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Full Length Research Paper

Evaluation of hydrogeological properties of fractured granitic aquifer in a micro watershed of Kandukuru - Southern India

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Aquifer performance tests were conducted in a fractured granitic bedrock aquifer to determine the well performance and hydraulic characteristics of bore wells in a micro watershed of Kandukuru from Southern India. The long duration pump tests under constant rate conditions (ranges: 216-363 m^3/day) were conducted independently at 6 bore wells to examine the variations in transmissivity. Different analytical methods were employed for the same test data, in order to extract possible variability in hydrogeological parameters. The estimated transmissivity values from different methods are in agreement with at least two of the applied methods. The transmissivity varied from 10.28 to 90.06 m^2/day with mean of 33.6 m^2/day whereas the specific capacity ranges between 10.40 and 67.31 lpm/m/dd. The values of both these parameters are in concurrence with each other for some tested wells. Application of multiple analytical methods confirmed that Jacob straight line method is an ideal for obtaining agreeable well hydraulic properties of fractured granitic aquifers. The tests have revealed that the sparsely fractured bedrock has feeble multi-dimensional interconnected fracture system. The lamellar hydraulic conductivity is extensive throughout the aquifer. Variations in transmissivity among the closely spaced wells exhibit heterogeneity and anisotropic characteristics. The aquifer has a trend of increasing transmissivity from southeast to northwest. The hydraulic conductivity between few extraction wells is particularly high indicating that they are connected by a highly transmissive fracture. The highly contradictory aquifer parameters within a close range pointed out that the area is subjected to selective structural disturbances. The development of secondary porosity and permeability in the form of fractures system are uneven and superficial.

Key words: Aquifer characteristics, fractured granitic terrain, transmissivity, specific capacity, bore well performance.

INTRODUCTION

Determination and evaluation of hydrological characteristics of an aquifer has become an integral part of groundwater assessment and management study (Sarwade et al., 2007; Mondal et al., 2012). In the light of growing demand for water and judicious utilization of available resources, an effective management strategies need to be propagated by scientifically assessing availability of extractable water (Mondal and Das, 2012). The principal tool to evaluate the sustainability of management scenarios for hydro-systems is groundwater modeling (Mondal et al., 2009). One of the major prerequisites for establishing the reliability of such models is an accurate knowledge of the geometry and the hydrodynamic properties of the aquifer (Maréchal et al., 2004).

After successful development of groundwater structures, a

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long duration of pump test is empowered for the user with basic inputs on quantity of water and one can safely withdraw for appropriate time duration without causing undue strain on the aquifer (Mondal and Das, 2012). The aquifer performance test is aided in gathering various scientific inputs on aquifer hydraulics which can help in judicious utilization of water resources in an area or watershed etc. Evaluation of aquifer parameters, namely transmissivity (T) and storage coefficient (S), from aquifer test data has been a continual field research (Birpinar, 2003). Well test analyses in porous and fractured geologic media continue to be a topic of great importance because the parameters estimated from such tests have a direct bearing on the field-scale prediction of groundwater flow and contaminant transportation (Illman and Tartakovsky, 2006).

Kandukuru watershed, a rapidly growing sub-urban town of Hyderabad city in Southern India is totally dependent on groundwater for meeting its water requirement of agriculture, industries and upcoming settlements and colonies. The impact of high rate of groundwater exploitation from a locally fractured granitic terrain results in sharp fall in groundwater levels, gradual decrease of well discharge and even drying up of much of the unconfined and part of the semi-confined aquifer zones. This area is already listed as over exploited (OE) watershed by Andhra Pradesh State Ground Water Department imposing restrictions on further extraction of groundwater in select locations (APSGWD, 2008). In order to locate suitable potential pockets for further groundwater development to meet the ever increasing water demand of the area, a micro level independent study was conducted in Kandukur watershed. Fractured granitic terrain forming part of peninsular gneissic complex has fascinated many scientists and is being the subject of study for many decades. Although lots of theories are postulated on hard rock well hydraulic, many of them are based on regional study. To gather finer micro level hydrogeological and hydrological information, an area of 0.44 km^2, used for irrigation purposes, was identified. The selected study area represents a true hydrogeological scenario of a semi-arid groundwater dependant granitic terrain. To have a comprehensive picture of sub-surface fracture disposition, closely spaced bore wells were tested assuming them to be tapping inter-connected multi-polar fractured aquifer as the matrix permeability of igneous rocks is generally small.

Pump test and determination of hydrological parameters

The fractured granite symbolizes an anisotropic, heterogeneous aquifer as it is known for exhibiting three-dimensional anisotropy due to disconnected fracture network. The individual test in closely-nit wells, where exists difference in hydraulic conductivity, will explain the fracture dispositions and potentialities of each set of micro fractures system. The fracture network mainly controls the hydraulic behavior of the reservoir and the characterization of the fractures is then crucial for the study of flows and for production optimization (Massart et al., 2010). Due to field limitations single well test was conducted and other neighboring wells could not be used as observation wells because the precise hydrogeological details of these wells were not available. In single well test drawdown in a pumped well is influenced by well losses as well as well-bore storage. Since the bore wells in granitic terrain is naked except for few meters in the weathered zone, the well losses assumed to be negligible and to offset well-bore loss the log-log plot of drawdown vs pumping time and recovery time were applied to cross verify the hydraulic parameters which obtained by Jacob straight-line and Theis methods.

Though there are several analytic techniques based on steady-state and transient analysis of drawdown, the most suitable methods for the prevailing hydrological set up of the area were adopted. Theis curve-fitting method (Theis, 1935) was used considering that the flow to the well was in unsteady state and hydraulic gradient was not constant with time. Many data sets cannot be analyzed with type curves because of external forcing, small pressure responses, early-time nonlinear effects, and rock heterogeneity alter the pressure transients and preclude a good fit between the data and the type curves (Illman and Neuman, 2001; Illman and Tartakovsky, 2006; Willard, 2007). Jacob's straight line method (Cooper and Jacob, 1946) also satisfies the present field and test conditions namely, the flow to the well is in unsteady state, radius (r) of the well is small and pumping time (t) is sufficiently large, though some plot points deviate from the straight-line relationship in the initial or late stages of the test due to natural local hydrological anomalies. Recovery test results were also used and estimated aquifer parameters with an aim to compare with the output of pumping (drawdown) data. Residual drawdown data (s) are more reliable than test data because recovery occurs at a constant rate whereas a constant discharge pumping is often difficult to achieve in the field (Kruseman and de Ridder, 1990). More precise and recovery readings can be obtained from the well in relatively under-saturated state aquifer than those during pumping. The data was processed using Jacob straight line method as well as Theis recovery method to obtain precise hydraulic characteristics and to standardize the results. Though these classical methods are mainly devised for granular aquifers, they are found to be valid in fractured rock aquifer as well (Subramanian, 1981).

Study area

The study area constituting an area of 0.44 km^2 is situated 53 km from the Hyderabad city on Kalwakurthy road in the southeastern part of Ranga Reddy district. It is located between latitudes 17°05′55.3″N and 17°06′24.1″N, longitudes 78°28′43.9″E and 78°28′54″E (Figure 1). The area is located on a minor elevated terrain having an altitude of about 635 m above mean sea level (amsl) in the east. The west boundary follows the elevation contour of 625 m amsl. In 2 km radius of the study area contour elevation difference is 10 m amsl. The area is pediment-pediplain possessing two minor lineaments traversing in N-S and NE-SW directions. The area forms a deep erosion landform of two elevated mounds separated by narrow lineaments. Extensive erosion has left a thin veneer of soil sitting on hard/disintegrated rock. The drainage course is towards northwest to southeast and northeast to southwest directions. The drainage pattern is dendritic to sub-dendritic and is of first order type, having well defined courses traversing discontinuously within the scattered cultivated agricultural fields. There are two minor irrigation ponds present in North and Southern part of the study area. The climate of this study area is characterized by hot summer and general dryness except during south-west monsoon season. The normal annual rainfall of the study area is about 743 mm.

Geology and hydrogeological set-up

The study area is a part of the stable Southern Indian Peninsular Gneissic Complex (PGC) of Archaean age. Major part of the PGC constitutes grey granite gneiss, granites, grano-diorite which is intruded by basic dykes, and quartz veins, pegmatite reefs in the northeast and southwest part. Basically, the dyke is massive discordant body striking in northeast to southwest direction which is exposed as discontinuous. The country rock, granites are coarse grained, grey to pink colored, weathered down to ~10 m and fractured from 25 to 50 m depths along course of two lineaments (L-1 and L-2; Figure 1). There are many groundwater extraction structures in lowland areas. Bore wells are successful along the identified lineaments.

Depths of dug wells are shallow (ranges: 10 to 19 m below ground level, bgl) whereas the depth of irrigation bore wells ranges from 50 to 90 m (bgl). Depth to water varies between 17 to 25 m (bgl). The groundwater flow is from east-west to south direction due to the regional topographical elevation. In the northern upland from northwest to southeast direction bore well are successful due to the structural control in this area. In central part of study area few bore wells were drilled and many of them are found to be dry as a dolerite dyke intruded in NE-SW direction (Figure 1). In general the yield of bore wells ranges from 3.0 to 4.5 liter per second (lps).

METHODOLOGY

Extensive fieldwork had been carried out in Kandukuru watershed from Southern India. Hydraulic tests at different sites were conducted to determine the hydrodynamic properties of fractured layer by way of pumping tests. Obtained results were interpreted using specific techniques for fractured media. The pumping tests were conducted at 6 bore wells independently from March to April, 2010 with the discharge rates of 2.5 to 4.5 lps. The head differences were collected with automated water level indicator placed at the pumping wells. The pumping was stopped after completion of 1000 min and recuperation readings were collected almost till the original static water level achieved. The data was analyzed both manually and using the computer aided software (AQTESOLVv4.5) to obtain aquifer characteristics. The pumping test data was also analyzed applying multiple methods namely, Theis and Jacob straight line methods. To normalize the results both drawdown and recovery data sets were plotted in semi-log as well as log-log cycle plots applying Jacob method. By comparing the entire test and analyzed results, appropriate transmissivity values for all the tested wells were determined.

RESULTS AND DISCUSSION

The long duration pumping tests conducted with constant discharge rates individually at 6 bore wells located in similar hydrogeological environment shown variable hydrological parameters. Initial water level measurements showed that water level was deeper in SE part of the study area which could be due to the elevation difference and differential fracture disposition. The drawdown after 1000 min of pumping was comparatively less but it was more at some wells located in SE part of the study area. The drawdown (dd) and transmissivity (T) values are in concurrence with each other (Table 1).

The specific capacity for the tested wells varied widely although these wells were tested by pumping out water at almost uniform rate of discharges. The specific capacity and T-values of bore well (BW) 5, 7 are in agreement with each other and also contradictory with BW 10. The T values obtained by different methods for each well were not only dissimilar but were incongruous. Among the results the best fit (at least by any of the two methods) T values were considered as appropriate. The BW 2, which located in WNW part of the studied area, had very high T value (110.70 m^2/day). All other tested wells had very low T value compared to the BW 2. The wells in SE part had low T values varying from 7.91 to 29.52 m^2/day which were in very close cluster (Table 1). But the estimated T-values at the wells in the N and NW parts of the study area were comparatively higher range: 15.81-110.70 m^2/day. This variation in T among closely spaced wells further strengthens the discontinuity and inhomogeneity among different sets of fractures within a hydrogeological unit. Deviations in calculated T among the different methods applied for a test could be due to discretion in choosing the log cycle for arriving at *delta 's'* (difference in drawdown among two log cycles) and variations in data curves. The data points in semi-log cycle for some of the tested wells (BW 2 and 3) were plotted and the flat drawdown curves indicated that the wells were being achieved boundary conditions after few hours of water extraction (Figure 2a). Curves of other wells reflect direct

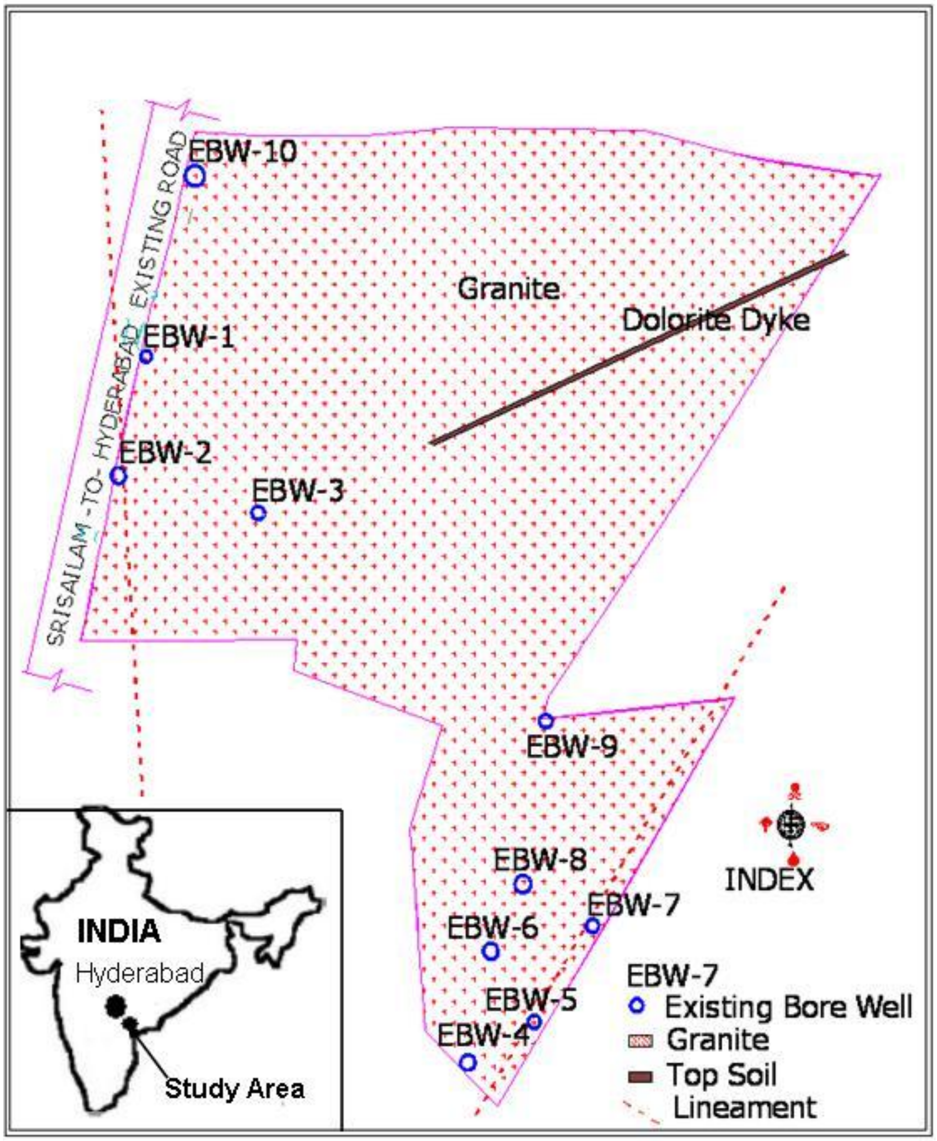


Figure 1. Location map with pumping test sites of the study area.

reaction to pumping by gradual fall in water levels indicating narrow and closed fracture system (Figures 2a, b). The plots in log-log cycle do not display clear fracture properties due to close spacing of curves and are apparently plotted parallel to each other (Figures 3a, b). However the BW 8 data curve is ideal for obtaining optimum *delta 's'* value from more reliable mid-time log cycle.

The recovery drawdown (rd) plots in semi-log graphs were akin to those of drawdown plots. The BW 3 had shown a very quick recovery in initial stages and water levels got stabilized thereafter, the curve of the well was not used for estimation of T as data was not consistent (Figures 4a and 5a). The data plots in log-log cycle for BW 2, 5 and 10 were similar to Theis type curve (Figures 5a, b). The results from Theis curve matching method for dd vs pumping time (t) test (Figures 6a, b) are in concurrence with Jacob straight-line plots for BW 2, 5 and 10. By adopting the multiple methods for analyzing drawdown as well as recovery data the agreeable results can be obtained. The study shows that evaluation of hydraulic characteristics of fractured granitic aquifer can be obtained finest results from time-tested classical Jacob straight-line method.

The plots of BW 2, 3 and 5 tend to align to straight-line indicating radial flow behavior suggesting that the fractures are well connected in all directions. The semi-log plots of BW 7, 10 and 8 indicate effect of well storage for 300 min and low initial drawdown is not due to high porosity. The near straight-line trend in mid log cycle (10 to 100) zone for BW 2 and 3 (Figure 3a) strengthens the assumption that linear flow is prevalent among intersecting

Table 1. Details of the pumping tests with estimated T-values (m^2/day).

Pump tested well No.	SWL of tested well [m (bgl)]	Drawdown after 1000 min pumping (m)	Constant pumping discharge (cum/day)	Specific capacity [Q/dd lpm/m/dd]	Transmissivity (T) by Jacob straight line method				T by Theis	Appropriate
					dd vs t		rdd vs t/t'		dd vs t	T value among
					Semi-log (m^2/day)	Log-log (m^2/day)	Semi-log (m^2/day)	Log-log (m^2/day)	Curve match (m^2/day)	Five methods (m^2/day)
BW -2	16.34	3.12	302	67.31	55.35	110.70	110.70	170.30	90.06	110.70
BW -3	20.81	6.11	302	34.37	27.67	27.67	Not analyzed	Not analyzed	32.64	27.67
BW -8	28.18	14.43	216	10.40	6.08	7.91	43.93	39.53	10.28	7.91
BW -7	28.39	9.64	302	21.78	9.22	10.06	44.28	52.71	24.06	10.06
BW -5	27.46	8.67	363	29.07	33.21	29.52	17.71	33.21	29.19	29.52
BW -10	21.32	11.89	259	15.14	13.55	15.81	9.99	93.02	15.96	15.81

SWL: Static water level, bgl: below ground level.

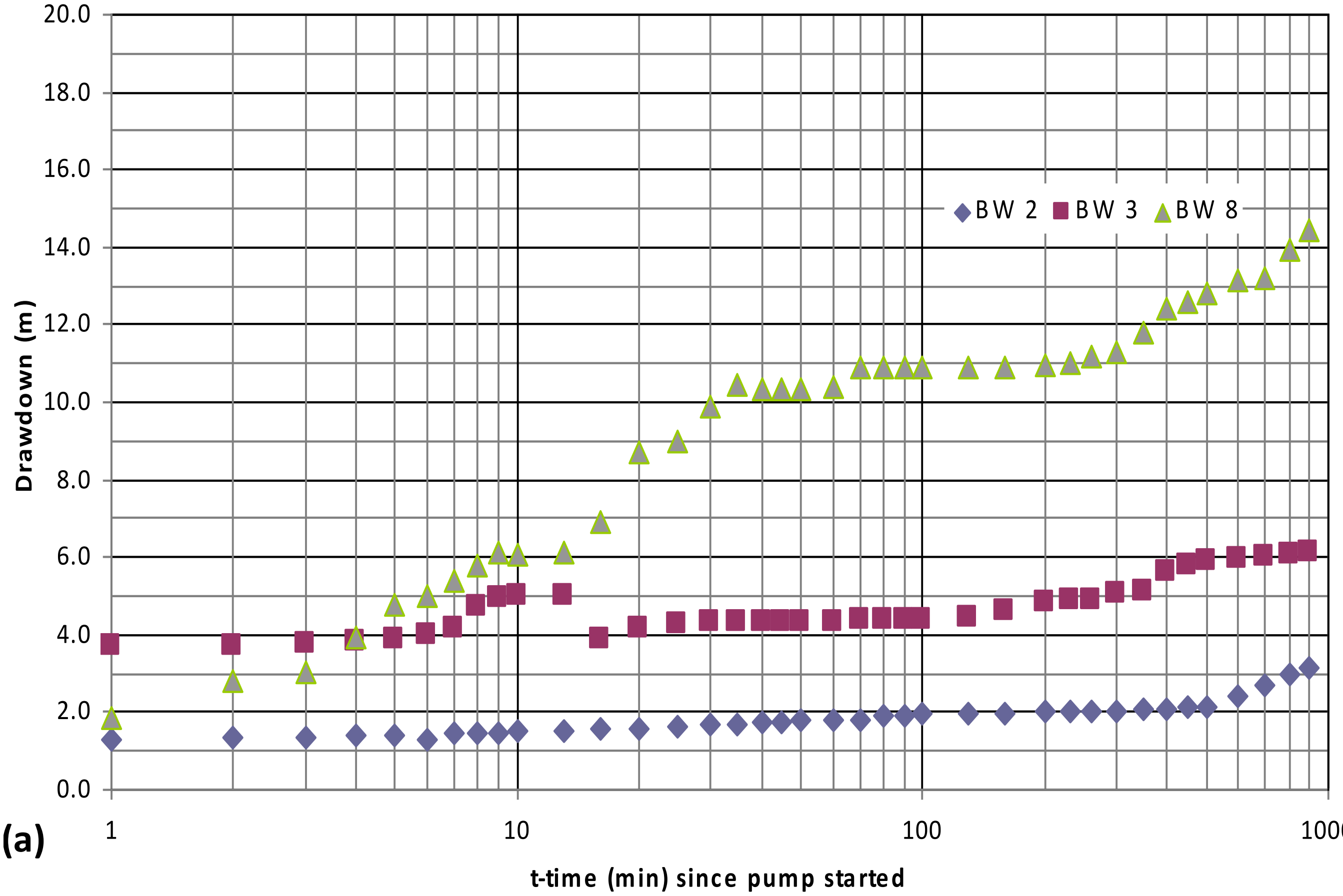
fractures which could be either vertical and/or horizontal. The massive rock matrix though occurs between sets of fractures, the multi-dimensional fractures sets remotely connected facilitate lateral flow improving the well yields.

Similar straight-line trend in initial cycle (0 to 10) could be attributed to well storage. The BW 3 and 5 (Figures 6a, b) have similar T value though are placed apart in different fracture pockets whereas the very closely placed BW 5, 7 and 8 so also BW 2 and 3 differ in their respective T values. It is apparent from the observation that the country rock has suffered selective local structural disturbances leading to development of secondary radial porosity and permeability which tapered off in close proximity. Intensity of structural disturbance and susceptibility of bedrock influenced the fracture development and also their interconnectivity. The granitic terrain in peninsular gneissic complex, though underwent high grade metamorphism and tectonic disturbances, development of well connected network of fracture system is seldom found.

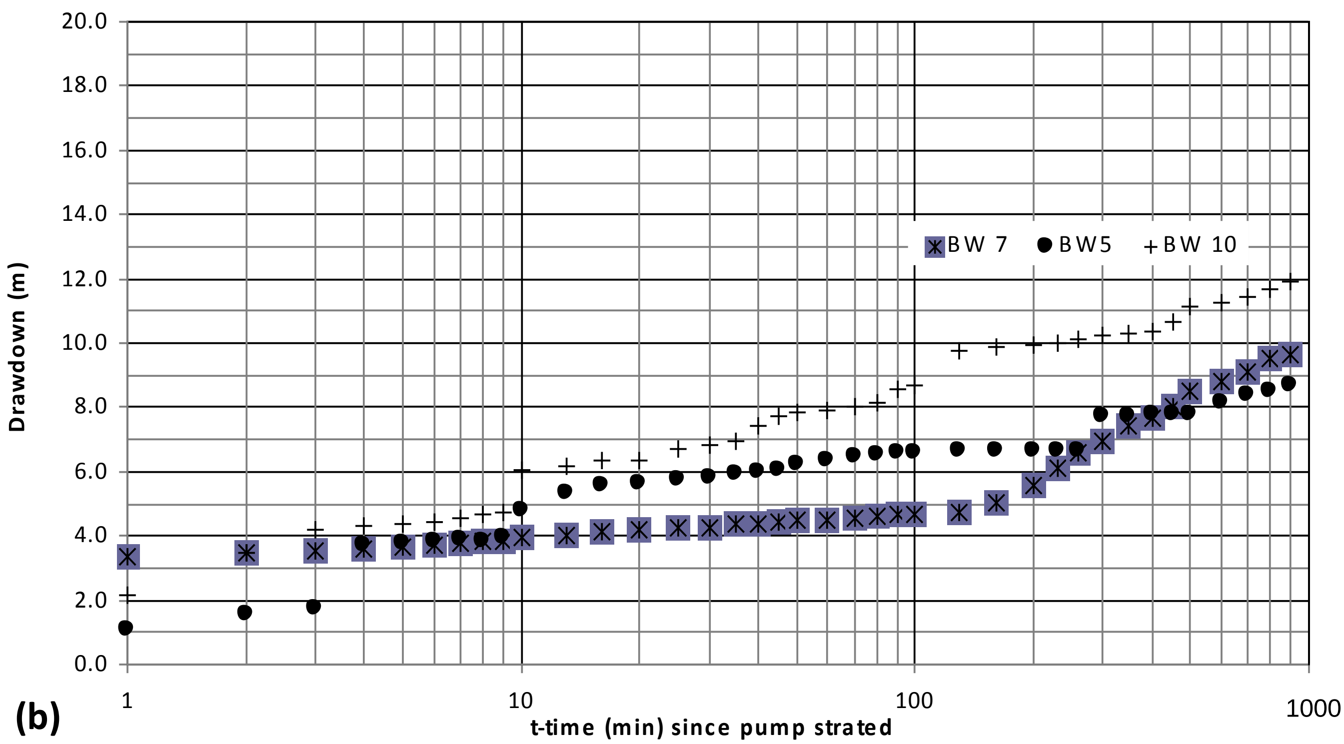
Variations in well hydraulics can be linked to wells encountering multiple fracture lineament or locally fractured bedrock. Identification of potential fracture system in hard rock terrain is a challenging task in spite of applying all available tools as is normally does not manifest on the surface. The identifiable features are mostly camouflaged by subsequent natural erosion process or manmade development. A very high T value at BW 2 in NNW part of the study area shows that the BW is located on lineament. The well at this location, though drilled to normal depth as other wells, is exhibiting high hydraulic conductivity. Other well (BW 3) even though placed near the lineament does not show similar conductivity as the T value is lesser by 4-times than that of BW 2. The hydraulic connectivity is high in NW part of the study area and diminishes in SE direction. The groundwater flow is from SE to NW direction due to fracture alignment and high intensity fractures are concentrated in NW location. The cone of depression in SE is in accordance with fracture frequency and local aquifer characteristics. Similar well hydraulics and water level conditions in isolated pockets exhibit highly localized fractures and their horizontal connectivity. The opaque massive rock matrix among set of local fractures is hindering vertical flow but it can be speculated that they are partially connected with few multidimensional fractures.

Conclusions

The study demonstrates the usefulness of different interpretation techniques in order to evaluate hydraulic properties of the fractured hard rock aquifer. The test results illustrate wide variation in hydrological parameters in a micro watershed of Kandukuru from Southern India having similar hydrogeological environment emphasizing the prevalence of anisotropy and heterogeneity which is a typical feature of fractured granitic gneiss. The transmissivity values vary from 10.28 to 90.06 m^2/day with an average of 33.69 m^2/day at the 6 tested wells but excluding high end T value reduces to 20.64 m^2/day. It could be a classic example to demonstrate that each well is unique in hard roc terrain; and hydraulic parameters cannot be generalized so aquifer potentiality and predicted theoretically precisely. The study substantiates

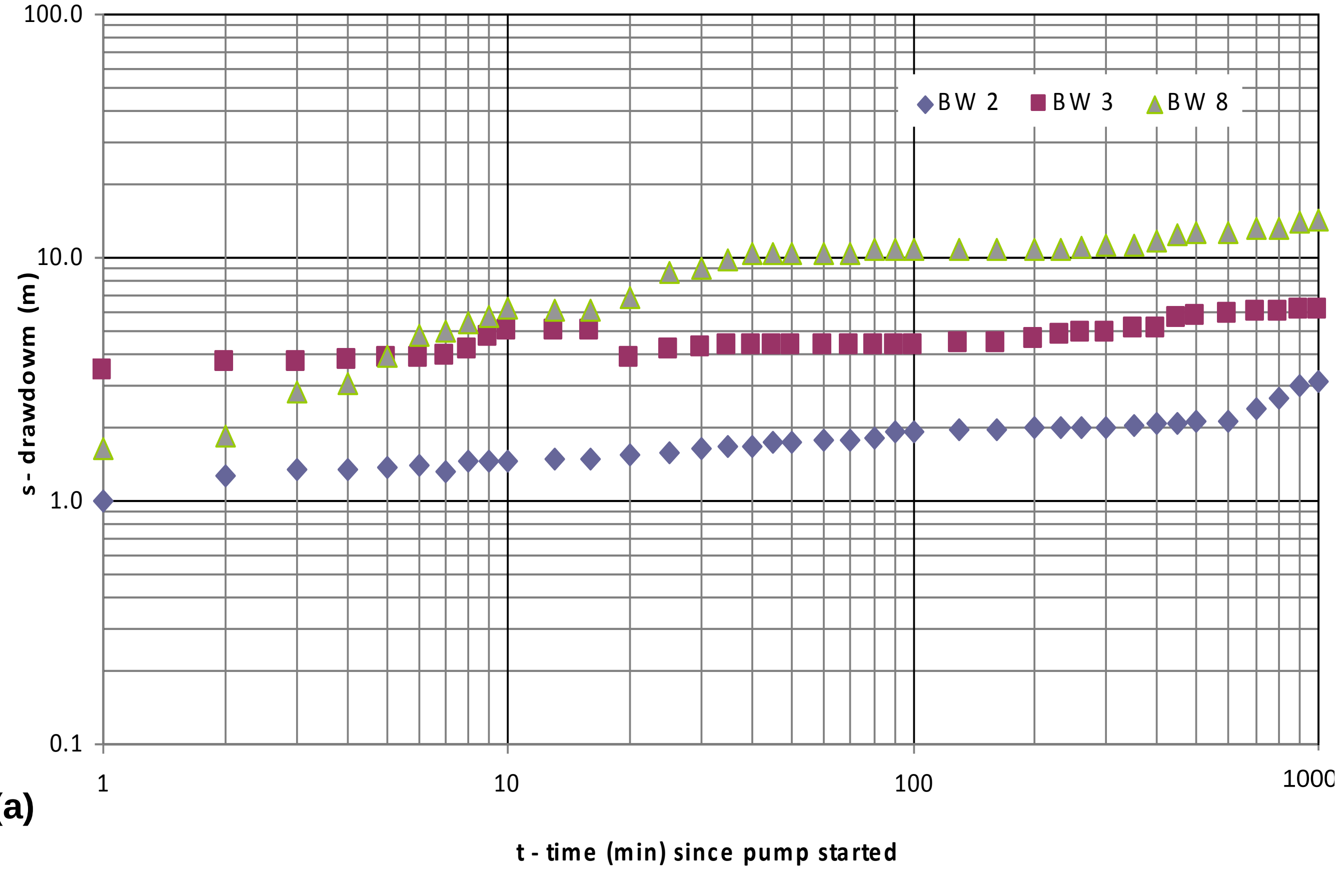


(a)



(b)

Figure 2. Jacob plots for drawdown time (semi-log) at (a) BW 2, 3 and 8. (b) BW 5, 7 and 10.



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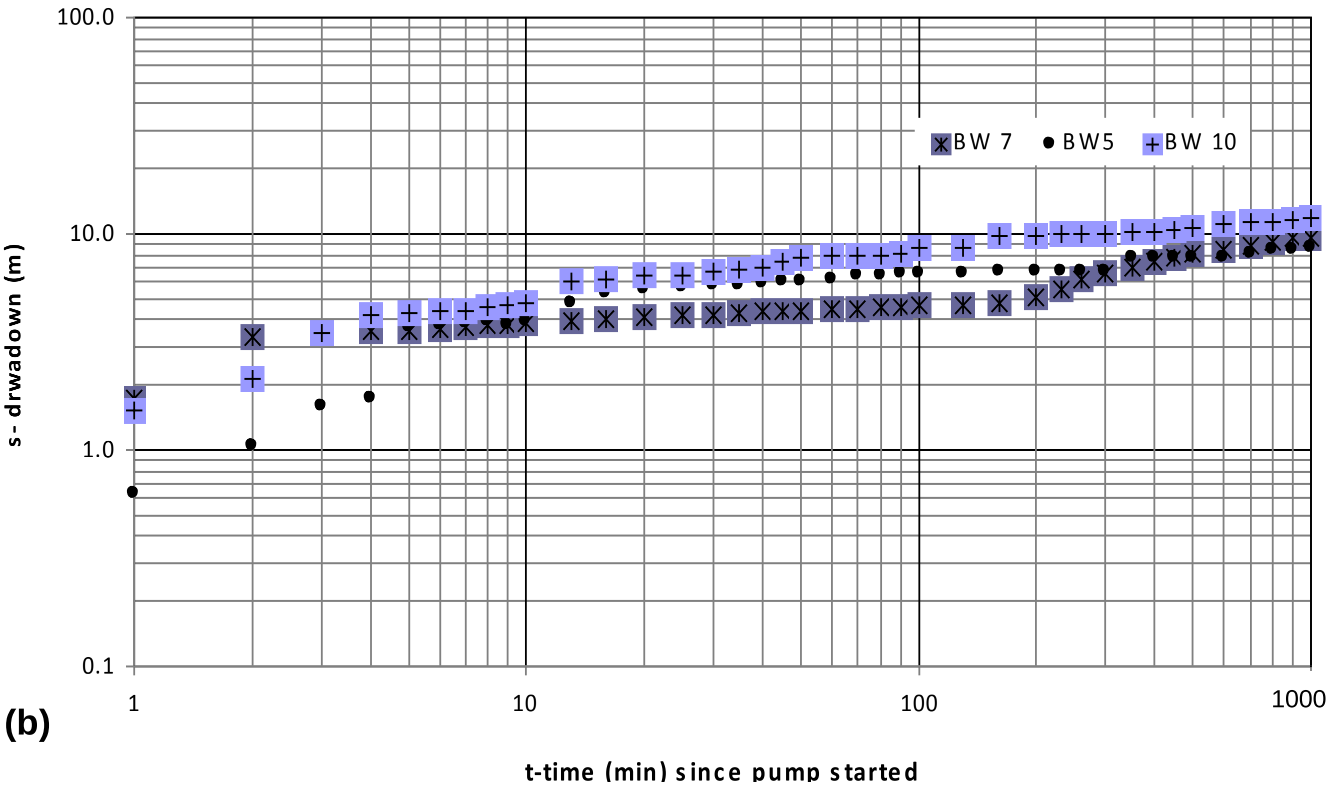
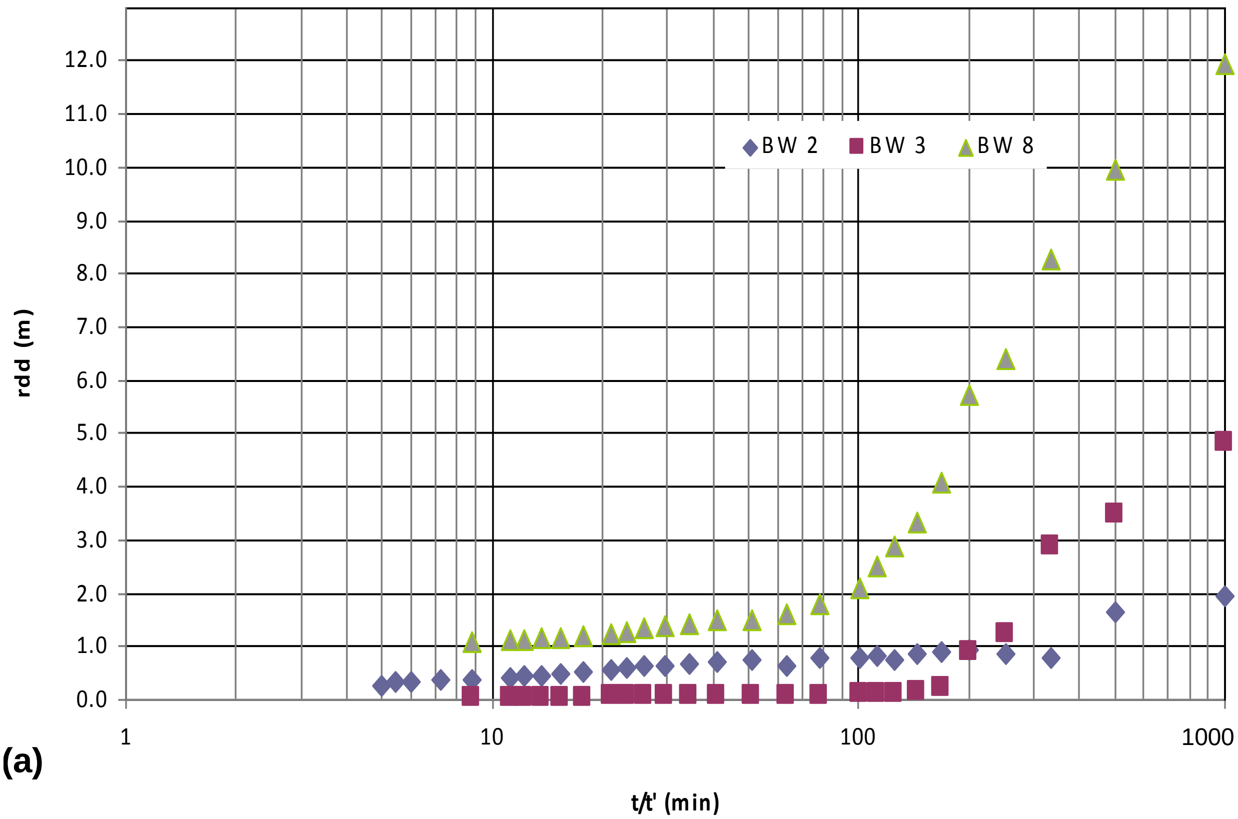
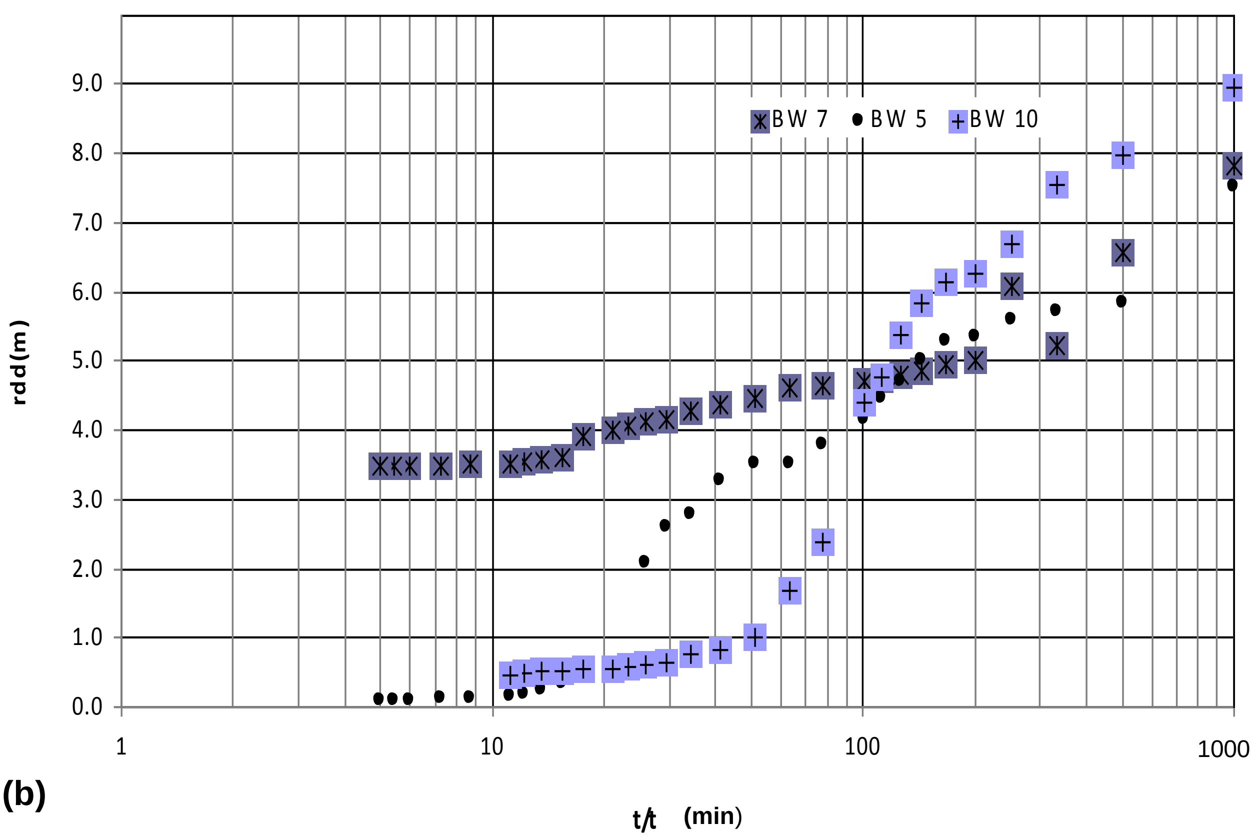


(b)

Figure 3. Jacob plots for drawdown versus time (log-log) at (a) BW 2, 3 and 8. (b) BW 5, 7 and 10.



(a)



(b)

Figure 4. Jacob plots for rdd versus time (semi-log) at (a) BW 2, 3 and 8. (b) BW 5, 7 and 10.

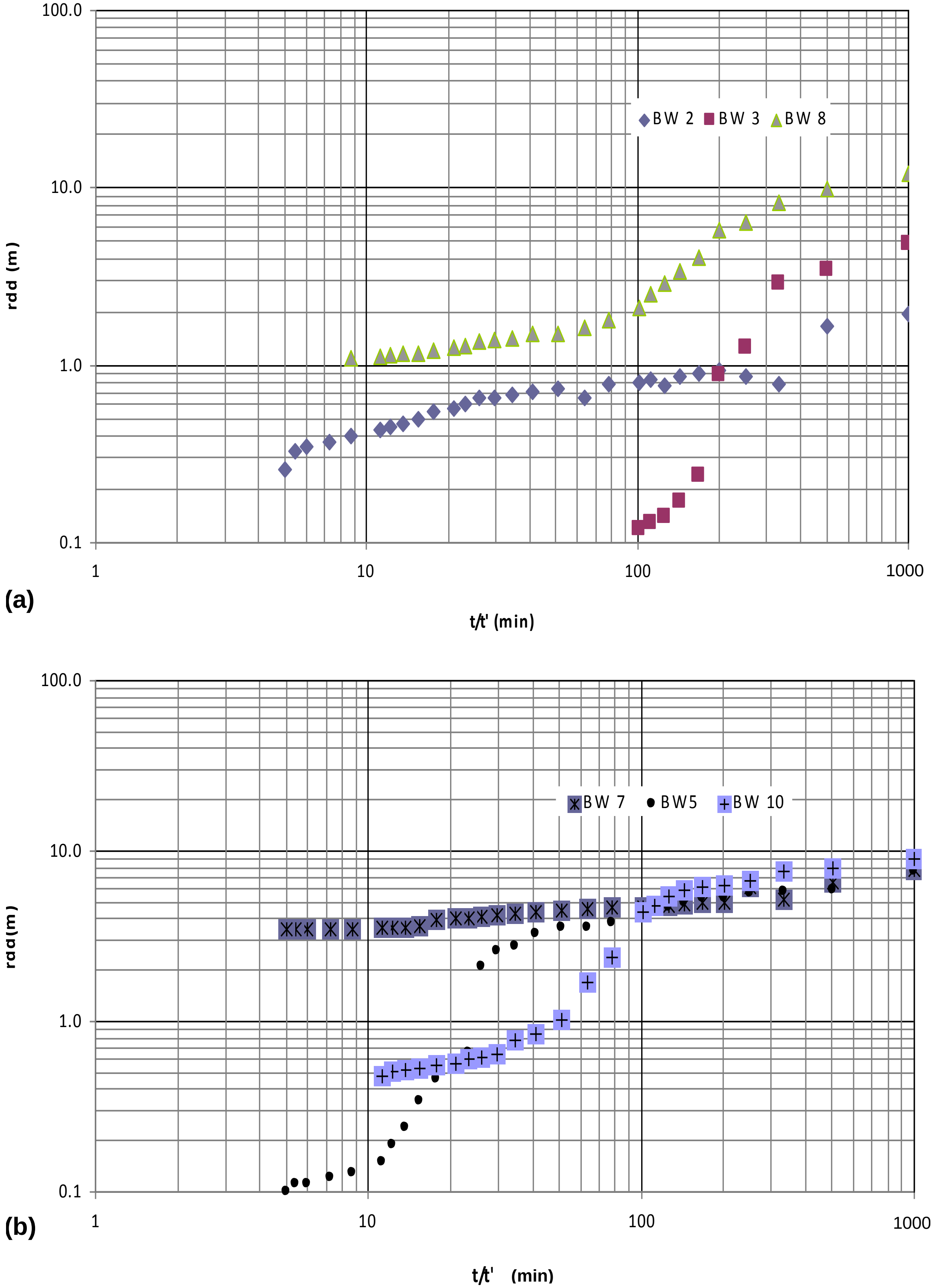


Figure 5. Jacob plots for rdd versus time (log-log) at (a) BW 2, 3 and 8. (b) BW 5, 7 and 10

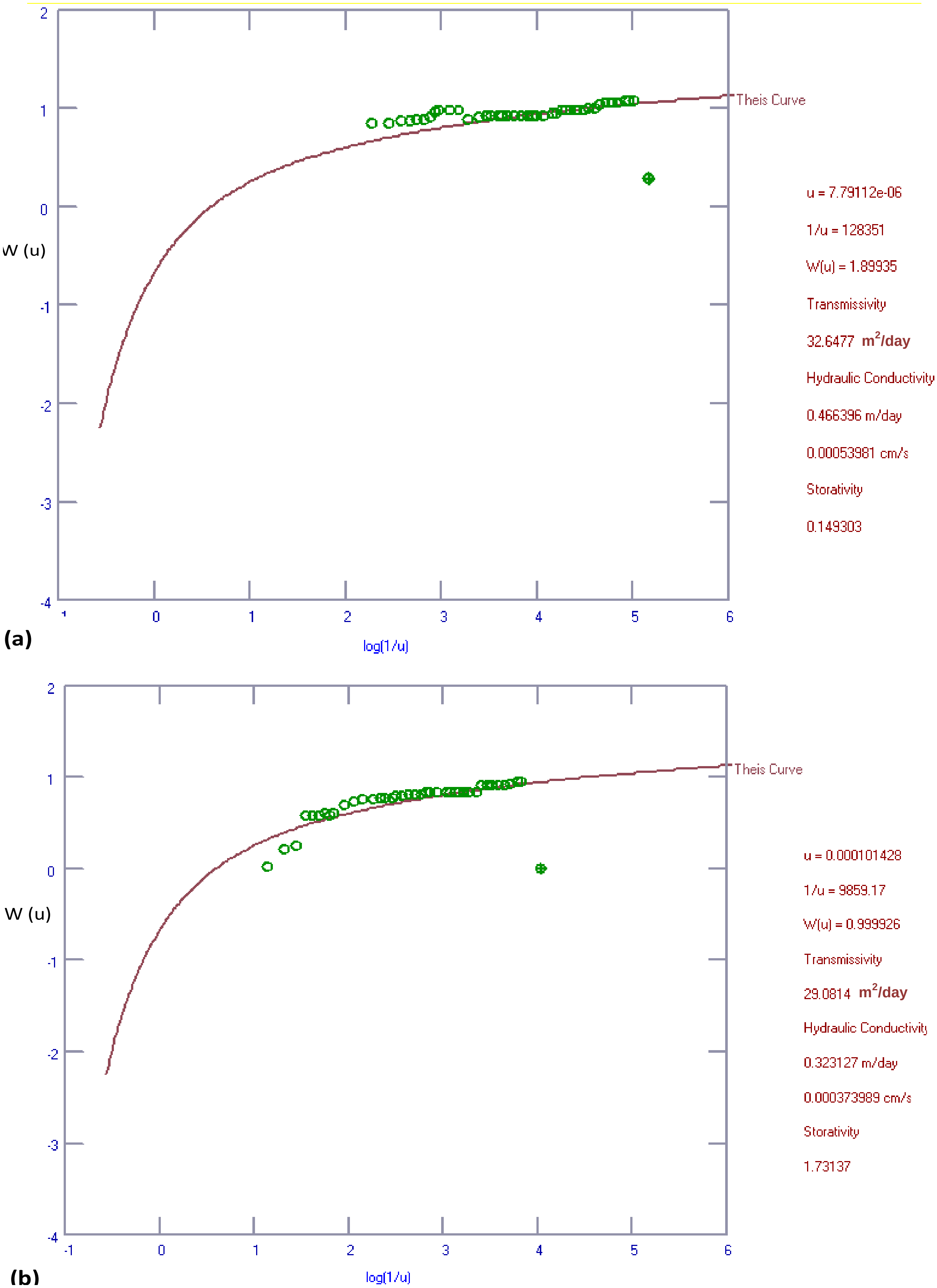


Figure 6. Log- Log plot of time versus drawdown is superposition on Theis type-curve at (a) B-3 (b) B-5 in Kandukuru site.

each well is an exploratory well and a detail pumping test can only help in assessing the well performance and capability. Utilization of available and extractable groundwater resources can be precisely planned by this exercise.

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