ORIGINAL ARTICLE

Evaluation of aquifer characteristics using well logging tools and pumping tests in a typical khondalitic aquifer in the Northern parts of Eastern Ghats of India

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Abstract

Aquifer parameters from geophysical well logs and pumping tests were used to evaluate the potential of fractured aquifer of khondalitic terrain of Northern parts of Eastern Ghats of India. The parameters under consideration are porosity and formation-water resistivity for the highly weathered material and the fractured khondalitic aquifer. The resistivity of fractured zones ranged between 28 and 30 Ω m. The aquifer porosity varied from 28% in the fractured khondalitic aquifer to 18% for the kaolinized formation. Pumping tests revealed the aquifer transmissivity and storativity in the range of 26–230 m^2/day and 1.9×10^{-4}–87.5×10^{-4} respectively. High values of transmissivity and storativity were obtained from the flat uplands, whereas low values characterized the low laying areas. The aquifer parameters have to unravelled the hydrogeological characteristics of the khondalitic terrain.

Keywords Khondalitic rocks · Kaolinization · Aquifer characteristics · Well logging tools · Pumping tests

Introduction

The khondalitic suite (Garneti ferrous sillimanite/biotite gneiss) of hard rocks occurring in Eastern Ghats of India constitutes nearly one-fourth of the hard rock areas of the country. Like other hard rocks such as granites and basalts in peninsular India, the aquifers in khondalites of Eastern Ghats of India are also anisotropic and non-homogeneous, as such hydrogeological conditions vary widely within short distances. According to Mahadevan (1929), due to the action of water the khondalites are altered in two different manners. The rock is weathered lateritic top soil and lower kaolinitic material (alters as kaolin by interaction of water). This typical nature of khondalitic aquifers has been focused

by many hydrogeologists in this region (Krishna Rao 1952; Sarma 1967). The movement and occurrence of groundwater in khondalitic terrain poses a different pattern compared to other hard rock terrains. Like in other hard rock terrains, in the khondalites also, groundwater occurs under water table condition in weathered zone and semi-confined conditions in deeper fractures. Except in kaolinised zones (highly weathered material) in the khondalitic rocks, the weathered zone in khondalites is generally more permeable when compared to other rock types. From the hydrogeological point of view, the saturated highly weathered material (kaolinised) is overlying the saturated weathered/fractured khondalitic aquifer. The evaluation of aquifer constants for both kaolinized material (upper material) and weathered/fractured khondalitic aquifer (bottom material) have not been reported so far by hydrogeologists in this khondalitic terrain. In this region, one-dimensional (1D) and two-dimensional (2D) resistivity imaging surveys have confirmed that, the deeper kaolinisation is a predominant factor for non-yielding of bore wells (Venkateswara Rao et al. 2013). Successful wells and failed wells in this region co-exist due to varying degree of kaolinisation depths. The drilling results have also confirmed that the highly weathered (kaolinised) material extended to deeper depths near the streams in this terrain (Venkateswara Rao et al. 2013). Aquifer is denoted as the geological

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formation which is capable of yielding copious amount of water and its characterization is mainly depends on the various petro-physical properties such as porosity, formation-resistivity, transmissivity and storativity. The degree of fracturation is related to the variation of the hydrogeological parameters such as porosity (Zouhri and Lutz 2016). Porosity is the basic parameter by which storage and transmitting capacities of an aquifer are affected (Folk 1974). In the khondalitic terrain, this parameter is quantitatively determined from geophysical well logging investigations. The estimation of hydraulic properties using geophysical well logging tools is more important to solve the problems associated with groundwater flow in hard rock material. The primary advantage of borehole geophysical logs is that they can provide a near-continuous high-resolution record of in-situ formation properties of the aquifer and can be used to evaluate porosity types and distribution (Maliva et al. 2009; Zouhri and Lutz 2016). Hence it is important in the khondalitic terrain that the estimation of aquifer parameters (which control groundwater movement and storage of water bearing fractures) is highly useful in the assessment of aquifer potential. The aquifer properties such as porosity and formation resistivity of both saturated kaolinised material and saturated weathered/fractured khondalitic aquifer are estimated using well logging tools for the first time in this region. In additon to the well logging investigations, the another aquifer parameters (transimissivity and storativity) are evaluated using pumping tests. These aquifer parameters are evaluated in terms of its ability to store (storativity) and its ability to transmit water (transmissivity) and analysed their characteristics in high and low lying areas.

Location and hydrogeology of the study area

The study area is Kandivalasa river sub-basin located in Vizianagaram district of Andhra Pradesh, India (Fig. 1). The Digital Elevation Map (DEM) using SRTM (30 m resolution) is presented in Fig.1.In the DEM, the Kandivalasa river can be observed in the lower elevation part (middle) of the image. The study area is covered by the khondalitic
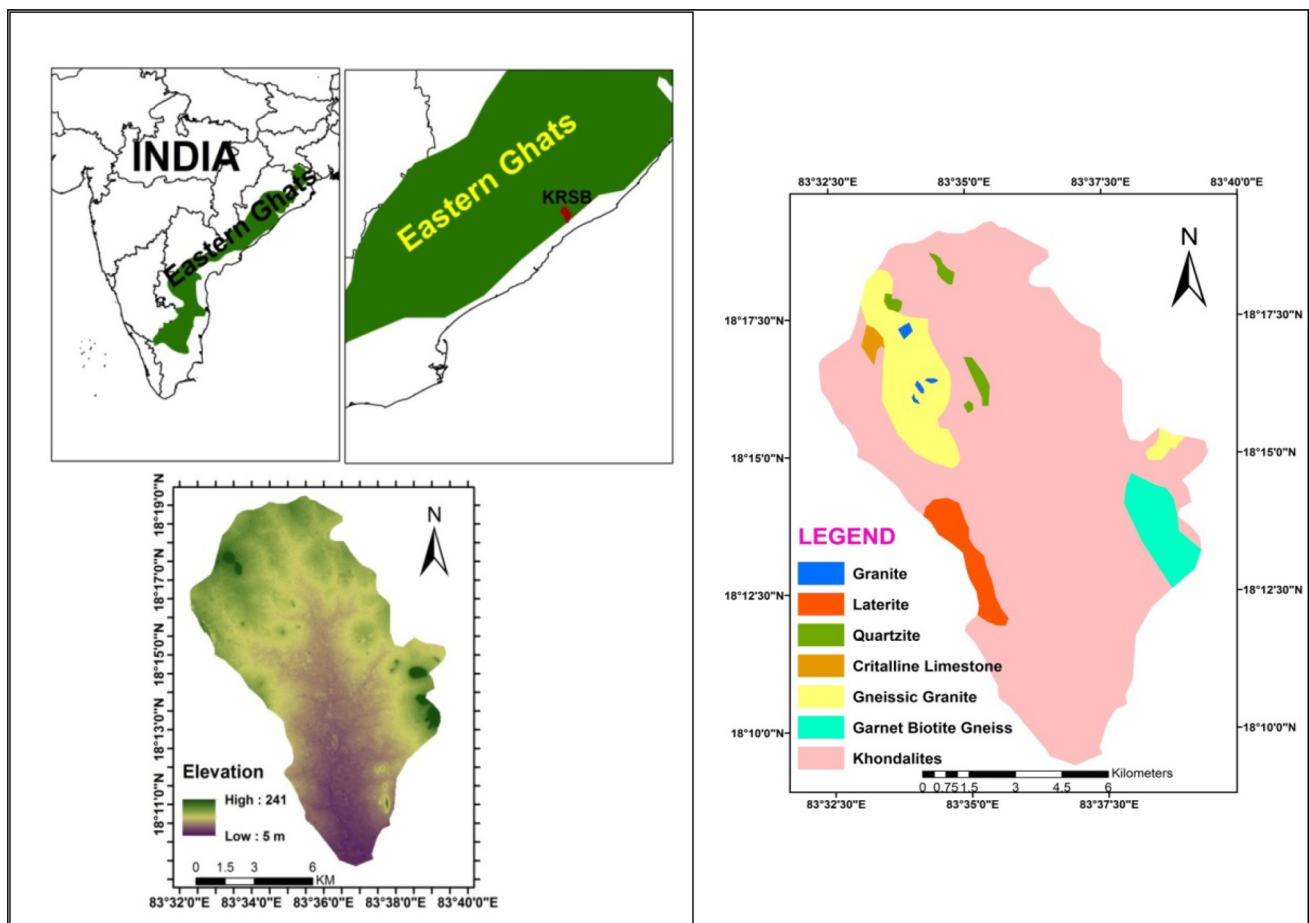

Fig. 1 Location, elevation and geology map of Kandivalasa river sub basin in the Eastern Ghats khondalites

terrain, which is basically sedimentary in origin and has become hard rock after high grade metamorphism (Krishna Rao 1952). In this terrain well yields are high (above 8000 L per h) where the country rock is observed to have silici-fication. Mostly groundwater occurs in the weathered and fractured khondalite. The main problem in the khondalitic terrain is kaolinisation of khondalite which is not properly recognized using vertical electrical sounding data. The khondalite becoming partly clay due to kaolinisation and is unable to support high well yield (Venkateswara Rao 1998). Hence it is noted that the well failures are very common scenario in this terrain as the depth extent of saturated highly weathered material (kaolinisation) which is responsible for low yields (Fig. 2). Due to differences in depth extension of kaolinisation, a high yielding well (successful well) and low yielding well (failed well) co-exist within few tens of metres of distance (Venkateswara Rao et al. 2013). A general schematic diagram is prepared (Fig. 2) on the basis of strong lithological data which were collected during drilling of bore holes in the Kandivalasa river sub-basin (Venkateswara Rao 1998). The khondalitic terrain has two distinct sub-surface geological layers. The area profile is a soil cover underlain by a khondalitic formation (upper highly weathered aquitard; lower main khondalitic fractured aquifer), which is underlain by basement (granite gneiss) (Fig. 2).

Materials and methods

ERT surveys

Multi-electrode two-dimensional (2D) and three-dimensional (3D) electrical resistivity tomography (ERT) surveys were employed using Terrameter SAS (Signal Averaging System) 1000 resistivity meter (Loke and Barker 1996; Shemang and Chaoka 2003; Owen et al. 2006; Aizebeokhai 2010; Chirindja et al. 2017; Gao et al. 2018). To identify successful well site where already a pair of success well and failed well exists (less than 150 m apart), three parallel 2D geoelectrical resistivity profiles were conducted at this pair to delineate the extent of kaolinisation and potential fractured environment. Every 2D survey has a layout (315 m length) of 64 electrodes with 5 m electrode spacing. Inter line spacing of 10 m between each of the 2D profiles provided. The observed apparent resistivity data for each of the 2D profiles were processed with RES2DINV software. The three parallel 2D resistivity images are collated into a single 3D resistivity block image using RES3DINV (Aizebeokhai and Singh 2013) and Slicer-Dicer Software (Aizebeokhai et al. 2011; Badmus et al. 2013).
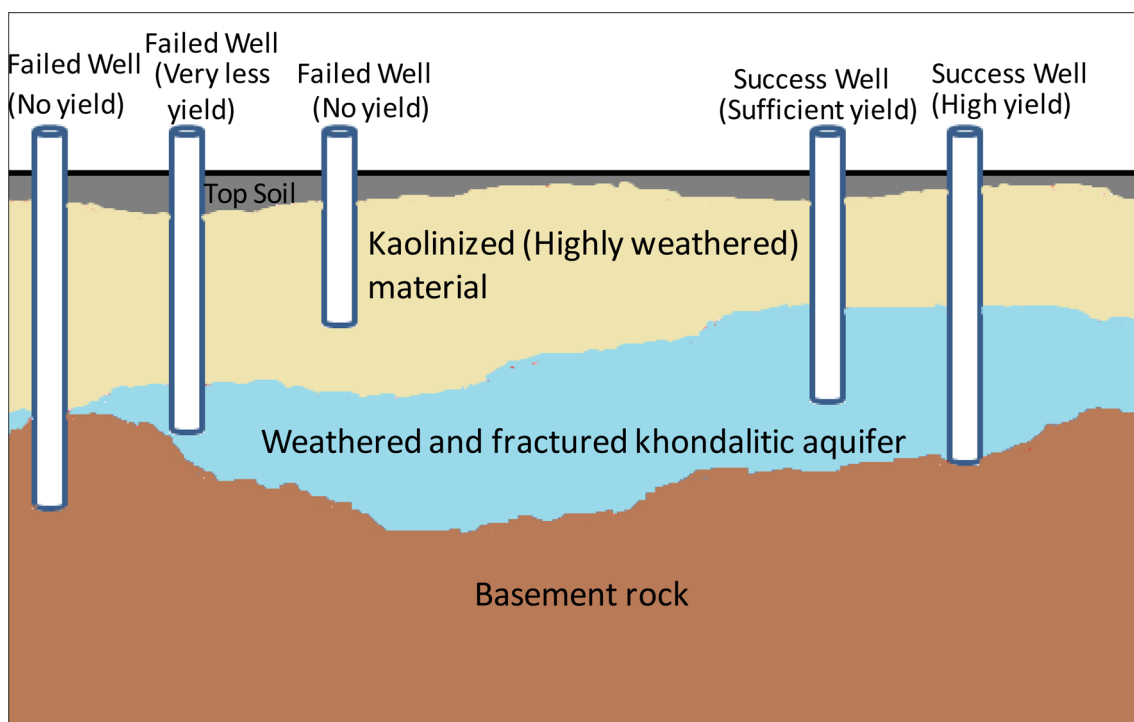

Fig. 2 Schematic diagram of various layers and their effects on different well yields in the khondalitic terrain (Venkateswara Rao 1998)

Well logging investigations

The well logging is the subsurface recording of various geophysical parameters associated with earth formations penetrated by borehole. The most widely used geophysical logging technique in water wells is electrical logging. The self-potential (SP) logs, indicate natural electrical potentials found within the earth. The potential can be caused by an electrochemical behaviour that results at the junction between the fluid-filled borehole and the boundary between formations of dissimilar composition and between permeable and impermeable beds. The spontaneous potential in a well is determined by measuring the potential difference between a single electrode lowered into the uncased well and a reference electrode at the surface. The potential at the reference electrode remains relatively constant. The impermeable formations usually produce zero or very low SP's and permeable formations produce high SP's which may be either positive or negative in sign (Klinmanee and Dürrast 2012). The spontaneous electrical potential is an extremely useful tool to identify permeable beds and to locate the tops and bottoms of beds. Permeable beds usually are indicated by either positive or negative SP deflections and formation boundaries are marked by points of inflection (Klinmanee and Dürrast 2012).

Resistivity logging in a well, like SP logging, involves lowering of resistivity Sonde into the uncased well and placing a reference electrode at the surface. A combination of several electrode arrangements with current settings is used to achieve varying radii of effective formation penetration. A constant logging current is maintained between electrodes and a recording galvanometer measures the potential between potential electrodes with l6-inch spacing for short normal (SN) resistivity, with 64-inch spacing for long-normal (LN) resistivity, and with 72-inch spacing for lateral resistivity. The resistivity logs are helpful for identification of the fracture zones in hard rock terrains apart from determination of various porous and permeable formations (Henriksen and Braathen 2006; Khalil et al. 2011). The LN, SN and lateral resistivity logs are useful to determine the resistivity of various layers in the subsurface (Kamble et al. 2012). The resistivity readings of SN are greatly affected by the borehole, while the resistivity readings of the LN and lateral devices are relatively unaffected by the borehole and are closer to the true formation resistivity. Temperature logs of a well directly measure the temperature of the water in the borehole. Temperature logs are used to determine the water temperature variation with depth.

The well logging investigations were carried out in newly drilled success well. The geophysical well logging investigations are conducted using Terrameter SAS 300 Logger. The Logger is used together with the Terrameter SAS 1000 resistivity meter. The logging system is efficient to delineate formation boundaries, porous and permeable formations with the help of SP and resistivity measurements (Loke 2010). Water flow boundaries can also be detected by measuring temperature changes. The temperature (in °C) and SP logging (in milli Volt) are measured in down-logging and the resistivity logging (SN, LN and Lateral logs) (in Ω m) is measured in up-logging. The logging measurements are noted at every 1 m interval in boreholes and the resulting values are plotted. At every 1 m in down logging, the 71 measurements are taken for Temperature and SP logging. For up-logging, the resistivity logs of SN, LN and lateral logging have 70, 69, 65 measurements respectively. The fluid resistivity has the measurements of 70 in every 1 m during up-logging. The effective porosity of kaolinised formation and fractured khondalitic aquifer is determined from the electric logs from the Archie's formula as described below.

$$\frac{R_0}{R_w} = \frac{1}{\phi^m}$$

where 'R_0' is resistivity of the rock saturated with conducting fluid, 'R_w' is the resistivity of saturating fluid, 'm' is the cementation factor and 'ϕ' is effective porosity. In the present case, R_0 is the resistivity of the formation saturated with groundwater and R_w is the resistivity of the formation water.

Pumping tests

Pumping test is the best method to evaluate aquifer parameters. At 14 locations the aquifer characteristics such as transmissivity, storativity and specific-capacity are estimated in the study area. The pumping test involves extracting water from a well (pumping well) at a controlled rate and observing the water level changes in the pumped well and/or in one or more observation wells, with respect to time (Singhal and Gupta 1999). Several different methods are available to analyse the pumping test data (Theis 1935; Cooper and Jacob 1946; Hantush and Jacob 1955; Hantush 1960, 1966). Cooper and Jacob (1946) have modified the Theis method and suggested an easy method to determine aquifer parameters. The Cooper-Jacob method (Cooper and Jacob 1946; Kirlas and Katsifarakis 2020) is used in the present study to estimate transmissivity and storativity to define aquifer characteristics of the khondalitic aquifer. Drawdown values are measured in the nearby observation well till steady state conditions were achieved (Gernand and Heidtman 1997) that took nearly 2 h. In the Cooper-Jacob method, plots of time-drawdown data on semi-logarithmic paper are prepared by drawing a straight line through the late time data points and extending it backward to the point of zero drawdown (time axis intercept which is designated as 't_0' at $s = 0$) and the slope of the straight line (Δs) is determined (Meier et al.

1998; Khadri and Moharir 2016). During pumping tests, drawdown measurements are taken for every 5 min interval with maximum period of 120–135 min until the water level reaches the steady state condition. The values for transmissivity (T) and storativity (S) are calculated from the following equations (Cooper and Jacob 1946).

Transmissivity $T = \dfrac{2.3Q}{4\pi\Delta s}$ and Storativity $S = \dfrac{2.25Tt_0}{r^2}$

where 'Q' is the constant pumping rate, 'Δs' is drawdown for one log-cycle time, 't_0' is the time since pumping began to just before drawdown starts and 'r' is the radial distance to the observation well. The specific-capacity (S_c) of a bore well is the rate at which water is pumped out of the well divided by the fall in water level (Khalil et al. 2011). It is a very valuable parameter that can be used to determine the maximum yield for a well (Johnson 2005).

Results and discussion

Identification of a new borehole location

The resistivity imaging surveys (2D and 3D) have helped to identify the extent of kaolinisation in the khondalitic terrain. The layers with resistivities less than 25 Ω m. are interpreted as kaolinised layers and the range of aquifer (weathered and fractured khondalite) resistivity is identified as 25–65 Ω m (Venkateswara Rao et al. 2013). The 2D (Fig. 3a) and 3D ERT (Fig. 3b) have clearly demarcated the depth of kaolinisation at the successful well and failed well locations. The set of parallel 2D ERT surveys and their corresponding 3D block images at nearby successful well and failed well pair in the Sivaram village (near the stream) have shown in Fig. 3. The depth of kaolinised material at failed well is extended to deeper depths than the successful well. The kaolinised layer at successful well is thinner and the aquifer is thicker. The higher kaolinisation effect is observed at the failed well location (Fig. 3).

Well logging investigations

On the basis of resistivity data obtained near successful and failed well, a new borehole was drilled where the thickness of the kaolinised layer is relatively thin. The newly drilled borehole with moderate yield is located at about 50 m from the existing failed well (Fig. 3b). The drilling results revealed that there are two aquifers at different depths. The first aquifer characterised by a low yield is at depth of 25–30 m with respect to the ground surface and the second aquifer with relatively high yield was encountered at a depth of about 60 m. The well logging investigations were

then performed in both the new and old boreholes to determine the hydraulic properties of the kaolinised material and fractured khondalitic aquifer (Fig. 4). The well logs such as spontaneous potential (SP), lateral resistivity, short normal (SN) resistivity, long normal (LN) resistivity, temperature and fluid resistivity are obtained at different depths for new successful well and old failed well. All well logging results are correlated and related with the drilling results (Table 1). Based on the drilling results at newly drilled success well, various layers and their corresponding depth ranges are presented in Table 1. The resistivity values of their corresponding layers are taken from lateral logging results.

The kaolinised material is the only layer from which logging results were obtained from the old failed well. The logging operations could not be possible beyond the depth of 20 m in the old failed well due to the presence of thick kaolin beyond this depth and the well could not be drilled. The logging measurements are taken from newly drilled success well up to the depth of 76 m where drilling process is completed due to the presence of fractured khondalite followed by hard granitic basement. In the newly drilled success well, the boundary between layers are obtained from the SP logging at first aquifer and not distinctive at the second aquifer due to the presence of kaolinisation resulting in higher electro chemical potentials. SP logging gives, a clear demarcation between kaolinised material and weathered khondalitic aquifer at the depth of 24 m (Fig. 4). The two aquifers at different depths are identified with the resistivity logs. With the lateral resistivity, the mean resistivity values of 28 Ω m and 30 Ω m are identified at first and second aquifers respectively. It is observed from well logs obtained from earlier failed well and newly drilled success well that, the fluid resistivity of failed well is comparatively greater than that of success well. The well logging investigations have revealed that, porosity of kaolinised material is in the range of 18–20% and the fractured khondalitic aquifer porosity is in the order of 26% in the region (Table 2).

Pumping tests

The kaolinisation is a process that makes the khondalitic rock becoming clay due to high weathering when it is in contact with water. Hence in the khondalitic region, the kaolinised layer is acting as barrier at low lying areas near the stream (Kandivalasa river) and causing accumulation of water at mid land areas (Venkateswara Rao and Briz-Kishore 1991). Earlier geophysical investigations in this terrain have revealed the fact that all along the length of the river, the aquifer thickness is least due to kaolinisation of the formation (Venkateswara Rao 1998). It is verified in the present work that whether the low lying areas (nearer to the river) have low values of transmissivity and storativity due to the kaolinisation effect. To quantify the aquifer potential
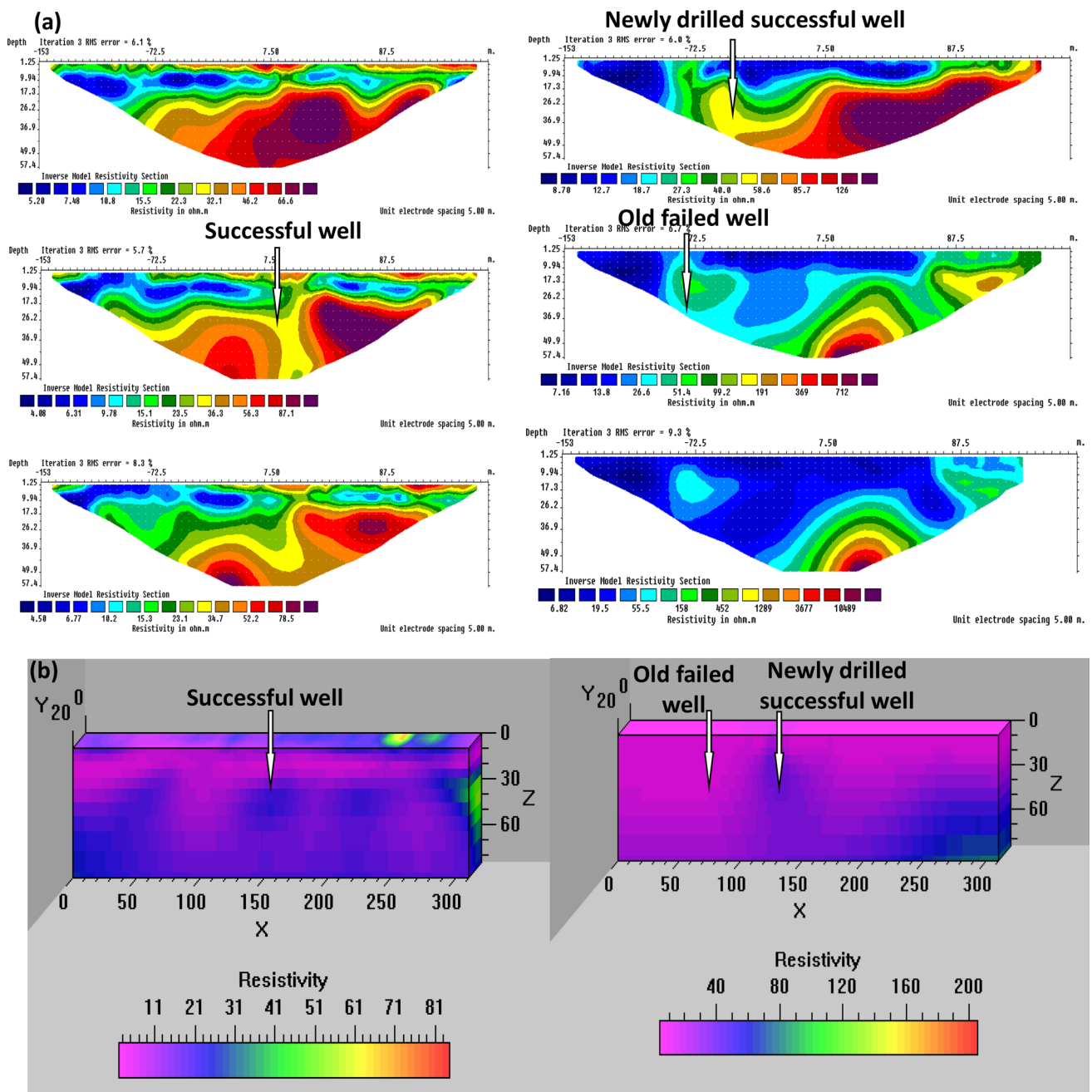
Fig. 3 **a** A set of parallel 2D resistivity imaging profiles, **b** 3D block image at success well and failed well pair near the stream of Sivaram village

(in terms of its transmissivity and storativity), the pumping tests are carried out and the groundwater potential zones are characterized in this region. A total of 13 pumping tests were performed in low lying areas and flat uplands to evolve the transmissivity (T) and storativity (S), discharge rates (Q), specific-capacity (S_c) values. The graphical representation of drawdown pattern as a function of time in an observation well is shown in Fig. 5. The productivity (water bearing property) of an aquifer can be expressed in terms of its

transmissivity and storativity. It is observed from the pumping tests that, the higher the transmissivity and the storativity values the more the aquifer is productive and those wells yield sufficient quantity of groundwater. Transmissivity, storativity and specific-capacity of khondalitic aquifer are presented in Table 3.

From the pumping tests results (Table 3), very low transmissivity and storativity values of 26 to30 m^2/day and 1.9×10^{-4} to 2.8×10^{-4} respectively are obtained at the low lying
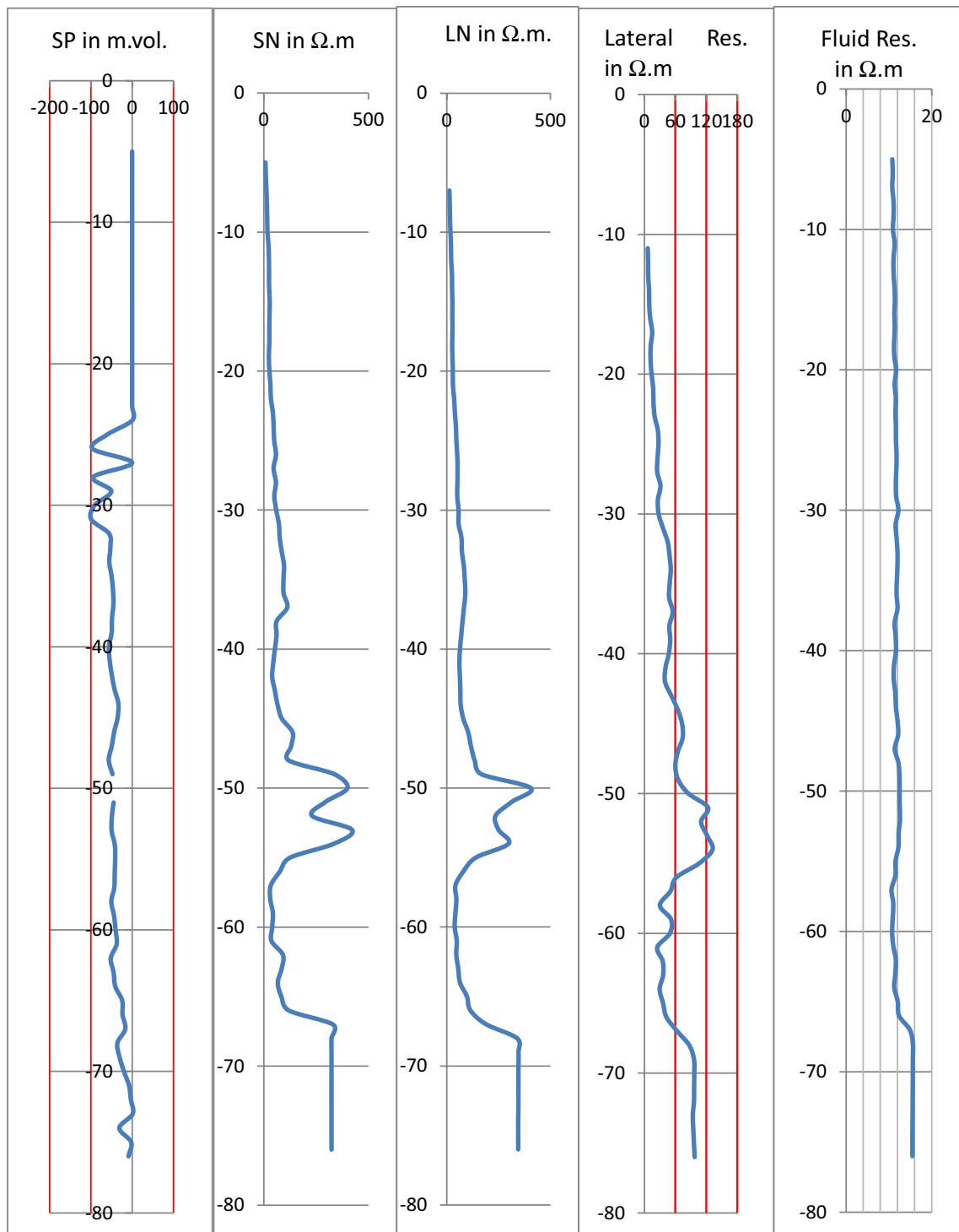
Fig. 4 SP, SN, LN, Lateral and fluid resistivity logs at newly drilled success well

areas in the khondalitic terrain. The low transmissivity and storativity values at low lying areas are due to the infilling of fractures with kaolinite and other weathering products which lead to reduction in the yields. The higher transmissivity (186–230 m^2/day) and storativity (63.3 $\times$ 10^{-4} to 87.5 $\times$ 10^{-4})

are obtained at flat upland areas (Fig. 6). Hence the aquifers which are close to the streams have less productive and their productivity increases as they move away from the streams to uplands. Thus, the adjacent upland areas are having more potential than the lower topographic elevations (DEM in

Table 1 Ranges of resistivity value for various layers in the newly drilled success well

Layer	Depth range in 'm'	Description of lithology	Resistivity value from lateral log in Ω m
Top soil	0–10	Mostly silt and sand	<7
Kaolinised or highly weathered layer	12–24	Sticky clay material	7–25
First aquifer	24–30	Weathered khondalitic rock with low permeability and less yield	25–31
Weathered layer	30–49	Weathered khondalitic rock with very low permeability and very less yield	30–65
Khondalitic rock	49–58	Hard khondalitic rock with very less permeability	65–132
Second aquifer	58–65	Fractured khondalitic rock with moderate porosity and high yield	24–36
Geo-electrical basement which is non-productive and has basement characteristics	65–77	Hard basement rock with no permeability	>65

Table 2 Borehole logging results at newly drilled success well and earlier failed well in the khondalitic terrain

Type of well	Layer	SP in m vol	Lateral resistivity in Ω m	Fluid resistivity in Ω m	Temp. in °C	R_{mf}/R_w	R_w	Porosity in % (%)
Old failed well	Kaolinised material	− 90	20	14	29.9	17.5	0.8	20
Newly drilled successful well	Kaolinised material	− 95	18	11.5	29.9	19	0.6	18
Newly drilled successful well	Aquifer-1	− 95	28	11.5	29.9	19	0.6	14
Newly drilled successful well	Aquifer-2	− 50	30	10.5	29.9	5	2.1	26

Fig. 1) in the middle of the basin. The specific-capacity is estimated for the performance evaluation of wells. A wide range of specific-capacity values (145–1386 m²/day) are observed in this region which provide to design pumping rate for the well and to estimate the transmissivity of the surrounding formations. On the basis of transmissivity and storativity distribution in the Kandivalasa river sub basin (Fig. 6), the groundwater potential is more at middle and flat uplands on either side of the main stream. The pumping tests have implied that, the maximum effect of kaolinisation is felt all along the main stream and its tributaries that lead the less productivity of the aquifer along the streams.

The estimated aquifer characteristics using well logging tools and pumping tests are helpful for formulating the groundwater flow model in the khondalitic region. The importance of this research is to estimate the aquifer properties (porosity and formation-water resistivity, transmissivity and storativity) as it has not reported earlier. The main limitation in this study is, the well logging investigations are conducted only in a couple of boreholes based on which

porosity and formation-water resistivity are calculated for both kaolinised and aquifer materials. The more well logging investigations are needed to be studied to acquire greater information on these aquifer parameters. However, the present evaluation of aquifer characteristics has given proper understanding of the hydrogeology of khondalitic terrain supporting the concepts proposed earlier by the authors.

Conclusions

The geophysical logging investigations and pumping tests in the khondalitic terrain of Northern parts of Eastern Ghats of India have given insights for understanding of its hydrogeology and for acquiring the hydrological data of essential aquifer parameters. In the newly drilled successful well, the
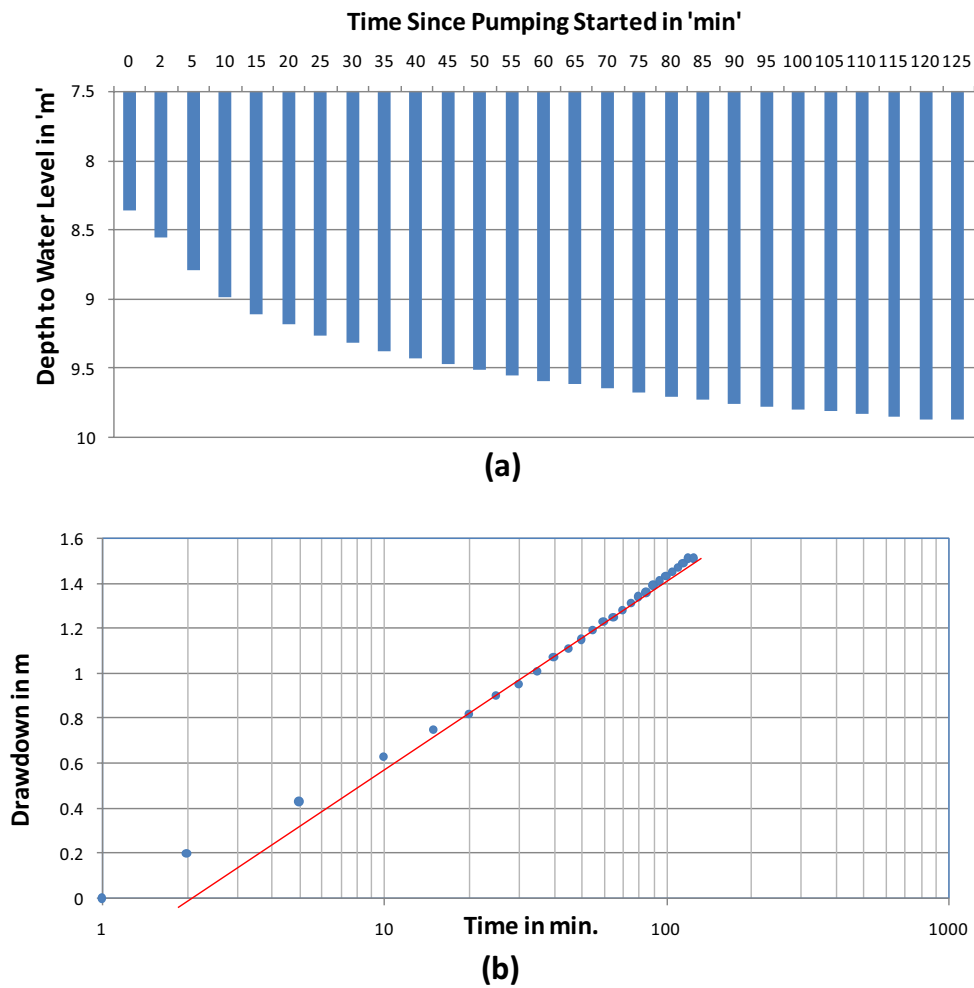
(a)

(b)

Fig. 5 **a** Time vs depth to water level, **b** time vs drawdown graph of an observation well (at Ravivalasa village in Cheepurupalli mandal) of khondalitic terrain

Table 3 The results of pumping tests in the Kandivalasa River Sub basin of khondalitic terrain

| S. no.	Name of the village	T (m²/day)	S	Q (m³/day)	Δs (m)	S_c (m²/day)
1	Ravivalasa	95	7.4×10^{-4}	444	0.82	541
2	Boppadam	68	23.4×10^{-4}	345	0.91	379
3	Dummeda	186	87.5×10^{-4}	367	0.36	1017
4	Chinanadipalli	230	63.3×10^{-4}	531	0.42	1265
5	Sivaram	118	22.7×10^{-4}	161	0.22	731
6	Peripi	158	13.6×10^{-4}	290	0.21	1380
7	Boddapeta	154	42.8×10^{-4}	226	0.21	1076
8	Karkam	30	2.8×10^{-4}	475	2.34	203
9	Itekarlapalli	26	1.9×10^{-4}	378	2.6	145
10	Konuru	126	3.3×10^{-4}	372	0.53	701
11	Arjunavalasa	85	11.2×10^{-4}	397	0.86	461
12	Mulagamu	140	3.2×10^{-4}	351	0.46	763
13	Nadipannapeta	104	33.6×10^{-4}	457	0.8	572
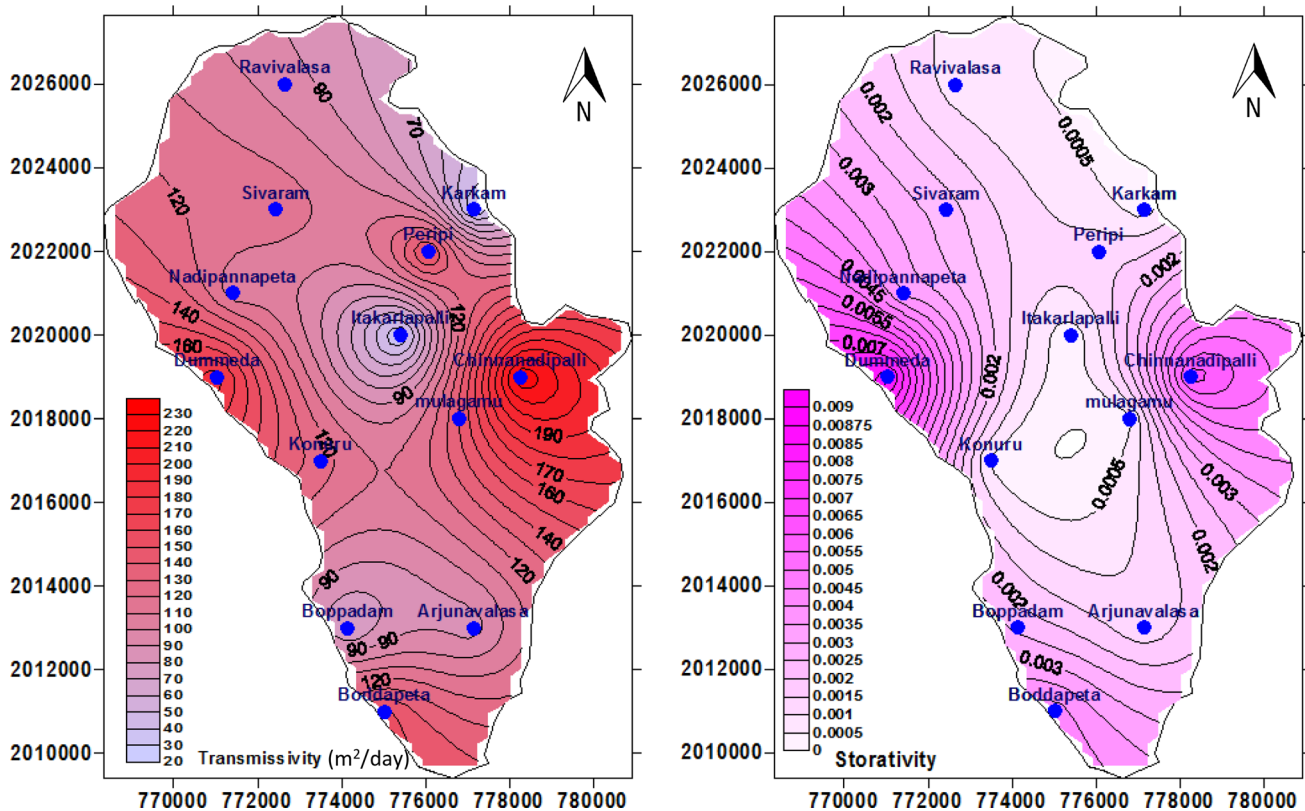
Fig. 6 Transmissivity and storativity distribution in Kandivalasa river sub-basin in khondatic terrain

boundaries between various layers are obtained from the SP logging and the two aquifers at different depths are identified with the resistivity logs. With the lateral resistivity logging in the newly drilled success well, the fractured zones having the resistivity range of 28–30 Ω m are identified as aquifer. The porosity of kaolinised material is obtained in the range of 18–20% and the porosity of fractured khondalitic aquifer is revealed in the order of 26%. From the analysis of pumping tests data, the transmissivity values are in the range of 26–230 m^2/day and the storativity values are in the range of 1.9×10^{-4} to 87.5×10^{-4}. The high transmissivity and storativity values are obtained at flat uplands whereas low transmissivity and storativity values are existed at low laying areas proving the concept that the flat upland areas are more productive than low lying areas.

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