

# Identification of water-bearing fractured zones using electrical conductivity logging in granitic terrain, Andhra Pradesh, India

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**Application of EC (electrical conductivity) logging was carried out to precisely delineate fractured zones in hard-rock terrain. The experiment was carried out in three different phases, viz. before pumping, during pumping and during the recovery period of the wells. The purpose was to excite the aquifer system to enhance the response into the well. EC logging was performed in a well that was chosen in the vicinity of the pumping well. All the necessary precautions and measurements is required for the pumping test were taken. Changes were observed in the EC values at certain depths, which was attributed to the presence of water-bearing fractured zones. The results were correlated with information collected during the field investigation and geophysical studies. EC logging also provides other information such as hydrochemical information, water quality and water–rock interactions. Out of six EC loggings carried out in the study area, three showed changes in the EC values in the water-bearing fractured zones, while the other three did not show any changes until the depth of the borewells.**

**Keywords:** EC logging, fractured zones, groundwater, hard-rock terrain, vertical electrical sounding.

IDENTIFICATION of water-bearing fractures in granitic terrain is useful for groundwater exploration. There are several techniques available for detecting fractures in hard rock. Some techniques where surface measurements are carried out are electrical resistivity methods<sup>1,2</sup>, Ground Penetrating Radar (GPR) profiles, and resistivity 2D imaging<sup>3</sup>. The other techniques are sub-surface measurements, namely self-potential, resistivity well logging, core drilling<sup>4</sup> and Mise-a-la-masse techniques<sup>5</sup>. Additionally, there are a few other techniques like down-hole televiwer or borehole packer test. Some of these techniques are expensive and time-consuming like geophysical well logging, core drilling and down-hole televiwer or borehole packer test, while others are cost-effective and quick in operation like electrical resistivity and self-potential methods and Mise-a-la-masse technique.

The sub-surface measurements are more relevant and accurate than the surface measurements. For example, a technique was developed to locate contaminated groundwater discharge by mapping variation in electrical conductivity (EC) of the bottom sediments in shallow surface water in an artificially created seepage area of a small, shallow lake<sup>6,7</sup>. Besides these, there are several techniques available for identifying fractures that are conductive in boreholes<sup>1,5,8–10</sup>.

Anomalous EC logs were attributed to the presence of water-bearing fractures. They can also quantify the EC changes caused by the inflow that determines the quality of water. The interpreted EC logs of borewells clearly indicate recharge and discharge of the groundwater zone, and also provide preliminary information about the quality of water, in particular, the salinity. This provides useful information about saturation, super saturation and under saturation conditions of the aquifer formation.

Among all the above-mentioned techniques, EC logging is suitable for any terrain because it is cost-effective, quick in operation, easy to carry out, and also provides fruitful results. Such measurements are made using boreholes or underground openings in hard-rock areas to determine the water flowing through fractures containing fluids with different chemical compositions and ion contents, and hence having different EC values<sup>11</sup>. The groundwater flow is responsible for an electric field called the streaming potential<sup>12</sup>, which is the main component of the self-potential anomalies. In the present study on the identification of fractured zones, EC logging has been carried out in three different phases, i.e. before pumping phase, during pumping, and during the recovery phase of the wells. The boreholes were chosen such that each EC logging well had a pumping well near it. The results from EC measurements are discussed here and correlated with electrical resistivity sounding data.

## Study area

The Wailpally watershed area lies in Nalgonda District, Andhra Pradesh, India. The present study area lies between 17°2′–17°07′N lat. and 78°48′–79°0′E long., as shown in Figure 1. The entire area is covered by granite

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and gneissic complex rock type. In the western region, the area is covered by hilly terrain. The major soil types are red soil, loamy soil and sandy soil; few patches of black soil are also found at places<sup>13</sup>. The drainage pattern is dendritic to sub-dendritic.

### Hydrogeology of the study area

Groundwater in the study area occurs under water table conditions, and the movement is confined to weathered, semi-weathered and fractured zones. Groundwater is tapped by shallow to deep borewells with depths ranging from 30 to 100 m below ground level (bgl). The depth of the water levels ranges from 10 to 30 m bgl. Majority of wells are from weathered–semi-weathered formation, with moderate to average yield. The borewells drilled below the hard rock are well connected to the fractured rock and have good yield.

### Geophysical investigation

Among all the surface geophysical techniques used for groundwater prospecting, the electrical resistivity method

is widely applied. This is because of its efficacy to detect the water-bearing layers, besides being simple and inexpensive to carry out field investigations<sup>14</sup>. In general, for measuring the resistivity of the subsurface formations, four electrodes are required. A current of electrical intensity ( $I$ ) is introduced between one pair of electrodes called current electrodes. The current electrodes can be identified as  $A$  and  $B$  and sometimes  $+I$  and  $-I$ , denoting source and sink respectively. The potential difference produced as a result of current flow is measured with the help of the another pair of electrodes called the potential electrodes or probes. The potential electrodes may be represented as  $M$  and  $N$ . Let  $\Delta V$  represent the potential difference. The apparent resistivity measured is  $G (\Delta V/I)$ , where  $G$  is the geometrical constant.

The configuration or geometric factor of the Schlumberger array is given by:

$$G = \frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{\left(\frac{MN}{2}\right)} \frac{\pi}{2},$$

where  $AB$  is the distance between the current electrodes,  $MN$  is the distance between the potential electrodes, and the apparent resistivity is obtained using the formula:

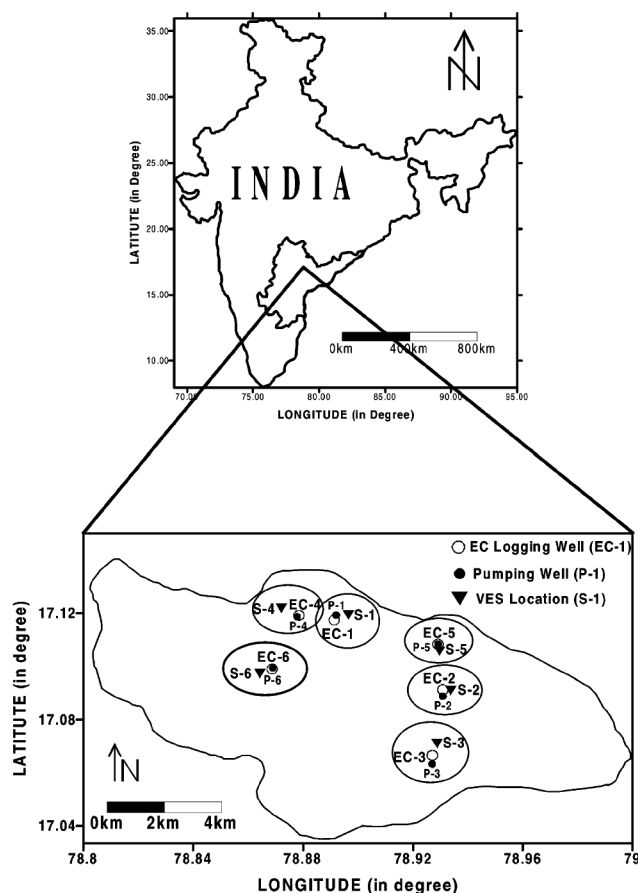
$$\rho_a = G(\Delta V/I),$$

where  $(\Delta V/I)$  is the potential difference between the potential electrodes to that of the current flowing.

A curve is interpreted by matching the field curve with the master curves of two, three and four layer cases for various ratios of absolute resistivity<sup>15</sup>, to arrive at the resistivity and thickness of the sub-surface. These interpreted layer parameters are then given as model parameters for iteration<sup>16</sup> to arrive at more accurate results of the interpreted layer parameters. The interpreted results of vertical electrical sounding (VES) curves are given in Table 1 and their location along with EC logging and observation well are shown in Figure 1. Their respective curves are shown in Figure 2. The resistivity ranges of different sub-surface layers are as follows: Top soil cover, 2–480 Ohm-m; weathered formation, 20–100 Ohm-m; semi-weathered formation, 100–300 Ohm-m; Hard Rock, >300 Ohm-m.

### Constraints and limitations in resistivity data interpretation

The resistivity data obtained from VES were first interpreted using master curves<sup>15</sup>, to identify various the sub-surface lithological units given in Table 1. However, in order to reduce inaccuracies, the manually interpreted sounding curves obtained by matching the field curves with the master curves, can be further subjected to inver-



**Figure 1.** Key map showing the location of the study area, Vertical electrical sounding (VES), pumping well and EC logging well.

**Table 1.** Interpreted layer parameters of vertical electrical sounding curves at EC logging sites

VES no.	Interpreted layer parameters							Total $H$ (m)
	$\rho_1$ (Ohm-m)	$h_1$ (m)	$\rho_2$ (Ohm-m)	$h_2$ (m)	$\rho_3$ (Ohm-m)	$h_3$ (m)	$\rho_4$ (Ohm-m)	
S1	64	0.7	186	3.7	438	3.5	2658	7.9
S2	23	0.6	8	3.2	95	14	9991	17.6
S3	14	0.5	146	3.9	201	6.5	1661	10.7
S4	25	4.8	62	16.2	726	–	–	21
S5	14	1.6	28	4.8	85	13.2	1316	19.6
S6	58	0.7	16	5.9	125	13.1	517	19.7

sion<sup>16</sup> using modern software packages. However, detection of thin fracture layer with low resistivity values is impossible by this method, as this fracture layer is sandwiched between two high resistive layers where the ‘principle of suppression’ exists<sup>17</sup>. In case of VES method as we move away from the centre, the separation between the current electrodes also varies, which results in its inability to detect the thin fractured layer.

### EC logger techniques

The EC logger used in this study (Wissenschaftlich Technische-Werkstätten (WTW), Germany) consists of an EC meter, logger and sensor, with a facility for continuous EC, TDS, salinity and temperature measurements at depths up to 200 m. The sensor attached to the logger can be lowered into the borehole and depths measured with its graduated cable. Observations were taken at 1.0 m or even smaller intervals, as desired. When the sensor interacts with the water, the meter records EC, temperature and depth. Prior to EC logging, the water level in the pumping borewell as well as in the EC logging borewell are monitored and static water levels measured repetitively. After monitoring of the water levels, the EC logger is lowered into the borewell and the EC value recorded at the static water level. For example, at borewell no. 1 in Jangoan, the static water level at the EC logging well is 29.55 m bgl. The next EC value reading is taken at 30 m by lowering the logger into the borewell. Then the EC readings are recorded at 1 m interval, gradually up to the depth of the borewell. Technical details of this device are given in Table 2.

### Correlation of EC logging with geophysical data

VES nos S1–S3 at borewells 1–3 showed four layers of resistivity of 64, 186, 434 and 2658 Ohm-m; 23, 8, 95 and 9991 Ohm-m, and 14, 146, 201 and 1661 Ohm-m respectively, without indication of any fractured zone. The total depth of investigation encountered at these locations was 7.9, 17.8 and 10.7 m respectively. The last layer resistivity of these soundings indicates a hard rock. VES no. S4 at borewell 4 showed three layers of resistivity of 25, 62 and 726 Ohm-m, while S5 and S6 at borewells 5

and 6 showed four layers of resistivity of 14, 28, 85 and 1316 Ohm-m and 58, 16, 125 and 517 Ohm-m respectively. The total depth encountered at S4, S5 and S6 was 21, 19.6 and 19.7 m respectively. The last layer resistivity at these sites was lower compared to S1, S2 and S3, indicating the presence of fractured zone in hard rock layer. From EC logging at S4 and S5, the fractured zone was encountered from 19 to 28 m and 16 to 21 m depth respectively. The sounding curve for these location is shown in Figure 2 *a–f* and the interpreted layer parameters are given in Table 1. After comparing the S4, S5 and S6 given in Table 1 and EC values observed in logging borewells where the fractured zone was encountered, comparative lithologs of three borewells were deduced. The comparative lithologs along with the VES parameters are shown in Figure 3.

### Results and discussion

In order to ascertain the presence of fracture it is response of EC in delineating these fractured zones at sub-surface, six EC loggings were carried out. The location of EC logging wells and pumping wells is shown in Figure 1. EC loggings were carried out in three different phases: before pumping, during pumping, i.e. after observing sufficient drawdown in EC logging well, and after pumping, i.e. during the recovery phase. The results of the analysis of pumping well and EC logging well are given in Table 3 and further details are described in the following.

#### Borewell no. 1

EC logging in the Jangoan village borewell measured the static water level at 29.55 m bgl and depth 100 m bgl, whereas the pumping well measured the water level at 33.70 m bgl and depth 60 m bgl. The distance between the pumping and EC logging well was 1.63 m. EC did not show any changes before pumping. After suitable pumping in the pumping well and 3.9 m drawdown observed in EC logging well, the EC was measured again in the EC logging well during the pumping period, which also did not show any changes, and discharge of pumping well measured was 364.81 m<sup>3</sup>/day. Similarly, in the recovery

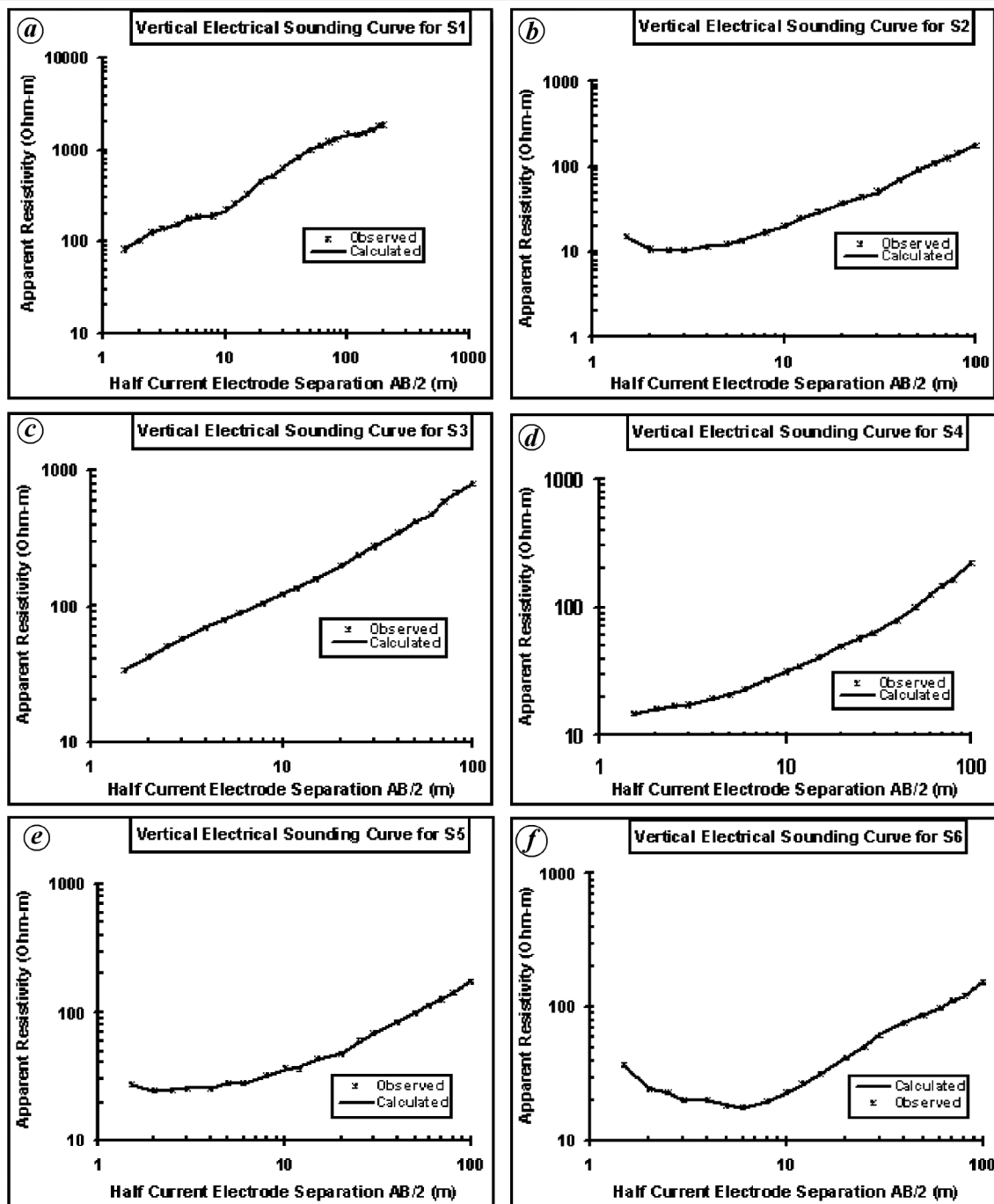


Figure 2. Vertical electrical sounding curves at EC logging sites.

phase the EC did not vary significantly. Thus, from all the three phases it can be inferred that there is no fracture in this well. The observed EC during all the three phases is shown in Figure 4 a.

#### Borewell no. 2

The second EC logging was carried out at Yelmakanna village, with the EC logging well having 60 m of depth

and water level at 7.51 m, while the pumping well also had depth of 60 m and water level at 7.25 m. The distance between the pumping well and EC logging well was 103 m and the drawdown observed in EC logging was 0.22 m after a certain interval of pumping in the pumping well at a rate of 347.82 m<sup>3</sup>/day. The EC observed in all the three phases did not show much variation. Hence it can be concluded that there is no fracture present in this well. The observed EC during all the three phases is shown in Figure 4 b.

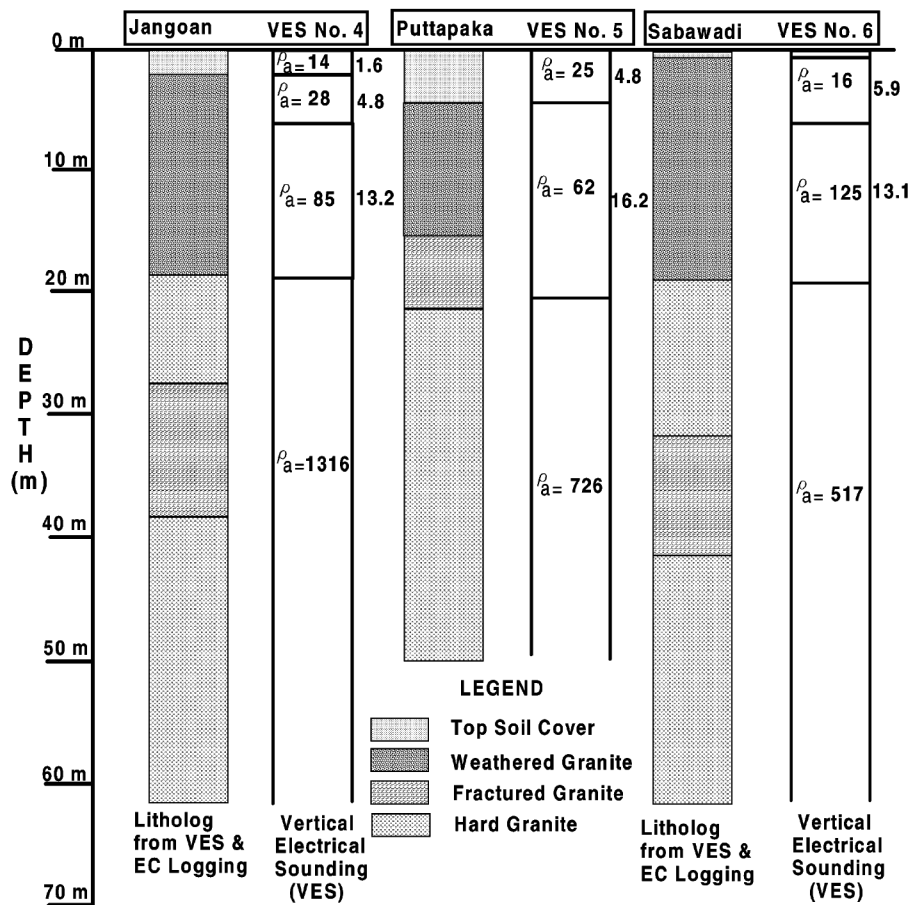


Figure 3. Comparative lithologies deduced after VES and EC log values at three sites.

Table 2. Technical details of the EC logger

Features	Description
Number of electrodes	Four
Electrode material	Graphite
Shaft material	Epoxy black
Connection head	Stainless steel, protection hood
Weight of sensor	690 g
Weight of protection hood	423 g
Shift diagram	15.3 mm
Shaft length	120 mm
Connection hood diameter	21.7 mm
Length of sensor	162.5 mm
Cable length	200 m
Immersion depth	36 mm
Pressure resistance	2 bar

Borewell no. 3

The third EC logging was conducted at Ghutuppal village, with the pumping and EC logging wells having a depth of 60 and 58 m, and water level at 15.51 and 12.34 m respectively. The drawdown observed was 0.42 m, the distance between the wells was 29.80 m and the discharge

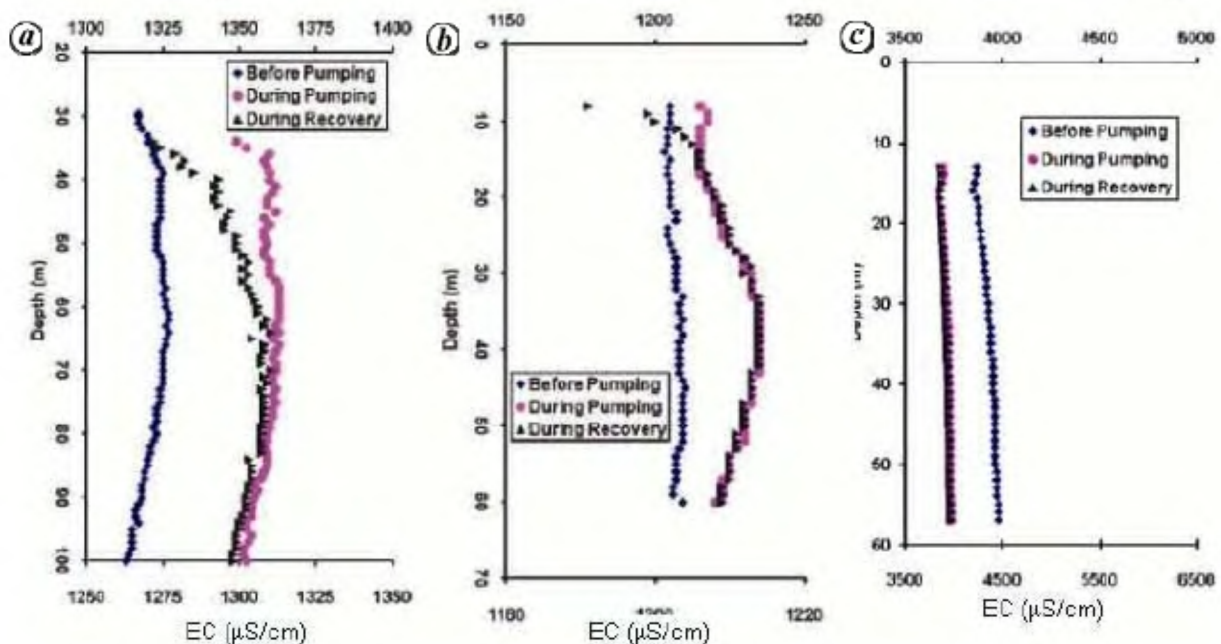
rate observed was 743.28 m<sup>3</sup>/day. In this borewell also no EC changes were observed. Hence it can be concluded that there is no fracture in this well. The observed EC during all the three phases is shown in Figure 4 c.

Borewell no. 4

EC logging was carried out at Jangoan village, with the pumping well and EC logging well having the same depth, i.e. 63 m; the water level observed was 22.23 and 22.44 respectively. The drawdown observed in EC logging was 0.74 m, the discharge rate measured in the pumping well was about 151.09 m<sup>3</sup>/day and the distance between the pumping and logging wells was 22.60 m. Fluctuations were observed in EC from a depth of 28 to 38 m in all the three phases of logging. Thus it is confirmed that the fractured zone is found at these depths, which lowers the EC from 2020 μS/cm at a depth of 27 m to 1977 μS/cm at a depth of 28 m till a depth of 38 m, thus showing a decreasing trend; after 38 m, the EC was normal. The fluctuation in EC was due to dissolution of freshwater coming from fractures. The graphical representation of this logging is shown in Figure 5 a.

**Table 3.** Results of the analysis pumping well and EC logging well

Location	Depth of pumping well (m)	Static water level of pumping well (m)	Discharge of pumping well (m <sup>3</sup> /day)	Depth of EC logging well (m)	Static water level of EC logging well (m)	Drawdown observed in EC logging well (m)	Distance between pumping well and EC logging well (m)
Jangoan	60	33.70	364.81	100	29.55	3.9	1.63
Yelmakanna	60	7.25	347.82	60	7.51	0.22	103
Ghutuppall	60	15.51	743.28	58	12.34	0.42	29.80
Jangoan	63	22.33	151.09	63	22.44	0.74	22.60
Puttapaka	50	11.58	597.58	50	12.23	0.44	46.50
Sabawadi	62	9.62	440.19	59	10.28	0.15	52

**Figure 4.** *a-c*, EC logging at Jangoan (*a*), Yelmakanna (*b*) and Ghutuppall (*c*) villages.

#### Borewell no. 5

The fifth EC logging was conducted at Puttapaka village. The pumping and logging wells have the same depth of 50 m and the water level observed in them was 11.58 and 12.23 m respectively. The discharge measured in the pumping well was 597.58 m<sup>3</sup>/day and the drawdown observed in logging well was 0.44 m. The distance between the wells was 46.50 m. In this case also EC showed changes from a depth of 16 to 22 m in all the three phases of measurements, indicating the presence of the fractured zone at this depth. After 22 m depth, EC was normal and did not show any changes. The observed EC in all the three phases is shown in Figure 5 *b*.

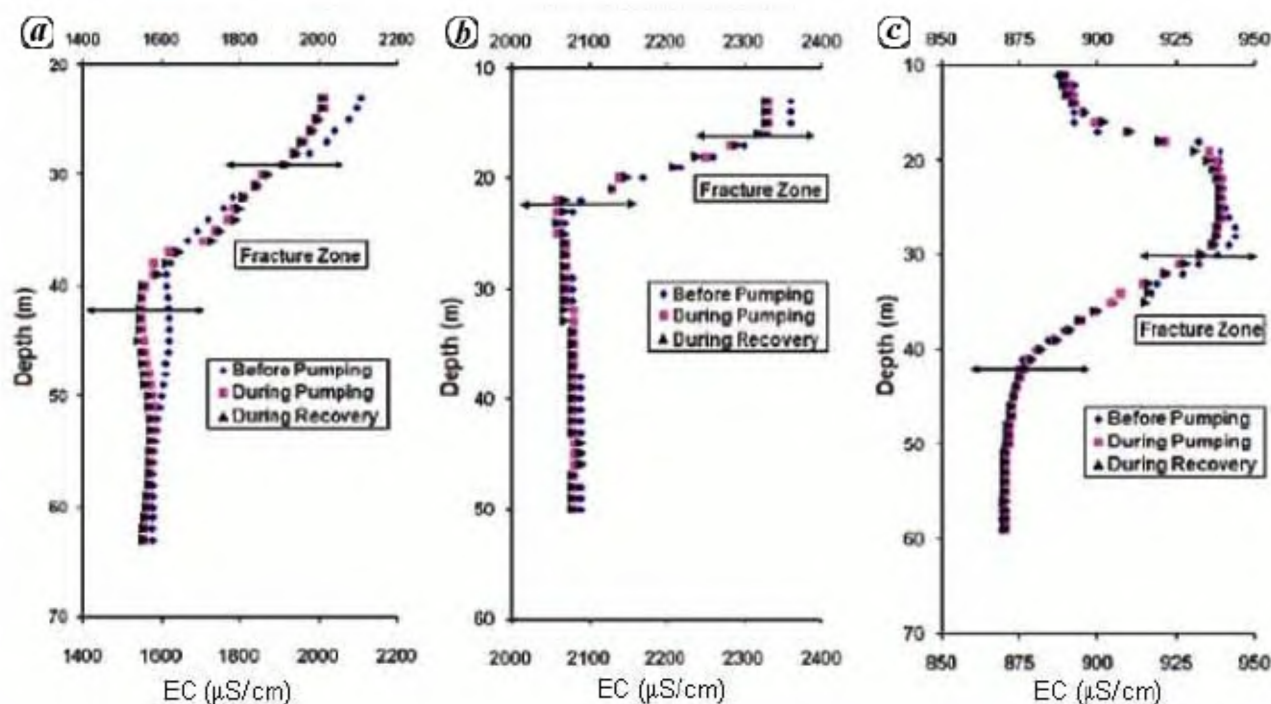
#### Borewell no. 6

This EC logging was conducted at Sabawadi village. The depth of the pumping and EC logging wells was 62 and 59 m and the water level measured was 9.62 and 10.28 m respectively. The discharge measured during the pumping

phase was 440.19 m<sup>3</sup>/day. The distance between the wells was 52 m and the drawdown observed in pumping well was 0.15 m. In this logging, fractured zones were identified at a depth of 32 to 43 m in all the three phases of EC measurements. The EC values were normal otherwise. The observed EC in all the three phases is shown in Figure 5 *c*.

#### Conclusion

The EC logging techniques has been found to be successful in identifying the water-bearing rock formation and fractured rock at shallow and greater depths in borewells in the hard rock terrain. The EC logging data are quite comparable with the other information, such as drilling data collected during the field study and also agree with those of geophysical and geological studies. This may be considered as a secondary method when electrical resistivity methods pose difficulties while identifying fractures. This method of identifying fractures is quick and



**Figure 5.** EC logging at Jangoan (a), Puttapaka (b) and Sabawadi (c) villages.

cost-effective, and can be carried out at any desired location. Besides, EC logging tool also provides information about temperature, salinity and the chemistry/quality of water for future studies.

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