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ORIGINAL ARTICLE

Well Hydraulics in Parts of Western Vidarbha Region in Deccan Traps, India

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ABSTRACT

Deccan Traps cover about 15% (500,000 sq. km) of India's landmass, and about 82% of Maharashtra state. They deliver fluctuating hydraulic results due to their disposition as a multilayered aquifer system. The drawdown and recovery data of eight exploratory wells in Akola, Buldhana and Washim districts of western Vidarbha region in Maharashtra state were analyzed to define the aquifer characteristics in basalts. Conventional methods such as those suggested by Theis (1935), Jacob-Cooper (1946), Chow (1952) and Walton (1962) were used to estimate aquifer parameters such as transmissivity (T) and storativity (S). The advantages and limitations of these methods were critically examined from their applicability perspective. Estimated values of T ranged from 7 to 133 m^2/day and those of S from 6.05×10^{-4} to 1.63×10^{-2}, showing poor yields in most parts. In this study, Jacob-Cooper (1945) and Theis recovery (1935) methods were found easy to adopt and yielded rapid results compared to Theis curve matching (1935), Chow (1952) and Walton (1962) methods that typically involve either curve matching or complex computational techniques.

INTRODUCTION

Deccan traps occupy almost 15% of landmass in India (Rao et al., 2022), and constitute the major aquifer systems in Maharashtra state covering about 82% of its geographical area (Kulkarni 2000). They were formed by a series of basaltic lava flows that erupted through fissures in upper Cretaceous to Paleocene Epoch (Sprain et al, 2019; Krishnamurthy, 2020). These basalts represent a multi-layered aquifer system in which a water bearing layer is typically sandwiched between two massive basaltic layers (Singhal, 1997). While primary porosity in basalts is due to presence of vesicles, flow contacts and lava tubes, secondary porosity is due to fracturing, jointing and weathering. Deolankar (1981), Kulkarni et al. (2000), Naik et al. (2001), Duraiswami et al. (2012) have described in detailed the occurrence and movement of groundwater in basalts.

The Vidarbha region (Fig. 1) in Maharashtra State within the Deccan traps has been in bad light due to the highest number of farmer suicides in the country. From 2001-2018, the region recorded about 17,547 deaths of farmers due to suicides (Talule, 2020). Dongre (2012) ascribe these deaths to debt, poor pricing, crop failure, etc. One of the major causes of farmer suicides is possibly the high rain dependency on farming. Erratic rains and spells with longer gaps leave no stone unturned in destroying crops unless supported by groundwater resources. But overdependence on groundwater has led to its over-exploitation and consequent depletion. Farmer centric policies for subsidized power and easy loans for sinking deep borewells have exacerbated the situation (Duraiswami, 2007; 2008). Many larger dams have been constructed in the region, but somehow they fail to deliver the anticipated results. In summer people suffer from non-availability of clean and safe drinking water. While surface sources aren't enough for water supply, groundwater table reaches extremely lower levels often with deteriorated quality (Kelker, 2013).

Aquifer parameters such as transmissivity (T) and storativity (S) play important roles in monitoring changes in groundwater levels, assessing the groundwater potential, identifying water stressed zones and demarcating areas suitable for recharge/withdrawal. Transmissivity (T) is the rate at which groundwater of the prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient (Lohman et al., 1972). It is a function of liquid properties, the porous media, and the thickness of the porous media, i.e., aquifer (Fetter, 1994).

Storativity or coefficient of storage (S) is the volume of water that a vertical column of the aquifer of unit cross-sectional area releases from storage or takes into storage as the average head within this column declines or rises at a unit distance (Todd, 2005). In a confined water body, the water derived from storage with decline in head comes from expansion of water and compression of the aquifer. Similarly, water added to storage with a rise in head is accommodated partly by compression of water and partly by expansion of the aquifer (Moore, 2012). In an unconfined water body, the amount of water derived from or added to the aquifer by these processes generally is negligible; hence, in an unconfined water body, the storage coefficient is virtually equal to the specific yield (Lohman et al., 1972).

The objective of this contribution is to estimate aquifer parameters (T and S) in parts of Akola, Buldhana and Washim districts in western Vidarbha region of Maharashtra state (Fig. 1), draw a comparative analysis of these parameters from different conventional methods and find out the most suitable methods in basalts in different field conditions. Several workers have worked on the T and S values in basalts in various parts of the world (Singhal, 1997; Gingerich,

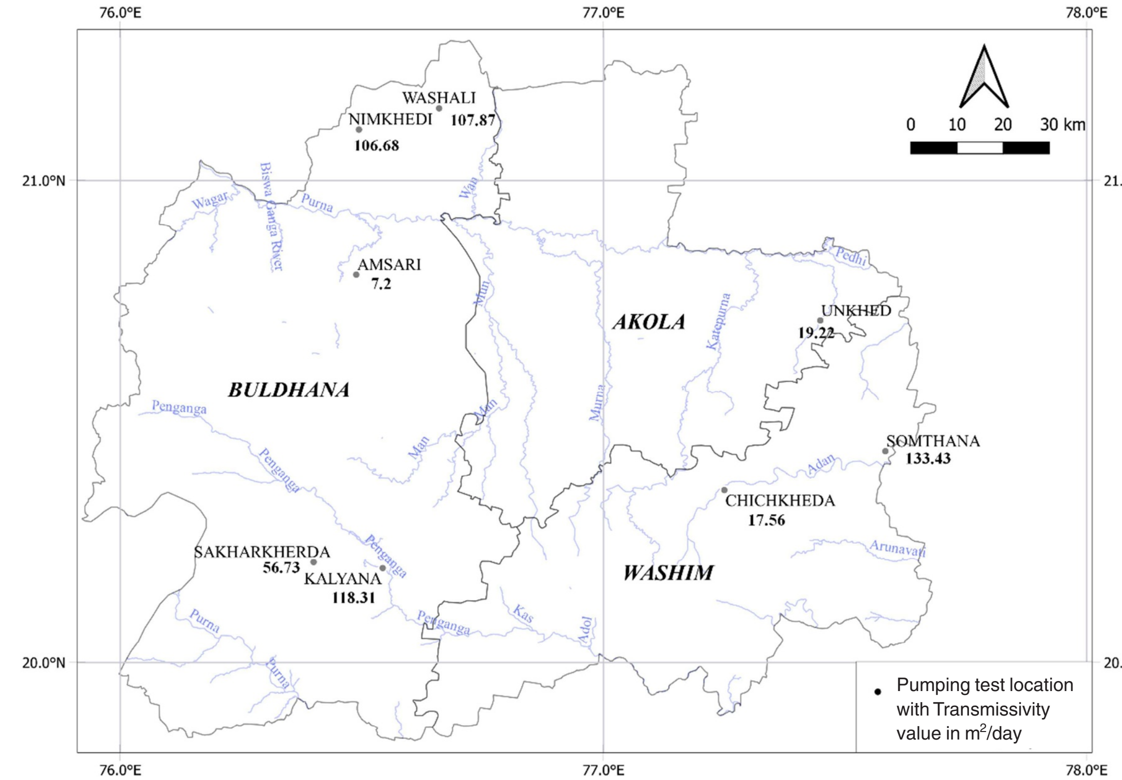

Fig. 1. Study area in parts of western Vidarbha region in Akola, Buldhana and Washim Districts, Maharashtra State, India.

1999; Naik et al., 2001; Jalludin and Razack, 2004; Moghaddam and Fijani, 2009; McGrail et al. 2011; Duraiswami et al., 2012; Varade et al., 2014; Katpatal et al., 2014; Hagos et al., 2021). This work, therefore, has global applicability.

STUDY AREA

The study area in parts of Akola, Buldhana and Washim districts of western Vidarbha region in Maharashtra State is bounded by N latitudes 19°30'36" - 21°10'12" and E longitudes 75°34'12" - 77°40'. The area has a population of about five million. It is drained by the tributaries of the Tapti and Godavari Rivers, such as the Purna, Penganga, Morna, Man, Arunavati and Katepurna. Major irrigation structures built in their catchments are mostly earthen dams, which store and supply water for irrigation and domestic purposes. Southwestern monsoon with an average rainfall of 750-900 mm is the major source of groundwater recharge, and the major crops sown are cotton, gram, soyabean, pulses, cereals, etc.

Hydrogeology of the region district-wise has been described by CGWB in detail (CGWB, 2018a, b; 2019). The geology is mostly composed of Deccan trap lava flows that are highly heterogeneous in nature. Groundwater occurs under unconfined to confined conditions from shallower to deeper levels. Dugwells tap the shallow aquifers at depths ranging between 5 and 34 m; deeper aquifers are tapped by borewells at 30-180 m depth.

Groundwater levels in shallow aquifers generally vary between 4 and 25 m below ground level (mbgl) during premosoon season and between 2 and 12 m bgl during postmonsoon period with a seasonal fluctuation of 1-15 m. The well yields in the region have been a function of aquifer permeability and transmissivity. With a moderate amount of rainfall, the higher seasonal fluctuations in the dugwells tapping the hard massive basalt are indicative of poor transmissivity of aquifers, because much of the recharge remains stored in these dugwells rather than being transmitted into the adjoining aquifer material.

Well yields are generally poor in the region and groundwater levels have a declining trend due to inadequate saturation of aquifers. It is estimated that groundwater levels have declined at least to up 4 m during the past two decades in the region.

PUMPING TESTS

Values of the aquifer parameters based on pumping tests are the most reliable, so selection of the right method for computation of these parameters is important (Kruseman and De Ridder, 1970). Several methods have been introduced by researchers for conducting pumping tests, but these methods depend on several factors, such as type of aquifer, type of well, field assumptions, etc.

There are broadly two types of methods used during pumping tests viz. conventional methods and numerical methods. Conventional methods are based on either curve matching or straight-line fitting to pumped data or finding an infliction point. Therefore, results from these methods are often user-dependent. Some of the conventional methods are those of Theis (1935), Jacob-Cooper (1946), Theis-Recovery (1935), Chow (1952) and Walton (1962). Numerical methods generate best fit between the modeled results and the actual field results and are model-dependent.

In this study, pumping tests were conducted by the second author in eight different exploratory wells drilled by Central Ground Water Board (CGWB), Department of Water Resources, River Development and Ganga Rejuvenation, Ministry of Jal Shakti, Government of India. These wells are listed in Table 1 and shown in Fig. 1. Their well logs are shown in Supplementary Fig. S1.

During the tests, pumping of the wells were carried out for a period of 900-1060 minutes and recovery for 100-900 minutes. Depth to water levels during pumping and recuperation phases in these wells were recorded at site in both exploratory wells and their observation wells. Later these data were converted into drawdown and residual drawdown formats. Water samples were also collected at different depths for quality analysis. Litho-logs were prepared to understand the geology at site (Fig. S1). The conventional methods mentioned above were then applied to estimate the aquifer transmissivity and storativity. Detailed procedures how to apply these methods with examples have been given by CGWB (1992).

RESULTS AND DISCUSSION

Estimated T and S Values in the Study Area

The data collected during pumping tests at different exploratory sites are presented in Table 1. Fig. 2 shows the selected data plots by various methods. While Table 2 tabulates the aquifer parameters (T and S), Fig. 1 shows their distribution in the study area. Transmissivity values in the area vary between 7 – 133 m^2/day and S values between 6.05×10^{-4} – 1.63×10^{-2}. The S values are indicative of semi-confined to confined aquifers at depth (Cheremisinoff, 1997). These parameters are highly dependent on the degree of weathering, intensity of joints and fractures and topographic setting of the aquifers. Therefore, the potential areas for groundwater occurrence are highly localized due to large variation in the secondary porosity developed by these features.

Applicability of Various Methods for Estimation T and S

Theis type curve method (1935) is used for analysis of unsteady state of flow in confined aquifers, when field data plot of drawdown (s) versus time (t) on a double-log paper makes a good match with the standard type curve for estimation of T and S values. It cannot, however, be applied effectively to flatter curves since only few matching points can be located.

Cooper-Jacob's straight-line method (1946) can be applied for smaller value of u (i.e., u ≥ 0.01) when the observation well distance (r) from the pumped well is small and duration of pumping (t) is large.

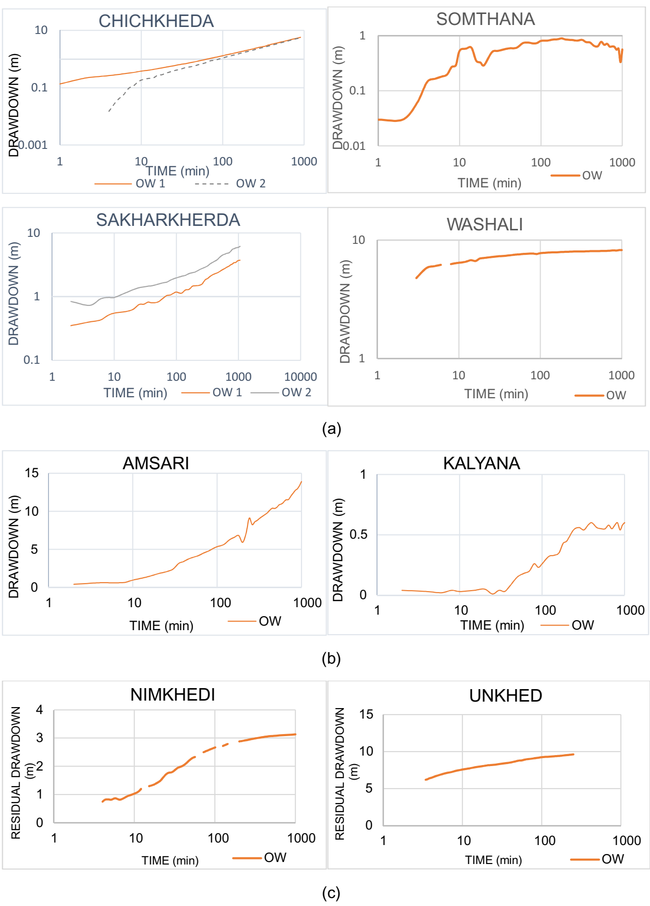

Fig. 2. Field data curves in various methods used in this study: **(a)** Theis type curve (1935) and Walton (1962) methods, **(b)** Jacob-Cooper method (1946), **(c)** Theis recovery method (1935).

It can also be applied when the plot of drawdown (s) versus log (t) is a straight line. This method cannot be applied to pump test data of shorter duration or for observation wells located at a greater distance from the pumped well. This method is easier to apply and interpret.

Chow's method (1952) can be applied to any value of u, as there is no restriction for the observation well distance to be smaller or pumping duration to be larger. Also, it overcomes the flaws of curve matching as in case of Theis type curve method (1935). But this method is based on interpolation and calculation of values from pre-defined tables, making it complex and dependent over some external data which may not be relevant to the actual site conditions.

Theis recovery method (1935) is best applicable to wells where observation well data are not available. Analysis includes matching of a straight line with the residual drawdown data (s') collected after termination of pumping. This method is applicable to small diameter wells (so that storage within the well can be neglected) and smaller value of u' (i.e., observation well distance (r) from the pumped well is small and duration of pumping (t) is large). This method is the most effective method to analyze pumping well data. Storativity cannot be estimated by this method.

Walton's type curve method (1962) is used for the analysis of unsteady-state flow in a semi-confined aquifer without release of water from storage in confining beds. Technically this method is much better than other methods due to consideration of leakage factor. The geology of the Deccan basalts makes the leakage factor essential for accurate estimation and validation of pumping test results. Shorter duration pumping tests can be analyzed using this method. However, when a sufficient number of initial points are not available, it becomes difficult to find a match with Walton's family type curves.

Theis curve matching method (1935) and Walton method (1962) are difficult to use because of disparity in estimated results due to curve matching. These methods need log-log plots between drawdown and time. The estimated values of transmissivity vary in the curve matching method if data are highly varying, since most of the plotted data do not overlap with the standard type curves. For example, field data curves for Amsari, Sakharkherda, Unkhed, Washali and Chichkheda matched well with standard curves, while matching was not as good for Somthana, Kalyana and Nimkhedi that showed undulated plots (not shown in figure).

Again, while applying Theis recovery (1935) method, Nimkhedi Unkhed, Somthana, Sakharkherda, Washali, Chichkheda and Amsari showed rapid recovery in the beginning with steep slope, and later became flatter with time. Kalyana was the only station which displayed highly fluctuating recovery with lots of crests and troughs in the graphical representation (not shown). Possible reasons for these undulations could be faulty measurement or parallel pumping or recharging in nearby area. Some plots have discontinuous lines due to non-availability of time or drawdown data (ex. Nimkhedi – not shown).

Trinchero (2008) too observed similar problem in type curve matching methods. Even the non-type curve matching methods, such as those of Jacob-Cooper (1946), Theis-Recovery (1935) and Chow (1952), often show similar problems when a straight line is plotted as the best fit line from the dispersed data plots. For example, in Jacob-Cooper (1946) method, plotting of field data plots for the well sites Amsari, Sakharkherda, Unkhed and Washali was easy, while the data for Somthana, Kalyana, Nimkhedi and Chichkheda were highly fluctuating to trace the best fit line. Results can be processed with fluctuating data too, but they may not be as reliable.

Highly dispersed data are mostly due to errors while conducting pumping test, such as draining of pumped water in proximity to the pumping well, discontinuous discharge from the pump, other pumps being operated nearby or measurement errors. Therefore, an approach to ensure least errors in field data measurements must be adopted to achieve best possible results while conducting pumping tests. Besides,

Table 1. Field data at the exploratory well sites in parts of western Vidarbha region in Deccan Traps, India.

Location with District name	Latitude	Longitude	Type of well	Depth of well (mbgl)	Static water level (mbgl)	Fracture zones encountered		Discharge (m^3/day)	Pumping duration (minutes)	Drawdown (m)	Recovery duration (minutes)	Recovery (m)	Distance of observation well (m)
						Depth (m bgl)	Type of formation						
Amsari	20.805	76.4883	EW	158.50	7.29	19.5-23	JMB			15.84		12.86	
(Buldhana)						80-83	FMB	287.71	1000		100		17
			OW	200	7.72	92-95	FMB			13.9		10.11	
						156-158.5	FVB						
Chichkheda	20.3575	77.25	EW	82	35.58					5.79		2.62	
(Washim)			OW-1	112.05	35.04	74-76	JMB	619.49	900	5.74	900	2.61	16.55
			OW-2	74.45	36.23	77-82	FVB			5.51		2.55	36.55
Kalyana	20.19583	76.54305	EW	200	6.04	7-13.5	JFMB			1.93		0.22	
(Buldhana)						83.50-89	JFMB	312.77	1000		200		
			OW	200	6.23	108-111	JFMB			0.6		0.35	29.05
						161-163	JFMB						
Nimkhedi	21.1061	76.49388	EW	135.45	34.93	12-14.5	WFMB	911.52	1000	3.17	330	2.41	20
(Buldhana)			OW	130.35	34.86	61-65	JMB			3.42		2.38	
Sakhar-kherda	20.20833	76.4	EW	141.55	4.83	9-15	JFVB			6.75		4.42	
(Buldhana)			OW-1		4.63	108-110	JFVB	979.78	1060	3.73	320	2.17	25.90
			OW-2	143.55	4.67					6.15		4.05	11.80
Somthana	20.4388	77.5833	EW	115	8.58	10.35-13.45	JMB	353.89	1000	12.38	140	8.23	28.70
(Washim)			OW	123.25	6.15	22-25.65	FMB			0.89		-0.28	
Unkhed	20.70944	77.44861	EW	111.15	2.42	74-77	WFVB	466.56	1000	10.52	410	3.58	
(Akola)			OW	111.05	2.88	91.75-92.75	FMB			10.24		3.43	17.85
Washali	21.15	76.65972	EW	160	16.73	48-53	JFMB	692.92	1000	19.63		9.26	12
(Buldhana)			OW	123.25	16.38	92-96	FVB				310		
						108-117	JMB			8.24		4.54	

Abbreviations: EW = Exploratory Well, OW = Observation Well, bgl = below ground level. JMB= Jointed Massive Basalt, FVB= Fractured Vesicular Basalt, JFMB= Jointed and Fractured Massive Basalt, FMB= Fractured Massive Basalt, WFMB= Weathered and Fractured Massive Basalt, JFVB= Jointed and Fractured Vesicular Basalt, WFVB= Weathered and Fractured Vesicular Basalt.

Table 2. Estimated transmissivity and storativity values by different methods in parts of western Vidarbha region in Deccan Traps, India.

S. No	Place	Discharge m^3/day	Theis method (1935)		Jacob method (1946)		Chow's method (1952)		Theis recovery (1935)	Walton's method (1962)		Average	
			T (m^2/day)	S	T (m^2/day)	S	T (m^2/day)	S	T (m^2/day)	T (m^2/day)	S	T (m^2/day)	S
1.	Amsari	287.71	6.54	$9.12x10^{-4}$	9.4	$5.59x10^{-4}$	6.37	$9.4x10^{-4}$	4.54	9.158	$6.16x10^{-4}$	7.2	$7.57x10^{-4}$
2.	Chichkheda	619.49	16.43	$1.50x10^{-2}$	-	-	24.61	$1.39x10^{-2}$		14.092	$2x10^{-7}$	17.56	$5.80x10^{-3}$
			16.43	$3.42x10^{-3}$	17.39	$2.48x10^{-3}$	-	-	-	16.44	$2.7x10^{-6}$		
3.	Kalyana	312.76	99.61	$7.54x10^{-3}$	106.09	$1.87x10^{-2}$	124.35	$4.74x10^{-3}$	143.18	-	-	118.31	$1.03x10^{-2}$
4.	Nimkhedi	911.52	120.89	$7.56x10^{-4}$	114.27	$7.36x10^{-4}$	100.57	$1.02x10^{-3}$	106.94	90.71	$7.56x10^{-4}$	106.68	$8.38x10^{-4}$
5.	Sakhar-kherda	979.77	51.98	$1.40x10^{-2}$	62.27	$9.57x10^{-3}$	51.92	$1.26x10^{-2}$	91.03	48.73	$1.41x10^{-3}$	56.73	$1.63x10^{-2}$
			43.32	$3.24x10^{-2}$	34.75	$3.23x10^{-2}$	55.30	$2.49x10^{-2}$	83.40	44.55	$3.47x10^{-3}$		
6.	Somthana	353.89	140.80	$6.65x10^{-4}$	142.35	$5.40x10^{-4}$	138.66	$6.10x10^{-4}$	104.47	140.88	$6.65x10^{-4}$	133.43	$6.05x10^{-4}$
7.	Unkhed	466.56	9.28	$4.45x10^{-3}$	11.24	$3.08x10^{-3}$	12.99	$3.29x10^{-3}$	50.23	12.38	$3.24x10^{-3}$	19.22	$3.51x10^{-3}$
8.	Washali	692.92	100.31	$3.87x10^{-8}$	105.74	-	-	-	133.5	91.95	$2.13x10^{-7}$	107.87	

Abbreviations: T = Transmissivity, S = Storativity with increasing number of assumptions and interpolations, actual field conditions are heavily compromised that ultimately reflect in the final results of the aquifer parameters.

In fact, not all methods give similar results due to consideration of a number of different parameters in each method. This is the reason that T values by different workers often vary widely even within the same type of aquifer because most of them select only the method they feel convenient to use. Inhomogeneity in basalts further adds to this problem.

Theis (1935), Jacob (1946), Chow (1952) and Theis recovery (1935) are good for confined aquifer systems, while Walton (1962) specifically focusses on semi-confined aquifers. Often, these methods ignore the vertical flow of water in the formation. Ignoring vertical flow of water or contribution to aquifer leads to reduced estimated parameter values. Jacob (1946) requires large pumping duration for satisfying results, whereas Chow (1952) removes this constraint and allows to work on short duration pump tests. So based on assumptions and parameters involved in estimation, all methods cannot yield similar results. Small variations can be justified, while large variations must be looked upon for the method(s) used, quality of field data, formation type and standard practices followed.

Despite these field constraints, of all the methods discussed, for convenience in application and quicker results, Jacob-Cooper (1946) and Theis-Recovery (1935) methods may be adopted. These methods are easier to apply since they do not require any curve-matching or complex computations using predefined values. Theis-recovery has an added advantage that estimations can be done using a single well; no observation wells are required. In case of low budget exploration, this method is very useful.

SUMMARY AND CONCLUSIONS

Aquifer parameters, such as transmissivity and storativity, were estimated from eight exploratory well sites of depths varying between 82 - 160 m in parts of Akola, Buldhana and Washim districts of western Vidarbha region in Maharashtra state, India in Deccan traps. The pumping duration varied between 900-1000 minutes and that of recuperation between 100-900 minutes. Transmissivity values were as low as 7 m^2/day at Amsari (Buldhana) to as high as 133 m^2/day at Somthana (Washim). Storativity values ranged between 6.05×10^{-4} and 1.63×10^{-2} at Somthana and Sakharkherda sites, respectively, in Washim and Buldhana districts.

Application of a suitable method for estimation of aquifer parameters solely depends upon field data plots. If a data plot can be easily overlapped over a standard curve, Theis curve matching method (1935) or Walton's method (1962) may be applied. But in this study, Jacob-Cooper (1945) and Theis-Recovery (1935) methods yielded rapid results and were found easy to adopt compared to Theis curve matching (1935), Chow (1952) and Walton (1962) methods.

Theis-Recovery method (1935) can be used when no any observation well is available at an exploratory site or an observation well does not show any change in water levels. Jacob-Cooper (1946) and Theis-recovery (1935) methods are easy to use because of their simplicity in data processing and obtaining results, as no curve matching is required or tabular values are needed to be referred. Chow method (1952) is simple to use, but its dependence over a predefined table often limits its results within a certain range and restricts its usage.

Highly dispersed data at some stations led to doubtful and erroneous end results. In fact, even if curve matching methods are not used, dispersed data do not provide authentic results in any of the methods. Since quality of data impacts the test outcomes, a better, easier and more accurate procedure to collect field data must be worked upon.

The outcome of this work has global applicability in all basaltic terrains across the world. How these methods work in other hard rock terrains need to be worked upon in the future.

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