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Delineation of aquifer layer along Anjar-Rapar Corridor, eastern Kachchh basin, Gujarat using electromagnetic investigations

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ABSTRACT
Kachchh basin is an intraplate region of rifted Precambrian craton in the Gujarat state of the north-western India. The basin is characterized by a thick succession of sedimentary rocks of middle Jurassic to Holocene that overlie the Precambrian basement. Kachchh district is a water scarce region and ground water has become one of the important sources to meet the water requirements of various sectors. Tertiary and Mesozoic formations in general do not form promising aquifer mainly because of the clayey nature and poor groundwater quality. The upper Bhuj (Mesozoic) and Kankawathi (Tertiary) series of formations constitute a relatively good aquifer due to low salinity. We have carried out a time domain electromagnetic (TDEM) survey along the Anjar - Rapar (AR) corridor in the eastern part of the Kachchh basin to map potential aquifer layer in the region. Twelve fixed in-loop TDEM soundings with 100m sided transmitter loop were carried out. The measured transient decay curves are used to delineate the depth and subsurface resistivity of the underlying structures. The modelled 1-D section reveals a 20 to 50m thick conductive layer of 10-15 Ωm resistivity with its top surface at 10-15 m depth. We infer this conductive layer as a probable aquifer comprising saturated sandstone with moderate salinity. At some places along the corridor, we have also obtained a second aquifer layer at deeper levels(150-250m) overlying a relatively low resistive layer probably comprising clay and/or clayey sand. Apart from the first layer, subsequent subsurface formations (up to 200-250m) appear to be heterogeneous in nature and are inferred to be composed of clay (>5 Ωm), Clayey sand/sandy clay/ sandstone with high content of saline water (5-10 Ωm) and shale (20-50 Ωm). The results are integrated with well-log data to better constrain the geophysical inferences.

Key words: Time domain electromagnetic method, Kachchh, resistivity, aquifer mapping, Groundwater

INTRODUCTION

Shallow or near surface exploration techniques are being widely used to delineate aquifers, mineral deposits, in site selection for DC power transmission,and for mapping of stratigraphic sequence/lithology of an area (Aktarakciet al.,1977; Ebraheem et al., 1990; Danielsenet al., 2003; Carrasquilla and Ulugergerli, 2006; Yadavet al., 2010; Manglik et al., 2011; Sinha et al., 2013; Rai et al., 2013). Among various shallow geophysical techniques, electrical resistivity methods are versatile and economical for groundwater prospecting in different geological settings due to wide spectrum of resistivity compared to other geophysical parameters. All geoelectric, particularly, geo-electromagnetic methods are generally suitable for studying groundwater salinity owing to the close relationship that exists between the salinity and electrical resistivity (conductivity) measured by these methods. Both theoretical investigations and extensive practical studies (Fitterman and Stewart, 1986; Nabighian and Macnae, 1991; Goldman et al.,1991; Yadavet al., 2010; Sinhaet al., 2013; Chandra et al., 2010, 2012; Kumar, 2012; Rai et al., 2013; Kumar et al., 2014) show the superiority of the methods in detecting potential aquifer zones and saline water-saturated layers in different types of geological settings.

The Time domain electromagnetic (TDEM) method is one of the near surface exploration techniques through which we can estimate the electrical resistivity of the subsurface up to 500-600m depth (McNeill, 1990). TDEM measurements utilize strong step-function excitation direct currents to generate the primary electromagnetic (EM) fields. In response to the step-function interruption in current flow in transmitter loop, eddy currents are inducted in the neighboring conductive materials. Secondary fields due to the induced eddy currents are then measured at receiver (McNeill, 1990; Nabighian and Macnae, 1991). The method has been successfully applied to delineate stratified structures of geological interest as well as in the prospecting of groundwater, geothermal bodies, sulphide ores, deep graphite conductors, groundwater contamination, microzonation studies, etc. (King and Pesowski, 1993; Goldman and Neubauer, 1994; Taylor et al., 1992; Chandra et al., 2011, Pavan Kumar et al., 2013, 2014). In addition to the above objectives, the TDEM data can also be useful for the treatment of "static shift" effects in magnetotelluric (MT) soundings (Sternberg et al.,1988). The method is particularly useful for discriminating between layers having low resistivity and consequently for monitoring salt water intrusion and diffusion in an area (Mills et al.,1988; Goldman et al.,1991). The method possesses the highest

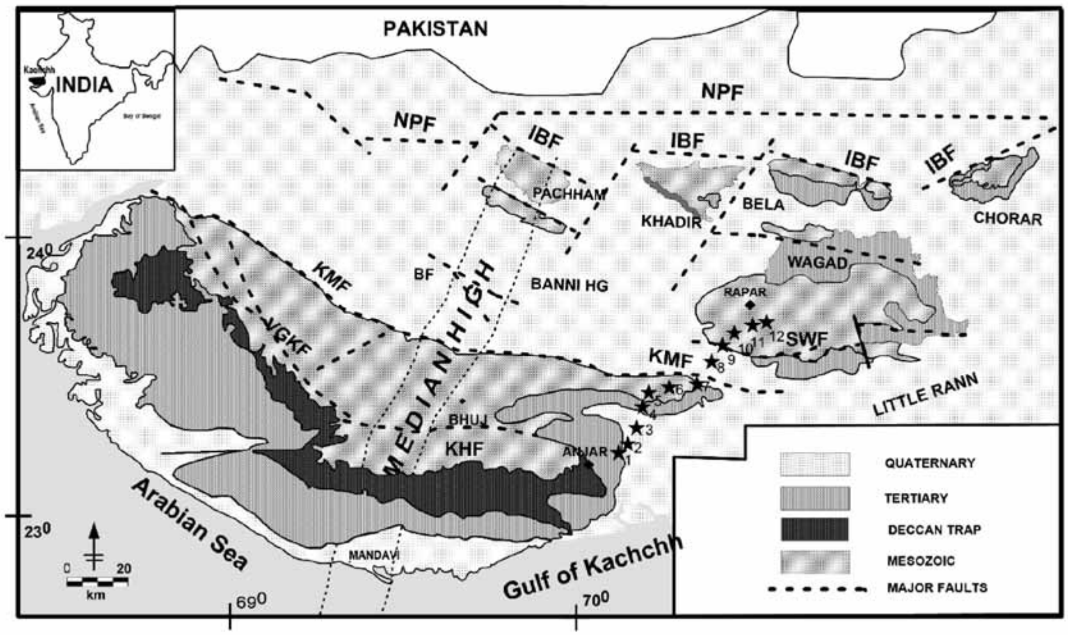

Figure 1. Geological map of Kachchh showing locations of the TDEM sites (stars) [modified after Maurya et al., 2006];

sensitivity to electrically conductive targets, provides good vertical and lateral resolution, and contrary to traditional resistivity methods, can be easily employed in terrains with electrically difficult surface conditions such as dry sands, hard rocks, etc.

Kachchh district located towards western side of Gujarat state is an arid region with water crisis and repetitive drought cycles. It has a very low potential of surface and potable groundwater resources. However, overall resource potential of the region, mainly coastal resources becomes one of the most added attractions and ideal regions for industrial development. Along with industrialization, population and basic infrastructure have also grown. This has resulted in manifold increase in industrial and domestic water demands and put groundwater resource of the region under tremendous stress. This inadequacy also adversely affected long practiced agricultural industries of the region. As the area is adjoining the seacoast, over exploitation of groundwater has also resulted in seawater intrusion in the aquifers having considerable environmental implications. In this paper, we present the results of the TDEM investigations carried out along the Anjar – Rapar corridor of eastern part of the Kachchh basin to map the shallow subsurface resistivity structure of the region and possible identification of potential aquifer layer. The results are integrated with nearby borehole data/lithologs to better constrain the geophysical inferences.

General geology and tectonics of the region

The Kachchh, located between latitude 23.13°-24.68°N and longitude 68.10°-71.80°E, forms the western most part of India and constitutes the Kachchh district of Gujarat State. Its 352 km long southern margin is demarcated by the Gulf of Kachchh, which separates the region from Saurashtra Figure 1.

The Kachchh basin is an intraplate region of rifted Precambrian craton in north western India that evolved during 135 Ma bounded by two major basin-forming faults namely the south-dipping Nagar Parkar Fault (NPF) in the north and north-dipping Kathiawar Fault (KF) in the south. It is characterized by the Mesozoic rocks which are exposed in the uplifted land masses while Tertiary rocks have occupied the structure lows within the basin. The sedimentary deposition of the basin took place in early, syn- and post-rift stages of the basin (Biswas, 1977). These sediments have a zone of Deccan Trap volcanics sandwiched between Jurassic rocks of the northern part and Eocene sediments in the south towards the coast. Limestone, shale and sandstones are the most common rocks.The sediment fill thickens from less than 500 m in the north to over 4000 m in the south and from 200 m in the east to over 2500 m in the west (Biswas, 1982, 2005). Mesozoic rocks of Kachchh region are grouped into several formations (Biswas,1977, 2005): (i) Patcham/ Pachham Formation marks the beginning of Jurassic marine transgression in Kachchh. It consists of 300 m thick succession of limestone, marl and shale and has yielded pelecypods, corals and ammonites. (ii) Chari Formation consists of 400 m thick succession of limestone, marl and shale. It contains fossil remains of ammonites and gastropods. (iii) Katrol Formation is a 750 m thick succession of shale, limestone and sandstone deposited during Late Jurassic. The Katrol Formation has yielded

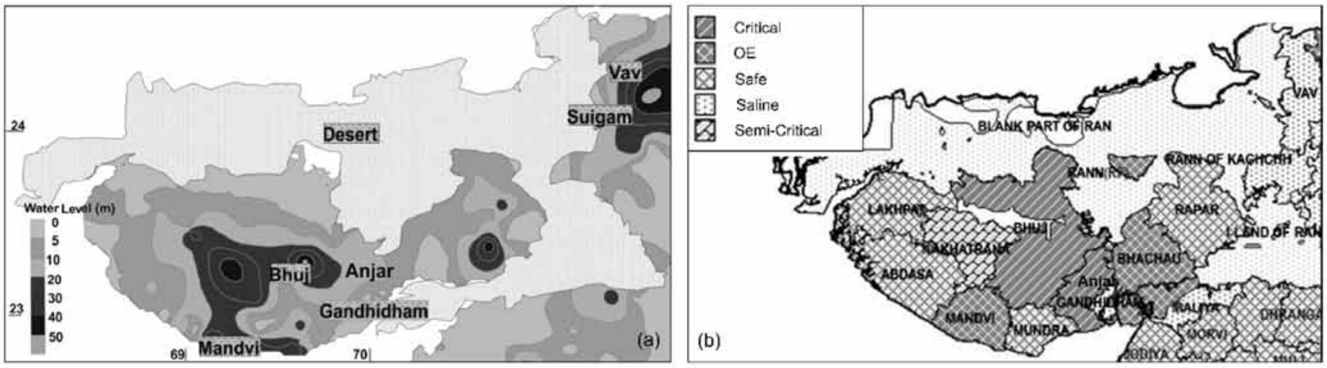

Figure 2. (a) Depth to water level (during 2013) and (b) groundwater condition maps (March -2011) of Kachchh district [GWRDC, Gujarat].

Table 1. Table showing trend of rainfall in Gujarat state (Shah and Pandya, 2011). The table highlights the low annual rainfall with few rainy days in Kachchh.

Sr. No	Region	Average Annual rainfall	Rainy days
1	South Gujarat	> 1100 mm	120
2	Central Gujarat	800 – 1000 mm	30-70
3	Saurashtra	400 – 800 mm	20-30
4	Kachchh	< 400 mm	10-20

fossils. (iv)Umia Formation is about 550 m thick succession of sandstone, sandy shale and marl. This formation is characterized by presence of ammonite fossils like. (v) Bhuj Formation comprises sandstone and shale and is characterized by presence of plant fossils. The Bhuj sandstone zone is considered to be main groundwater zone in the Kachchh region.

The tectonic fabric of Kachchh is dominated by E–W trend Figure 1, which is reflected in the geomorphic set up also. The major faults in the region are the E–W trending Allah Bund Fault (ABF), BanniFault (BF), Gedi Fault (GF), Kachchh Mainland Fault (KMF), Katrol Hill Fault (KHF), Island Belt Fault (IBF), Nagar Parkar Fault (NPF), North Kathiawar Fault (NKF), and South Wagad Fault (SWF).

Geo-hydrological status of the area

The state of Gujarat has some very specific geological and geo-hydrological conditions leading to regional variations in the availability of groundwater due to variations in physical-factors such as climate, hydrology, geology, soils, topography and vegetation. The state has a hydrogeology representative of almost all aquifer types and depositional and formation eras.Kachchh is characterized by complex geology of Limestone, Clay, Sandstone and alluvial stretches. The Kachchh district has very low annual rainfall spread over a few rainy days (Table. 1). In this region, ground water level is in the range of 10-20 m below ground level (bgl) Figure 2a.

Hydro-geologically, Kachchh is bestowed with huge pile of sedimentary sequence. However, most of the geological formations are deposited in marine environment having inherent salinity. Therefore, availability of potable groundwater is highly restricted. Only Bhuj Formation of Cretaceous period deposited in fluvial environment and Kankavati Formation sandstone of Tertiary age provide good to moderate quality groundwater. These two aquifers are backbone for drinking and irrigation water supply (Taylor et al.,1964; Groundwater resource development corporation (GWRDC), Gujarat). Central Groundwater Board(CGWB) has reported that tube wells are constructed to a depth of 200m tapping Upper Bhuj aquifers. These tube wells yield groundwater ranging between 240 to 9000 m^3/day, for a drawdown of 10 m. This ground-water reservoir functions essentially as a single hydrologic unit. It is sustained and recharged in most years by direct infiltration from rainfall and from ephemeral streams while in flood during the southwest monsoon. Salinity of the aquifers gradually increases towards the discharge areas and at contact areas with younger formation.

In coastal areas of the Kachchh district, the depth to water level varies from 3 to 10 m bgl in general. Exploratory drilling in the depth range of 150 to 458 m bgl carried out in coastal area has revealed the existence of confined aquifers of limited thickness. The quality of ground water in deeper aquifers is saline, except for a small pocket around Kapaiya in Mundra-Mandvi area. The quality of water in the shallow aquifer is also saline with a few localized

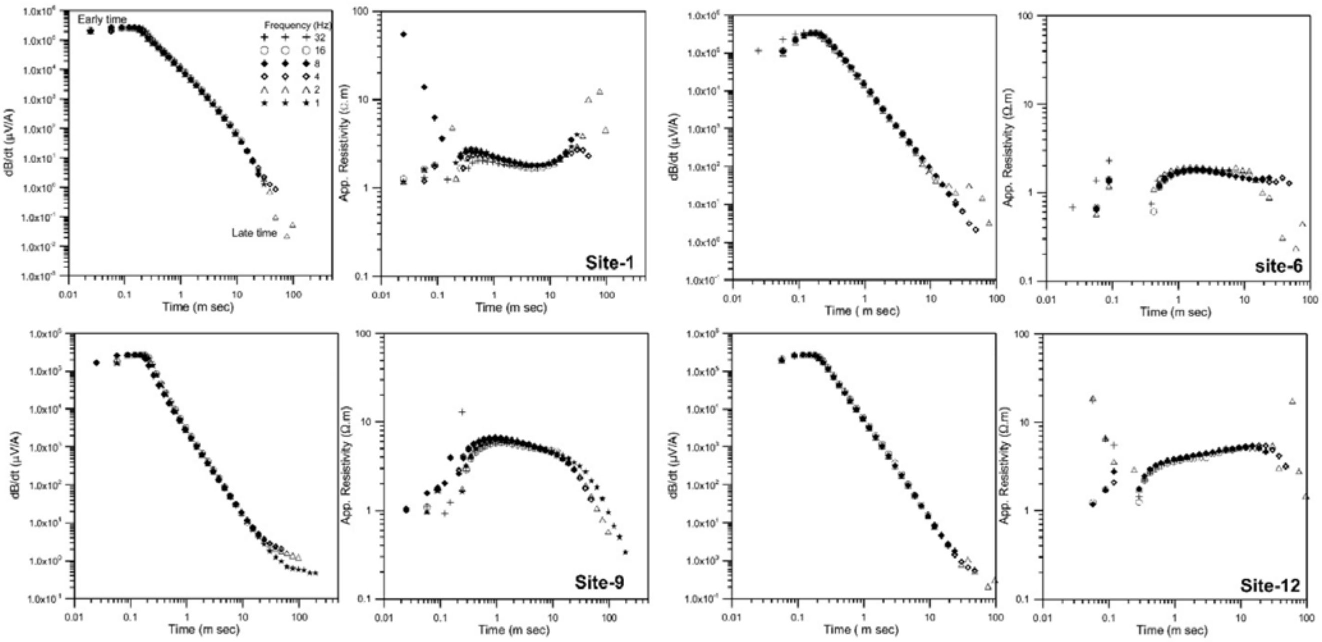

Figure 3. Transient decay curve (left) and the computed apparent resistivity curve (right) for some sites.

pockets of brackish to fresh water. Tube wells ranging in depth from 116 to 169 m bgl tapping the aquifers in Tertiary sandstones of Manchar series, yield 1600 to 3200 m^3/day. The yield of Tertiary aquifers tapped in Mandvi area in the depth range of 14 to 50 m is also considerably high (CGWB, 2014; GWRDC, Gujarat).

The ground water category for the pre-monsoon period (March -2011) is shown in Figure 2b. Significant number of talukas of the district is under either critical or over exploitation (OE) category. Even though rest of the talukas are pointed as safe category, the talukas in coastal side are suffering with salt water intrusion or high salinity.

TDEM data acquisition and processing

Twelve fixed in loop time domain electromagnetic (TDEM) investigations are carried out along Anjar –Rapar corridor of eastern Kachchh basin Figure 1 for mapping shallow-subsurface structure of the region in terms of resistivity and identify the possible depth to the aquifer layer and its thickness along the corridor. The north-south corridor crosses different geological settings of the region, namely, Tertiary formations in south, Quaternary in the south-central, Bhuj formation in central portion and Mesozoic formations (Wagad sandstone) in the extreme north of the profile. Locations of the TDEM sites are shown in Figure 1. The GDP 32-II data acquisition unit (Zonge, USA) together with a transmitter, either generator-powered GGT-30 for larger loops or battery-powered system was used to conduct TDEM field survey with 100 m sided square transmitter loop. The GDP 32-II was positioned at the centre of each loop and ferrite-cored antenna is used in order to take the measurements. The locations of the loops were chosen in areas free of cultural noise such as power lines, fences, and pipelines.

The most typical TDEM array is represented by a square loop, in which a trapezoidal (typically square wave form) current waveform is driven. This current induces secondary (eddy) currents within the Earth, the time rate of change of which produces an electromotive force (emf) that is picked up by a receiver coil normally located in the loop centre. The amount of current injected in the transmitter loop is 9 Amp for all the TDEM sites. For each loop, the transmitter is operated for a sequence of data repetition frequencies ranging from 32 Hz to 1 Hz (32, 16,8,4,2 and 1Hz). In the early time and late times, the apparent resistivity is in general- noisy and removed for further inversion process whenever necessary. These transient decay curves obtained by the survey were used to find out the depth and subsurface resistivity of the basin fill.

Using robust processing mode, data are accepted or rejected according to the coherency and outlier limit tests. At most of the sites, good quality transient responses at late times (later recording windows of receiver) up to 100ms are also obtained, which give considerably deeper information. Apparent resistivity is computed from the observed magnetic field (related to induced voltage in the receiver coil and the current injected in the loop). Decay curve and computed apparent resistivity curves for all the repetition frequencies as function of time for some sites are shown in Figure 3.

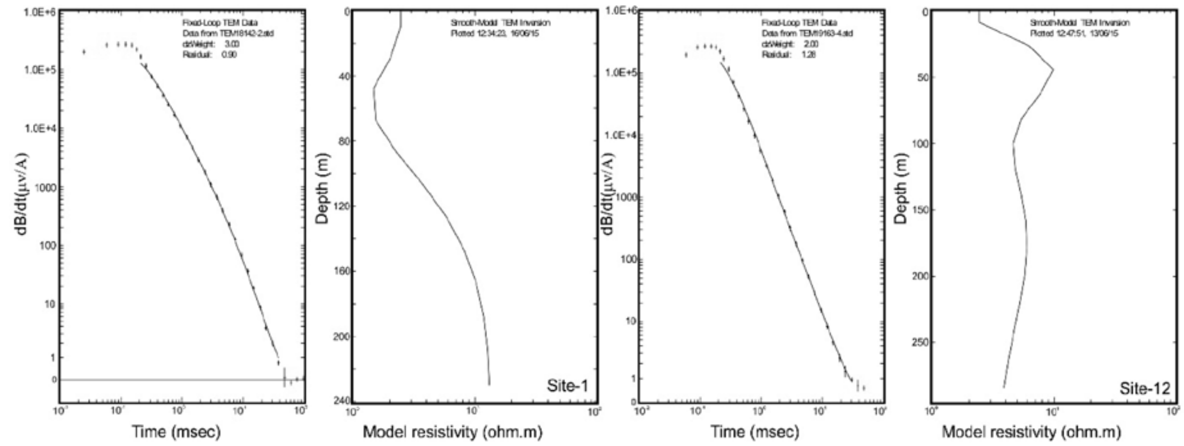

Figure 4. Data fit (right) between observed and computed response from the Inversion model (left).

Table 2. The characteristic resistivity values inferred from the 1-D model and its geological formations.

S. No.	Characteristics resistivity inferred from the 1-D model	Geological formations	Groundwater prospects
1	< 5Ωm	Clay	Very poor
2	5-10 Ωm	Clayey sand / sandstone with high clay/ silty clay/sandy clay	Moderate but not good for drinking purpose
3	~10-15 Ωm	Sandstone with moderate saline water	Moderate to good
4	20-50 Ωm	Shale	Poor

One dimensional (1-D) inversion of the data

We used the data recorded at 4Hz transmitter frequency for one dimensional (1D) inversion as the data are less erroneous at late times (10-100 ms). 1-D modelling of the TDEM soundings using STEMINV (Zonge, USA) package is undertaken to prepare layered-earth resistivity models which uses an iterating best-fit algorithm to minimise the RMS residuals between the observed and calculated apparent resistivities. After generating the initial model, data points that are either anomalous or could not fit to any earth model due to large error bars are selectively discarded from the voltage vs. time decay curve. After removing the anomalous points, the inversion is re-executed to create the best possible model. Inversion results for two sites along the profile and its fit between voltage vs. time decay curve are shown in Figure 4.

The 1-D models of all 12 sites are shown in Figure 5. The obtained 1-D inversion gives resistivity information up to 250m for maximum number of sites. We could, however, obtain information only to a depth of 160-180 m, for sites 2 and 7. For these sites, we infer homogeneous conductive zone at depths > 80 m resulting unfavourable (lack of strong heterogeneity) conditions for generation of secondary EM fields, which lead to low depth of penetration.

RESULTS AND DISCUSSION

The resistivity sounding data are first analyzed in terms of resistivity and thickness of the layers. These parameters are then correlated with the existing lithological information to interpret the nature of sub-surface layers. The stratigraphic interfaces are not always associated with changes in lithological characters and a proper correlation was sometimes difficult for many reasons, e.g., thin layers embedded ina thick layer of different lithology, significant variation in quality of groundwater, and a lithological unit consisting of a number of geoelectrical interfaces without any variation in their physical properties (Sinha et al.,2013).

We combined 1-D models of all the sites along the corridor to map possible aquifer layer in the region Figure 5. We have observed a ~10 Ωm moderate conductive layer at 10-15m depth along the profile. This layer is considerably at deeper level at sites 1 and 6 (150m and 70 m respectively). The thickness of the moderately conductive layer varies from site to site. It is maximum at site 5 (~50m) and minimum at site 12 (<20 m).We also observe, a highly conductive layer (< 10 Ωm) overlaying the moderate conductive layer. Another moderately conductive layer of resistivity ~10-15 Ωm (marked with ellipses in Figure 5 is observed at deeper depths (90-140m), at sites 1, 3, 4, 9, 10, 11 and 12.

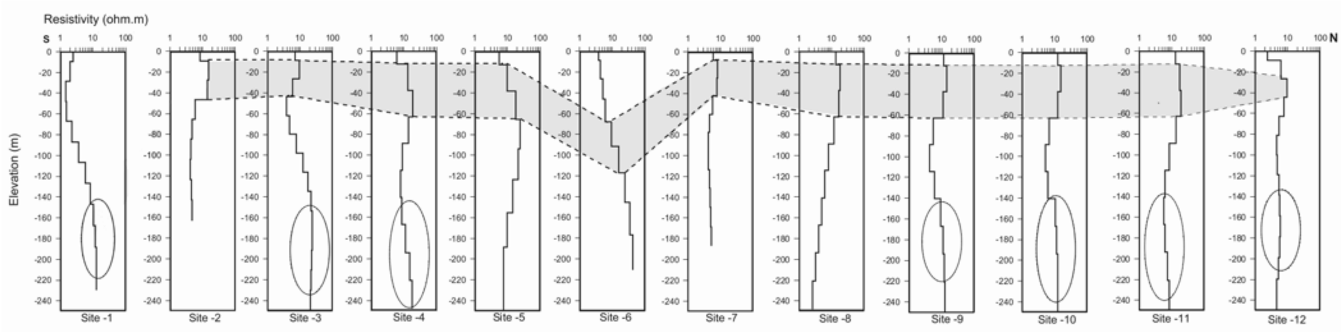

Figure 5. Combined One dimensional resistivity structure of the all the sites along the corridor. The masked zone is the inferred aquifer layer in the region.The secondaquifer layer at some sites at deeper levels is marked with ellipses.

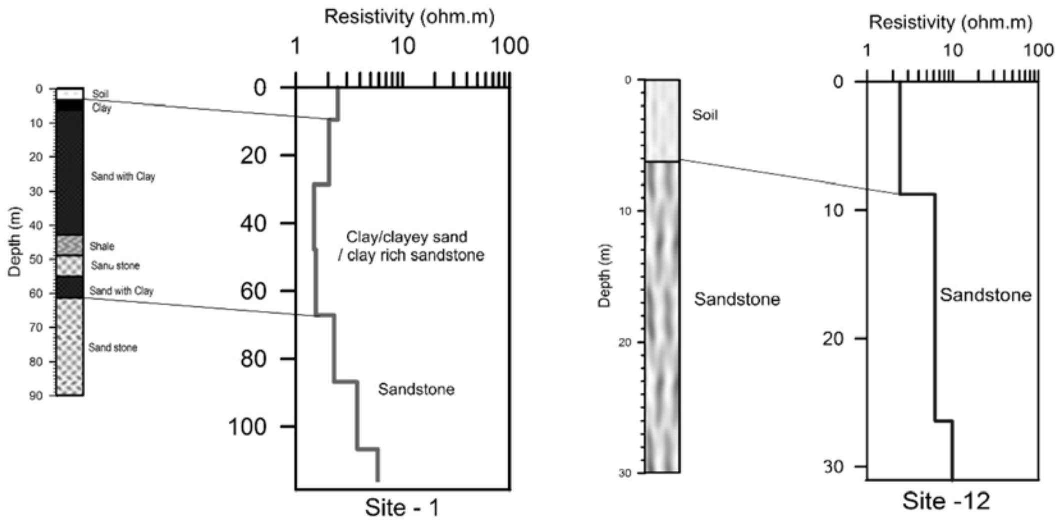

Figure 6. Calibration of resistivity sounding data from site 1 and 12with the lithologs.

The interpreted results are subsequently correlated with the available lithological information to confirm the resistivity ranges for different lithological units. The characteristic resistivities inferred from the 1-D model and its geological formations is listed in Table.2. These interpreted geological formations are clay, silty sand, clayey sand, and sandstone. The inferred resistivity from the inverted 1-D resistivity models for clay lies in the range <5 Ωm, clayey sand and sand possess resistivity between ~5 and 10Ωm and sandstone saturated with water (moderate to low salinity) shows 10-15Ωm (Table 2). For shale, the resistivity values are between 20 and 50Ωm.

The correlation of 1-D model at site-1 with litholog of the near by region Figure 6 suggest that the low resistivity values up to depth of 60-65mis composed of clay and clayey sand and clay rich sandstone. Thus, the low resistivity layer might represent the Quaternary/Tertiary sediments in the region. It is also observed in the litholog that two thin segments (<10m)of shale and sandstone are sandwiched by a sandstone layer with high content of clay. However, these two thin zones are not reflected in the 1-D resistivity model of the region. This might be due to high sensitivity of the TDEM method for conductive feature over moderate resistive zones. Since the TDEM method is very sensitive to conductive zones, it appears as a single layer of highly conductive in nature. Below the depth of 65 m, increase in resistivity values (close to 10 Ωm) is observed in the model. This might represent the Tertiary sandstone in the region Figure 6. This is supported by the litholog of nearby area. In the similar way, we correlated the 1-D resistivity structure at site 12 with the available lithologs of nearby well locations. The resistivity value closely matches with characteristic resistivity ranges of the sandstone (Mesozoic). Its thickness is about 25m at 15m depth Figure 6. The resistivity values decrease with depth, suggesting the clay rich sandstone/sand in the region of the respective geological formations as found from the lithologs.

We suggest that the sandstone layer observed in study area forms the aquifer layer with inherent salinity representing the upper Bhuj series (Mesozoic) in central and northern parts of corridor, whereas the sandstone inferred in southern part of the corridor could be Tertiary in age. However, at some sites, the aquifer is lying above a highly conducive layer. This might be clayey sandstone/ sand or clayey shale layer having low permeability. The presence of impermeable medium results in no recharge to the aquifer from its top. We therefore infer that the second Mesozoic sandstone layer at deeper depths (≥ 90 m) observed at some places of the study region Figure 5 could be the potential aquifer.

The occurrence of the aquifer at deeper levels, at site-1 and site -6, is interesting Figure 5. The location of the site-1 falls in Anjar city area, which is now developing as one of the major industrial areas in the Kachchh district leading to over exploitation of the groundwater resources. We therefore infer that the deeper aquifer level could be due to the excess usage of groundwater with no recharge or presence of thick quaternary sediments in the site. Deepening of the aquifer layer is also observed in site-6 located at the contact zone between Mesozoic and Tertiary sediments (in the vicinity of KMF). We infer that the presence of aquifer at deeper level is due to vertical displacement of the layer in the fault environment. However, detailed studies at some more sites are required to constrain the depth of the layer in this fault environment.

CONCLUSIONS

Twelve fixed in-loop TEM soundings with 100m-sided transmitter loop estimated the possible depth and thickness of the aquifer layer along the Anjar – Rapar corridor of the eastern Kachchh basin. Considering all the 1-D soundings along the corridor and correlating the well log data, we infer 20 to 50m thick probable aquifer comprising saturated sandstone (Tertiary in southern and Mesozoic in central and northern most parts of the corridor) with moderate to high salinity with its top surface at 10-15 m depth. The estimated depth of the aquifer layer matches fairly with regional groundwater level map prepared by Central Ground Water Board Figure 2. We also suggest a second aquifer layer at some sites along the corridor at deeper levels(150-250 m) overlying a relatively low resistive layer, probably comprising clay and/or clayey sand. We infer that the second Mesozoic sandstone layer could be the potential aquifer at some places of the region. Since the top sandstone region is overlying a non-permeable clay rich layer, this leads to no recharge in the upper layer.

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