Characterization of basaltic rock aquifer parameters using hydraulic parameters, Theis’s method and aquifer test software in the hard rock area of Buchakewadi watershed Maharashtra, India

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Abstract
The twelve wells were selected to carry out the various test, duration of pumping (min), maximum draw drown (m), duration of recovery (min), residual drawdown, and aquifer type in the basaltic rock aquifer parameters of Buchakewadi watershed. The source and flow of groundwater are essential concerns in hydrological systems that concern both spatially and temporally components of groundwater discharge and water supply problems. The content and temperature of groundwater flowing through an aquifer might change depending on the aquifer environment. As a result, hydrodynamic analyses can provide valuable information about a region’s subsurface geology. The present research attempts of aquifer variables such as transmissivity ($T$) and storativity ($S$) estimation are significant for groundwater resource development and evaluation. There are numerous approaches for calculating precise aquifer characteristics (i.e., hydrograph analysis, pumping test, etc.). A most frequent in situ analysis is a well-pumping test, which accurately measures the decline and rise of groundwater levels. During an aquifer pumping test, to characterize aquifer properties in an undiscovered location to forecast the rate of depletion of the groundwater table/potentiometric surface. The shallow, weathering subsurface water accessible above the Deccan traps in an unconfined state is insufficient to satisfy the ever-increasing pressure on water supplies. Maharashtra is similarly dominated by hard rocks, whose rainfall susceptibility is limited by weathering and primary porosity, as is their volume to store and convey water. Based on the hydraulic parameters and Theis method, results are optimized. Aquifer mapping and pumping test results can be more important for solving problems such as water scarcity, nonpolluting water, health issues, and source of fresh water on the earth surface. However, the characterization of aquifer parameters should be significant role in the scientific planning and engineering practices.

Keywords Aquifer parameters · Theis method · Hydraulic parameters · Basaltic rock · Transmissivity

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Introduction

The need of water for manufacturing, farming, and domestic purposes is rising constantly, while freshwater resources are decreasing. Groundwater management is a significant issue for coming generations against this backdrop. The term "groundwater management" refers to managing of groundwater resources' availability and value. The first tens of meters from the top are occupied by a hard rock aquifer (Detay et al. 1989; Taylor and Howard 2000). Groundwater is found in weathering and fractured strata with unique hydrodynamic characteristics from top to bottom. It is in unconfined to semi-confined regimes. Groundwater resource quantification and comprehension of hydrogeologic systems are crucial for proper and long-term groundwater resource development and management (Sophocleous 1991; Wyns et al. 2002; Vander Gun and Lipponen 2010; Pande et al. 2020). To develop the geologic architecture for proper aquifers study and their hydrological features, groundwater tables in aquifers, how it changes over time, and an incidence of anthropogenic and natural pollutants that effect the mobility of groundwater are all predicted to benefit from systematic aquifer mapping. This research will help planners, administrators, and other user's natural resources management tools like long-term aquifer observation systems and theoretical and statistical local ground-water-flow models (Khadri et al. 2016a; Moharir et al. 2017). Aquifer modeling at the adequate level can benefit in the making plans, execution, and surveillance of different management approaches aimed at securing the continuing sustainability of our valuable water resources, which will, in flip, support the achievement of drinking water protection, human health, proper irrigation facilities, and water resource sustainable development in the affected areas (Moharir et al. 2017; Moharir et al. 2020). The pumping test is a relatively straightforward procedure. A screened aquifer well is pumped, and the drop in groundwater level (drawdown) is recorded at periodic intervals from pumping wells and/or the adjacent monitoring wells (Khadri et al. 2016b). The groundwater level rises as the pumping stops, and this rise is also observed at suitable intervals. The aquifer properties are determined using the measured groundwater levels (Vander Gun and Lipponen 2010; Pande et al. 2021). This is especially important for India, where hard rocks dominate 80 percent of the Indian peninsula and a dominant semi-arid environment (Pathak 1984).

The color of the basaltic flows varies from dark grey to purple and pink. Every lava flow consists of a vesicular upper unit and a huge lower unit that might or may not be fragmented or joined. Inter-trappean alluvium areas separate the two lava flows in certain places. Distinct further hard rocks, the Deccan traps function as a multi-aquifer mechanism, like to a sedimentary rock trend. The Deccan traps, for example, are widely recognized for their extreme groundwater deficit (Khadri et al. 2016; Medici et al. 2021; Pande et al. 2022). The shallow, weathering subsurface water accessible above the Deccan traps in an unconfined state is insufficient to satisfy the ever-increasing pressure on water supplies. Maharashtra is similarly dominated by hard rocks, whose rainfall susceptibility is limited by weathering and primary porosity, as is their volume to store and convey water. As an outcome, water scarcity occurs throughout the summer months, even in sections of the state with high rainfall. Hard rock's aquifer status is determined by secondary porosity, which develops over time due to decomposition and weathering processes (Radhakrishna 1970).

In order to ensure the long-term sustainability of our valuable groundwater resources, aquifer mapping at the necessary level can help with the planning, implementation, and monitoring of many management methods. This will, in turn, help with the success of safe drinking water, improved irrigation services, and overall water resource development sustainability in the country. Large diameter wells are common in Asian and Southeast Asian countries, and they are often a cost-effective method of conducting pumping tests used of the farmer's pump. Some approaches for determining aquifer characteristics from pumping test data involve curve matching and numerical methods. Pumping tests and data interpretation, performed at several places in a basaltic environment, require special attention (Moharir et al. 2020). The results are evaluated and compared by using both numerical and analytical techniques. The aquifer's transmissivity determines the period between the start of pumping and the start of a substantial flow of water from the aquifer to the well. In the absence of other factors, the lower the aquifer transmissivity, the longer the pumping time necessary to provide pumping test data with a clear sign that may be analyzed to infer aquifer parameters (Fig. 1). In this study, we analyzed the characteristics of twelve well datasets using advanced plotting and Theis methods. These pumping wells were extensively examined using aquifer test software and statistical analysis. In this research, our main aim is to contribute to the characterization of basaltic rock aquifer parameters using hydraulic parameters and aquifer test software in the hard rock area, which principal to a practical norm for the scope of recovery of water levels can be observed.
for the understanding of the groundwater levels in the hard rock region.

**Study area**

The village Buchakewadi is located in the Junnar block of Maharashtra's Pune district, India. The village has weathered, fractured, jointed, and vesicular Basalts rock formations. It is located between 19° 9' N and 19° 16' N latitude and 73° 47' E and 73° 64'E longitude, as depicted in Fig. 1 by the Survey of India (SOI) on a 1:50,000 scale. The boundary of the Buchakewadi watershed has been delineated using Survey of India (SOI) Topo-sheet No. E43B16 on a scale of 1:50,000 for delineation of the watershed. The research area is 1028.21 hectares (10.28 km²). With an average annual rainfall of 741.90 mm, it has a continental climate classed as sub-tropical and sub-humid. Summer temperatures range from 40 to 28 °C, while winter temperatures range from 36 to 14 °C. The village's highest point is 1097 m above sea level, while its lowest point is 738 m. The Bhima drainage system includes the primary drainage line. Buchakewadi village is prone to high climatic stresses, further compounding the problem. Figure 2 depicts the Buchakewadi watershed's position. Groundwater is used as a backup source of drinking and irrigation water, ensuring that soil and water stay clean and abundant. It is essential for food security, water resource management, protective irrigation and water supply, crop patterns, soil erosion, drainage efficiency, agricultural land capacity, climate change mitigation, and economic development. Groundwater levels are raised by surface runoff, controlled by factors such as stream kinds, density, and watershed catchments. Maharashtra is basalt and hard rock zone in west-central India, located inside the country's peninsular shield zone. Hard rocks make up around 94% of the whole geographical area, while dispersed sediments and alluvial deposits make up the remaining 6%. The gravel and sand stream channels have developed substantially, as have the thin alluvial deposits. The Deccan Trap Basalt age is 67.4 ± 0.7 million years (Upper cretaceous to Eocene). This rock formed from a cooling lava flow. The basalts are divided into three types: tholeiites, transitional alkali basalts and alkali olivine basalts. Drought and changes in the water table affect a large part of Maharashtra state, directly impacting sustainable crop yields, irrigation, and energy systems.
Methodology

This technique was the first to develop a method for assessing aquifer characteristics from a bore well-pumping test in a restricted aquifer. Since then, multiple methods for examining the pumping test data (time-drawdown) have been created. The pumping test data and information can be useful to planning and creation of hydraulic circumstances, we have calculated the aquifer thickness transmissivity, pumping flow rate and storativity \( T = K_b, Q = TW \) \((dh/dl)\) flow through an aquifer. The procedure of pumping test was used to analyze the information in the Aquifer mapping 2002v.software, which showed a rapid and straightforward approach to understanding the software system's data. It's intended primarily for graphical analysis and interpretation of pumping test results. This software includes two types of methods to generate pumping and slug tests. Implementing a software program to create a pumping test procedure is being used in this research. We have selected the twelve pumping well to understand the depth of wells, aquifer properties, discharge, and recovery of pumping wells. However, the well site is predetermined when an established wells are utilized for testing, when the hydraulic characteristics of a specific site is needed, and it cannot be relocated to a more suitable place. However, when one choose, additional considerations should be made: which criteria are important for selecting pumping wells in the following conditions such as.

1. The hydrogeological parameters must be consistent across short distances and reflective in consideration.
2. The site must not be close railways or motorways where passing trains or heavy traffic might create quantifiable variations in the hydraulic head of a confined aquifer.

Fig. 2 Location map of study area
3. The pumping location must not be area of a present discharging wells.
4. The pumped water must be discharged in method that avoids, its reoccurrence to the aquifer.
5. The gradient of the piezometric surface or groundwater depth should be low.
6. Manpower and tools necessity be capable to scope location definitely.

**Hydraulic properties of aquifers**

The hydraulic parameters of an aquifer are transmissibility ($T$), storage coefficient ($S$), and specific capacity ($C$). The average hydraulic conductivity (m/s) is multiplied by the aquifer thickness to calculate transmissibility (Figs. 3, 4). The capacity of water out or kept per unit surface zone of the aquifer per unit charge in the constituent of head usual to that external at main high temperature is indicated by the storage coefficient, a dimensionless value. The discharge per unit draw determines a well's particular capacity. Pumping tests are performed on wells for a variety of reasons. One of the purposes could be to determine the well's yield. The pumping test results offer information on the well's yield and drawdown. These figures calculate the well's specific capacity or discharge-drawdown ratio. As a result, the well's manufacture capacity is obtained, which aids a selecting pump volume and other factors. Furthermore, the data from the pumping tests offers important information on the aquifer's features. These statistics determine two characteristics: Transmissivity ($T$) and Storativity ($S$). These tests are known as aquifer tests since they provide information on aquifer behavior. This data is crucial for investigations of regional groundwater flow.

**Pumping test**

It is most precise technique to define the aquifer characteristics. This includes the formulation of extracting water from pumping wells at a specific rate and monitoring variation in the groundwater table in pumped well and one or many other wells over time (Theis 1935; Singhal and Gupta 1999). Several techniques for analyzing pumping test information
and predicting aquifer parameters have been proposed by geology and hydrology scientists during the last few years (Theis 1935; Javandel and Witherspoon 1983; Raj 2001). Traditional and numerical techniques would be better for interpreting pumping test data and hydraulic parameters. These methods are included three important norms representing such as (1) graph matching, (2) discovery inflection points, and (3) Field outputs are often visualized and compared to the outcomes of numerical solutions in curved matching techniques Table 2). There are also approaches for evaluating aquifer property from the pumping stage (log–log plots), along with ways for calculating aquifer characteristics from the recovery period (log–log plots). Somewhat, a numerical approach has been used to an individual model to describe a “better fitted” between ground data and modeled outcomes. These all results could be helpful for pumping and recovery levels based on various factors of aquifer mapping. A trial-and-error technique has been used. Typically, the comprehensive calculating technique and the hydrological equation formulas are written into a computer algorithm (s) (Singh et al. 1986). One of the above approaches would be based on fundamental hypotheses about the primary types of wells, such as well diameter, dug well, and bore well. As a result, it is critical to select the appropriate technique of explanation with the help of the ground situations (Kruseman and de Ridder 1970).

### Measurements of pumping test

There are primarily two quantities obtained in pumping test. The extraction rate from the pumping well and the wells’ groundwater table are also monitored here. During

**Table 1** Range of interval between water-level measurements in pumping well

| Time since pump started (min) | Time intervals (min) |
|-------------------------------|----------------------|
| 0–5                           | ½                    |
| 5–60                          | 5                    |
| 60–120                        | 20                   |
| Above 120                     | 60                   |
the pumping test, water depth interpretations are occupied at systematic breaks in all wells. The water level drops quickly in the first several hours of the test. As a result, the water level is observed at regular intervals during the early stages. The difference in water level grows smaller and less as the test progresses. As a result, the assessment gap is enhanced at a later stage. Table 1 lists the most valuable time intervals.

After pumping stops, the water level in the wells is also observed. During the restoration phase, the water level increases fast in the early hours as well. As a result, water table data were measured at small breaks in an early hours. The water table must be observed unless a near-complete restoration has been completed.

Duration of pumping test

As the pumping proceeds, the rate of water table drop reduces. The rise in drawdown is quite minimal after a while. In all other terms, the system has attained a near-steady-state condition. The amount of time it takes to accomplish this situation is defined by the kind of aquifer and the pumping rate. As a result, calculating how long the test should last in advance is challenging. However, as the rise in drawdown decreases significantly during the test, the test can be ended. This state is quickly obtained in a confined aquifer, whereas in an unconfined aquifer, it requires more effort (Table 2).

Data processing

Before being used for analysis, the period drawdown and discharge information obtained during the pumping test is analyzed. The temporal data is transformed into a single unit set. The time is transformed into a single unit after being reported in various units (in days). Water depth data are also standardized to a single unit (in meters). The drawdowns are derived from the water depth obtained during the pumping test. The drawdowns are computed from the water depth available in multiple wells. Similarly, the residual drawdown is calculated using the water level obtained during recovery.

Transmissivity

According to the findings, the value of transmissivity varies from 92.05 m²/day to more than 686.74 m²/day. This monitors the usual design of rising value from east to west, that is, from the upper to lower half of the basin. The hydraulic gradient is likewise gradually increasing. Transmissivity values of 686.74 m²/day (Table 2).

Specific yield

Duration of the specific yield values from 0.0086 m³/day to above 0.0312 m³/day. The locations with the highest yield are nearby to extension fractures then have high lineament values (Table 2).
Fig. 5  

(a) Graph of time versus drawdown of well-1 to well-4.  

(b) Graph of time and drawdown of well-5 to well-8.  

c Graph of time and drawdown of well-8 to well-12
Results and discussion

The findings of the pumping training dataset demonstrate that the transmissivity, specific yield, depth of well, well diameter, aquifer type, and test duration values in every basin are quite comparable, reflecting free drive-in groundwater inside the basin borders with an existence of a permeability barrier near the 'high,' where the numbers decrease dramatically. Various values will also aid in identifying the basin’s boundaries, which are distinct from those of the other rivers in these regards. Given the free circulation of waters within the basin’s borders, the contour shapes could be used to pinpoint the site of a well. The findings from the pumping tests indicate that the region’s groundwater potential is restricted, necessitating cautious management and planning of the accessible water resources. In the basaltic rock mostly, we have found large diameter wells. We have observed the 3.44 m most minor diameter of well-1 values, while 7.20 m highest diameter of well-7. The water depth of wells ranges from 9.00 to 16.45 m. However, eleven wells are above 10 m water level in the basaltic rock. A transmissivity of wells values is range between 290 and 686.74 m²/day. Estimated minimum and maximum specific yield ranges are 0.0086 and 0.1913 (Sy), which are equivalent to the standard ranges of basaltic rock aquifers, and this area found the tough, compact, and massive rock in higher and lower heights entire area. The details of pumping test outcomes values are present in Table 2.

In this study area, we have done 12 pumping selected for pumping test parameters, found out the that their kind of wells such as good, moderate, and poor are reported, as per the hydraulic aquifer data and time vs. drawdown graph we found well-4 and well-8 are shown good potential for the exploration of water, the well-1, 2, 3, 6, 7, 9, 10, 11, and 12 are displayed moderate potential to an exploration of water from the basaltic rock for drinking and irrigation purpose, Whereas one well-5 is under poor potential for groundwater uses. Based on these results, we have suggested that the well-1, 2, 3, 6, 7, 9, 10, 11 and 12 water levels increase due to water conservation and watershed planning and development. At that time, automatically moderate wells will be good options for water utilization under drought situations because of so many climates changing worldwide. At the same time, all-natural resources should be increased and maintained on every local, national and international scale Fig. 5a–c. Only one well is under poor class for groundwater exploration in this area because so much water is used for irrigation and drinking purposes. Water levels in these impoverished areas are steadily dropping, and wells are used frequently for irrigation and drinking. One well has been identified in this zone therefore groundwater development close to this zone is suggested. We have found that rain, winter, and summer seasons are cultivated crops by farmers

![Fig. 6 Plotting of recovery rate of well-1 using aquifer mapping software](image-url)
and that so much water is utilized for irrigation purposes due to rising temperatures. The suggestion includes further developing wells no. 2, 10, and 14, increasing groundwater potential with an upward rise with safe yields, whereas well no. 4 and 8 do not need more improvement because they touched specific yield levels of production. The pumping test results indicated that the area’s groundwater possibilities are restricted, requiring precise planning and utilization of the present groundwater sources (Table 2). We have measured the Time (s) and drawdown (m) graphs of wells using aquifer software 2020v. The curves used for pumping data fitted are shown in Fig. 5a–c.
Theis's type curve method

The proposed type curve approach consists of plotted values of $W(u)$ and $1/u$ on a log–log sheet. The reported values of drawdown and time are plotted on a comparable log–log sheet. The field curve is connected with the type curve, with the curves' axes parallel (Fig. 6). A match point is chosen in the linked situation. The kind of curve is being used to determine the values of $W(u)$ and $1/u$ for this match point. The values of $s$ and $t$ are also taken from the site curve. Therefore, two categories of graphs, such as recovery rate and log–log method, are done to study Theis's curve technique.

Fig. 9 Plotting of recovery rate of well-4 using aquifer mapping software

Fig. 10 Plotting of recovery rate of well-5 using aquifer mapping software
Fig. 11  Plotting of recovery rate of well-6 using aquifer mapping software

Fig. 12  Plotting of recovery rate of well-7 using aquifer mapping software
Recovery rate

In the recovery graphs of 12 wells was prepared using aquifer mapping software for understanding of the how much time require for recharging of wells. This plotting is very properly systemically understood recovery rate of wells. The spatial scattering of the recovery rates increases from bottom of wells and upper side more time required for recharging wells. The regions with the highest recovery rates are also in close proximity to those with the highest optimal yields. The recovery graphs of twelve wells are presented in Figs. 6, 7, 8, 9, 10, 11 and 12.
Time drawn method (log log method)

The method of Cooper and Jacob (1946) improved Theis’s technique and recommended a simple way to obtain a characterization of aquifer parameters. Aquifer mapping software has included all methods related to pumping test analysis. Very few researchers work on the aquifer parameters now (Figs. 13, 14, 15, 16). It is very important to study in the upcoming future and understand the variation of groundwater flow and aquifer characteristics (Pathak...
The technique does not need to be curve fitted. The temporal drawdown information is depicted (time on the log axis and drawdown on the linear axis). The extra situation necessary to usage this technique is test and showed for adequate period so that the range of $u$ must be less than 0.01 (Figs. 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28 and 29). A straightforward graph is marked using the data points, and straight line's slope ($s$) is calculated. The time ($t_0$) where the linear model crosses the time axis is also indicated (i.e. at $s = 0$).

The aquifer parameters are computed by following equations as follows:

$$ T = 2.3 \frac{Q}{(4\pi \Delta s)} $$

$$ S = 2.25 \frac{T_{t_0}}{r.R} $$

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**Fig. 17** Plotting of recovery rate of well-12 using aquifer mapping software

**Fig. 18** Theis’s method of pumping well-1
Correlation matrix

It is nothing more than matrix that shows correlation coefficients for various variables. The matrix denotes the correlation between whole potential value pairings in a table. It's a useful tool for speedily describing a big dataset and finding and visualizing trends in the data. When an increase in one parameter generates a rise in another, the correlation is positive; when an
increase inside one parameter reasons a reduction in another, the correlation is said to be negative. The standard range of correlation coefficient \((r)\) is \(-1\) and \(+1\). In this paper, we have created the correlated heat map for understanding pumping test and aquifer parameters with the help of python programming. We measured the five parameters: well diameter, depth of well, test duration, transmissivity, and specific yield. The correlation heat map systematically explains which parameters correlated with positive and negative values ranging between \(-0.75\) to \(1\) (Figs. 29, 30). Pair plots are my preferred statistical display for understanding mixed data, and the pair plot algorithm creates them automatically (Fig. 31).

Fig. 21  Theis’s method of pumping well-4

Fig. 22  Theis’s method of pumping well-5
Conclusions

This study area needs proper aquifer mapping and systematic groundwater management planning using aquifer methods such as Theis techniques like log–log and recovery rate methods. Aquifer parameter estimate is critical for analyzing and managing groundwater resources. The current trend of increasing water withdrawals from the basaltic rock aquifer to accommodate expanding irrigation requirements, in particular, is anticipated. Currently increase groundwater extraction from shallow aquifers in some regions of India can be beyond what is ecological.
from restricted groundwater resources, as a result, groundwater tables are falling. The possibility of reduced water recharge due to climatic variations will aggravate the issues. Over-abstraction and reduction of water can be enormously costly. A very little research work is available on the shallow aquifer in basalts rock, these have been conducted to better recognize the groundwater structure, measure recharge, and evaluate the impact of pumped agriculture wells on the regional groundwater level. As a result, such a study is required if prudent development for sustainable water and agricultural development is conducted. During pumping studies with poor permeability and wells storage effect is significant in hard rock aquifers. If well storage is neglected, the typical interpretive method provides unclear results. A radial flow model has been proposed to account for the well preservation impact, resulting in an accurate calculation of aquifer characteristics. A comprehensive study plan was devised to ensure the long-term viability of water supplies in the study area. The recharge due to irrigation and precipitation was
calculated using CGWB (2009) techniques. The return flow component model was used to calculate irrigation recharge, while the precipitation infiltration factor and the aquifer fluctuation method were used to assess rainwater recharge. In this research outcome of the study area, small works are being ongoing related to confined aquifer in study area. It is used to know the groundwater scheme and development, calculate water recharge, or measure the impact of pumped irrigation wells on the natural water level. The organized process provided is beneficial not just for manual models but also for programmed models. Using the guidebook technique using adopted procedure, computer models can readily add geological research and expertise to the calibration procedure. The results will be
supportive to development of groundwater resources and aquifer recharging with proper planning of extraction of water from the basaltic aquifer in area. The Theis method has been strongly recommended to examine pumping tests and aquifer characteristics.

Fig. 29  Theis’s method of pumping well-12

Fig. 30  Correlation heat of aquifer parameters
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Data availability The data and materials of analysis should be available from the corresponding author.

Fig. 31 Pair plots of aquifer parameters

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

Consent to participate The manuscript has been read and approved for submission by all the named authors.

Consent to publish Yes, there is consent to publish this paper.

Ethical approval All the contents of this paper are unique and with minimum plagiarism. This manuscript is original, has not been published before, and is not currently considered elsewhere.

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