

ECONOMIC CONSIDERATIONS
ON
GROUND WATER EXPLORATION AND DEVELOPMENT
IN
IGNEOUS AND METAMORPHIC ROCKS⁺

By
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INTRODUCTION

The increasing need for water in the world has generated a strong demand for ground water, especially in crystalline rock areas. Current master plans for rural water-supplies make provisions on the basis of a minimum of one well for 500 to 1000 inhabitants (United Nations 1973). This is considered a critical minimum below which high rates of migration will be experienced, which further stresses new areas, etc. The water supply required under such critical conditions is approximately 10 liters per capita per day, supplied by wells; one or more wells would be required to produce 25 m³/day for a village of 1000 inhabitants only. Adding village requirements for 500 head of livestock, a ground water supply of 50 m³/day becomes the critical minimum water supply for the village. Of course, supply requirements would increase linearly with population increase.

It was estimated that for the period 1973-1978, tropical Africa would require a minimum of 150,000 wells. During the same period, India required 200,000 wells (United Nations, 1973). In countries such as Ghana, the Sudan and the United Republic of Tanzania, the need was estimated as several thousand wells per year, but budgeting and technical limitations have allowed only a fraction of this number of wells to be constructed. This is a widespread problem of critical proportions in most crystalline rock areas (Dijon, 1971).

In such areas, drilled wells, although capital intensive compared to dug wells, serve two roles; the first role is to supply emergency requirements, since such wells can be drilled in a matter of a day or two - as opposed to a month or more to construct a 30 meter-deep dug well. The second role is to promote rapid development of an area to assist in producing cash crops and industrial products (mining and small industry), which in turn increases the regions wealth. When

⁺ Paper presented at Inter-Regional Seminar on Groundwater in Hard Rocks, Coimbatore, India: November 22 through December 20, 1979. No. UNESCO/SIDA/GWB/TNAU.

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a region begins to generate cash income, labor intensive activities (i.e. dug wells) become less attractive and capital becomes available for capital intensive activities (i.e. drilled wells, mining, etc.) which further enhance economies of scale and subsequently standards of living.

It is apparent that both dug wells and drilled wells must play their particular roles in crystalline rock areas, especially those areas with low ground water potential (relative to sedimentary basins where ground-water potential is generally high).

BASIC ECONOMIC CONSIDERATIONS

In an evaluation of ground water development costs in hard rock areas, the following main sources of expenditure are to be considered: 1) geological and geophysical investigations; 2) well construction; 3) pumping installations and 4) operation and maintenance.

The costs of geological and geophysical investigations vary widely, depending upon the geographical conditions, the accessibility of the resource in crystalline rock areas, the areal extent, the nature of the geological formations within the area of interest and the techniques and methods employed. The cost of a preliminary survey involving only field reconnaissance and the interpretation of aerial photographs is in the range of a few tens of dollars per square kilometer, while more detailed investigations involving geophysical exploration and reconnaissance drilling could reach several hundreds of dollars per square kilometer. The cost of a subcontracted geophysical team (one geophysicist, two operators and the rental of seismic or resistivity equipment) can range as high as \$15,000 (120,000 Rs) to \$20,000 (160,000 Rs) per month; the cost of siting only a few wells for a tropical village in Africa may be relatively high. However, a systematic, long-term program resulting in the selection of a number of well sites would be economically advantageous on a per site basis (United Nations, 1979).

The cost of a reconnaissance exploration drilling program involving many wells would normally be in the range of \$40 to \$70 (320-560 Rs) per meter or \$12.20 to \$21.30 per foot for 4-1/2 inch boreholes (mobilization and demobilization, tests and all other costs included), \$80 to \$110 (640-880 Rs) per meter or \$24.40 to \$33.50 per foot for 6-inch casing and \$110 to \$160 (880-1280 Rs) per meter or \$33.50 to \$48.80 per foot for 8-inch casing.

The smaller the number of holes drilled, the higher the per well price, i.e. an example of the lack of economies involved in limited scale operations. For instance, for drilling one hole with 6-inch casing in West Africa, the price in 1971 went up to \$250 (2,000 Rs) per meter or \$76.20 per foot. In a desert nation of East Africa, for some 25 fully equipped boreholes located some distance apart, 150 meters (492 feet) deep with 8-inch to 10-inch casing, including the testing of several aquifers, the cost amounted to \$135 to \$175 per meter (1,080-1,400 Rs) or \$41.20 to \$53.40 per foot.

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In general, international drilling operations are costly and therefore capital intensive. This is due to high and increasing costs and increasing selling prices world-wide for drilling equipment, vehicles, supplies and competent expatriate drilling personnel. Basic costs, however, can be estimated. For example, in 1973, drilling costs for single wells within the United States could be calculated on the basis of \$1.25 (10 Rs) per inch diameter per foot of well depth, e.g. 6-inch well, 200 feet (61 meters) deep sold for \$1,500 (120,000 Rs), not including pump, or \$7.50 per foot. In 1975, with the effects of inflation considered, the same well would cost the buyer \$3,120 (26,000 Rs) (that is \$2.60 (21 Rs) per inch diameter per foot depth or \$15.60 per foot of well depth). Costs in 1978 were in excess of \$3.00 (24 Rs). This was equivalent to \$18.00 (144 Rs) per foot (\$5.49 (44 Rs) per meter) for a 6-inch well drilled to 200 feet (61 m).

To these costs must be added mobilization, tests and other related costs. Figure 1 illustrates typical costs for 4.5 and 6-inch individual wells drilled within the United States in 1969 and 1975; this illustrates the significant increase in costs due to inflation.

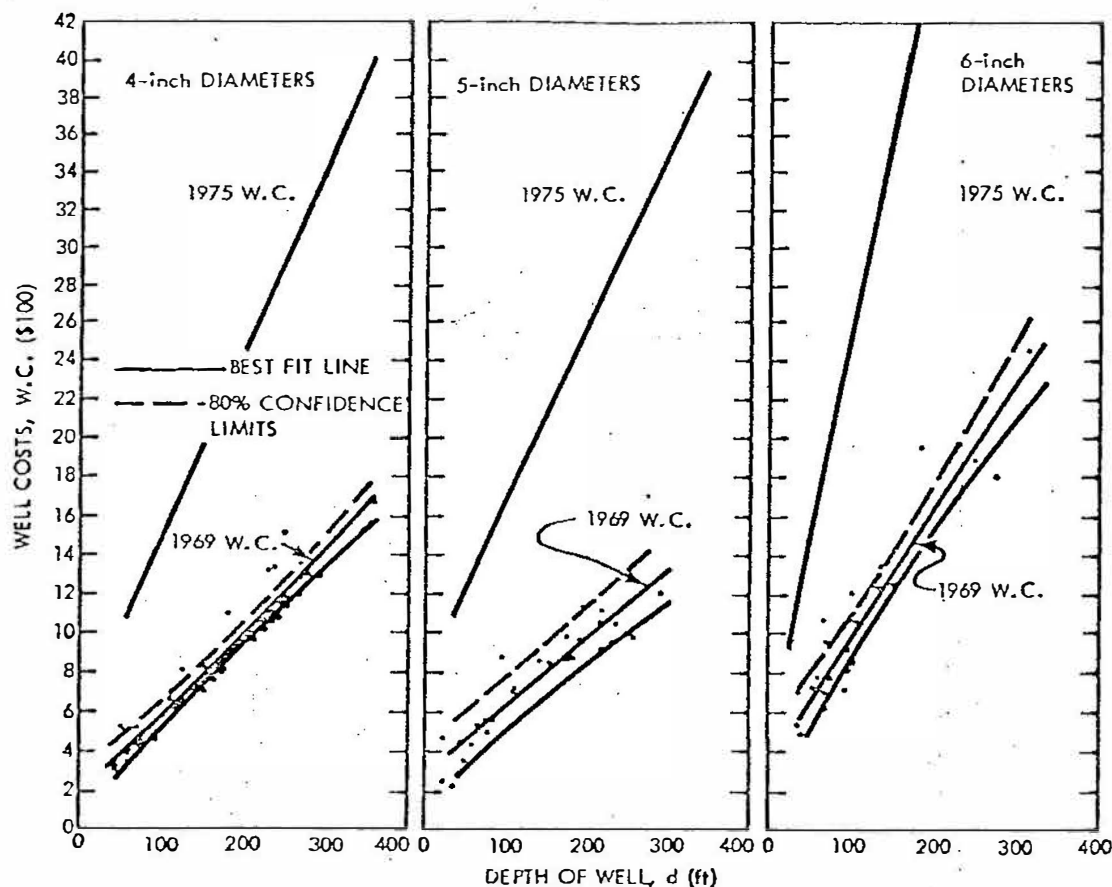


FIGURE 1 COST OF 4, 5 AND 6-INCH WELLS IN CONSOLIDATED ROCK (after Gibb, 1971)

BASIC ECONOMIC CONSIDERATIONS

For international operations, these add-on costs plus personnel costs assume major proportions and result in approximately 300 per cent add-on costs. To this must also be added a consideration of demand for drilling services. However, if a large number of wells were drilled and completed, the per foot cost would be reduced substantially. As a general rule, private international drilling costs would be approximately 3 times the cost within the contractor's home country. Usually only very large international drilling programs are economically feasible, i.e. a cost per foot of drilling below \$20.00 per foot. On the international scene, drilling services are in a seller's market whereby the need is great, both in the home country and internationally. Prices are therefore structured such that more profit could be made internationally than within the home country. If this were not the inducement, drilling companies would not consider the inherent risks in often difficult foreign environments and conditions.

However, it has been reported that even when the volume of work is significant, local drilling companies may have higher costs than companies selected from the international scene (United Nations, 1973). In a number of countries, government drilling units often have low productivity in terms of meters drilled (1/2 to 1/5 the total average of all drilling programs). The situation can be improved if the units are operated as they should be in a private, profit-oriented enterprise, that is 2-3 shifts per day, a bonus for drilling above a minimum, the discharge of unsatisfactory personnel and a swift procedure for the acquisition of equipment, spare parts and supplies. In some cases, the introduction of a United Nations Technical Assistance component or private consultant into a national drilling organization has contributed significantly to an increase of the drilling output and, therefore, to a reduction of unit costs (in a further attempt to optimize economies of scale).

High well-construction costs represent a major apparent limiting factor to ground-water development in crystalline rock areas, since such construction is capital intensive. When capital is available for drilling, exploration programs must be designed in such a manner that the relative hydrogeological potential can be systematically and cost effectively evaluated, thus reducing to a minimum the risk of unsuccessful drilling programs in igneous and metamorphic rocks.

In addition, whenever possible, once the ground-water potential has been generally established via comprehensive hydrogeological evaluations, well-construction operations should be conducted on a large scale, multi-well basis, if the need exists. Small scale drilling programs result in escalated unit prices. Furthermore, well design should be based on the specific, local geological requirements.

Equipment longevity will vary significantly, depending on the appropriateness of its design, frequency of use and on the maintenance program, if any. Longevity also will be determined by how the equipment responds to the effects of stress imposed by such environmental factors as corrosive water and soils, temperature extremes and humidity. Under extremely corrosive conditions, for example, submersible well pumps have been known to fail in six months, while

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the same model pump operated nearby in a more benign environment may last 10 or 15 years, or more.

Well design also determines the longevity of the well. For example, in a recent coal mining project in the Western United States, the need for a water supply was critically required for the mining operations. Ground water offered a reliable source of water, but it was known only to exist at a depth of 3,000 feet (915 meters) to the top of an artesian aquifer. The peizometric surface was assumed to be above the surface at the mine site, which suggested a flowing well. The well design adopted a 4-inch casing to total depth. The well was drilled and after development, the standing water level was reported to be at a depth of 350 feet (107 meters). A 3-7/8 inch stainless steel pump (at cost of approximately \$3,000 or 24,000 Rs) was installed at a depth of approximately 450 feet (135 meters). The pump capacity was rated at 50 gpm (3.2 l/s). After 4 months of operation, the pumping level declined and the pump had to be lowered. Attempts to remove the pump failed because it had become stuck as a result of corrosion and incrustation. The well was abandoned for a total loss of approximately \$150,000 (1.2 million Rs). This problem could have been avoided if the well design had included larger diameter casing and if a proper pump testing program had been conducted to establish the safe yield and appropriate pump setting. This would have cost an additional \$50,000 but the mine's water supply would have been secured for a cost of approximately \$0.09 per gallon, including all associated capital and operation and maintenance costs over 20 year life of the mine (Campbell (in preparation). Similar, although perhaps not as costly mistakes, are often made in well designs as a result of inadequate assessment of the local geology as it affects well design.

All equipment will fail at some date, that being the nature of mechanical and electrical equipment. A graph which shows the percentage of units of a particular type of component which is still working after a certain number of years is called a survivor curve (Figure 2).

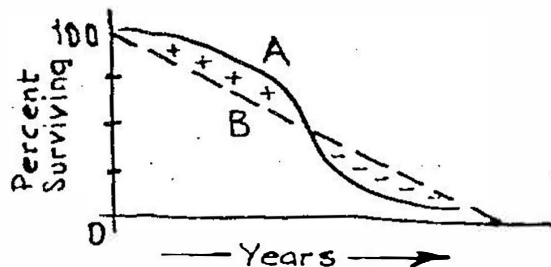


FIGURE 2 SURVIVOR CURVES (Campbell and Lehr, 1974)

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Survivor curve A depicts a group of units of which very few fail for a number of years, after which most experience failure within a very few years. Curve B represents a situation wherein a constant number of units fail every year. This occurrence is rarely observed. The equipment represented by curves A and B both have about the same average service life (mean time before failure). However, in many of the high-capacity well systems, an awareness of such failure characteristics should be incorporated in the operation program. Many system operation plans have in the past incorporated straight-line failure rates. Because of a lack of early failures, O & M budgets were not maintained. When failures began to occur rapidly over a short period of time, funds were not available and the system failed. Some components should be replaced on a regular basis under a preventive maintenance program and O & M budgets must be maintained.

GROUND WATER SYSTEMS COST ANALYSIS

The economics of well systems and their cost effectiveness depend almost exclusively on the success of the exploration program and well depth. If the rate of success in locating desirable quantities of ground water in igneous and metamorphic rocks could be improved, the cost effectiveness of ground-water exploration and development programs would be significantly elevated above present levels. This seminar is devoted to improving the success rate of ground water exploration and development programs in hard rock areas, which includes production from the shallow, weathered zone, often overlying igneous and metamorphic rocks.

Present approaches to the economics of exploration and development in crystalline rocks in the United States presently emphasize the role of well depth as the controlling economic factor. Most of the economic evaluations are based on the assumption that ground water production of wells diminishes with depth. Drilling and material costs and personnel costs are also directly related to the depth of a particular well. The drilling method employed dictates personnel costs, e.g., that time required to drill a well to a given depth (cable-tool versus air rotary percussion). The cost of casing for a given well is depth dependent, as is the cost of casing installation. The type of casing used (plastic versus steel) can affect costs, e.g., relative ease of transportation, resistance to corrosion and/or incrustation and relative acquisition costs.

Pumping costs are also depth dependent. Therefore, the unit cost of ground water increases with depth, even assuming water-bearing zones at depth could be located with a higher success rate than generally experienced at present. If, however, unit drilling costs could be minimized, as in a large program, such costs would tend to offset the costs associated with increased depths. It should be clearly noted, however, that the cost of ground water to the consumer (private or government agency) will vary according to the inherent local geological conditions. Management aspirations of standardizing ground water costs in a region of vastly differing geological conditions are futile.

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Optimizing costs by considerations of appropriate well design, cost effective drilling and pumping equipment selection and effective operation and maintenance programs would be a worthwhile pursuit in maintaining sound ground water exploration, development and O & M programs.

In a cost analysis of ground water systems, not only is minimizing well depth important to cost effectiveness but maximizing well efficiency must also be included as a significant economic factor that directly affects system costs. Well losses can be reduced by adjustments in either well design or operation, but losses due to aquifer factors can not usually be improved. However, some attempts have been made along these lines, e.g. (Stewart, 1974 and Mullern and Eriksson, 1977). Well efficiency can be improved by pumping at rates less than maximum capacity, by pumping over longer periods (and implicitly using surface storage facilities) and by spreading the required water volume over more than one well in one area.

All alternatives should be considered: surface water versus ground water; high-capacity well systems or multiple or "cluster" well systems versus dug wells. The selection of the appropriate water source or method of extraction is often complex, involving not only basic economic considerations but also social considerations. Based on economics, the cost of water for supplying the needs of a small village would be low if dug wells were constructed by local labor without concern for the construction time required, often up to 3 months or more. However, and not considering vulnerability of pollution inherent with dug wells, drilled wells, which can produce higher yields than dug wells, offer economic advantages (Figure 3).

For example, construction costs in India vary significantly throughout the country depending upon the local geology, e.g., sand and gravel, consolidated sedimentary (sandstone and limestone) basalt (Deccan Traps) and, of course, igneous and metamorphic rocks. A recent estimate (Allison, pers. com.) of costs for drilled wells and dug wells in the crystalline areas of Southern India (see Figure 4), favors drilled wells over dug wells. In India, the construction of dug wells has become a capital intensive activity and a highly mechanical endeavor. Wells are urgently needed throughout India and, in an attempt to reduce the construction time involved in dug wells, quarrying equipment and blasting have replaced labor intensive methods of construction. Such new methods can reduce construction time by 50 percent and more. However, when comparing alternative approaches, dug wells no longer have an economic advantage over drilled wells, especially in areas where ground water levels are deep (up to 10 meters). However, in the absence of readily available drilling equipment, dug wells will remain an expedient although cost ineffective alternative for water supply development in India. In Africa, however, labor intensive methods are still employed because capital is not available and inexpensive labor is plentiful. As the collective economy of Africa expands, dug wells will be replaced by drilled wells as required by basic economies.

The next discussion that must be made is on the type of drilled well to be constructed. This decision also involves strong social-economics factors, e.g. population density, water usage, ground water availability and distance to end

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users. Often, social patterns must be interrupted by relocating villages and agricultural activities in new areas where adequate water supplies can be developed. This not only meets social needs, but also increases the cost effectiveness of local, state or federal governments' water supply development programs.

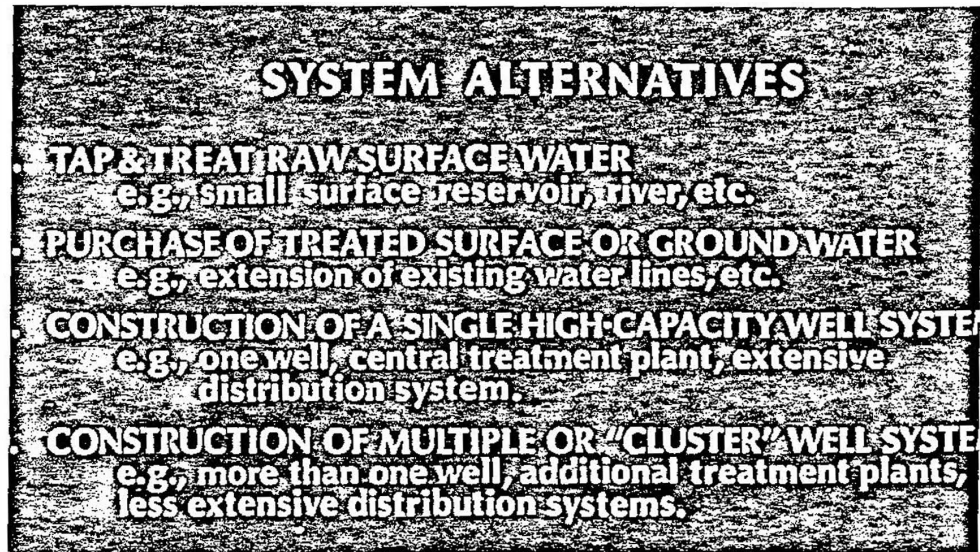


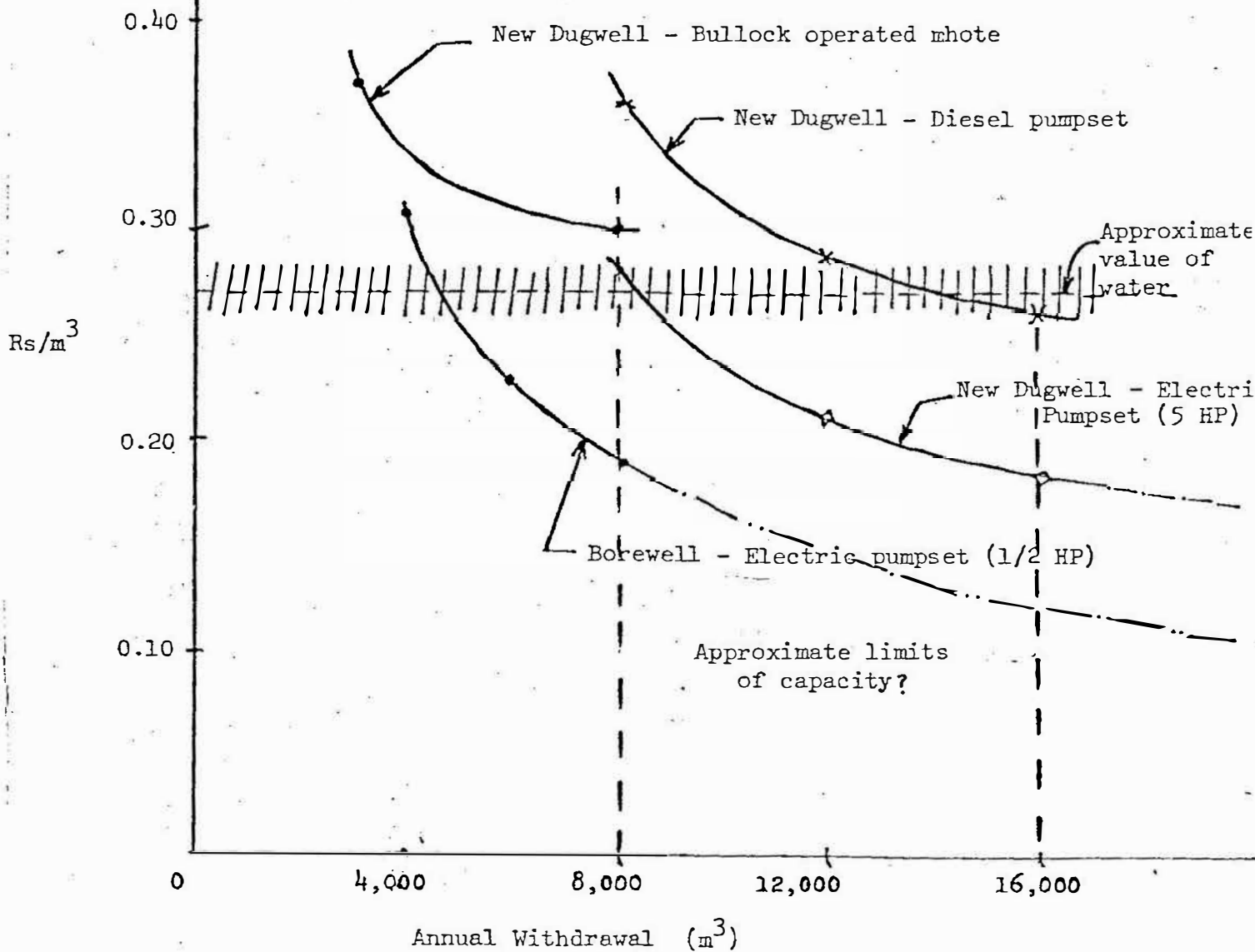
FIGURE 3 WATER SYSTEMS ALTERNATIVES (from Campbell and Lehr, 1975).

Davis and Turk (1964) presented an economic analysis that produced a graphic comparison between costs for purchased water and ground water. Although the costs were derived more than 14 years ago, the approach is nonetheless applicable here. The important assumptions used in generating the curves shown in Figure 5 were:

1. Well construction cost = \$10.00/foot (80 Rs/foot)
2. Power cost = 2 cents (0.16 Rs)
3. Interest rate = 6 percent
4. Well life = 30 years
5. Average depth to water table = 30 feet (9.2 meters)

As mentioned previously, the first step in an economic analysis is to compare the cost of developing ground water with the cost of water from other sources. Although curves must be constructed for the specific area of interest because of variations in local economic and geologic factors, the general shape of all curves using the Davis & Turk approach is probably quite similar.

FIGURE 4 COSTS AND RETURNS TO
GROUND-WATER DEVELOPMENT
IN THE HARD ROCK AREAS OF
SOUTHERN INDIA (after Allison,
1979 Pers. Com.)



GROUND WATER SYSTEMS COST ANALYSIS

In Figure 5 a fixed unit cost has been assumed for water from sources other than wells. The straight lines show the cost of various volumes of water per unit time for different unit charges. It can be observed that, under the assumed conditions, water derived from wells is more expensive than other water on a 5 cents (0.4 Rs) per 1000 gallons (3.785 liters) basis but is less expensive than other water at 50 cents (4 Rs) per 1000 gallons. Between these extremes, the choice should be based on a study of economic factors.

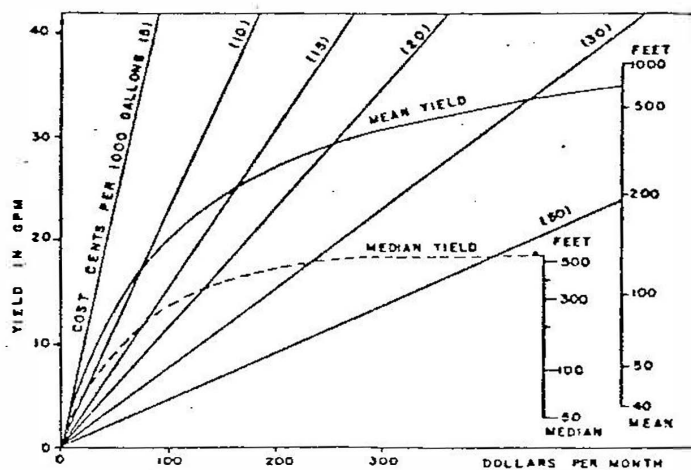


FIGURE 5 COST OF DEVELOPING GROUND WATER IN CRYSTALLINE ROCKS AND PURCHASE OF MUNICIPAL WATER IN EASTERN UNITED STATES (from Davis and Turk, 1964).

The approach by Davis and Turk (1964) can be used to assist in determining the optimum economic depth of wells, if choices are available. For example, a local government has a choice of either constructing a large number of wells (drilled or dug varieties) or importing water from outside the area of interest at a fixed rate of 20 cents (1.6 Rs) per 1000 gallons (3,785 liters). From the mean curve in Figure 5, it is indicated that ground water will be cheaper only if the depths of wells are generally less than 350 feet (107 meters). The maximum economic advantage is gained for each well at the withdrawal rate which gives the greatest horizontal separation between the

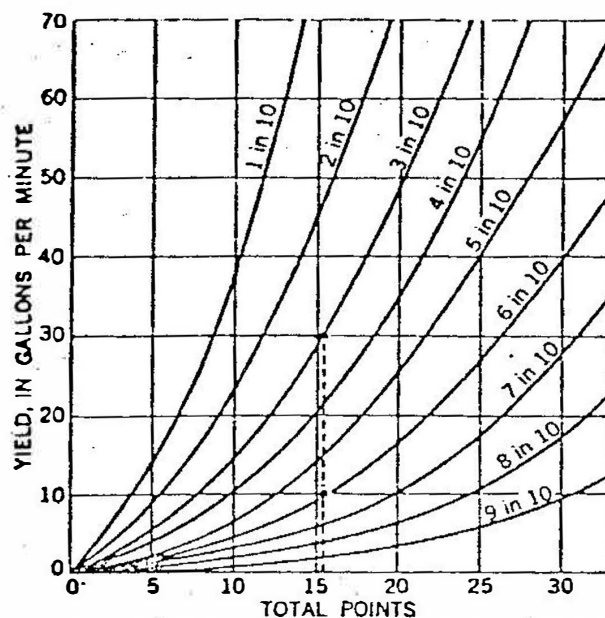
GROUND WATER SYSTEMS COST ANALYSIS

mean yield curve and the 20 cent line (1.6 Rs). The indicated withdrawal or pumping rate is approximately 19 gpm (1.20 lps) which can be obtained at a depth of about 150 feet (46 meters), a depth considered to be optimum under the given assumptions. This example is correct only if a large number of wells are to be constructed. In such case, a few wells which have high yields will compensate for the wells which are failures or which produce only a small volume.

On the other hand, if a single well is to be constructed, the most likely, or median, yield is of most interest. As an example, if a very small industry requires 20 gpm (1.26 lps), the median yield curve indicates that it is unlikely that this amount of water can be obtained from a single well at a reasonable cost. Using the previously discussed LeGrand (1967) method of estimating success rate, only one chance in four exists for obtaining the desired water from a single well (see Figure 6). A very good chance exists, however, for the development of the water volume from 5 wells having depths of from 40 to 80 feet (12 to 24 meters). The projected cost of this water is less than 15 cents per 1000 gallons. Of the five wells constructed, one would probably be a failure, three might product 2 gpm (0.13 lps) each and the other wells might product 15 gpm (0.95 lps). The collective production would be 4.2 gpm (0.27 lps); the average, or mean, yield would be 4.2 gpm (0.27 lps); but the most likely, or median, yield of a single well would be only 2 gpm (0.13 lps).

The analytical approach discussed consists of a total system cost comparison of all elements within each alternative under review (Figure 7), which also includes the relative economic effects of well efficiency and operation and maintenance. Often, the comparative review usually reduces to the selection of either a central well (or high-capacity) system or a "cluster" well or or (multiple-well low capacity) system (Figure 8), the latter system is usually favored under certain conditions in the United States and elsewhere on the basis of the factors previously discussed that involve well efficiency and cost effectiveness (Campbell and Lehr, 1973, 1975).

GROUND WATER SYSTEMS COST ANALYSIS



Example: A site with 16 points has 3 chances in 10 of yielding at least 30 gallons per minute and 6 chances in 10 of yielding 10 gallons per minute

FIGURE 6 PROBABILITY OF OBTAINING A CERTAIN WELL YIELD USING THE LeGRAND APPROACH (LeGrand, 1967)



FIGURE 7 TOTAL WATER SYSTEMS COMPARISONS (from Campbell and Lehr, 1975)

CENTRAL WELL SYSTEM VS. CLUSTER WELL SYSTEM

$$\frac{S_c}{S_u} = C_R$$

or :

$$\frac{W_{cc} + I_{cc} + D_{cc} + O_{cc} + M_{cc}}{\sum_{i=1}^n W_{cu_i} + I_{cu_i} + D_{cu_i} + O_{cu_i} + M_{cu_i}} = C_R$$

where : C_R : TOTAL SYSTEM COST RATIO
 S_c : TOTAL SYSTEM COST OF HIGH CAPACITY
 OR CENTRAL WELL SYSTEM
 S_u : TOTAL SYSTEM COST OF MEDIUM LOW
 CAPACITY OR MULTIPLE WELL SYSTEM

FIGURE 8 COMPARATIVE COST ANALYSIS OF A CENTRAL WELL SYSTEM AND A CLUSTER WELL SYSTEM (from Campbell and Lehr, 1975)

TEST DRILLING PHILOSOPHY

The desirability of adequate test drilling is well founded in cost analysis (Cederstrom, 1973). It should be noted, however, that indiscriminate drilling should not be undertaken in the hope of developing higher yield wells than those obtained in a minimum drilling program. An expansion of an initial program should be based on the following considerations:

1. The initial program of a few holes indicate that average yields for the rock type have not been developed (experience to date).
2. Favorable areas are present and have not been tested (geological interpretation).

To reinforce the above concepts regarding the low cost of test drilling, assume that a low-capacity water supply is imperative in a particularly unfavorable igneous and metamorphic rock area. Figure 9 indicates that capital cost and cost/1000 gallons where 10 test holes were drilled and one or more of these were completed as production wells yielding 75 gpm (4.7 lps).

TEST DRILLING PHILOSOPHY

The cost of a 400-foot (122 meter) test hole is assumed to be US \$2,700 (22,000 Rs) and the cost of a completed well is US \$11,914 (95,000 Rs) less US \$2,700 (22,000 Rs) or about US \$9,200 (74,000 Rs). Where only one of the 10 test wells can be finished as a producing well with a yield of 75 gpm (4.7 lps), the cost of water at the well head is about 11 cents (.88 Rs) per 1000 gallons. When two wells out of 10 are successful, the cost per 1000 gallons is about 7 cents (.56 Rs) per 1000, etc. It should be noted that only small reductions in cost per 1000 gallons are achieved as the success rate rises from four successful wells out of 10 test holes to the point where all holes are capable of being completed as producers. This relationship shows rather clearly that only moderate success in test drilling is necessary to obtain a ground water supply at a reasonable cost; or conversely, the cost of drilling "extra" test holes is small where a moderate success is finally achieved. In the example considered above, each unsuccessful test hole drilled added only 8.2 miles (100 miles = 1 cent) to the cost/1000 gallons to the water eventually produced from one 75 gpm (4.7 lps) well pumping 60% of the time. Cost would also be somewhat less if test holes in excess of 250 feet (76 miles) were abandoned, on the basis that operating costs (pumping) would be excessive and serve to increase the unit cost of water. It should be clearly noted that in many cases variations in the cost of water will be unavoidable and hence, full utilization of all available water resources must be considered.

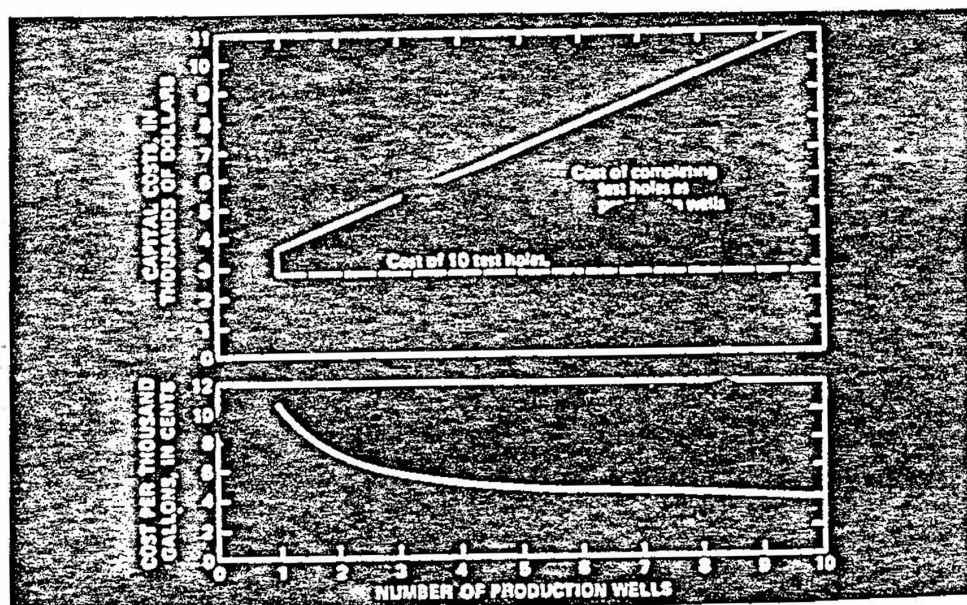


FIGURE 9 COST OF WATER WHERE ONE OR MORE OF 10 TEST HOLES ARE COMPLETED AS PRODUCING WELLS, EACH YIELDING 75 GPM (4.7 lps) (from Cederstrom, 1973).

LOW CAPACITY SYSTEMS

Economic evaluations should cover every conceivable aspect of water development, from optimizing exploration techniques through well construction to pumping systems and irrigation practices. Although the latter is beyond the scope of the topics discussed here, pumping systems, in terms of energy and equipment costs, are one of the key focal points of all ground water development programs. Technological advances are being made that may reduce the present difficulties of the many small farmers and isolated villages that do not have electricity (Allison, pers. com.).

Many areas in India, and elsewhere in the world, experience extended dry seasons during which the climate is sufficient for more than one crop. Finances, however, for energy and for appropriately sized pumping units are not available to the many small farmers. Small vertical turbine pumps, electrically driven by inexpensive solar cell arrays or semi-conductor devices, may be available in the near future. Such systems could allow the small farmer to develop more than one cash crop per year and small industries could develop in isolated areas.

It should be noted that low cost solar micro-pump systems now appear to be a manufacturing and industrial development task. The systems are no longer a research item of academic curiosity. Such technological developments must be monitored closely for potential, widespread application to ground water programs. In many areas where ground water occurs only in igneous and metamorphic rocks, the climate is either semi-arid or a desert of the low latitudes. Many such areas are characterized by many hours of sunlight during the year. Solar-generated electrical pump systems should prove to be useful in such areas, thereby reducing significantly the cost of pumping, both the costs associated with energy requirements as well as the costs of low capacity pumping equipment.

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