



Delineation of groundwater resources using electrical resistivity tomography

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Abstract

Chandrabhaga basin of the Nagpur district is a part of the drought prone Vidarbha region of Maharashtra, India. This region is facing acute shortage of water for drinking and irrigation purposes. The basin is located at the eastern fringe of the Deccan traps consisting of volcanic rocks. Presently, dug wells penetrating composite layers of the weathered mantle and highly fractured rocks overlying stratified basaltic lava flows are the main source of water supply. However, water available in the dug wells is inadequate to meet the ever increasing demand for water causing considerable economic losses to the farming community. In this work, we present the results of an electrical resistivity tomography (ERT) survey carried out in the basin for the delineation of groundwater potential zones. Validity of the hydrogeological setup obtained from the ERT results has been confirmed by bore well drillings at two investigated sites. The study demonstrates the efficacy of the ERT technique in delineation of groundwater potential zones in the hydrogeologically complex basaltic terrain of the Deccan traps.

Keywords Deccan traps · Basalt · Electrical resistivity tomography · Chandrabhaga River basin · Gondwana

Introduction

Groundwater is widely used to meet the ever increasing demand of water for domestic, industrial and agricultural purposes. In India, groundwater occurs both in sandy alluvial aquifers and fractured hard rocks. Almost two third of the surface area of the country is occupied by different types of hard rock terrains which include basalt, granite, gneisses, charnockite, quartzite, khondalite, etc. Occurrence and movement of groundwater in hard rock terrains is controlled by secondary porosity developed due to geological processes like weathering, faulting, fracturing, etc. (Limaye 2010). Therefore, there is always a need for locating the geological formations and structures in hard rock terrains favorable for groundwater occurrence. Electrical resistivity method is the one of the most suitable geophysical methods for groundwater exploration in hard rock terrains because of good contrast between the electrical resistivity of water-saturated weathered/fractured geological formations and the massive

hard rock devoid of water (Yadav and Singh 2007). In earlier studies, mostly vertical electrical sounding (VES) technique with four-electrode configuration was used (Bose and Ramkrishna 1978; Rao et al. 1983; Muralidharan et al. 1994; Rai et al. 2011, 2012, 2013a). The greatest limitation of the VES technique is that it provides only 1D model of the resistivity variation below the center of the survey line and does not take into account lateral variations in the resistivity value due to the presence of geological formations/structures such as faults, fractures, joints, etc. on either sides of the center which can lead to the delineation of groundwater potential zones away from the center (Loke 2000). Therefore, delineation of water-bearing formations by 1D model is not always possible unless these formations/structures coincidentally lie below the center of the profile. But in hard rock terrains, hydrogeological setup changes within a few meters distance. Therefore, a more accurate model of the subsurface litho-units would be a 2D model which provides information about the resistivity variations in the vertical as well as lateral direction along the survey line. This will lead to the delineation of subsurface image of litho-units along the entire stretch of the survey line which in turn will facilitate identification of groundwater potential zones.

Development of 2D resistivity models has become possible with the development of electrical resistivity

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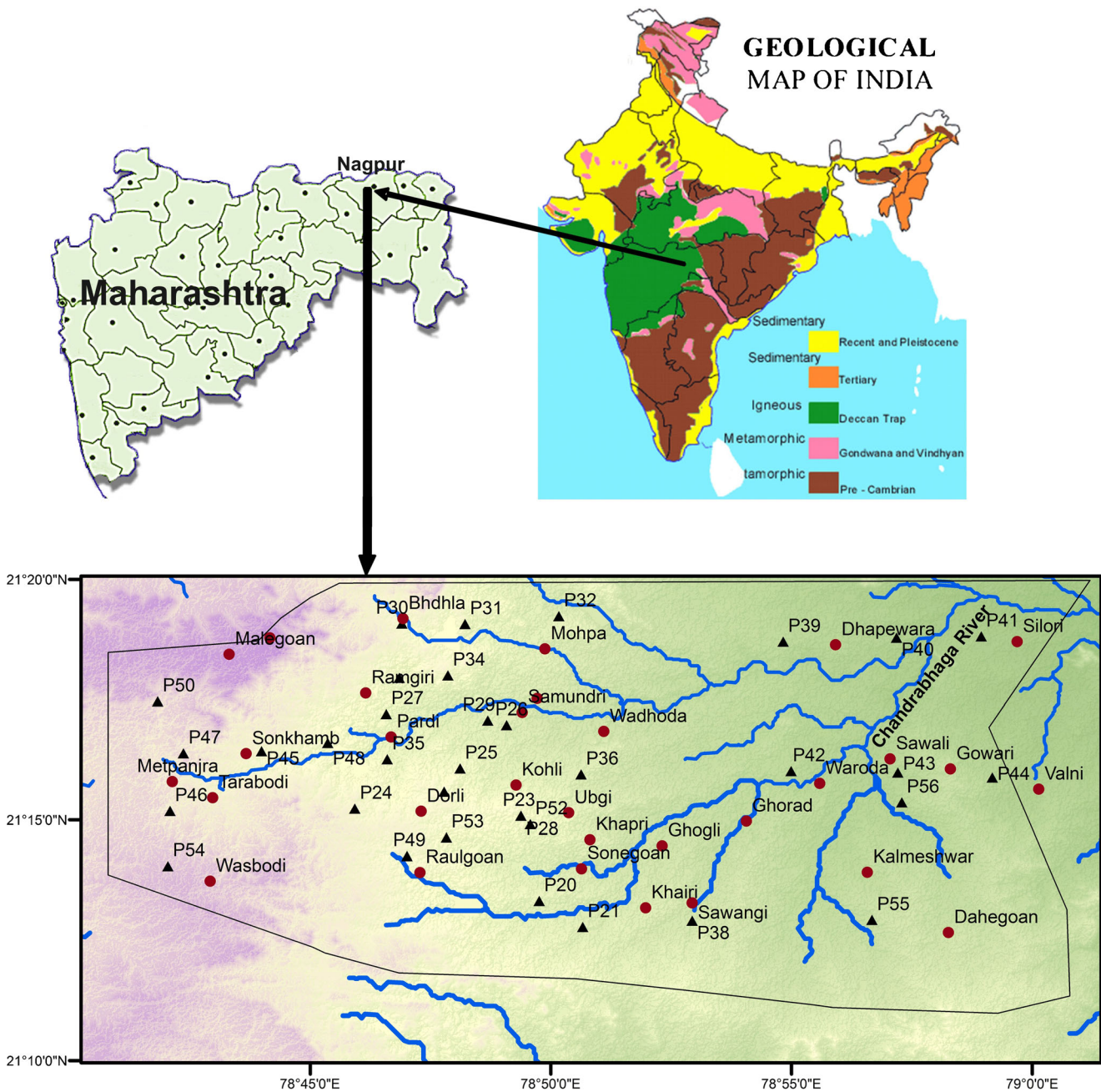
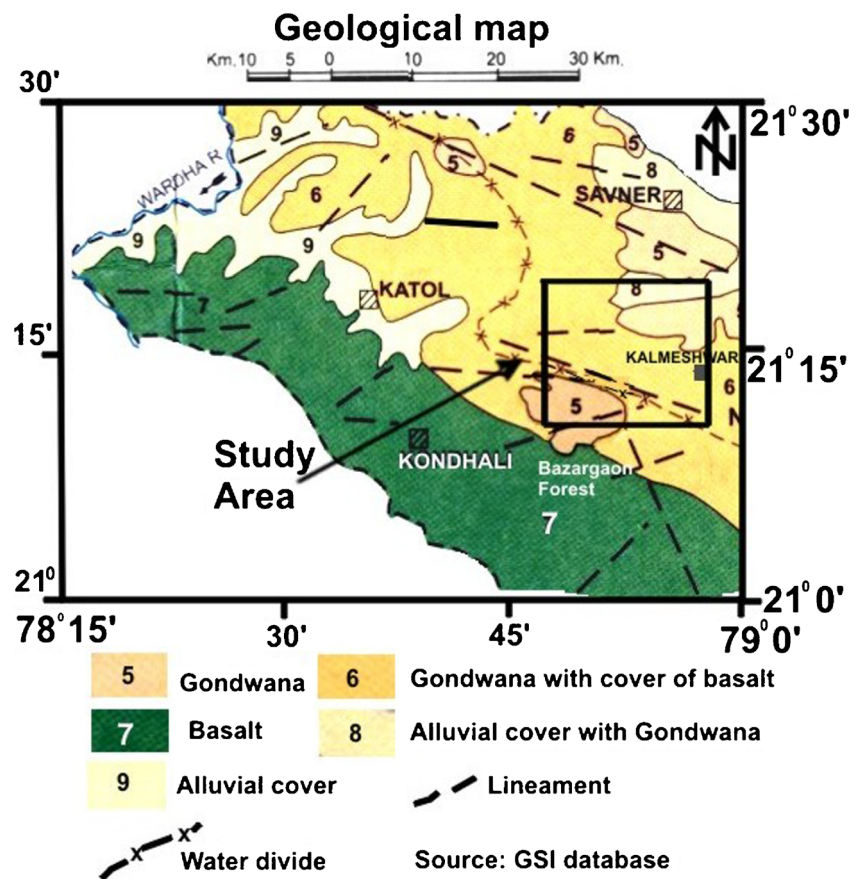


Fig. 1 Map of the Chandrabhaga River basin with the locations of electrical resistivity tomography sites represented by filled triangles

tomography (ERT) technique. The main advantages of the ERT technique are (i) automated acquisition of large amount of data in less time and cost and (2) imaging of the subsurface geological formations/structures in both horizontal and vertical directions along the survey line. The ERT technique is being used worldwide for different purposes such as for delineation of groundwater potential zones in complex hydrogeological setups, selection of suitable sites for waste disposal, identification of geothermal reservoirs, dewatering of mining area, etc. (Loke 2000). To mention a few examples, it was conducted over

meta-sedimentary strata and meta-volcanics in the Harare greenstone belt in northeastern Zimbabwe as part of groundwater resource investigation (Owen et al. 2005) and to map the thicknesses of aquifers and bedrock in Banting, Selangor in Malaysia as part of the groundwater exploration programs (Hamzah et al. 2006). The technique has been used to investigate the subsurface seepage conditions and to identify possible weak zones/seepage paths at the periphery of the Ahmadu Bello University farm dam in northern Nigeria (Osazuwa and Chii 2010). It has also been applied to delineate fractures at a solid

Fig. 2 Geological map of the study area and its surroundings



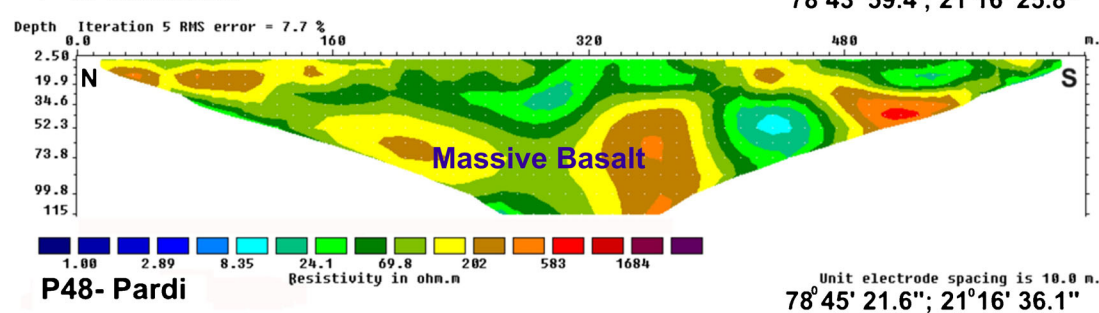
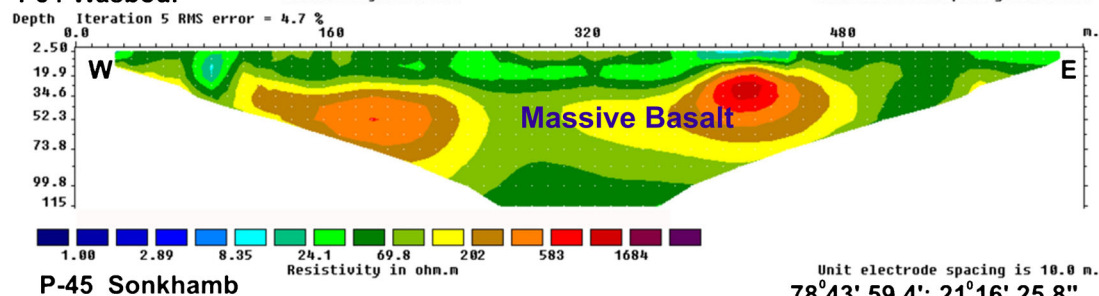
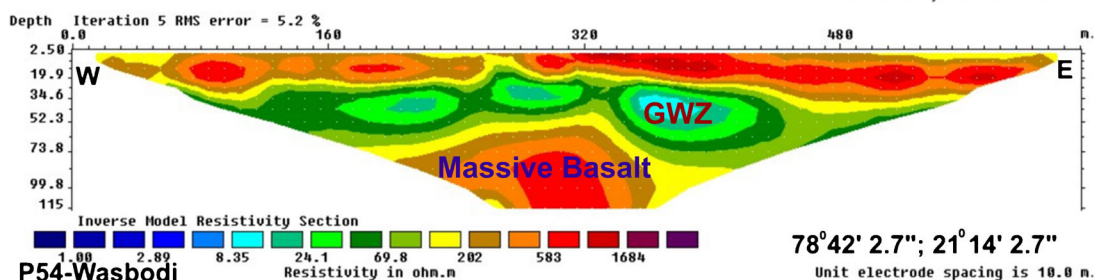
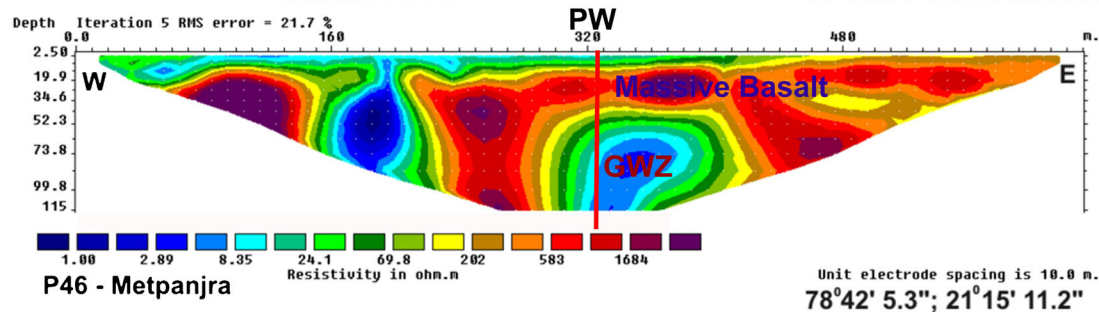
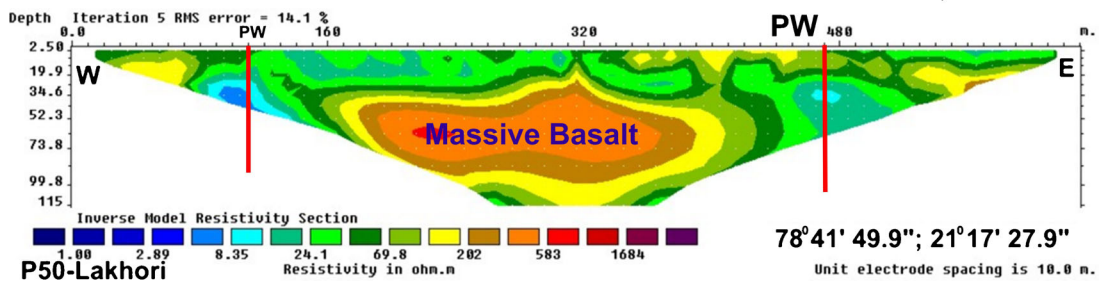
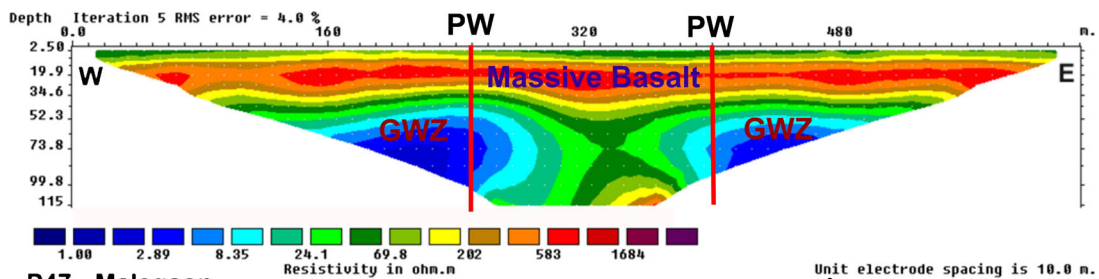
waste disposal site in Unguwan Dosa, Kaduna State, Nigeria that could provide pathways for contaminant transport (Abdullahi et al. 2011). To decipher groundwater potential zones for irrigation and drinking purposes, ERT was carried out in Pagoh and Johor, Malaysia (Kadri and Nawawi 2010) and in parts of Kubanni River Basin, Zaria, Nigeria (Anthony and John 2010). Kumar et al. (2011) have conducted ERT in the Chiplun taluk of the Ratnagiri district of Maharashtra, India, to delineate aquifers in search for geothermal reservoir and potential zones of groundwater with normal temperature. Ratnakumari et al. (2012) have carried out ERT in a small segment of the Chandrabhaga basin for the delineation of groundwater resources. The ERT has been carried out in the granitic

terrain of the CSIR-National Geophysical Research Institute campus located in Hyderabad, India (Rai et al. 2013b) and in the Tawarja basin located in the severely draught prone Marathwada region of Maharashtra, India (Rai et al. 2015) to delineate groundwater potential zones in order to suggest suitable sites for bore well drilling and managing of aquifer recharge.

The present study deals with the delineation of groundwater potential zones in the Chandrabhaga river basin using ERT technique for identification of suitable sites for bore well drilling and for managing aquifer recharge. For this purpose, ERT survey was conducted at 35 sites spread over the entire basin. The profiles corresponding to these sites, named as P20 to P56, are shown in Fig. 1.

Table 1 Regional stratigraphy (after Mehta 1989)

Age	Formation	Lithology
Recent to Quaternary	Alluvium	Black cotton soil, silt and clay
Lower Eocene to upper Cretaceous	Deccan lava flows	Massive and vesicular units of basaltic Lava flows with intervening intertrappean sediments
Permian	Lameta beds	Thin sedimentary sequences
Permian to Carboniferous	Gondwana group	Medium to coarse grain sandstones with stratified clay/shale
Archaeans	Granites	Granite gneisses, meta-sediments of Sausar and Sakoli series



◀ **Fig. 3** Resistivity models indicating different geological formations/structures for profiles P47, P50, P46, P54, P45, and P48; PW proposed bore well, GWZ groundwater zone

Study area

Chandrabhaga basin is located in the Nagpur district of the Vidarbha region which is facing acute water shortage. The basin is spread over 78°42'E–79°E longitude and 21°11'N–21°20'N latitude (Fig. 1). It occupies about 500 sq km area encompassing 50 villages and falls under the semi-arid climatic condition. Western part of the basin falls under the Katol taluk, central part under the Kalmeshwar taluk and a small segment of the eastern part under the Nagpur rural district. The average annual rainfall in this region, which is the main source for groundwater recharge, is about 1100 mm. It is mainly associated with the southwest monsoon during June and September (CGWB 2003).

The basin is a part of the eastern fringe of the Deccan traps in which the thickness of the traps varies from a few meters to few tens of meters (Mehta 1989; CGWB 2003). The basin consists of the alluvial (black cotton) soil of varying thickness at the surface, followed by the weathered mantle and then moderately to highly fractured basalt. The composite layer of weathered mantle and fractured basalt forms the unconfined aquifer which is the main source of groundwater supply to dug wells. This composite layer is underlain by stratified basaltic lava flows and intertrappeans (sedimentary formations trapped between two consecutive lava flows). Each layer of lava flow consists of two units, vesicular basalt at the top and massive basalt at the bottom. The vesicular unit together with the overlying intertrappean forms confined to semi-confined aquifers. At some places, intertrappeans are clayey sediments called bole beds (Ghosh et al. 2006). Exposures of Gondwana sedimentary formation are found towards the southern boundary of the Chandrabhaga basin in Bazargaon forest and towards its northern boundary around Adasa village (CGWB 2003; Muralidharan et al. 1994). This indicates the possibility of the presence of Gondwana formation below the traps within the basin. Geological map of the study area and its surrounding region is shown in Fig. 2. Bore well results have confirmed Gondwana formations as another potential source of groundwater below the traps. The Lameta bed lies between the traps and the Gondwana formation (Mehta 1989). The regional stratigraphy of the basin is given in Table 1.

The basin is drained by Chandrabhaga River and five major creeks which are the tributaries of the river as shown in Fig. 1. Chandrabhaga River traverses the entire basin from west to east in the northern part of the basin and flows out of the basin east of Yarandgaon village to join Kolar River. Two

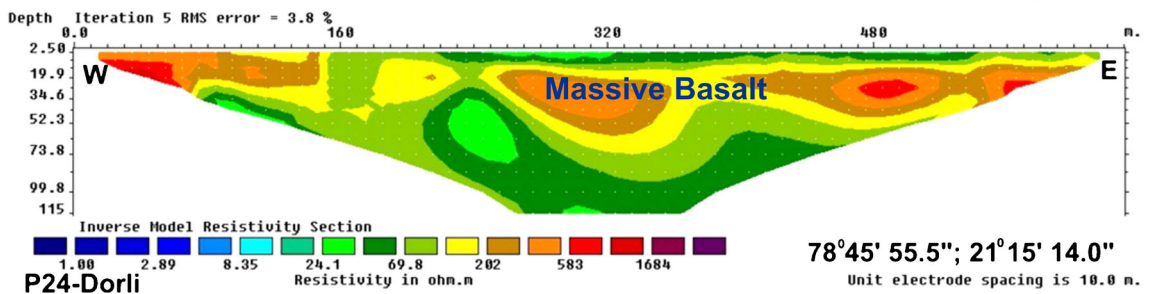
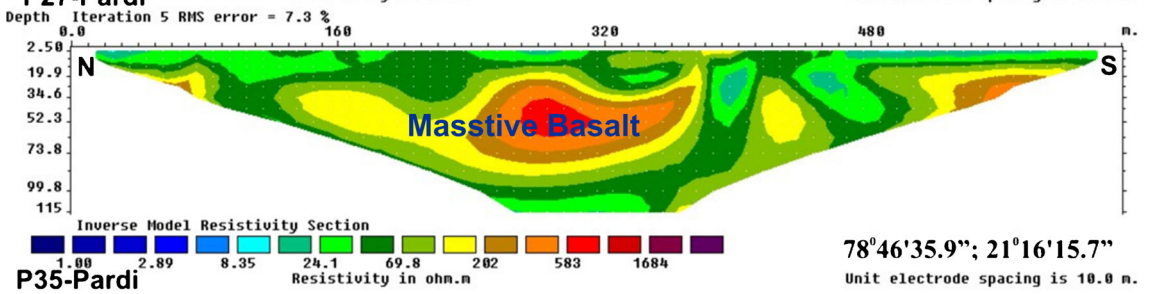
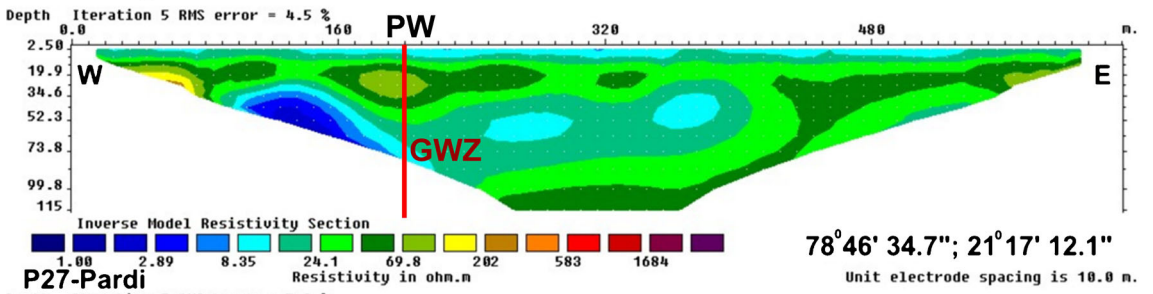
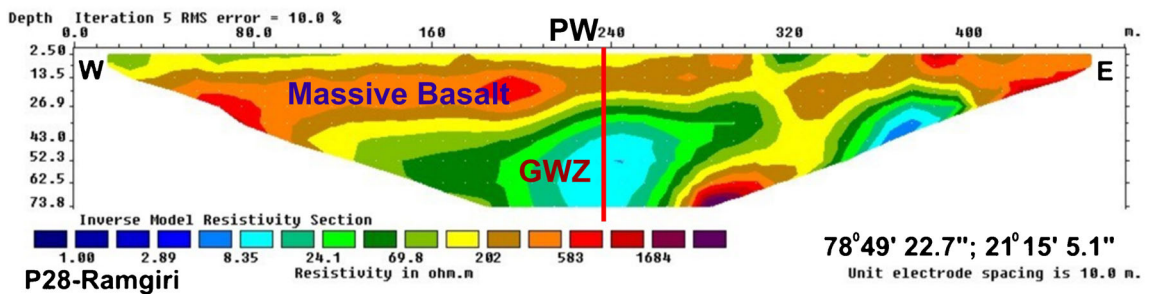
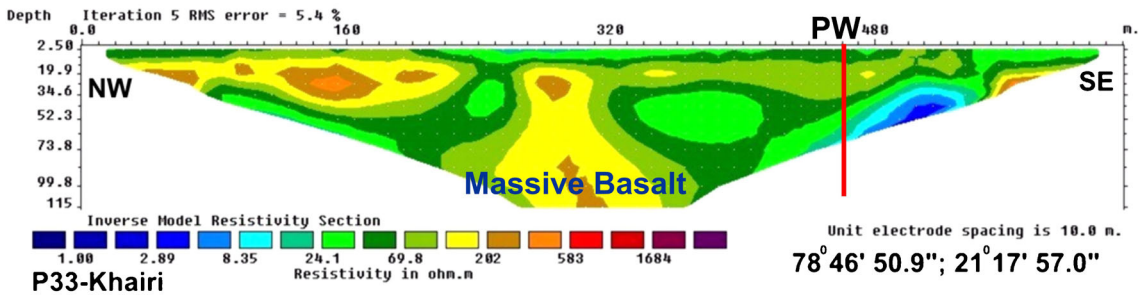
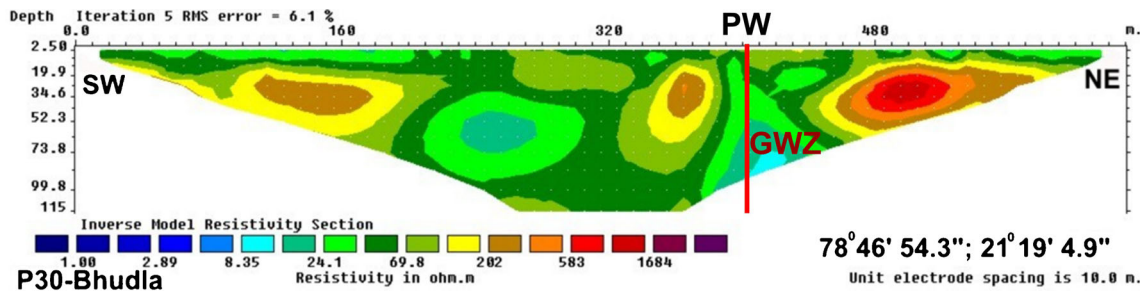
creeks lay north of Kalmeshwar-Katol road. One of them runs in west to east direction via Adasa village along the northern boundary of the basin and joins Chandrabhaga River near Yarandgaon village. The other one flows via Ubali village between Chandrabhaga and Saptdhara rivers and joins Saptdhara River north of Sawali village. Other three creeks originate south of Kalmeshwar-Katol road. Two of them flow east to west and join together near Ghogali village to form a single major creek which is referred as Saptdhara River south of the Kalmeshwar-Katol road. Saptdhara River flows in the north-east direction and joins Chandrabhaga River near Dhukhera village. The third creek flows in the south to north direction and joins Saptdhara River north of Gowari village as shown in Fig. 1. Chandrabhaga River and its tributary creeks cut through the entire thickness of the top weathered formation and are responsible for draining of groundwater away from this formation. As a result, many dug wells of this region go dry with the onset of summer (CGWB 2003). Thus, the Chandrabhaga River and its tributaries play a major role in controlling the groundwater dynamics of unconfined aquifers which are the main source of water supply to the dug wells.

ERT survey procedure data acquisition and processing

In the present work, ERT survey has been carried out by using ABEM multi-electrode resistivity imaging system SAS-4000. The ERT is carried out using four units of multi-core cables each having 16 electrodes. Spacing between two electrodes is 10 m. In the present study, Wenner configuration is used. The apparent resistivity is computed by using expression $\rho_a = 2\pi a(\Delta V/I)$ in which I is the applied current, ΔV is the potential difference, and a is the spacing between two electrodes (in this case 10 m). More details about the field layout of ERT and procedure of data acquisition are described by Loke (2000) and Rai et al. (2013b). The apparent resistivity measurements are taken automatically and stored in a computer for further processing and inverse modeling using RES2DINV program (Loke 1997). The final output is in the form of 2D resistivity model which is interpreted in terms of geological formations in order to identify groundwater potential zones for drilling bore well and for selection of suitable sites for managing aquifer recharge.

Interpretation

2D resistivity models for the profiles P20 to P56 are presented in Figs. 3, 4, 5, 6, 9, and 10. Each resistivity model is presented with the site number denoted by Pn ($n = 20$ to 56), nearby



◀ **Fig. 4** Resistivity models indicating different geological formations/structures for profiles P30, P33, P28, P27, P35, and P24; PW proposed bore well, GWZ groundwater zone

village name, coordinates of the center of the profile, color index showing the range of variation in resistivity values of geological formations, and electrode spacing. Location of each electrode is marked on top of the resistivity model at 10 m spacing along the profile by small vertical spikes. The position of the first electrode is marked at the 0th and 64th electrode is placed at 630 m distance. The distance of interpreted subsurface geological formations in horizontal direction is measured from the first electrode. The depth of the investigation is limited to 115 m. The resistivity models also present modeling errors in the form of root mean square (RMS) values.

For hydrogeological interpretation of these resistivity models to identify groundwater potential zones, we use the resistivity values of different litho-units of the Deccan traps (Table 2) suggested by Central Ground Water Board (CGWB) based on the resistivity surveys carried out in parts of the Deccan traps occupied Nagpur, Amaravati, Akola, and Jalgaon districts.

Resistivity of the water saturated Lameta bed is < 15 Ohm m. From our field experience, we have found that the Gondwana formations (sand/sandstone, etc.) characterized by resistivity of 20–40 Ohm m are good aquifers (Rai et al. 2012). These values of resistivity are considered for the interpretation of the 2D resistivity models. As per the resistivity values given in Table 2, the geological formations/structures having resistivity values within the range of 20 to 40 Ω m are interpreted as potential sources of groundwater suitable for exploitation. Groundwater-saturated zones are marked as GWZ in the figures of resistivity models.

Resistivity models of profiles P47, P50, P46, P54, P45, and P48

Resistivity models of profiles P47, P50, P46, P54, P45, and P48 are presented in Fig. 3 in sequence from north to south. The resistivity model of profile P47 presents a layered structure. The top thin layer with < 25 Ohm m resistivity represents the composite layer of soil and weathered formation of ~ 3 m thickness. This is underlain by massive basalt (> 70 Ohm m) layer which extends up to 35–40 m. Two groundwater potential zones (< 40 Ohm m) are obtained beneath this layer of massive basalt. Both zones, separated by a moderately fractured basalt unit (50–70 Ohm m), are suitable for groundwater exploitation by bore well drilling at 250 m or at 400 m profile distance. The probable locations of proposed bore wells are marked by vertical red lines as PW. The same notations are used also for other profiles. Criterion for the selection of bore

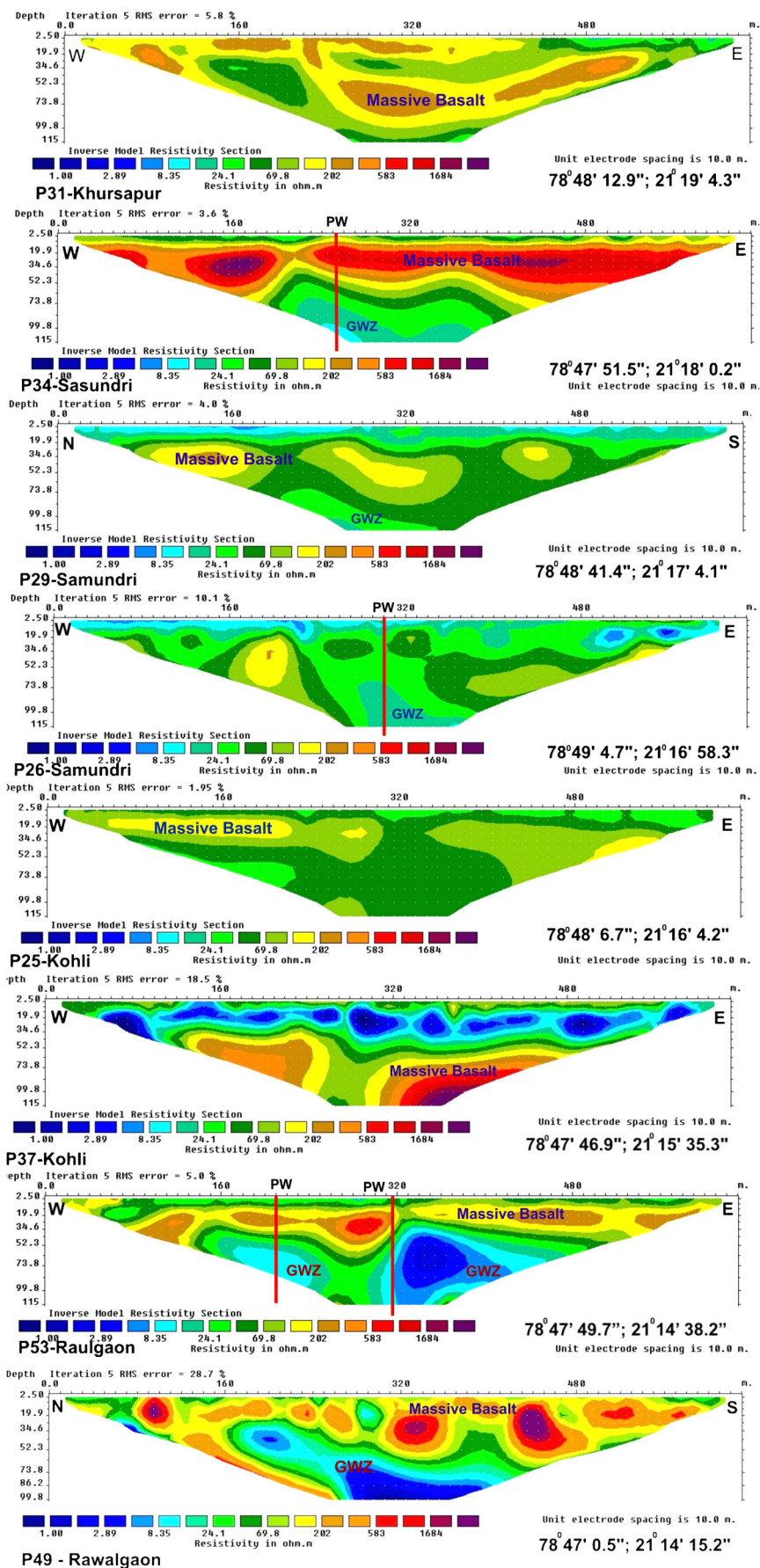
well sites is based on the experience that the contact zone between water-saturated weathered/fractured formations and massive unit of the hard rock formation forms in general the groundwater potential zone.

Resistivity model of profile P50 shows three units of massive basalt. The first one is exposed up to 70 m distance. The second one lies beneath ~ 15–20-m-thick cover of soil/weathered formations between 160 and 400 m. Exposure of the second unit is connected to the exposure of third unit of massive basalt at 480 m. The first and second units of massive basalt are separated by a fracture zone which is connected to the top layer of soil/weathered formation at 120 m distance. This is the site of recharging for the fracture zone. This fracture zone is extending downward below the second unit of the massive basalt. The second and third units of the massive basalt are also separated by a fracture zone. Both fracture zones appear to be groundwater potential zone. Suitable locations for bore well drilling could be either at 110 or 470 m profile distance.

Resistivity model of profile P46 shows two units of massive basalts. Both units are separated by a fracture zone filled with clayey formation. Another water-bearing zone is also visible between 310 and 370 m at ~ 50 m depth enveloped by the second unit of the massive basalt. This zone and the above mentioned fracture zone appear to be of finite areal extent. Hence, resistivity model of this profile does not indicate any favorable site for groundwater exploitation. Resistivity model of profile P54 presents a three-layered structure. The top layer is massive basalt (< 70 Ohm m). The middle layer is moderately fractured basalt (50–70 Ohm m) which envelops three lenses of low resistivity formation (< 40 Ohm m). The bottom one is again massive basalt. This model does not indicate any groundwater potential zone.

Resistivity model of profile P45 also indicates a three-layered structure. The top ~ 15–20-m-thick layer represents moderately fractured basalt (~ 40–60 Ohm m). The middle layer of massive basalt (> 70 Ohm) is underlain by a layer of moderately fractured basalt. This profile also does not indicate any potential source of groundwater. Profile P48 is in north-south direction. Its resistivity model presents a heterogeneous geological setup. This model shows two units of massive basalt (< 70 Ohm m). The first unit is exposed on the ground surface up to 280 m distance. This massive basalt unit is extended further southward up to 400 m distance beneath a stratum of weathered /fractured (< 40 Ohm m) which is exposed on the ground surface between 310 and 370 m. The second unit of massive basalt which is exposed on the ground surface between 400 and 440 m is extending southward underneath a layer of soil/weathered formation. Both units of massive basalts are separated by a fracture zone (< 40 Ohm m) which appears to be extending vertically beyond 70 m depth. Because of small size, this fracture zone does not appear to be favorable for groundwater

Fig. 5 Resistivity models indicating different geological formations/structures for profiles P31, P34, P29, P26, P25, P37, P53, and P49; PW proposed bore well, GWZ groundwater zone



exploitation. Hence, this profile does not show any site suitable for groundwater exploitation.

Resistivity models of profiles P30, P33, P28, P27, P35, and P24

Resistivity models of profiles P30, P33, P28, P27, P35, and P24 are presented in Fig. 4. Profile P30 near Budhla village is in the SW to NE direction. Resistivity model of this profile presents heterogeneous set up of litho-units. Only two water-bearing zones (< 40 Ohm m) are seen in the model. One lies at ~30 m depth between 210 and 280 m profile distance enveloped by moderately fractured basalt unit (50–70 Ohm m). The other one is exposed at 400 m and is extending downward between two units of massive basalt. This zone appears to be suitable for groundwater exploitation. A bore well is drilled to confirm the occurrence of groundwater in the interpreted geological formation.

Resistivity model of profile P33 indicates three units of massive basalt. The first unit of ~10 to 30 m thicknesses extends horizontally up to 230 m distance. The second unit of massive basalt extends from 260 to 530 m distance and covers the entire depth of the resistivity section in the central portion of the profile. These two units are separated by a moderately fractured basalt unit (> 50 Ohm m). Upper boundary of the third unit of massive basalt is also visible east of 550 m distance. The second and third units are also separated by a fracture zone which is exposed at the surface at 540 m profile distance which may be a recharging site. This fracture zone extends downward with north-west dip and appears to be favorable for groundwater extraction. A suitable site for drilling bore well is suggested at 460 m distance. Resistivity model of profile P28 indicates two water-bearing zones (< 40 Ohm m) within massive basalt unit. The first zone lies almost in the center of the profile between 190 and 280 m at ~30 m depth and appears to be extending beyond 74 m in depth. The second one lies at 25 m depth. Both water-bearing zones are separated by a massive basalt unit. However, both zones are not suitable for groundwater exploitation because of their small sizes.

Resistivity model of profile P27 indicates the presence of groundwater-bearing weathered/fractured formation (< 40 Ohm m) from 80 m onward to the eastern edge of the profile and up to 100 m depth. This site appears to be favorable for groundwater exploitation by bore well drilling anywhere between 160 and 480 m distance. Resistivity model of profile P35 shows the presence of moderately fractured (50–70 Ohm m) to massive basalt (> 70 Ohm m) underneath a thin cover of soil. This site is not favorable for groundwater exploitation. Resistivity model of profile P24 indicates a massive basalt unit (>70 Ohm m) spread along the entire spread of the profile. This layer is underlain by moderately fractured basalt (~50–

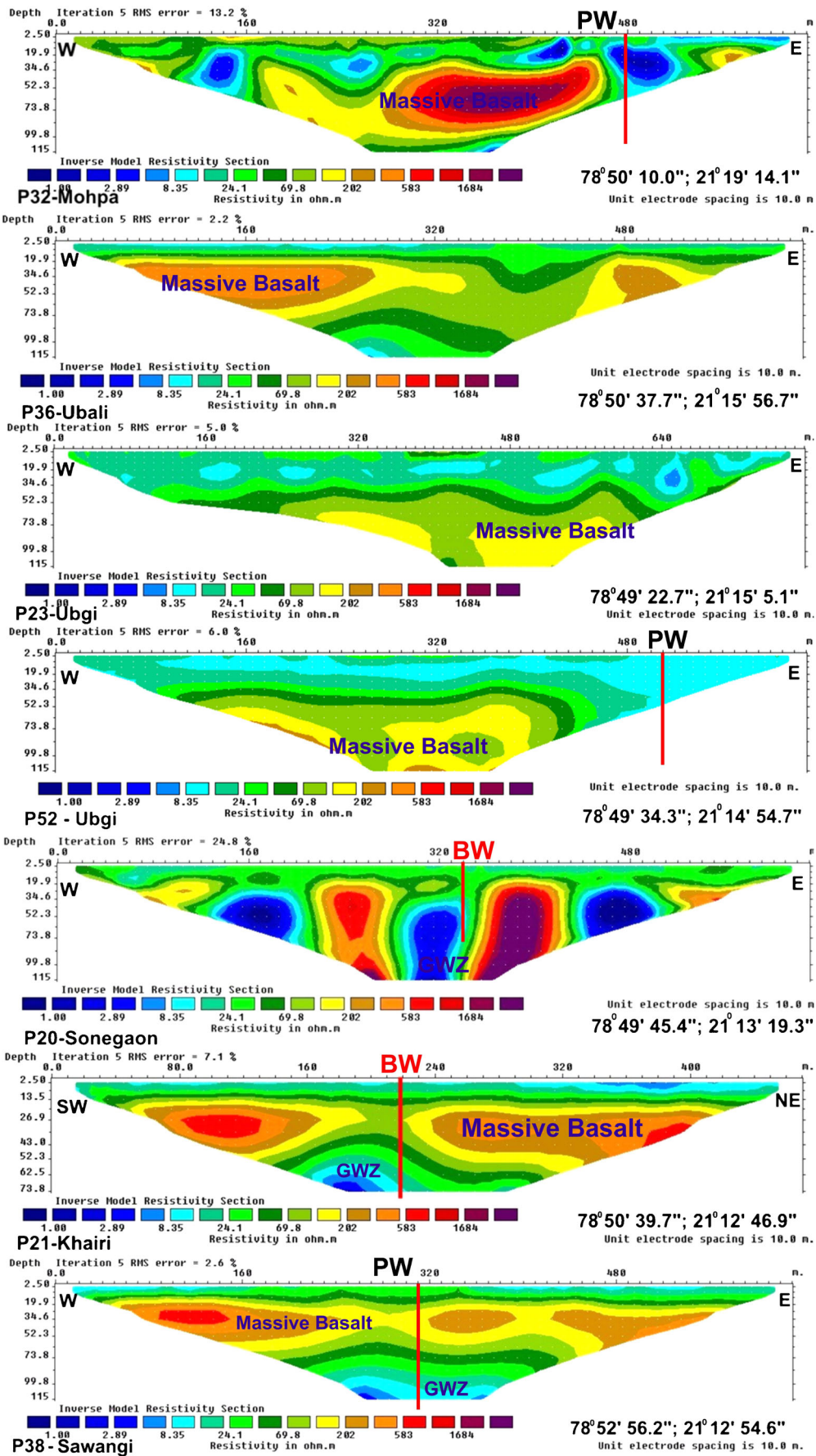
70 Ohm m). This site also does not indicate presence of groundwater potential zone.

Resistivity models of profiles P31, P34, P29, P26, P25, P37, P53, P49

Resistivity models for profiles P31, P34, P29, P26, P25, P37, P53, and P49 are presented in Fig. 5. Resistivity model of profile P31 located near Khursapur village shows moderately fractured basalt (50–70 Ohm m) to massive basalts (> 70 Ohm m) spread in the entire region below the profile. This profile does not indicate presence of potential groundwater zone. Resistivity model of profile P34 near Sasundri village indicates water-bearing formation (< 40 Ohm m) at ~60–70 m depth between 200 and 390 m distances underneath a thick layer of massive basalt (> 70 Ohm m). This water-bearing formation may be Gondwana sedimentary formation and appears to be extending beyond 115 m depth and is suitable for groundwater exploitation.

Profile P29 is in the N-S direction. Resistivity model of this profile presents the three-layered structure. The top one is the composite layer of soil and weathered/fractured basalt (< 40 Ohm m) in the depth range of ~10 to 20 m. Below, it lies moderately fractured basalt (~50–70 Ohm m) unit which is extended beyond 115 m depth south of 360 m distance. A zone of low resistivity (< 40 Ohm m) can be seen below the fractured basalt layer between 200 and 360 m distance at the bottom which could to be a water-bearing formation. Resistivity model of profile P26 indicates two units of massive basalt below a ~20–50-m-thick composite layer of soil (< 15 Ohm m) and weathered formation (< 40 Ohm m). Both units are separated by a wide fracture zone which is exposed to the ground surface between 200 and 300 m distance. This west dipping fracture zone extends beyond 115 m depth and is favorable for groundwater exploitation. A suitable location for the bore well drilling could be at 300 m distance.

Resistivity model of profile P25 shows the presence of moderately fractured and massive basalt over the entire profile length. This profile does not show any potential groundwater zone. Resistivity model of profile P37 indicates the presence of a composite layer of soil/weathered formations with thickness varying between 20 and 40 m. It is underlain by massive basalt. This site is not suitable for groundwater exploitation. Resistivity model of P53 profile indicates the presence of massive basalt in the depth range of 20 to 40 m. This is underlain by a water-bearing zone (< 40 Ohm m) between 160 and 480 m profile distance. This zone is suitable for groundwater exploitation. The suitable sites for bore well drilling could be at 210 and 310 m distances. Resistivity model of profile P49 shows a water-bearing zone (< 40 Ohm m) intruded into massive basalt unit. This zone is extended southward from 180 m distance onward and showing its downward



◀ **Fig. 6** Resistivity models indicating different geological formations/structures for profiles P32, P36, P23, P52, P20, P21, and P38; PW proposed bore well, GWZ groundwater zone

expansion in the central part of the profile. This zone appears to be suitable for groundwater exploitation by drilling bore well at 280 m distance in the central part of the profile.

Resistivity models of profiles P32, P36, P23, P52, P20, P21, and P38

Resistivity models of profiles P32, P36, P23, P52, P20, P21, and P38 are presented in Fig. 6. Resistivity model of profile P32 indicates the presence of two water-saturated fracture zones separating three units of massive basalt. The first fracture zone is located between 120 and 160 m distance and the second between 460 and 520 m distance. The fracture zone extends downward below the central unit of massive basalt and joins a water-bearing formation lying at the base of this unit at ~ 110 m depth. The second fracture zone is favorable for groundwater exploitation. The water-bearing formation below the second unit of massive basalt could be Gondwana formation. A suitable site for bore well drilling could be at 480 m distance.

Resistivity model of profile P36 presents a three-layered structure. The top composite layer of soil/weathered formation of ~5 m thickness is stretched along the entire profile length except between 380 and 400 m where its thickness is ~25 m. This top layer is underlain by a massive basalt layer (> 70 Ohm m) spread over the entire profile length. Another water-bearing formation lies below it, which is seen only in the central part of the profile in the depth range of ~ 80 to

115 m. This layer could be water-bearing Gondwana formation (< 40 Ω m) suitable for groundwater exploitation.

Profile P23 is located near Ubgi village. Its resistivity model indicates a two-layered structure. The top one is the composite layer of soil and weathered/fractured basalt (< 40 Ohm m) and the bottom layer is massive basalt (> 70 Ohm m). This resistivity model does not show any potential water-bearing zone. Profile P52 also belongs to Ubgi village and is located east of profile P23. Its resistivity model also yields a two-layered structure similar to that of P23. The top one is the composite layer of soil and weathered/fractured basalt (< 40 Ohm m) of ~35 m thickness which is present up to 450 m profile distance. This layer is underlain by massive basalt up to 450 m distance. Beyond this distance up to the eastern edge of the profile, the top layer of weathered/fractured basalt is extended downward and is suitable for groundwater exploitation by drilling bore well at 500 m distance.

Resistivity model of profile P20 presents a very heterogeneous geological setup. Four vertical units of massive basalts can be seen below a thin soil cover. These massive basalt units are separated by three fracture zones which are connected to the top soil cover. These fracture zones appear to be filled with sediments (< 10 Ohm m) in their central parts. In order to validate the interpreted results, a bore well was drilled at 340 m distance up to 73 m depth through a fracture zone. Location of the bore well is marked as BW on the profile. This bore well is penetrating through ~12-m-thick composite layer of soil and weathered basalt, and thereafter a unit of massive basalt up to 30 m depth. This is again followed by fractured basalt up to 45 m depth and thereafter fractured basalt till 73 m depth. A comparison of the sequence of litho-units obtained from the bore well with the corresponding

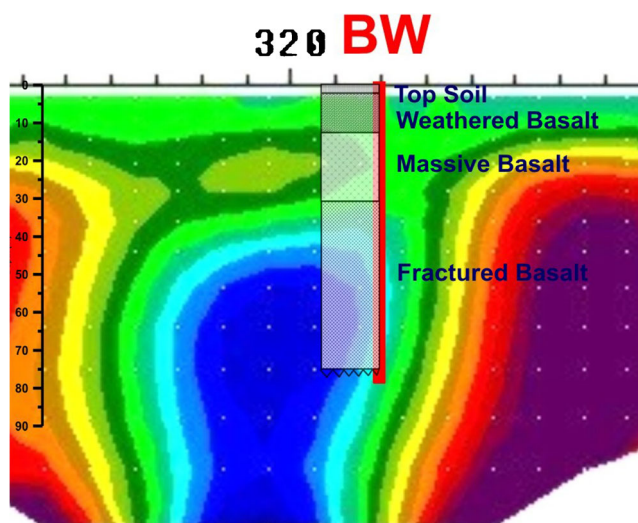


Fig. 7 A comparison of the sequence of litho-units obtained from bore well with the sequence of litho-units obtained from resistivity model of profile P20

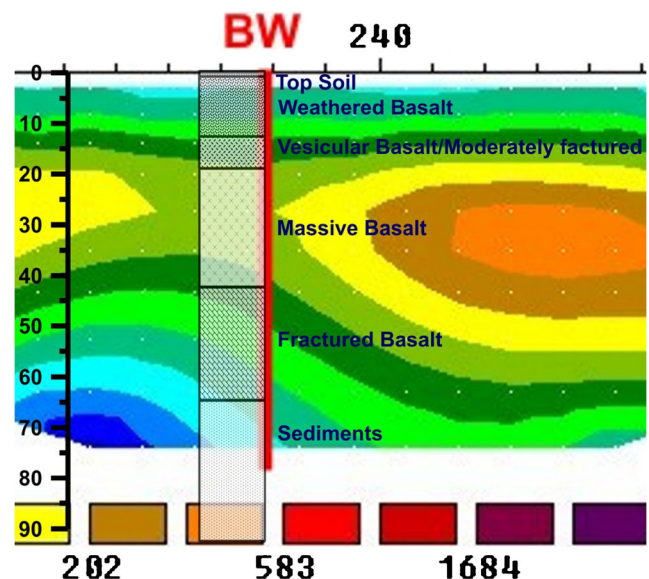


Fig. 8 A comparison of the sequence of litho-units obtained from bore well with the sequence of litho-units obtained from resistivity model of profile P21

litho-units obtained from the resistivity model is presented in Fig. 7. Litho-units obtained from modeling are shown up to 115 m depth which is the depth of investigation. It is evident from the figure that the both sequences of litho-units are found in good agreement which validates the interpreted resistivity model.

Resistivity model of profile P21 presents four layers of geological formations. On top is a composite layer of soil/weathered formation of ~ 10 m thickness. Below it is a thin layer of moderately fractured basalt (40–70 Ohm m) followed by a layer of massive basalt (> 70 Ohm m) which is spread along the entire stretch of the profile. Thickness of the massive basalt layer is minimum (~ 37 m) at 215 m distance. The massive basalt layer is underlain by another thin layer of the moderately fractured basalt which is obtained between 130 and 300 m distance. Below the moderately fractured basalt layer is a composite layer of water saturated fractured/vesicular basalt (20–40 Ohm m). At the bottom is a sedimentary formation characterized with the resistivity value < 15 Ohm m which may be Lameta bed followed by Gondwana sedimentary formation. In order to verify the interpreted results of this resistivity model, a bore well was drilled up to 97 m depth at 215 m profile distance. The sequence of the litho-units obtained from the bore well is compared with the corresponding sequence of litho-units obtained from the resistivity model in Fig. 8. It is evident from the figure that the sequence of litho-units obtained from bore well is in close agreement with that of the resistivity model. This validates the interpreted results of the

Fig. 10 Resistivity models indicating different geological formations/structures for profiles P40, P41, P43, P44, P56, and P55; PW proposed bore well, GWZ groundwater zone

resistivity model. As expected from the interpreted results, groundwater was struck at ~ 10 and 44 m depths in water-saturated fractured basalt units.

Profile P38 is located near Sawangi village. Resistivity model of profile P38 presents sequence of litho-units similar to that of P21. A ~ 8–10-m-thick layer of soil followed by weathered formation (< 40 Ohm m) is present on the top. This is underlain by a thin layer of moderately fractured basalt (40–70 Ohm m). Below it lies a layer of massive basalt (> 70 Ohm m) which is spread along the entire profile length. The massive basalt layer is underlain by another thin layer of moderately fractured basalt layer followed by a water-bearing fractured basalt (< 40 Ohm m) layer, and at ~ 100 m depth sandy clay formation (< 10 Ohm m) which may be Gondwana formation as in the case of P21. For this model, location of a suitable site for bore well drilling could be at 320 m distance.

Resistivity models of profiles P39 and P42

Resistivity models of profiles P39 and P42 are presented in Fig. 9. Resistivity model of profile P39 presents a peculiar ~ 100-m-thick clay-rich formation (< 10 Ohm m) up to 230 m profile distance beyond which its thickness continuously decreases towards east. This profile appears to be at the site of a

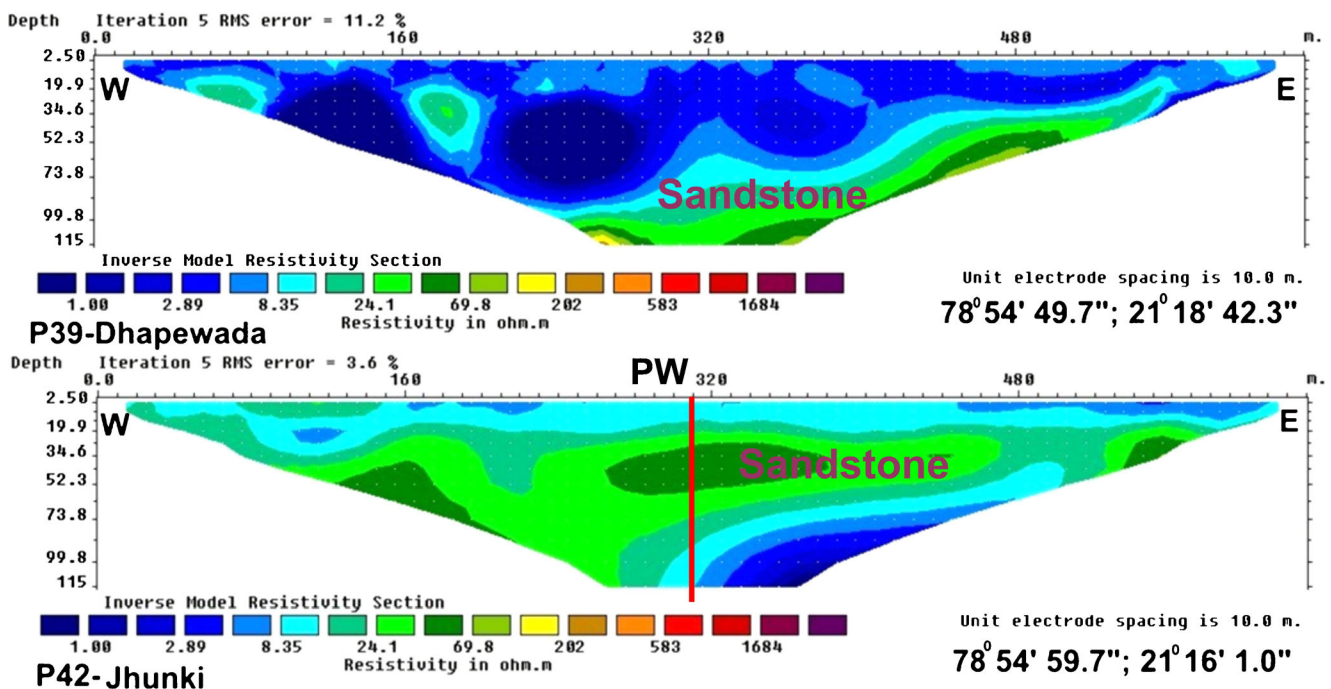
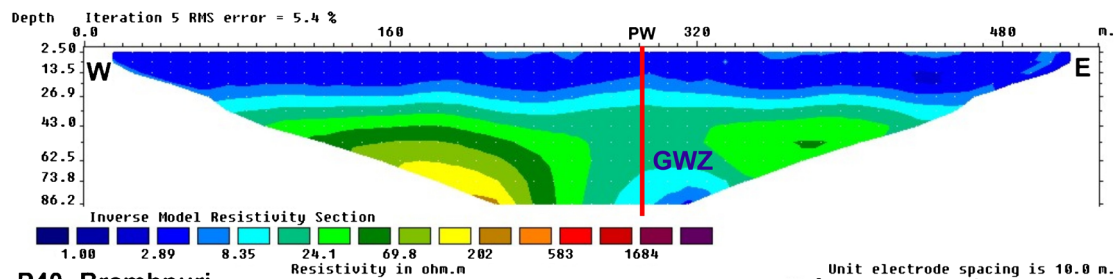
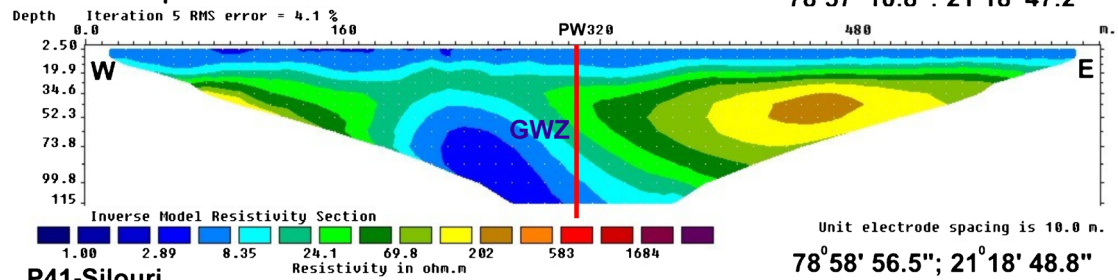


Fig. 9 Resistivity models indicating different geological formations/structures for profiles P39 and P42; PW proposed bore well, GWZ groundwater zone



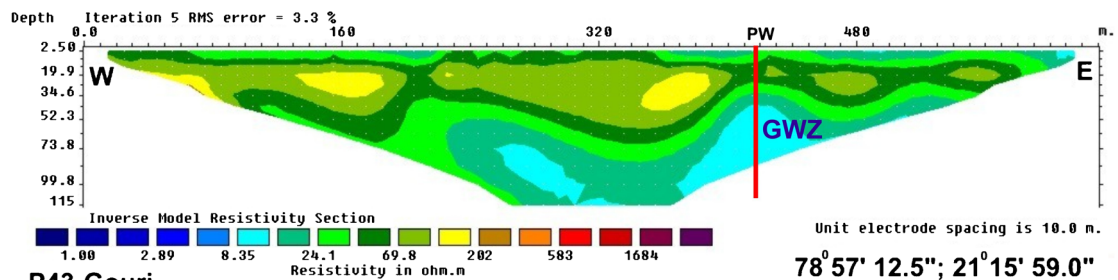
P40- Bramhpuri

78°57' 10.8"; 21°18' 47.2"



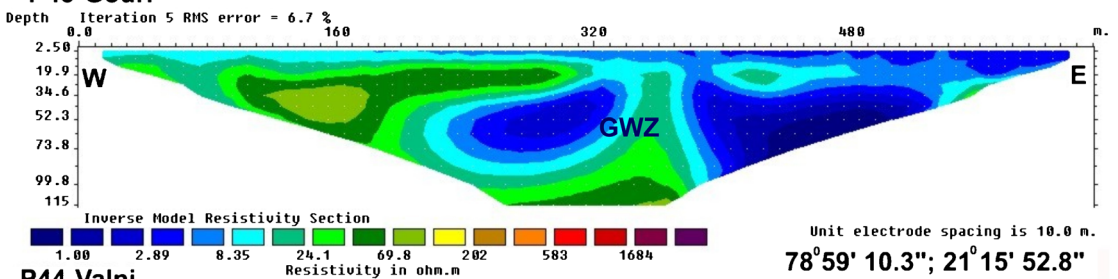
P41-Silouri

78°58' 56.5"; 21°18' 48.8"



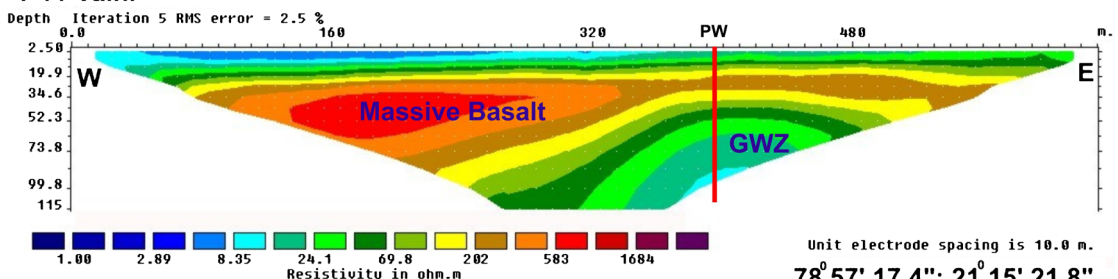
P43-Gouri

78°57' 12.5"; 21°15' 59.0"



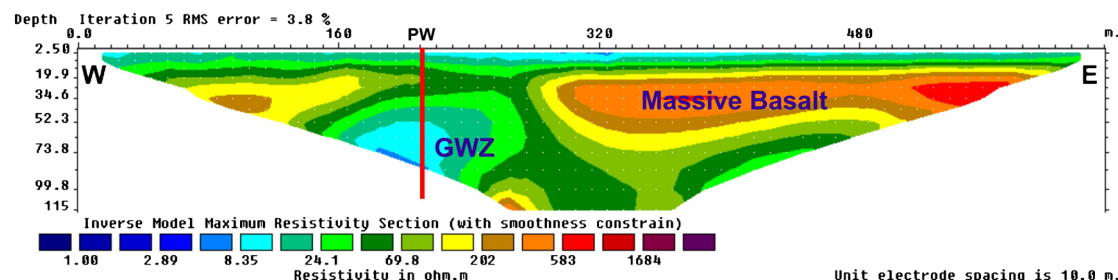
P44-Valni

78°59' 10.3"; 21°15' 52.8"



P56 - Khairi

78°57' 17.4"; 21°15' 21.8"



P55 - Dahegaon

78°56' 40.2"; 21°12' 55.6"

Table 2 Resistivity values of different litho-units in the study area (source: CGWB website)

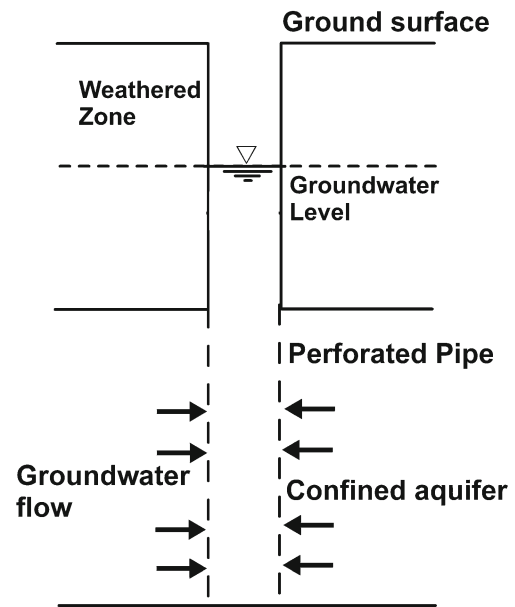
Geological formation	Resistivity (Ohm m)
Alluvial, black cotton, bole bed (water saturated)	5–10
Alluvial, black cotton (dry)	10–20
Weathered/fractured/ vesicular basalt saturated with water	20–40
Moderately weathered/fractured/vesicular basalt with water	40–70
Massive basalt	> 70
Water saturated Gondwana sandstone	< 50
Gondwana fractured/compact sandstone	> 50

valley filled with the clayey sediments. This layer is followed by water-saturated layer of sediments (< 40 Ohm m) which is continuously extending upward up to ~ 15 m depth towards the eastern edge of the profile. This layer is underlain by sediments mixed with basalt unit whose upper boundary is visible at > 100 m depth. This massive basalt unit appears to be extending upward and is seen up to 500 m distance at ~ 40 m depth. A suitable site for a bore well could be in the centre of the profile at 320 m distance.

Resistivity model of profile P42 indicates a ~ 15-m thick layer of soil (~ 15 Ohm m) on the top. This soil layer is underlain by water-saturated fractured basalt (25–40 Ohm m) which is extended beyond 115 m depth at 270 m distance. Beyond this distance, its thickness decreases. The fractured basalt unit is underlain by Gondwana sandy clayey formation (< 10 Ohm m) which is extending upward from 300 m distance and reaches to 35 m depth at 500 m profile distance. A bore well drilled up to a depth of 132 m by Central Ground Water Board (2006) at a site nearby the investigated profile has also indicated presence of mixed sediments at 30 m depth. This layer is followed by sandstone and sediments. This validates the interpreted results of profile P42. This site is favorable for groundwater exploitation by a bore well located between 300 and 480 m distance.

Resistivity models of profiles P40, P41, P43, P44, P56, and P55

Resistivity models of profiles P40, P41, P43, P56, and P55 are presented in Fig. 10. Resistivity model of profile P40 indicates approximately 25-m-thick layer of clayey sand (< 10 Ohm m) on top. This is followed by water-saturated Gondwana sandstone (20–40 Ohm m) in the middle and dry compact sandstone (> 50 Ohm m) at the bottom which is extended up to 230 m distance. Beyond this distance, the middle layer of water-saturated fractured Gondwana sandstone is seen in the

**Fig. 11** Diagram showing design of bore well casing

remaining portion of the profile. The middle layer is suitable for groundwater exploitation.

Profile P41 is located near Silori. Its resistivity model presents ~ 5–10-m-thick soil and Gondwana sediments followed by two units of dry compact sandstone which are separated by a water-saturated fracture zone. This fracture zone is connected to the ground surface between 160 and 320 m profile distance which may be used as a recharge site. This fracture zone appears to be the potential source of groundwater. Suitable location of a bore well is suggested at 350 m distance.

Profile P43 indicates the presence of dry sandstone (~ 70 Ohm m) layer underneath a thin cover of soil. This layer is overlying a water-bearing Gondwana sedimentary formation (< 40 Ohm m) which is extended downward beyond 115 m and is suitable for groundwater exploitation. A suitable site for bore well is suggested at 320 m distance. Resistivity model of profile P44 also indicates the presence of a layer of dry Gondwana sandstone (~ 70 Ohm m) up to 370 m distance underneath a thin cover of soil. This is underlain by Gondwana formation. Beyond 370 m distance, clayey formation is extended up to the eastern end of the profile. A suitable location for bore well could be at 370 m distance.

Resistivity model of Profile P56 shows a layer of massive basalt spread over the entire length of the profile underneath a thin cover of the soil/weathered basalt. Thickness of the massive basalt unit appears to be extended close to 115 m depth up to 260 m profile distance. Thereafter, its thickness decreases towards the eastern edge of the profile and attains minimum thickness up to 30 m depth below 380 m distance. Below massive basalt layer lies a formation (< 40 Ohm m) which is extended from the center of the profile towards the eastern edge of the profile. This profile does not indicate the presence of a potential groundwater zone. The resistivity model of

profile P55 which is located near Dahegaon village presents three units of massive basalt underneath a thin cover of soil and weathered formation (< 40 Ohm m). The first unit is extended up to 210 m distance. Tip of the second unit is seen below 260 m distance at ~ 100 m depth. The third unit is extended from 280 m onwards towards the eastern edge of the profile. The first and second units of massive basalt are separated by a water-bearing fracture zone (< 40 Ohm m) having inclination towards west. This zone may be favorable for groundwater exploration. The third unit of the massive basalt is overlying a formation having < 40 Ohm m resistivity and whose tip is visible between 380 and 450 m distances at ~ 75 m depth. This may be water-bearing Gondwana sedimentary formation. A suitable location for bore well could be at 240 m distance.

Conclusion

Electrical resistivity tomography was carried out along 35 profiles for the delineation of groundwater potential zones in the draught-prone basaltic terrain of the Chandrabhaga River basin. Geological formations/structures having resistivity values within the range of 20 to 40 Ohms m are identified as potential sources of groundwater. Out of 35 profiles, the resistivity models of profiles, P54, P45, P48, P35, P24, P31, P29, P25, P36, P37, P23, and P56 do not indicate the presence of groundwater potential zones. Resistivity models of the remaining profiles indicate the presence of groundwater potential zones. Profile-wise suitable sites for bore well drilling are suggested. Groundwater zones are found to be in the depth range of 10 to > 100 m, under unconfined conditions at shallow depth to confined conditions within intertrappeans at deeper levels. The presence of Gondwana sedimentary formations (sand/sandstone/clay etc.) are also identified in some profiles. Interpreted geological setup for profiles P20, P21, and P30 are validated by observed geological set up obtained from the drilled bore wells. Resistivity models have also indicated sites of groundwater recharging. This study demonstrates the efficacy of ERT for the delineation of potential groundwater zones and sites for managing groundwater recharge.

Casing with perforated pipes should be done within the top layer of weathered/fracture zone to capture infiltrating rain water and within the water-bearing formations/structures such as intertrappeans, Gondwana formations weathered/fractured zones, in order to prevent the entering of sediments into well along with water (Fig. 11). This measure will help in sustaining the yield of bore wells for a longer period.

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