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Pumping test analysis for assessment of hydraulic parameters and aquifer system formation in hilly terrain

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ABSTRACT

Groundwater conditions (GWCs) of an area depends on aquifer hydraulic parameters such as storativity (*Sr*) or storage coefficient (*Sc*), transmissivity (*Tr*) and hydraulic conductivity (*k*). It plays a key role concerning groundwater flow modeling, well performance, solute and contaminant transport assessment and also for identification of areas for additional hydrologic testing. Specifically, the geologic formation of a region controls the porosity and permeability; however, in hilly terrain prospecting ground water potential is more challenging due to its limited extent and its occurrences that are usually confined to fractures and weathered rocks. The present study aims at estimating the hydraulic parameters through pumping test analysis to assess aquifer system formation on hilly terrain from 16 bore wells. The aforesaid parameters were examined through a case study in some selective regions of Hamirpur district of Himachal Pradesh, India. The study area is controlled under two main geological horizons that is the post-tertiary and tertiary. The papers end with comparative results of hydraulic parameters and the aquifer systems formation on different GWCs, which may be helpful in the outlook of sustainable groundwater resource in the regions.

Key words: aquifer system formation, hilly terrain, hydraulic parameters, pumping test

HIGHLIGHTS

- To ensure proper management of vital groundwater resources a prior knowledge of aquifer parameters is essential.
- The majority of observation wells are at low potential zones are based on Gheorghe Standards.
- Formation materials by and large are claystone, claystone along with traces of conglomerates, sandstones and gravels mixed.
- Two aquifer systems, i.e. confined and a free layer (unconfined) aquifers exists in the study area.

INTRODUCTION

Groundwater is the vital source of fresh water supply for industrial, agricultural and domestic purposes and hence largely contributes to the economic development of a region. Several inherent advantages of groundwater against the surface source escalate its demand. However, due to rapid population growth, urbanization and overwhelming pollution, there is an urgent need to ensure efficiently its sustainable utilization. Thus, to ensure proper management of vital groundwater resources, a prior knowledge of aquifer parameters is necessary. Groundwater zones designate the water bearing formation in the earth crust that acts as conduits for transmission and as reservoirs for storing water. Prospecting potential groundwater zones is a crucial task for the hydrogeologists especially in hilly terrain regions and those areas exposed to arid and semi-arid climatic conditions (Chandra *et al.* 2010). The availability of groundwater in hilly terrain is of limited extent because its occurrences that are usually confined to fractures and weathered rocks. The distributions and location of groundwater can be examined based on direct or through indirect analysis of some observable terrain features such as geologic, geomorphic, landforms and their hydrologic characteristics (Ndatuwong & Yadav 2014). For the past few decades characterizing aquifer systems and identifying groundwater resources has become of prime importance in the field of hydrogeology (Lachaal *et al.* 2011).

Conversely, mismanagement of water resources in an area causes negative effects including depletion of the aquifer storage, declination of groundwater level, seawater intrusion in coastal areas, land subsidence, quality deterioration and thereby creating environmental problems in other water bodies (Voudouris 2006). Such problems could be better understood by evaluating the local geological and hydrogeological characteristics that account for the hydraulic properties of these aquifers (Konkul *et al.* 2014). Hence, the necessity for groundwater management and the conservation studies at watershed level has gained importance worldwide (Gaur *et al.* 2011). In addition, proper delineation of potential groundwater resource is of prime importance in the scheme of water resource management (Bhuiyan 2020).

Pumping test is one of the suitable means for computing reliable and representative values of the hydraulic characteristics of aquifers (Kruseman & de Ridder 1994; Mawlood 2019). Pumping rate, flow pattern of groundwater due to pumping, etc. plays an important role for the management and sustainable development of groundwater resource (Zahid *et al.* 2017). The test is attempted by pumping a well at an almost constant pace while measuring water level variations at the same pumped well and a nearby well if possible (Mawlood & Ismail 2019).

It is estimated that 10 percent of the world's food supply is based on unsustainable pumping of groundwater (World Bank 1998). Hence, in order to evolve pragmatic and scientific planning for the management of groundwater resources, one needs to quantify the characteristic of hydro-geologic parameters. This requires knowledge of aquifer properties, specifically hydraulic conductivity and transmissivity (Sinha *et al.* 2008; Sattar *et al.* 2014).

The present study conducted a pumping test analysis for the estimation of hydraulic parameters and examined aquifer system formations in hilly terrain. The study use 16 bore wells in some selected regions of Hamirpur district, Himachal Pradesh, India.

Study area description

Hamirpur district is one among the 12 districts of Himachal Pradesh (H.P), India covering a total area of 1,118 sq. km (2.01% of total state area). It lies between latitudes 31 °24′ 48″ to 31 ° 53′35″ and longitudes 76 °17′50″ to 76 ° 43′42″ and is separated from Kangra district by Beas river in the north, Bakar and Sir khads from Mandi district in the east while Una district falls in its west and it touches Bilaspur district in the south. The district terrains are mostly undulating and hilly. The surface elevation ranges from 400 m to 600 m above mean sea level (MSL) along the Beas river valley and in lower reaches of Kunah Khad in the northern part of the district. In the eastern part, the district elevation is above 900 m above the MSL. The variation in altitude is typically in between 600–900 m above MSL. The western side hill ranges of Sola Singhi mark the boundary, with elevation reaching about 1,145 m above MSL. However, in the north-eastern region gorges and deep gulleys form part of the district. Figure 1 shows the map of the study area.

Geological set-up and lithology

The study area comprises two main geological horizons; that is, the post-tertiary and tertiary formations. Major portions of the study area are underlain by tertiary formations, which are characterised by Siwalik-type rocks (Upper, Middle and Lower Siwalik). Figure 2 shows the geological map of the study area. Table 1 summarizes the geological sequences and the lithological details of the study area. Upper Siwaliks consist of conglomerates, coarse-grained sandstones, interbedded with grey and pink clays/silts and sand stone or pebble beds. Middle Siwaliks are comprised of massive sandstone, medium to coarse-grained sandstone with claystone and conglomerate. Conversely, the lower Siwaliks have massive dark grey sandstone and purple shales that are overlain by the micaceous sandstone and grey clay/shales of the middle Siwalik.

Hydrogeology

The nature of the aquifers in the study area is of discontinuous and isolated types. The permeability and porosity settings of the study area are low to moderate and hence the aquifers underlain are not of high yielding types. The eastern part of the study area is widely underlain by boulder beds and conglomerates which are hard and compact, and are usually the reason behind low water bearing horizons. However, in low topographic regions the compact conglomerates formations is overlain by weathered conglomerates, forming potential and shallow aquifers. In the western and central regions feasible groundwater zones are found near major thrusts or faults in sandstone formations having fracture and contact zones.

Due to varied topography and geological structures development of groundwater, the area can be broadly discussed as hilly and valley regions. In the hilly regions, springs are the major source of groundwater development and based on ways of tapping they are called by many names in regional languages such as Bowris, Magars,

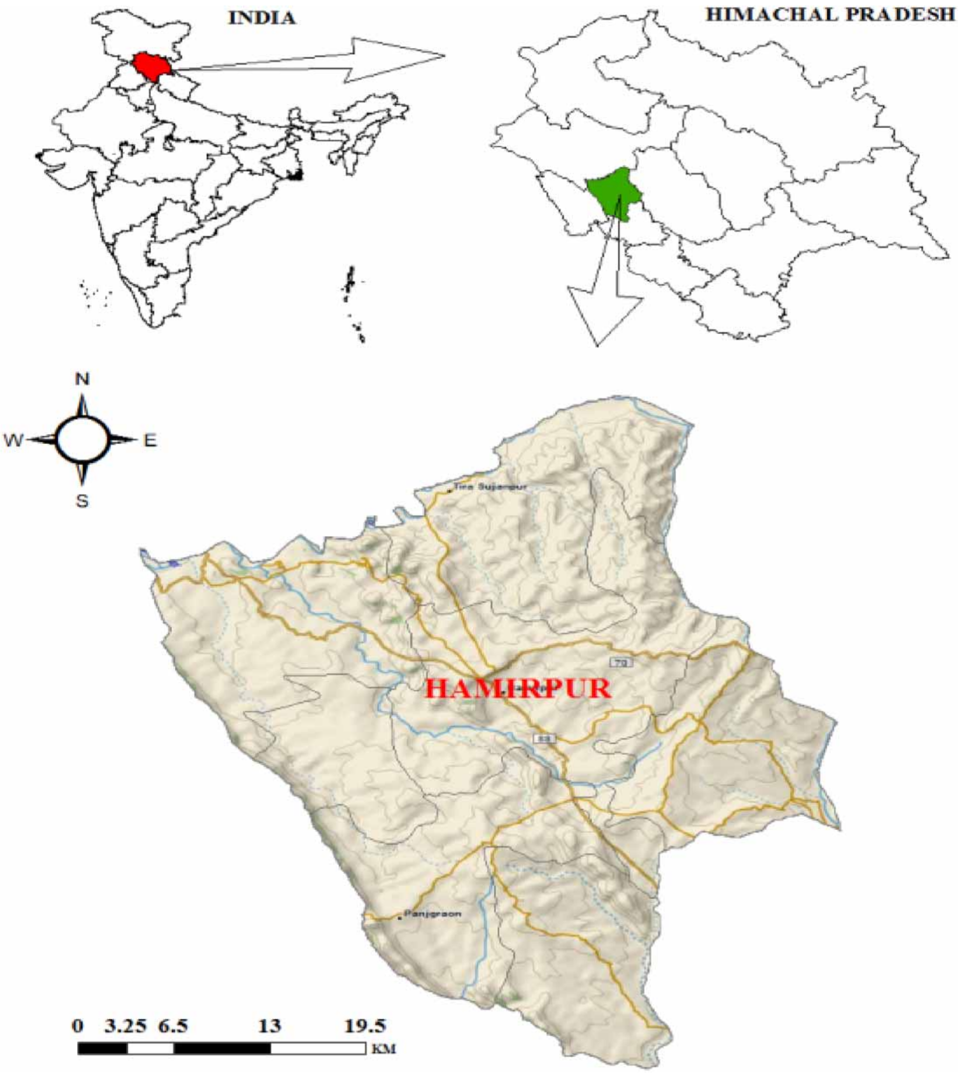

Figure 1 | Study area.

Chasmas, and so on. Few tappings are done through state agencies like Irrigation & Public Health Department (I&PH) through some schemes to feed the inhabitants. Overall, in the hilly regions, sources of water for domestic and agriculture are obtained through open and/or tube wells, springs and hand pumps. On the other hand, valley areas in comparison to hilly areas are densely populated, thereby inflicting more demand for water for agriculture and domestic purposes. However, in such areas, the state agencies serve various water supply schemes extracted from nearby major rivers, streams (or Nallas) or tributaries with a perennial nature.

MATERIALS AND METHOD

Pumping test data from 16 boreholes were obtained from the study area. Table 2 summarizes the details of the boreholes considered for the hydraulic properties' assessment. The study area is categorized into two main regions (i.e. upper and lower regions) based on ground elevation and well locations. The upper region wells are located in the elevation range ≥ 800 m while the lower region lies below 800 m. The calculations involve applications of two methods, viz. the Cooper Jacob and Theis methods.

Theis (1935) found non-steady flow of groundwater to be analogous to the unsteady flow of heat in a homogeneous solid. The equation is then recognized to be most widely used in transient groundwater hydraulics. The solution in terms of drawdown can be defined as:

$$s(r,\ t) = \frac{Q}{4\Omega T} W(u) \tag{1}$$

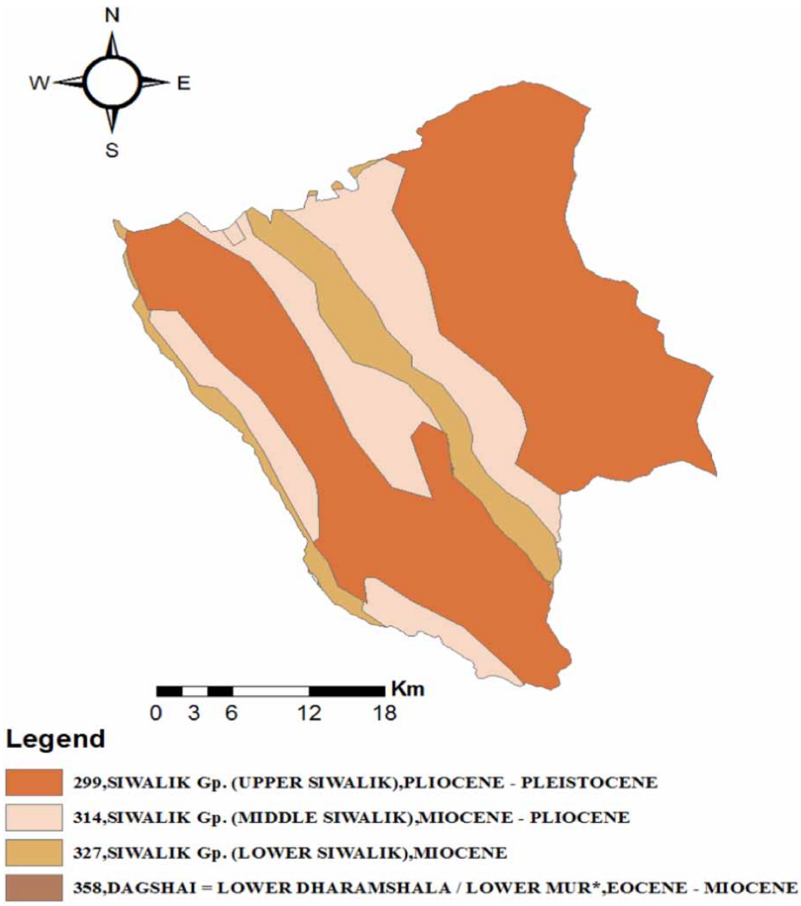

Figure 2 | Geological map of the study area.

Table 1 | Geology and lithology details of the study area

Group			**Lithology**	**Thickness**
Newer alluvium			**Sand, silt, gravel and pebbles**	**Variable**
Siwalik Group	Upper Siwalik	B	Predominantly massive conglomerate with red and orange clay as matrix and minor sandstone and earthy buff and brown clay stone	2,300 meter
		A	Sandstone, clay and conglomerate alternation	
	Middle Siwalik	B	Native claystone variegated and prodigious claystone with alternated conglomerate.	1,400–2,000 meter
		A	Predominantly medium to coarse- grained sandstone and red clay alternation, soft pebbly with subordinate clays stone, locally thick prism of conglomerate	
	Lower Siwalik	B	Calcareous cement, pebbly sandstone alternation (fine-medium), claystone (median maroon-chocolate form) in the mid-segment.	1,600 meter
		A	Claystone (mauve-red) having interpolated medium-fine grains of sandstone.	

where, $s(r, t)$ designates the drawdown at a radial distance r from the well at time t after the start of pumping, $u = r^2 S/4Tt$ is the dimensionless quantity that varies with r of the observation well at time t, T represents the transmissivity (m^2/day) and Q denotes the pumping rate (m^3/d). S is the aquifer Storativity (dimensionless) and $W(u)$ is the dimensionless exponential integral known as well function which can be approximated as:

$$W(u) = \int_u^\infty \frac{e^{-y}}{y} dy = -\gamma - lnu + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} + \dots \quad (2)$$

Table 2 | Wells spatial locations and other information

Latitude	Longitude	Well Nos.	Water table (m)	Well depth (m)	Flow rates (m^3/s)	Source type
31.707	76.523	W1	18.00	60	16.66	Bore well
31.709	76.526	W2	12.00	50	15.10	–
31.702	76.524	W3	39.00	65	11.11	–
31.704	76.524	W4	25.00	70	10.10	–
31.704	76.525	W5	60.00	70	8.90	–
31.704	76.525	W6	72.00	150	8.5	–
31.707	76.529	W7	81.00	150	8.5	–
31.706	76.527	W8	90.00	150	8.5	–
31.675	76.533	W9	98.00	120	8.5	–
31.676	76.534	W10	102.00	120	8.5	–
31.884	76.584	W11	2.73	80	446	–
31.872	76.641	W12	1.67	40	946	–
31.494	76.497	W13	4.13	82	66	–
31.624	76.707	W14	9.60	84	20	–
31.759	76.367	W15	5.32	82	1,078	–
31.735	76.352	W16	5.16	61	150	–

where, γ denotes the Euler`s constant with a value of 0.577215665. The well function $W(u)$ and $1/u$ is determined through the Theis curve matching technique. In this technique, two log curves (double log) are combined i.e. elapse time (t) against drawdown (s) with the standard Theis curve.

The Cooper & Jacob (1946) method is a simplification of the Theis method (Theis, 1935) as mentioned above in Equations (1) and (2). In other words, the Cooper-Jacob method involves truncation of the infinite Taylor series that is used to estimate the well function $W(u)$.

Such truncation leads to avoidance of data that are measured at early stage, and were not counted as valid for the analysis. It is valid for $u \leq 0.01$ (u values having error of 0.02 i.e. 2% error is acceptable). Thus, u becomes small, for small values of r and at large value of time t, Equation (2) can be written as:

$$W(u) = -0.5772 - \ln(u) \tag{3}$$

After substituting $W(u)$ in Equation (1), the resulting equation becomes:

$$s = \left(\frac{2.3Q}{4\Pi T}\right) log_{10}\left(\frac{2.25Tt}{r^2 S}\right) \tag{4}$$

$$s = \left(\frac{Q}{4\pi T}\right) ln\left(\frac{2.25Tt}{r^2 S}\right) \tag{5}$$

Based on the observations of t and r values the Cooper-Jacob method can be used in three ways: (a) Time-Drawdown Method (when r is constant; that is, the observation well is fixed); (b) Distance-Drawdown Method (when t is constant/fixed; that is, a reading taken from a different observation well), and (c) Time-Distance-Drawdown Method (simultaneous observations are made on drawdown in three or more observation wells). The study adopted the Time-Drawdown Cooper-Jacob method for estimation of the hydraulic parameters. The above equation is plotted as a straight line on semi-logarithmic paper if the limiting condition is met. Thus, straight-line plots of s versus t can occur after sufficient time has elapsed. In the case were multiple OWs (observations wells) are considered, more distant wells are deprived to the meet the conditions rather than the adjacent one. The logarithmic x-axis is taken as time (t) scale while the linear y-axis is plotted for drawdown (s). Both Tr

and *Sr* and be estimated as below:

$$Tr = \frac{2.3Q}{2\pi\Delta s} \quad (6)$$

$$Sr = \frac{2.25T\, t_0}{r^2} \quad (7)$$

RESULTS AND ANALYSIS

Both Theis and Cooper-Jacob methods were suitably employed to estimate the aquifer hydraulic parameters in the study area. Tables 3 and 4 show the estimated values of *Tr* and *Sr* obtained from the simulated drawdown for all the wells using both methods. Figures 3–7 show the scatter plots of data fitting in Cooper Jacob and Theis curve fitting on drawdown data from the observation wells in both upper and lower regions. It is observed that a good match is obtained between the Theis drawdown and simulated data for the entire pumping period.

For the Cooper-Jacob method, Equations (3)–(6) were used for the estimation of aquifer hydraulic parameters. The single well model is utilized in the case where no observation wells are available. This implies considerations of a pumping well to serves as the piezometer; the straight line obtained for the semi-log plot of drawdown against time indicates the radial flow of water into the pumped well. The aquifer was tested for a period between 180 and 240 minutes or was subject to time where equilibrium is reached. In a semi-log graph, data from the pumping phase are plotted against corresponding *t* values, and then a straight line is plotted through field data points. The values of the drawdown per log cycle of time were determined from the slope of the graph as Δs.

From the estimated hydraulic parameters summarized in Tables 3 and 4, it is observed that the least *Tr* values were recorded in W13 and W14 whereas the highest *Tr* is recorded in W15. The *Tr* potential is classified into five grades as per Gheorghe Standards (1978) (Table 5) that includes: high potential (>500), moderate potential (50–500), low potential (5–50), very low potential (0.5–5) and Negligible (flat) potentials (below 0 .5) respectively.

Table 3 | Estimated *Tr* and *Sr* values based on single pumping well tests in the upper region of the study area

		Copper-Jacob		Theis		Mean		
Well no.	W.T. (m)	*Tr* (m²/day)	*Sr*	*Tr* (m²/day)	*Sr*	*Tr* (m²/day)	*Sr*	K (m/day)
W1	18	14.63	5.71E-05	13.58	5.66E-05	14.10	5.69E-05	0.125
W2	12	12.25	4.79E-05	11.95	4.22E-05	12.10	4.5E-05	0.100
W3	39	5.66	2.21E-05	4.88	1.88E-05	5.27	2.05E-05	0.190
W4	25	5.73	1.11E-04	5.23	1.01E-04	5.48	0.000106	0.210
W5	60	2.98	1.16E-05	3.20	1.19E-05	3.09	1.18E-05	0.111
W6	72	2.80	1.09E-05	2.90	1.12E-05	2.85	1.11E-05	0.060
W7	81	2.44	9.51E-06	2.50	9.54E-06	2.47	9.53E-06	0.080
W8	90	2.92	1.14E-05	3.10	1.23E-05	3.01	1.19E-05	0.060
W9	98	3.85	1.50E-05	3.55	1.46E-05	3.70	1.48E-05	0.075
W10	102	3.25	1.50E-05	3.40	1.61E-05	3.33	1.56E-05	0.088

Table 4 | Estimated *Tr* and *Sr* values based on single pumping well tests in the lower region of the study area

		Copper-Jacob		Theis		Mean		
Well No.	W.T (m)	*Tr* (m²/day)	*Sr*	*Tr* (m²/day)	*Sr*	*Tr* (m²/day)	*Sr*	K (m/day)
W11	2.73	294.60	1.473	291.50	1.450	293.05	1.462	95.060
W12	1.67	624.00	3.120	630.00	3.142	627.00	3.131	102.250
W13	4.13	Low discharge	–	Low discharge	–	–	–	low
W14	9.60	Low discharge	–	Low discharge	–	–	–	low
W15	5.32	712.06	3.560	714.10	3.668	713.08	3.614	270.100
W16	5.16	7.61	0.03805	7.50	0.0225	7.555	7.555	0.255

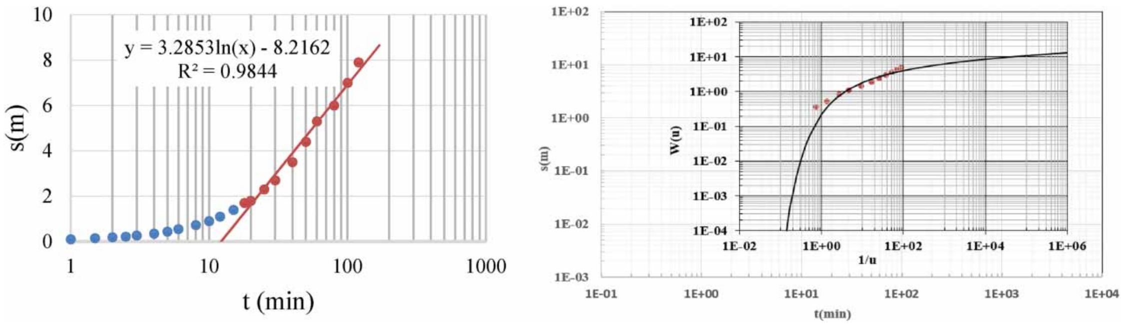

Figure 3 | Scatter plots showing data fitting in Cooper Jacob and Theis curve matching of *W*5.

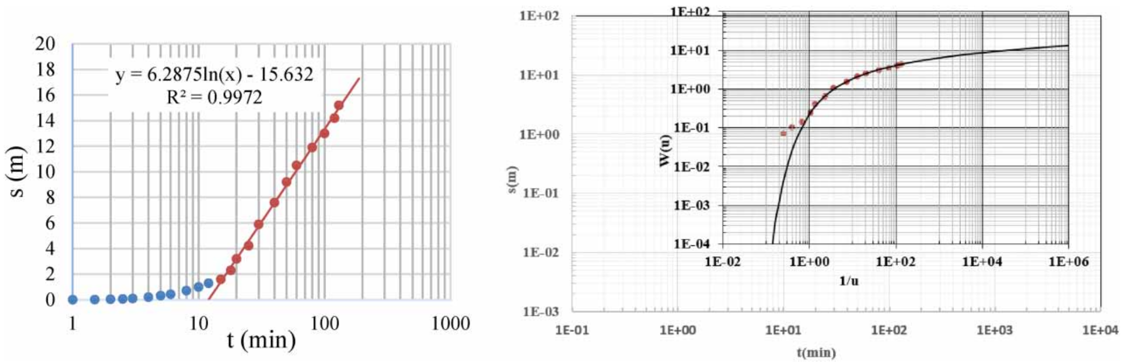

Figure 4 | Scatter plots showing data fitting in Cooper Jacob and Theis curve matching of *W*6.

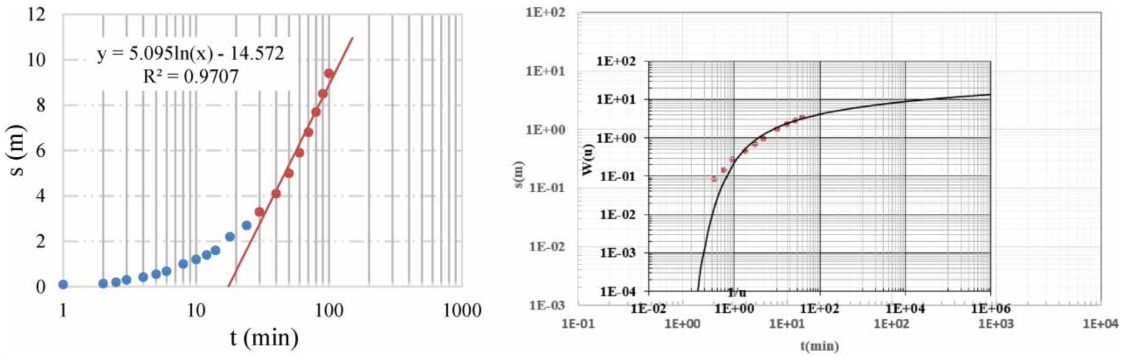

Figure 5 | Scatter plots showing data fitting in Cooper Jacob and Theis curve matching of *W*14.

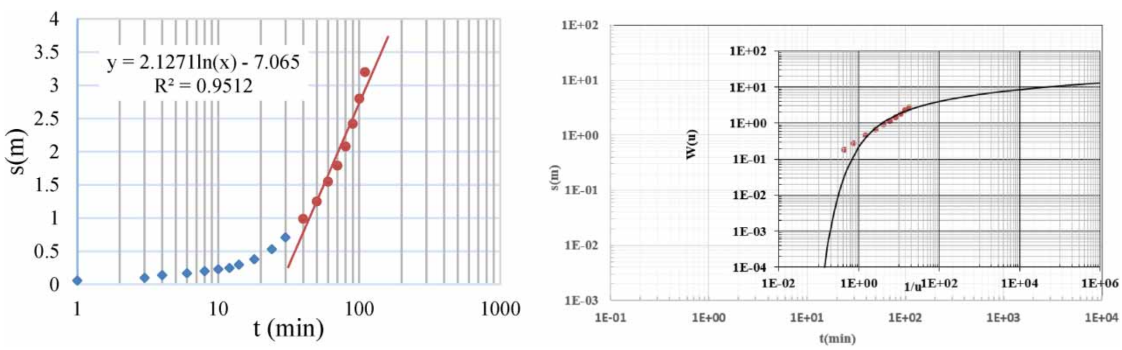

Figure 6 | Scatter plots showing data fitting in Cooper Jacob and Theis curve matching of *W*15.

Table 5 | Observed ***Tr*** potential based on Gheorghe Standards

Well No.	*Tr* range (m^2/day)	Transmissivity potential
W12, W15	>500	High potential
W11	50–500	Moderate potential
W1-W4, W16	5–50	Low potential
W5, W6, W7, W8, W9, W10	0.5–5	Very low potential
W13, W14	Below 0.5	Negligible

Table 6 | Observed ***K*** values and material descriptions based on Bouwer Standards

Bouwer's standard (*K*)	Observed (*K*)	Well No	Materials
0.2	0.210; 0.255	W4, W16	Clay soils (surface)
10^{-8}–10^{-2}	0.060; 0.080; 0.060; 0.075; 0.088	W6, W7, W8, W9, W10, W13,W14	Deep clay beds
0.1–1	0.125; 0.100; 0.190; 0.111	W1, W2, W3,W5	Loam soils
1–5	–	–	Fine sand
5–20	–	–	Medium sand
20–100	95.060	W11	Coarse sand
100–1,000	102.250; 270.100	W12, W15	Gravel
5–100	95.060	W11	Sand and gravel mixes
0.001–0.1	0.125; 0.100; 0.190; 0.111	W1, W2, W3,W5	Clay, sand and gravel mix

Accordingly, it is observed that W12, W15 has high *Tr* potential while W13 and W14 fall under least or negligible *Tr* potentials. Similarly, the trends for moderate potential is recorded only for W3, low *Tr* potential for W1-W4, W16 and very low potential for W5, W6, W7,W 8, W9 and W10 respectively. Low discharge in Table 4 has the observed *Tr* range of 0.5 m^2/day.

Similarly, the values of *K* and *Sr* can be assigned based on Todd (1980), Domenico & Schwartz (1990), Lohman (1972) and Bouwer (1978). The value of *K* is found to be in the ranges of 0.06 to 270.10. Table 6 shows the observed *K* values according to Bouwer standards.

Based on Todd (1980), Domenico & Schwartz (1990), Lohman (1972) and Bouwer (1978), and from the ranges of *Sr* values the aquifer layer types can be categorized as a confined aquifer (0.00005–0.005), Leaky or Semi-confined (0.005–0.05) and unconfined (0.05–0.3). Accordingly, it can be observed that from Tables 3 and 4, the upper regions of the study area are mostly confined aquifers whereas the lower regions falls under unconfined aquifer layers.

To further validate the lithology profile of the bore well, a resistivity survey is also carried out at the site. It is observed that the depth or thicknesses of the lithological layers obtained from VES (vertical electrical sounding) interpretation provides close conformity with the obtained hydraulic parameters. Figure 7 shows the lithological profiles of the wells considering the upper region (W5 and W6) and lower regions wells (W16 and W17) in the study area. These plots were established using the LogPlot Software (Ver. 7.6.138.174). It is observed that in both the regions of the study area, the lithological horizons comprise mostly claystone with traces of conglomerate, and a mixture of clay, gravel, and sandstone. Except for W14, the topmost layers in Figure 7 are generally found to be claystone. The bottom-most layer is usually the gravel content, which is the common water bearing strata in the study area in question.

CONCLUSION

The present study reports on the assessment of hydraulic parameters and the aquifer system formation in hilly terrain, a case study of some selective regions of Hamirpur district, H.P., India. It is observed that the obtained mean *Tr* values are found to be in the range of 2.47–713.08 while *Sr* ranges from 9.5E-06–7.56 and the hydraulic conductivity *K* in the range of 0.06–270.10. Based on the obtained hydraulic parameters, the subsurface formation at the well sites are mainly composed of an assortment of claystone, claystone along with traces of

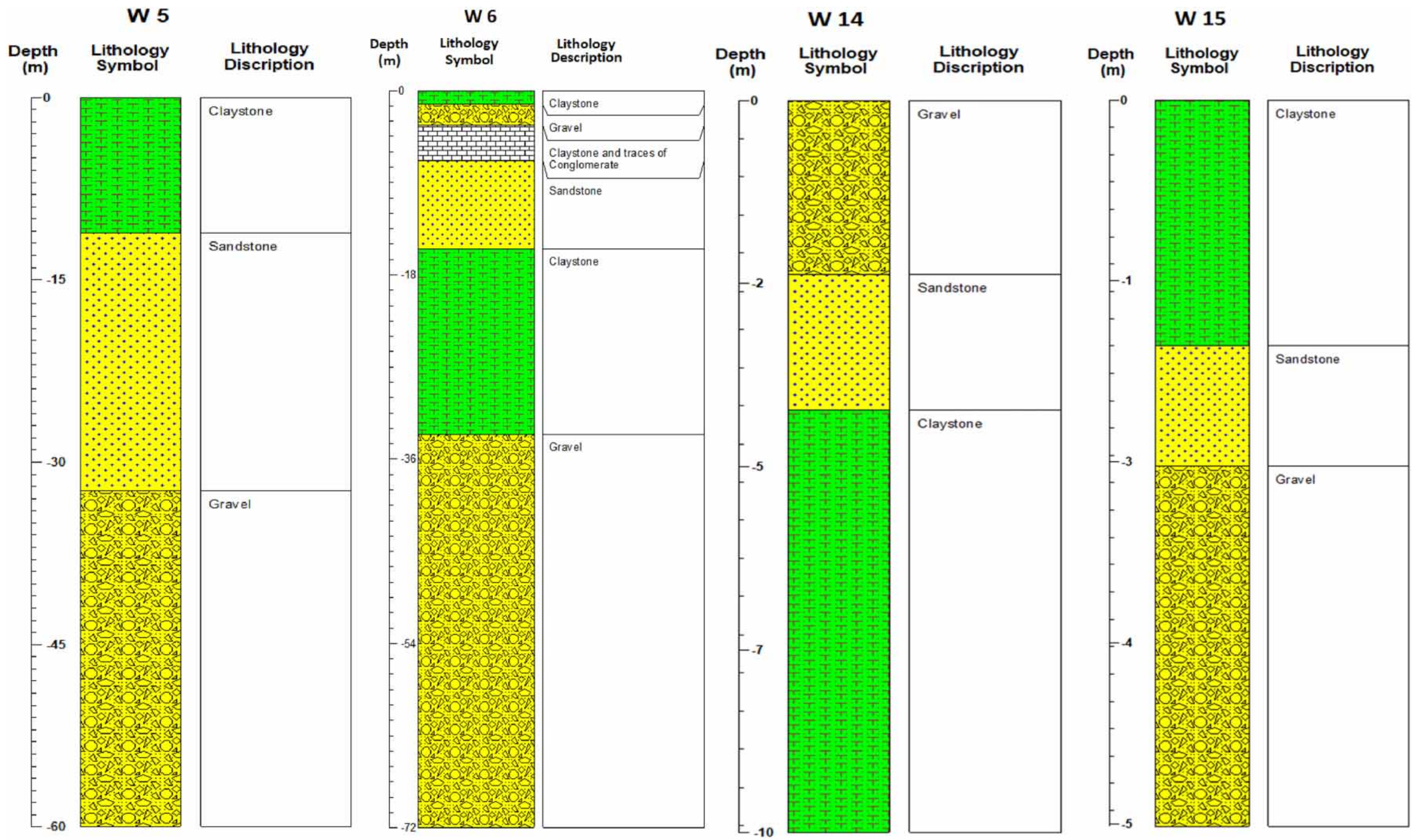

Figure 7 | Lithology profile of bore wells W5 & W6 (upper region) and bore wells W14 & W15 (lower region).

conglomerates, sandstones and gravels which are consistent with the VES data and visual observations in the field. Based on the obtained results, two types of aquifer system were observed; that is, the upper regions aquifer layers is characterised as confined while the lower regions is unconfined (or free layers) type. In future, further study may be carried out on the estimation of infiltration rate and contaminant transport assessment.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare that are relevant to the content of this article.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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