Case Study

Parameter Estimation and Vulnerability Assessment of Coastal Unconfined Aquifer to Saltwater Intrusion

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Abstract: The focus of the present work is to characterize a tropical, coastal aquifer and to carry out its vulnerability to saltwater intrusion using hydrogeological parameters. The characterization of the aquifer involves pumping tests, vertical electrical sounding, and water quality analysis carried out at 41 monitoring wells. The area under investigation lies between two tropical, seasonal, tidal rivers, i.e., Pavanje and Gurpur rivers, joining the Arabian on the west coast of India. The aquifer is predominantly shallow and unconfined, having moderate to good groundwater potential with transimissivity and specific yield ranging from 49.2 to 461.4 m^2/day and 0.00058 to 0.2805, respectively. The electrical resistivity tests indicated that the thickness of the aquifer ranges from 18 to 30 m. The study also investigates the saltwater affected areas in the region the vertical electrical sounding and water quality analysis. The resistivity results revealed several probable isolated saltwater intruded pockets in the region with resistivity less than 70 Ωm. From the salinity analysis of water, the locations that are affected during February to May (summer) and throughout the year are identified. The wells that are located close to the coast (< 350 m) and at lower elevations (well bottom $< +1$ m) were found to be saline throughout the year. Also, wells along the banks of the river show considerable salinity (> 200 ppm) during the summer period from tidal inflow along the rivers. The water samples were also analyzed for chloride to bicarbonate ratios during December to May at all the monitoring wells and were found to be exceeding the allowable limit at several locations. The saltwater vulnerability maps are derived for the area by the index-based method using the hydrogeological parameters. The method was found to be effective while compared to the field observations. The results from the analysis indicate that the aquifer is medium to highly vulnerable to saltwater intrusion at majority of the locations. The impact of projected sea level rise by 0.25 and 0.50 m from the climate change is also assessed on the vulnerability of the region to saltwater intrusion. **DOI: 10.1061/(ASCE)HE.1943-5584.0000524.** © *2012 American Society of Civil Engineers.*

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Introduction

Mangalore, a coastal city of south India with a population of about 1.5million has been experiencing unprecedented growth over the last few years because of industrialization and urbanization. At present, the domestic as well as industrial water requirements are mainly met by the Nethravathi River water, which is being supplied by the Mangalore city corporation and locally from groundwater wells. However, because of the seasonal and tidal nature of the rivers in the coastal region, the freshwater aquifers become saline during February to May up to several kilometers inland on either side of the rivers. Under the above scenario, it is essential to consider the effective and optimal utilization of coastal aquifer for freshwater supply. Because withdrawals from the aquifer system can affect the groundwater levels, quality, coastal groundwater discharge, and surface water-groundwater interactions, a better understanding of the groundwater flow system of the study area is needed for effective water resources management.

The coastal aquifers that are prone to saline water intrusion are identified by relatively low resistivity values, indicating presence of saltwater. In Florida, the electrical resistivity method was used to locate the aquifers affected by the saltwater intrusion (Fretwell and Stewart 1981; Fitterman 1996). In addition, Fretwell and Stewart (1981) observed higher concentrations of chlorides in the adjoining area of the river were from the landward movement of saline water. In the present work, a similar attempt was made to estimate the saltwater intrusion affected areas using Schulmberger resistivity technique (Nath et al. 2000). A weightage-driven approach (Chachadi et al. 2005) is used to assess the vulnerability of coastal aquifers to saltwater intrusion using hydrogeological parameters. The most important factors that control the saltwater intrusion are indicated in the acronym for this method, GALDIT (Ferreira et al. 2005)—**g**roundwater occurrence (aquifer type; unconfined, confined, and leaky confined), **a**quifer hydraulic conductivity, height of groundwater **l**evel above sea level, **d**istance from the shore (distance inland perpendicular from shoreline), **I**mpact of existing status of saltwater intrusion in the area, and **t**hickness of the aquifer, which is being mapped. Ferreira et al. (2005) reported the first application of this index method to Monte Gordo aquifer in Portugal in the framework of the EU-India INCO-DEV COASTIN project, aiming the assessment of aquifer vulnerability to saltwater intrusion in coastal aquifers. The vulnerability of central-western Sardinia to

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saltwater intrusion was assessed (Barrocu et al. 2006) on the basis of the GALDIT index in association with geographical information system (GIS) tools. The expansion of agricultural and cattle raising in the region resulted in groundwater overexploitation by wells. Being the new approach, the method is used for the scientific assessment of the study area in estimating the vulnerability of the region to saltwater intrusion.

Change in groundwater levels with respect to mean sea elevation along the coast largely influences the extent of saltwater intrusion in the freshwater aquifers. Past observations on the mean sea level along the Indian coast indicate a long-term rising trend of about 2.5 mm per year on an annual mean basis (Aggarwal and Lal 2001). The thermal expansion related sea level rise is expected to be 15 to 38 cm by the middle of this century and 46 to 59 cm by the end of the century (Aggarwal and Lal 2001). This anticipated rise in the sea level along the Indian coastline is comparable with the projected global mean sea level rise of 50 cm by the end of this century and may have significant impact along the coastal zones of India. The Intergovernmental Panel on Climate Change (IPCC) (2001) predicts that the global seas may rise by an additional 0.2 to 1.0 m by 2100, with a best estimate of 0.5 m (Masterson and Garabedian 2006). In the present study, a reasonable estimate of 0.25 and 0.5 m rise of sea level by the end of the century is made for assessing the vulnerability of region to saltwater intrusion.

The objective of the present work is to assess the capability of the coastal aquifer to sustain anticipated future groundwater developments in the region. The present investigation focuses on the characterization of the aquifer between the Gurpur and Pavanje rivers through pumping tests, electrical resistivity tests, and groundwater quality analyses. The study area lacks scientific assessment of extent of saltwater intrusion, and hence it is proposed to take up the investigation on the vulnerability of the region to saltwater intrusion through an index based method using the hydrogeological parameters. The results obtained from the investigation are broad- based, but, would be useful to evolve a proper management strategy to protect the coastal aquifer from the adverse effects of overexploitation. The study also attempts to assess the impact sea level rise on the groundwater quality because of anticipated climate change. A microlevel investigation, however, would be required with detailed field investigations combined with a transport simulator to develop a comprehensive approach toward development in the region.

Study Area

The study area lies between 74° 45′ E to 74° 54′ E and 12° 50′ N to 13° 4′ N in the Pavanje and Gurpur river basins (Fig. 1) of southern India, which is within the Mangalore city corporation limits. Because the Gurpur and Pavanje rivers are seasonal and tidal in nature, the adjoining aquifers get contaminated by salt water through these rivers for considerable distance upstream during February to May. The area is surrounded by the Arabian Sea on the west, and the eastern boundary is located along the ridge line. The areal extent of the region is about 5,000 ha. A total of 41 monitoring wells are considered in the area and their locations are indicated in Fig. 1. The spread of wells is planned in such a way to accommodate the required density limit and considering the existing problem of saltwater intrusion. The sparse region in the figure either does not have habitations or have industrial establishments. The major groundwater withdrawal at present is limited to a few locations with the pumping rate ranging from about 500 to 2,500 m^3/day.

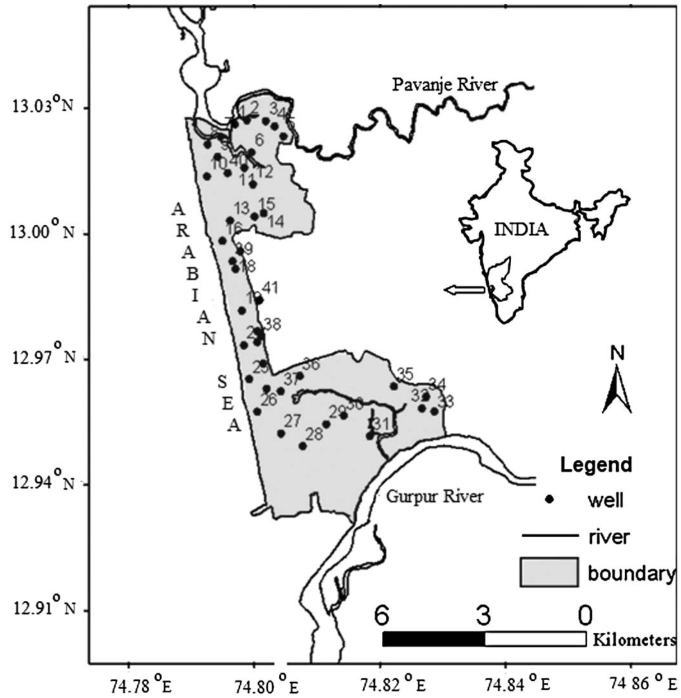

Fig. 1. Study area with observation wells

The area under investigation has lateritic formation under laid by a thin bed of clay, granites, gneisses, and coastal alluvium along the coast. Rao (1974) conducted bore log investigations in the coastal area, which indicated the nature and depth of aquifer. A lithologic cross section of the aquifer (Dept. of Applied Mechanics and Hydraulics 1996) at one of the locations in the basin is shown in Fig. 2. The basin is predominantly an unconfined aquifer with depth ranging from 12 to 28 m as per earlier investigations (Rao 1974; Srikantiah 1987; Lokesh 1997). In the coastal belt, at least one clay layer was found to be covered by several noncohesive sand layers. In the interior part, the subsurface mainly consists of laterites. The depth of lateritic formation varies from 5 to 20 m. The porous nature of laterites drains away rainwater leaving the surface to dry quickly. The rugged topography and porous nature of soil induces the bulk of the infiltrated water to escape as subsurface outflow (Lokesh 1989).

There are two types of soils in the study area—coastal alluvium and laterite soils. The coastal alluvium exists along with silt and clay, which was evident from laboratory tests (Jayappa 1991). The clay deposits differ from each other, depending on geological processes such as sea level changes, degenesis, erosion of superimposed load, and desiccation (Rao 1974). The clay layer in the region has low permeability and poor drainage characteristics (Lokesh 1989). The study area has tropical humid type of climate. Four seasons are identified for the region by the India Meteorological Department. They are the monsoon (June to September), postmonsoon (October to November), winter (December to January), and premonsoon or summer (February to May) seasons. The mean maximum and minimum temperatures in the region are 36°C (May) and 21°C (December), respectively. The southwest monsoon season is the principal rainy season for the region during June to September, and 100% humidity is recorded during June to August. The annual average rainfall is about 3,500 mm with most of it (about 90%) confined to June to September. Because of uneven distribution of rainfall and inadequate surface storage, there exists a prolonged dry period during January to May.

Methodology

Pumping Tests

Two conceptual approaches have been used to analytically model the release of water from the zone above the water table

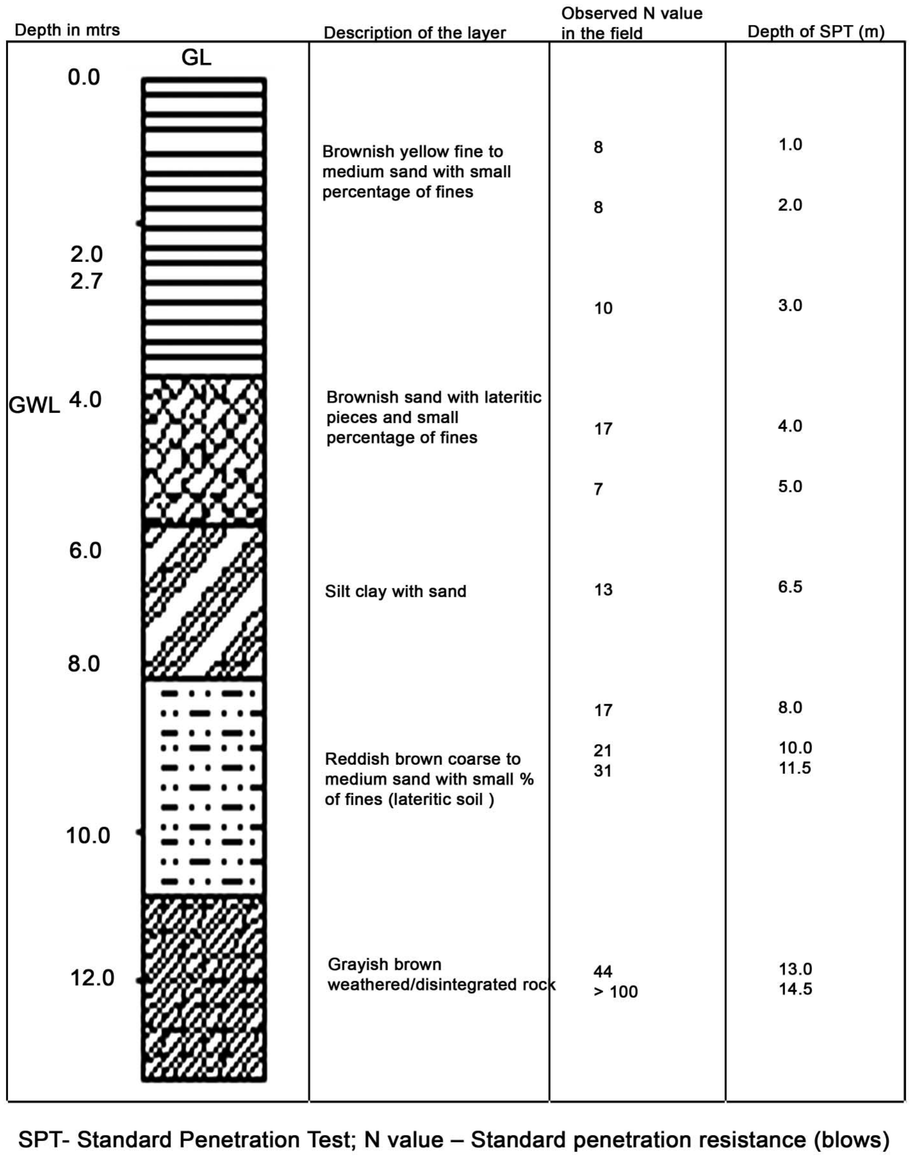

Fig. 2. Lithologic cross section of aquifer

in unconfined aquifers. In the first approach, developed primarily by Boulton (1954, 1963), drainage from the zone above the water table is assumed to occur gradually in a manner that varies exponentially with time in response to a unit decline in the elevation of the water table. In the second approach, developed by Neuman (1972, 1974), water is assumed to be released instantaneously from the zone above the water table in response to lowering of the water table. Neuman (1974) justified this assumption, in part, based on numerical models that appeared to show that effects of flow from the unsaturated zone upon drawdown in the saturated zone were negligible; this assumption was also agreed on by Moench (1994). The present investigation considers the Neuman (1974) approach for the estimation of aquifer parameters, which has the following assumptions: (1) aquifer has infinite aerial extent, (2) aquifer is homogeneous, isotropic, and of uniform thickness, (3) aquifer is unconfined, (4) flow is unsteady, and (5) diameter of pumping well is small, so that storage in the well can be neglected. The pumping test data from 18 wells are analyzed using Aquifer Win32 software.

Surface Geoelectric Measurements

The resistivity of soils is a complicated function of porosity, permeability, ionic content of the pore fluids, and clay mineralization. The most common electrical method used in hydrogeologic and environmental investigations is the vertical electrical soundings (VES) or resistivity soundings. In the study area, the aquifer was to be characterized, and, because drilling the bore holes is an expensive proposition, VES was carried out at the sampling locations. The apparent resistivity values (in Ωm) are obtained from VES using Schlumberger's configuration (Nath et al. 2000). A total of 22 vertical electrical soundings were carried out in the study area in February 2007. The instrument used was Aquameter CRM 50, a micro processor-based resistivity meter, designed and manufactured by Anvic Systems in Pune, India. The electrical resistivity tests were also conducted at a few specific locations during February/March 2008 using Wenner configuration (Loke 2004). Syscal resistivity meter by Iris Instruments with 72 electrodes was used for the research.

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Vulnerability Assessment

The aquifer vulnerability to saltwater intrusion as defined by Ferreira and Cabral (1991) is "the sensitivity of groundwater quality to an imposed groundwater pumpage or sea level rise or both in the coastal belt, which is determined by the intrinsic characteristics of the aquifer". The GALDIT method (Chachadi and Ferreira 2001) is a weightage-driven approach to assess the vulnerability of coastal aquifers using hydrogeological parameters. The various parameters adopted in the evolution of the method includes identification of all the parameters influencing saltwater intrusion process through extensive discussions and consultations with the experts, academicians, etc. (Ferreira et al. 2005). These factors, in combination, are used to assess the general saltwater intrusion potential of each hydrogeologic setting. The system contains three significant components—weights, ranges, and importance ratings and the details are reported elsewhere (Chachadi and Ferreira 2001). The basic assumption made in the analysis is that the bottom of the aquifer lies below the mean sea level.

The indicator weights depict the relative importance of the indicator to the process of saltwater intrusion. The most significant indicators for saltwater intrusion have a maximum weight of 4 and the least have a minimum weight of 1. Each of the indicators is subdivided into variables according to the specified attributes to determine the relative significance of the variable in question on the process of saltwater intrusion. The indicator weights are decided based on results from the studies related to saltwater intrusion from the peers in the field (Ferreira et al. 2005). The importance ratings range between 2.5 and 10 on a 10-point scale, and higher importance rating indicates greater vulnerability to saltwater intrusion.

Computation of GALDIT-Index

The GALDIT-index is obtained by computing the individual indicator scores and summing them as per the following expression (Chachadi and Ferreira 2001):

$$\text{GALDIT-Index} \quad = \sum_{i=1}^{6}\{(W_i)R_i\} \bigg/ \sum_{i=1}^{6} W_i \tag{1}$$

where W_i = weight of the ith indicator and R_i = importance rating of the ith indicator.

This system allows the user to determine a numerical value for any hydrogeological setting by using this additive model. Once the GALDIT-Index has been computed, it is possible to classify the coastal area into various categories of saltwater intrusion vulnerability (Chachadi and Ferreira 2001). The range of GALDIT-Index scores (i.e., 2.5 to 10) is divided into 3 groups—≥ 7.5 as highly vulnerable; 5–7.5 as moderately vulnerable; and < 5 as low vulnerable. The summary of GALDIT parameter weights, rates, and ranges are given elsewhere (Chachadi and Ferreira 2001) for different hydro-geological settings. The GALDIT method is based on results from hydrogeological investigations on saltwater intrusion by peers and other established relationships between the extent of saltwater intrusion and aquifer parameters (Bear and Verruijt 1987). The method is well established through field checks as reported in (Ferriera et al. 2005). Also, the method includes existing status of saltwater intrusion in the form of chloride-bicarbonate ratio as a counter check to the estimated vulnerability.

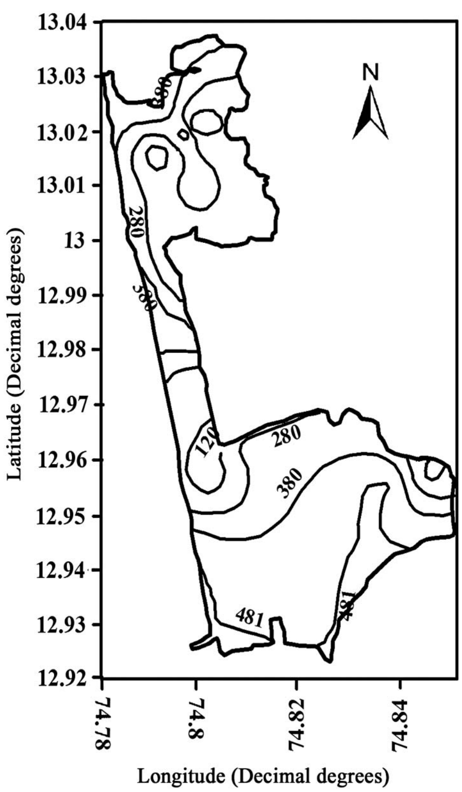

Fig. 3. Transmissivity distribution (m^2/day) in study area

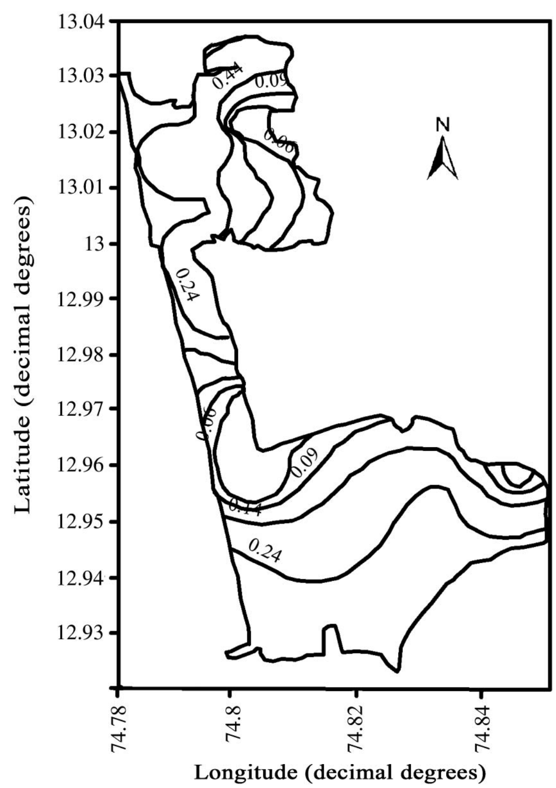

Fig. 4. Specific yield distribution in study area

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Table 1. Apparent Resistivity (in Ωm) and Lithology at Selected Locations in the Study Area

$AB/2$ (m)	W3	W4	W7	W13	W14	W17	W19	W24	W26	W31	W32	W33	W35	W36	W38
10	114	83	839	20	160	59	204	47	319	441	289	106	294	410	78
20	221	167	71	63	2	113	71	4	29	108	54	37	209	73	106
30	557	289	296	109	115	174	131	31	45	19	128	321	246	224	81
40	1080	578	622	207	980	308	25	358	251	383	88	239	201	798	289
50	1539	862	892	314	480	2303	10	480	314	59	421	29	108	1519	2577
60	2254	1656	921	304	745	480	1421	294	—	69	186	480	78	176	1166
70	29	941	862	294	1107	2979	235	794	—	706	941	363	284	323	813
80	2652	1446	1808	—	—	824	201	1527	—	1607	804	865	683	1507	1808
Overburden	24 m	28 m	24 m	22 m	24 m	22 m	24 m	24 m	24 m	24 m	30 m	20 m	24 m	24 m	26 m
Salinity	56 m		18 m		16 m		35 m	16 m	16 m	24 m	16 m	16 m			
Fractures	16, 24, 56 m	32, 56 m	32, 58 m	56 m	40 m	30, 60 m	35, 60 m	48 m	32, 40 m	40, 50 m	32, 48, 64 m	40 m	50 m	48, 56 m	56 m
Lithology	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil	Soil
	—	—	Sand, silt	—	—	—	—	Sand, silt	—	—	—	—	Sand, silt	—	—
	Laterite	Laterite	Laterite	Late-rite	Late-rite	Laterite	Laterite	Laterite	Laterite	Laterite	Laterite	Laterite	Laterite	Laterite	Laterite
	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clay	Clays	Clay	Clay	Clay	Clay
	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss	Gneiss

Results and Discussion

Characterization of Aquifer

In total, 18 pumping tests are conducted in the area on wells, which are of shallow depth (< 10 m). From the field observations, it is evident that the aquifer is shallow and unconfined in nature. It was found that transmissivity and specific yield range from 49.2 to 461.4 m^2/day and 0.00058 to 0.2805, respectively in the study area, which indicates that the aquifer has medium to good groundwater potential. The areal distribution of the above parameters is depicted in Figs. 3 and 4. The transmissivity values are found to be higher on the north-western and southern regions, and the lowest transmissivity was found in the midregion. However, the values are sufficiently high to categorize the aquifer as good yielding aquifer. Fig. 3 also indicates that higher values of specific yield are observed in the southern and north-western portion of the study area with values greater than 0.1, which is also in conformity with the earlier field studies (Raghunth et al. 2001).

The results of the vertical electrical sounding tests were given in Table 1 for specific locations where saltwater intrusion is suspected. Underneath the overburden, the hard rock is represented by gneiss in the area. The presence of salinity is estimated for the areas with low values of the resistivity (< 70 Ωm.). The estimated depth to saline layer is indicated in the results. The fractures refer to the estimated depths at which major groundwater bearing aquifer formations are expected to strike while drilling bore wells. The longest profile surveyed using the Wenner configuration at a specific location (13° 0′ 58.138″ N and 74°47′ 33.411″ E) is shown in Fig. 5. From the resistivity plots, we observe that the Wenner beta sequence has penetrated up to about 50 m depth. In Fig. 5, the resistivity values between 80–300 Ωm are the depths suitable for groundwater exploration. The presence of clay or such other material is indicated with low resistivity in Fig. 5. The interpretation of resistivity values indicates a homogeneous top layer with resistivity values above 400 Ωm for about 5 m depth. This is followed by the second layer having patches of low resistivity in the range of 15–400 Ωm and with a thickness of about 25 m.

Lithology of the study area is constructed based on the field observations coupled by VES studies. The soil and sand, silt and laterite, and clays constitute the total overburden in the area. The top soil is a mixture of loamy soil, sand, and laterites. Below this, a regular, hard lateritic zone is present in most of the locations except a few where sandy soil layer exists. Based on the VES data, the fence diagrams are drawn along different directions and the fence diagram drawn through three well locations along the coastal belt is shown in Fig. 6. Per the resistivity investigations, the average depth of overburden varies from 18 to 30 m with the exception of a few locations where the massive igneous rocks with resistivity greater than 1000 Ωm are observed at depths beyond 80 m.

In Table 1, saltwater intrusion is suspected at the locations with the resistivity values < 70 Ωm. The estimated depth of saline intrusion is given in the table for the respective locations (row 11). Fig. 7 shows the probable saltwater intrusion affected locations in the study area with resistivity < 70 Ωm. From these results, it indicates that the areal extent of saltwater intrusion at present is not significant. According to the Fig. 6, well numbers 3 (Haleyangadi), 7 (Mukka), 14 (Munchoor) and 19 (Idya), 24 (Hosabettu), 26 (Chitrapur), 31 (Baikampady), 32 (Kenjar), and 33 (Jokatte) seems to be affected by saltwater intrusion at depths ranging from 15 to 55 m from the ground surface. The above wells are located at an elevation almost equal to the mean sea level or lower than that and are within 800 m either from the sea or the tidal river.

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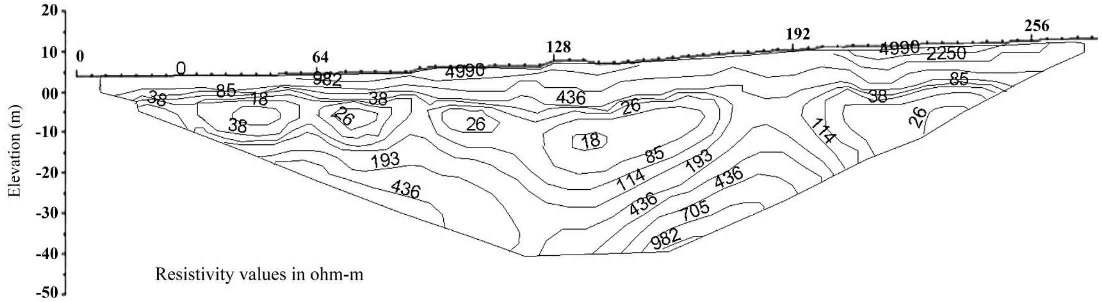

Fig. 5. Wenner beta sequence resistivity at specific location

Groundwater Occurrence, G

From the field tests, it is evident that the aquifer is unconfined in nature with rich groundwater potential, and hence a rating of 7.5 is adopted as per the specifications. The parameters are rated on a 1 to 10-point scale. The unconfined aquifer is found to be less vulnerable to saltwater intrusion compared to confined aquifer because of smaller cone of depression and delayed release of water to wells during pumping. Hence, rating for unconfined aquifer was set to a lower value, i.e., 7.5 compared to 10 (maximum) for confined aquifers, which are above atmospheric pressure condition, relatively faster release of water, and larger cone of depression during pumping. The ratings are set by looking into different field hydrologic settings, and the reasons for choosing rate and weights for different parameters are given in Chachadi and Ferriera (2001).

Aquifer Hydraulic Conductivity, A

From the characterization of the aquifer, the hydraulic conductivity is estimated to be greater than 40 m/day, which was also established elsewhere (Ranganna et al. 1985). Hence, a maximum and common GALDIT rating of 10 is assigned for the entire study area. The extent of intrusion is directly related to the hydraulic conductivity and nature of aquifer as specified in Bear and Verruijt (1987). Higher the aquifer conductivity, the greater the length of intrusion and the wider the cone of depression. As per Bear and Verruijt (1987), the equations for the length of saltwater intrusion in confined and unconfined aquifers are governed by the hydraulic conductivity (K), saturated thickness (B), freshwater flow (q) toward sea, and the density of saltwater. By substituting identical values of K, B, and q in the equations, the length of intrusion would be nearly identical, and hence the weights are reassigned for aquifer hydraulic conductivity by Chachadi and Ferreira (2005) from that suggested by Aller et al. (1987) considering the effect of saturated thickness and recharge on the extent of saltwater intrusion.

Height of Water above Sea Level, L

The groundwater level plays a crucial role in maintaining the hydraulic pressure along the coast to push back saltwater. The ratings are assigned depending on their effect on length of intrusion as described in the dynamic saltwater intrusion models. The water table elevation less than 1 from the mean sea level is considered as the case with highest importance rating of 10 indicating the region's high vulnerability to saltwater intrusion. The water table elevation greater than 2 m from the mean sea level is considered to be having least vulnerability with a rating of 2.5. The lowest water table elevation may be considered for estimation as a conservative approach during a year. In the study area, the groundwater levels were measured on monthly basis during January 2005 to September 2007, and monthly vulnerability indices are estimated. The parameter required for the present study, L is obtained by reducing the water

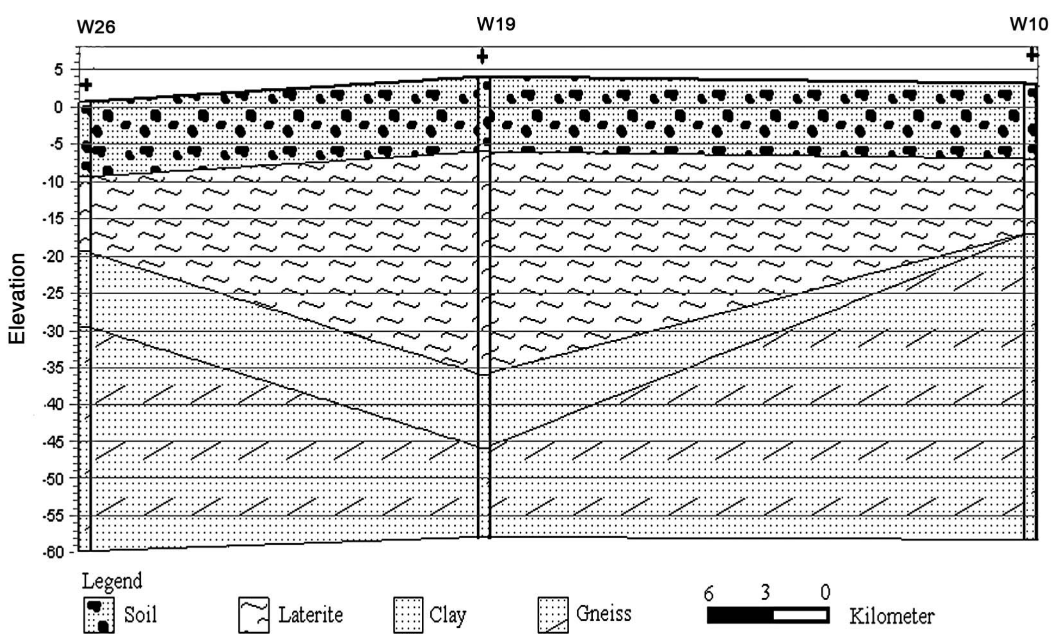

Fig. 6. Fence diagram through well locations along coastal belt

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level with respect to the mean sea level. In the study area, the wells are sunk in the porous soil. They are shallow and get filled to the brim during the rainy season. The water level gradually declines after the rains. In the area, we can observe some negative values (below the mean sea level), which need to be exploited very carefully considering the possibility of saltwater intrusion. From the field observations, the water table contours are prepared and the water table elevation was found to reach its maximum level during July and August. The maximum and minimum water levels observed in all the wells are 7.73 and −3.75 m with respect to the mean sea level, respectively. The water level in the wells 6, 32, 33, 34, and 35 are below mean sea level throughout the year with a minimum level of −3.75 m in well number 35 during Ma, 2007. The water level drops by a maximum of 5.57 m during November to January and by about 2.30 m during the premonsoon season (February to May). The driest period was observed to be the end of April because the area experiences premonsoon showers during May or the monsoon advancing to May. The water table distribution in the study area indicates that the parameter L is lowest along the coast and around the Pavanje and Gurupur rivers. This low water table scenario spreads over larger area as the summer approaches and becomes the lowest in April and May.

Distance from Shore/River, D

The magnitude of saltwater intrusion is directly related to the perpendicular distance from the coast. The ratings for this parameter are assigned as per the data reported from the numerous field tests. Under normal soil conditions, a distance of less than 500 m from the coast is considered to be highly vulnerable to saltwater intrusion with the highest rating of 10, and a distance of more than 1,000 m is considered to be with lowest vulnerability with a rating of 2.5. The perpendicular distance of each monitoring well in the study area either from the sea or the river is established. Because the Gurpur and Pavanje rivers are tidal in nature, the adjoining aquifers get contaminated by saltwater from these rivers for considerable distance upstream during the non monsoon period. Hence, these rivers are also treated as saline sources for the computation of the parameter D. It is found (Ranganna et al. 1985) that saline water intrudes up to a distance of about 22,000 m along the Gurupur River in the intense summer month of May. Along the Pavanje River, the intrusion of saltwater is prevented by means of a saltwater exclusion dam at a distance of about 9,000 m from the river mouth. Out of the monitoring network of wells, the nearest location

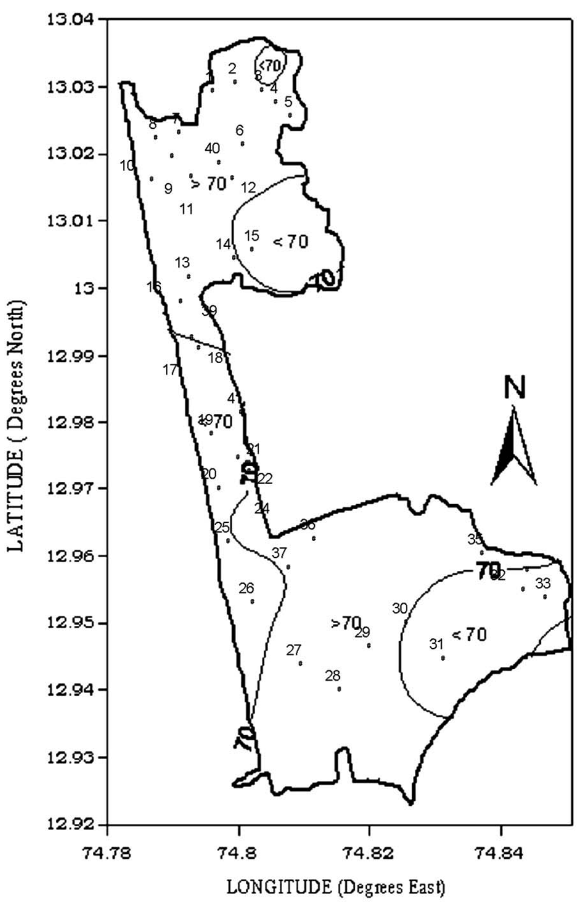

Fig. 7. Saltwater intrusion affected areas estimated from VES data

Table 2. Ratio of Cl/HCO_3 for Samples Collected from Monitoring Wells

Well number	Cl/HCO_3 Dec (06)	Jan (07)	Feb (07)	Mar (07)	Apr (07)		May (07)	
1	4.308	3.717	3.397	3.525	2.938	2.674	3.408	3.231
2	1.481	1.474	2.193	1.859	1.316	1.161	1.175	1.511
3	1.123	1.156	0.992	0.940	0.751	0.940	0.979	0.995
4	1.156	1.100	0.931	0.858	0.876	1.047	1.152	1.009
5	0.588	0.564	0.564	0.737	0.419	0.385	0.415	0.373
6	8.460	6.833	8.076	14.355	6.635	6.043	4.700	5.640
8	0.987	1.058	0.932	1.354	0.665	1.160	1.168	1.253
9	2.403	1.987	2.081	2.023	1.870	1.763	2.115	2.115
10	0.397	0.470	0.415	0.524	0.427	0.518	0.463	0.464
11	5.961	6.639	4.089	9.988	8.930	9.400	11.562	9.762
12	2.065	1.939	2.603	2.726	3.217	2.986	2.977	2.996
13	1.790	1.821	1.923	1.821	1.163	1.410	1.898	1.561
14	2.977	2.679	2.397	2.891	2.436	2.436	2.712	2.386
16	0.959	0.963	0.804	0.959	0.674	0.846	0.954	0.974
17	0.604	1.296	1.287	1.259	1.293	1.276	0.951	1.312
18	0.513	0.595	0.684	0.695	0.470	0.513	0.584	0.529
19	3.701	0.458	0.412	0.222	0.321	0.362	0.489	0.401
20	0.613	0.743	0.740	0.75	0.872	0.728	0.823	0.889
21	0.697	0.834	1.090	0.623	0.857	0.886	0.917	0.627
22	0.308	0.338	0.308	0.318	0.276	0.346	0.353	0.377
23	0.653	0.745	0.714	0.715	0.763	0.836	0.468	0.823
24	0.237	0.235	0.192	0.203	0.201	0.231	0.222	0.508
25	2.969	2.836	3.620	3.493	2.593	4.070	4.291	3.917
26	0.677	0.691	0.679	0.718	0.679	0.734	0.859	0.804
27	2.332	1.837	1.554	2.136	2.095	2.076	3.102	1.992
28	1.721	1.674	1.987	2.281	2.074	2.115	3.878	2.256
29	4.935	5.718	5.217	5.852	4.772	6.922	8.284	8.46
30	0.809	0.977	0.722	0.452	0.499	0.713	1.472	1.32
31	1.448	1.888	2.247	2.557	3.102	3.644	3.704	3.856
32	1.723	2.136	2.328	2.35	2.238	3.924	4.005	4.583
33	0.453	0.517	0.887	1.775	1.309	1.819	2.247	1.457
34	1.763	1.799	1.216	1.334	1.095	1.064	1.039	0.582
35	1.263	1.704	1.833	1.873	0.366	0.305	1.808	1.338
36	0.831	1.598	1.293	1.108	1.012	1.154	1.226	1.074
37	2.820	3.205	4.442	3.408	2.019	1.720	1.316	1.251
38	0.521	0.625	0.526	1.138	0.672	0.694	0.786	0.547
39	1.168	1.933	1.895	1.866	1.620	2.256	2.115	2.041
40	0.572	0.726	0.546	0.533	0.492	0.683	0.578	0.578
41	2.891	4.331	3.525	3.384	2.256	2.440	2.495	2.585

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to the saline source is well number 1 ($D = 160$ m) and the farthest location is well number 29 ($D = 1813$ m).

Impact of Existing Status of Saltwater Intrusion, I

The stress on the aquifer need to be taken into account while considering the natural balance between salt water and fresh water, which affects the vulnerability of aquifer. Several studies (Edet and Okereke 2001) have used the chloride concentration of groundwater to define the extent of saltwater intrusion, which specify the threshold chloride concentration in the range of 40 to 300 mg/L as indicative of saltwater invasion. The present results (Table 2) infer that the aquifer water is contaminated at specific locations with saltwater, Cl^-, the most abundant ion in saltwater, in higher proportions. The HCO_3^- ion, which is the most dominant ion in fresh groundwater, occurs generally in small amounts in salt water. Cl/HCO_3 values above 1.5 may be considered to be affected by saltwater intrusion.

From Table 2, it is observed that wells 1, 6, 11, and 29 show high values of Cl/HCO_3, ranging from 2.938 to 14.355. The first three wells are located closer to the Pavanje River than to the shore and well 29 is nearer to the Gurupur River. Wells 12, 14, 41, and 25 also show ratios greater than 2 throughout. Wells 25 and 41 are 284.29 and 696.25 m away from the shore. Wells 31 ad 32 are within 900 m from the tidal (Gurupur) River, and hence show values greater than 3 in the summer months of April and May. Overall, the values of Cl/HCO_3 range from 0.235 to 8.460 during the postmonsoon period and from 0.192 to 14.355 during the premonsoon (summer) period. Fig. 8 shows the contour of Cl/HCO_3 in the study area during December and May 2007. The higher ratio in the southern part of the study area, i.e., around the Gurupur River spreads over a larger area as summer approaches. This is because wells 29, 30, 31,32,33,34, and 35 are closer to the Gurupur River. Also, Baikampady, Kenjar, and Jokatte are the low-lying areas. Thus, GALDIT method involves vulnerability assessment by actual parameters affecting saltwater intrusion. In view of this, this chemical parameter is included to determine the weight and rating. The chloride-bicarbonate ratios have been categorized into different vulnerability groups, which would assess the existing scenario. This parameter, however, can also be used to countercheck the overall rating obtained by the vulnerability assessment, matching in the present study.

Thickness of Aquifer, T

The thickness of the aquifer is directly affecting the extent of saltwater intrusion per the relationship specified in Bear and Verruijt (1987). The thickness of the aquifer is obtained from the electrical resistivity survey conducted in the study area at 22 locations. In Table 2, the results of the electrical resistivity survey are tabulated for suspected saltwater intrusion locations, where the overburden is estimated. The resistivity survey indicated that the area consists of shallow, unconfined aquifer with the thickness ranging from 18 to 30 m. Because the thickness of the aquifer is greater than 10 m, the GALDIT rating of 10 is adopted throughout the study area.

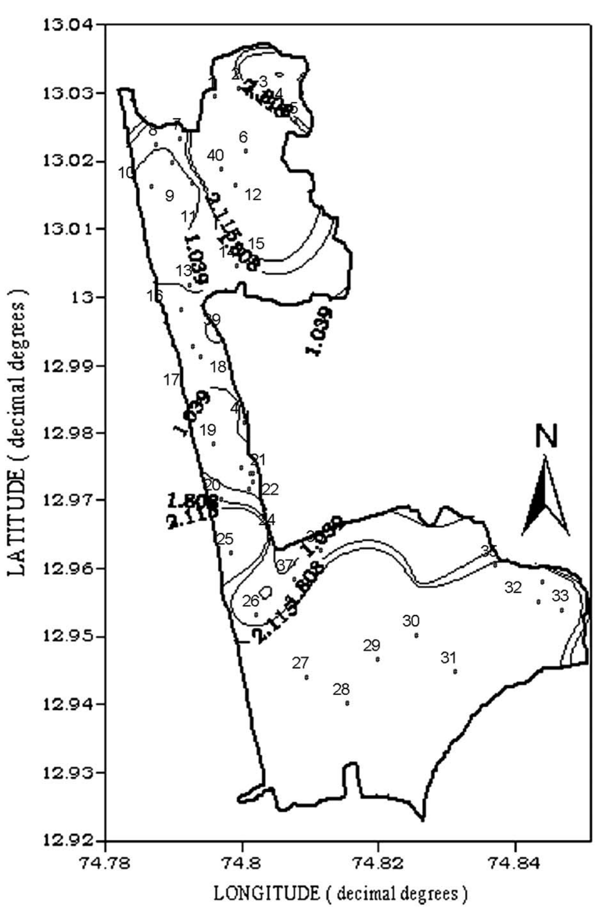

Fig. 8. Distribution of chloride-bicarbonate ratio in study area on May 9, 2007

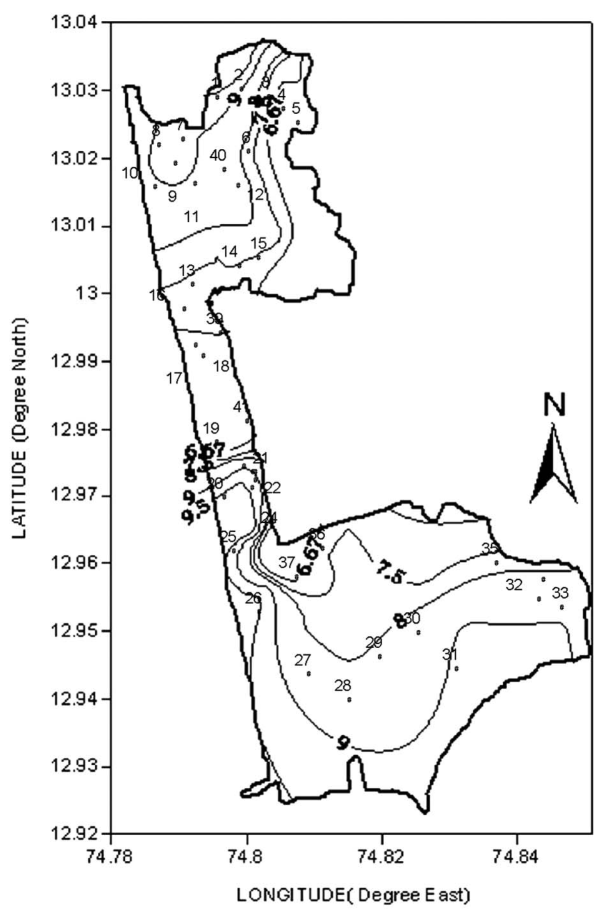

Fig. 9. Saltwater-intrusion vulnerability map as depicted by GALDIT scores for normal sea level (April 2007)

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Vulnerability Assessment through GALDIT-Index

The GALDIT indices are calculated for the study area from the month of November 2006 to May 2007. The reduced levels (RL) of the bottom of wells 3, 5, 13, 16, 18, 19, 23, 27, 28, 39, and 41 are positive, which indicate that the well bottom is above the mean sea level. Hence, the GALDIT-index for these wells is to be assigned zero, which may be considered as low vulnerable region for saltwater intrusion.Except for wells 5, 18, 19, and 23, other wells have the ratio of Cl/HCO_3 greater than unity, and hence may be considered as medium vulnerable region for saltwater intrusion. Fig. 9 shows the saltwater intrusion vulnerability map as depicted by GALDIT scores for the normal sea level during May 2007. As shown by Fig. 9, the study area falls under three categories of vulnerability, i.e., low, moderate, and highly vulnerable to saltwater intrusion, and it is also evident that the study area is worst affected in the month of April. The area on the northern side viz Chelaru, Mukka, Pavanje, and Haleyangadi are less affected during November to January. However, during February to May, they come under the zone of highly vulnerable category. The areas down south namely, Baikampady, Kenjar, Jokatte, and Kulai are seen to be greatly affected by the saltwater intrusion in the month of April and May.

Vulnerability Assessment for Sea Level Rise

The effect of climate change on the water resources of the earth is already being significantly felt. With the present trend continuing, the rise in sea level is becoming a reality that may largely influence the extent of saltwater intrusion in the coastal freshwater aquifers. The GALDIT rating is evaluated for a rise of 0.25 m in the sea level for the intense summer months of April and May. With 0.25 m rise in sea level, no significant change is observed in the GALDIT-index vulnerability map for the study area, except that wells 23 and 37 (in the Kulai area) turn highly vulnerable to saltwater intrusion in the month of April, unlike during the normal sea level condition (Fig. 9). However, with a sea level rise of 0.5 m, the area is susceptible to aggressive saltwater intrusion compared to the present level.

Groundwater Quality

The major thrust in the study was to assess the extent of saltwater intrusion the basin. Hence, salinity of groundwater collected from the wells is analyzed during the period January 2005 to September 2007 on a monthly basis. The results indicate salinity ranging from 0 to 2,900 mg/L in the wells. The wells 4, 7, 12, 19, 11, 24, 25, 26, 27, 30, 31, 32, 33, and 35 are having salinity greater than 300 mg/L and are severely affected by saltwater intrusion because of proximity to the sea. Some of the wells show the salinity with the advancement of summer. The spatial salinity distribution over the region is given in Fig. 10 for April 2007. In Fig. 10, the wells in the elevated region indicate zero salinity even during the summer. The salinity is minimal during the monsoon and starts increasing in the area after the withdrawal of the monsoon season. The maximum salinity of greater than 2,000 mg/L was observed along the coastline and adjoining the tidal rivers during April/May, especially during summer 2005. Well 7 (Fig. 10) shows consistently higher salinity ($>$ 400 mg/L) almost throughout the year. The bottom of this well is at -1.6 m and is about 350 and 870 m away from the Pavanje River and from the sea, respectively. Wells 11 and 34 show high salinity during summer 2005 only. This may be from the absence of premonsoon rainfall during that period. The other wells have the salinity normally within 200 mg/L.

From the field tests, the results are consolidated considering the existing saltwater problem/vulnerability to saltwater intrusion and are presented in Table 3. The results from the field studies indicate that the wells 3, 7, 11, 19, 25, 26, 31, 32, 33, and 35 are severely affected by saltwater intrusion. These wells, as we can observe from Table 3, are located at low-lying areas and are nearer to either the tidal river or the sea. Hence, the wells located at higher elevation, i.e., about 2 m above the mean sea level are not being affected with the existing rate of pumping. Thus, the field observations carried out through water quality and resistivity analyses confirm the effectiveness of GALDIT method, which is also evident from Figs. 7, 8, and 10, when compared to Fig. 9.

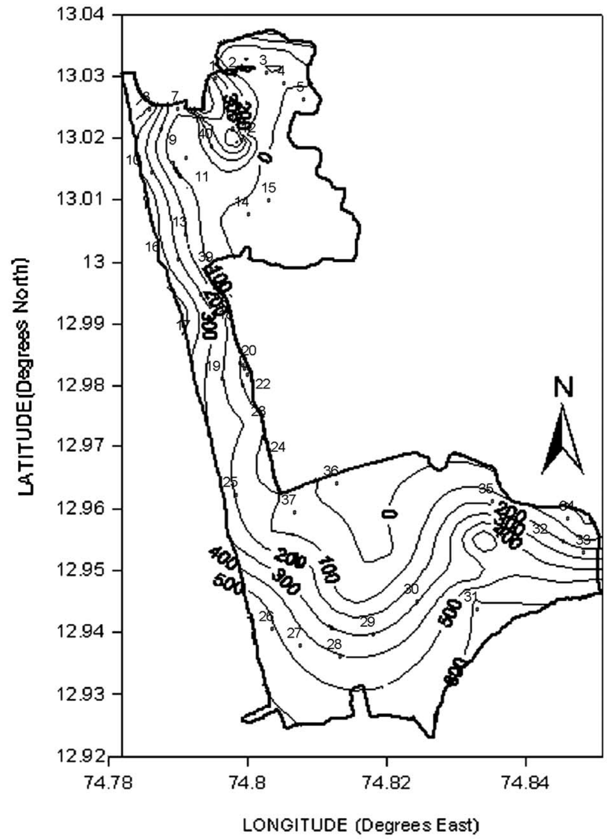

Fig. 10. Salinity (mg/L) distribution during April 2007

Conclusions

In the present study, an attempt was made to characterize and assess the extent of saltwater intrusion in the tropical, coastal aquifer. All the methods adopted to assess the extent of saltwater intrusion are in conformity with each other. Considering the scenarios of urbanization, overstressing of aquifer, and possible sea level rise, the area is categorized into different vulnerable regions to saltwater intrusion based on the hydro-geological parameters. The results from the study may be useful for further investigations related to groundwater potential and saltwater intrusion in view of increased groundwater developments. The study area under investigation is having moderate to good groundwater potential as evident from pumping tests. Because the area has an average annual rainfall of about 3,500 mm, it recharges the water table to the maximum extent (top of aquifer) every year by the end of July and then shows a declining trend until the onset of next monsoon. The observed water table variation over a year was quite significant and was found to be up to about 7.17 m in a well. The groundwater

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Table 3. Consolidated Results of Field Tests and Water Quality Analysis in Affected Areas

Well. number	Location	VES Ωm at depth, m	Salinity, mg/L (0)	Cond. μsimen/cm (750)	TDS, mg/L (500)	Cl/HCO_3 (1)	RL of well bottom, m	Distance to sea/river, m
01	Pavanje	76.2 at 90 m	200	< 750	< 500	4.31[a]	−2.28	160-r
03	Haleyangadi	29.4 at 56 m	100	< 750	< 500	1.2[a]	0.74	237-r
04	Chelaru	82.8 at 10 m	600	772	800	1.16	−0.50	307-r
06	Pavanje	No test	200	< 750	< 500	14.36[a]	−1.98	1081-r
07	Mukka	70.5 at 18 m	800[a]	1382[a]	967[a]	—	−1.62	351-r
09	Mukka	No salinity	100	< 750	1390	2.40[a]	−1.50	708-s
11	Padre	200 at 20 m	2900[a]	1376	4100	9.99[a]	−2.94	1387-r
12	Padre	136 at 20 m	500	< 750	5300	3.00[a]	−3.26	1537-s
14	Munchoor	1.7 at 16 m	100	< 750	< 500	2.98[a]	−2.10	1690-s
19	Idya	25.12 at 35 m	400[a]	751	529	3.70	0.41	459-s
24	Hosabettu	3.48 at 16 m	400[a]	< 750	501	< 1	−1.59	285-s
25	Chitrapur	No test	1000[a]	1763[a]	1120[a]	4.07[a]	−0.65	284-r
26	Chitrapur	28.8 at 16 m	300[a]	686	< 500	< 1	−1.87	313-s
29	Baikampady	No test	100	< 750	< 500	8.28[a]	−0.31	1814-r
31	Baikampady	18.66 at 24 m	400[a]	966	607	3.86[a]	−3.48	641-r
32	Kenjar	53.94 at 16 m	500[a]	1222	784	4.58[a]	−4.28	826-r
33	Jokatte	36.54 at 16 m	500[a]	< 750	700	2.25	−3.52	662-r
35	Jokatte	78.4 at 60 m	2400	2744	3300	1.87	−3.20	1644-r
37	Kulai	No test	100	< 750	< 500	4.44[a]	−2.11	1090-s

Note: -r = distance from river; -s = distance from sea.
[a]Saltwater affected throughout the year.

developmental works are not recommended for the areas where water levels are always below or within a meter from the mean sea level.

From the VES geoelectrical studies conducted, it is evident that the study area consists of a shallow, unconfined aquifer with an average thickness up to about 30 m. Also, from the studies, the likely areas affected by saltwater intrusion are identified. The water quality results indicate that the wells that are close to the coast, with a distance of less than about 350 m, were found to be saline throughout the year. Also, the wells along the banks of the Pavanje and Gurpur rivers, with a distance less than 500 m, show considerable salinity in the summer period at a depth range of 20 to 60 m.

The variations in the chloride-bicarbonate ratios and salinity confirm the above findings with the limits being exceeded at a few locations either permanently or during the summer period only. The wells located at higher elevation (bed level > +2.0 m), i.e., above the mean sea level are not being affected by saltwater intrusion at the present rate of pumping. However, the status on saltwater intrusion may have to be reassessed for increased rate/depth of pumping in the wells. There are several locations where the saltwater intrusion is already being significant and may require immediate attention before planning any developmental activities.

The GALDIT method for vulnerability assessment of a region to saltwater intrusion is found to be quite effective and reasonable while comparing with the field observations. The saltwater vulnerability maps derived using this method for the area for normal and anticipated sea level rise indicate that the aquifer is medium to highly vulnerable to saltwater intrusion at majority of the locations. Hence, further developments in the region involving groundwater extraction may have to be avoided to protect the freshwater aquifer. The results from the investigations may be useful for judicious planning of groundwater development in the tropical, coastal aquifers worldwide.

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