsoon in the wells near coastal areas (C4 and C5) and Ravva

terminal wells (C29 to C34). This is due to the presence of seawater. In the post monsoon, it was being increased, indicating substantial aquifer recharge due to rainfall.

Correlation of ERT results with water quality

The use of resistivity data with hydrochemical data (dissolved solids [TDS] or EC measurements) in groundwater wells can help to identify the contaminated zones. The combination of hydrogeological, geochemical and geophysical investigations can be very effective tools to detect the contaminant migration in groundwater due to waste disposals, to investigate the seawater intrusion, to identify oilfield leakage and mine seepage (Warner 1969; Abu-Zeid et al. 2004; Bernstone and Dahlin 1997; Bisdorf and Lucius 1999; Barker 1981; Barker and Moore 1998). Comparison of resistivity data with hydrochemical data increase the reliability and reduces the 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. In the present study, the sampling

depth of dug wells and hand pumps (C1 to C28 and C35 to C42) is <3.5 m and bore wells (C29 to C34) located near in Ravva Terminal is 10–13.5 m. The sampling depth of all samples are confined to the first layer in ERT images (discussed in the above section), and groundwater quality varied depending on mixing of saline water and other depositional conditions. The resistivity values varied from Bay of Bengal to Amalapuram based on the combined effect of depositional conditions and saline water mixing. The resistivity values show very low values in alluvial aquifers rich in sands, clay and fine-grained, compared to other aquifer materials in the subsurface. Indeed, fine-grained sand formation contain high TDS (>1,000 mg l^{-1}) in groundwater may be responsible for the low resistivity value of the aquifer in the area, and any formation having less than this optimum resistivity value may represent either clay or sand formation. The elevated TDS, sulphate, chloride, and sodium concentrations are reported at Surasaniyanam, Devaguptham, Vasalatippa, and N. Kottapalli villages, which are falling in the lower reaches of the Delta and are in close proximity to the Bay of Bengal. The same thing was reflected in ERT images, particularly those corresponding

images with low resistivity, <0.5 Ω m (P4, P12). The higher concentrations and low resistivity may be due to infiltration of seawater during high tides. Saline water in intruding in the Pikaleru, Kanavaram, and Vasalatippa drains during the high tides and infiltrating into the groundwater. Gollavelli village has a good quality of groundwater in the upper part of the delta; in the image, areas near this village exhibits resistivity of 17 to 50 Ω m in the top layer (P10) due to sand exposures with fresh water.

The lowering of resistivity may be due to the infiltration of seawater into the freshwater zones in the area. ERT profiles and elevated chloride concentrations confirm the brackish condition of the groundwater. The elevated TDS, sulphate, chloride, and sodium concentrations reported in the delta may be due to in situ salinity from the overlying clay formations. The interpretation of ERT images indicated sand and saline water-saturated sand are mostly found near surface up to 10–15 m. Coarse-grained sands with clay followed by saline water-saturated clay layer are present with a thickness of 30–35 m. The interpreted section across the area show that near-surface thick marine clays (~15 m)

Fig. 11 a Spatial distribution of SO$_4$/Cl ratios (meq/l) >0.05 may represent presence of water. b Spatial distribution of SO$_4$/Cl ratios (meq/l) >0.05 may represent presence of water
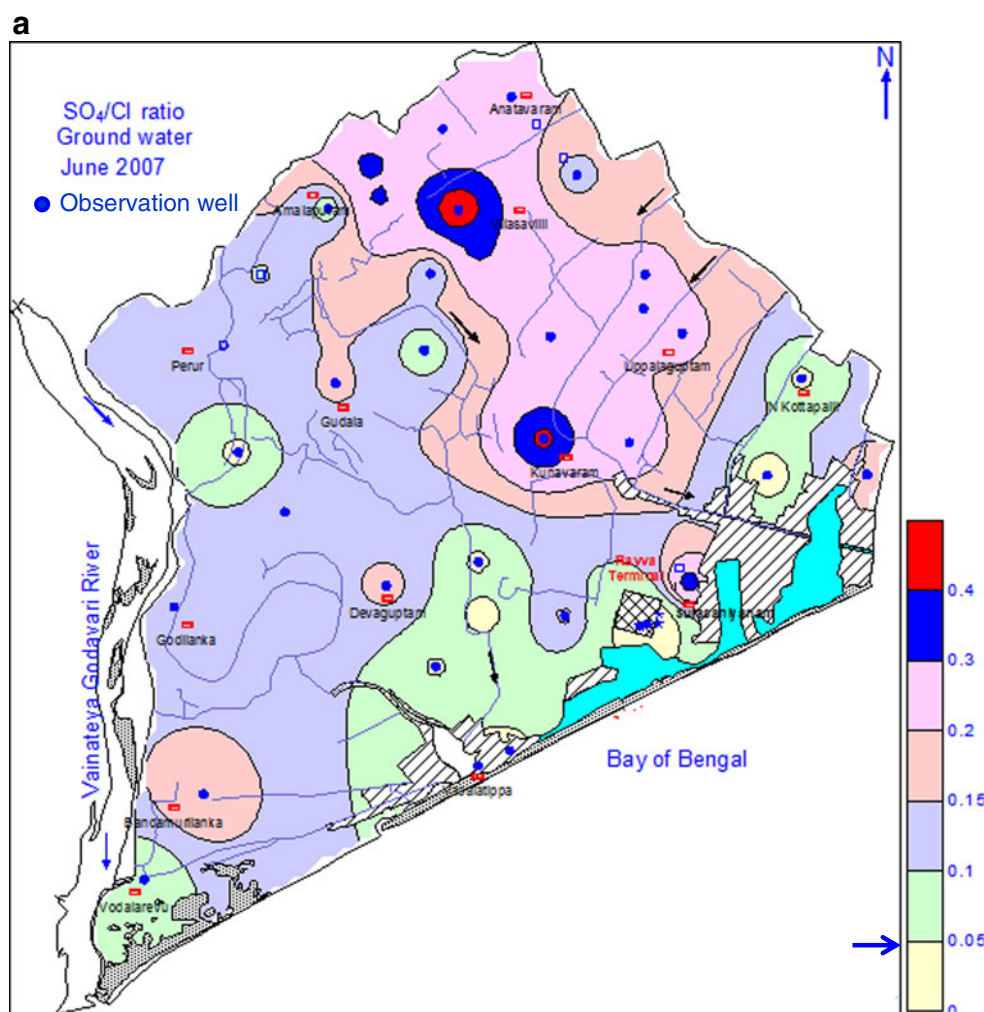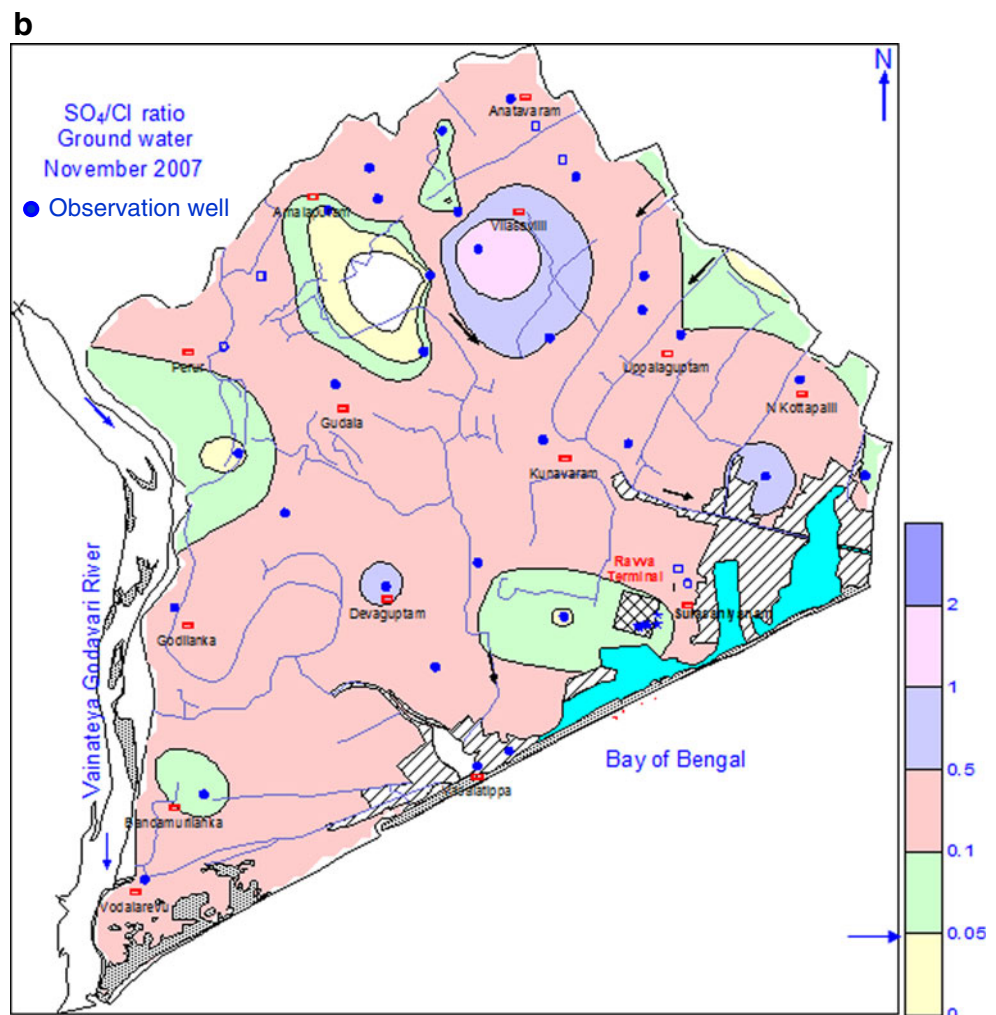
are deposited near the shore (P4) and gradually become thicker away from the sea, and the same has been reflected in ERT profiles. This implies that clay might have been deposited below the seawater possibly during marine transgression. The absence of any significant saline water intrusion at the deeper levels can be explained by the presence of impervious clay layers at depth and their possible extensions under the sea.

Ionic ratios

Groundwater chemistry plays an important role for the study of groundwater quality in the costal aquifers (Hem 1985; Karanath 1987; Saxena et al. 2003, 2004; Subba Rao 2006). Major ion chemistry can help to understand groundwater quality variation and to identify the contamination source. Major ion chemistry and molar ratio of different ions were successfully used to evaluate the seawater intrusion process in the coastal areas (Mercado 1985; Howard and Mullings 1996). Ionic ratios and different ionic relationships (Bentor 1961; Valyashko and Lavrova 1976; Breen et al. 1985; Mondal et al. 2010) were

helpful to understand the groundwater saline water mixing process in the coastal region. GIS method based on Na^+/Cl^-, Na^+/Ca^{2+}, Mg^{2+}/Ca^{2+}, EC, SAR and mixing ratios is the best tool to assess the geochemical process and to identify the source of salinity in the groundwater (Somay and Gemici 2009).

In the present study, Na^+/Cl^- and SO_4^{-2}/Cl^- ratios were considered to distinguish the source of the salinity. The Na/Cl ratio, 0.85–1 and SO_4^{-2}/Cl^- <0.05 indicate seawater intrusion (Vengosh and Ben–Zvi 1994; Vengosh et al. 1999). The spatial distribution of the ionic ratios (Na^+/Cl^- and SO_4^{-2}/Cl^-) for both pre- and post-monsoon periods of 2007 are shown in Figs. 10a, b and 11a,b. The elevated Na^+/Cl^- ratio in the Bandamurilanka and upstream of the delta indicated upconing of palaeosalinity due to local pumping for aquaculture ponds preparation in the dry season (June) (Fig. 10a). In the post monsoon (October), the ratio indicated saline water intrusion in the entire delta. This is because dilution of clay minerals rich in sodium increased Na^+/Cl^- ratio, whereas in Ravva Terminal, Amalapuram, Uppalaguttapm, N. Kottapalli and S. Yanama villages, it was not very significant (Fig. 10b). The low values of Na^+/Cl^-

(<0.46) upstream of the delta is due to the presence of sand exposures with fresh water.

In Ravva Onshore Teerminal wells, Vasalatippa and Kunavaram villages, SO_4^{-2}/Cl^- (<0.05) indicate the presence of saline water in pre-monsoon due to upconing of salty water and mixing of seawater during high tides in the region. In the post-monsoon period, the quality of the groundwater was improved due substantial surface water flows. It was clear that in the pre-monsoon, the seawater is mixing into the groundwater system in the delta during high tides along the drains (Fig. 11a and b). The geochemical ratios of the deltaic wells did not show any elevated concentrations, which represent saline water intrusion. The observed geochemical ratio describes the salinity in the delta mainly due to the dissolution of marine sediments in groundwater.

Conclusions

Geophysical and hydrochemical analysis were carried out to assess the subsurface geological formations, aquifer geometry, saline water intrusion and salinity origin in the Central Godavari delta, Bay of Bengal Coast, in Andhra Pradesh, India. The consistent groundwater flow direction is towards the Bay of Bengal coast from Amalapuram area. Geophysical investigations indicated that thick marine clays are present on the surface and extended up to a thickness of about 12–15 m in the subsurface. The low resistivity in Kanavaram, near Vasalatippa drain and in Surasaniyanam, was due to the mixing and infiltration of saline water in to the freshwater zones during high tides from the surface water drains. Hydrochemical analysis results indicated effects of the seawater mixing; in particular, TDS and chloride concentrations are the simplest indicators for assessment of the mixing process. The established groundwater flow direction in the area is to towards the Bay of Bengal from the Amalapuram. The large thicknesses of clay formations are responsible for groundwater salinity in the Godavari delta. The marine clays possess palaeosalinity due to the recession of the sea level. The depositional history and the elevated values of TDS, Na^+, SO_4^{-2}, Cl^- concentrations indicate that salinity is due to in situ salinity of groundwater in the marine clays rather than the lateral movement of seawater from Bay of Bengal. The enrichment of chloride and TDS in pre monsoon indicated that groundwater is contaminated by saline water due to infiltration of seawater during high tides along drains. The ionic ratio of SO_4^{-2}/Cl^- and Na^{+2}/Cl^- indicated that salinity in the delta region is not due to seawater intrusion, but is rather due to dissolution of evaporites and dilution of marine clays rich in sodium.

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