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A Study on the Behavior of the Dissolved Oxygen in the Shallow Coastal Wells of Cuddalore District, Tamilnadu, India

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Abstract Dissolved oxygen content in a water column serves as an indicator of pollution and it indirectly indicates the geochemical nature of the water. An attempt has been made in this study to understand the behavior of Dissolved Oxygen (DO) in eleven open wells along the coast of Cuddalore District, Tamilnadu, South India. Observations were made in situ for DO and Electrical Conductivity (EC) depth wise for 24 hours during a full moon period of every two hours. The study indicates that a definite stratification exists in a certain location and mixing trends in some locations. It also shows that there are fluctuations of these values with time and it has a definite relation at specific location. The temporal and the spatial relationships between EC and DO were also used in an attempt to understand the coastal ecosystem in the natural environment.

Keywords Dissolve oxygen · Coastal groundwater · Electrical conductivity · Tamilnadu

Introduction

Dissolved oxygen plays an important role in the determination of the water quality. The DO level in natural aquatic system is a highly informative variable which can elucidate atmosphere–water interactions, ocean water mass movements, net primary productivity and carbon remineralization processes. DO level indicates how well the water is aerated and it is a commonly measured parameter because it is an immediate indicator; inadequate oxygen levels will quickly affect aquatic life and be threatening vitality for all aquatic life. DO is a major factor in both the ecology and evolution of aquatic organisms dependent on aerobic respiration. When DO concentrations are reduced, aquatic animals are forced to alter their breathing patterns or lower their level of activity. There is a long history of using quantitative techniques to assess the impacts of pollutants with DO (Cox 2003).

Dissolved oxygen studies in the natural environments have been carried out in different categories as:

1. Groundwater (Stierhoff et al. 2003; Alikunhi et al. 1951; Babu et al. 2006)
2. Estuary (Gao and Song 2008; Zhang et al. 2002; Breitburg et al. 2003; Eby and Crowder 2002; Ishikawa et al. 2004; Kurup and Hamilton 2002; Buzzelli et al. 2002; Sharp 2010)
3. Lakes (Woodbury 1941; Mallin et al. 2006) and
4. Sea water (Skjelvan et al. 2001; Justic et al. 1996; Gardner and Gorman 1984; Smith and Able 2003; Timmerman and Chapman 2004; Kuo and Neilson 1987)

The review of literature survey on the studies of the dissolved oxygen reveals that most of the studies are pertaining to the surface water bodies and it is limited in the groundwater environment.

The dynamics of DO in water bodies involves complex interactions between physical and biogeochemical processes; i.e., (1) vertical and horizontal mixing, (2) air water exchange, (3) nutrient loadings and speciation, (4) photosynthesis, (5) sediment and water column oxygen demand, and (6) chemical oxygen demand. These processes

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can vary semi-independently from one another. Hence, several studies (Williams et al. 2000; Moatar et al. 2001; Hearn and Robson 2001; Hagy et al. 2004) have attempted to understand how temporal variations in nutrient loadings, temperature and stratification of the water column manifest themselves in bottom water with DO depletion. They founded that DO concentration of a water mass is largely determined by a balance between the exchange of atmospheric oxygen with the upper mixed layer, net increases due to photosynthetic processes and net decreases due to respiratory demands and heterotrophic processes. Variations in temperature, freshwater discharge, saltwater intrusion, bathymetry, circulation, meteorology, biological production and respiration combine to produce strong DO gradients (Falkowski et al. 1980; Stanley and Nixon 1992; Stanley 1993). Recharge of groundwater with oxic storm water can increase the DO flux, thereby re-oxygenating shallow water table aquifers that often exhibit low DO concentrations (Starr and Gillham 1993; Chapelle 2000). Saline water intrusion in many coastal areas resulted in the contamination of groundwater and consequently leading to environmental problems (Ginsberg and Levanton 1976; Frohlich et al. 1994). Earlier works carried out in coastal aquifers along the southeast coast of Tamilnadu indicates the seasonal variations of major ions in groundwater quality (Ramanathan et al. 1999; Chidambaram et al. 2005; Satheesh Herbet Singh and Lawrence 2007; Prasanna 2008). In recent studies focus was on the micro observations, which in turn help us in understanding the environmental dynamics and management of the coastal system. This study is a micro level (hourly) in situ observation, which helps us to understand the microdynamics of the coastal aquifers. In this juncture, an attempt has been made in this study to find the variation of DO and its relationship to the conductivity in the shallow coastal groundwater with depth and time, which in turn will reflect the behavior of other ions and the natural productivity of the system.

Description of the Study Area

The study area (Fig. 1) extends from the southern part of Cuddalore to northern part of Nagapattinam district of Tamilnadu. It is predominately an agricultural region. The coastal plain extends as a narrow stretch on the eastern part of the region all along the Bay of Bengal. The coastal plain consists of gently sloping land with chains of sand dunes extending along the coast of Bay of Bengal. The dunes are almost parallel to the coast. Sand dunes are scarcely distributed near Palaiyar. The study area is occupied by the flood plain of fluvial origin formed under the influence of Ponnaiyar, Vellar and Coleroon river systems. The Coleroon river flowing in the study area forms an estuary with marshy

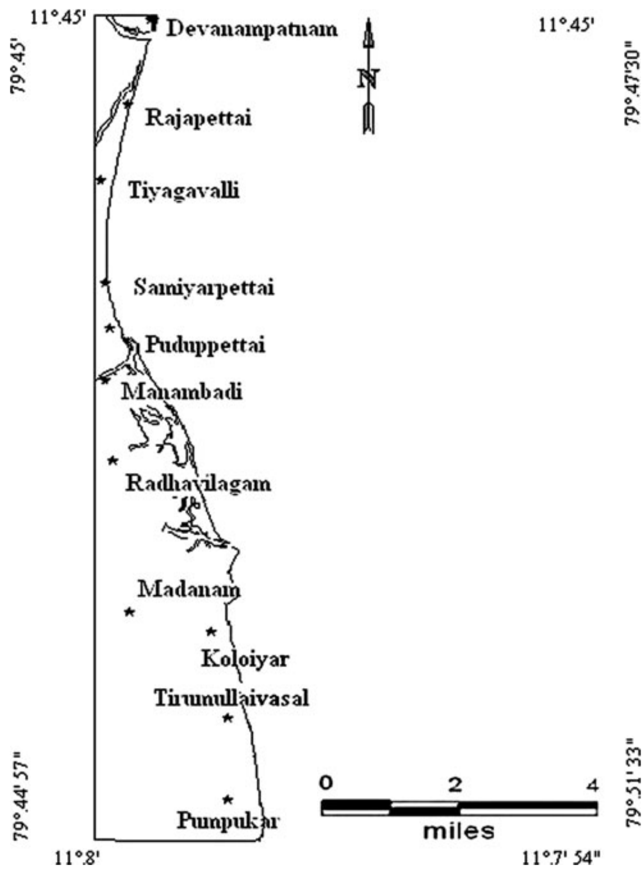


Fig. 1 Sampling location map of the study area

mangrove environment at Pichavaram. The region has major distributaries of the river Cavery, all of them behave as the back water during summer at the river mouth due to lack of sufficient flow of river water to the sea during the non monsoonal periods. Marine sedimentary plain is noted all along the eastern coastal region. In between the marine sedimentary plain and fluvial flood plains, fluvio marine deposits are noted, which consist of sand dunes and back swamp areas (Dinagaran 2009).

Groundwater in the study area occurs in recent alluvial formation. The unconsolidated quaternary sediments consist of laterite and fluvial coastal alluvium. The unconsolidated quaternary alluvium and the Cuddalore sandstone form the principal and potential aquifers in the area. The thickness of Cuddalore sandstone extends up to a depth of about 100 m below ground level, where the alluvium formation varies from 20 to 40 m below ground level (CGWB 1997). However, these aquifers are very shallow. The confined aquifers are deep in nature. These aquifers are available from 100 to 450 m below ground level. The nature and distribution of different lithologic layers in some location of the study area as represented by depth wise resistivity values were correlated with geoelectrical logging data (Prasanna et al. 2008). The top layer of fine-grained sand (10 m) is underlain by a

10–20 m thick intermediate layer of sand with clay, followed by 20–30 m thick medium grained sand layer, which further grades downward into the 30–55 m thick clay with sand.

The average rainfall is 1164 mm per year. The general aquifer system is discontinuous, unconfined and confined to semi confined aquifers. The important sources of irrigation in the area are wells, canals and tanks. This area is under irrigation and forms a part of about 50000 ha groundwater irrigated region. Out of the various groundwater abstracting structure the dug wells and tanks are of significance.

The tidal observations were made in the site specific location of the study area (Singaraja 2011) and show that there is a tidal fluctuation diurnal with time in six hours interval. The highest (1.98 m amsl) and the lowest tide level (0.18 m amsl) were also made. The lowest tide and the highest tide are noted at 02:00 h and 08:00 am, respectively.

Table 1 Details of the dissolved oxygen range in the study area

S. No.	Name	Dissolved oxygen range (mg/l)		
		Surface	Middle	Deep
1	Devanampatnam	1.43–2.76	1–1.75	0.41–0.95
2	Puduppettai	4.88–6.29	4.67–4.93	4.36–5.56
3	Pumpukar	0.1–0.29	0.03–0.08	0.05–0.2
4	Rajapettai	1.52–2	1.23–1.89	0.79–1.97
5	Tirumullaivasal	3.54–5.73	3.31–4.64	0.26–1.98
6	Manambadi	3.01–6.21	2.52–3.83	2.36–3.66
7	Koloiyar	2.16–3.4	2.13–2.25	2.13–2.55
8	Radhavilagam	1.57–2.2	1.26–1.89	1.34–1.99
9	Samiyarpettai	1.32–1.99	1.08–1.49	0.62–1.08
10	Tiyagavalli	0.04–0.64	0–0.12	0.01–0.85
11	Madanam	2–3.5	1–1.4	0.01–1.4

Materials and Methods

Eleven different opens wells were selected along the coastal region for observations during full moon period (Fig. 1). The observations were made for 24 hrs, in two hour intervals for Electrical Conductivity and Dissolved Oxygen. These parameters were observed at three different depths in the same well denoted as surface, middle and deep. Thirteen observations were made in each well for these three different depths, according to the total depth of the well. The depth wise measurements were made by using HACH depth probes. IntelliCAL LDO probes were used to measure DO (mg/L). Standard IntellliCAL LDO probes are waterproof for 24 hours fully immersed to a maximum depth of 10 meters, features stainless steel reinforced cable and stainless steel body with a polymer shroud being used to protect the probe from the rigors of field use. Similarly EC measurements were made by using HACH depth probes.

Results

The ranges of the DO values observed at different depths from different sampling locations are presented in the Table 1. The plot of DO against time variation at Devanampatnam (Fig. 2) shows that there are three layers recorded with different DO concentrations. The surface layer had a higher DO concentration than that of middle and deep layer, leading to the difference between the three layers. The middle and deep layers show a clear indication of hypoxia as the concentration of dissolved oxygen (DO) is less than 2.0 mg l^{-1} in the water column (Diaz and Rosenberg 2008). In general, the DO shows a decreasing trend in all layers with time. Puduppettai (Fig. 3) shows higher DO variations in the surface and deep layer and only minor variations were noted in the middle layer. The figure indicates that higher values are noted at the surface layer. The DO of the middle layer shows a gradual increase with time and does not match with the patterns of the shallow and the deeper groundwater; this may be attributed to the tidal variations.

The DO observations at Pumpukar (Fig. 4) shows similar trend as that of Devanampatnam but all the three layers shows stratification under hypoxia conditions. The well at Rajapettai (Fig. 5) is located near the river mouth and the sea. All the three layers, surface, middle and deep show a decrease in DO concentration gradually with the increase of time until 2:00 hrs. Later, the DO concentration increases in the surface and the middle layers after 2.00 hrs, this matches directly with the tidal trend observed (Singaraja 2011). Hence, it is evident that the variation of salinity influences the DO of the region.

Tirumullaivasal shows higher DO variation in all the depths (Fig. 6) with almost similar values in the surface and middle layers. In general, the DO decreases in surface and middle layers till 10:00 hrs and then shows an increasing trend. The trend of the DO at this location inversely matches with the tidal observations made by Singaraja (2011). As he states the tidal height increases from 2.00 hrs to 10.00 hrs and later it decreases from 10.00 hrs to 14.00 hrs. This inverse relation identifies the fresh water inflow into the aquifer when the tide retreads. At Manambadi (Fig. 7) higher DO variation is noted in all the depths, but the surface, middle and deep layers have almost similar values. It is also noted that after 01:00 hr a mixed trend occurs in the study area. At Koloiyar (Fig. 8) the DO shows a miscellaneous trend, higher DO variations were noted at the surface layer. At Radhavilagam (Fig. 9) the DO at that surface, middle and deep layers depicts a gradual decreasing trend from 16:00 hrs to 04:00 hrs. There is an increasing trend from 04.00 to 12.00 hrs, which matches with the high tide period observed (Singaraja 2011). It is also proved by

Fig. 2 Depth wise variation in DO at Devanampatnam (mg/l)

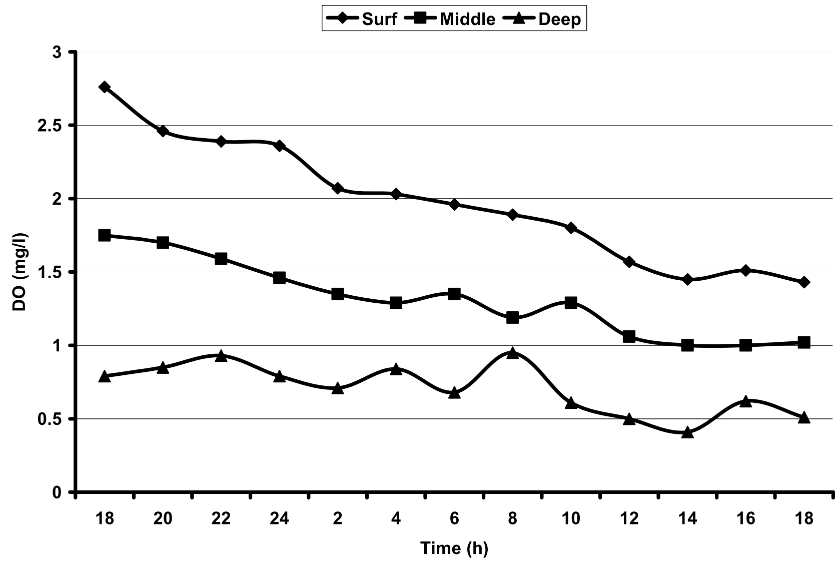


Fig. 3 Depth wise variation in DO at Puduppettai (mg/l)

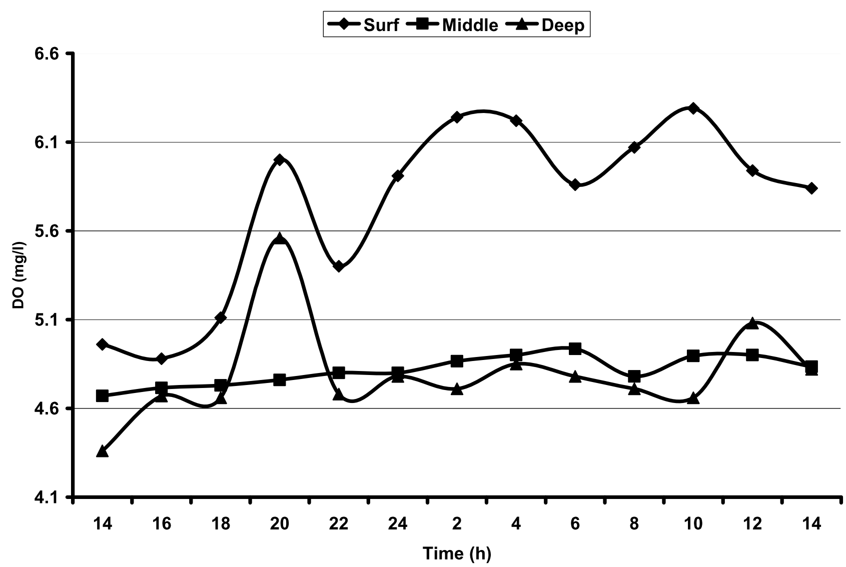


Fig. 4 Depth wise variation in DO at Pumpukar (mg/l)

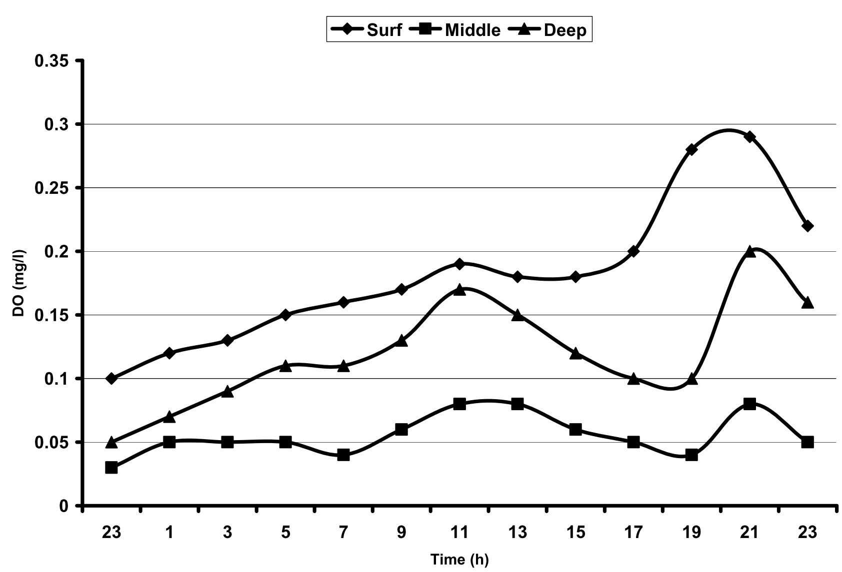


Fig. 5 Depth wise variation in DO at Rajapettai (mg/l)

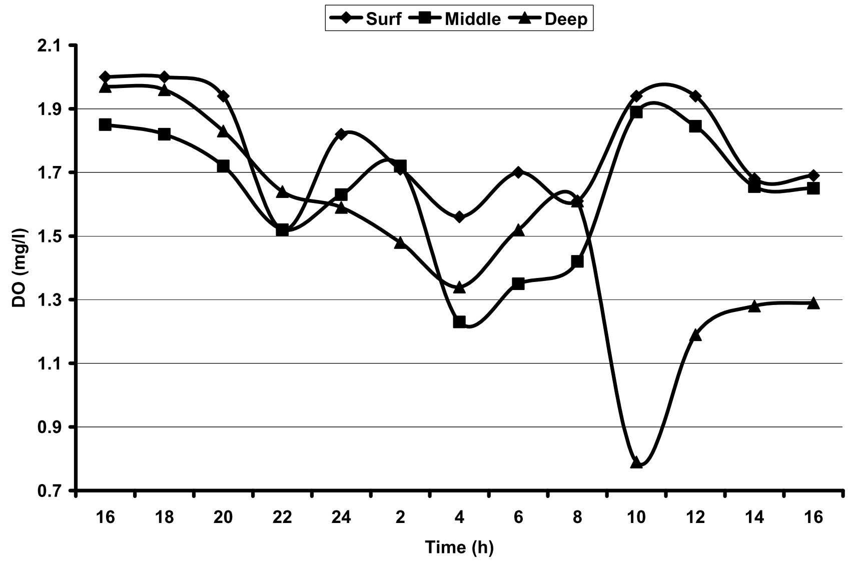


Fig. 6 Depth wise variation in DO at Tirumullaivasal (mg/l)

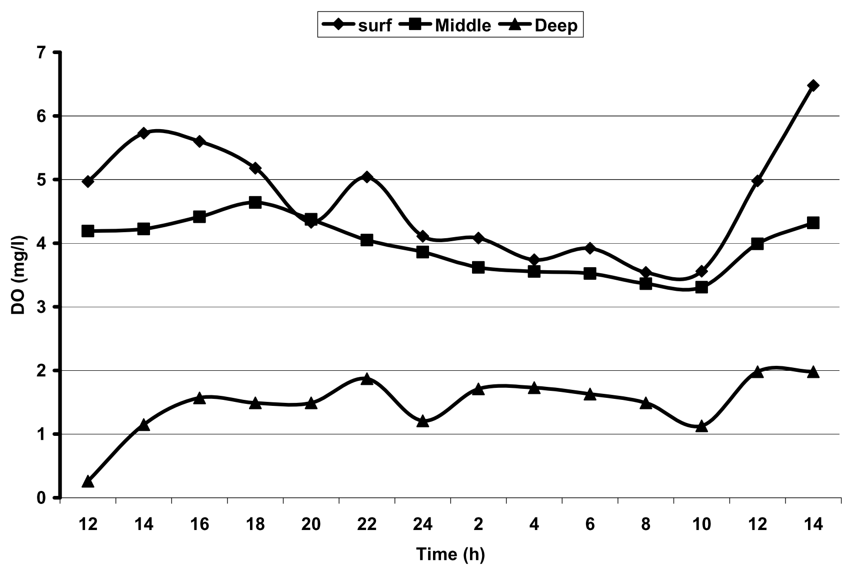
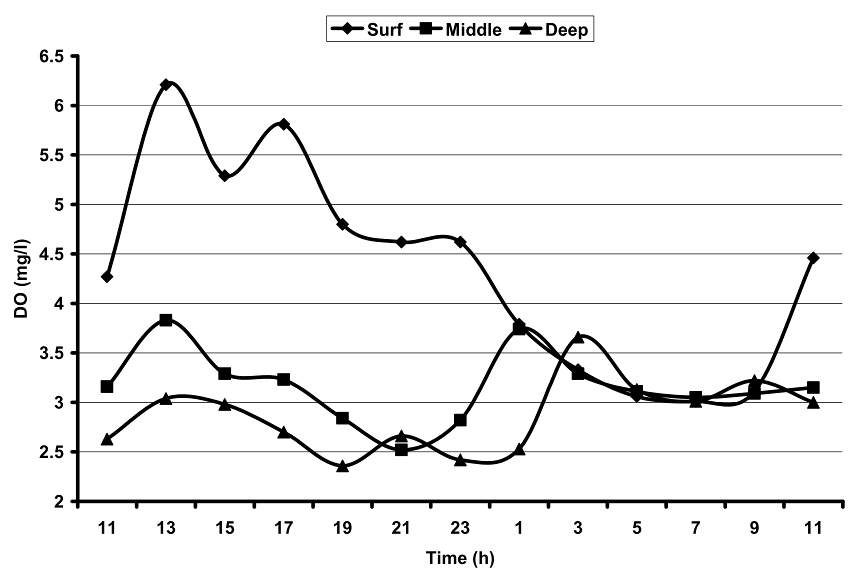


Fig. 7 Depth wise variation in DO at Manambadi (mg/l)



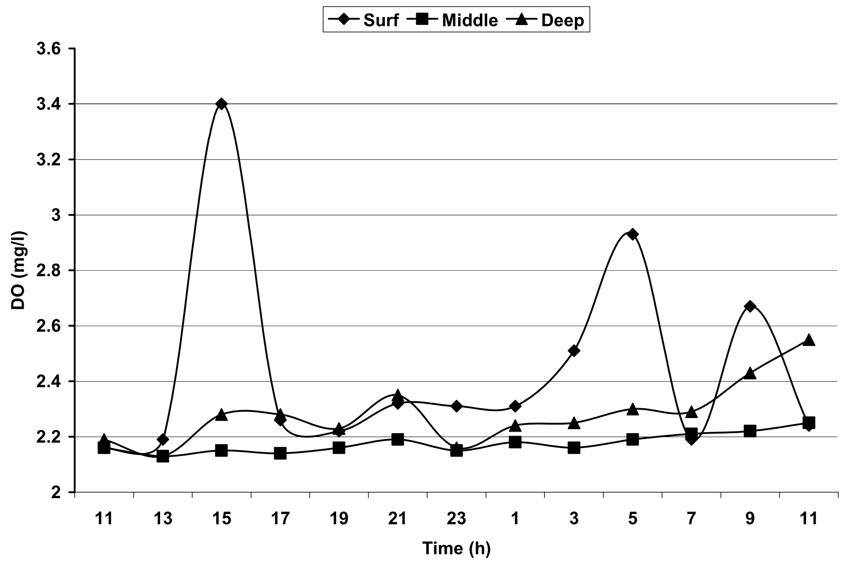


Fig. 8 Depth wise variation in DO at Koloiyar (mg/l)

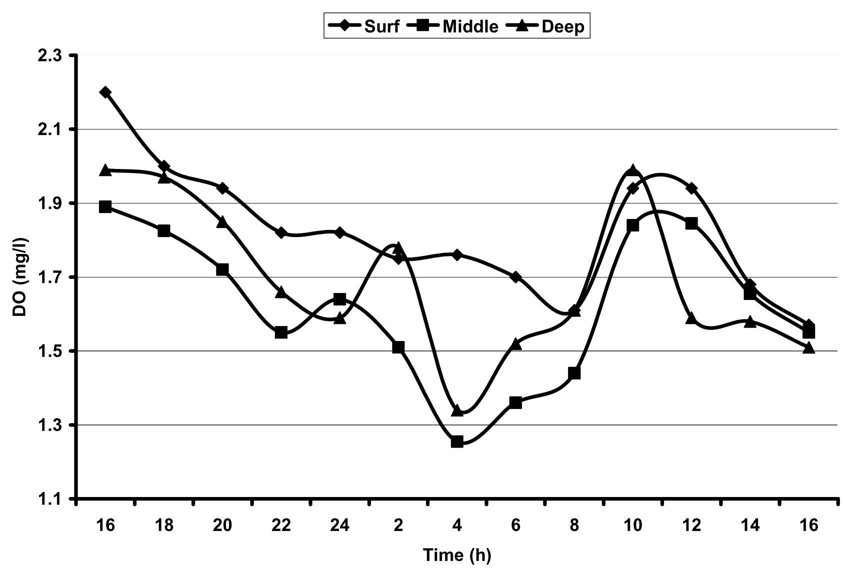


Fig. 9 Depth wise variation in DO at Radhavilagam (mg/l)

different authors that the increase of DO concentration may also be attributed to the oxygen generated from photosynthesis (Gao and Song 2008). Stratification is noted with respect to DO concentration indicating feeble or no mixing between the layers.

The Samiyarpettai shows (Fig. 10) that higher DO variation is at surface than the deep layers. In general, the DO shows a gradually decreasing trend at the surface, middle and deep layers. The DO values observed show that there is no vertical mixing of the oxygen in this region and do not show any tidal variations. At Tiyagavalli (Fig. 11) the DO shows that all values are smaller and the observations clearly show anoxic conditions. In general, the DO shows assorted trends. There is a general decreasing trend of the DO values with time in the deeper levels. At Madanam (Fig. 12) depth wise observation of the DO shows that the surface and the deeper level behave similarly and the middle layer is independent of the other two layers. Hypoxia conditions are noted in the middle and at the deeper layer.

Discussion

The variability of DO in the water column generally results from the interplay between physical transport and biological consumption of oxygen. Thus, bottom DO gets depleted when the rates of consumption exceed rates of supply. Hypoxia is a seasonal phenomenon that occurs in shallow water in most temperate coastal regions (e.g., Buzzelli et al. 2002; Hagy et al. 2004). The occurrence of hypoxia in shallow waters appears to be increasing in almost all the locations, and it is accelerated by human activities (Diaz and Rosenberg 1995). A similar kind of hypoxic condition has been

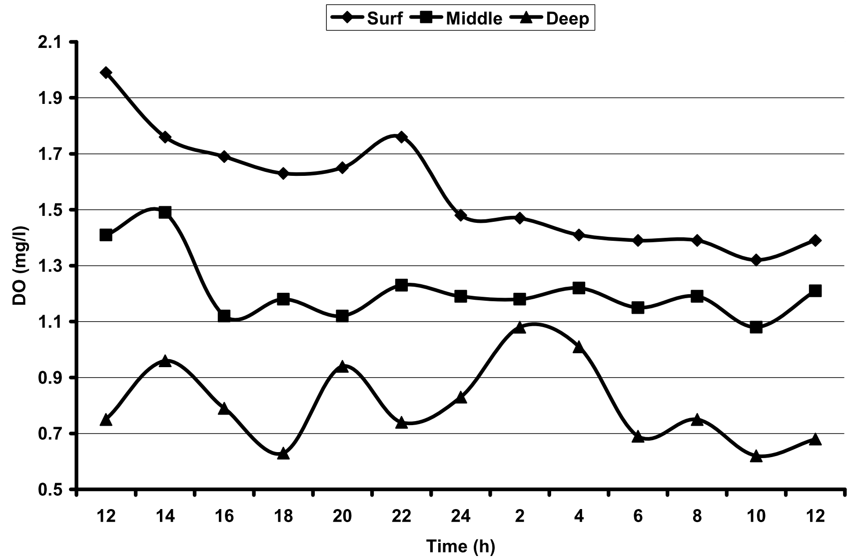


Fig. 10 Depth wise variation in DO at Samiyarpettai (mg/l)

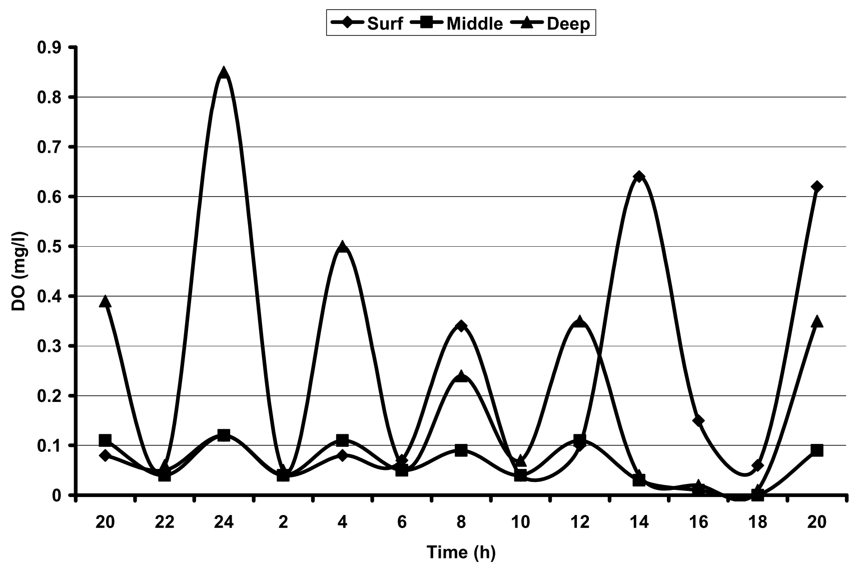


Fig. 11 Depth wise variation in DO at Tiyagavalli (mg/l)

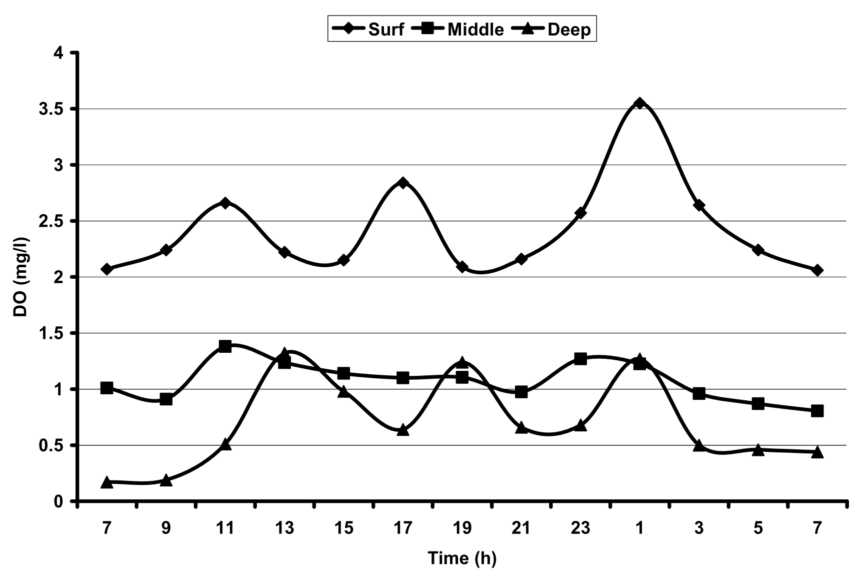


Fig. 12 Depth wise variation in DO at Madanam (mg/l)

reported in estuaries and coastal groundwaters globally in recent years (Virginia et al. 1999; Diaz 2000; Lin et al. 2006; Mallin et al. 2006).

There are physical processes controlling the density structure of the water column which may indirectly indicate the depth of dense salt water intrusion into the aquifer. The variation of density in the water column is mainly due to the tidal influence or due to the fresh water inflow into this coastal aquifer (Anderson and Taylor 2001). The variation of DO within a short span of time (24 hrs) will not reveal the sea water intrusion into the aquifer but rather will aid to identify the tidal variation in the aquifer. The DO patterns in a certain location matches with the tidal observations like Rajapettai, Tirumullaivasal, Tiyagavalli and Radhavilagam. The saline dense layers prevent the further penetration of the dissolved oxygen into the deeper layers.

Depth wise observation of the DO shows that higher variation between the surface values and the other depth values at Manambadi, from 11:00 hrs to 01:00 hrs then after the value decreases for all depths. It may be due to the fact that the water at noon holds high levels of DO due to oxygen generated from photosynthesis; once night falls, photosynthesis stops and plants consume oxygen as they respire, thereby decreasing DO levels (Gao and Song 2008). This observation was also supported by the presence of plants along the walls of the well. Waters stratified in locations like Samiyarpettai and Devanampatnam, which means a layer of warmer, fresher water forms over a colder, saltier layer as the sea water intrusion in these regions, were also reported by earlier studies (Chidambaram et al. 2010; Prasanna et al. 2010). Thus, oxygen is unable to reach the lower depths, resulting in lower DO levels at deeper depths and higher levels near the surface. Oxygen will be transported horizontally by adjective forces and vertically by air–gas exchange as well as by mixing in the water column. Hence it is found that in all the locations the upper (surface) layer has higher DO than the other layers (Buzzelli et al. 2002; Hagy et al. 2004).

Relationship of EC and DO

The variation of EC during the period of observation shows two different trends: 1. Variation of EC with time 2. Variation of EC with depth. Figures 13, 14, 15 and 16 indicate that there is a relationship with depth and it can be classified into four different classes as stratified, mixed, mixing of shallow and middle and mixing of middle and deep.

Stratified

In this category there is a clear demarcation of layers, with different DO/EC values. Devanampatnam, Samiyarpettai, and Madanam (Figs. 13a, b, c) fall in this category. It is clear that in single observations of a well there is a distinct variation in DO and EC values with depth. There is a decrease of DO with depth and an increase in EC. In Devanampatnam and Samiyarpettai the stratification is of a definite trend: the DO of the surface decreases with increase in EC. The middle and deeper layer almost have similar EC values but there is a distinct variation in the DO values. Madanam shows a wide range of EC values for middle and deeper layers than that of the surface. There is distinct demarcation of DO layering with less relationship to EC in this region. Though there are variations noted in both DO and EC the stratification is mainly due to DO rather than EC. Hence, it is clear that this is mainly governed by the temperature stratification rather than by the salinity gradient. It is also observed that the temperature differences at different depths affect the quantity of oxygen and its water holding capacity (Manasrah et al. 2006).

Mixed

The observation of DO and EC for three distinct depths does not have a definite characterization and all the depths have higher to lower EC and DO. Hence it is understood that we have vertical mixing in these region. This nature is characteristic in Koloiyar and Pumpukar (Figs. 14a, b) regions. It is mainly due to the presence of the agricultural activities (Prasanna et al. 2010) in the region forcing the extraction of groundwater from these aquifers, which in turn helps in vertical mixing.

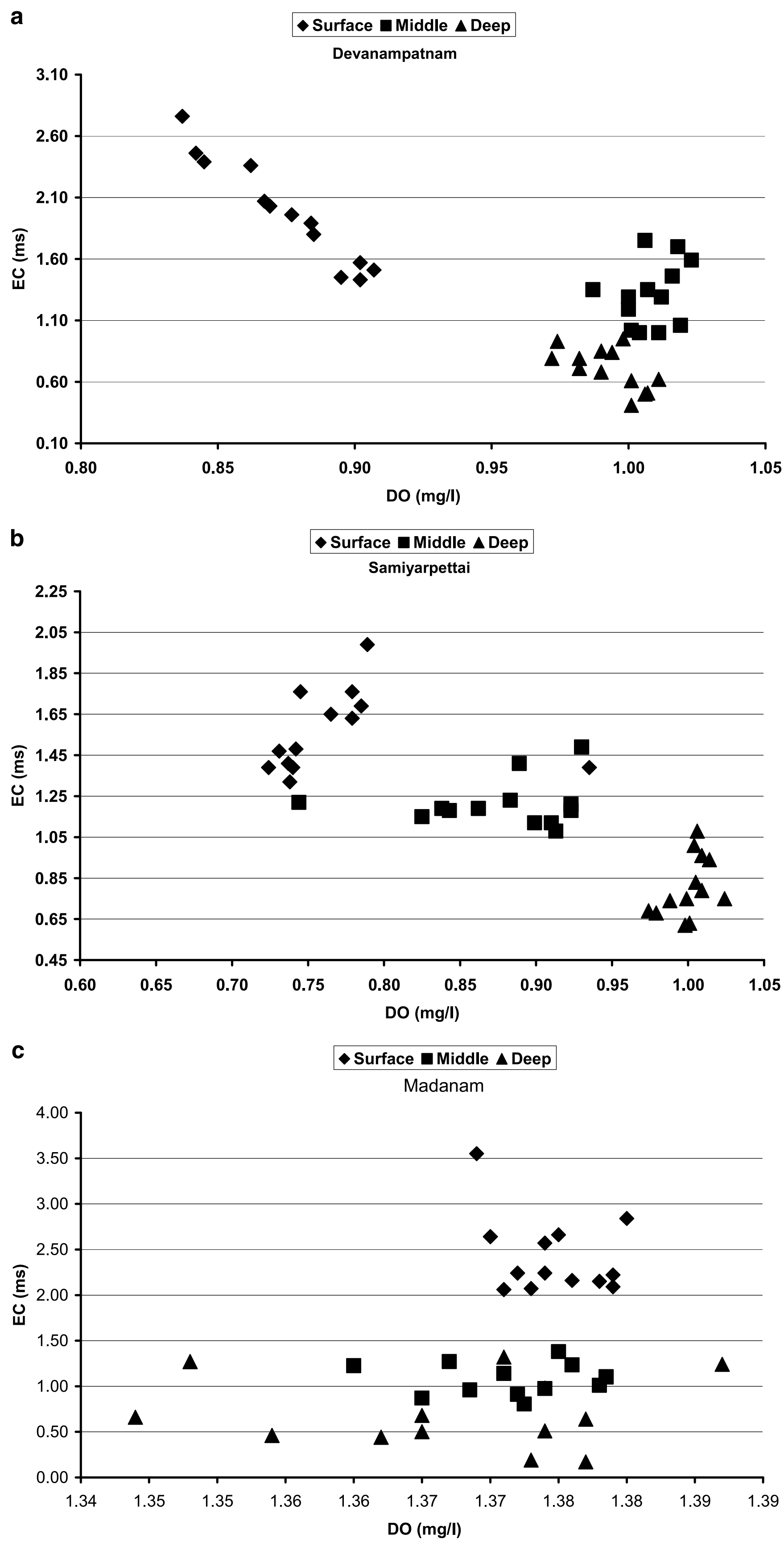
Mixing of Shallow and Middle

This is observed in three locations Radhavilagam, Rajapettai and Tiyagavalli (Figs. 15a, b, c). In Tiyagavalli there is wide range of EC values in the deeper layer when compared to surface and middle. Though the EC of surface and middle layer falls on a specific higher range, the DO shows mixing between the top two layers which are independent of bottom layer in Tiyagavalli. In the other two regions, Rajapettai and Radhavilagam, the surface and the middle have comparatively higher DO lesser EC and the deeper layer shows higher EC irrespective of DO due to the higher inflow of fresh water.

Mixing of Middle and Deep

There is a wide range of EC values with lesser DO variation with respect to depth. The almost similar values of deeper and middle layer of Puduppettai, Manambadi and Tirumullaivasal indicate mixing (Figs. 16a, b, c). The DO shows distinctly higher values within a specific range of EC in these regions which indicate a clear mixing of middle and deep layers.

Fig. 13 Relationship of EC and DO at: (**a**) Devanampatnam; (**b**) Samiyarpettai; (**c**) Madanam



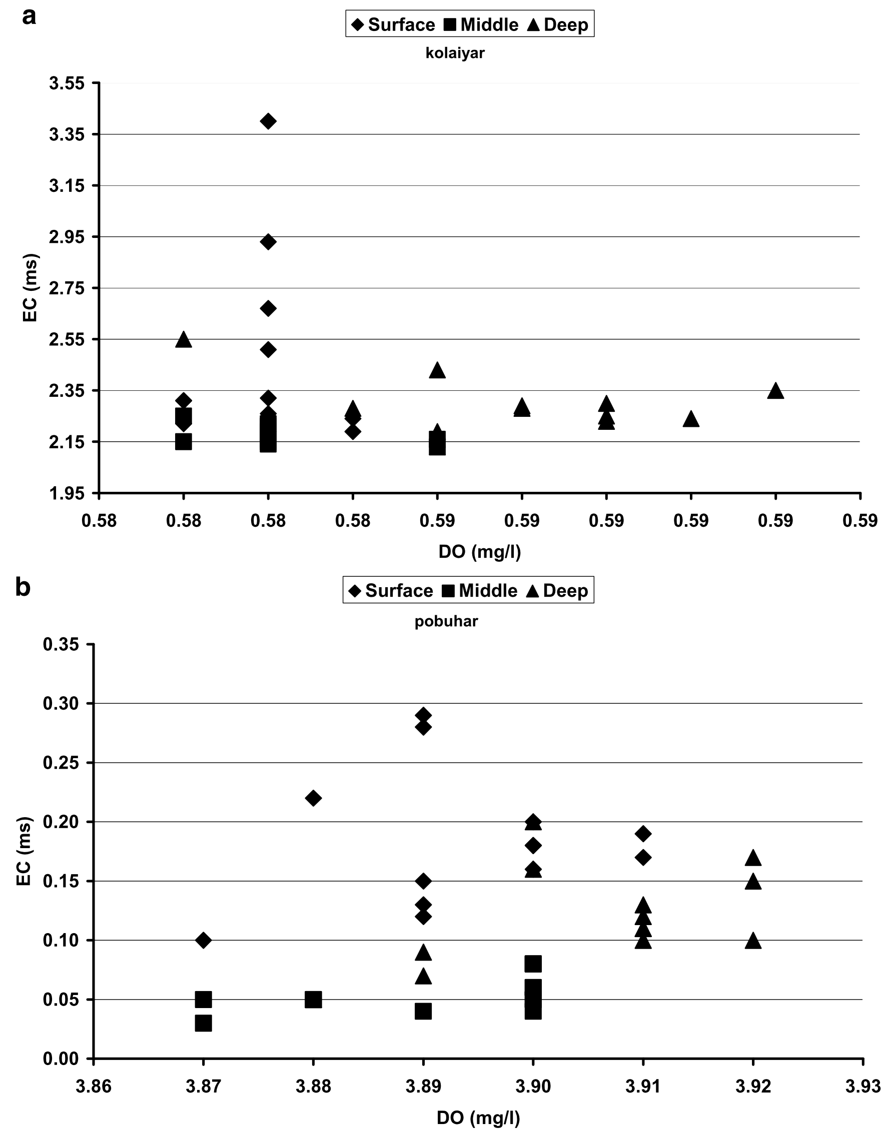


Fig. 14 Relationship of EC and DO at: (**a**) Koloiyar, (**b**) Pumpukar

It is interesting to note that the operation status of the wells also plays an important role in the stratification process; basically the observation wells are more static than the extraction wells (Table 2). Devanampatnam and Samiyarpettai are extraction wells and they show stratification, which is due to the increase of salinity with depth and the reduction of DO in the aquifer is due to the salt water intrusion. In the other regions, Radhavilagam, Rajapettai and Tirumullaivasal also fall in the extractive wells indicating dense saline layer at the deeper layer. The Koloiyar shows a mixing trend due do extensive extraction. The stratification in Madanam well is due do absence of vertical mixing as it is a static well. A mixed type of water is found at different depths in Tiyagavalli and Pumpukar, this may be due do the lateral recharge from neighboring ground water bodies. Madanam and Puduppettai show stratification with respect to surface and other layers though it is a static well.

Table 2 Details of the distance between the locations points to sea and well type

S. No.	Location	Distance from sea	Depth of the well (m)	Well type
1	Manambadi	3 km	2.98	Static wells
2	Puduppettai	1.98 km	3.85	Static wells
3	Devanampatnam	613 m	2.35	Extraction wells
4	Rajapettai	460 m	2.46	Extraction wells
5	Tiyagavalli	970 m	1.45	Static wells
6	Koloiyar	364 m	2.1	Extraction wells
7	Radhavilagam	5 km	2.7	Extraction wells
8	Tirumullaivasal	493 m	3.55	Extraction wells
9	Madanam	6 km	2.46	Static wells
10	Pumpukar	650 m	2.18	Static wells
11	Samiyarpettai	486 m	3.3	Extraction wells

Fig. 15 Relationship of EC and DO at: (**a**) Radhavilagam, (**b**) Rajapettai, (**c**) Tiyagavalli

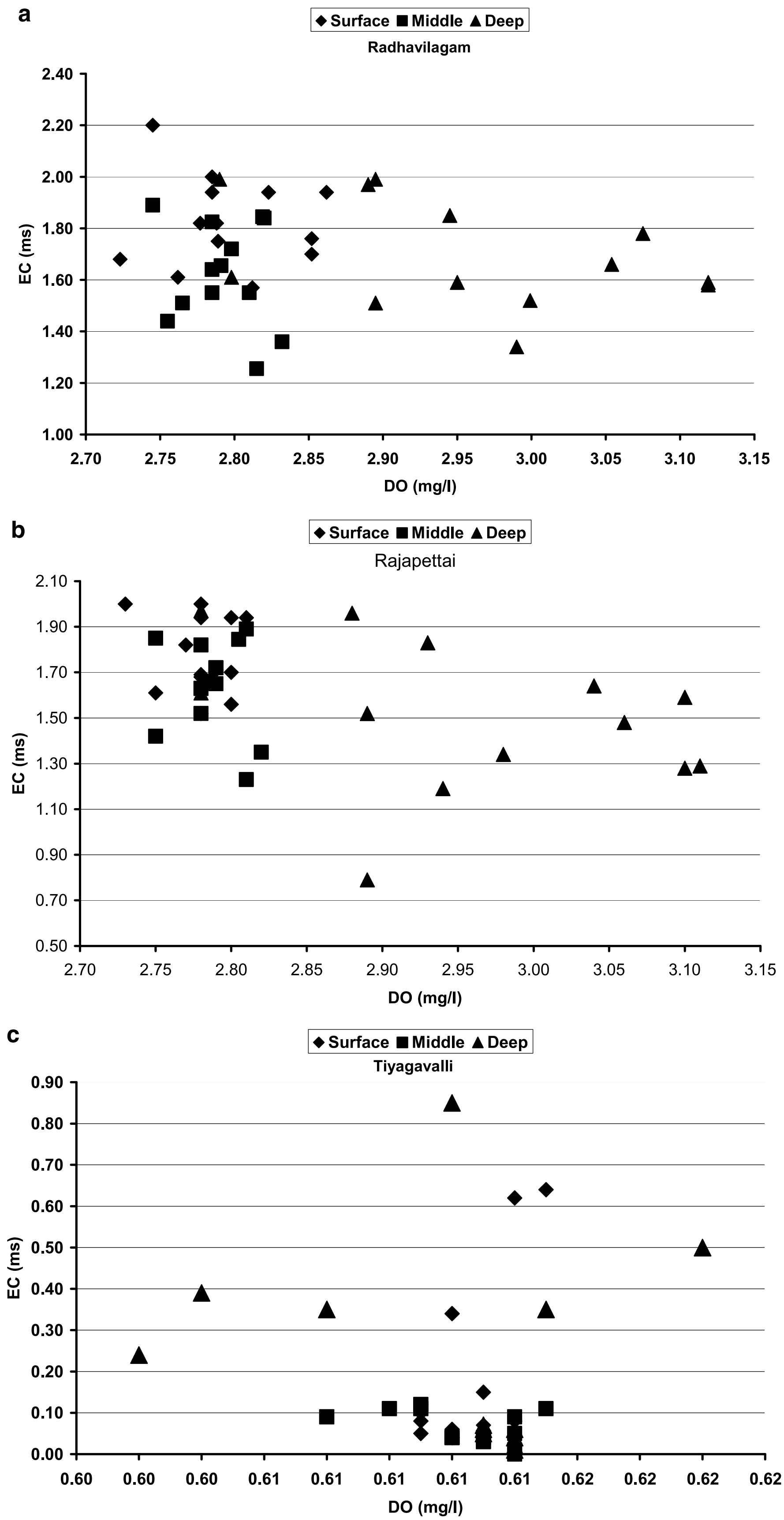
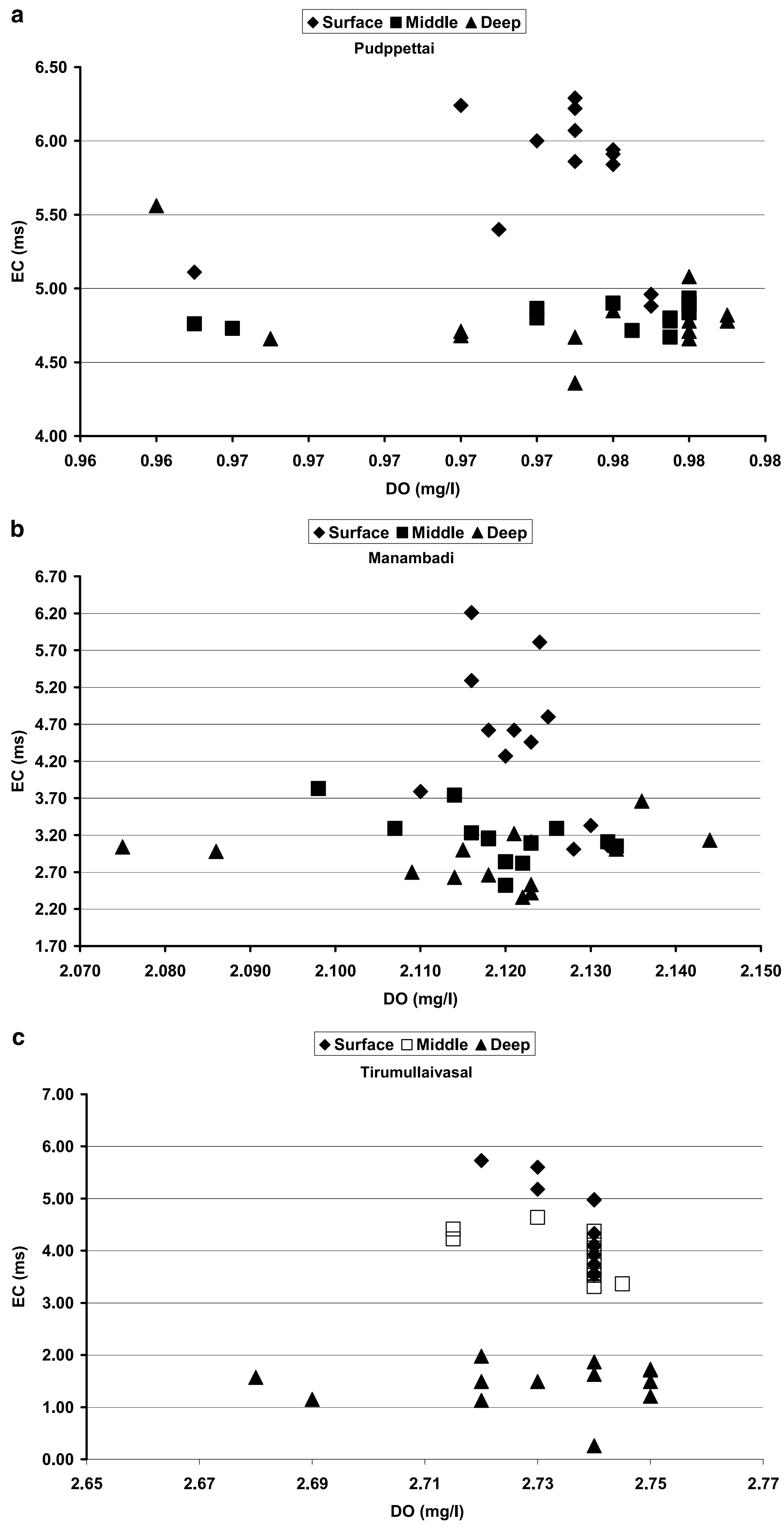


Fig. 16 Relationship of EC and DO at: (**a**) Pduppettai, (**b**) Manambadi, (**c**) Tirumullaivasal



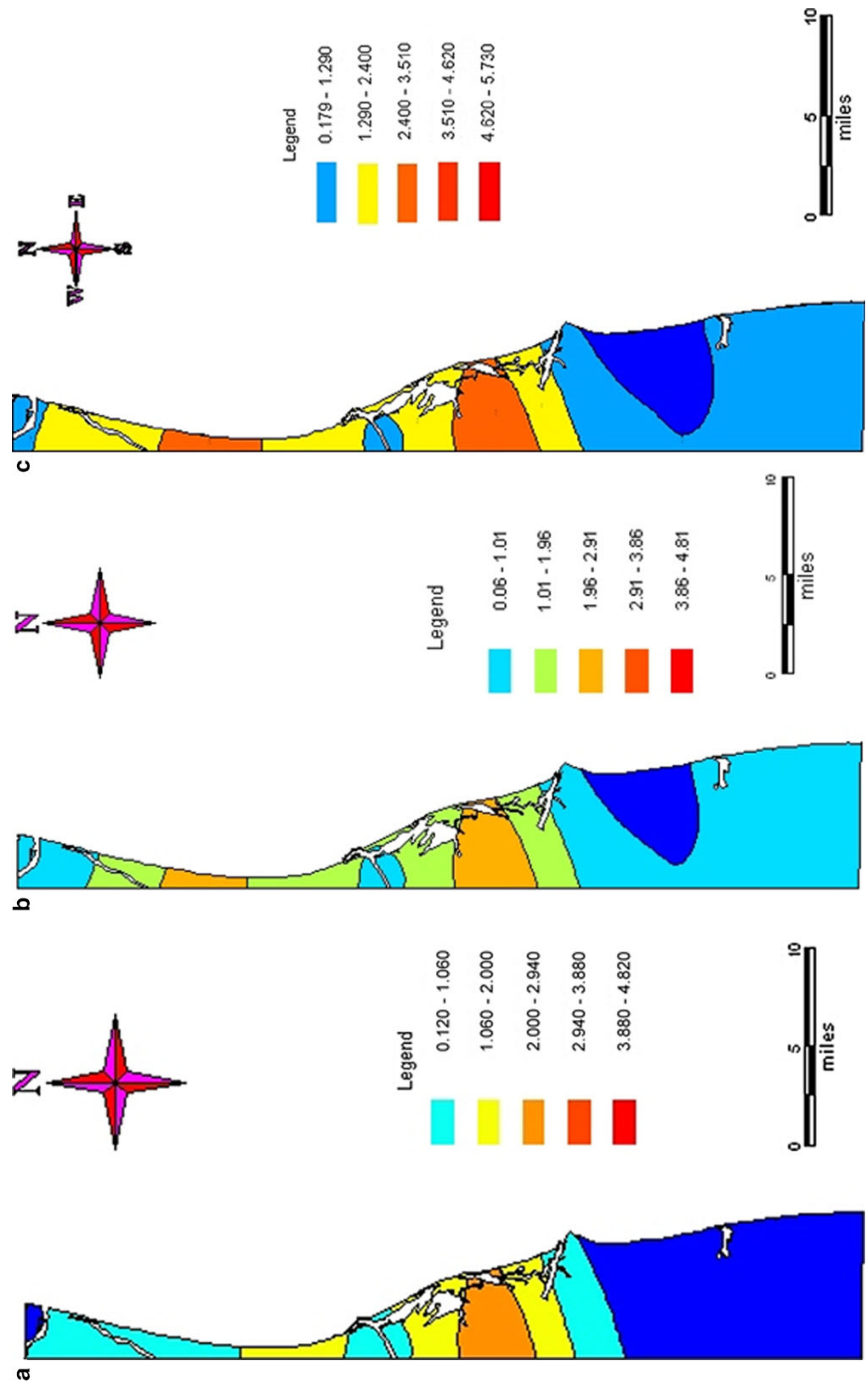


Fig. 17 Spatial distribution of DO (mg/L) in: (**a**) Deep layer, (**b**) Middle layer, (**c**) Surface layer

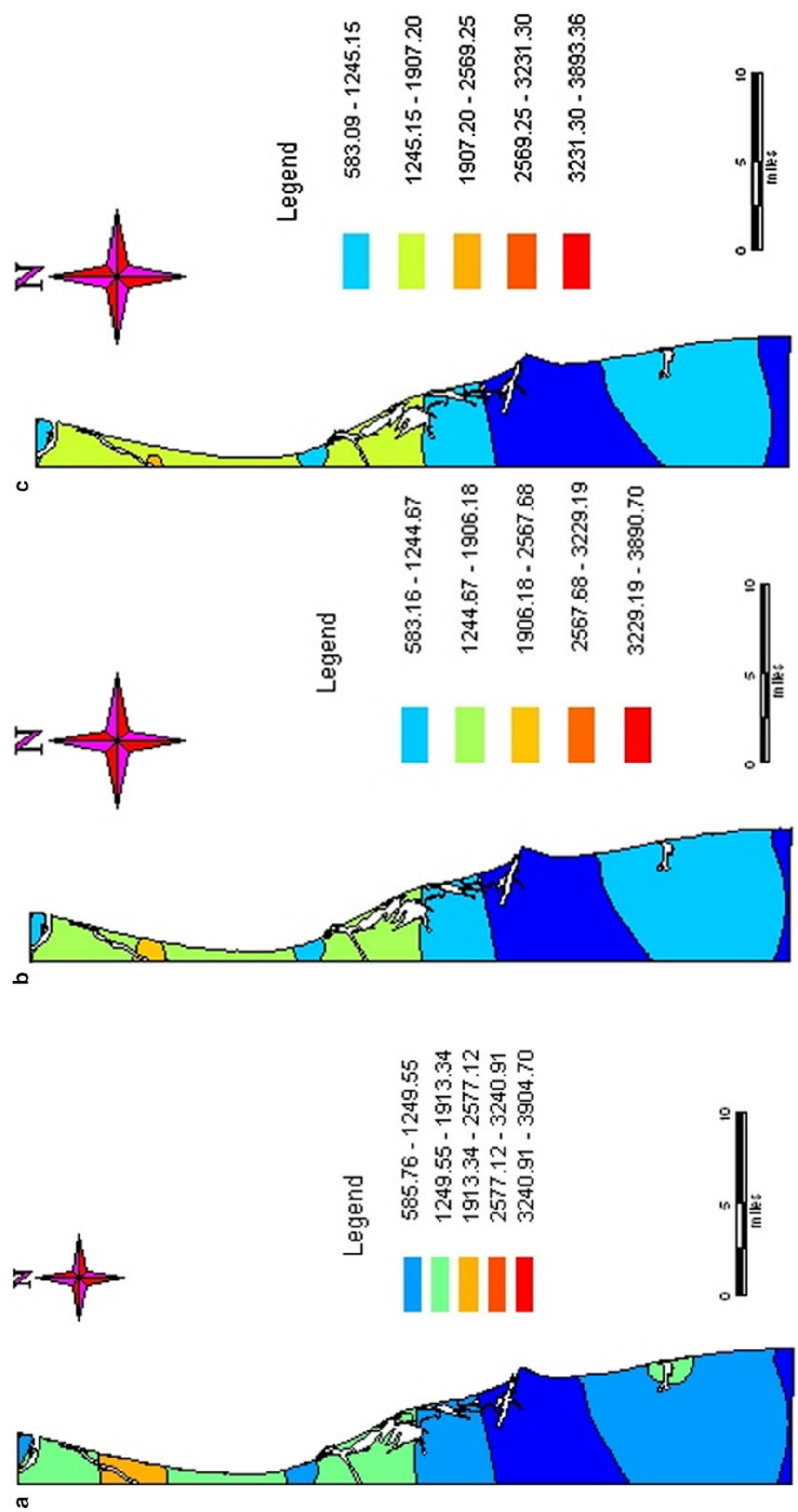


Fig. 18 Spatial distribution of EC (μs/cm) in: (**a**) Deep layer, (**b**) Middle layer, (**c**) Surface layer

Spatial Distribution of EC and DO

The spatial distribution for the average values of the DO for each location were calculated and plotted for three different depths (deep, middle and surface) (Figs. 17a, b, c). Figures 17b, c representing the middle and the surface layers show that the values are higher in the west of the Mangrove region and a region in the south of Uppanar. The similar results are reflected in the spatial representation of the DO (Fig. 17a) observations for deeper depths. In general there is a decrease in DO values in the spatial diagrams from the surface to the deep layers. The spatial variations of EC (Figs. 18a, b, c) also indicate that the lesser values are noted along the west of the mangrove region i.e. in the regions corresponding to the areas with higher DO values, indicating the presence of fresh water. The probable subsurface discharge of this fresh water into this mangrove region helps in the primary productivity of this ecosystem, but this has to be probed in detail.

Conclusion

The in situ observations made in the open wells along this coastal region indicate that there exists a distinct variation in the DO and EC values with depth and time in the coastal aquifers. This variation is due to the tidal influence in the coastal aquifers at Rajapettai, Tirumullaivasal, Tiyagavalli and Radhavilagam. The correlation between the EC and DO generally shows that there is a negative relationship to each other. The nature of these parameters shows perfect stratification and mixing trends in the observation wells. This is attributed to the status of the wells (extraction/static) and their distance from the sea. The spatial variations of EC also indicate that the lesser values are noted along the west of the mangrove region which matches with the regions of higher DO values. The study on the in situ DO observations reveals significant hidden relationship between the coastal saline and fresh water interface. The sustainable management of the coastal environment is mainly dependent on the availability of fresh water and its quality. The biodiversity of the region is dependent basically on the EC and DO of the available fresh water. The depth wise observation will aid in determining the depth of well construction. The study reveals that the coastal ground waters with less DO and high EC has to be judiciously used for the further development of this fragile eco system.

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