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On the Need to Evaluate Factors Influencing Hard Rock Well Yield in Northeastern Brazil

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Abstract

Geological mapping, aerial photograph interpretations, geophysical techniques and more recently satellite imagery, have been used and are almost universally considered to be recommended techniques to apply in lineaments and fracture zones identification for water well location purposes in hard rock areas. Nonetheless, such methodologies need to be combined in the search for high yielding wells in fractured basement rocks. As a result of the uncomplementary use of such exploratory techniques, one should recognize that they cannot garantee how transmissive a fracture zone can be. Experiences involving approximately 70.000 water wells drilled in Northeastern Brazil, in the last 35 years, demonstrate that for crystalline rocks in general and for every specific rock type there is yet no consistent proof of lithology and or structural patterns influences in hard rock well yields. In all cases, listed information on well yields seem to indicate that successful yield in crystalline rock aquifers is a game of chance. So, a call for introducing a more efficient integration of the available technologies is urgent in the search for high yielding wells in frasctured rock basement. So far, it should be emphasized that a better understanding of the process and rates of recharge, including the induced recharges through a conjunctive surface and ground water use, shall be acquired. This induced recharge may improve the water quality, due to the water freshness process

Introduction

The Northeastern Brazil (1.6 million km² and 42.5 million inhabitants) lies between Lat°20 and 18° S. and Long. 35° and 48° W. Average rainfall ranges between over 2000 mm/year in the eastern coastal belt and in the Amazon west border, and 500 mm/year in the central area, so called Sertão (*Fig. 1*).
Rainfall concentration over 3 to 4 months should correspond to a tropical hydrological regime. However, the interaction of climatic and physical factors provoke deformations towards the semi-aridity over 800 thousand km² of the central area.

In the context of crystalline rocks, that is, almost 60% of the semi-arid region, the hydrographic network is very dense and the rivers are noticed by their temporary regime. Consequently, a constellation of small dams, that is, with less than 100 thousand m³, have plready been constructed, and about 1,500 dams with individual storage capacity of more than 100 thousand m³. Also, there is about 450 having each one storage capacity between 1 million m³ and 34 billion m³ .

Many of the local water supply and sanitation problems in this area are the result of ill-planned development. Although water quality problems generally are more severe in the urban areas, rural populations are adversely affected by untreated domestic wastewater discharged into rivers and dams, whose potential for dilution is increasingly limited, mostly during the drought periods. Thus, from a social and economic point of view, ground water resources are particularly important because they remain practicaly stable over time and because they can be used much more inexpensively to supply a good quality water. Even in the crystalline rock context, where ground water resources are limited and often of poor chemical quality, they are of considerable importance, particularly for domestic uses and livestock, because the presence of usable water is critical during the dry season.

State of the Art

Statistics of the well yields

Since the 1960s, specifically in the hard rock domain, hydrogeologists in Northeastern Brazil have been using aerial photograph for geological interpretations, *in situ* geological mapping and structural analysis methodologies for locating successful water wells. Geophysical techniques (resistivity) have been introduced in well location only by the 1980s, with no significant general progress as far as water well yield is concerned. It is worth to say however that a certain reduction in the index of unsuccessful wells (ie. wells producing less than 0.1 m^3/h), which used to be on the order of 20 to 30%, has been noticed in some local water well drilling programs in Ceará State (Marques, 1985, CAGECE-KFW 1992).

Silva (1992) reports that in Paraiba State the index of unsuccessful wells from a sample of 973 listed information on water wells drilled by the Mineral Resources Development Company (CDRM) in five different lithologic types is about 25% (ie. 242 out of 973 wells) as shown in *table 1*. While it is noteworth that migmatite and phyllite "appear' to present the highest indexes of success, differences in the number of drilled wells in each lithology certainly make it difficult to associate these statistics of success/unsuccess to lithology (see *table 1*). In that respect, Silva (1992) who have carried out a detailed analysis of frequency distribution of water well specific capacity in the hard rock domain of Paraiba State concludes that risks always exist in drilling water wells in crystalline rocks (ie. for any hard rock lithology) and chances are of good and bad surprises.

Probably in very few local conditions the structural *in situ* analysis permits to identify zones of open fractures which are potential aquifers in terms of fluid transmissivity (Neves, B.B., personal communication). Otherwise the 35 years experience of hard rock water well drilling in northeastern semi and zone of Brazil appear to confirm the Norwegian experience in which case, as reported by Banks (1994), borehole drilling in crystalline rock aquifers is to a large extent a game of chance. In fact pumping test data from wells located on many prominent fracture zones in Norway, seem to indicate that neither a geophysical technique nor a topographic anomaly is able to distinguish between a transmissive and a non transmissive zone (Banks et al. 1994).

In spite of several thousands of wells drilled in hard rock aquifers, detailed investigations of ground water in igneous and metamorphic rocks in the semi arid region of Brazil are not numerous. The most important ones date from the 1970s and were developed by SUDENE, the Federal Government Agency for Regional Development. Such investigations have focused on aerial photo analysis and *in situ* geological mapping to identifie the fracture and joint zones for water well location in order to provide water supply in rural areas.

Much of current research on basement aquifers is directed towards more cost effective well siting. Consequently, taking into account that the yields are very low, only enouhg to supply domestic and livestock rural need, attention shall be paid for the cost/benefit ratios. In recent years the Company for Mineral Resources Research (CPRM), now transformed in the National Geological Survey (SGN) and the National Institute for Space Research (INPE) are among the institutions which are introducing new methodologies such as satellite imagery, remote sensing and geophysical techniques.

In a experimental study remote sensing techniques followed *by in situ* observations were used in a area of 832 km^2 in the southeast zone of São Paulo State (Caçapava-Jambeiro-Paraibuna), which is underlained by deep weathered Precambrian basement. By using a GIS (Geographycal Information System) to extend directional fracture frequency distribution for each lithology, *favourable and unfavourable* ground water storage zones have been mapped on scale 1:50,000. Several points have been suggested for well but no evidence exist of the effectiveness until the proposed wells are drilled (Rocio 1993).

Costa (1986) suggests a series of factors that supposely influence hard rock well yield and water quality establishing a classification of field conditions to be taken into account in locating water wells in the semi-arid zone of Brazil (see *table 2*). By including lithology and types of fracture in the classification, the author assumes that low grade metamorphic rocks (ie. phyllite, slate) are less resistant than the high grade ones (ie. gneiss) to shear stress and so generate very high levels of breaking cumulated energy. Stress and strain rupture forces in this case would tend to be of high magnitude producing fractures with thin apertures. Albuquerque (1984) however, states that fracture opening in such low grade metamorphic rocks tend to be open as long as their genesis takes place closer to the earth surface.

The typical histogram of well yields in Northeastern Brazil (Paraiba and Rio Grande do Norte States) including five crystalline rock types (granite, gneiss, migmatite, schist and phyllite) is shown in *figure 2* (Rebouças e Manoel Filho, 1994).

By excluding about 25% of unsuccessful wells, the effective well yield ranges from 0.15 to 32.7 m^3/h. However 82% of the yields are less than 5 m^3/h and 60% less than 2.5 m^3/h. Such results reflect a high percentage of unsuccessful and low yield wells, a low percentage of medium to high well yield and a very low percentage of high well yield (only 2.9% producing more than 1 0 m^3/h.).

Influence of lithology

In Northeastern Brazil differences in hard rock well yields, examined in samples of 100 wells for three hard rocks types are very high and range from 0.25 to 18 m^3/h in granite, 0.2 to 32 m^3/h in gneiss and 0.2 to 24 m^3/h in schist (Rebougas and Manoel Filho, 1994). It appears from these figures to be possible to obtain very high and very low yields in any hard roch types. In that respect lithology cannot be included as a significant factor influencing hard rock well yield.

This conclusion is in agreement with the findings of many authors in other parts of the world who recognised that the distribution of yields is very skewed towards low values in almost any rock types (Banks et al. 1994).

The role of tectonic

Densily fractured zones are typically located through aerial photo analysis, use of remote sensing and geophysical techniques (resistivity profiles, electromagnetic VLF). Based on very detailed studies carried out in Norway, Banks et al. (1994) report that lineaments and major fracture zones may behave in their hydrogeological character, very differently from a place to place as far as fluid conductivity is concerned. Experiences show that fracture zones may have different modes of genesis, deformation and reativation. Fracture apertures may be open, tighted by stresses of high magnitude or may be filled to varying degrees by secondary mineralisations. The same authors report that many others have found correlations between stress orientation of fractured zones and permeability. Such correlations were identified both in regional scale (Larsson 1972, Huntoon 1986 and Rohr-Torp 1987) and *in situ* scale investigations (Olsson 1979, Carlsson and Christiansson 1987)

By examining water leakages and mineralisations in one site, Sundquist et al. (1988) have concluded that fractures oriented along the maximum horizontal *in situ* stress (σH) were the most hydraulically open. In another site however, Banks et al. (1993) report that no significant difference was found in leakages from fractures in boreholes drilled perpendicular to σH (which were supposed to cross open fractures) and boreholes drilled parallel to σH Observed very low rates of leakage were explained as a result of the very high magnitude of *in situ* stresses (up to 15MPa) which keeped fractures tightly closed.

Other interesting experiences carried out in Sweden by Neretnieks (1987), Bolvede and Christiansson (1987) are reported by Tsang and Tsang (1989). Both, by examining water leakages from fractures over 14,000 m^2 Of tunnel excavated in granite and by performing permeability tests in 92 sections isolated by packers in 15 deep boreholes, it has been demonstrated that ground water flow in fractures takes place along very few preferential paths. It is noteworth that 83 out of 92 (ie. 90.2%) of the sections have generated only 8.3% of total flow while just 3 out 92 (ie. 3.3%) of the sections have produced 77.3% of total flow.

On The Need of a More Efficient Approach

Wright (1985) reports that using standard geophysical siting techniques (magnetometer and resistivity) one quote a probability of less 10% to achieve a borehole yield of 8m^3/h in an area in Botswana underlain by granitegneiss. A more detailed geophysical survey was utilised which incorporated additionally to these techniques, satellite imagery enhancement and aeromagnetic and electromagnetic ground survey data and in consequence of which a number of high yielding zones were identified.

Hydrofracturing has been used successfully since 1947 in oil wells to create reservoir fractures that improve well productivity (Howard and Fast, 1970). More recently this method has been used to increase the yields of lowproduction water wells in fractured zone aquifers (Waltz and Decker, 1981). Yields improvements in the Denver wells, after hydrofracturing were from 50 to 130%, although these increases represent only a small volume of water, for example, from around 3 to 6 m^3/day (Stewart, 1973).

Climate (basically rainfall distribution/watershed budget) and topography (recharge/transient/discharge areas identification) are important controls affecting the yield and quality of ground water from fractured rock aquifers in this semi-arid zone. In fact, many of the valley bottoms are commonly developed along fracture traces. The baseflow recession of the river basins indicated an average annual recharge in the basement fractured rock aquifers of about 1-2% of the average precipitation of 700 mm/year (Rebouças and Gaspary, 1966; Rebouças, 1973). Ground water quality tends to be best (TDS < 200 mg/L) in the regions where average rainfall is more than 800 mm/year. The quality tends to be poor where the average annual rainfall is less than 600 mm.

Concerning the hydrological regimes, Rebouças (1973) reports that the fractured aquifer zones can be considered as an organism: it was born (tectonic/rock mechanic patterns), grows (physical/chemical weathering process) and will die eventually (physical/chemical plugging). It has an input, throughput and output of energy in various forms. In this conceptual model the fractured zone is no longer the central focus of interest. In fact it is not the aquifer which acts as the main functional unit but the water flow systems in which the fracture zone is included. As ground water is in constant movement, infiltrated water that reaches the water table does not become stored in the underground reservoirs. In fact while freshly infiltrated precipitation is entering the aquifer zones, the ground water flow is discharging into the associated streams. It should be emphasized that the ground water discharge values to streams, characterizing the natural productivity of the ground water flow systems, are the main indicator of the ground water resources availability in an area.

When the pumping effect reaches the valley bottoms, the potenciometric gradient toward these discharge areas is lowered and the amount of natural discharge is proportionally reduced. Thus, it may induce additional recharge of ground water that was previously rejected. In any event, the pumping effect will continue to grow until it has sufficiently reduced natural discharges or increased the recharges to balance the volume of water removed by pumping. With this occurrence, a new condition of dynamic equilibrium is reached. Under such conditions, an important source of available ground water resources is the induced recharge generated by the conjunctive use of surface and ground water. In this case, the thopusands dams may represent important sources for induced recharges. On the other hand, such induced recharge may improve water quality due to the water freshness process.

Thus, when estimating the available ground water resources of the fractured aquifer zones, one should consider the possibility of using natural storage, natural recharges and induced recharges formed in the course of the development (intake of surface water, reuse of treated wastewater, or use of storm runoff). Experience has shown that it is good management practice to overdraft water table aquifers during prolonged dry periods. This reduction in the water table is temporary, and rapid recovery can be expected once precipitations return to normal. During prolonged drought, the flow of ground water to rivers may be reduced by greater ground water withdrawals, because use of part of this ground water discharges may be more beneficial than maintaining normal stream levels. In many semi-arid areas of the world, exceeding the 'safe yield' for periods as long as 10-15 years is not injurious to the volume of water storage, because either all or nearly all of the overdraft can be made up in the first year or two of normal rainfall (Ambroggi, 1978). These conditions are specially favorable in this semi-arid region because, as a rule, drought periods are separated by two or four years so rainy that catastrophic floods occur. These procedures are currently being used successfully in areas where water resources are limited. Often these procedures, even those requiring water treatment, do not add prohibitively to the cost of water.

Conclusions

Vast areas of Northeastern Brazil are floored by crystalline basement rocks and although associated aquifers are not highly productive they are of considerable importance, particularly for rural water supply. Aquifers may occur in the fractured bedrock and standard development is by drilled well. Most of these are generally 150 mm in diameter and less than 100 m deep. The frequency of occurrence of productive fractures in crystalline rocks decreases with depth, with the optimal zone considered to be around 60 m. The storage capacity of these aquifer zones is restricted to the interconnected systems of fratures, joints and fissures, such openings being primarily the result of regional tectonic phenomena. These patterns are often clearly visible in the topography, and areal photographs and satellite imagery are good tools for recognizing major structures.

It appears however, given the known well yield results that aerial photo analysis and geological mapping are not effective techniques to distinguish densely fractured zones which are transmissive from the ones which are not. It may be a problem of scale ie., there is probably a need to find out the right mapping scale of geological and structure mapping for water well location pruposes in hard rock aquifers.

Pumping test results and experiments measuring leakage along fractures, demonstrate that field *in situ* densely fractured zones may respond very differently from laboratory rock mechanics based experiments. In fact such zones may exibit various genesis, deformation and reativation processes and thus fracture apertures may be either open or closed depending upon the magnitude of stress and strain forces or may be filled by secondary mineralisations or by clayish material.

Structural analysis, geophysical and remote sensing techniques need to be more efficiently combined in the search for high yielding wells in fractured basement rocks. Moreover, surface drainage networks are commonly aligned along fracture systems in the underlying rock. As a result, new techniques of improved siting of localised high yielding wells require that a better understanding be acquired of the process and rates of recharge.

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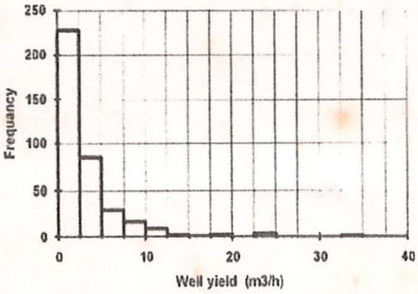

Histigram of hard rock well yeild in Northeastern Brazil
(from Rebouças and Manoel Filho, 1994)