2D Electrical resistivity imaging for delineation of deeper aquifers in a part of the Chandrabhaga river basin, Nagpur District, Maharashtra, India

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Water scarcity in hard-rock terrains such as volcanic Deccan traps in central and western India is well known due to occurrence of groundwater in limited quantity within unevenly distributed weathered formations, faults, fractures and joints of the limited areal extent. The region under study is a part of Chandrabhaga river basin in Kalmeshwar taluk, Nagpur District, Maharashtra, and lies at the eastern margin of the Deccan traps. This region is facing acute shortage of water supply, unable to meet the domestic and irrigation demands. The present work deals with 2D electrical resistivity imaging carried out in drought-prone Deccan traps terrain of Chandrabhaga river basin to delineate deeper aquifers concealed within and below the traps. The 2D inverse models of resistivity variation with depth suggest the occurrence of potential aquifers mostly in weathered/fractured zones within the traps or below it. To verify the interpreted results, a bore well was drilled at a site near Ghogali village. A potential water-bearing aquifer was struck at a depth of 35 m, which is in good agreement with the interpreted results.

Keywords: Aquifers, electrical resistivity imaging, groundwater, water scarcity.

ABOUT half a million square kilometre area in central and western India extending from Mumbai to Nagpur in the west to east direction is occupied by the Deccan traps, which is pile of several basaltic lava flows erupted intermittently during Late Cretaceous to early Eocene about 65 million years ago. Its thickness varies from approximately 2 km near Mumbai to a few tens of metre east of Nagpur City, which marks the eastern fringe of the Deccan traps[1,2]. Groundwater in the Deccan traps occurs in weathered mantle, intertrappeans, fractures, faults and joints. Acute shortage of groundwater prevails in the Deccan traps region due to sporadic occurrence of these groundwater-bearing formations/structures of limited areal extent. The DC electrical resistivity method is the most suitable method among all the geophysical methods for delineation of aquifer in complex, hard-rocks terrains such as the Deccan traps because a reasonably good contrast exists between resistivity of water-bearing zones and water-devoid zones. Geophysical electrical surveys have been carried out at numerous places in the Deccan traps region by many workers to decipher aquifers for groundwater. Bose and Ramkrishna[3] have carried out electrical resistivity surveys for delineation of groundwater potential zones in the Deccan traps region of Sangli District, Maharashtra. Murthy *et al.*[4] have carried out geophysical studies employing deep electrical survey other than gravity, magnetic surveys in Umrer trough, Nagpur District for mapping depth of Gondwana sedimentary formation below the traps. Muralidharan *et al.*[5] have carried out deep resistivity surveys for delineation of suitable sites for groundwater exploration in the traps-covered region of Jam river basin, Nagpur District. Geo-electrical survey has been carried out to decipher aquifers in the Deccan traps region of Godavari–Purna basin, Aurangbad District, Maharashtra[6].

In all the above-mentioned studies, electrical resistivity survey was conducted using four electrode configurations to provide 1D model of resistivity variation with depth only below the central point of the array. This type of electrical resistivity survey fails to locate water-bearing zones between two points of study. Therefore, a more accurate subsurface model would be the 2D model, where resistivity changes in the vertical as well as horizontal direction are presented. This problem is overcome by the development of 2D electrical resistivity imaging technique using multi-electrode electrical resistivity imaging (ERI) system and effective data processing software based on inversion techniques[7–11]. The main advantages of the survey using multi-electrode ERI system are: (1) fast computer-controlled data acquisition, (2) simultaneous study of both lateral and vertical variation of resistivity below the entire spread length of the profile and (3) increased resolution of the computed images of the subsurface geological formation due to large amount of data acquisition. Such surveys are usually carried out using a

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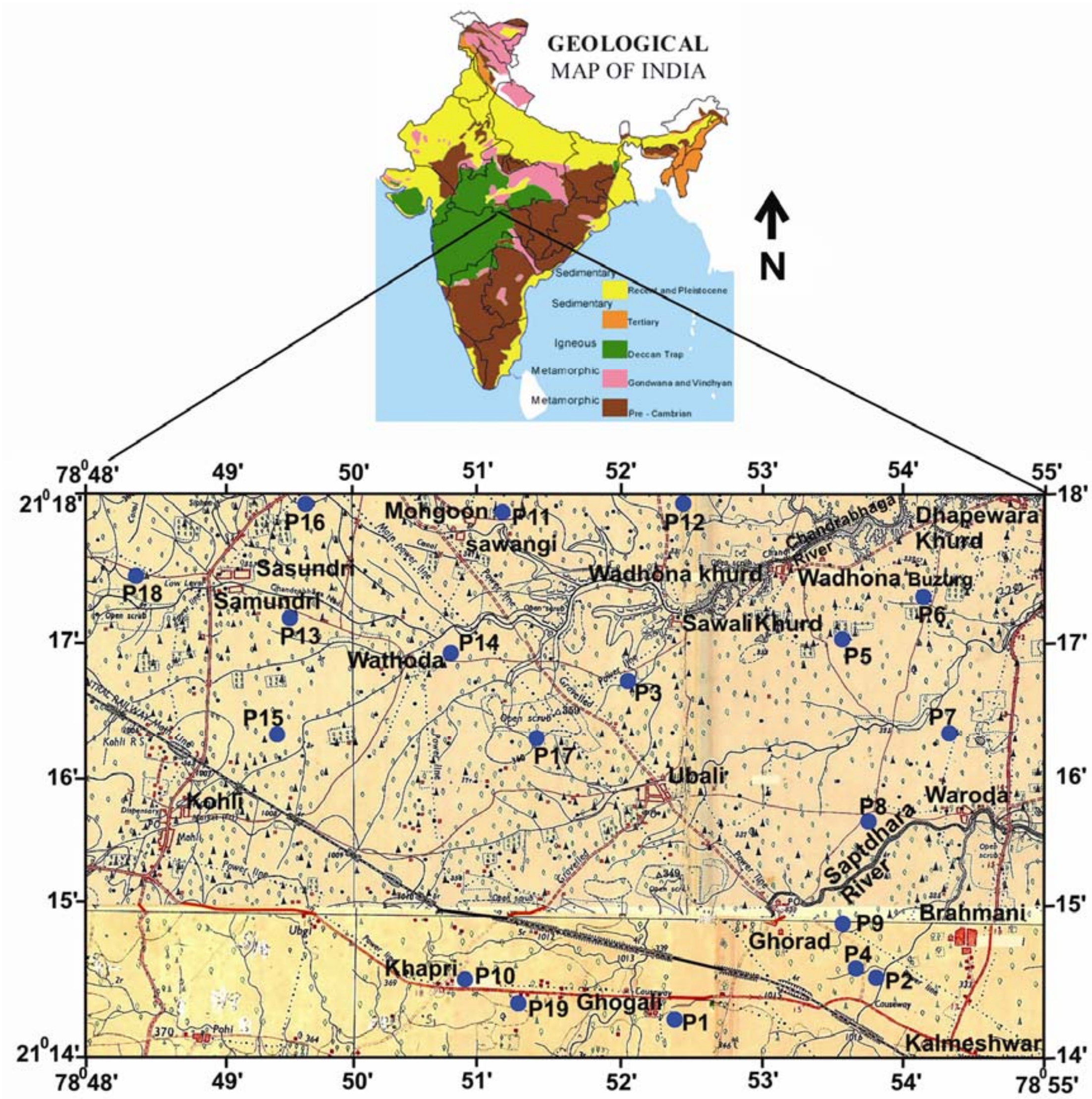

Figure 1. Location map of the study area with electrical resistivity imaging survey sites (modified after SOI Toposheet nos 55K/15 and 55K/16).

large number of electrodes, 24, 48, 64 or more, connected to a multi-core cable. A laptop together with an electronic switching unit is used to automatically select the four relevant electrodes for each measurement. The ERI technique is being extensively used in groundwater prospecting, geotechnical problems and environmental studies. Dutta *et al*.[12] have carried out ERI survey for delineation of water-bearing fracture zones in the hard terrain of the Maheshwaram watershed, Ranga Reddy District, Andhra Pradesh. Krishnamurthy *et al*.[13] have used the ERI technique to delineate coal seam barrier thickness and to demarcate water-filled voids. Kumar *et al*.[14] have carried out ERI survey to delineate potential aquifer zones and zeolite-bearing zones in the Deccan traps terrain in Aurangabad District. Two-dimensional electrical imaging survey has been carried out by Shamaun Kabir *et al.*[15] for characterization of the near-surface variation in geologic and soil strata in the Madhupur tract, Bangladesh. ERI survey has been carried out to delineate groundwater potential zones in the Deccan traps terrain of the Ghatiya watershed, Ujjain District, Madhya Pradesh[16]. Francese *et al.*[17] have used ERI survey to delineate fractured aquifers in the Scansano-Magliano in Toscana Ridge, southern Tuscany, Italy. The present work deals with the delineation of aquifers concealed within and below the traps in the Deccan traps-covered terrain using 2D ERI. Details about the study area are as follows.

Study area

The region under study is a part of the eastern fringe of Deccan traps in Chandrabhaga river basin falling under Kalmeshwar taluk, Nagpur District. It lies between long.

78°48′E and 78°55′E, and lat. 21°14′N and 21°18′N in NW of Nagpur city about 25 km away and is spread over an area of 96 sq. km encompassing 14 villages, namely Khapri, Ghogali, Ghorad, Waroda, Ubali, Wadhoda Burz, Sawai Khurd, Wadhona Khurd, Wathoda, Mohgaon, Mara Sawangi, Sasundri, Samundri and Kohli, as shown in Figure 1. It is evident from Figure 1 that the entire region under study is traversed by a dense network of channels. In the northern region a number of channels join together around Wathoda to form the Chandrabhaga river. The central region is traversed by a channel which passes through Ubali and joins the Chandrabhaga river east of Dhapewara Khurd. The southern region is traversed by two channels which cross Kalmeshwar–Katol road near Ghogali and west of Kalmeshwar, and join together to form the Saptadhara river near Ghorad. This is also a tributary of the Chandrabhaga river. The climatic condition is semi-arid. Annual precipitation is about 1100 mm. Precipitation is the only source of groundwater recharging. Because of the presence of a dense network of channels, run-off is high. Only a small portion of the precipitation is available for aquifer recharging. In summer, groundwater derived from the shallow unconfined aquifer flows through many deep channels as base flow. As a result, many dug wells go dry during summer season beginning from the March. This situation prevails till the onset of monsoon in July. This results in acute shortage of water for domestic uses. Thus these channels have significant influence on groundwater dynamics of this region. There is an urgent need to augment the present supply from deeper aquifers.

In the Deccan traps terrain, the top layer is mostly alluvial soil. Below it is the weathered mantle and highly to moderately fractured basalt which constitutes the unconfined aquifer system. The weathered mantle is underlain by volcanic lava flows. The lava flows are separated by sedimentary formations known as intertrappeans. The intertrappeans are deposited during the interval of two consecutive lava eruptions. Each lava flow consists of an upper vesicular basalt unit and an underlying massive basalt unit. The upper vesicular basalt units together with the overlying intertrappeans is a potential source of groundwater. At some places clay-rich sediments are deposited in the form of intertrappeans which are not good aquifers, and are known as bole beds[18,19]. Deep bore-well drillings in adjoining areas have indicated the presence of Gondawana sedimentary formations which could be another deeper source of groundwater[4,5]. Other signature about the presence of Gondwana sedimentary formations below the traps is their exposures in the Bazargaon forest area on the southern side and near Adasa on the northern side of the studied area. Occurrence of broad, low-gravity anomaly in NW of Nagpur city over the studied area is another indication of the presence of Gondwana sedimentary formation below the traps[20]. Between the traps and Gondwana formation lie the Lameta beds, which represent the palaeo ground surface before the commencement of lava flow. If the Lameta bed is not clayey, then it is a good aquifer. From field experience it is noticed that the identification of water-saturated Lameta bed and Gondwana sedimentary formation is difficult. Their identity can be confirmed by bore-well results. The present study is aimed to decipher groundwater potential zones in the form of intertrappeans, fractures and joints concealed within the traps, and Lameta and Gondwana sedimentary formations below the traps using 2D electrical ERI survey.

ERI survey

An ABEM-make Terameter SAS 4000 system was used for 2D ERI survey with Wenner configuration at 19 sites spread over the entire region of study. The studied sites with their number, P_n, are shown in Figure 1. Site P1 (78°52′9.6″E, 21°14′19.2″N) belongs to Ghogali village, P2 (78°53′44.6″E, 21°14′39.9″N), P4 (78°53′29.5″E, 21°14′46.4″N) and P9 (78°53′20.5″E, 21°15′5.4″N) to Ghorad village, P7 (78°54′20.1″E, 21°16′25.6″N) and P8 (78°53′48.6″E, 21°1′45.4″N) to Waroda village, P5 (78°53′23″E, 21°17′1.5″N) to Wadhona Buzurg village, P6 (78°54′1.4″E, 21°17′24.4″N) to Dhapewara Khurd village, P14 (78°50′38.9″E, 21°16′56.8″N) to Wathoda village, P3 (78°51′49.2″E, 21°16′48.6″N) and P17 (78°51′34.2″E, 21°16′17.8″N) to Ubali village, P10 (78°50′48″E, 21°14′42.1″N) and P19 (78°50′53.8″E, 21°14′32.2″N) to Khapri village, P13 (78°54′20.1″E, 21°16′25.6″N) to Samundri village, P16 (78°49′25.2″E, 21°17′27.0″N) and P18 (78°48′30.4″E, 21°17′30.2″N) to Sasundri village P11 (78°51′8.1″E, 21°18′5.9″N) to Mohgoon village and P12 (78°52′28.4″E, 21°17′51.1″N) to Mara Sawangi village. Surveys were conducted at different times. Hence the numbering of the sites was done in that sequence. Locations of each site given within the brackets were taken as the centre of the corresponding profiles. Apparent resistivity values for Wenner configuration were measured at each site. Inverse modelling of the measured apparent resistivity data was carried out by using the RES2DINV program. This program automatically creates a 2D model by dividing the subsurface into rectangular blocks. Thereafter, it calculates the apparent resistivity values of the model blocks and compares these calculated apparent resistivity values with the measured apparent resistivity values. The resistivity value of the model block is adjusted iteratively until the calculated apparent resistivity values of the model are in close agreement with the measured values. The final output is the 2D inverse model of true resistivity variation. Using this approach, 2D inverse models of true resistivity variation for all the 19 studied sites have been computed. Henceforth, the inverse model of true resistivity variation will be simply referred to as the resistivity model in the following sections.

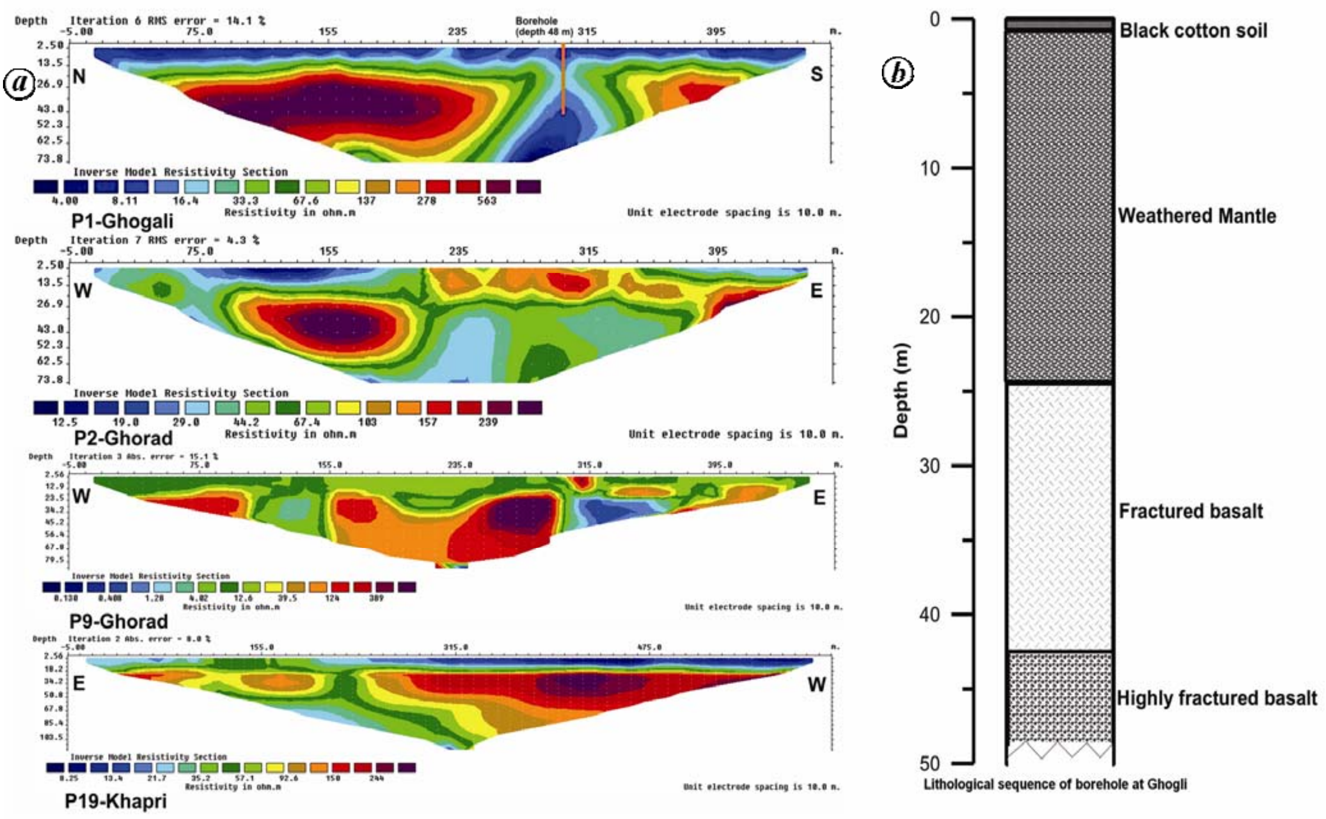

Figure 2. ***a***, Resistivity models for profiles P1, P2, P9 and P19. ***b***, Lithological sequence from bore hole at P1 site.

Results and discussion

The next step is the interpretation of 2D resistivity models in hydrogeological terms in order to identify groundwater potential zones. Based on the resistivity surveys carried out in the nearby Deccan traps terrains under Nagpur, Amaravati, Akola and Jalgaon districts of Maharashtra, the Central Ground Water Board (CGWB) of India has suggested the following resistivity values for the different litho units of the traps-occupied regions:

Alluvial, black cotton soil, Lameta beds: 5–15 ohm m; weathered/fractured/vesicular basalt saturated with water: 20–45 ohm m; moderately weathered/fractured/vesicular basalt saturated with water: 40–70 ohm m; massive basalt: > 70 ohm m; water-saturated Gondwana formation: < 50 ohm m; and Gondwana formation without water: > 50 ohm m. Our experience based on the 1D electrical resistivity survey and confirmation of interpreted results from bore-well drilling in the nearby region suggests that the resistivity of the water-saturated Gondwana formation is < 30 ohm m and that of water-saturated Lameta bed is < 15 ohm m. These values are used for hydrogeological interpretation of the computed 2D inverse models of true resistivity variations. Hydrogeological interpretation of the resistivity models is presented below.

P1, P2, P9 and P19

P1 belongs to Ghogali village, whereas P2 and P9 belong to the nearby Ghorad village and P19 belongs to Khapri (Figure 1). Two-dimensional resistivity models for P1, P2, P9 and P19 profiles are presented in Figure 2 *a*. Directions and distances are measured from left to right along the profiles and depths are measured from the ground surface as shown in Figure 2 *a*.

Resistivity model for P1 shows 10–12 m thick layer of alluvium/weathered formation which constitutes the unconfined aquifer. This layer is underlain by moderately fractured basalt (40–70 ohm m) followed by two units of massive basalts (> 70 ohm m). The massive basalt units are separated by a fracture zone at 300 m distance, below which lies a potential groundwater zone (< 20 ohm m) at 35 m depth. This water-bearing zone is found to widen with depth between both units of massive basalt and extends beyond the depth of study, i.e. 73.5 m. The interpreted litho units are verified by comparing with litho units of an exploratory bore well drilled at 300 m. Both sets of litho units were found to be in good agreement. Bore-well litho-section is presented in Figure 2 *b*. As expected from the interpretation, groundwater was struck at 35 m depth, but the well was drilled up to 45 m depth. Bore-well yield was found to be 15,900 lph (4200 gph).

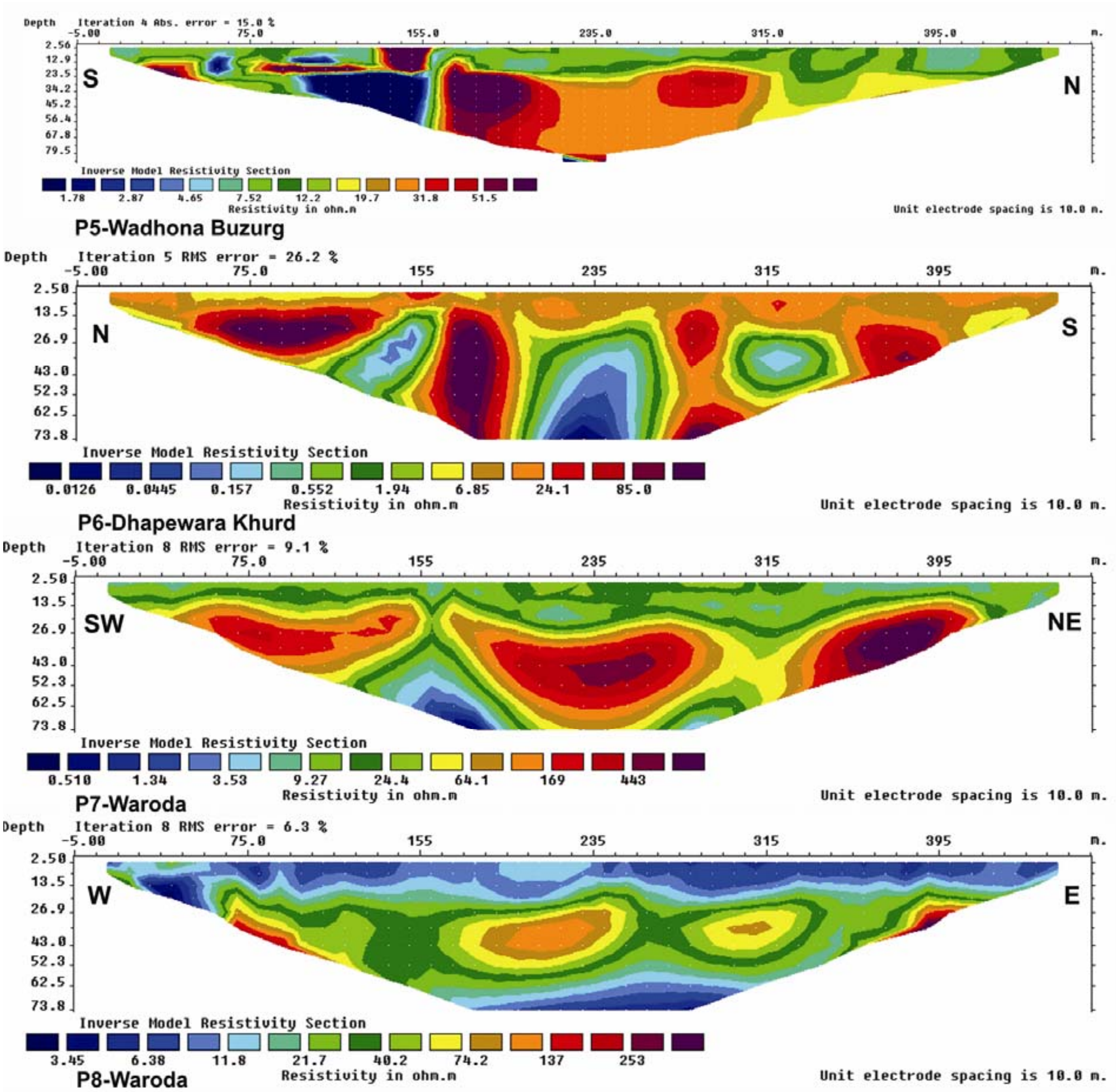

Figure 3. Resistivity models for profiles P5, P6, P7 and P8.

A vertical section of the 2D resistivity model for P2 profile indicates a ~ 10 m thick layer of alluvium between 65 and 185 m, which is underlain by a thin layer of moderately weathered/fractured formation (40–70 ohm m). Below it lies an oval-shaped massive basalt unit (> 70 ohm m) which is extended up to ~ 60 m depth. This massive basalt unit is separated by eastward-dipping fractured zone from a 25 m thick layer of massive basalt, which is exposed to the ground surface between 215 and 345 m. This layer is found dipping further westward to join another unit of massive basalt below a thin cover of alluvium. Possibility of occurrence of groundwater at this site is in an aquifer (< 30 ohm m), whose tip is lying below the western margin of the exposed massive basalt unit below 30 m depth. This aquifer is extending upward towards the west below the oval-shaped massive basalt unit, and is exposed to the ground surface at the eastern margin of the profile. Continuity of this aquifer westwards below the massive basalt unit is not visible, but its fraction can be seen below 75 m and exposure to the ground surface at the western edge of the profile. The resistivity model for profile P9 shows a heterogeneous subsurface structure. The model indicates the presence of 10–30 m thick layer of the alluvial (< 12 ohm m) along the profile up to 300 m. This alluvial formation is extended downward between 105 and 155 m separating two units of massive basalt. This zone appears to be a good aquifer favourable for groundwater exploration. In the case of P19, two units of massive basalt are seen below a < 10 m thick layer of alluvial/weathered mantle.

An aquifer zone is visible at 50 m depth between 155 and 305 m, below the massive basalt units. This aquifer is connected to the top layer through a fracture zone (< 60 ohm m) which separates both the units of the massive basalt. This fracture zone appears to be the recharging site of the aquifer.

P5, P6, P7 and P8

Profiles P5 and P6 are located in Wadhona Buzurg and Dhapewara Khurd villages respectively, whereas P7 and P8 are located in Waroda village (Figure 1). Resistivity models of these profiles are presented in Figure 3. The model for P5 presents a heterogeneous picture of subsurface litho units up to 155 m distance. Beyond this lies a ~ 10–12 m thick layer of alluvium (< 15 ohm m) along the rest of the profile. Its thickness increases up to 45 m between 325 and 365 m, and is underlain by a weathered mantle. This zone appears to be favourable for groundwater exploration. The model also indicates the presence of a massive basalt unit between 165 and 205 m, at 25 m depth. Towards south of this massive basalt unit lies a clayey formation (< 5 ohm m). The resistivity model for P6 indicates three aquifer zones separated by two vertical units of massive basalt. The first aquifer zone with a tip below 155 m is found lying below a horizontal layer of massive basalt and is extending downward. The second aquifer zone is located between 205 and 265 m in the central part of the profile, and is bounded by two vertical blocks of massive basalt. This zone is extended downward beyond the depth of study. The third aquifer zone is small and is enclosed by massive basalt from three sides. These aquifers are being vertically recharged. The first and second zones appear to be favourable for groundwater exploration.

The resistivity model for profile P7 shows three distinct units of massive basalt below a 10–20 m thick layer of alluvium/weathered mantle (< 25 ohm m). These three units are separated from each other by weathered/fractured zones at 155 and 315 m distance. Below the massive basalt unit lies a water-saturated formations (< 25 ohm m) which is linked to the top layer through fractured zone located around 155 m distance. This fracture zone appears to be the recharge site of the lower aquifer. This site could be favourable for bore-well drilling. This aquifer seems to be extended below the central unit of the massive basalt. Profile P8 is in close vicinity of the Saptdhara river and depicts three horizontal layers. The top layer of 10–12 m thickness is composed of alluvial/clayey formation (< 12 ohm m). This layer is underlain by a thick layer of weathered (< 30 ohm m) to moderately weathered (> 30 ohm m) formation and is extended up to ~ 60 m depth. Below this layer is another layer of low resistivity (< 10–15 ohm m), similar to the top layer. This layer is another potential source of groundwater. Four separate blocks of massive basalt (> 70 ohm m) can be seen within the middle layer. This site appears to be most favourable for groundwater exploration.

P3, P17, P13 and P14

Profiles P3 and P17 fall under the Ubali village, whereas profiles P13 and P14 fall under Samundri and Wathoda village respectively. Sites of these profiles are located south of the Chandrabhaga river. Resistivity models for P3, P17, P13 and P14 are presented in Figure 4. In the case of P3, a thick layer of massive basalt with root is spread over eastward from 165 m. This massive basalt unit is separated from another small unit of massive basalt lying west of 155 m by a fractured zone. This zone is linked to an aquifer lying at about 30 m depth. This aquifer is being recharged through the overlying fractured zone and is suitable for groundwater exploration. A tip of another aquifer zone is visible on the eastern side of the root at same depth, i.e. 30 m. Resistivity model of P17 indicates that the entire subsurface zone is occupied by massive basalt, except a small zone of aquifer at a depth of 40 m between 135 and 225 m. This small zone of aquifer appears to be surrounded by massive basalt and is not favourable for groundwater exploration.

Resistivity model for P13 indicates the presence of a massive basalt layer extending eastward from 135 m onward. Its thickness progressively increases westward. Below this layer of massive basalt lies an aquifer system which is extending upwards towards the western side underneath the massive basalt unit and is exposed to the ground surface at 135 m. This location appears to be the site of recharging. Resistivity model for P14 shows a horizontal layer of massive basalt along the entire length of the profile with a root zone extending downward. A groundwater potential zone (< 25 ohm m) is visible at ~ 60 m depth towards the eastern side of the root of massive basalt. This aquifer zone is suitable for groundwater exploration. Tips of another groundwater potential zone are visible at the same depth on the western side of the root.

P11, P12, P16 and P18

Profiles P11, P12, P16 and P18 are under the administrative jurisdiction of Mohgaon, Sawangi, Sasundari and Samundri villages respectively, and located north of the Chandrabhaga river. Two-dimensional resistivity models for these profiles are presented in Figure 5. The resistivity model for P11 shows that below ~ 5 m thick cover of alluvium, the subsurface is divided into two contrasting geological formations. Half of the subsurface towards the southern side is fully occupied by massive basalt,

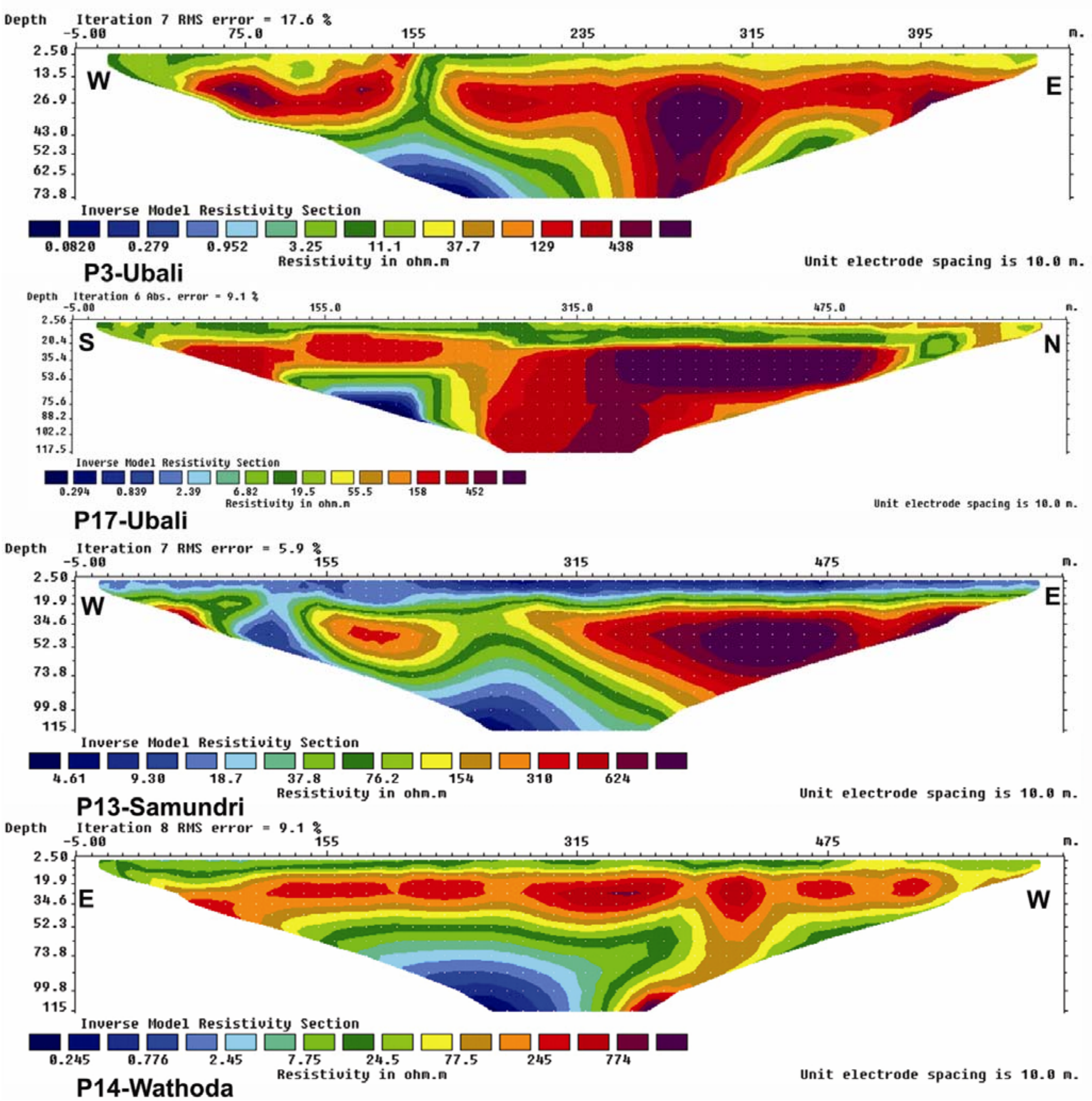

Figure 4. Resistivity models for profiles P3, P17, P13 and P14.

whereas half of the subsurface towards the northern side is occupied by weathered mantle up to 35 m depth, and below that a low resistivity clayey formation (< 10 ohm m). The top layer of weathered formation is extending downward in the centre of the profile between clayey formation and massive basalt. Therefore, the prospect of groundwater occurrence is only up to the centre of the profile, i.e. up to 245 m. Beyond 245 m, there is no scope for groundwater occurrence. Resistivity model for P12 profile indicates the presence of a massive basalt (> 70 ohm m) in the central part of the profile between 185 and 265 m, below a 20 m thick layer of weathered formation (20–40 ohm m). The zone of massive basalt is bounded by clayey formation from both sides. Another small zone of massive basalt enveloped by weathered formation can be seen at 245 m. Potential aquifer zone appears to lie above the clayey formation between 245 and 375 m. Resistivity model for P16 shows only massive basalt (> 70 ohm m) below a 2–3 m thin cover of alluvium/weathered formation. There is no sign of the presence of aquifer. In the case of profile P18 also, a horizontal layer of massive basalt (< 70 ohm m) is spread

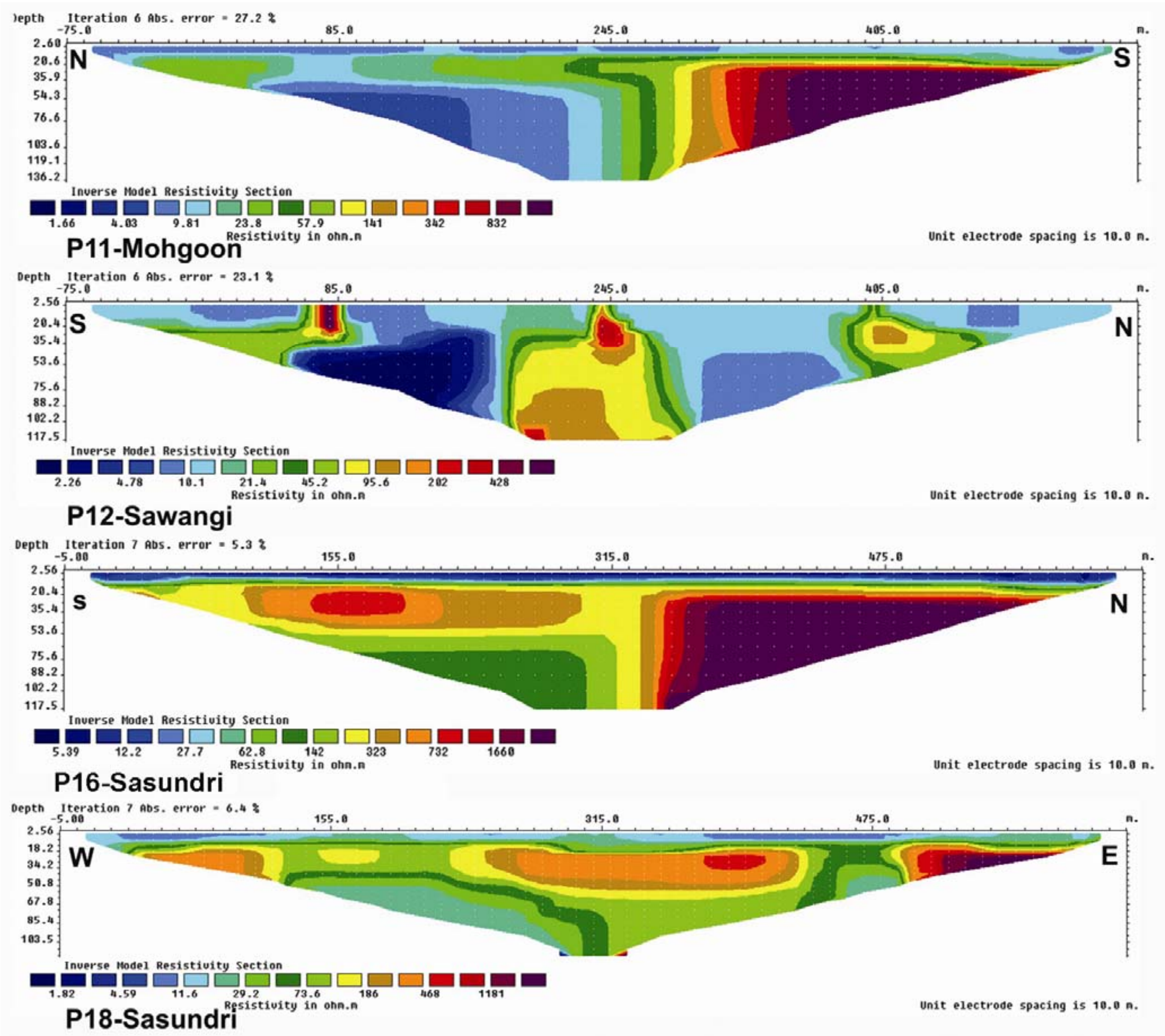

Figure 5. Resistivity models for profiles P11, P12, P16 and P18.

over the entire length of the profile with a root extending downward between 315 and 445 m. On the western side of the root an aquifer zone (< 30 ohm m) is visible below 50 m, between 125 and 315 m, and another small aquifer zone is visible on its eastern side at 20 m depth, between 435 and 475 m. The aquifer on the western side of the root can be explored for groundwater.

Conclusions

Resistivity models suggest that the hydrogeology of the studied region is highly complex and the ERI survey has successfully identified potential zones of groundwater in such a heterogeneous environment. Resistivity models produced by inverse modelling of measured apparent resistivity data indicate the presence of single lava flow (massive basalt), which is fragmented into multiple units due to weathering, fracturing, faulting, etc. Thickness of the massive basalt units is controlled by palaeo topography that existed before the pouring of volcanic lava. Massive basaltic layer is covered by alluvium and weathered mantle produced by erosion and subsequent deposition, and from unconfined aquifers which are the main sources of groundwater to dug wells. Resistivity models have indicated potential groundwater zones at several sites in this top layer which can be explored for groundwater. Similarly, resistivity models have deciphered groundwater potential zones within and below traps in the Lameta/Gondwana formations. Interpreted results of resistivity model for P1 have been verified by bore drilling. Resistivity models suggest the favourable sites of deep bore-well drilling for P2 at 235 m, for P9 between 105 and 155 m, for P5 around 325 m, for P6 at 145 and 235 m, for P7 at 155 m, for P8 between 105 and 315 m, for P16 up to 225 m, for P12 between 285 and 435 m, for P13 between 235 and 27 m, for P14 between 155 and 300 m, for P18 between 155 and 215 m, for P3 at 165 m, for P17 at 210 m, and for P19 between 155 and 295 m. As mentioned above, deep channels are responsible for draining groundwater from unconfined aquifers. Because of this many dug wells go dry during summer. Construction of few check dams across the channels, especially near villages, is recommended to retain groundwater in the dug wells.

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