Geoelectrical study for groundwater resources in parts of the Ahmedabad and Gandhinagar cities, Gujarat, India

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The central alluvial plains of Gujarat, western India, consist of deposits of north–south flowing rivers from the Aravalli hills. The Gandhinagar and Ahmedabad districts in the state form a part of the Cambay basin and are occupied by Quaternary alluvium comprising mainly of sand, gravel, silt clay, kankar, etc. Direct current (DC) electrical resistivity studies have been carried out at six sites in Gandhinagar and Ahmedabad cities to map groundwater levels and major shallow subsurface geoelectric layers using a 72-electrode resistivity imaging system. Two dimensional (2D) resistivity models and borehole data infer a multilayered aquifer system in Ahmedabad. The top confined aquifer is at a depth of 22–25 m and the second unconfined aquifer is at a 60–65 m depth. These two aquifers are separated by highly compacted clay/clayey sand. For the two locations in Ahmedabad city, the 2D resistivity model suggests 10–15 m variation in the groundwater level. In Gandhinagar, as the survey location is close to the Sabarmati River and the exploitation of groundwater is less than in Ahmedabad, the groundwater table is at shallow level. Further, the resistivity estimates suggest that, at all three locations, the groundwater is moderately saline. The infer resistivity sections are correlated with groundwater level and borehole data.

Keywords: Aquifers, borehole data, groundwater, sedimentary basins, two-dimensional resistivity imaging.

IN terms of regional variations in physical elements like climate, hydrology, geology, soil, terrain and vegetation, the state of Gujarat in India has some highly unique geological and hydrological conditions that affect groundwater availability. The state's hydrogeology spans nearly all aquifer types, depositional ages and formation eras[1]. Apart from selected locations like Junagadh in the south and Chotila in the north, Saurashtra in the western part of Gujarat comprises the Deccan basaltic terrain and has flat to medium slopes. Complex structures of limestone, clay, sandstone, and alluvial stretches make up the geology of Kachchh. The massive deposits of rivers flowing from the Aravallis constitute the north–south range aquifers of the Gujarat central alluvial plains. The Dang district has hilly terrain in the southern region of the state. The Aravalli mountain range in the northeast has aquifers that are naturally crystalline hard rock. The major rivers are Narmada, Tapi, Mahi and Sabarmati, which flow through the alluvial terrain. The variable climatic conditions in the state primarily responsible for complex hydrological conditions. The environment is humid in southern Gujarat and highly arid in the Kachchh region. The annual rainfall ranges from an average of 2500 mm maximum in the southeast to 300 mm minimum in the Northwestern parts of Kachchh. In general, the average rainfall is less in the north and west and more in the east and south.

The term 'groundwater' is used for all kinds of water occurring beneath the ground surface and is an important constituent of the hydrological cycle. Infiltration of rainwater, return flow of irrigation, seepage through river/reservoir beds, etc. are the main sources of groundwater. The geological formations which can store groundwater and allow its flow (significant amount) under ordinary field conditions are known as aquifers. Based on the storage and transmissivity characteristics of groundwater, aquifers are classified into two types. Those bounded by impermeable beds from the top and bottom are confined aquifers. In this type of aquifer, groundwater is stored at more than atmospheric pressure. If an aquifer has an impervious base and the upper boundary is the water table, it is known as an unconfined aquifer. For mapping aquifers, mineral deposits, stratigraphic sequence and lithology shallow subsurface exploration techniques are widely used[2–10]. The electrical resistivity methods are versatile and cost-effective for groundwater exploration in various geological terrains because of the large spectrum of resistivity compared to other geophysical parameters. Generally, rocks that are more porous and have high water content show lower resistivity values than those that are less porous and have low water content. Wet soil also has lower resistivity. The water-saturated formations or structures like faults, cracks, fracture zones and joints show good resistivity contrast between the

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structures and undisturbed formations. The water-saturated structures show lower resistivity than the undisturbed formations. Therefore, the electrical resistivity method is superior to all other geophysical techniques for groundwater studies. In hard-rock terrains, groundwater-bearing formations or favourable geological structures like fractures, faults, etc. exist from a few metres to tens of metres. The DC resistivity technique is employed to image the resistivity structure of bedrock, and aquifer zones at particular depths, which depend on the profile length of the array.

We have carried out two-dimensional (2D) DC-electrical resistivity studies in three different places (total of six profiles) of Gandhinagar and Ahmedabad cities, Gujarat (Figure 1) to map the depth of groundwater table and major subsurface layers (Figure 2). The results were correlated with borehole data from nearby regions.

Study area

Geologically, Gandhinagar district is located in the Cambay Basin and comprises Quaternary alluvium which includes sand, gravel, kankar and silty clay[11]. The aquifers in the district are phreatic and semi-confined; they are less than 25 m thick in the east and more than 80 m thick in the west. The groundwater is extracted by majority of shallow tube wells and dug wells[12]. However, it has dried up over time and is now only found as a saturated zone close to the Sabarmati River and in the eastern parts of Gandhinagar taluka. Gandhinagar and its surrounding areas fall under the semi-arid region. The average annual rainfall in Gandhinagar region is about 750–850 mm. The maximum rainfall occurs during rainy season (June–September). Precipitation is the main source of groundwater recharging. The estimated groundwater recharge is 6–8% of the rainfall[12].

Geology and hydrogeology of Gandhinagar and Ahmedabad

The study area is located in the tectonically active Cambay Basin, bounded by the north–south trending East Cambay Fault and West Cambay Fault. The Basin is completely filled with Tertiary and Quaternary sediments that constitute the alluvial plains of mainland Gujarat[13] (Figure 3). The Quaternary sedimentary thickness in the basin ranges from 250 to 400 m (Table 1). In the study area, sediment thickness is expected to be around 250 m. The origin of the sediments is mainly from fluvial and aeolian deposits[14]. The area shows variation in lithounits, e.g. alternate bends of sand, silt and clay layers with calcrete lenses. The thickness of different layers varies between 3 and 10 m, whereas the calcrete lenses are 1–2 m thick.

In the Ahmedabad district, sediments make up a majority (93.5%) of the area. There are older Miocene rocks underneath the post-Miocene alluvial deposits at the top. The sedimentary formations consist of sand, gravel, silt, clay, clay stone, siltstone and kankar, fine to coarse-grained in size. Near Dholka, the post-Miocene alluvial deposits are more than 419 m thick. At Rampur, groundwater is found in the granular horizons of the sedimentary rock under phreatic and constrained conditions. The unconfined aquifer, composed of medium to fine-grained sand, silt, and lenses of sandy clay and clay, is found in the upper strata and extends to a maximum depth of 60–75 m below ground level (bgl). Medium to fine-grained size sand can be found in the northeast part of the district. Gravel marks the base of the alluvium in this area, which only has phreatic aquifers. Further south and southwest, near Dholka and Sanand taluka, fine-grained sand with silt is present. The aquifer thickness varies from 20 to 45 m, at a depth between 3 and 75 m bgl. The northeastern portion of the district is where the groundwater is found in phreatic conditions. The pre-monsoon period (May 2012) showed a variation in groundwater level from 2.28 to 22.58 m bgl. Gamph area reported the most shallow water level of 2.28 m bgl, and Vastrapur Lake Pz-II recorded the deepest water level of 22.28 m (ref. 12).

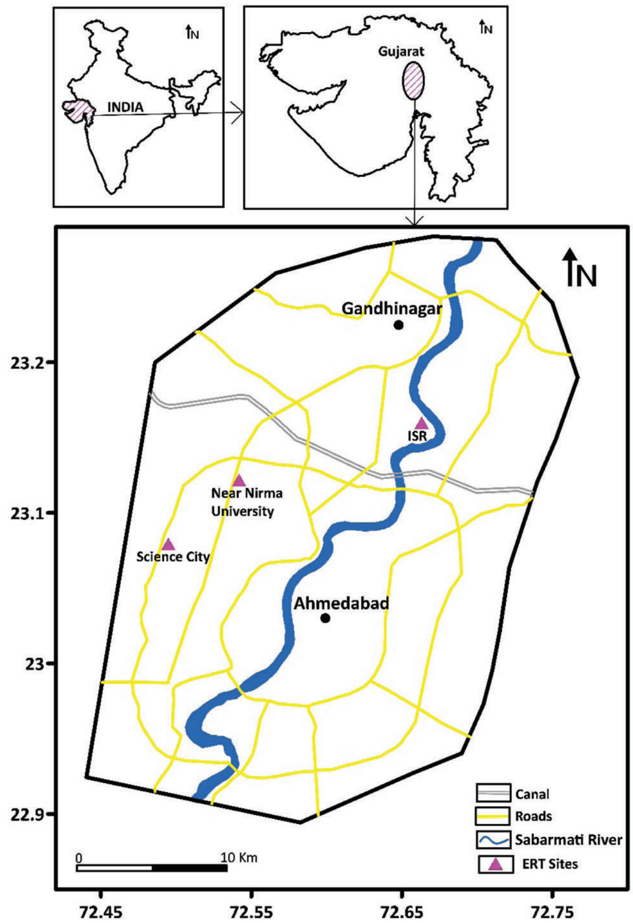

Figure 1. Location map of the study area in the Gandhinagar and Ahmedabad cities, Gujarat, India.

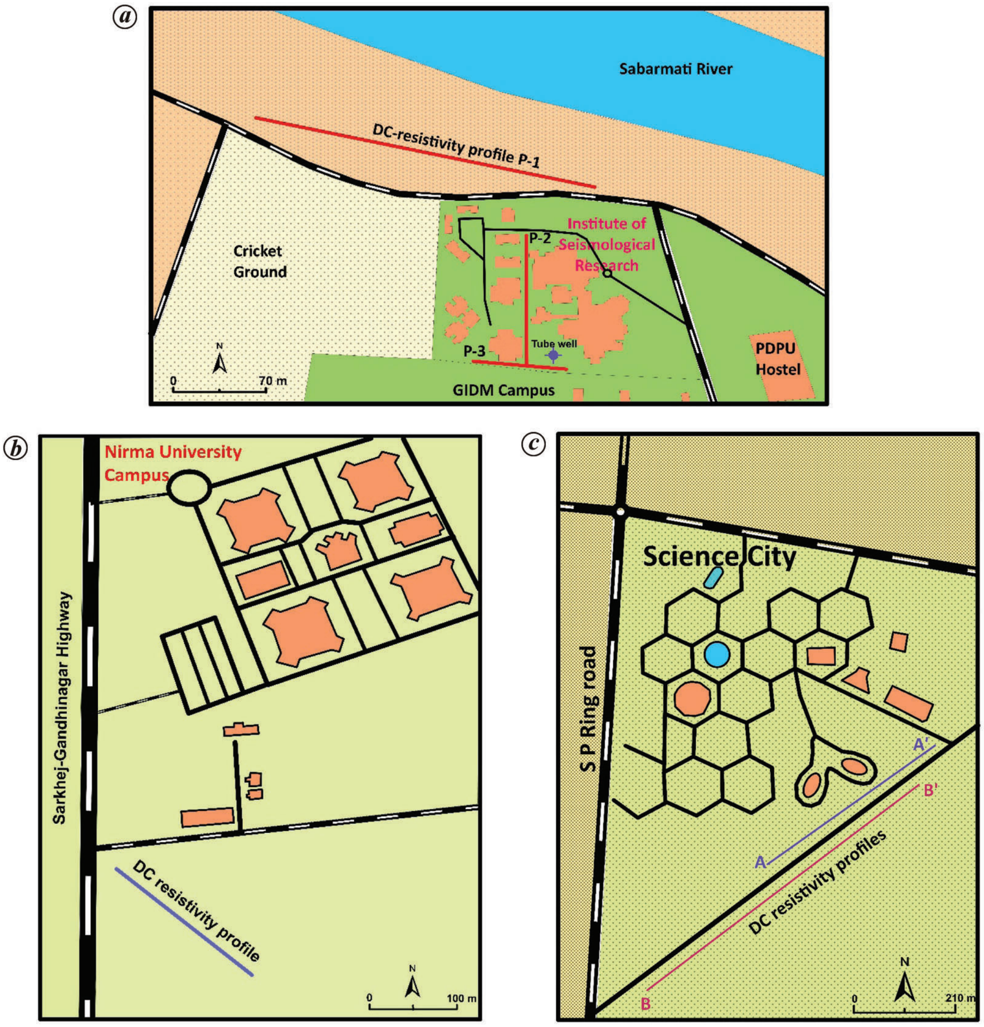

Figure 2. Location maps of DC resistivity profile: ***a***, around ISR campus (location-1), Gandhinagar; ***b***, near Nirma University (location-2), Ahmedabad; ***c***, in Science City campus (*AA′* and *BB′*) (location-3), Ahmedabad.

Methodology

The DC resistivity method involves passing an electric current between a pair of outer electrodes and measuring the potential difference between a pair of inner electrodes to determine the electrical resistance. In the homogenous ground, the electrode separation determines the depth of current penetration, and changing the electrode separation reveals the stratification of the ground. There are various methods for electrode arrangement, i.e. Wenner method, Schlumberger, pole–pole, dipole–dipole and pole–dipole methods. The Schlumberger method was employed in this study, in which all 72 electrodes were maintained in a straight line with a consistent spacing between the inner electrodes[15] (Figure 4).

2D electrical resistivity tomography

An advancement in the electrical resistivity method is the use of 2D electrical resistivity tomography (ERT), also known as electrical resistivity imaging (ERI). This is used to delineate the true resistivity variation of subsurface lithounits continuously along the line of a profile[16]. In the context of hydrological studies, ERT is widely used for mapping aquifer dimensions and contaminated subsurface geological formations. The main benefits of ERT are the automated acquisition of a large data set in a sufficient time and cost effective, as well as the presentation of images of subsurface lithounits along the entire spread length with high resolution due to mapping of the same location multiple times for various electrode spacings.

In the present study, ERT surveys were carried out in the three locations using a 72-electrode resisting imaging system (Syscal Pro Imaging System, IRIS, France). Figure 4 shows a multi-electrode set-up for ERT that combines multicore cables with numerous electrode takeouts and allows the user to choose any four electrodes (two for current injection and two for potential measurement). The profiles along which resistivity measurements were taken are shown in Figure 2 for respective sites.

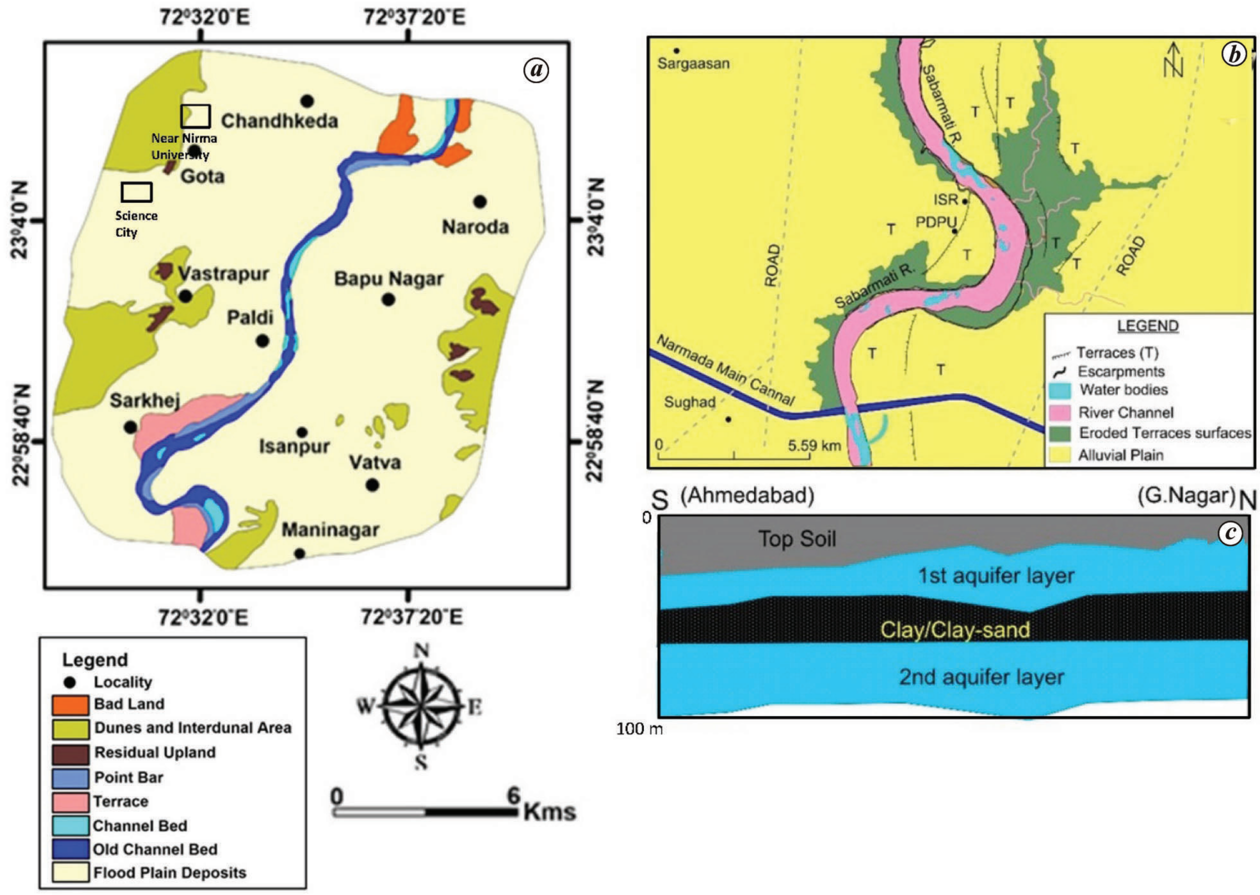

Figure 3. Geological/geomorphological map of (***a***) Ahmedabad and (***b***) Gandhinagar cities showing DC resistivity imaging sites. ***c***, Schematic diagram showing aquifer system inferred from the study (modified after Vinay *et al.*[18]).

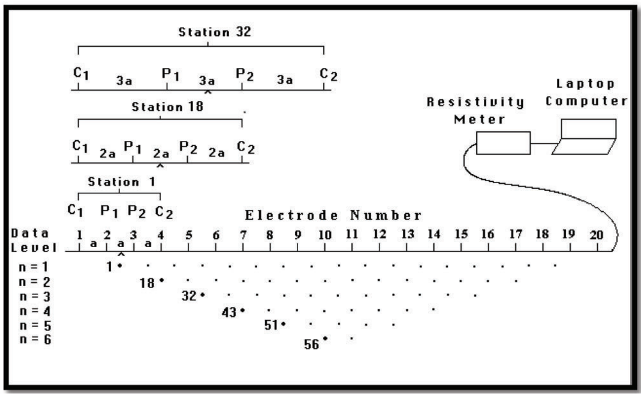

Figure 4. Sketch of the electrodes for 2D geoelectrical resistivity survey and sequence of measurement for building the pseudo section[15].

For location-1, i.e. around the Institute of Seismological Research (ISR) campus in Raisan village, Gandhinagar, we acquired data along three profiles. The length of profiles-1, -2 and -3 was 340, 144 and 72 m respectively. For profile-1, we used 5 m electrode spacing, whereas for profile-2 the electrode spacing was 2 m. For location-2, at a site near Nirma University, Ahmedabad, the resistivity imaging data were acquired along one profile having electrode spacing of 3 m. In location-3, near Science City, Ahmedabad, we carried out ERT survey along two parallel profiles with electrode spacing of 6 and 10 m respectively. The northern profile *AA′* had a length of 426 m and the southern profile *BB′* had 710 m length. The ERT survey was conducted using eight multi-electrode cables, each having nine electrodes. The response of subsurface to the induced current in terms of reduced voltage was recorded along these three locations along the profiles (Figure 2).

Data processing and inversion

The observed data were processed to get the apparent resistivity distribution from the voltage difference measured between the respective voltage electrodes. In the present study, the data was processed using the PROSYS II software (IRIS, France). To improve the data quality, bad datum points, which often show up as spikes in the data, were removed. The next step after data processing was the inversion of the apparent resistivity distribution as a function of electrode spacing to determine the true resistivity of the subsurface.

Table 1. Geology of the study region[14]

Period	Epoch	Lithology	Thickness (m)
Quaternary	Holocene	Sand, silt, clay and gravel	80–100 (~80 m near Gandhinagar)
	Pleistocene	Yellow and grey clay, coarse sand, gravel and kankar	300
Tertiary	Pliocene	Clay stone, sandstone and conglomerate	200
	Miocene	Ferruginous sandstone, conglomerate and grey clay	400
	Oligocene	Grey shale, sandy shale and argillaceous sandstone	~600
	Eocene	Black shale, carbonaceous shale	430
	Palaeocene	Volcanic conglomerates, Deccan Trap basalt	More than 1000

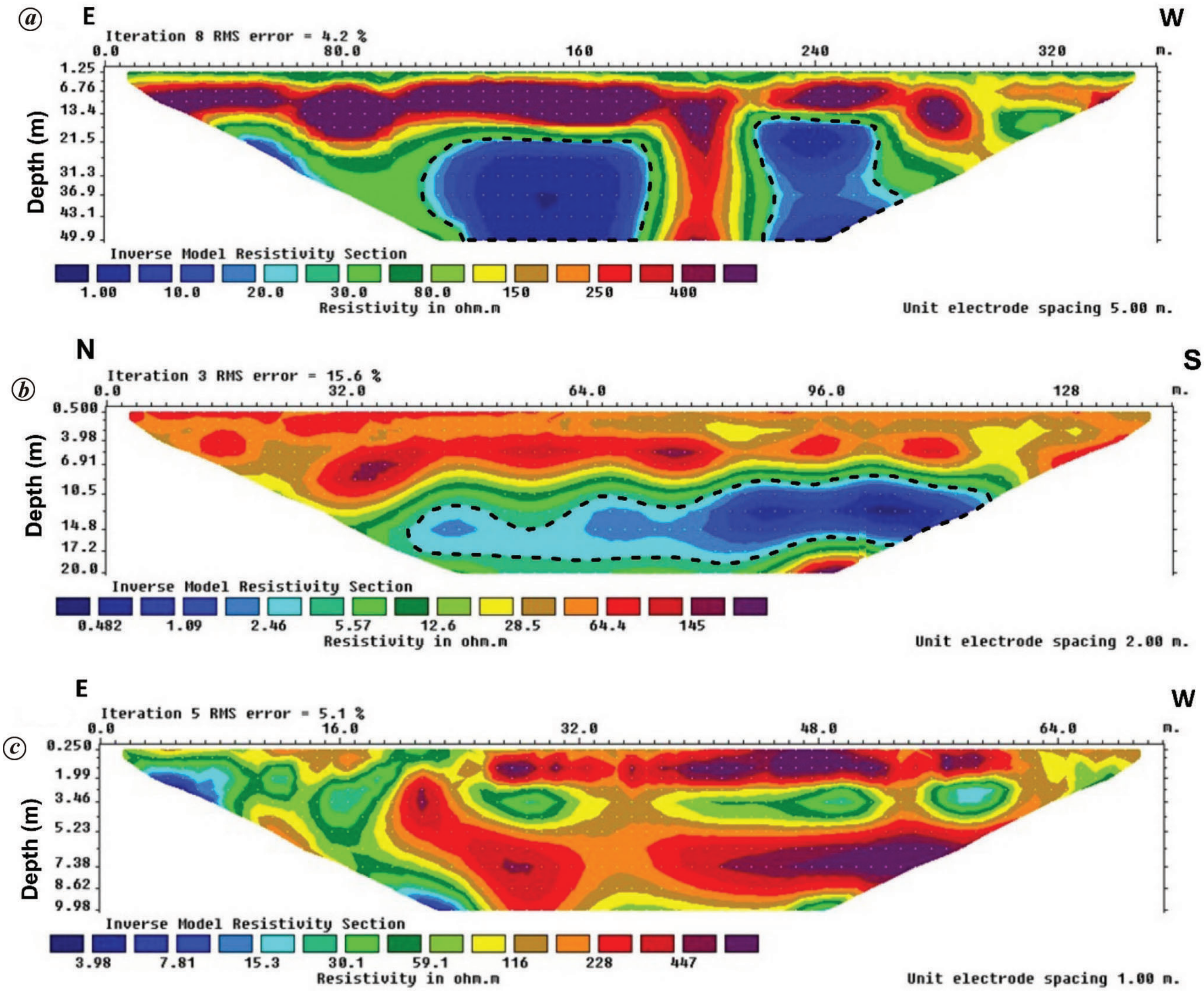

Figure 5. ***a***, Inverse resistivity model along profile-1 near ISR campus (location-1). ***b***, 2D resistivity model along the north–south profile-2 in ISR campus (location-1). ***c***, 2D resistivity model of profile-3 in ISR campus (location-1).

The true resistivity structure was estimated by inverting the apparent resistivity distribution of the subsurface structure using the commercial RES2DINV software (IRIS, France). The RES2DINV program was used to construct a subsurface resistivity model by performing inverse modelling on the measured apparent resistivity data[17]. The initial iteration of the approach combines a Jacobian matrix calculation with a 2D smoothness constrained least-squares inversion, and subsequently uses a quasi-Newtonian technique to minimize numerical calculations. Once the difference in the root mean square (RMS) error between the current and prior iterations is less than 0.1%, the inversion is terminated. When data are inverted, a 2D resistivity distribution map is created, which can be used to understand shallow

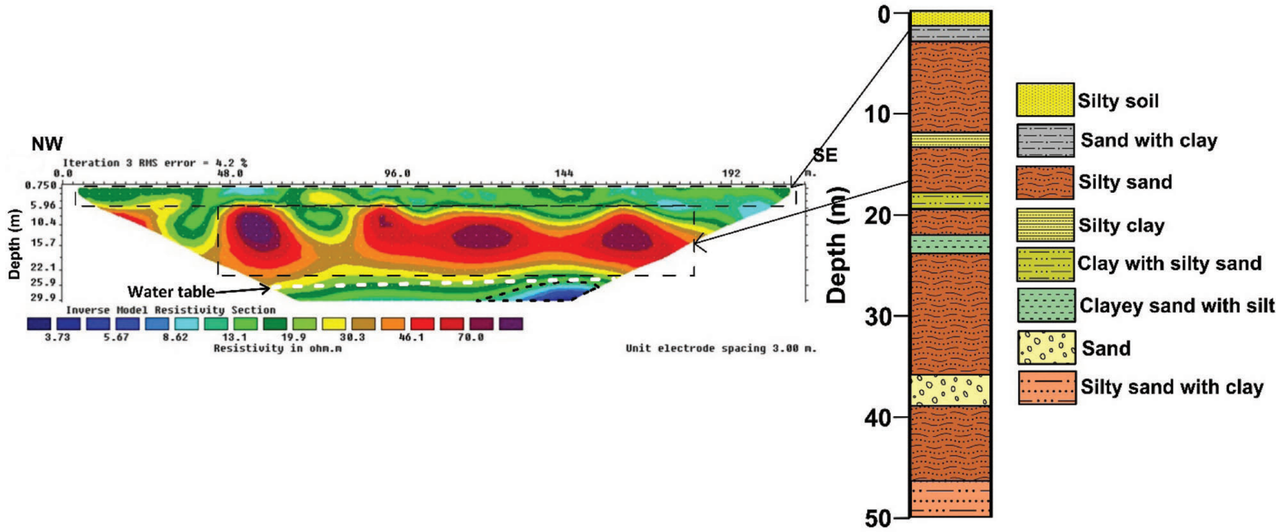

Figure 6. 2D resistivity image along the profile with litholog data near Nirma University (location-2).

subsurface structures for groundwater investigation. The 2D resistivity models along the profiles at the three locations are shown in Figure 2. Figures 5–7 show the inverted resistivity models along the given profiles.

Results and discussion

We now discuss the 2D resistivity images of all three locations and interpret them in terms of depth of groundwater and aquifer zones.

Site 1: Around ISR campus, Gandhinagar

The ERT profiles lie on the western bank of the Sabarmati River, mainly covered by Quaternary alluvial plains (Figure 3 *b*). The 2D resistivity section along the E–W profile-1 was inferred as a two-layered geological formation up to 50 m, with sharp changes in resistivity below 20 m depth in two localized zones (Figure 5 *a*). The conductive layer (>10 Ωm) at a depth of 22–24 m was observed in the modelled section. This highly conductive layer might be a groundwater table with moderate salinity. The top 1–3 m layer of resistivity 30–50 Ωm might comprise topsoil, with silty sand. An ~250–600 Ωm zone was observed in the section at a depth of 3–24 m with a thickness of 21 m, which could be highly compacted clay/clayey sand. A lithology near the eastern bank of the Sabarmati River also suggests a clay layer with low plasticity. The groundwater level was 10 m correlated with the tube-well water table at the ISR campus.

The 2D resistivity section for profile-2 infers, in general, two-layered structure down to 20 m (Figure 5 *b*). A highly conductive layer (≤1 Ωm) at the depth between 10 and 20 m was observed. This top margin of the high conductive layer was inferred as the groundwater table, and the geological formation between 10 and 20 m depth was indicative of high salinity or clay saturated with water. The top 10 m layer of resistivity 20–150 Ωm comprised of brownish silty sand. A moderate conductive layer of resistivity ≤5 Ωm was observed between 10 and 18 m depth (marked with dashed ellipse), which could be part of the groundwater table with moderate salinity.

The 2D resistivity section along profile-3 near the buildings and dug well infers complex layered structures up to 10 m (Figure 5 *c*). The section also infers the presence of silty sand, concrete material and gravel, which are reflected as high resistive zones (116–500 Ωm) in the delineated resistivity structure. A high conductive zone ≤15 Ωm was observed in the eastern part of the profile inferred from groundwater table at 10 m.

Site 2: Near Nirma University, Ahmedabad

Two-dimensional DC resistivity survey near Nirma University, Ahmedabad was carried out with electrode spacing of 3 m. Figure 6 shows results of the survey. The 2D resistivity section was correlated with borehole data to infer three-layered structure up to 30 m depth. A moderately conductive layer (≤20 Ωm) up to a depth of 5–6 m was observed in the entire resistivity section. We infer that this layer might represent the topsoil, comprising silty sand/sand. Below this layer, a high resistivity 30–100 Ωm layer with a thickness of 20 m was observed in the model, which could be a layer of coarse-grained silty sand. A moderate conductive layer of resistivity ≤15 Ωm was observed in the model at depth of 26–27 m, which is the top portion of the groundwater table in the region.

Site 3: Near Science City, Ahmedabad

Figure 7 shows 2D resistivity images for two profiles in Ahmedabad Urban Development Authority (AUDA) garden, near Science City campus. The 2D resistivity section infers,

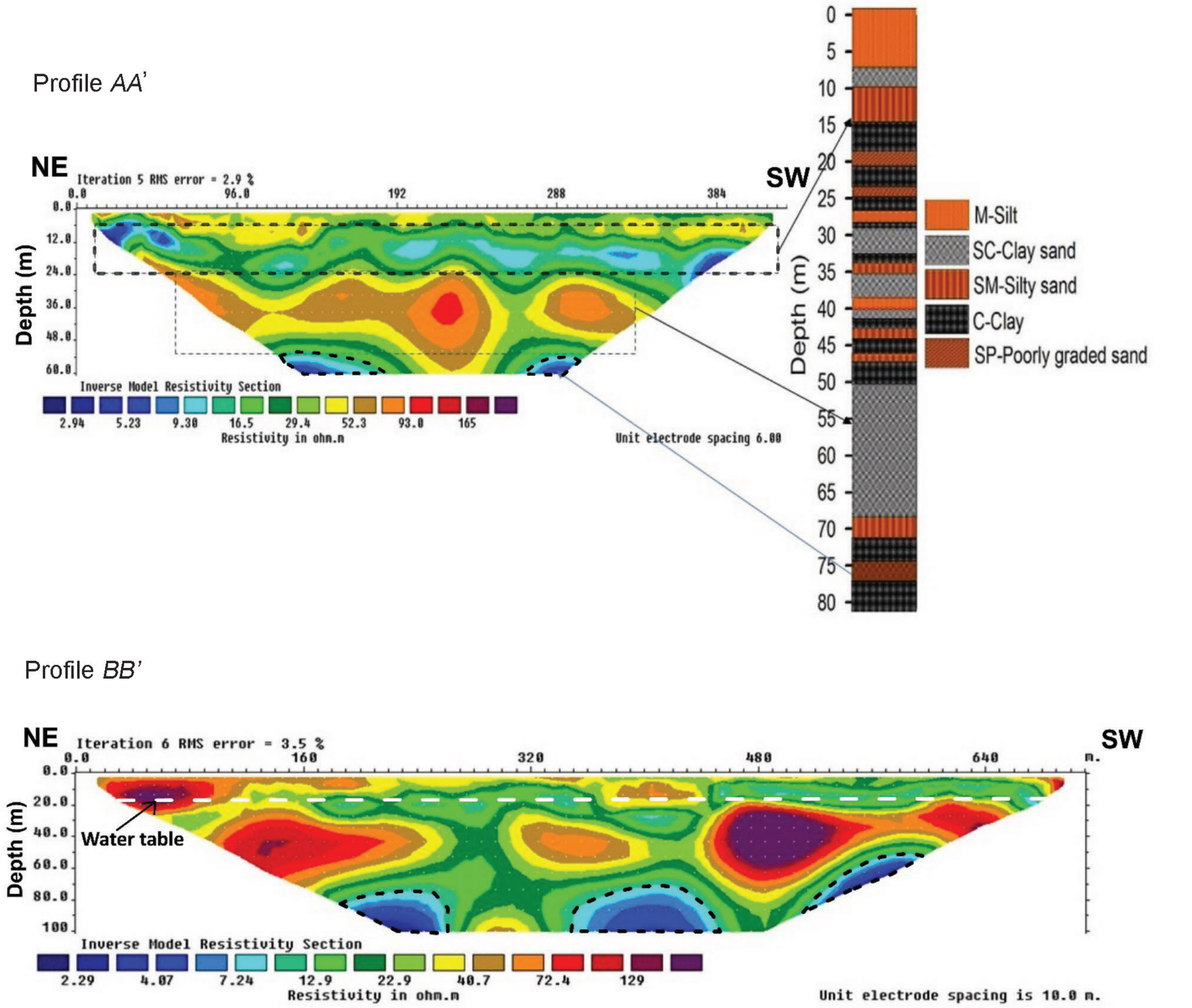

Figure 7. 2D resistivity images along the profiles *AA′* and *BB′* in AUDA garden (location-3). The resistivity image along profile *AA′* was correlated with litholog of a borehole at Science City campus close to location-3.

in general, four-layered structure up to 100 m depth. The top layer with resistivity less than or equal to 40 Ωm and thickness of 10 m (with some undulations) was observed, which could indicate sand/silt sand. In profile *AA′*, the second layer with resistivity less than or equal to 20 Ωm at a depth of 15–16 m could represent sandstone with high porosity, which can be considered a shallow confined aquifer. A moderate resistive layer of resistivity greater than 50–60 Ωm was observed along the end of profile *BB′* at depth of 20–25 m and 32–35 m in the northern profile. These layers might represent the highly compacted sandstone. The conductive zone (shown as ellipses in Figure 7), which was observed at 52–55 m depth in the profile *AA′*, could indicate the presence of a second deep aquifer zone. A similar conductive zone was also seen down to 70–75 m depth in profile *BB′*, which can be interpreted as a potential groundwater aquifer. Figure 7 also shows the lithology of a borehole drilled near the site. The lithology indicates the presence of clayey sand at a depth of 50–55 m, which correlates well with the resistivity values (40–50 Ωm) observed in the model. The presence of clay/clay-dominated sand is clearly indicated in the borehole data[18].

For the two locations in Ahmedabad city, the 2D resistivity model suggests 10–15 m variations in the groundwater level. The variations in the depth of groundwater could be attributed to its exploitation in the study area. In Gandhinagar, as the survey location is close to banks of the Sabarmati River and the groundwater exploitation is less compared to Ahmedabad, the groundwater table is observed at 10 m. The 2D resistivity models infer low resistivity range of 1–15 Ωm in moderately saline water. We therefore conclude that the aquifers are characterized by moderately saline water-bearing aquifers in these regions. The possible presence of fluoride in the groundwater has also been reported in the analysis of the groundwater by Central Ground Water Board[12]. A detailed study is necessary to distinguish the contaminated and uncontaminated aquifers, and proper steps must be taken to decrease the fluoride content through natural and artificial recharge of the aquifers.

Conclusion

A 2D resistivity imaging survey at three locations in Ahmedabad and Gandhinagar cities was carried out to delineate the depth of groundwater table and shallow subsurface structure. The 2D resistivity section inferred that the three locations in Ahmedabad district have a multi-layered aquifer system. The top confined aquifer is at a depth of 22–25 m, and the second unconfined aquifer is observed at 60–65 m depth. These two aquifers are separated by highly compacted clay/ clayey sand. For the two locations in Ahmedabad city, the 2D resistivity model suggests 10–15 m variation in the groundwater level. In Gandhinagar, as the survey location is close to the banks of the Sabarmati River and the groundwater exploitation is less compared to Ahmedabad, the groundwater table is observed at 10 m. Further, the resistivity estimates suggest that, at all three locations, the groundwater is either contaminated with minerals or is moderately saline (≤15 Ωm). We further infer that the highly impermeable vertical block observed near the ISR campus, might act as a barrier to the northern and southern river aquifers. However, more sites should be considered in order to understand the dynamics of the aquifers and the variations in the extent of contamination in groundwater zones.

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