

GEOHYDROLOGICAL GUIDES
FOR
DRILLING AND TEST PUMPING
IN
IGNEOUS AND METAMORPHIC ROCKS⁺

By
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INTRODUCTION

The site-specific occurrence of ground water in igneous and metamorphic rocks is often difficult to predict. The ground-water production potential from such rocks is considered by many ground-water professionals to be generally low. Production can vary, however, from very low (or nil) to very high sustained production rates, that is, greater than 300 gpm (19 l/s) (Ellis, 1909; Stewart, 1962). Limited knowledge of the geological conditions that have combined to yield ground water at relatively high production rates have been major constraints to cost-effective and successful ground-water exploration and development of such rocks in the past.

The pressing need for obtaining even a limited water supply (less than 1 gpm or 0.06 l/s) has prompted random drilling, augmented occasionally by preliminary and often superficial geological evaluations. Drilling has been conducted in many areas underlain by crystalline rocks, and voluminous data resulting from such drilling also indicate a broad range in the productivity of such rocks. In Brazil, for example, approximately 63 percent of the country is underlain by igneous and metamorphic rocks. Reboucas (1976) reports that approximately 15,000 wells have been drilled in fractured crystalline rocks, of which 92 percent considered successful. Many of such wells have been in use for more than 30 years. The average well yield of the successful wells is approximately 0.03 liters per second per meter of aquifer penetrated (or 0.13 gpm/feet of aquifer), which is consistent with previous investigations conducted in other countries.

A sixty meter (197 feet) depth limitation has been suggested by many professionals as a maximum economic drilling depth, which has also been supported in other countries on the assumption that potential ground-water production decreases with increasing depth. For example, typical reported well yields in crystalline rock areas of Africa, India, Korea and parts of the Western Hemisphere are indicated in Tables 1 and 2. When an unusually high rate of

⁺ Paper presented at Inter-regional Seminar on Groundwater in Hard Rocks, Coimbatore, India: November 22 - December 20, 1979, UNESCO/SIDA/CGWB/TNAU

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TABLE 1

Reported yields from wells in hard rocks of Africa. (After UN ST/ECA/147, Ground water in Africa, 1973)

Country	Average rainfall (mm)	Province or area	Rock types	Yield per well (m ³ /h)	Well depth (m)	Remarks
Angola	1000	South Catuiti	Metamorphics Weathered tectonized granites	0.6 3 to 30		Fracture yields up to 80 m ³ /h
Botswana	100-250		Granites, gneisses and schists	0.4 to 10		Under exceptionally favorable geological conditions
Central African Empire	800-1400		Gneisses, schists and quartzites	0.5 to 5	3-15	Of 400 dug wells put down during 1967-69 90 % were productive in the weathered layer above the basement.
Benin	750-1250	Central region	Granite gneisses, mica schists	1-4		
Ethiopia	1000-2000	Sidamo	Granite, gneiss and schist	Low		Weathered layers poorly developed. Yields from fractured zones low and water often of poor quality.
Ghana	750-2000	Accra plains Upper and northern regions	Gr., gn., qtz. and biotite schist Granite	0.5-11 0.4-24	34	Depth based on 280 wells.
Ivory Coast	1000-2000	Western Region	Granite	2 to 5	10-15	
Malawi	800-1500		Biotite gneiss Gneiss w/dolerites Graphite gneisses Gneiss (basal complex) Weathered zone of gneiss	5 0.5 4 1.2-3.6 1.2-5	60 30 45 25-40 25-40	Avg. 1.8 m ³ /h Avg. 3.5 m ³ /h
Mozambique	500	General	Orthogneiss, granite and paragneiss	4-8		w/"thick" surface weathered layer (10-25 m ³ /h reported)
Rhodesia	300-1200	Central area				
Sudan	20-500	Southern Kordofan	Granite, gneiss, schist	0.5-6		Weathered layer 10 to 50 m thick
South Africa	400-1500	Precambrian basement area	Granite gneisses and schists	0.5-10		Weathered layer 30 to 150 m thick. Detected by electrical resistivity surveys. About 50 % of the boreholes in the country tap water in weathered layer.
Swaziland	500-1750	Central area	Granite gneiss	2 to 8	20-30	Weathered layer 10 to 30 m thick.
Togo	1000	Papango Kande Dahomean	Granite-gneiss Schists Gneiss, granite and migmatites	3-175 .5-1 .25-.50	0-8 0-11 0-20	Drawdown: 6-18 m Artesian in part
Uganda	1000	General	Granite gneiss	.2-2	30-100	
Upper Volta	400-1000	General	Granite gneiss and schists	.2-2		3m ³ /h reported maximum
Zaire	1500-2000	Orientale Maniema Bas-Congo	Weathered zone in Precambrian basement " " " "	1-8 1-8 1-8	25-100 40-100	0.2 to 2 specific yield l/s/m "
Zambia	500-1500	Kalomo-Choma Munali Pass Copper Belt	Weathered granite- gneiss, quartz veins and pegmatites Biotite schist Quartz veins Schist	3-5.5 1-2 1-2 1-2	35	Quartz veins have slight head (yield up to 11 m ³ /h)

TABLE 2

Reported yields from wells in hard rocks of the Western hemisphere, India and Korea.

Country	Average rainfall (mm) or area	Province or area	Rock types	Yield per well (m ³ /h)	Well depth (m)	Remarks
Brazil	300	Semi-arid region (Northeast)	Granite, gneiss, schists and other metamorphic and igneous rocks	0.3-8 (aver. 4)	20-40	Weathered layer ranges from 5 to 10 m thick. Water commonly contains more than 3000 mg/l. Spec. cap. 0.1 to 1.0 m ³ /h/m.
	2000	Humid region (South and South-central)		0.5-20 (aver. 4)	10-30	Weathered layer ranges from 10 to 20 m thick. Water commonly contains less than 3000 mg/l. Spec. cap. 0.2 to 4 m ³ /h/m.
Canada	750-1200	General	Gneiss Granite	1.0-3.0	30	Depths greater than 30 m commonly produce saline water.
India	700	Semi-arid region (Rajasthan)	Granite Slates	0.9-2.8 0.6-4.0 (aver. 2.2)	20-40	Wells tap weathered layer which is 12 to 25 m thick. Water brackish to slightly saline.
	1500	Sub-humid region (Karnataka)	Granite	0.15-15 (aver. 3.2)	13	Wells tap weathered layer at depths generally less than 15 m.
			Cordierite, hornblende and biotite gneiss Crystalline schist Clayey schist and phyllite	0.3-10 (aver. 3.2) " Low	"	" Weathered layer clayey with poor aquifers.
Korea	1100-1300	General	Granite	12.2 (avg.)	74 (avg.)	Yield range: 0.2-34 (39 wells) Well depth range: 30-200 m
			Schist	7.0 (avg.)	97 (avg.)	Yield range: 0.6-17 (22 wells) Well depth range: 30-146 m
			Gneiss	5.3 (avg.)	88 (avg.)	Yield range: 0.5-21 (16 wells) Well depth range: 42-135 m
United States	500-1000	Piedmont region; Southeastern states	Gneiss and schist most common with some granite and other intrusive rocks	3 to 10 occasionally 20 or more (>180)	40-50	Weathered layer ranges from 15 to 30 m thick. Water generally contains less than 500 mg/l.
		New England Connecticut	Granite	2.6 (avg.)	44 (avg.)	Based on 217 wells
			Gneiss	2.4 "	40 "	Based on 261 wells
			Schist	3.1 "	44 "	Based on 63 wells
		New Jersey	Biotite gneiss	2.2 "	37 "	Based on 29 wells
			Granite (Hornblende)	2.1 "	48 "	Based on 81 wells
			Pyroxene Granite and gneiss	1.9 "	47 "	Based on 162 wells
			Amphibolite	1.5 "	49 "	Based on 31 wells
			Quartz Diorite gneiss	1.4 "	71 "	Based on 31 wells
Uruguay	1000-2000	South	Granite, gneiss metamorphics	0.2 to 8 (aver. 5)	20-40	Sp. cap.: 0.1 to 1.8 m ³ /h/m.

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production was encountered, the geological conditions (fractures, joints, faults, etc.) that permitted such productivity have been considered too complex to evaluate any detail and were considered as an anomalous occurrence. The general impression was that such productivity could not have been forecast because of the apparent complexity of the geological conditions. However, the type of systematic investigations discussed during this seminar demonstrates that the regional and local structural history of igneous and metamorphic rocks in selected regions, combined with appropriate surface geophysical and hydrochemical techniques, can serve to identify areas that may be capable of producing large, sustained ground-water supplies. The rigorous use of an integrated approach has resulted in an increased rate of exploration success and, consequently, the cost effectiveness of such programs.

INTEGRATED PLAN OF ACTION

As discussed in detail by previous lecturers during this seminar the value of appropriate photogeological, structural, hydrological and geophysical information will reduce uncertainty in all ground-water exploration programs. As more detailed geological information is developed, the more cost effective development programs can become. This can be accomplished if systematic procedures are employed that utilize all existing data initially, followed by implementation of locally appropriate techniques of investigation (see Figure 1).

Geological Considerations During Test Drilling

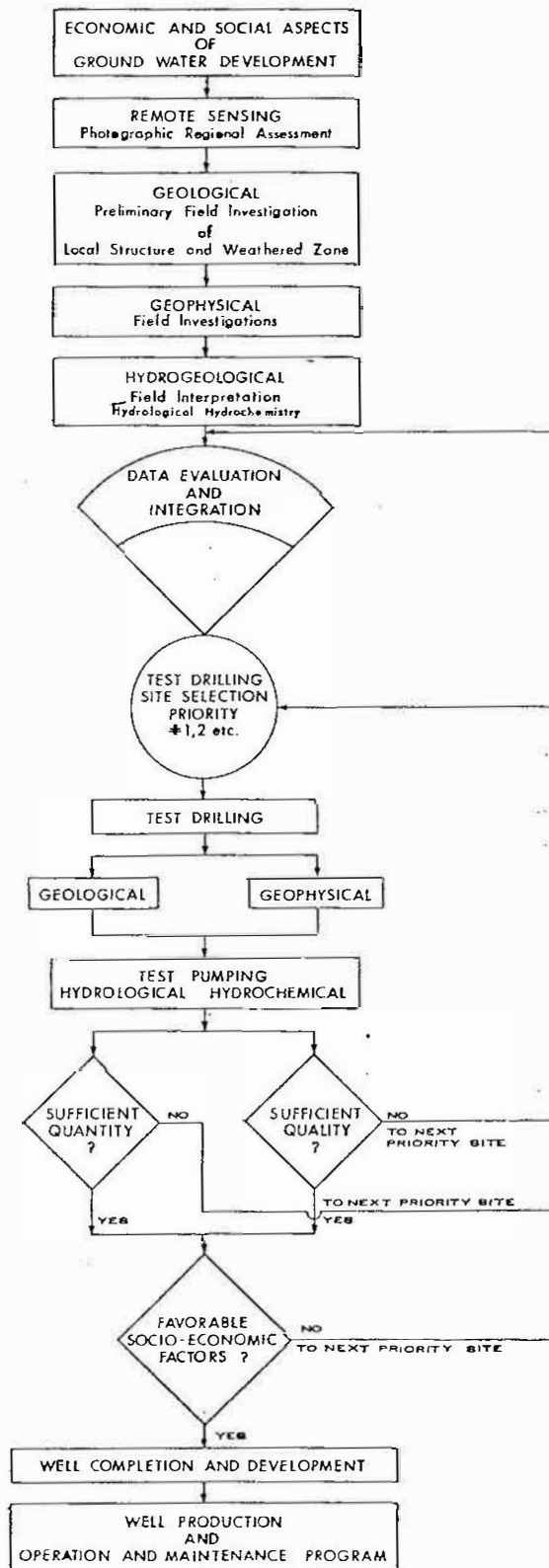
Once the test-drilling site has been selected, its geographic location must be fixed within reasonable limits, which are controlled by the complexity of the local geological picture. As subsurface information is generated by the test drilling so must its location be known in order to augment previously developed structural, surface, geophysical and hydrogeological interpretations.

Direct subsurface geological information: Both rotary and percussion drilled boreholes produce cuttings, the size of which in terms of geological interpretation depends on: 1) the type of drilling rig employed, 2) the type of drilling bit used, 3) the type of rock penetrated and, 4) the penetration rate (Campbell and Lehr, 1973). Size of cuttings is important because the smaller the chip size the less geological information is available on the rock type encountered, which, as discussed by others during this seminar, has important ramifications on well yields.

There are two basic types of direct geological information made available during test drilling programs. One is from the driller in the form of a driller's log. Most good drillers will make any reasonable type of log desired. Usually this is limited to: 1) a basic geological log, incorporating generalized rock types ("hard" rock, granite, schist, gneiss, etc.), 2) a penetration rate log, in terms of rate of penetration per foot or meter over a specific time period, and 3) a water influx log, with notations concerning the depths at which ground water influx was noted (and often a guesstimate of the influx capacity).

FIGURE 1

THE
SYSTEMATICS
OF
GROUND WATER EXPLORATION AND DEVELOPMENT
IN
HARD ROCKS



INTEGRATED PLAN OF ACTION

The second type of direct subsurface information is generated by the well-site geologist assigned the responsibility of obtaining all information possible during the test drilling program. It is his responsibility to prepare a detailed geological log from the cuttings as drilling proceeds. This function is often filled by young geologists with considerable knowledge of igneous and metamorphic rocks. A good rapport between the driller and the geologist is mandatory to ensure that good, reliable data is obtained. The driller, who is usually engaged by senior level geological personnel, should be clearly instructed that the well-site geologist will make all geological decisions affecting the drilling operations. Older drillers and young geologists often do not communicate well, especially if they are of different national backgrounds. It behooves the well-site geologist to be in communication or have clear policies established with his supervisor, usually a senior geologist or manager, on major decisions such as total well depth, rig location, length of drilling day, drilling break periods, driller's sampling procedures, drilling penetration rates, etc.

As cuttings are produced, whether via air drilling, mud drilling or down-hole percussions, they should not only be considered a valuable source of information for the present project but also for future geological investigations in ground water and in mineral exploration programs. Cuttings should be taken for examination at no greater than 5-foot intervals, with special care exercised in monitoring drill cutting returns from thin quartz zones or other intervals that may be of vital importance to local geological interpretations. The well-site geologist should, therefore, be well versed on all geological information developed previously to ensure full integration of data. If storage facilities are available, all cuttings, including the upper soil or alluvium zones should be bagged and clearly tagged for well identification, depth of sample, date, keyed to the geological log prepared and returned to the office for storage and later evaluation, if required. Where storage facilities do not exist or when logistics do not permit sample transfer, one method commonly employed for field storage of cuttings is to: 1) select a standard distance and direction from the rig, 2) dig shallow depressions (usually 20 per row representing 100 feet), 3) place samples in plastic bags, and 4) cover via a thin layer of protective soil, each marked by a rock so that parallel rows of rocks will mark the site of well samples for future explorations.

Good office records are necessary in such programs. It is often advisable to prepare a brief summary of each well along with the geological log which includes notations on sample locations, storage sites, etc., for future reference. A significant part of the value to the respective country of each test drilling program completed is in the future use of the data generated, either for the present ground-water project, future ground-water projects or for future mineral exploration programs.

Although there are many types of standardized geological logging procedures, the key to the effectiveness of such is in their uniformity. Rock units observed in outcrop during the project's previous field reconnaissance should be clearly defined according to the standard rock nomenclature used or developed

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in cooperation with the professional staff of the host country. Standardization is always a problem but can be solved by preplanning and by cooperation between field personnel and between multinational groups, although vigorous national preferences exist. Under such conditions, a dual system could be functional as long as specific definitions are exchanged early in the project (United Nations, 1974).

Other areas relating to uniformity of geological descriptions involve similar subjective qualities such as rock color. In such a case, color charts are useful for standardization purposes. The Geological Society of America has published a comprehensive color-number code system which could be adapted to a wide variety of regional conditions. As long as one shade of a color can be assigned a number, the chances are good that the same color can be reported by others, except for those who wear sunglasses during the preparation of the geological log.

In addition to drill cuttings, cores are another type of direct subsurface geological information. Although very useful, cores are relatively expensive and are obtained only when outcrop data are scarce or when additional information is required for a particular rock type or a particular structural setting. Such cores should never be discarded for obvious reasons. Again, standard procedures should be developed regarding core descriptions, packaging, marking, orienting, etc. It is often advisable to take field photographs of the cores with proper labeling to ensure that a record is retained of the physical appearance, texture, color, etc. in the event the core is lost, which is not an uncommon occurrence.

A secondary type of potentially important geological data is the surface geology within a few hundred yards radius of the drilling rig. The well-site geologist should make detailed surveys of this area, with special emphasis on surface water courses, outcrops of bedrock and of overlying granular material and its composition, texture and relationship with bedrock. Of course, although his principle responsibility centers around the drill rig, many occasions will arise when rig repairs, or other short down-time periods, will allow for such excursions and which may result in significant observations that may affect the success of the project.

Much of the information obtained from drill cuttings and/or cores helps to calibrate the indirect subsurface geological information obtained during borehole geophysical logging. Although direct geological information is very useful, only a small part of the rock units drilled can be observed. Indirect information contributes additional worthwhile data not available otherwise to the well-site geologist.

Indirect subsurface geological information: Geophysical measurements of various kinds can be made in drillholes and have been extensively used in sedimentary areas for stratigraphic correlation, study of aquifer characteristics, moisture estimates, etc. Most of these techniques need elaborate corrections if reliable results are to be obtained. In sedimentary areas the geophysical well logs are usually supplemented by a caliper log that measures the diameter of the hole continuously along its length. All such techniques can be adapted

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to crystalline rock areas but their scope is somewhat different and in many cases more limited (Houtkamp and Jacks, 1972).

A number of down-hole devices or logs are available to assist the well-site geologist in characterizing the subsurface geology and water-bearing zones (such logs have been very useful in clarifying local structural interpretations and in monitoring the behavior of the ground-water system (Mr. Houtkamp has presented operating information on this topic during the field demonstrations of the seminar).

GEOLOGICAL INTERPRETATION OF TEST DRILLING INFORMATION

After the results of the various geological and geophysical techniques have been integrated and assessed as completely as possible, their collective input expresses, in the horizontal dimension, the geological conditions anticipated in the subsurface. However, it should be noted that each of the above techniques employed usually do not produce unique solutions, that being the nature of the science of geology and of geohydrology in particular. Of all the physical sciences, geology is the most subjective, relying, to an uncomfortable extent at times, on probabilities and on relative degrees of accuracy of subsurface geological and related geohydrological data.

In the past, the exploration for ground water in igneous and metamorphic rocks has been considered a matter of chance. As has been discussed previously during this seminar, the first steps have been taken in applying systematic procedures to locating useable quantities of ground water in such rocks without resorting to random, unnecessary drilling.

The ultimate test of an integrated geological interpretation, whether it be designed to locate ground water or a specific mineral, is to drill into the subsurface, testing the third dimension. In test drilling, effective site selection is of significant importance to the success of a project. During this seminar, most of the techniques have been discussed that will assist in optimizing well-site selection.

Exploration money must be spent on the basis of the best available geological information. But chance still plays a dominant role because although one site may appear to be better than another, any choice is one more level of subjective interpretation which is based on previous subjective interpretations involved in each of the exploration techniques employed, no matter how integrated they may have become.

Test drilling sites are usually selected according to relative priorities, the highest priority site being the one site where all geological information suggests the greatest chance of encountering significant and useful ground-water production. Of course, significant production in one region may not be significant or useful production in another. This depends on what volumes are required and for what use the produced water is intended. Furthermore, significant

GEOLOGICAL INTERPRETATIONS OF TEST DRILLING INFORMATION

production may be possible but the pumping depths may, and often are, excessive, resulting in very high drilling costs per well during construction and/or very high pumping costs (energy requirements) during the anticipated operational life of the particular well. Added to these considerations is the anticipated ground-water quality which also plays a role in well-site selection.

After test drilling has been completed, it is at this point in the exploration program that geological considerations must be combined with socio-economic considerations. Each region must define the degree to which the latter will direct the former. Figure 1 illustrates the general systematic procedures involved in ground-water exploration and development programs in hard rock regions and clearly emphasizes the critical role local socio-economic factors play both at the beginning and end of such programs.

AQUIFER TESTING

Evaluations of Available Production

After the borehole has been drilled or dug to the desired depth and after the borehole has been pumped for a period to remove all fine-grained material created by the drilling process or hand cleaned if dug by hand, pump testing is undertaken. Proper testing can provide good information about the well yield, aquifer properties and boundaries, and makes possible the prediction of future well capacities. The basic procedures associated with a pumping test usually include the following:

- 1) Monitor static-water level several days before pump testing is to begin.
- 2) Measure pumping discharge at different rates, usually by increasing steps.
- 3) Record drawdown associated with discharge.
- 4) Test should be of sufficient duration to show a definitive response in the nearest observation well, if possible.
- 5) Well discharge should be removed from the area so that it cannot return to the subsurface and invalidate the test.
- 6) Record recovery of water level after pumping ceases accurately, especially as recovery level approaches the original static level.

Aquifer tests in igneous and metamorphic rocks are commonly not subject to the general interpretations and procedures used in porous media such as sandstone, sand and gravel, etc. (United Nations, 1973). The simple fact is that the assumptions upon which the standard aquifer tests are based are not applicable to flow in fractured rocks. Although such general physical conditions as a cone of depression and cone of pressure relief are apparent during pumping in igneous and metamorphic rocks, the yield of all wells in such rock is obtained by drawing water directly from inter-connected fractures and related permeable zones and in some cases from the overlying weathered zone, especially in recharge

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areas. However, considerable, additional research is necessary to more clearly define the hydraulics of ground water in igneous and metamorphic rocks. In the meantime, the standard Theis, Jacob, Hantush and Bolton techniques will be employed for want of viable alternatives, which should become available within the next 10 years. Of the recent efforts made, Streltsova-Adams (1978) presents a succinct review of well hydraulics in fractured rocks and Gringarten and Witherspoon (1972) and Witherspoon, et al (1979) treat pump test data analysis and hydraulic properties of fractured rocks.

It is apparent that the percentage of relative yield is not directly proportional to the percentage of drawdown of the water level during pumping tests; the highest percentage of yield is reached before the highest percentage of drawdown. This has been attributed to a combination of well loss (due to turbulent flow in and around the well) and aquifer loss (due to variations in permeability within the fracture system being disturbed by pumping and due to turbulent flow in the aquifer at some distance from the well being pumped).

Figure 2 shows the approximate relationship of drawdown to yield in the hard rock region of southeastern U.S. (LeGrand, 1967). As an example of this relationship between yield and drawdown, a well 220 feet (67 meters) in depth has a static water level of 20 feet (6 meters) below the surface. In the example well (Figure 3), it yields 40 gpm (2.5 lps) with a pumping level at a depth of nearly 220 feet (67 meters); if the pump were set at 120 feet (37 meters) (50 percent of drawdown or approximately half of the thickness of the water), approximately 36 gpm (2.3 lps) or 90 percent of the relative yield could be obtained. It is uneconomical to lower the drawdown to a position near the bottom of the well unless the yield is so low that the water stored in the well is required. The difference in pumping costs (power and pump equipment) between the two pumping levels could be significant over a period of a year; over the life of the well, power cost savings based on the adjusted pumping level would be substantial.

The common method of determining well productivity is to measure the drawdown in the well at various pumping rates over a specified period of time. As indicated, the effect of pumping on a nearby observation well would also assist in determining the extent of interfracture communication in the area, although it should be noted that such communication is not always apparent. Observation wells may be tapping two fracture systems of limited communication. The problem also arises concerning the impact of other pumping wells in the area, which in an area where well density is high, time drawdown data may be difficult to interpret.

However, a plot of drawdown versus time is commonly made during the test (as well as recovery of drawdown versus time after pumping ceased). From these data specific capacity (per foot or meter of drawdown) can be assessed based on the following relationship:

$$\text{Specific Capacity} = \frac{\text{Rate of Discharge (gpm or lps)}}{\text{Drawdown (in feet or meters)}}$$

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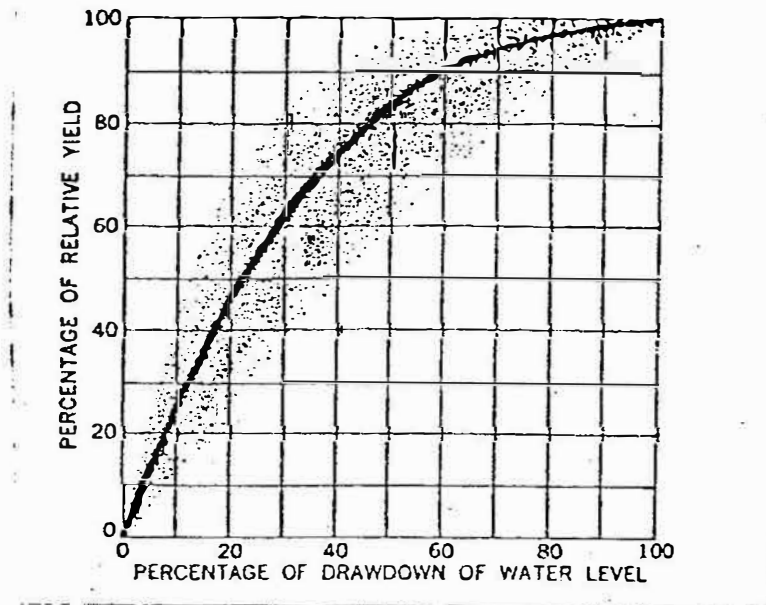


FIGURE 2 RELATIONSHIP BETWEEN PERCENT OF WELL YIELD AND PERCENT OF DRAWDOWN. EXAMPLE: A YIELD 80% RESULTS WITH A DRAWDOWN OF ONLY 45% (after LeGrand, 1967)

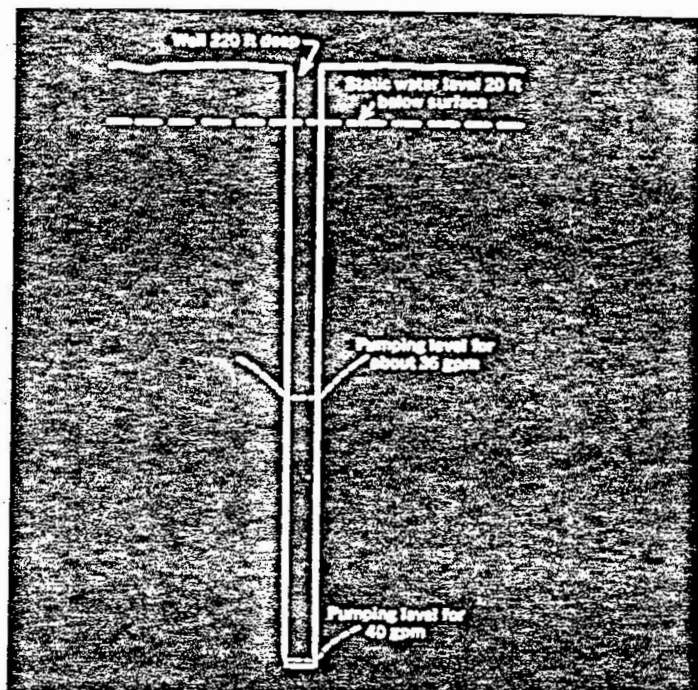


FIGURE 3 YIELD OF A HYPOTHETICAL WELL AT TWO DIFFERENT PUMPING RATES (after LeGrand, 1967)

AQUIFER TESTING

It should be apparent that the various combinations of fracture location, fracture width, fracture content (fine-grained material) and amount of ground water in storage in the aquifer can result in a drawdown curve of various configurations.

A number of reviews of the hydraulics in fractured, jointed and related rocks have appeared in the literature (Lewis and Burgy, 1963; Moore, 1973; Zdankus, 1975; Robinson, 1976 and Streltsova-Adams, 1978). Figure 4 illustrates a few cases of typical drawdown curves for selected geological conditions. In each well having encountered the water level, there exists a pumping rate wherein drawdown will stabilize at a specific discharge rate and thereby the well will be characterized by its long term calculated specific capacity. If the particular well has a very low or a very high specific capacity, both are extremely difficult to evaluate without the proper pumping equipment. Usually, the range of well yields is generally known and the appropriate pumps are available.

In evaluating drawdown curves, a feature that is very common in wells drawing from fracture systems is a high or moderate initial yield that decreases rapidly with time. The cause is often related to insufficient storage of ground water in the vicinity of the well. Davis and DeWiest (1966) suggest that wells should be located so that they can draw water from overlying weathered zones or from saturated alluvium or colluvium because these materials contain from twenty to forty times the water per unit volume that is contained in the unweathered crystalline rock. A well location within the influence of a perennial stream to prevent depletion and dewatering of the fracture system is also suggested, if contamination is not a potential problem. However, as is usually the case, such "soil" cover or weathered zone and significant surface recharge is only available in selected area of crystalline rock regions. The advantage of using the overburden as recharge sites is clearly supported by LeGrand field method of well-site selection (LeGrand, 1967).

Figure 5 shows a few additional typical drawdown curves. Figure 5A shows the response related to pumping in fracture rock that may have several levels of open, saturated fractures. Figure 5B illustrates the typical case where fracture filling material is released during pumping causing minor rises in pumping levels. If this well were initially pumped at high rate for development purposes of removing fine materials loosely held within the fractures, the well's yield may be increased significantly by increasing communication with a greater number of fractures than before such development pumping. One indication of such effectiveness is that excessive turbidity may be temporarily evident in the discharge.

Figure 5C and D illustrate the typical effects of an impermeable boundary and a recharge boundary, respectively. The former case shows an abrupt decrease in the drawdown while the latter stabilizes as the drawdown cone of depression (or pressure relief) reaches and begins to draw from a surface water body. It should be also noted that this drawdown curve is symptomatic of the discharge water from the very well being tested reentering the fracture system from above. Of course, there are many other drawdown curve shapes and other interpretations of the drawdown curves than presented herein but it should also be stressed that

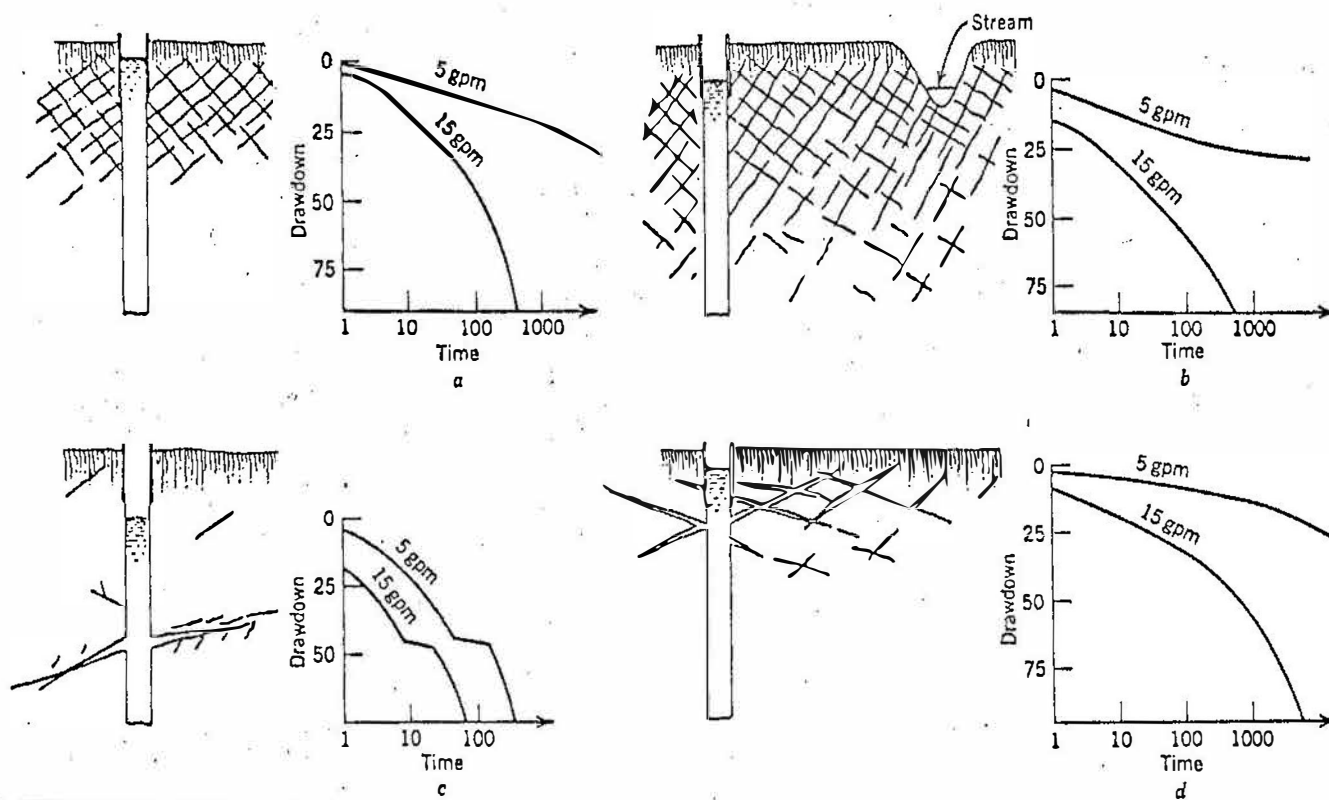


FIGURE 4: HYPOTHETICAL DRAWDOWN CURVES FOR WELLS IN FRACTURED CRYSTALLINE ROCK AT VARIOUS PUMPING RATES. a) Production From Small, Near-surface Fractures; b) Production From Extensive And Widespread Fracture System; c) Production From Large But Limited Fracture; d) Production From Large And Shallow Fractures That Drain Overlying Weathered Rock or Soil (From Davis and DeWiest, 1966).

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caution is required in conducting and evaluating pumping tests, especially when the standard porous media techniques are employed. A short-term test should never be the basis for determining the long-range potential of a ground-water reservoir in such rocks, although practical expediency is often the rule.

Well discharge rate can be obtained in a number of ways, that is, pitot tubes, full-flow pipe discharge, orifice plates and totalizing water flow rate meters. For low-rate flows the pitot-tube method is most practical. For medium rates of flow the full-flow pipe discharge measurement method is an acceptable method and for high rates of flow, the orifice-plate method is in common use, although there are other approaches to measuring discharge (Campbell and Lehr, 1973).

Field Applications

The general characteristics of aquifer testing have been discussed previously. When applied to any specific project, however, local geological and economic conditions play important roles in the design of the well testing program. Although local experience is a guide, interregional transfer of experiences and techniques as presented during this seminar by the delegates and by personnel of the Central Ground Water Board and the Coimbatore Project, is very constructive and, in many cases, reduces duplication of effort.

Instead of discussing "typical" testing procedures for ground water production from igneous and metamorphic aquifers in specific field applications, a summary reference list, by area of emphasis is offered here for future reference:

<u>AREA</u>	<u>REFERENCE</u>
General	Davis and Turk, 1964 Gringarten and Witherspoon, 1972 Streltsova-Adams, 1978 Witherspoon, et al., 1979 Kiraly, 1971 Maini and Noorishad, 1973
Australia	Lawrence, 1973
Brazil	Floyd and Peace, 1974 Reboucas, 1976
Ghana	Bannerman, 1973
India	Krupanidhi et al., 1973 Limaye and Limaye, 1973 Rajuetal, 1979 Romani, 1973 Uhl and Sharma, 1978
Korea	Callahan and Choi, 1973

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<u>AREA</u>	<u>REFERENCE</u>
Sardinia	Larsson, et al., 1977
Soviet Union	Zdankus, 1973, 1975
Sweden	Larsson, et al., 1977 Mullern and Eriksson, 1977
Uganda	Faillance, 1973
United States	James, 1967 Landers and Turk, 1973 LeGrand, 1954, 1967 Lewis and Burgy, 1963 Sever, 1964 Stewart, 1974 Summers, 1972
Upper Volta	Bierschenk, 1968

CONCLUSIONS

In the final analysis, if only 30 percent of a region's future dry holes (insignificant production) could be converted to useful production wells as a result of incorporating more effective methods of well-site selection than presently employed, the value of such systematic techniques would be apparent. It is toward this goal that the integrated approach, discussed at length during this seminar, is presently directed. The approach is not necessarily the ultimate solution, but it will serve as a firm step in the proper direction of decreasing the present cost of ground-water exploration and development. Refinements will no doubt evolve from diligent geological work in the field and in the laboratories throughout the world in countries wherein ground water is only available from igneous and metamorphic rocks.

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