Results of Pumping Tests in Crystalline-Rock Aquifers[a]

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ABSTRACT

The Evangelical Lutheran Church (E.L.C.) Water Development Project, headquartered in Betul, Madhya Pradesh, India, has been involved since 1971 in developing ground-water supplies in the Satpura Hill Region of Central India. To date, over 400 wells have been drilled in crystalline rocks and more than 100 of these wells have been pump-tested to determine aquifer hydrologic characteristics.

Crystalline rocks crop out in roughly 20 percent of the Satpura Hill Region and the main rock types are granite, gneiss, and schist. The crystalline-rock country is gently undulating and ground-water flow systems are of the local type being limited to small drainage basins of a few square miles in area.

The controlled testing and detailed analysis of over 100 pumping tests provided an excellent opportunity to evaluate the applicability of standard analytical models for the analysis of pumping tests in crystalline-rock aquifers.

Step-test data were analyzed by Rorabaugh's (1953) method and by a graphical method. The results indicate that well losses are significant in a number of wells tested and appear to be related to non-Darcian flow in the aquifer adjacent to a pumped well.

Constant-rate pumping tests were used to determine aquifer transmissivity. 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 orders of magnitude from 10^2 to 10^4 gpd/ft (1.24 to 1.24×10^2 m^2/day). Pumping-test results often enabled the prediction of aquifer conditions, such as limited aquifers, recharge and leakage boundaries, and aquifer dewatering.

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INTRODUCTION

The Evangelical Lutheran Church (E.L.C.) Water Development Project has been involved in developing ground-water supplies in Central India since 1971. The project's area of operation in the Satpura Hill Region includes the districts of Betul, Chhindwara, and Seoni. To date, over 1,000 tube wells have been drilled for agricultural, village, industrial, institutional, and municipal water supplies. Prior to 1971, these districts were almost entirely dependent for water supply on surface water and shallow open wells, 30 to 40 feet (9.1 to 12.2 meters) deep.

More than 100 pumping tests have been carried out on production wells which were drilled in crystalline rocks. Testing procedures generally consisted of a step-drawdown test followed by a constant-rate test, and test data were analyzed by standard analytical models.

The purposes of this paper are as follows:

1. to describe the pertinent geologic and hydrogeologic features of the crystalline rocks in the study area;

2. to review the results of step-drawdown 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. to discuss practical applications of step-drawdown tests;

4. to review the results of the constant-rate pumping rates in order to ascertain the applicability of certain analytical models for analyzing pumping-test data; and

5. to present examples of constant-rate pumping tests and ranges of aquifer transmissivity and specific capacity.

AREA

The subject area is located in the south-central part of Madhya Pradesh State, India, 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. The subject districts occupy an area of 11,800 square miles (30,490 square kilometers) and contain 5,156 villages and towns with a total population of 2.4 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. The crystalline-rock country is characterized by gently undulating hills and small drainage basins.

The bulk of precipitation occurs during the southwest monsoon (June to September) and the average annual rainfall ranges from 38 to 48 inches (95 to 120 centimeters).

HYDROGEOLOGY

Crystalline metamorphic and igneous rocks crop out in approximately 20 percent of the study area. The metamorphic rocks are Precambrian in age and common rock types include gneiss, schist, and quartzite. The igneous rocks are coarse-grained, porphyritic, intrusive granite and pegmatite veins. These igneous rocks exhibit an intrusive relationship with the Precambrian metamorphic bedrock and as such are younger in age.

The metamorphic rocks strike in a general east-northeast to west-southwest direction, dip 70° to 90°, and are folded in places. Quartz pegmatite veins are a common feature and occur as broad dikes and thin strings. These veins are generally porphyritic and occur along the prominent joint system of the metamorphic rocks. Figure 1 is a surface geologic map of the study area.

The crystalline-rock country is gently undulating; ground-water basins are conterminous with surface drainage sub-basins, which are a few square miles in area, and drainage patterns are dendritic. The sub-basin relief is on the order of

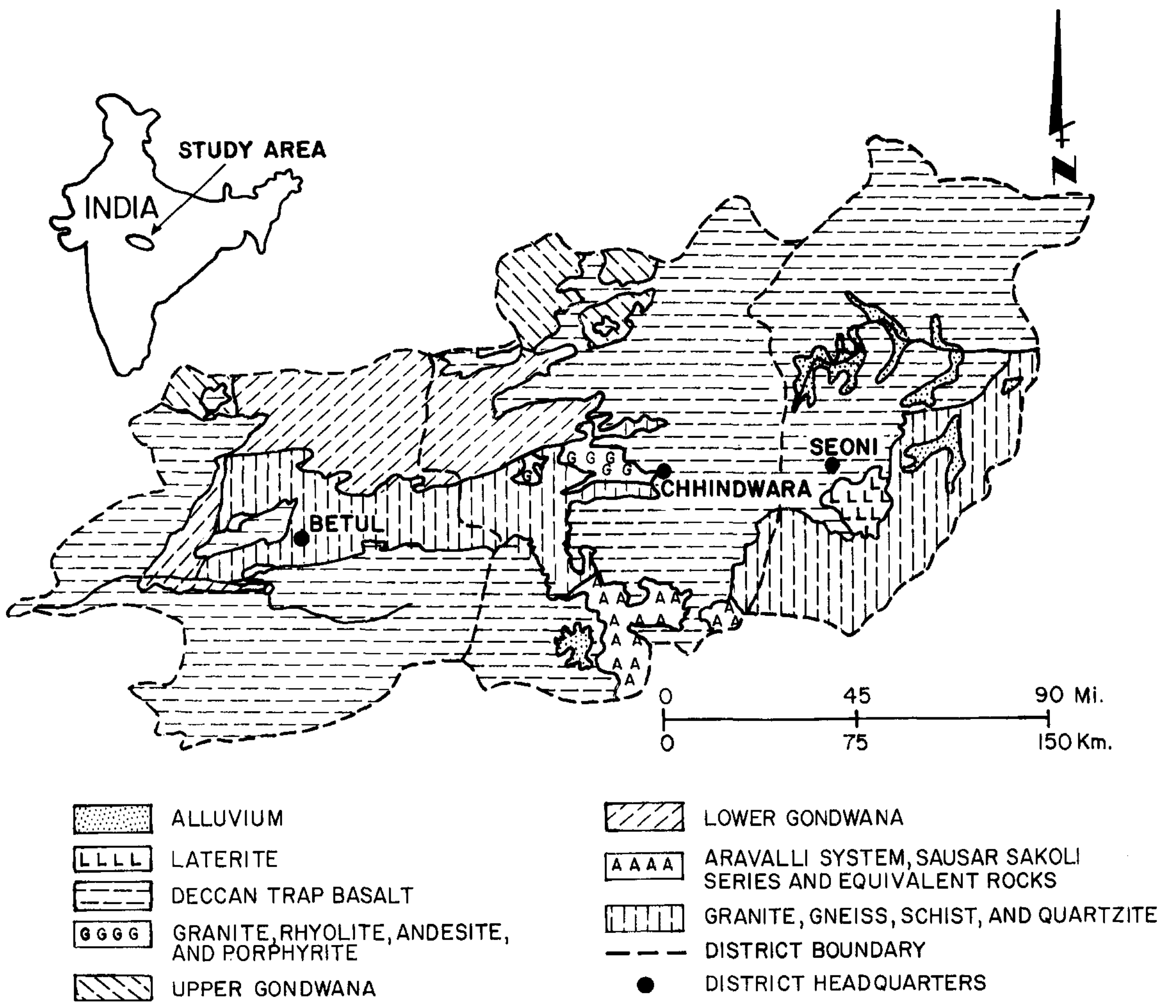

Fig. 1. Surface geologic map of the study area.

50 to 100 feet (15 to 30 meters). Ground-water flow systems are of the local type, a local system having its recharge area at a topographic high and its discharge area at a topographic low which are adjacent to each other. Intermediate and regional ground-water flow systems do not exist because of negligible hydraulic conductivity with depth.

Crystalline rocks generally do not possess original or primary openings and fresh crystalline rocks have less than one percent porosity and negligible hydraulic conductivity. The ability of crystalline rocks to store and transmit water is dependent on the development of secondary openings which are formed by fracturing and weathering.

The weathered zone in crystalline rocks or saprolite is of particular importance both as a storage zone for ground water and as an aquifer for open wells and shallow tube wells. Thicknesses of saprolite in the study area range from about 4 to 114 feet (1 to 35 meters) and average 42 feet (12.8 meters) in depth. Significant differences exist in the permeability of saprolite zones. These differences, although not measured quantitatively, were noted in the field during drilling operations. In general, shallow tube wells that derive water primarily from the saprolite zone, have low well yields ranging from 0 to 10 gpm (0 to 37 lpm).

The structure of the crystalline rocks in the study area has undergone considerable modification through geologic time. Times of particular importance, structurally, were during the Satpura uplift and when the igneous granite rocks were intruded into the Precambrian crystalline rocks.

In addition to the permeable saprolite layer, aquifers occur where bedrock and the quartz-pegmatite intrusive veins are jointed and fractured. The yield of an individual well is dependent largely on the thickness and permeability of the saprolite, and for the deeper rock wells upon the intensity, areal extent and interconnection of joints, fractures, and fractured quartz-pegmatite veins. Fractures tend to close down with depth, and this accounts for the shallow ground-water circulation in crystalline rocks. Parker *et al.* (1964, p. 40) report similar conditions in the crystalline rocks of the Delaware River Basin where such rocks "contain small but significant quantities of water; however, few such openings extend deeper than 300 feet and most of the water is contained at much shallower depths."

The more productive wells in these crystalline rocks were generally completed in jointed and fractured bedrock and, in a few of the highly productive wells, the fracture zones are 30 to 40 feet (9 to 12 meters) thick. In less productive wells, saprolite is generally followed by massive or slightly jointed bedrock. Significant variations in well yield have been known to occur at close distances but in general, ground-water discharge areas [mean well yield 45.0 gpm (170 lpm)] are more productive sites for wells than ground-water recharge areas [mean well yield 18.8 gpm (71.2 lpm)]. Figure 2, which is a cumulative frequency plot of well yields in various topographic locations, illustrates this difference in well yields where valleys represent ground-water discharge areas and flat uplands and plains represent ground-water recharge areas. LeGrand (1954) reports similar variations in

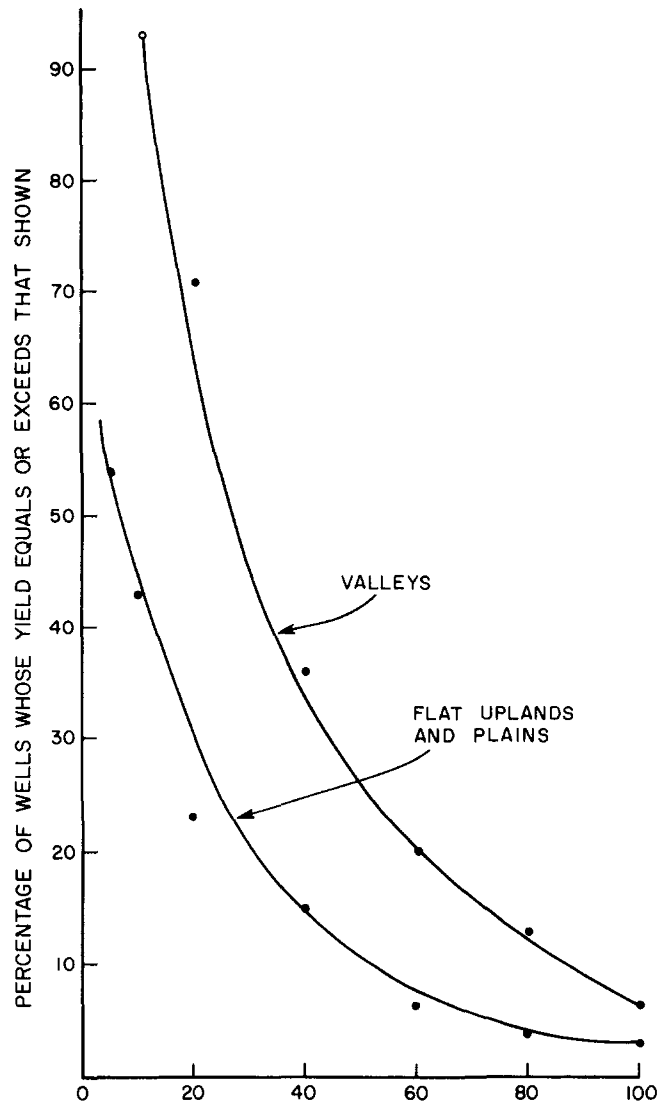

Fig. 2. Cumulative frequency plot of well yields in various topographic locations in crystalline rocks.

well yields with topographic location in crystalline rocks in the Piedmont region of North Carolina. Taking a closer look at the aquifer system, the bulk of ground-water storage in the system is in weathered zones, except where fracture zones are fairly thick. In general, the hydraulic conductivity of the saprolite is less than that of fractured rocks in which the fractures act more as conduits for pumped wells, and during prolonged pumping, the bulk of water pumped is derived from overlying weathered materials.

To summarize, the pertinent hydrogeologic features of the study area are:

1. Recharge to the ground-water system occurs from June to September when 90 percent of the annual rainfall occurs.

2. Ground-water flow systems are of the local type, coincident with surface-water basins, and generally only a few square miles in area.

3. In general, significant differences both in well yields and aquifer parameters occur between ground-water recharge areas and ground-water discharge areas. Annual water-level fluctuations are more pronounced in recharge areas [20 to 50 feet (6 to 15 meters)] than in discharge areas [0 to 10 feet (0 to 3 meters)].

4. Ground water occurs widely in weathered materials, in joints and fractures, and in fractured quartz-pegmatite veins. Fractures close with depth and the depth of ground-water circulation is 150 to 200 feet (45 to 60 meters) in most areas. The distinct recharge period and limited depth of ground water results in large changes in ground-water storage between monsoon periods. These differences are especially significant in ground-water recharge areas, where the greatest water-level fluctuations occur.

ANALYSIS OF PUMPING-TEST RESULTS

Introduction

Over 100 pumping tests have been conducted on wells which were drilled in crystalline rocks. Most of the wells are 6.0 to 6.5 inches (15.2 to 16.5 centimeters) in diameter and were drilled by air-hammer rigs. Submersible pumps of 5.75 and 3.75 inches (14.6 and 9.5 centimeters) in diameter were used for testing. The discharge pipes were equipped with standard totalizing water meters; water levels in the pumped well were measured by an electric sounder. The testing of each well was conducted in the following manner:

1. A step-drawdown test was conducted for 6 hours and consisted of 3 to 6 steps.

2. Recovery was measured for 12 hours before starting the next phase.

3. A constant-rate test was run for 12 to 24 hours and recovery was measured for the same duration as pumping.

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 were analyzed by the Cooper-Jacob (1946) modified non-leaky artesian formula. As testing work progressed and a number of tests were analyzed, anomalies in the test data proved helpful for interpreting aquifer conditions. For a number of tests hydraulic properties were obtained and were generally found to be reasonable. After drawdowns were corrected for well losses, values of corrected specific capacity (Q/s) for 12 hours 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.

The validity of utilizing analytical models for evaluating pumping tests in consolidated-rock aquifers has been a subject of debate for years. The derivation of the basic equation governing ground-water flow is dependent on a large number of assumptions, a few being that the aquifer is intergranular, homogeneous, isotropic, infinite in areal extent, of uniform thickness, and having Darcian flow. When one conceptualizes the mode of occurrence of ground water in crystalline-rock aquifers, that is, through joints and fractures, it is difficult to visualize homogeneity and isotropy except in highly fractured media. Furthermore, hydraulic conductivity in fractured-rock aquifers is greatest in the predominant direction of fracturing and jointing, and, in the vicinity of pumped wells, flow is generally non-Darcian.

Eagon and Johe (1972), in discussing the occurrence and movement of ground water in carbonate rocks, have noted that hydraulic characteristics seem to be inconsistent in the vicinity of the borehole. This may be of some importance initially in a pumping test, but as the cone of depression becomes larger and covers a representative area of the aquifer, these irregularities assume less importance. The larger the area considered, the more some carbonate aquifers effectively assume the hydraulic characteristics of a homogenous media. In effect, when the cone encompasses a representative area of the aquifer, the resultant drawdown in the well represents the sum-total effect of the hydraulic characteristics of the aquifer in the area encompassed by the cone, including any irregularities. It seems reasonable that in crystalline-rock or other hard-rock aquifers where there are a large number of interconnected fractures on an areal basis, the aquifer could assume the characteristics of a homogenous media. Parker's work in the limestone and dolomite rocks of the Floridan Aquifer demonstrates this phenomenon on a large scale and over several thousand square miles in Florida (Parker *et al.,* 1955).

Chase (1967) noted that "The theory and practice of analytical methods as applied to dense-rock aquifers seems applicable to aquifers with fractures, joints or cavities so well and closely distributed and so well interconnected that the composite model is one approaching homogeneity," and the "Methods yield results more difficult to interpret and perhaps less significant when the aquifer is supplied by one or a small number of large relatively widely spaced extensive fractures or cavities."

In conclusion, perhaps the best rule is one of caution when applying an analytical model to a pumping test. Also, before attempting to apply a specific model, consider:

1. the limitations of the model; and

2. the realities of the physical system being modeled.

Step-Drawdown 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 in time and proportional to the pumping rate squared (Q^2).

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

$$s_w = BQ + CQ^2 \qquad (1)$$

where:

s_w = the total drawdown in the well.

BQ = the aquifer or formation loss.

CQ^2 = the well loss.

B = the aquifer-loss constant. It represents the total resistance of the formation from the well face out to the radius of influence. Its units are sec/ft^2 or ft/gpm, and it increases with the log of time.

C = the well-loss constant. Its units are sec^2/ft^5 or ft/gpm^2. C is constant with time.

A simple technique for determining B and C is to write equation (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 pumping rate, Q, 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 turbulent 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, and for the turbulent flow regimen, to determine a value for n from a graphical solution of equation (3) on log-log paper. 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 [equation (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 [equation (3)] is applicable for the turbulent flow regimen:

$$Q < Q_c \quad s_w = BQ + C'Q \quad \text{(for laminar flow)} \qquad (2)$$

$$Q > Q_c \quad s_w = BQ + CQ^n \quad \text{(for turbulent flow)} \qquad (3)$$

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 well.

Rorabaugh attempts to compensate for this variation in the critical radius with discharge by applying two equations: equation (2) for laminar flow, and equation (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 equation (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 two methods: Rorabaugh's graphical method and by the graphical solution of the equation $s_W = BQ + CQ^2$. The graphical method, i.e., a plot of s_W/Q versus Q on rectilinear paper, proved to be the more practical method of analysis. This method is especially useful where dewatering or boundary conditions occur, as these can often be detected by a change in the slope of the plot of s_W/Q versus Q (Figure 3). 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, aquifer dewatering results in an increase of the slope.

An aquifer of limited extent (Figure 3) 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.

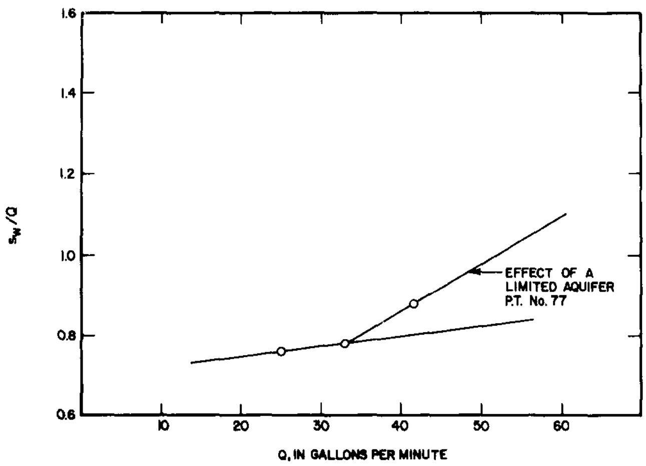

Fig. 3. Plot of s_W/Q versus Q noting the effect of a limited aquifer.

If recharge occurs during a test, the slope of the plot will decrease. The step-drawdown test technique is quite useful for determining depth to water-bearing fractures in a well with poor or non-existent records.

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

Table 1 contains the results of a number of step-drawdown tests that were conducted on crystalline-rock wells in the study area. Most of the data in Table 1 are self-explanatory. Columns 5 and 6 contain the aquifer and well-loss constants, determined from the graphical solution. Columns 7 and 8 contain the constants determined from

Table 1. Selected Results of Step-Drawdown Pumping Tests in Crystalline-Rock Aquifers

(1) *Well No.*	(2) *Pump Test No.*	(3) *Q, Maximum (gpm)*	(4) *Q/s at the End of Test (gpm/ft)*	(5) *B, Graphical Solution (ft/gpm)*	(6) *C, Graphical Solution (ft/gpm²)*	(7) *B, Rorabaugh (ft/gpm)*	(8) *C, Rorabaugh (ft/gpmⁿ)*	(9) *n, Rorabaugh*	(10) *Transmissivity (gpd/ft)*	(11) *BQ*	(12) *CQ^2*	(13) *BQ*	(14) *CQ^n*	(15) *Percent Reduction in Specific Capacity*
WDP 108	40	50.0	0.252	2.3	0.023	2.4	0.0125	2.13	–	115.0	57.50	120.0	53.60	17.0
A 1	54	77.5	6.73	0.053	0.000942	0.053	0.00098	2.0	–	4.10	5.64	4.10	5.90	43.5
A 59	63	42.0	4.12	0.165	0.00132	0.165	0.00132	2.0	3,000	6.90	2.32	6.90	2.32	5.4
WDP 175	84	40.0	2.10	0.155	0.008	0.25	0.000375	2.73	6,600	6.20	12.80	10.0	8.91	82.5
WDP 183	89	40.0	2.31	0.188	0.00604	0.188	0.008	1.91	7,900	7.52	9.66	7.52	9.2	35.2
WDP 184	90	52.0	1.02	0.65	0.0077	0.65	0.00054	2.56	4,300	28.50	20.82	33.80	13.35	39.7
WDP 188	92	25.0	0.63	0.4	0.0547	0.4	0.018	2.27	4,000	5.0	34.20	10.0	27.0	51.5
WDP 187	91	172.0	6.12	0.02	0.00033	0.02	0.024	1.32	12,000	15.30	9.76	3.44	21.40	22.5
WDP 189	93	59.0	5.75	0.122	0.00071	0.122	0.00065	2.0	9,700	7.22	2.48	7.22	2.26	16.0
WDP 195	98	196.0	6.04	0.102	0.00025	0.102	0.00027	2.0	5,000	20.10	9.60	20.10	10.40	7.86
WDP 196	99	196.0	11.58	0.0625	0.000075	0.0625	0.000069	2.0	20,000	12.20	2.88	12.20	2.65	15.6
WDP 131	100	42.0	1.55	0.31	0.008	0.31	0.008	2.0	18,500	13.0	14.10	13.0	14.11	35.0

Rorabaugh's method. In columns 11 and 12, the aquifer and well-loss components of drawdown are computed for maximum test discharge using B and C from the graphical solution. In columns 13 and 14, the same is done using B, C, and n from Rorabaugh's 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 appears to be a relationship between percent decrease in specific capacity and well loss. Generally, in wells with low well losses, the percent reduction in specific capacity is low and in wells with high well losses, the percent reduction is significant.

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. 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.

In conclusion:

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 graphical method of solution is preferable since anomalies in the test data can be useful for interpreting aquifer conditions; and

4. a step-drawdown test is a useful technique for testing wells with poor or non-existent records.

Constant-Rate Test Results

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 [equation (4)]. This modification is generally referred to as Jacob's method.

$$T = \frac{264\,Q}{\Delta s} \qquad (4)$$

where:

T = aquifer transmissivity in gpd/ft.

Q = pumping rate in gpm.

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. 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 an aquifer or 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. 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 semilogarithmic 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 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 examples are presented below.

Case 1

In Betul town at Kanjanpur, a well was drilled for the Municipal Corporation. The well, 6.5 inches

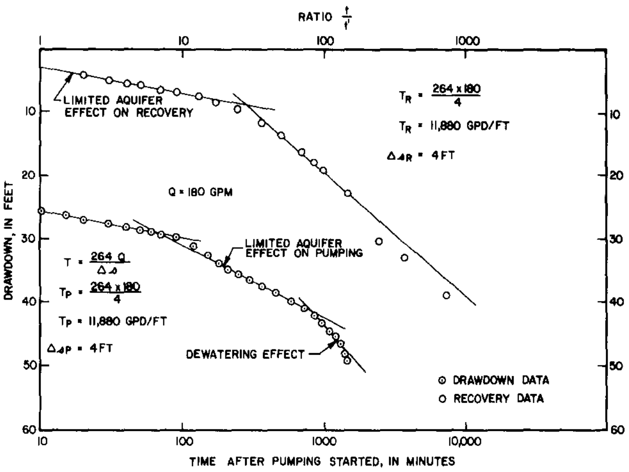

Fig. 4. Time-drawdown and residual-drawdown plots for pumping test at Kanjanpur, Betul town.

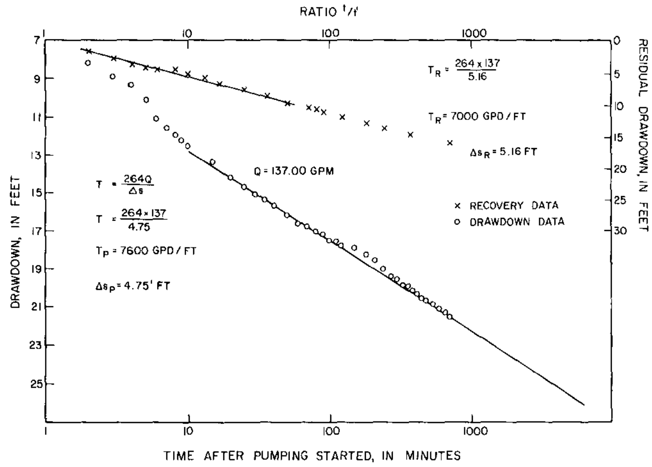

Fig. 5. Time-drawdown and residual-drawdown plots for pumping test at I.T.I., Chhindwara town.

(16.5 centimeters) in diameter, was drilled in gneiss to a depth of 124 feet (37.8 meters). During drilling, water-bearing fractures were noted at 42, 75, and 114 feet (12.8, 22.8, and 34.7 meters). A 24-hour pumping test was conducted and time-drawdown data and residual-drawdown data were plotted on semi-logarithmic paper (Figure 4). Two changes in the slope of the plot were noted. The first increase in slope occurred after 100 minutes of pumping. This linear increase in slope is generally caused by a barrier boundary or limited aquifer. However, decreases in transmissivity at a distance from the pumping well would have a similar effect on the time-drawdown response. The second increase in the slope of the plot occurred after 720 minutes of pumping when dewatering of the first fractured zone began. Aquifer dewatering generally results in a non-linear plot of drawdown versus time on semi-logarithmic paper. Aquifer dewatering poses problems using data from wells in shallow aquifers with limited available drawdown. In this test, values of aquifer transmissivity that were calculated from the pumping and recovery data correlated closely.

Case 2

In Chhindwara town, at the Indian Technical Institute, a well 6.5 inches (16.5 centimeters) in diameter was drilled to a depth of 100 feet (30 meters). During drilling, water-bearing fractures were noted at 42 feet (12.8 meters) and from 58 to 81 feet (17.6 to 24.6 meters). A 12-hour pumping test was conducted and plots of the time-drawdown and residual-drawdown data are given in Figure 5. Values of aquifer transmissivity, which were calculated from both the pumping and recovery data, correlated closely.

Case 3

In Betul town, at Tikari, a well was drilled for the Municipal Corporation. The well, 5 inches (12.7 centimeters) in diameter, was drilled to a depth of 120 feet (36.5 meters). Water-bearing fractures were noted from 47 to 66 feet (14.3 to 20.1 meters) and at 94 feet (28.6 meters) during drilling. A 12-hour pumping test was conducted and the time-drawdown and residual-drawdown data were plotted on semi-logarithmic paper (Figure 6). Drawdown stabilized after 400 minutes of pumping because leakage from the saprolite overlying the aquifer from 47 to 66 feet (14.3 to 20.1 meters) balanced pumping. The saprolite were permeable and saturated to the ground surface, as the test was run during the peak of the monsoon season.

Data from pumping tests in highly-fractured aquifers in ground-water discharge areas plotted with the least variance. This is expected because a highly-fractured media would best approximate

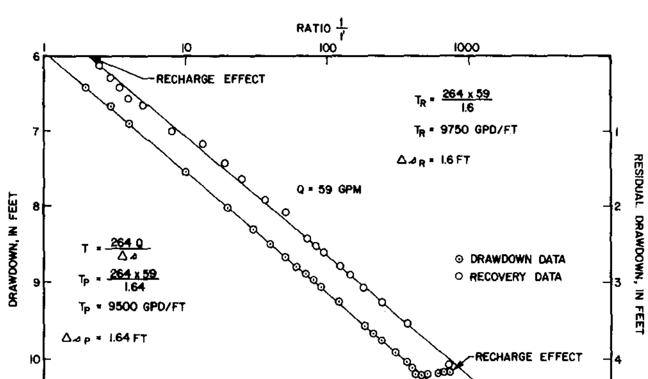

Fig. 6. Time-drawdown and residual-drawdown plots for pumping test at Tikari, Betul town.

Table 2. Selected Results of Constant-Rate Pumping Tests in Crystalline-Rock Aquifers

Well No.	*Pump Test No.*	*Pumping Duration (hours)*	*Test Discharge (gpm)*	*Static Water Level (ft)*	*Pumping Water Level (ft)*	*Q/s, Specific Capacity at End of Test (gpm/ft)*	*Transmissivity (gpd/ft) Pumping*	*Transmissivity (gpd/ft) Recovery*
WDP 123	46	10	16.7	15.33	76.75	0.27	1,250	1,200
A 55	60	12	56.0	21.17	31.66	5.3	13,500	13,500
WDP 163	79	12	5.0	31.83	70.92	0.12	210	220
WDP 164	80	12	6.0	31.0	50.5	0.30	590	600
WDP 175	84	12	40.0	17.5	60.5	0.92	3,000	6,600
WDP 183	89	12	55.0	15.0	46.0	1.77	7,900	9,200
WDP 184	90	6	66.7	3.66	59.83	1.12	4,300	–
WDP 187	91	24	180.0	6.5	55.75	3.65	11,900	11,900
WDP 186	92	12	30.0	5.83	55.92	0.60	4,000	5,700
WDP 188	93	12	59.0	16.33	26.5	5.85	9,600	9,800
WDP 195	98	12	196.0	8.42	71.0	3.13	5,700	4,900
WDP 196	99	12	196.0	11.83	32.0	9.72	11,800	20,000
WDP 131	100	12	42.0	21.17	48.83	1.52	18,500	18,500
WDP 222	118	12	84.5	11.17	28.08	4.95	22,000	29,000
WDP 227	126	8	13.2	11.33	99.66	0.15	350	250
WDP 225	127	12	23.8	7.25	45.0	0.61	850	1,250
WDP 216	128	12	23.8	7.5	36.66	0.82	1,600	2,500
WDP 237	131	12	59.4	36.33	80.92	1.33	5,700	6,300
WDP 241	135	12	200.0	+2.00	33.75	5.6	17,700	30,300
WDP 244	136	12	137.0	21.4	43.0	6.35	7,600	7,000
WDP 243	139	12	95.0	35.4	202.0	0.57	2,500	2,300
–	142	24	10.6	9.33	153.08	0.08	100	200
A 217	173	12	50.0	22.00	62.6	1.23	910	950
WDP 317	190	12	20.0	20.25	67.4	0.42	1,170	1,300
WDP 319	191	8.5	18.0	15.25	161.4	0.12	100	100
WDP 335	215	12	90.0	28.66	34.75	14.8	25,800	20,500

the assumptions upon which the equations describing ground-water flow are based. Aquifer dewatering is more common in the ground-water recharge areas, where available drawdown is generally limited.

Table 2 contains a summary of the results of the constant-rate pumping tests. Values of aquifer transmissivity range from 100 gpd/ft to 30,000 gpd/ft (1.24 to 372.0 m^2/day) and 12-hour specific capacities range from 0.08 gpm/ft to 14.8 gpm/ft (0.99 to 184.0 lpm/meters). In general, ground-water discharge areas have been more productive locations for drilling wells than ground-water recharge areas. This is mainly due to more pronounced fracturing in ground-water discharge areas.

Data on Table 2 indicate that transmissivity (recovery) is greater than transmissivity (pumping) for most tests. This may be attributed to less turbulence and non-Darcian flow during the recovery period than during pumping.

The theoretical relationship between specific capacity and transmissivity can be computed by the Theis equation if assumptions for storage coefficient, well radius, and duration of pumping are made. Because the duration of pumping and well radius for most tests were the same, and assuming that values of storage coefficient are of the same order of magnitude for these crystalline-rock aquifers, then high and low values of transmissivity should correspond to high and low values of specific capacity.

Theoretical plots of 12-hour specific capacity versus transmissivity were constructed in Figure 7, by assuming several values of the storage coefficient. Values of specific capacity (corrected for well loss) and transmissivity, which were determined from the pumping-test results, were also plotted. The

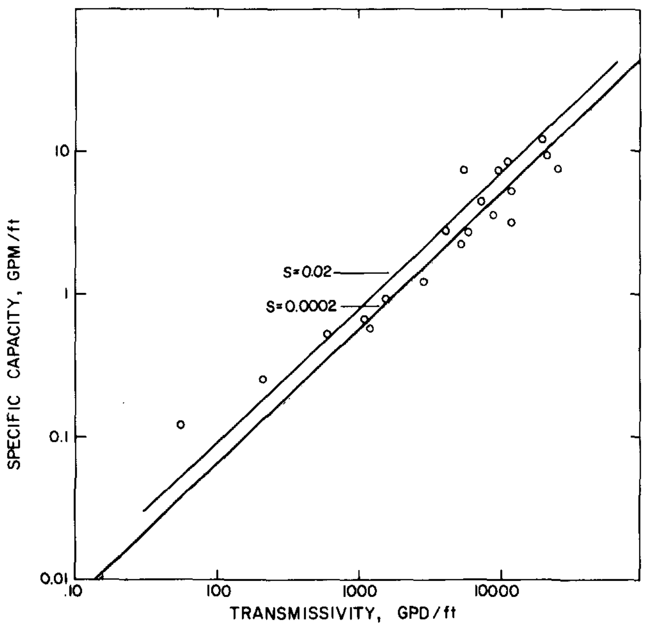

Fig. 7. Plot of Q/s versus T for wells drilled in crystalline rocks.

scatter of the data indicates that determining transmissivity from specific capacity data is a bit risky and a poor substitute for a pumping test (constant rate). However, since the data plot as well as they do,

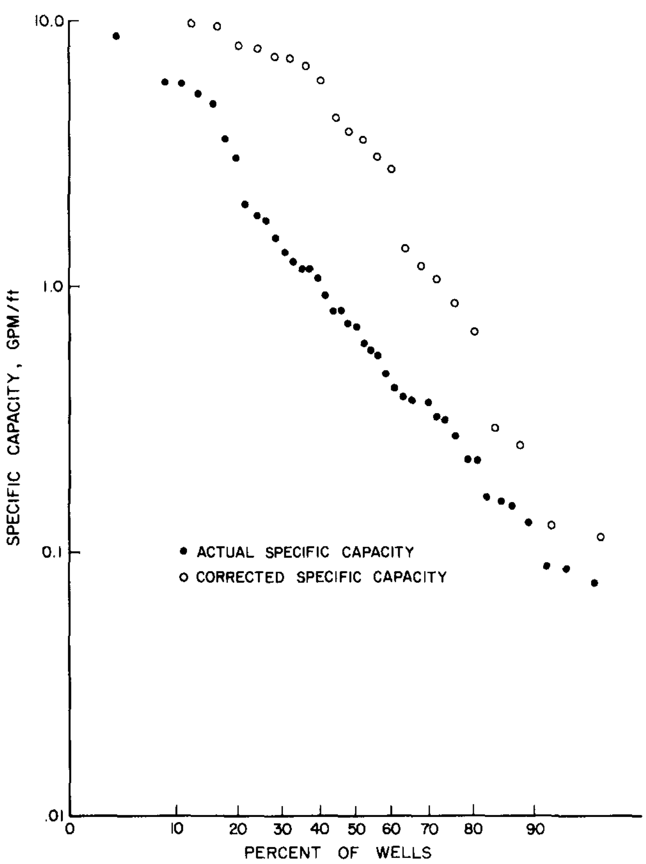

Fig. 8. Specific capacity frequency graphs for wells drilled in crystalline rocks.

there is the indication that for some pumping tests, the analytical methods that were used are reasonable. Frequency plots of both corrected and actual specific capacity were plotted in Figure 8. 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 area. If all the wells that were drilled had been tested, the plot would be displaced downward from the plots shown.

USE OF PUMPING-TEST DATA

Perhaps the most important use of a pumping test 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, ground-water flow system, recharge characteristics, fluctuations of water levels, ground-water storage, fluctuations in ground-water storage, and the location of the well with respect to ground-water recharge and discharge areas. Equally important is a knowledge of the geologic well log, well-construction techniques, and the location 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 response for this duration could be determined accurately. The author recommends 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 a sustained yield for a well. It should be noted that a 12- or 24-hour 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 India. Therefore, a test conducted in the monsoon may give different results than those of a test run in the dry season. This is particularly true in local ground-water flow systems which have limited ground-water storage and a fairly large change in ground-water 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 C, critical pumping levels (the depth to productive aquifers), aquifer transmissivity and the rate of drawdown with time, recharge characteristics, and the available drawdown.

Transmissivity and the rate of drawdown with time can be determined from a constant-rate 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 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, provided critical pumping levels are above the top of productive aquifers and there are no boundaries. Constant-rate test drawdowns are corrected for well losses; then the theoretical drawdowns at any rate of flow 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 actual drawdown in the well at the time of interest can be determined by adding the well losses for the pumping rate. Using this type of analysis, it can be determined if water levels for a particular pumping rate 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 the limited aquifer must 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 low in ground-water recharge areas; that is, the distance from the static water level to the top of principal water-bearing zones is small. Dewatering is probable in such wells, and the estimation of safe yields must be done with caution and care.

CONCLUSIONS

The pumping-test results were determined from short-term step-drawdown and constant-rate pumping tests, and values of transmissivity and specific capacity are short-term (12-hour) values. It is appreciated that results from a long-duration pumping test will generally result in lower values of transmissivity and specific capacity, but given the economics of the clients in the areas and pumping duration (9 to 12 hours per day), 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 are:

Step-Drawdown 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 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 is preferable since anomalies in the test data can be useful for interpreting aquifer conditions.

Constant-Rate Tests

1. Average well yields and specific capacities are significantly higher in ground-water discharge areas than in ground-water recharge areas. This is due to more extensive fracturing in discharge areas and more available drawdown.

2. Short-term aquifer transmissivities range from 100 gpd/ft to 30,000 gpd/ft (1.24 to 372.0 m^2/day).

3. Twelve (12)-hour specific capacities range from 0.08 gpm/ft to 14.8 gpm/ft (0.99 to 184.0 lpm/meter).

4. Test results have been useful for determining boundaries and aquifer dewatering.

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