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RESULTS OF PUMPING TESTS IN THE DECCAN TRAP BASALTS OF CENTRAL INDIA

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ABSTRACT

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The Satpura Hills Region of Central India is characterized by hilly to mountainous terrain, plateaus, and gently undulating country. The area is underlain by basalt, crystalline rocks and sandstone. Basalt rocks of Cretaceous age outcrop over about 60% of the area.

During the past 14 years the authors, through their association with the Evangelical Lutheran Church (ELC) Water Development Project, have been involved in the development of groundwater resources for village, town, agricultural, and industrial uses. To date, over 700 wells have been drilled in the basalt rocks and aquifer pumping tests have been run on more than 200 wells. As a result of the controlled testing and detailed analysis of these pumping tests, it was possible to evaluate the applicability of standard analytical models for the analysis of pumping tests in basalt-rock aquifers.

Step–drawdown pumping tests were run to determine the components of drawdown due to aquifer loss and well loss. Step-test data were analyzed by Rorabaugh's (1953) method and by a graphical method. The results indicate that well losses comprise a significant component of drawdown in most wells and these losses are probably a result of non-Darcian flow in the aquifer adjacent to a pumped well.

Constant-rate pumping tests were run to determine aquifer transmissivity and specific capacity. Time–drawdown data were analyzed by the Cooper–Jacob (1946) approximation to the Theis (1935) equation and recovery data were analyzed by the residual-drawdown method. Aquifer transmissivity ranged over two to three orders of magnitude from less than $10\,m^2\,day^{-1}$ to more than $300\,m^2\,day^{-1}$. Pumping test results often enabled the prediction of aquifer conditions such as limited aquifers, recharge boundaries and aquifer dewatering.

INTRODUCTION

Extrusive igneous rocks outcrop over several regions of the world as shown on Fig. 1. Several of these areas have been extensively studied (e.g., the Columbia Basin in Northwest U.S.A., and Hawaii) while the Deccan Plateau has been studied to an extent in recent years, especially in regard to the results of pumping tests on shallow hand-dug open wells (Adyalkar and Mani, 1974; Deolankar, 1981).

This paper summarizes the results of 200 pumping tests carried out on 10 to

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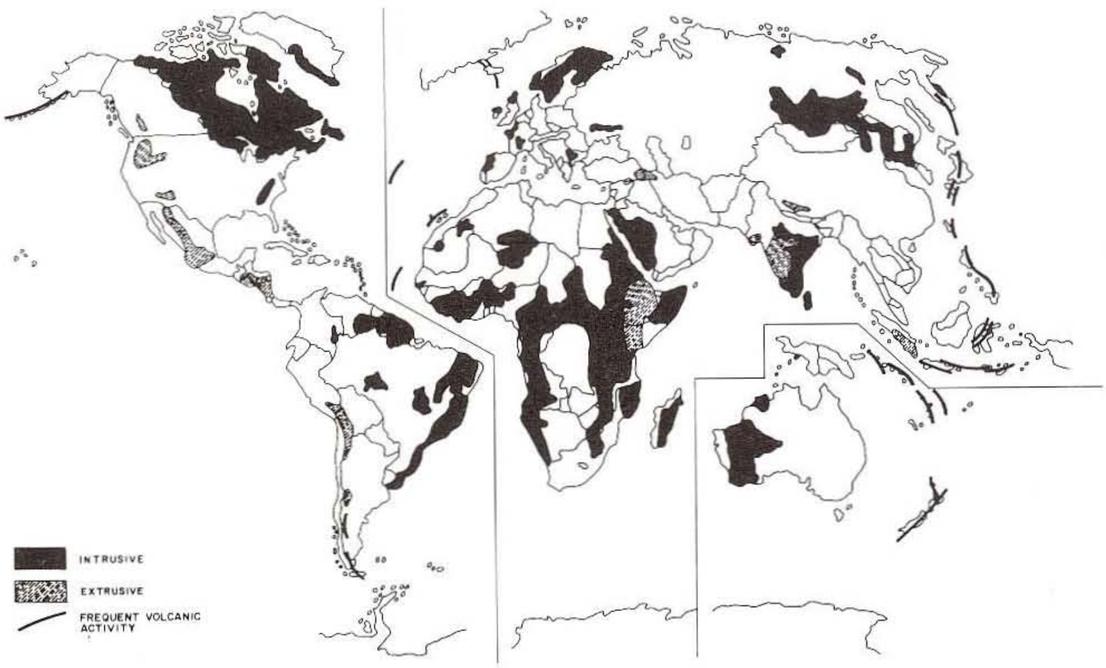

Fig. 1. Occurrence of intrusive and extrusive igneous rocks throughout the world (Trewartha et al., 1967).

16.5-cm diameter tubewells that were drilled to an average depth of about 65 m. In addition, a comparison of the study area's aquifer hydraulic characteristics to those of a basalt region (Columbia Plateau) of more recent geologic age is presented. The impact of age and weathering processes on the permeability of basalt-rock aquifers is discussed.

Figure 2, a geologic map of India, shows the extent of the Deccan Trap basalt in India. Figure 3 is a geologic map of the study area.

In 1971, a Water Development Project was initiated in Madhya Pradesh State, India with the objective of improving water-supply facilities for villages, farms, industries, and institutions in the Satpura Hills Region (Betul, Chhindwara and Seoni districts). Prior to 1971, these districts were almost entirely dependent on surface water and shallow open wells (9 to 15 m deep) for water-supply purposes. During the period 1971 to 1984, over 2000 wells were installed by the project in this region, and 700 of these wells were installed in the Deccan Trap Basalt.

Controlled aquifer pumping tests were run on over 200 basalt wells. Testing procedures generally consisted of a step–drawdown pumping test followed by a constant-rate pumping test. The test data were analyzed by standard analytical models.

The purposes of this paper are to:

(1) Describe the pertinent geologic and hydrogeologic features of Deccan Trap Basalt in the study area.

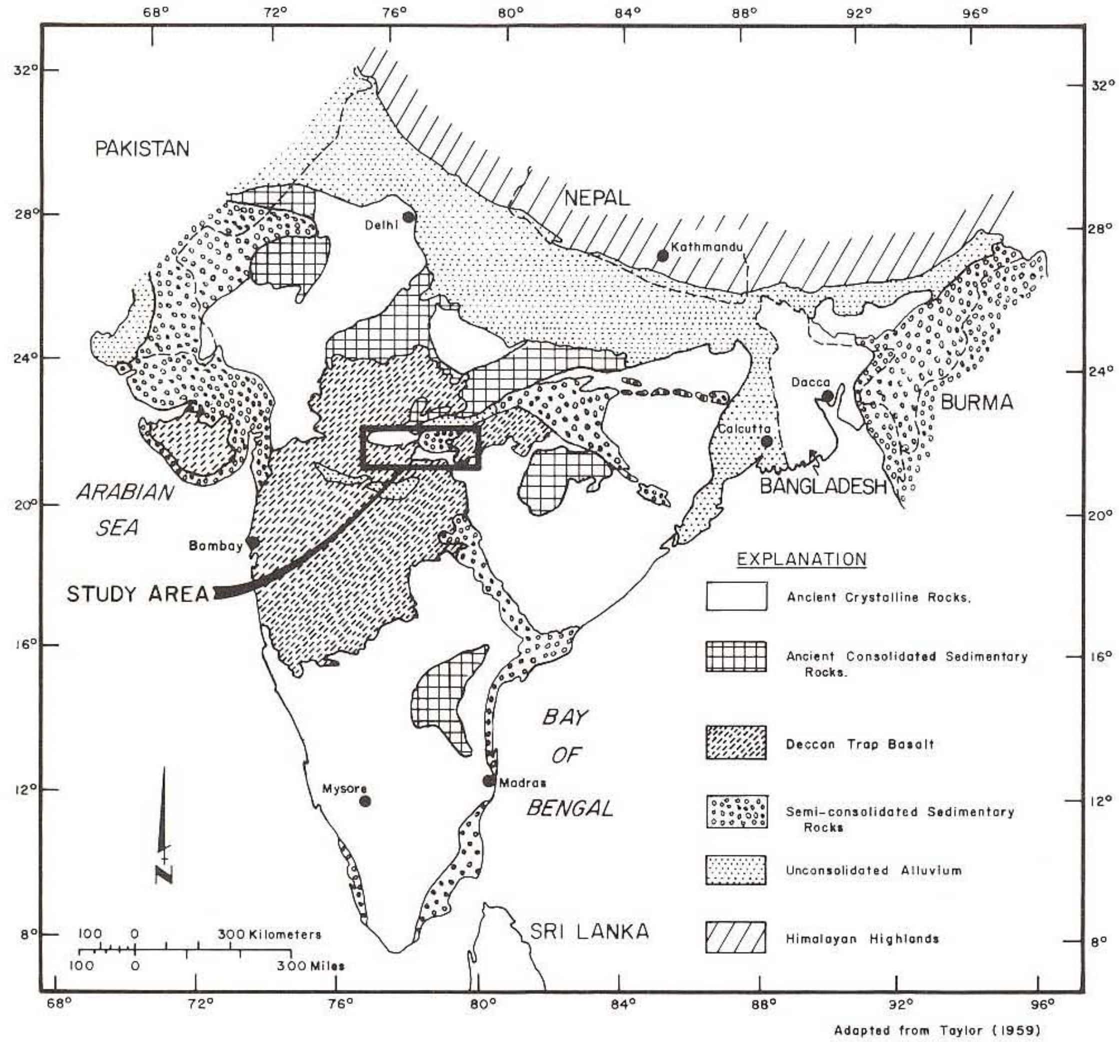

Fig. 2. Geologic map of India (Taylor, 1959).

(2) Review the results of step–drawdown pumping tests in an attempt to quantify the nature of well losses, and the proportion of drawdown due to well loss as compared to aquifer loss.

(3) Discuss practical applications of step–drawdown pumping tests.

(4) Review the results of the constant-rate pumping tests in order to ascertain the applicability of certain analytical models for analyzing pumping test data.

(5) Present examples of constant-rate pumping tests and ranges of aquifer transmissivity and specific capacity.

(6) Provide an overview of aquifer hydraulic characteristics in the study area.

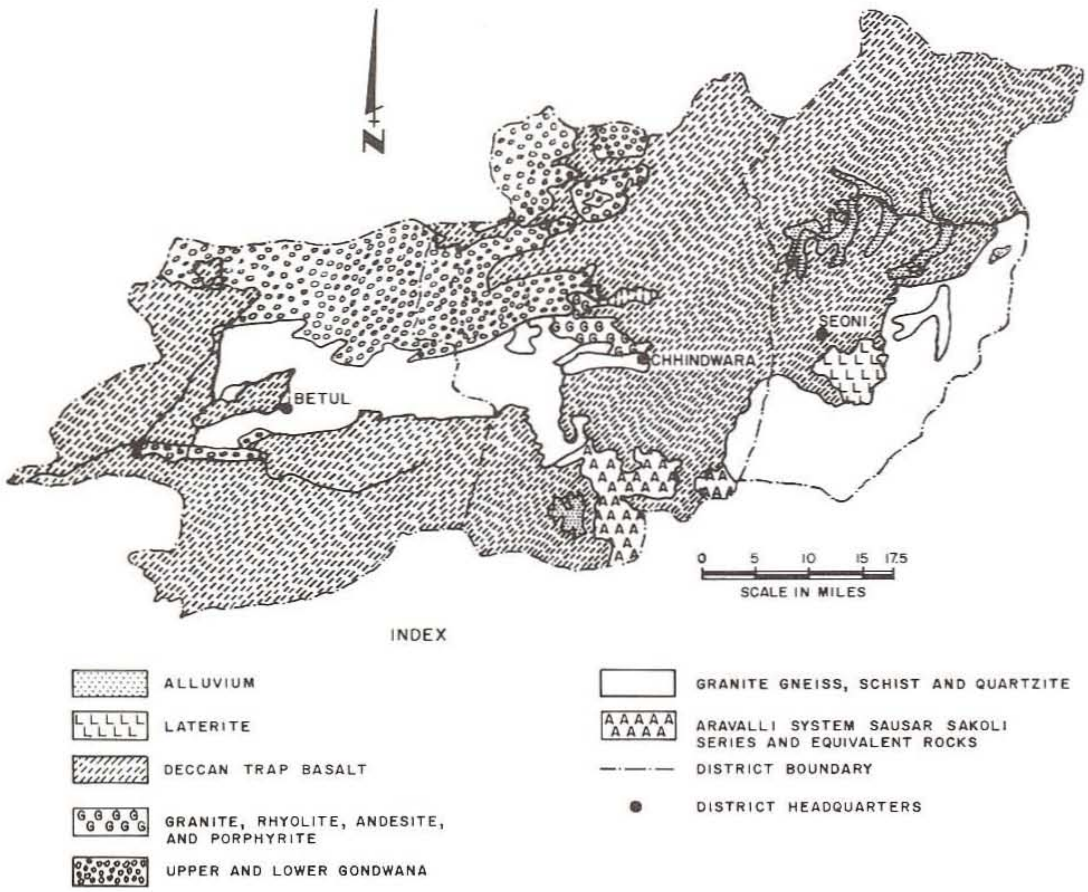

Fig. 3. Surface geologic map of Satpura Hills Region.

AREA

The study area is located in the southcentral part of Madhya Pradesh State, India (Fig. 3), and covers the districts of Betul, Chhindwara, and Seoni. These districts lie almost entirely on the Satpura Plateau and are traversed by the Satpura Hills. The area extends between longitudes 77° E to 80°30′ E and latitudes 21°30′ N to 23° N and encompasses some 30,490 km^2. The area contains 5156 villages and towns with a population of over 2.5 million. Approximately one-half of the area is forested and the remainder is under intense cultivation.

The Satpura Plateau is an uplifted feature; landforms vary from hilly mountainous terrain to flat plateau country and gently undulating hills. Areas underlain by Deccan Trap Basalt area characterized by flat plateaus and rugged dissected plateaus.

The bulk of precipitation occurs during the southwest monsoon season (June to September) with the average annual rainfall ranging from 95 to 120 cm.

HYDROGEOLOGY

The geologic formations in the study area range in age from Precambrian to Recent. Figure 3 shows the surface geologic features of the area. Deccan Trap (basalt) is the predominant rock type and crops out in roughly 60% of the study area. The basalts occur as consolidated lava sheets, which were formed as a result of fissure eruption activity during the late Cretaceous period. The Deccan Trap Basalts overlay the Precambrian crystalline rocks and Gondwana sandstones. In the eastern part of the study area, the basalts are overlain by river bank alluvium and laterite. The thickness of the basalts ranges from a few tens of meters to several hundred meters. The basalts are typically gray colored, fine-grained, compact, homogeneous rocks.

Basalt flows in the study area average about 25 m in thickness, and are greenish dark gray or black in color, fine-grained and amygdular in nature, and contain vesicles. A basalt flow is uniform in its lithological and mineralogical character. It is generally more vesicular and amygdular towards the top. The middle massive portion is either nonvesicular or very sparsely vesicular. The lower portion of a flow often contains vesicles and inverted Y shaped pipes.

The top of an exposed flow is generally weathered and exhibits spheroidal weathering and or thin lateritic capping. This is underlain by a zone of intersecting joints and fissures. The central zone of a flow is dark gray in color and exhibits doleritic texture and columnar joints. The bottom part of a flow is again fine-grained, amygdular and vesicular, and occasionally exhibits sheet joints; the bottom is generally marked by the presence of red bole, green earth or ash bed which occur throughout the study area. At places, thin beds of tuff, breccia, and of agglomerate have been noted. Generally, the amygdules are comprised of secondary silica and zeolites and lined with green glassy material. Figure 4 provides a cross section of a representative basalt flow in the Satpura Hills Region.

Beds of red bole and green earth clays, sand, or shale occur between lava flows at places. The thicknesses of these intertrappean beds seldom exceed a few meters. However, in parts of Chhindwara district, these beds are often 10 to 15 m thick.

Due to the nature of the basalt flows and their widespread regional occurrence, it is difficult to define structural features like folding in the Deccan Traps. An examination of the ERTS (satellite) imagery shows numerous lineaments in an east-northwest to west-southwest direction, and several in a north–south direction in the western part of the study area. These north–south lineaments may be due to irregularities in the strain produced by regional movement in the east–west direction.

Basalt is devoid of intergranular porosity. Primary openings occur in the form of vesicles and cooling joints. The vesicles range in size from a few millimeters to a few centimeters; the cooling joints are generally vertical and are commonly known as "columnar joints". These joints are more noticeable in intrusive basalt structures like dikes. Vesicular openings have been filled in

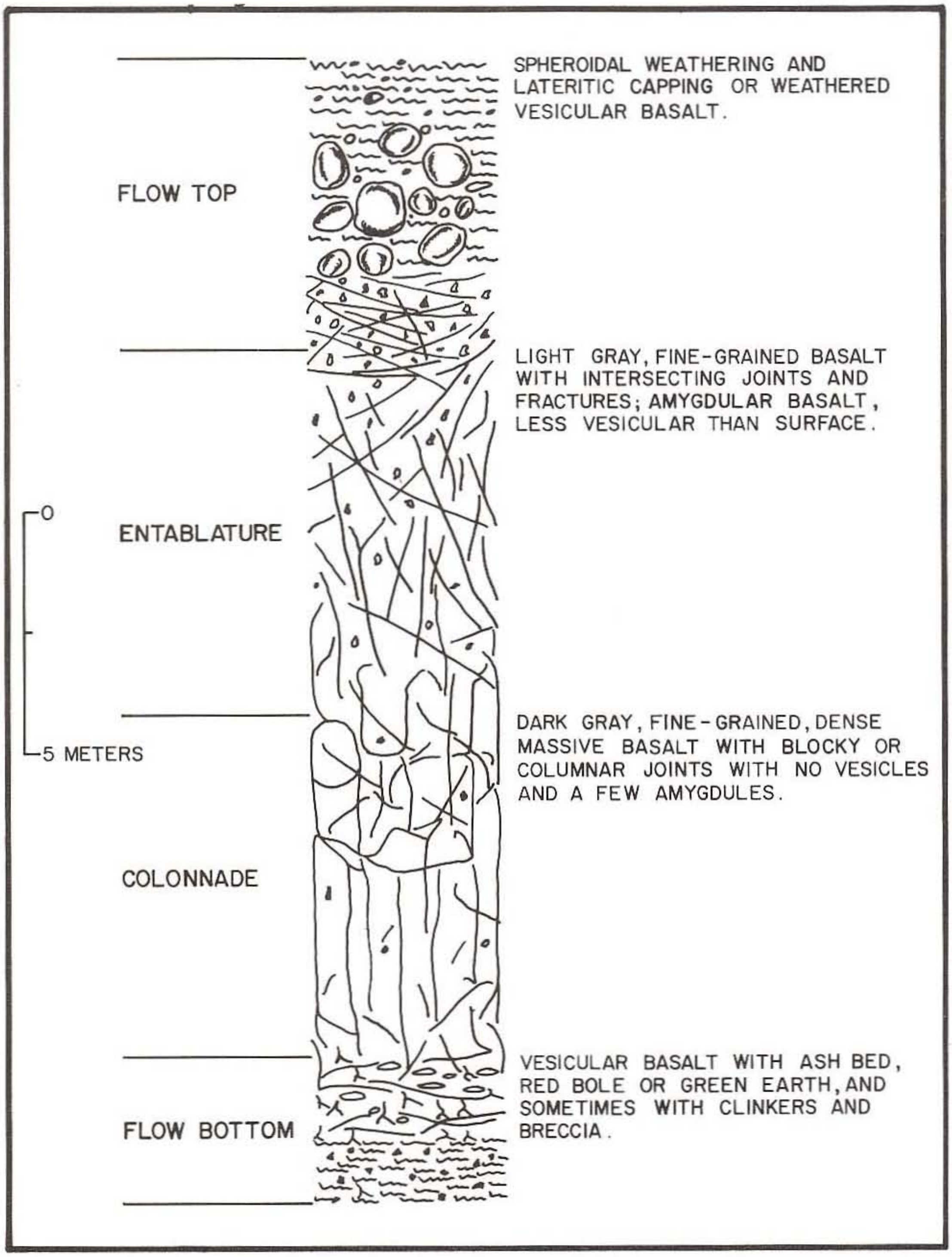

Fig. 4. Structure of a typical basalt flow in Satpura Hills Region.

at places with secondary deposits such as calcite, silica, and zeolite; these rocks are called amygdaloidal basalt. Secondary openings have been developed by fracturing due to tectonic movements, and by weathering. The thickness of the weathered zone, as determined from the geologic logs of over 300 wells, ranges from less than 1 m to 21 m and averages about 6 m.

Groundwater occurs in weathered zones, brecciated flow contacts, and fractured zones. In the youngest (uppermost) lava flow, shallow unconfined aquifers occur in the weathered zone; this zone generally consists of either vesicular and/or amygdaloidal rock. Deeper confined aquifers occur at brecciated and weathered flow contacts and in fracture openings. Aquifers at flow contacts overlain by fractured basalt are generally the most productive. Intertrappean beds, composed of clay and shale, do not yield much water. Groundwater flow systems in the Deccan Trap Basalts are of the local and intermediate type (Toth, 1963), depending on topographic conditions.

In the western part of the study area the differential weathering of trappean flows, and erosional characteristics of the trappean streams and post-trappean faults, have created a rugged topography characterized by narrow valleys,

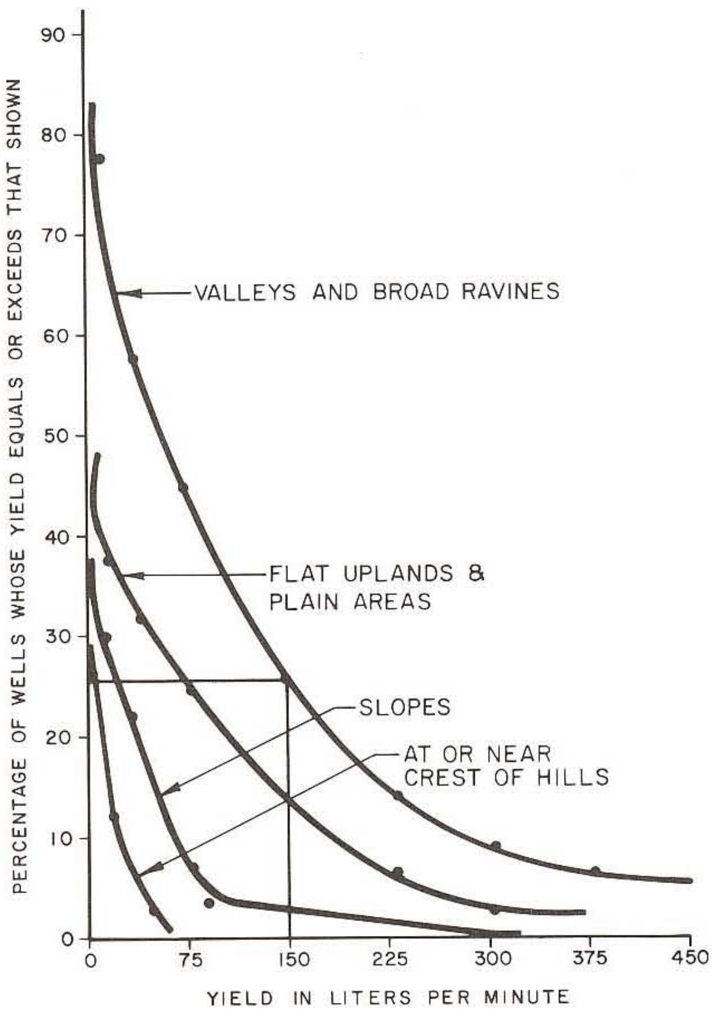

Fig. 5. Cumulative frequency distribution of well yields in various topographic settings; Satpura Hills Region.

TABLE 1

Summary of well yields according to topography

	Number of wells	Minimum ($l\,min^{-1}$)	Maximum ($l\,min^{-1}$)	Mean	Mode	Median
Total wells	255	< 1	651	65	< 1	16
Valleys	87	< 1	651	113	< 1	57
Flat uplands	101	< 1	568	52	< 1	10
Slopes	27	< 1	341	31	< 1	13
Hills	27	< 1	79	9	< 1	1.8

steep slopes, and rising hill ranges. In these areas, local groundwater flow systems are predominant, with recharge and discharge areas located at topographic high and low areas that are adjacent to each other. Groundwater often surfaces in the form of springs within short distances from recharge areas; these springs are commonly found in valley slopes well above stream beds.

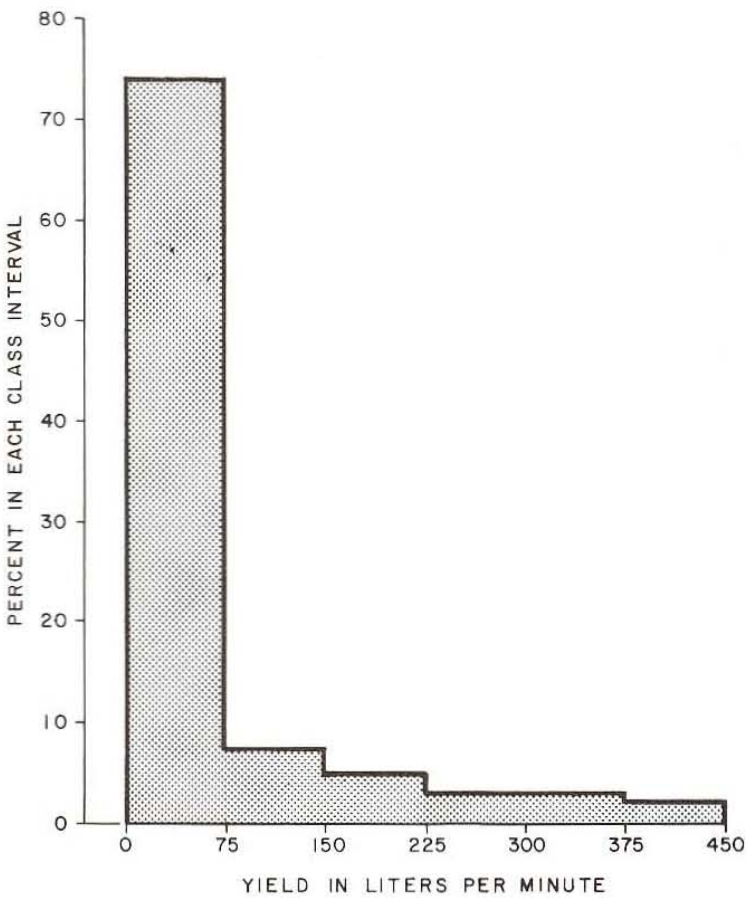

Fig. 6. Well yield histogram for Deccan Trap Basalts in the Satpura Hills Region.

The plateau areas (south-central Betul district, southern Chhindwara district and northern Seoni district) are characterized by both local and intermediate groundwater flow systems. The weathered parts of the youngest lava flows are characterized by shallow water-table aquifers and local flow systems.

Deeper confined aquifers are thought to be associated with intermediate flow systems. A few deep tubewells, in the plateau areas, encountered aquifers at depths greater than 100 m. One well drilled at Pandhurna (Chhindwara district), to a depth of 153 m (average well depth in study area is 65 m), encountered an aquifer at 140 m. This well has been used by the town over the past 9 yr. Another well, at Multai (Betul district), encountered an aquifer at 112 m. There is often a considerable head differential (downward) between shallow unconfined and deeper confined aquifers in these areas.

Significant variations in well yields have been noted for wells drilled in close proximity although in general well yields are higher in valley and flat upland areas as compared to slopes and hilly areas. Figure 5, a cumulative frequency plot of well yields in various topographic locations, illustrates these differences as does Table 1 which presents a summary of well yields according to topography.

In general, most wells yield 75 l min^{-1} or less with a smaller number of highly productive wells. This is apparent from the differences in mean and median yields for basalt wells shown in Table 1. Figure 6, a well yield histogram for basalts, illustrates this distribution.

ANALYSIS OF PUMPING TEST RESULTS

Introduction

Over 200 pumping tests have been conducted on wells drilled in the Deccan Trap Basalts. Most of the wells are 15 to 16.5 cm in diameter and were drilled by air-hammer rigs. Submersible pumps, 14.6 and 9.5 cm in diameter, were used for testing. The discharge pipes were equipped with standard totalizing water meters; water levels in the pumped wells were measured with an electric sounder. The testing of each well was generally conducted as follows:

(1) Pre-test water levels were measured for 1 to 2 h prior to the start-up of the step–drawdown test.

(2) A step–drawdown test was run for about 6 h consisting of three to six steps.

(3) Recovery was then measured for 12 h.

(4) Finally, a constant-rate test was run for 12 to 24 h with recovery measured for the same duration as pumping.

The step-test data were analyzed by Rorabaugh's method (1953) and by a graphical method discussed by Uhl et al. (1976). Constant-rate test data (drawdown) were analyzed by the Cooper–Jacob (1946) modified nonleaky artesian formula. Recovery data were analyzed by the residual-drawdown method. As testing work progressed and a number of tests were analyzed, anomalies in the test data proved helpful for interpreting aquifer conditions. After drawdowns were corrected for well losses, values of corrected specific capacity (Q/s) for 12 h of pumping and transmissivity (T) were compared to theoretical plots of Q/s versus T. Specific capacity frequency plots were constructed for actual and corrected specific capacities.

Step–drawdown pumping tests

Drawdown in a pumping well can be divided into two components. The first component termed "aquifer or formation loss" arises from the resistance of the formation to fluid flow. Aquifer losses are proportional to the pumping rate, Q, and increase with time as the cone of depression expands. The second component termed "well loss" represents the loss of head resulting from non-Darcian flow in the aquifer outside the pumped well and flow through the well screen and in the well casing. Well losses are constant over time and are approximately proportional to the pumping rate squared (Q^2).

The total drawdown in a pumped well can be expressed by the following equation (Jacob, 1947):

$$s_w = BQ + CQ^2 \tag{1}$$

where: s_w = the total drawdown in the well; BQ = aquifer or formation loss; CQ^2 = well loss; B = the aquifer loss constant which represents the total resistance of the formation from the well face out to the radius of influence; its units are $\mathrm{m\,lpm^{-1}}$. B increases with the log of time. C = the well loss constant; its units are $\mathrm{m\,lpm^{-2}}$; C is constant with time.

A simple technique for determining B and C is to write eqn. (1) in the following manner: $s_w/Q = B + CQ$, which is the equation of a straight line. Values of specific drawdown, s_w/Q, plotted against the pumping rate, Q, on rectilinear paper for each step should define a straight line. The intersection of the line with the vertical axis is the aquifer loss constant B and the slope of the line is the well loss constant C.

Jacob assumed that the head loss due to non-Darcian flow is approximately proportional to the square of the velocity. Rorabaugh (1953) suggested that instead of assuming a value of ($n = 2$) in the well loss term, it is best to first determine whether the flow is laminar or turbulent. Rorabaugh stated that drawdown in an artesian well, resulting from the withdrawal of water, is made up of head loss resulting from laminar flow in the formation, and head loss resulting from turbulent flow in the zone outside the well, through the well screen, and in the well casing. Two expressions were developed for computing the drawdown, s_w, in a well being pumped at rate Q. The first expression, $Q < Q_c$, $s_w = BQ + C'Q$ (eqn. 2) is applicable for laminar flow, where Q is less than some Q_c, which is the critical or transitional Q, below which laminar flow prevails. The second expression is applicable for the turbulent flow regime $Q > Q_c$, $s_w = BQ + CQ^n$ (eqn. 3).

Further, he noted that Jacob's use of $n = 2$ was based on the assumption that the critical or effective radius is constant as the pumping rate varies. It is more probable that at low pumping rates flow might be laminar, and as discharge is further increased, the boundary between laminar and turbulent flow will move outward into the formation. Rorabaugh attempts to compensate for this variation in the critical radius with discharge by applying two equations: eqn. (2) for laminar flow, and eqn. (3) for turbulent flow. The application of the exponent n in the term CQ^n compensates partially for the movement of the laminar turbulent flow interface with an increase in Q.

Rorabaugh devised an empirical solution for step-test data by a graphical solution of eqn. (3) on logarithmic graph paper. This method is fairly straightforward, but it does require some trial-and-error computation to reach a final solution.

Step–drawdown test results were analyzed by both Rorabaugh's graphical method and by the graphical solution of the equation $s_w = BQ + CQ^2$. The graphical method proved to be the more practical method of analysis. This method is especially useful where dewatering or boundary conditions occur, as they can often be detected by changes in the slope of the plot of s_w/Q versus Q. The hydraulic characteristics of the aquifer change when aquifer dewatering begins. The number of openings contributing water to the well is decreased by dewatering and this results in an increase in turbulence in the aquifer near the well face and consequent increase in the value of the well loss constant, C. Thus, in a plot of s_w/Q versus Q, aquifer dewatering results in an increase of the slope.

An aquifer of limited extent will have a similar effect on the plot of s_w/Q versus Q, but generally, the change in slope is not as pronounced as in the case of aquifer dewatering. If recharge occurs during a test, the slope of the plot will decrease. The step–drawdown test technique is also quite useful for determining depth to water-bearing fractures in wells with poor or nonexistent records.

If Rorabaugh's graphical method were applied to step-test data that contained anomalies, detection of the anomalies would be difficult since a trial-and-error procedure is used to fit all the points on a straight line when plotted on log–log paper.

Table 2 contains the results of a number of step–drawdown tests that were conducted on basalt-rock wells in the study area. Most of the data in Table 2 are self-explanatory. Columns *5* and *6* contain the aquifer- and well-loss constants, determined from the graphical solution and in columns *8* and *9*, the aquifer- and well-loss components of drawdown are computed for maximum test discharge using B and C from the graphical solution.

The results indicate that well losses are significant for the majority of wells tested. This fact assumes particular importance for wells with limited available drawdown. There does not appear to be any relationship between transmissivity and the proportion of drawdown due to well losses. In wells with low transmissivities, there are cases of wells with both high and low well losses.

TABLE 2

Results of selected step–drawdown pumping tests in Deccan Trap Basalts

(1) Well No.	(2) Test No.	(3) Q, Maximum (lpm)	(4) Q/s at end of test (lpm m^{-1})	(5) 'B' graphical (m lpm^{-1})	(6) 'C' graphical (m lpm^{-2})	(7) Transmissivity (m^2 day^{-1})	(8) $s_w = BQ + CQ^2$ — BQ	(9) CQ^2	(10) Percent reduction in specific capacity
WDP 168	75	155	3.8	0.13	0.00042	—	19.38	10.2	7.3
WDP 173	83	136	5.4	0.026	0.00015	—	3.51	2.86	28.0
WDP 176	86	314	8.4	0.024	0.0003	121	7.6	29.10	49.5
WDP 234	129	117	5.3	0.038	0.00045	13	4.56	6.13	30.0
PHED	133	374	92.0	0.005	0.0000032	173	1.84	0.45	31.0
AFPRO 194	145	314	10.5	0.003	0.000028	17	0.95	2.84	45.0
WDP 276	158	302	9.6	0.0048	0.00014	17	1.46	13.23	67.0
WDP 287	169	317	20.2	0.028	0.000043	44	9.0	4.29	28.8
WDP 323	194	283	17.6	0.0064	0.00016	72	1.8	13.33	70.4
WDP 320	196	684	70.6	0.0033	0.000015	77	2.28	7.19	29.1
AFPRO 305	208	189	64.3	0.011	0.000032	71	2.01	1.12	20.0
WDP 349	210	200	70.6	0.0053	0.000042	123	1.05	1.66	52.6
AFPRO 306	214	340	135.0	0.0023	0.000015	320	0.78	1.70	27.0
CP 150	280	605	504.0	0.0005	0.000003	175	0.29	1.07	60.0
CP 181	302	832	102.1	0.0059	0.0000036	200	4.93	2.46	34.8
CP 325	378	442	56.7	0.005	0.000026	105	2.10	5.00	54.0
CP 445	382	219	—	0.012	0.000038	62	2.75	1.82	70.0
AFPRO 479	451	321	60.0	0.0096	0.000017	75	3.10	1.73	31.0

(10) Percent reduction in specific capacity $= \dfrac{Q/s \text{ maximum} - A/s \text{ minimum}}{Q/s \text{ maximum}}$.

The same was observed for wells with high transmissivities. If a significant portion of well loss occurs in the aquifer adjacent to the pumped well, then the magnitude of well loss could depend on the number, orientation and nature of openings in the aquifer, adjacent to the pumped well.

Constant-rate pumping tests

Constant-rate pumping test data can be utilized to determine aquifer transmissivity and storage coefficient. Observation wells were not available for the majority of wells tested and hence, only values of aquifer transmissivity were determined. Time–drawdown data were analyzed using the Cooper–Jacob (1946) modification of the Theis formula (eqn. 4). This modification is generally referred to as Jacob's method:

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

where: T = aquifer transmissivity in $m^2 day^{-1}$; Q = pumping rate in $m^3 day^{-1}$; Δs = the slope of the time–drawdown graph expressed as the change in drawdown between any two values of time on the log scale whose ratio is 10.

One advantage of Jacob's method is that time–drawdown data can be plotted on semi-logarithmic paper (with time on the log scale and drawdown on the arithmetic scale) and if aquifer characteristics are in accordance with the basic assumptions, then the data will fall on a straight line. Deviations from a straight-line plot can often be used to delineate boundary conditions or aquifer dewatering.

Water-level measurements, made during the recovery period, provide a distinct set of information for a pumping test, thus providing a means of checking the results that were determined from the time–drawdown period.

Water-level recovery data are often more accurate than time–drawdown data, since the recovery period is not affected by pump vibrations and fluctuations in the pumping rate. In addition, although recovery data are affected by temporal variations in the earlier pumping history, the effect is somewhat less than during the pumping period because of the integration of all of the effects prior to the recovery period.

There are two common methods that are used to analyze water-level recovery data. In the first method, calculated recovery versus time after pumping stopped is plotted on semi-logarithmic paper. In the second method, residual drawdown versus t/t' is plotted on semi-logarithmic paper, where t is the time since pumping started and t' is the time since pumping stopped. The second method for analyzing water-level recovery data is preferred, as it provides a more independent check of the results that were calculated from the time–drawdown data. This is because the first method requires an extension of the time–drawdown plot for pumping and if there have been any deviations from a straight-line plot due to boundary effects or irregularities in the pumping rate, then the first method would provide erroneous results. Further, any errors in

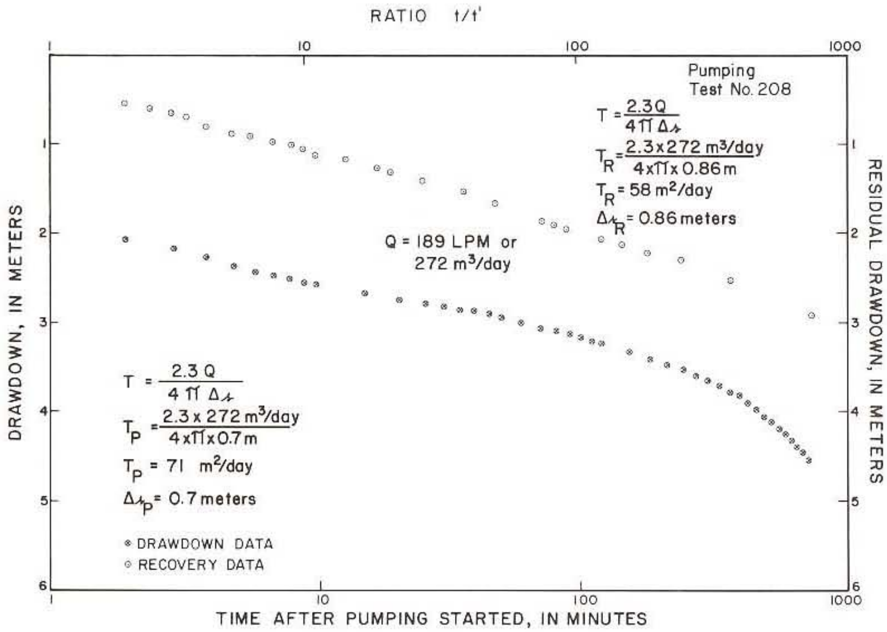

Fig. 7. Time–drawdown and residual-drawdown plots for pumping test at Multai Town (Betul district).

the time–drawdown data are carried over in the calculation of recovery.

Pumping test results often enabled the prediction of aquifer conditions, such as the presence of barrier boundaries, recharge and leakage effects, and aquifer dewatering. Test samples are presented below:

Case 1: A 16.5-cm diameter municipal well in Multai (Betul district) was drilled to a depth of 79 m. During drilling, water-bearing fractures were encountered from 18 to 20 m (weathered, fractured basalt) and from 20 to 39 m (minor fractures).

A 12-h pumping test was conducted. Time–drawdown and residual-drawdown data were plotted on semi-logarithmic paper (Fig. 7). A change in slope of the time–drawdown data occurred after 300 min of pumping indicating a limited aquifer or a decrease in transmissivity at a distance from the pumped well.

The residual-drawdown data also indicate an aquifer of limited extent. The values of aquifer transmissivity calculated from the pumping and recovery data correlate fairly well.

Case 2: An irrigation well was installed to a depth of 84 m at the Seja Experimental Farm in Chhindwara district. The major water-bearing fractures occurred from 44 to 47 m and from 58 to 59 m.

A 12-h constant-rate pumping test was conducted following the step–drawdown test. The time–drawdown and residual-drawdown plots are presented on Fig. 8. Drawdown stabilized after about 500 min of pumping and the recovery response indicated a recharge effect.

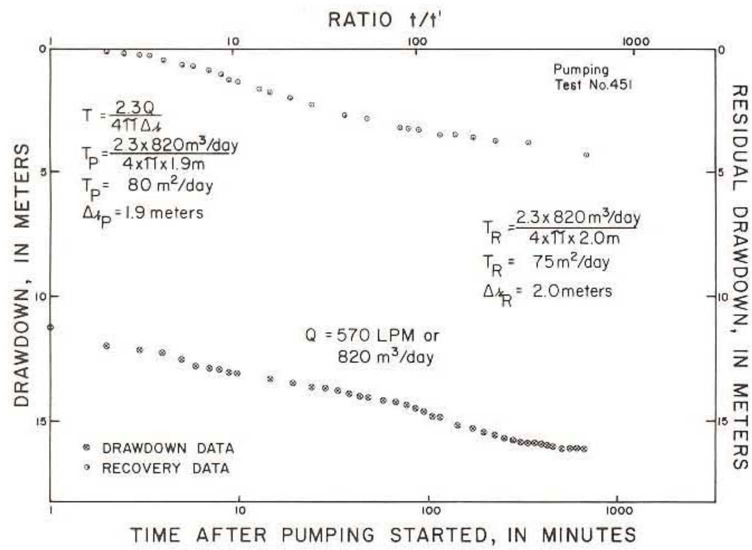

Fig. 8. Time–drawdown and residual-drawdown plots for pumping test at the Seja Experimental Farm (Chhindwara district).

Case 3: A water-supply well was installed to a depth of 67 m near Bhimgarh Dam in Seoni district. During drilling the principal water-bearing zone was encountered from 12 to 29 m. This was comprised of highly fractured basalt.

Figure 9 contains plots of time–drawdown and residual-drawdown data for the 12-h constant-rate pumping test. The data plotted reasonably well and

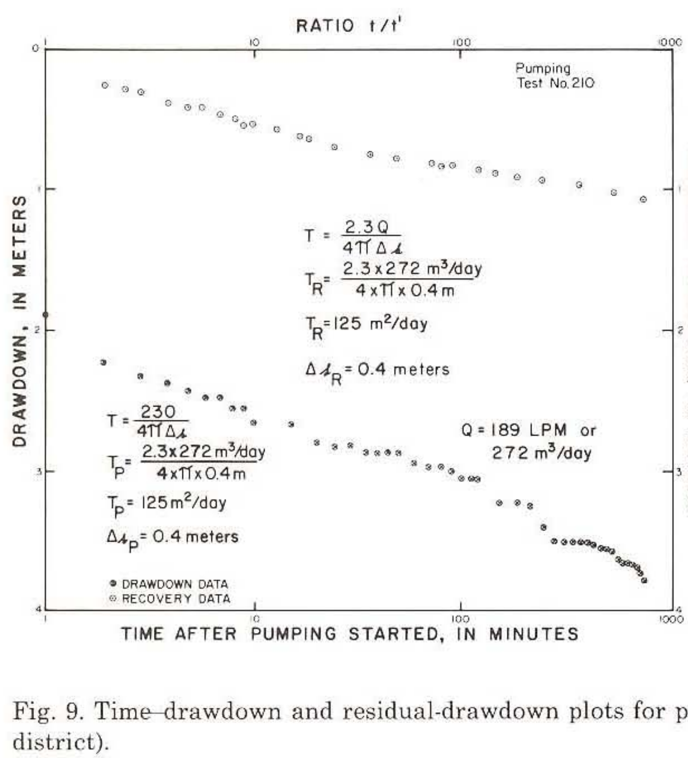

Fig. 9. Time–drawdown and residual-drawdown plots for pumping test at Bhimgarh Dam (Seoni district).

TABLE 3

Results of selected constant-rate pumping tests in Deccan Trap Basalts

Well No.	Pumping test No.	Pumping duration (h)	Test discharge (lpm)	Static-water levels (m)	Pumping-water levels (m)	Q/s, specific capacity at end of test (lpm m^{-1})	Transmissivity pumping (m^2 day^{-1})	Transmissivity recovery (m^2 day^{-1})
WDP 168	75	12	76	12.30	55.27	1.76	8.7	9.9
WDP 173	83	11	95	10.95	30.67	4.81	25.0	75.0
WDP 176	86	12	314	20.10	59.97	7.81	125.0	122.0
WDP 234	129	12	147	4.65	19.12	10.15	13.0	13.0
AFPRO 194	145	24	344	2.93	27.00	14.2	17.0	17.0
WDP 276	158	24	284	2.70	21.81	14.8	18.0	101.0
WDP 287	169	12	302	9.12	23.94	20.3	44.0	44.0
AFPRO 206	175	12	416	4.13	11.19	58.9	68.0	52.0
WDP 323	194	12	264	50.01	64.36	18.40	72.0	230.0
WDP 320	196	12	575	2.40	11.91	60.46	77.0	118.0
AFPRO 305	208	12	189	12.81	17.34	41.72	71.0	58.0
WDP 349	210	12	189	3.83	7.54	50.8	125.0	125.0
AFPRO 306	214	12	340	3.74	6.74	113.0	323.0	273.0
CP 150	280	12	605	69.90	71.40	336.42	174.0	261.0
CP 181	302	12	832	7.05	15.72	96.0	200.0	85.0
CP 325	378	12	442	7.53	15.04	58.9	100.0	100.0
CP 445	382	12	163	3.75	10.22	24.2	62.0	72.0

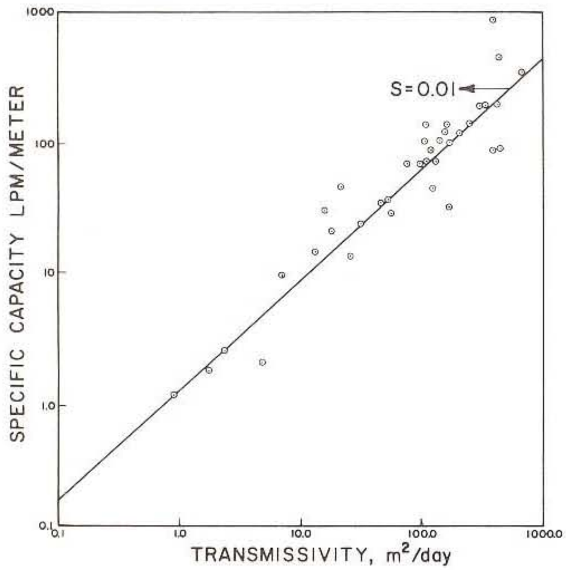

Fig. 10. Plot of specific capacity (Q/s) versus transmissivity (T) for wells drilled in Deccan Trap Basalts.

showed similar values for transmissivity during the pumping and recovery periods.

Tests conducted on wells that penetrated a single water-bearing zone (aquifer) tended to provide data plots that could be evaluated using standard analytical models. Pumping tests in multi-aquifer units, where the uppermost aquifers are present in shallow-weathered zones, were for the most part difficult to analyze due to the dewatering of shallow aquifer units during pumping.

Results of selected constant-rate pumping tests are presented in Table 3. Values of aquifer transmissivity range over three orders of magnitude, from less than $10\,m^2\,day^{-1}$ to more than $300\,m^2\,day^{-1}$ and 12-h specific capacities range from less than $2\,lpm^{-1}$ to more than $300\,lpm^{-1}$. In general, the most productive aquifers occur at brecciated flow contacts and also in valleys in the dissected plateau areas.

A theoretical relationship between specific capacity (Q/s) and transmissivity (T) was calculated using the Theis formula (1935) and plotted on Fig. 10. Values of specific capacity (corrected for well loss) and transmissivity, calculated from pumping tests, are also plotted. In general, high and low values of specific capacity correlate to high and low values of transmissivity. Specific capacities were found to range over three orders of magnitude, thus reflecting a wide range of aquifer hydraulic conditions. Since the data plot as well as they do, it would appear that for some pumping tests, the analytical methods that were used are reasonable.

Frequency plots of both corrected and actual specific capacity are plotted on Fig. 11. In general, production wells that were to be equipped with power pumps were tested; therefore, these plots represent the specific capacity frequency of the more productive wells in the study area. If all the wells that were drilled had been tested, the plots would be displaced downward from the plots shown.

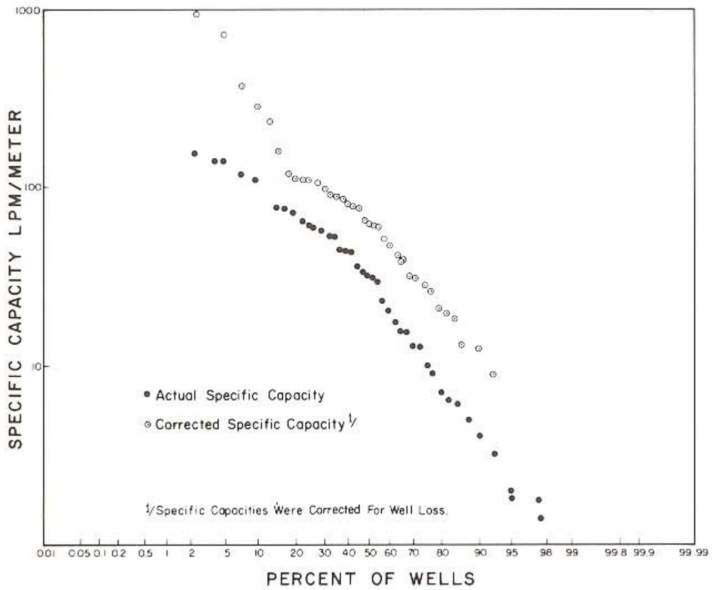

Fig. 11. Specific capacity frequency plots for wells drilled in Deccan Trap Basalts.

COMPARISON OF RESULTS WITH OTHER BASALT REGIONS

The results from a number of studies in basalt areas are available for rocks which range in geologic age from Precambrian to Holocene. Davis (1974) pointed out the effects of geologic time on porosity and permeability and noted

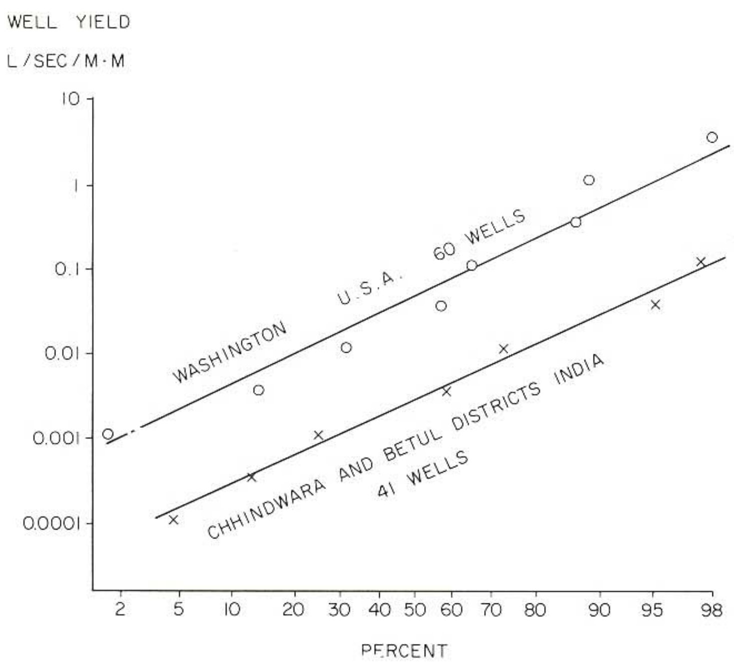

Fig. 12. Log–probability plot of specific capacity of wells divided by thickness of saturated basalt penetrated by wells (Davis, 1974).

that most of the reduction in porosity and permeability is accomplished in the following sequence of events:

(1) An early stage of weathering and compaction with an accumulation of the products of weathering within the pores.

(2) An intermediate stage of compaction and deposition of secondary mineral deposits within the pores.

(3) A final stage of compaction and metamorphism in which almost all permeability attributable to primary porosity is destroyed.

In the same paper, Davis (1974) presented log-probability plots (Fig. 12) of specific capacity of wells divided by saturated thickness for two areas in basalt. One area was the Satpura Hills Region where the Deccan Trap Basalts are of Cretaceous–Eocene age and the other area is in the State of Washington, where the basalt flows are of Miocene age. Specific capacities for wells in the State of Washington were on the average one order of magnitude higher than those for wells in the Satpura Hills Region.

Unfortunately, similar results are not available for other areas in India, and thus it is not possible to make a comparison of well yields or specific capacities with other basalt areas in India.

USE OF PUMPING-TEST DATA

Perhaps the most important use of a pumping test, in addition to increasing the understanding of the hydrogeologic system, is the application of the results to determine the sustained yield of a well or a group of wells. In determining the sustained yield it is important to have a good understanding of the local geology, groundwater flow system dynamics, recharge characteristics, fluctuations of water levels and groundwater storage, and the location of the well with respect to groundwater recharge and discharge areas. Equally important is a knowledge of the site-specific geologic conditions, well-construction techniques, and the location(s) of aquifers or water-bearing fractures.

The ideal method of determining the sustained yield of a well would be to run a long-term pumping test of several months' duration so that the aquifer's response for this duration could be determined accurately. The authors recommend long-term tests if technically and economically feasible. However, in most situations, long-term pumping tests are not feasible and the only substitute is a short-term test where the results of the test must be extrapolated into the future to determine the sustained yield of a well. It should be noted that a 12- to 24-h pumping test merely determines the response of that portion of an aquifer influenced by the test for the period of pumping. The test also determines the response of an aquifer for the particular time of year during which the test was conducted. This is particularly important in a climate where recharge is seasonal, as is the case in central India.

Therefore, a test conducted in the monsoon season may give different results from those of a test run in the dry season. This is particular true in local groundwater flow systems which have limited groundwater storage and a fairly large change in groundwater storage in a given year, with respect to total storage even under natural conditions (i.e., no pumping).

The following parameters must be known in order to estimate the sustained yield of a well: well-loss constant, critical pumping levels (the depth to productive aquifers), aquifer transmissivity and the rate of drawdown with time, recharge characteristics, and available drawdown.

Transmissivity and the rate of drawdown with time can be determined from a constant-rate pumping test. If only the pumped-well data are available, then the Cooper–Jacob (1946) modified equation must be used for the analysis. The components of drawdown due to aquifer loss and well loss can be determined from the results of a step–drawdown pumping test as well as values of the aquifer and well-loss constants. Thus, calculations of the drawdown due to well loss for any rate of flow can be determined. Recharge characteristics for the study area are fairly straightforward since there are distinct rainy and dry seasons. Critical pumping levels can be determined if the depth to productive aquifers is known; available drawdown will be the difference between seasonal low static-water levels and critical pumping levels. Lastly, the effects of interference from nearby pumping wells must be taken into account.

The analysis is fairly straightforward if the above parameters are known, and provided that critical pumping levels are above the top of productive aquifers and there are no boundaries. If constant-rate test drawdowns are corrected for well loss, then the theoretical drawdowns at any pumping rate can be determined because the rate of change of slope is directly proportional to the increase in Q. These curves can be extended to the time period of interest on a semi-log plot of drawdown versus time, and the drawdown in the well at the time of interest can be determined by adding the well loss for the pumping rate. Using this type of analysis, it can be determined if water levels for a specific pumping rate and at a particular time will be above or below critical levels.

The same method of analysis can be applied if the aquifer is of limited extent, but in this situation the rate of drawdown with time that occurs due to a limited aquifer should be used rather than the initial rate of drawdown with time. When dealing with wells in consolidated-rock aquifers, fracturing can be localized, resulting in aquifers with limited extent. A pumping test of sufficient duration to enable the delineation of boundaries is recommended.

Available drawdown is limited in groundwater recharge areas; that is, the distance from static-water levels to the top of principal water-bearing zones is small. Dewatering is possible in such wells, and the estimation of safe-yields must be done with caution and care.

CONCLUSIONS

The results of short-term step–drawdown and constant-rate pumping tests provided for an understanding of aquifer hydraulic characteristics for the

Deccan Trap Basalts in the Satpura Hills Regions. It is appreciated that results from long-duration pumping tests generally result in lower values of transmissivity and specific capacity, but given the economics of the clients in the area and pumping duration (9 to $12\,h\,day^{-1}$), short-term tests were often the only alternative. In effect, the values of transmissivity determined seem reasonable for short-term predictions when pumping is intermittent.

Some conclusions that can be derived from this study area are:

Hydrogeologic

(1) Groundwater flow systems are of the local type in the dissected plateau areas and in general, significant differences in well yields and aquifer parameters occur between groundwater recharge and discharge areas.

(2) In the dissected plateau areas, annual water-level fluctuations are more pronounced in recharge areas (up to 50 m) as compared to discharge areas (0–3 m).

(3) In plateau areas both local (weathered portion of youngest lava flows) and intermediate (deeper confined aquifers) flow systems occur.

(4) Groundwater occurs in weathered materials, brecciated flow contacts and in fractured zones. The distinct recharge period and overall low rock porosity results in large changes in groundwater storage between monsoon periods. These differences are especially significant in groundwater recharge areas where the greatest water-level fluctuations occur.

(5) Well yields range from less than 1 lpm to as much as 800 lpm.

Step–drawdown pumping tests

(1) Well losses comprise a significant portion of the total drawdown in a number of low and high yielding wells.

(2) The nature of well loss appears to be non-Darcian flow in the aquifer in the vicinity of the pumped well.

(3) The results indicate a relationship between percent of decrease in specific capacity and well loss. In wells with low well losses, the percent of reduction in specific capacity is low and in wells with high well losses the percent of reduction is high.

(4) There does not appear to be any relationship between transmissivity and the proportion of drawdown due to well losses.

(5) The graphical method of solution was found to be preferable since anomalies in the test data can be useful for interpreting aquifer conditions.

Constant-rate pumping tests

(1) Short-term aquifer transmissivities range from less than $10\,m^2\,day^{-1}$ to over $300\,m^2\,day^{-1}$.

(2) Twelve-hour specific capacities range from less than 2 lpm m^{-1} to as much as 300 lpm m^{-1}.

(3) Tests conducted on wells that penetrated a single water-bearing zone (aquifer) generally provided data plots that were possible to analyze by common analytical methods.

(4) Tests conducted in multi-aquifer units were generally more difficult to analyze.

(5) Test results were useful for determining boundaries and aquifer dewatering.

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