Well productivity controlling factors in crystalline terrains of southeastern Brazil

Mirna A. Neves · Norberto Morales

Abstract Over the last decades, increasing water demands have fostered research to obtain high well yields in crystalline terrains where, besides the intrinsic properties of rocks, the groundwater flow depends on several factors. The depth of the wells, the lithotypes, the presence and thickness of sedimentary coverings and weathered layers, the landforms, the geological structures, and the effects of tectonic stresses are among the most investigated factors considered as determinant of well productivity. The influence of these factors on productivity of wells that exploit the Crystalline Aquifer System in the Jundiaí River Catchment, southeastern Brazil, is investigated in this work. The largest region of the studied area is located on the Precambrian Basement, partially covered by sedimentary deposits. The results show that the sedimentary deposits and the weathered layer are important for high well yield, but it also depends on the existence of a net of open fractures, in order to maintain high productivity. The sites that have more possibility of occurrence of such structures are the regional shear and fault zones and other minor structures with NW–SE and E–W directions, which characterize areas subjected to transtensional stress related to the neotectonics.

Résumé Au cours des dernières décennies, les besoins en eaux croissants ont poussé les recherches vers l'obtention de débits importants dans des terrains cristallins, où les écoulements souterrains dépendent de nombreux facteurs, outre les propriétés intrinsèques des roches. La profondeur des puits, les lithotypes, la présence et l'épaisseur d'une couverture sédimentaire et d'une frange altérée, la morphologie, les structures géologiques et les effets des contraintes tectoniques comptent parmi les facteurs les plus étudiés, et sont considérés comme déterminants pour la productivité des ouvrages. La présente étude porte sur l'influence de ces facteurs sur la productivité de puits exploitant le Système Aquifère Cristallin du Bassin Versant de Jundiaí River (Sud-Est du Brésil). Le secteur le plus étendu de la zone d'étude se situe sur le Socle Précambrien partiellement recouvert de dépôts sédimentaires. Les résultats montrent que les dépôts sédimentaires et les franges altérées ont une importance certaine dans le débit exploitable des puits, mais que celui-ci dépend également de l'existence d'un réseau de fractures ouvertes, afin de préserver une productivité élevée. Les sites présentant les potentialités optimales de présence de telles structures sont les zones de cisaillement et de failles régionales, ainsi que d'autres structures mineures de direction NW–SE et E–W, caractéristiques des secteurs soumis à des contraintes transtensionnelles liées à une tectonique récente.

Resumen Durante las últimas décadas, las demandas de agua crecientes han impulsado la investigación, para obtener altos rendimientos de pozos en terrenos cristalinos, dónde el flujo del agua subterránea depende de varios factores, además de las propiedades intrínsecas de las rocas. La profundidad de los pozos, los litotipos, la presencia y espesor de cubiertas sedimentarias y de capas meteorizadas, las formas del relieve, las estructuras geológicas y los efectos de las fuerzas tectónicas, están entre los factores más investigados y considerados como determinantes de la productividad del pozo. En este trabajo, se investiga la influencia de estos factores en la productividad de pozos que aprovechan el Sistema Acuífero Cristalino en la Cuenca del Río Jundiaí, en el sudeste del Brasil. La región más grande del área estudiada, se localiza sobre el basamento Precámbrico, parcialmente cubierto por depósitos sedimentarios. Los resultados muestran que los depósitos sedimentarios y la capa meteorizada son importantes para el alto rendimiento de los pozos, pero también depende de la existencia de una red de fracturas abiertas, para mantener la productividad alta. Los sitios que tienen más posibilidades de ocurrencia de tales estructuras, son las zonas de cizalla regional y de falla y otras estructuras menores con

Received: 14 December 2005 / Accepted: 30 August 2006

M. A. Neves (✉)
Centro de Ciências Agrárias,
Universidade Federal do Espírito Santo (CCA/UFES),
Alto Universitário s/n., Alegre-ES 29500-000, Brazil
e-mail: mirnaan@gmail.com

N. Morales
Instituto de Geociências e Ciências Exatas,
Universidade Estadual Paulista (IGCE/UNESP),
Av. 24-A, 1515-Bela Vista, Rio Claro-SP 13506-900, Brazil

N. Morales
e-mail: nmorales@rc.unesp.br

 DOI 10.1007/s10040-006-0112-6

direcciones NW–SE y E–W, las cuales caracterizan las áreas sujetas a tensión transtensional relacionada a la Neotectónica.

Keywords Crystalline rocks · Control factors · Tectonics · Southeastern Brazil

Introduction

Studies of the behavior of groundwater in crystalline rocks usually point out that one factor or a set of factors are responsible for the high well-productivity variability, although no conclusive evidence is available.

The existence of more productive lithotypes is often regarded as one of the control factors (e.g., Mabee 1999; Singhal and Gupta 1999). However, Banks et al. (1996) affirm that even though the influence of the lithotype exists, its effects can be supplanted by the presence of a set of interconnected and open discontinuities. These authors also account for the role of in situ stress on well productivity; which may be masked by the massif's anisotropy, weathering, and secondary mineralization. The influence of in situ stress has also been studied by other researchers such as Henriksen (2003) and Morin and Savage (2002, 2003).

Gustafsson and Krásný (1994) stated that highly fractured zones, widespread over dozens of kilometers, might compound great hydraulic conductors, whereas others point out that the regional structures do not necessarily represent those with the highest productivity (e.g., Banks et al. 1992; Nilsen 1998). The influence of the filling of the discontinuities represents the main factor in this case, since large fractured zones tend to develop clayey filling resulting from the weathering of fragmented material.

Some studies (e.g., Chilton and Smith-Carington 1984; Banks and Robins 2002) consider that long-term well productivity relies on the presence of a weathered layer covering the fractured rock. This layer can display a high storage capacity and the productivity of the fractured rock can only be maintained if, in addition to open discontinuities, a constant recharge is available. Singhal and Gupta (1999) also emphasized the influence of the landforms. Since different landforms present distinct characteristics relating to the weathered layer thickness, they also have different water storage capacities.

The influence of topography on well productivity has been debated by several authors (e.g., LeGrand 1967; McFarlane et al. 1992). Parizek and Siddiqui (1969) showed that wells located in valleys could be eight times more productive than those on slopes or tops. According to Henriksen (1995), plain areas, even those on highlands, can be more productive due to the presence of thicker superficial coverings that allow good conditions for recharge. On the other hand, some authors (Yin and Brook 1992; Knopman and Hollyday 1996) regard topography as a minor feature and affirm that its influence over well productivity occurs in less than 10% of the observed variations. Therefore, it can be deduced that the factors that actually influence the productivity of wells in crystalline rocks have not been well established, or that these vary according to the particular characteristics of the area.

For a long time, the low permeability and the difficulties of drilling in hard rocks led to an underestimation of their potential as water source. However, as long as water demand has increased, groundwater in hard rocks has begun to be investigated more carefully. In several countries of Asia, Africa, and Latin America, a great emphasis has been given to the necessity of drinking water for the impoverished populations that inhabit crystalline terrains (Chilton and Foster 1995). In these areas, the development of efficient and low-cost methods for groundwater exploration is of utmost importance. Studies about hydrogeology of crystalline rocks are also relevant in richer countries, where they usually focus on the selection of sites for hazardous wastes disposal (e.g., Tirén et al. 1999).

In Brazil, despite the fact that a great part of the territory is comprised of crystalline rocks, studies of the behavior of fractured aquifers are rare. In the southeastern region, the urban and industrial concentration spread over the Precambrian Basement has brought severe problems of water availability. This fact is responsible for an increased prospecting for groundwater, resulting in the necessity of a better understanding of the regional hydrogeology.

This paper analyzes the influence of some factors which potentially interfere in the productivity of deep tubular wells that exploit the Crystalline Aquifer System in the Jundiaí River Catchment. The survey was done by using data from 1,006 wells (Neves 2005) registered in the Electrical Energy and Water Department (Departamento de Águas e Energia Elétrica, DAEE), the Brazilian Geological Survey (Serviço Geológico do Brasil, CPRM) and a private well drilling company.

Characterization of the studied area

The studied area represents a rectangular polygon involving the whole Jundiaí River Catchment, as portrayed at Fig. 1. It lies in an area of transition between subtropical and temperate climates (Setzer 1966), with mean annual temperature ranging from 18 to 20°C and total annual precipitation between 1,200 and 1,800 mm (São Paulo 2000).

Geological context

Figure 2 presents a simplified geological map of the studied area (Neves 2005). Most of the Jundiaí River Catchment is located on the Precambrian or Crystalline Basement where gneisses with intercalations of quartzites, schists, and amphibolites from the Amparo Complex predominate (Hasui et al. 1981). In the southern part of the area, there are rocks from the São Roque Domain, mainly composed of phyllites with intercalations of meta-

 DOI 10.1007/s10040-006-0112-6

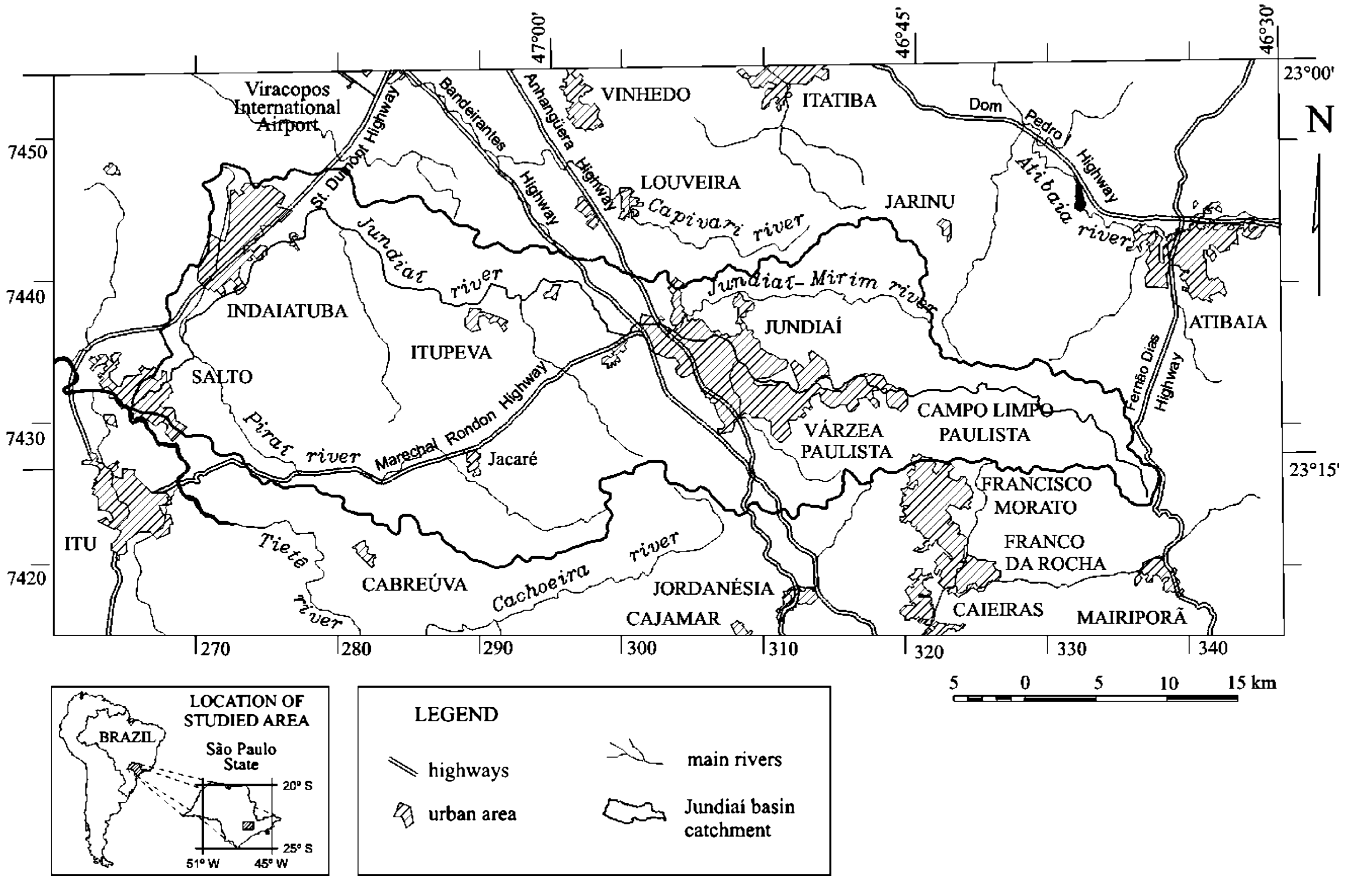


Fig. 1 Location of the studied area displaying the main rivers, urban areas, and highways

sandstones, quartzites, and calc-silicatic rocks, along with schists, metacherts, and marbles (Juliani and Beljavskis 1995). Intrusions of granite bodies are very common in both units.

In the western part, Paleozoic sedimentary rocks from the Itararé Group are found, composing the basal layers of the Paraná Sedimentary Basin. Moreover, there are other sedimentary covers such as the Tertiary deposits (Neves et al. 2005a) that occur around the Japi Mountain Range, the colluvial–eluvial deposits that cover a great part of the lithotypes previously described, and the Terrace and Quaternary alluvial deposits distributed along the main drainage channels (Neves 1999; Neves et al. 2005b).

Structural and tectonic contexts

The Jundiuvira, Extrema, Valinhos, and Campinas shear zones as well as the Itu, Piraí, Cururu, and Cachoeira faults are important geological structures that form fault scarps and delimit different morphostructural compartments (Neves et al. 2003). These morphostructural compartments constitute tectonic landforms whose topography is strongly influenced by the structure of underlying rocks that have undergone ductile and brittle deformation.

The morphostructural compartments were called Japi, Itu, Jardim, Cristais, Central, and Paraná Basin compartments by Neves (2005) but, in this paper, they will be respectively cited as I, II, III, IV, V, and VI compartments (Fig. 3). The I, II, III, and IV compartments compound highlands in relation to the topographically lowered V and VI compartments. The weathered layer tends to be thicker in the latter and most of the sedimentary covers are distributed throughout these tectonically lowered blocks.

According to their topographical and lithological characteristics, these compartments can be correlated with the typical crystalline landforms cited by Singhal and Gupta (1999). The I, II, and IV compartments can be considered as structural (or residual) hills; compartment III is similar to structural hills with pediments and compartments V and VI are similar to buried pediments. This information will be used later in this paper.

The shear zones that delimit those landforms are Precambrian in age. They arose under ductile conditions and developed an outstanding mylonitic foliation. As geological time passed, the conditions become more and more brittle, but the tectonic stresses were continuously alleviated along the structures, which began to act as crustal weakness zones during the following geological evolution.

From this evolution, it is worthwhile to point out two important tectonic stages whose understanding is essential to this work: the extensional regime that acted in the continental separation, and the transcurrent neotectonic regime; both of which are depicted in Fig. 4.

 DOI 10.1007/s10040-006-0112-6

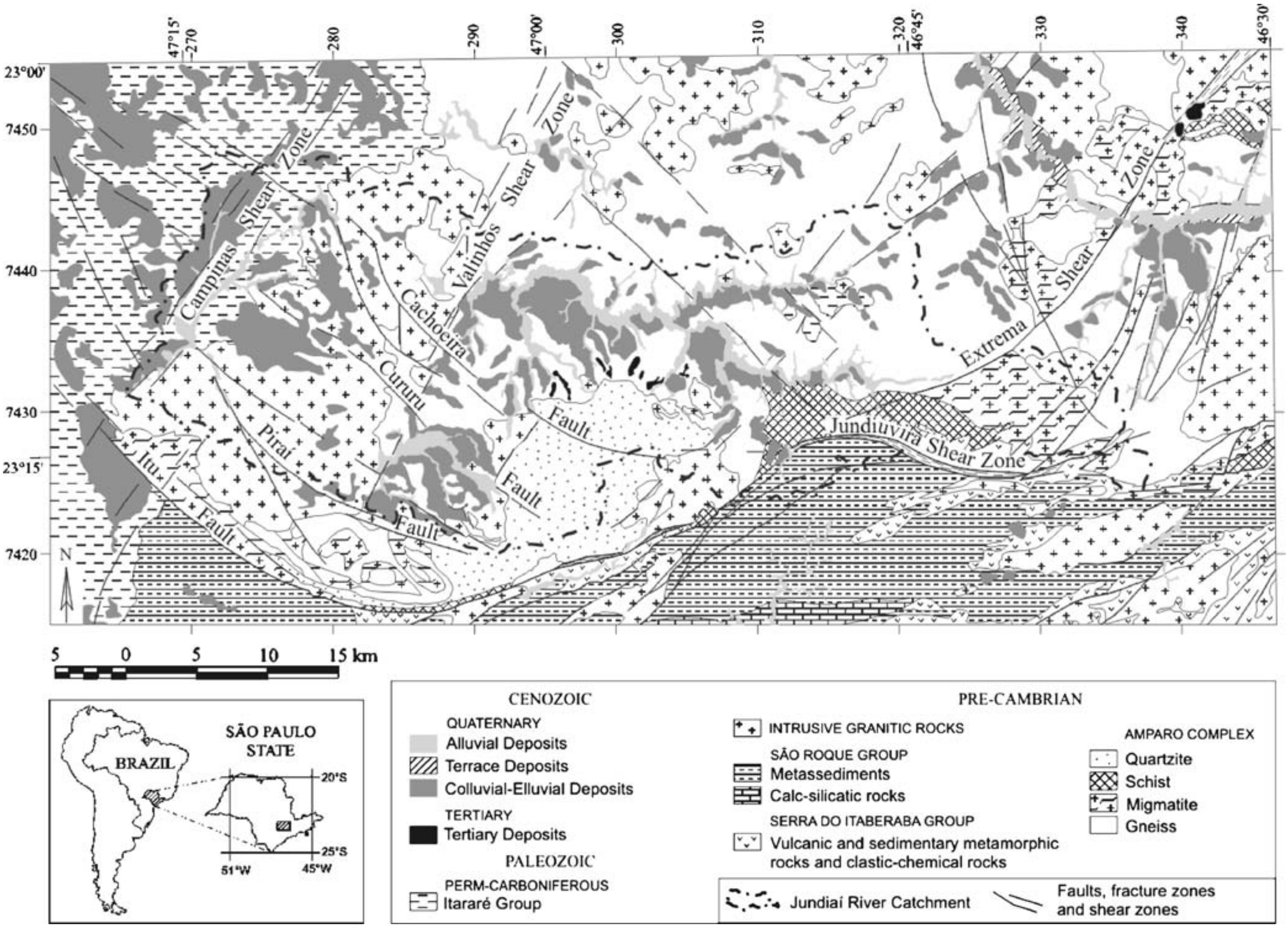


Fig. 2 Simplified geological map of the studied area (Neves 2005, modified)

The extensional regime, which culminated into the fragmentation of the Gondwana megacontinent and the continental separation, presented a regional tensor with the major axis vertically positioned, the intermediate axis horizontal with a NE–SW direction, and the minor axis horizontal with a NW–SE direction (Fig. 4a). Under this arrangement, normal faults and open joints were formed mainly in the NE–SW direction, and there was a tendency

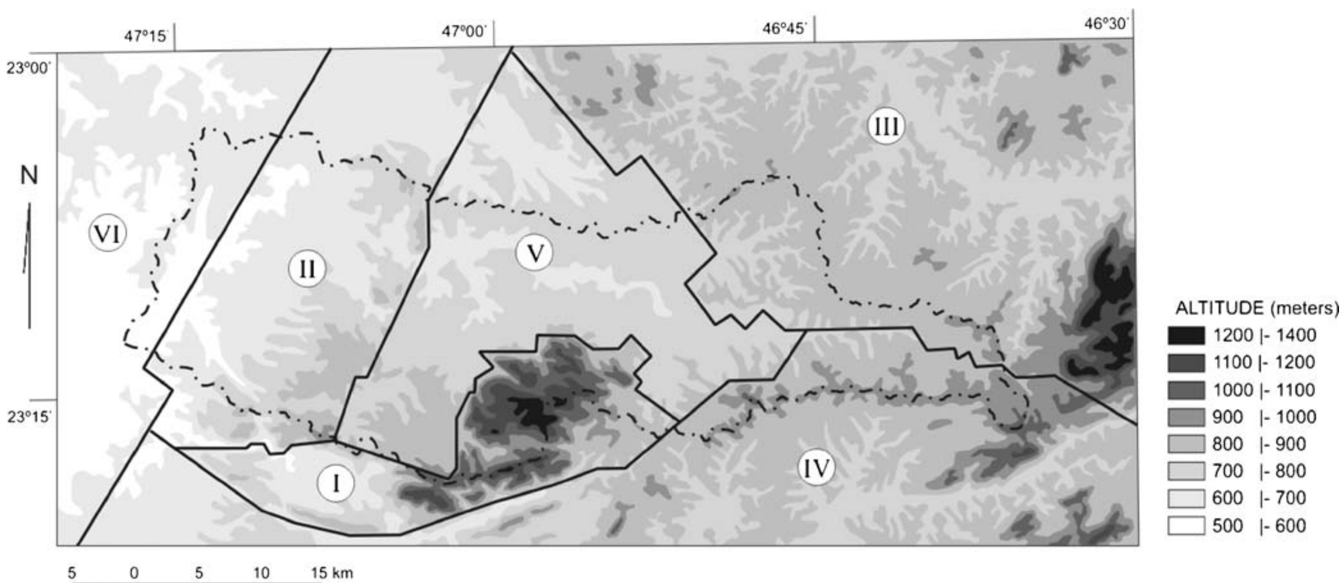
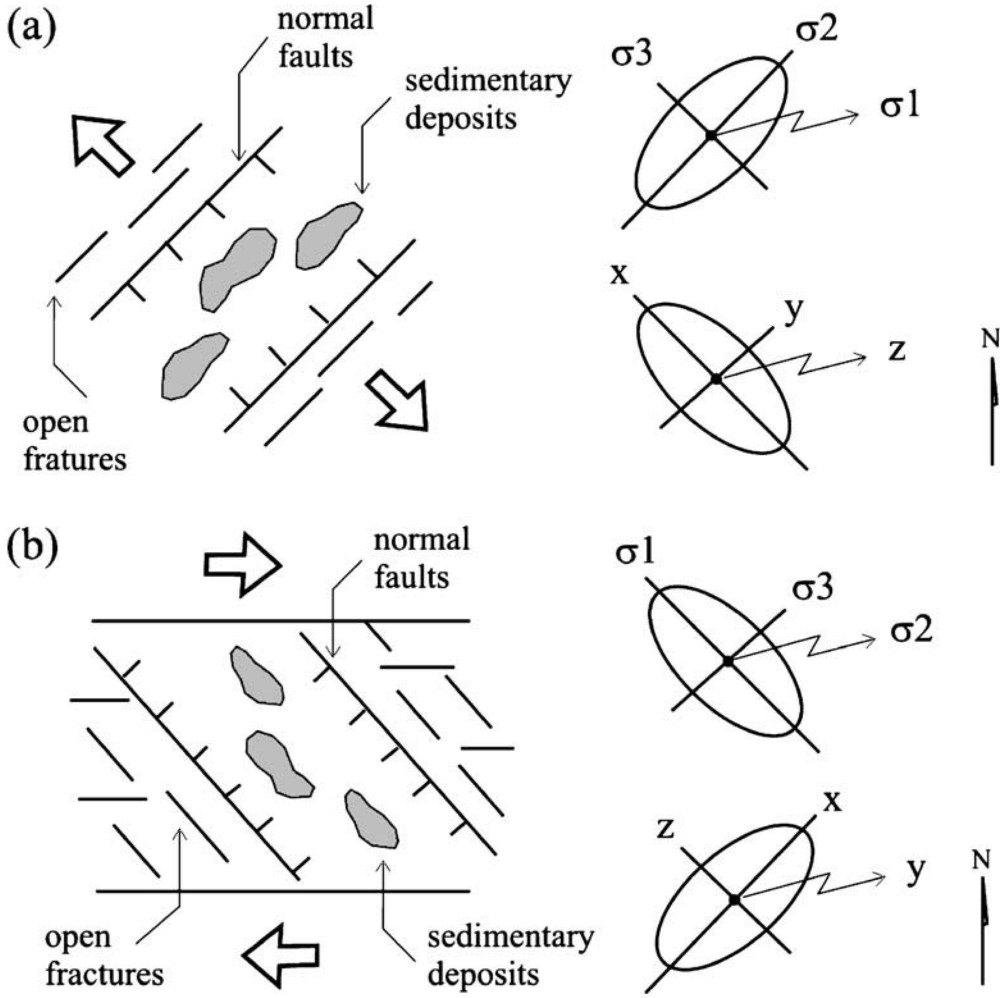


Fig. 3 Morphostructural compartments of the Jundiaí River Catchment (Neves 2005). The six tectonic blocks depicted are: *I* Japi; *II* Itu; *III* Jardim; *IV* Cristais; *V* Central; *VI* Paraná

 DOI 10.1007/s10040-006-0112-6

Fig. 4 Regional tectonic movements, the main structures that have arisen, and the stress and deformation ellipsoids that effected the South American Plate during **a** the extensional regime (from the Upper Cretaceous up to the Paleogene) and **b** the dextral transcurrent system (since the Miocene) in southeastern Brazil are depicted



for the NE–SW structures inherited from the Precambrian to open.

This regime was gradually replaced by a transcurrent one imposed by the rotation of the South American Plate towards the west, an event considered as belonging to neotectonics. Some divergences are found in the literature regarding the phases of neotectonic deformations in Brazil, but there is a certain consensus about the existence of a dextral transcurrent phase, which would be unique or, at least, highly relevant (e.g., Hasui 1990; Saadi 1993; Riccomini 1995). In this system, a conjugate E–W pair has been active, (Fig. 4b) favoring, e.g., the formation of open discontinuities in the NW–SE direction and dextral transcurrent faults in the E–W direction.

Hydrogeological context

The Crystalline Aquifer System occupies most of the Jundiaí River Catchment, as illustrated in Fig. 5. It is widespread within rocks from the Crystalline Basement, where the permeability is conditioned by the presence of discontinuities such as faults and joints and, in some cases, by lithologic contacts (Neves 2005). Over the fractured rock, the weathered layer may constitute a porous aquifer, responsible for great part of the base flow (Lopes 1994).

In the western part of the area lies the Tubarão Aquifer System, also known as the Itararé Aquifer, since it comprises rocks from Itararé Group. The vertical and horizontal heterogeneity of this unit determines low permeability and low water supply potential to the aquifer (Stevaux et al. 1987). Even where sandstone layers are considerably thick, there is high variability in the specific capacity of wells due to the small dimension and discontinuity of layers (Vidal 2002). Also, displaying a more restricted occurrence, there is the Cenozoic Aquifer System that occurs along the alluvial plains of the main channels.

Control factors on well productivity

The measurement of productivity of wells is based on their specific capacity, which has been considered the most representative parameter for productivity when transmissivity data are not available (Bertachini 1987;

 DOI 10.1007/s10040-006-0112-6

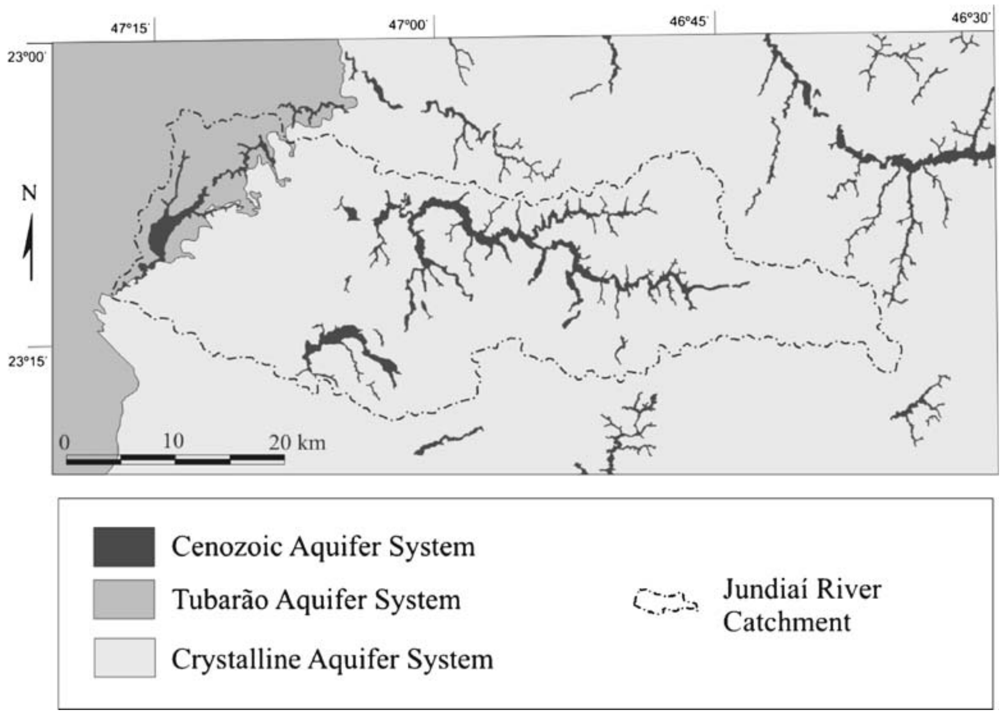


Fig. 5 Hydrogeological map of the studied area (Neves 2005, modified)

Chilton and Foster 1995). It is defined as the ratio between the outflow from a well (Q) and the drawdown (s), also known as "Q/s".

Well depth

Some papers have defined the best depth interval or the maximum depth that a well must reach in order to obtain satisfactory productivity in crystalline rocks (e.g., Davis and Turk 1964; Banks 1992). Most of them have shown that, because of the closure of discontinuities by lithostatic pressure in depth, the deeper the well, the lower the productivity.

In the Jundiaí River Catchment, a tendency of decreasing well productivity with increasing depth exists, but the correlation coefficient among the variables is considerably low (Fig. 6). It is remarkable that aligned points, indicating wells of identical depths (200, 250 and 300 m, for instance) often present distinctly specific capacity values. This logically leads to the thinking that well depth is defined according to contractual issues, user's necessity, and construction profits, which sometimes prevail over possible productivity gains by increasing the depth. Furthermore, although specific capacity values higher than 1.0 m^3/h/m are concentrated at depths lower than 150 m, the specific capacities of deeper wells are not necessarily low. At 300 m, for example, there are values ranging from 0.001 to more than 1.0 m^3/h/m.

Lithotypes

Morland (1997; in Banks and Robins 2002), studying crystalline rocks in Norway, verified that the productivity of gneisses was higher than that of metasediments, which were slightly more productive than granites. Singhal and Gupta (1999) stated that foliation was also an important factor, which means that schists should be more productive than granites and gneisses, since they have more conspicuous foliation.

However, the graph in Fig. 7 shows that specific capacity values provided by wells extracting water from schists were a little lower than other lithotypes in the studied area. Values close to the median were very similar for gneisses, granites, and schists (around 0.07 m^3/h/m). Nevertheless, the metasediments presented a remarkably higher distribution of values and the median is close to 0.2 m^3/h/m. In some layers, these rocks have important quantities of carbonated minerals and, thus, dissolution processes could be responsible for their striking productivity.

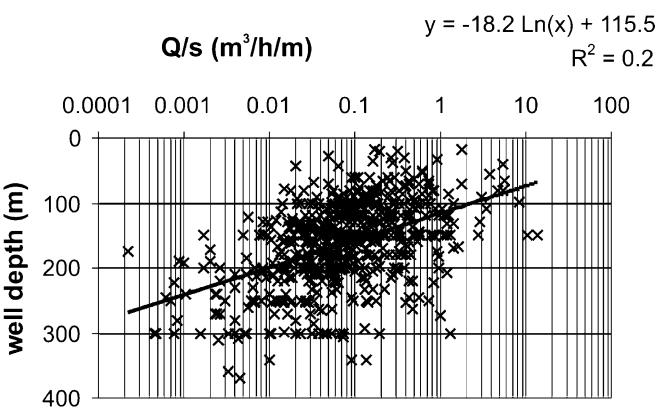


Fig. 6 Graph showing the correlation between specific capacity (Q/s) and well depth in the Jundiaí River Catchment

DOI 10.1007/s10040-006-0112-6

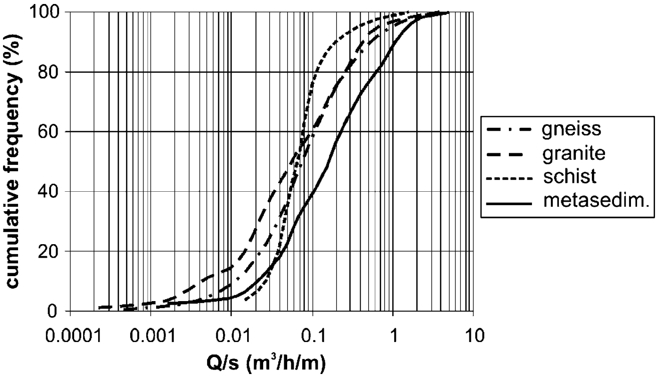


Fig. 7 Cumulative frequency of specific capacity (Q/s) from wells exploiting different kinds of crystalline rocks. *Metasedim* metasediments

Sedimentary coverings

Although a great portion of the studied area is located on crystalline rocks, the presence of sedimentary deposits covering these rocks is quite common. They are not very thick, but fairly widespread, and their potential as recharge zones suggests that high yield wells could be obtained in their sites of occurrence (Henriksen 1995; Banks and Robins 2002).

To test this hypothesis in the studied area, wells that exploit only the fractured rock but show sedimentary covering in their geological section were selected. The graph of cumulative frequency displayed in Fig. 8 shows that the specific capacity distribution of wells located in sites with colluvial cover and sedimentary rocks from the Itararé Group is quite similar to those wells without sedimentary covers (median around 0.07 m^3/h/m). On the other hand, wells with alluvial covers presented distribution of values remarkably higher (median equal to 0.11 m^3/h/m). It should be pointed out that these wells are sealed with casing up to the top of the unaltered rock and, therefore, the influence of covers on the recharge and the productivity of the fractured rock has been tested, not the productivity of the porous aquifer formed by the sedimentary cover.

Some wells lack any information about the kind of covering in the geological section, but have information about the depth of the top of the weathered rock. This measure corresponds to the distance between the land surface and the basis of the sedimentary cover, i.e., the thickness of the sedimentary layer. The graph in Fig. 9 shows a low correlation between both variables, indicating that there is no direct influence of sediment thickness on well productivity.

Weathered layer

The weathered layer formed by rock weathering has been regarded as an important recharge source in fractured aquifers (e.g., Lachassagne et al. 2001). To test the influence of this factor in regards to productivity in the studied area, wells with available data referring to the depth of the unaltered rock top and the depth of the casing were selected. The casing is used in the portion were the rock is weathered in order to prevent collapses or a possible contamination from the water table. Although the casing usually reaches a higher depth than the bottom of the weathered layer due to well construction safety, there is a tendency for an increase in the casing depth where the weathered layer is thicker. Thus, one can consider that the deeper the casing, the thicker the weathered layer. These variables are displayed in distinct graphs, since such data are not available for all the wells. The correlation with well productivity is weak in both cases, as illustrated in Fig. 10.

In some wells, casing without screens is installed along the weathered rock and only the water from the unaltered rock is exploited. In others, one or more screens are installed along the section across the weathered layer, mainly at the bottom or at the place of contact with the unaltered rock. These wells are able to exploit either the weathered layer only or both the fractured rock and the weathered layer.

The graph from Fig. 11 shows that wells exploiting only the fractured rock or both the fractured rock and the weathered layer are likely to be less productive than those exploiting solely the weathered layer (medians equal to 0.06 and 0.25 m^3/h/m, respectively). It is feasible that the latter ones are more productive since they can catch water

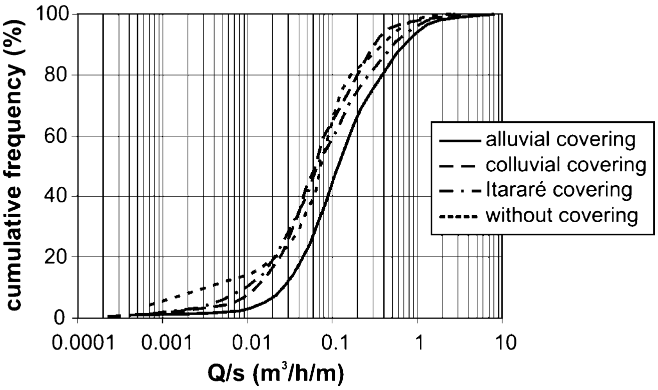


Fig. 8 Cumulative frequency of specific capacity (Q/s) from wells exploiting the fractured rock bearing different kinds of covers or without any sedimentary covers

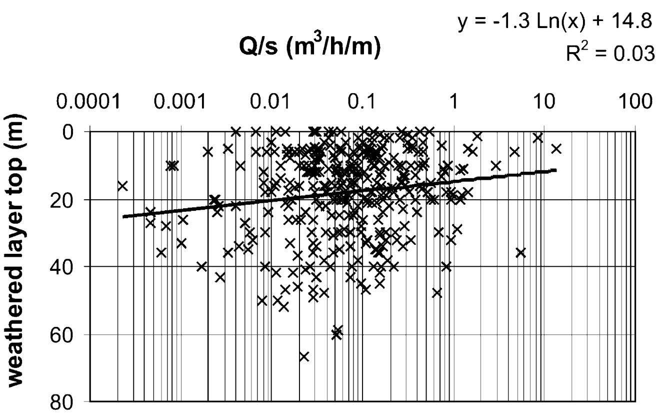


Fig. 9 Graph showing the correlation between specific capacity (Q/s) of wells and the depth of the top of weathered layer (corresponding to the thickness of sediments)

 DOI 10.1007/s10040-006-0112-6

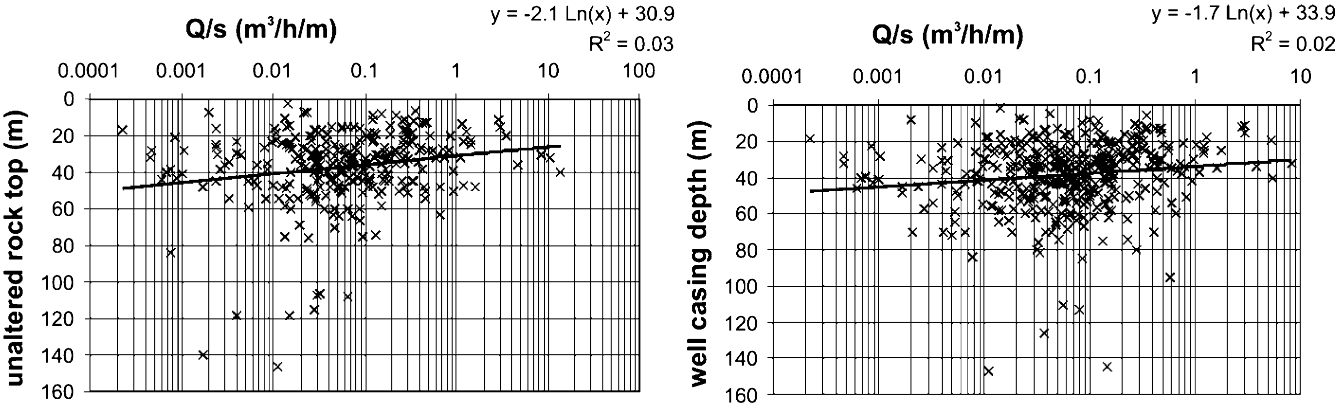


Fig. 10 Graphs showing the correlation among specific capacity (*Q/s*) and **a** unaltered rock top depth and **b** well casing depth in the Jundiaí River Catchment

from the horizontal flow that occurs between the weathered layer and the fractured rock, a fact corroborated by the conceptual model of Chilton and Foster (1995) in which the interface between the weathered layer and the unaltered rock presents high hydraulic conductivity. Similarly, Naik et al. (2002) pointed out that the lithological contrast among basaltic layers with different weathering degrees facilitates groundwater flow in the aquifer.

Therefore, it was expected that wells exploiting both the weathered layer and the unaltered rocks would be more productive, but that is not the case. It is assumed that they are located in sites where other unfavorable factors are present. If groundwater is not found in the weathered layer, the driller will tend to drill further into the crystalline rock, but the well water supply will remain low.

Morphostructural compartments

According to Singhal and Gupta (1999), the different landforms typically found in crystalline terrains have particular potentialities for providing groundwater. They attribute a low potential for groundwater supplying structural hills and inselbergs, a medium potential for the pediments and a high potential for the buried pediments and filled valleys.

The comparison of the productivity values of wells located at the morphostructural compartments of the area (Fig. 3) corroborates those observations. The graph from Fig. 12 shows that wells located in compartments I and II (structural hills) present lower specific capacity (medians of 0.03 and 0.04 m^3/h/m) than those in compartments III, V, and VI (structural hills with pediments and buried pediments; medians of 0.07 and 0.08 m^3/h/m). On the other hand, the values are considerably higher (median of 0.21 m^3/h/m) in compartment IV, which is also considered to be structural hills. It should be pointed out that, in this compartment, there are metasediments with carbonated minerals belonging to the São Roque Group (Fig. 2), whose susceptibility to solubilization can play a major role on well productivity (Fig. 7).

Tectonics and geological structures

The tracing of lineaments using remote sensing images is a very common procedure employed to search for geological structures that can furnish groundwater in crystalline terrains. Well productivity is often correlated to the distance between wells and lineaments, to the length

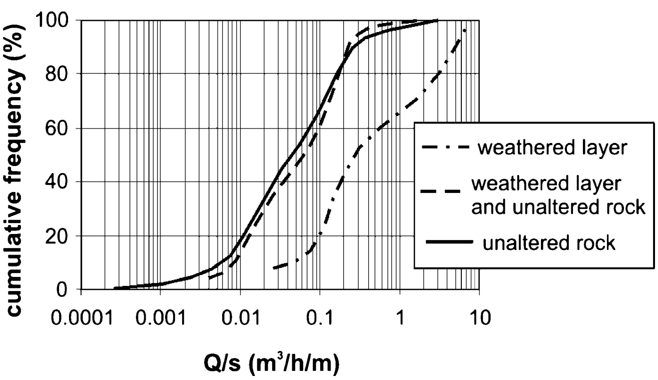


Fig. 11 Cumulative frequency of specific capacity (*Q/s*) from wells exploiting either the weathered layer only, both the weathered layer and the unaltered rock, or the unaltered rock in the Crystalline Aquifer System

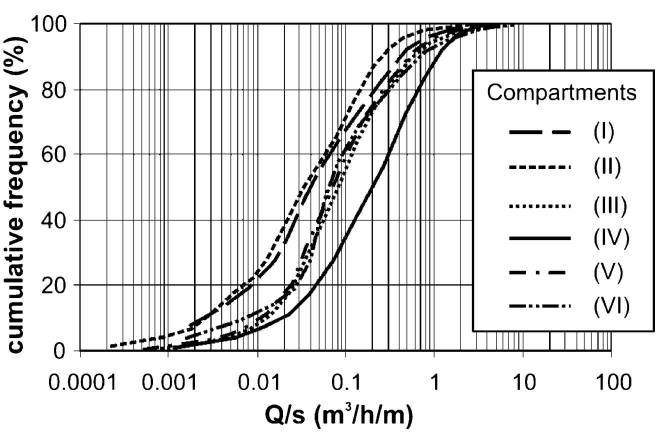


Fig. 12 Cumulative frequency of specific capacity (*Q/s*) from wells located in different morphostructural compartments of the studied area

 DOI 10.1007/s10040-006-0112-6

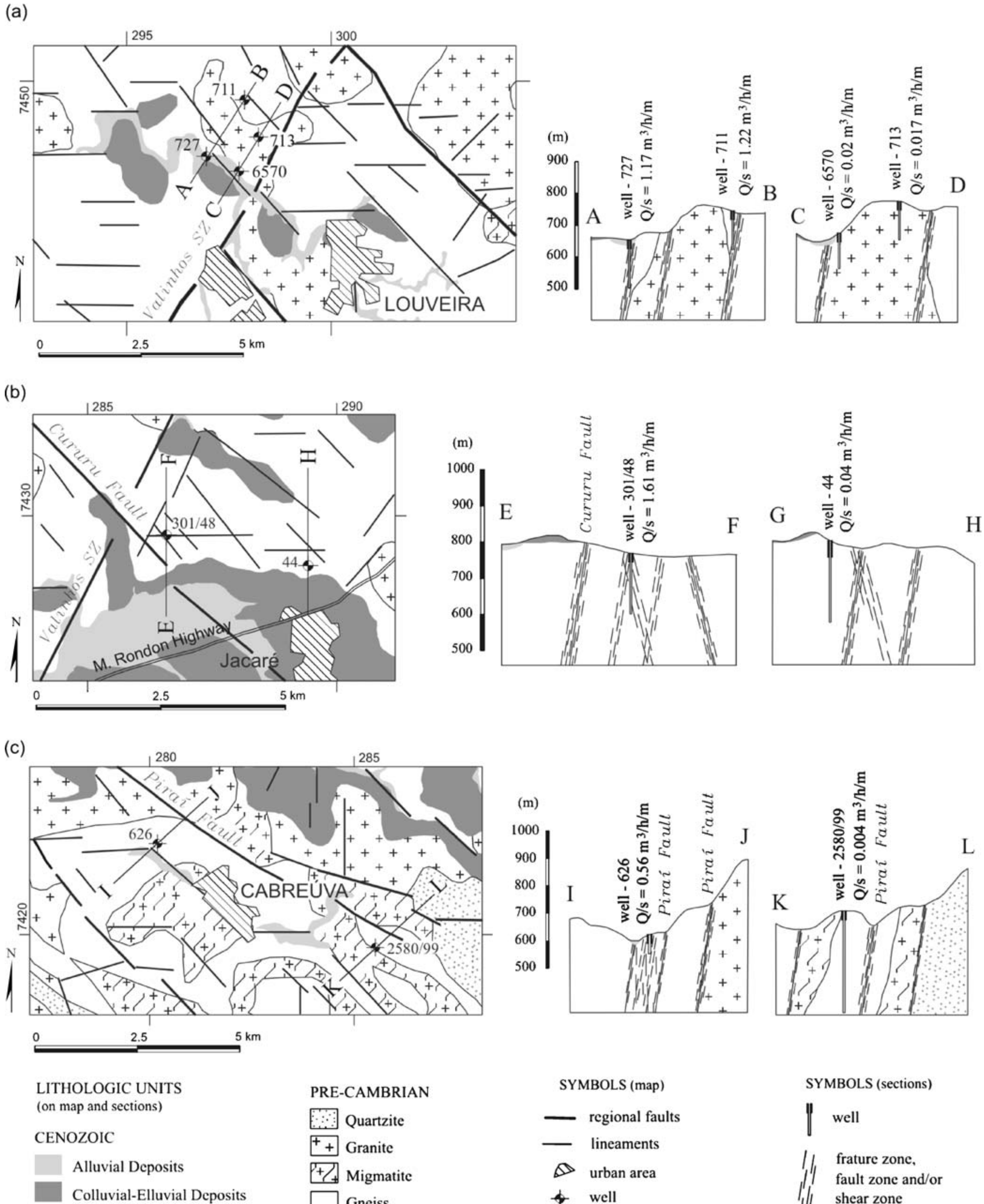


Fig. 13 Structural control over well productivity. The correlation between NW–SE and E–W structures indicates sites subjected to transtensional tectonic stress, usually linked to the formation of alluvial deposits that follow the main structural directions

 DOI 10.1007/s10040-006-0112-6

or density of lineaments, or to the number of lineament intersections. However, the subjective character of lineaments has been questioned by several authors (e.g., Wise 1982; Tam et al. 2004). Generally, the characteristics of the structural features that compound the lineaments such as its typology, dipping angle and genesis, are disregarded when using this method. Besides, the lack of correlation with other data discounts the influence of some factors that are able to affect well productivity.

In Jundiaí River Catchment, the sedimentary covers and the weathered layer might mask underlying basement structures and, consequently, the different lineament densities observed through remote sensing imagery may not reflect the degree of fracturing in the rocky bed. Therefore, this method could not be applied in the present work. An integrated study using structural data collected in the field, information from maps, and data from deep tubular wells is essential. Obviously, it is necessary to carry out a previous study of the lineaments obtained from radar imagery and aerial photographs in order to direct more detailed studies.

Using this procedure, Neves (2005) verified that regional geological structures which delimit the morphostructural compartments in the Jundiaí River Catchment (Fig. 2) constitute zones comprising high well yields. However, the single fact of being located close to these zones does not indicate that a well built there should be highly productive. It is necessary to locate the wells at a favorable position in relation to the structural dipping, with a depth that can reach the geological structure in the subsurface; and, furthermore, the direction of the structure should be favorable to opening via tectonical stresses.

The formation of open discontinuities and/or the opening of ancient discontinuities occurs according to the orientation of the highest horizontal tectonic stress. Since apertures have been considered as a major issue regarding the obtaining of high well yields in fractured rocks (Lachassagne et al. 2001; Banks et al. 1996; Banks and Robins 2002), the effects of extensional tectonics and transcurrent tectonics (Fig. 4) are very important to the groundwater flow in the studied area.

The tectonic events that acted in the region gave rise to structural arrangements in which the NW–SE and E–W joint systems, both with a high dip angle, are correlated (Fig. 4). In these sites, the structures are potentially open and the presence of alluvial deposits is quite common, following NW–SE, E–W and, subordinately, NE–SW directions. Wells located in these areas have presented a median specific capacity higher than the whole estimated median values of wells in the Crystalline Aquifer System. However, close to the more productive wells, there are also low-yield wells, generally misallocated in relation to the geological structures. This fact was observed at different sites such as demonstrated in the three examples from the Fig. 13.

Besides the structures formed or reactivated by the effects of the neotectonic regime, older structures might also have remained open throughout geological history, particularly in an intraplate environment where the tectonic stresses are less intense than within the plate's boundaries. Fault zones with a NE–SW direction, derived from the extensional regime that was at work during the separation of South America and Africa (Fig. 4), are likely to represent favorable structures to groundwater flow, as long as the weathering has not transformed the fragmented material into clay, which would cause the sealing of discontinuities.

The relevance of these structures on groundwater flow, even at relatively great depths, is supported by the presence of thermal sources along the Valinhos Shear Zone, as reported by Hasui et al. (1989). The association between high well yields and regional structures similar to those present in the Jundiaí River Catchment was also identified by Fernandes and Rudolph (2001) in the Campinas region, adjacent to the north limit of the studied area.

Finally, it is necessary to emphasize that the tectonic fractures should be found and mapped as precisely as possible in order to locate a productive well. The study of the geological evolution could allow for the defining of those sites that are potentially the most productive. Thereafter, the use of more expansive methods such as

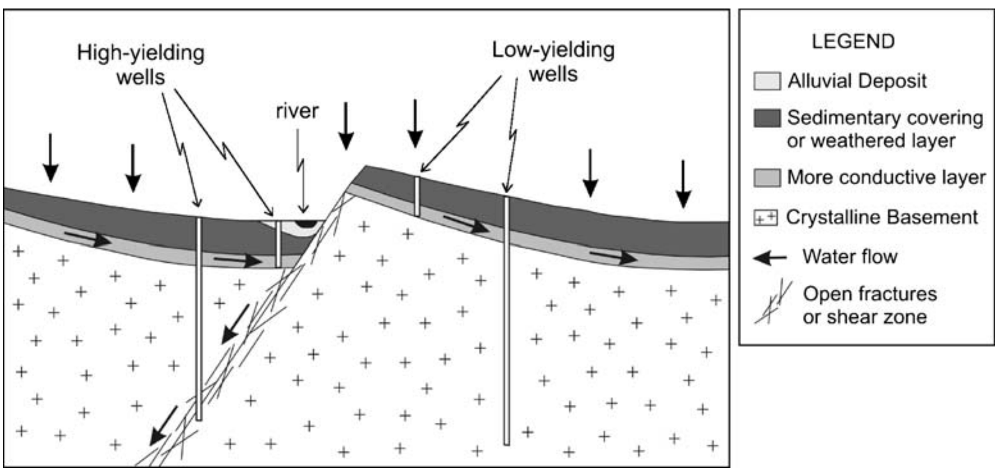


Fig. 14 Scheme of groundwater flow along the interface between sedimentary covers (or weathered layer) and fractured rock, and along open discontinuities originating in a fracture or shear zone (no scale)

 DOI 10.1007/s10040-006-0112-6

geophysical land measurements could permit the defining of the tectonic lines in a posterior detailed survey.

Discussion and conclusions

This paper shows that several factors can control well productivity in the Crystalline Aquifer System of Jundiaí River Catchment. When coupled, such factors can allow the obtainment of high well yields. It was not possible to define a best-yielding depth interval, since well depth is mainly defined by the driller's and user's needs. Although productivity tends to diminish with depth, a deeper well can be more productive if it reaches, in subsurface, a geological structure that is favorable to groundwater flow.

Minor influences related to the lithotype were identified, except for the geological unit whose rocks have carbonated minerals. Wells exploiting schists, gneisses, and granites presented similar conditions regarding the groundwater supply. It is important to point out that, despite the original foliation not being a determining factor for well productivity, the subvertical mylonitic foliation along shear zones might play an indirect role in groundwater flow, especially if it were reactivated by the later brittle deformation.

The alluvial deposits, mainly composed of permeable material such as sand and gravels, may constitute important recharge or discharge zones, depending on their topographic position. Besides the good permeability of the materials, the presence of high well yields in sites with alluvial covers is related to the fact that these sediments are often deposited in sites where NW–SE and E–W discontinuities are in correlation to each other, characterizing transtensional zones linked to neotectonic activity.

The thickness of the sedimentary and the weathered layer shows no direct influence on well productivity, but these layers are able to produce enough water to be used at a small scale. The flow at the bottom of covers and weathered layers is favored by the lithological contrast among different layers, and between them and the unaltered crystalline rock.

The low correlation between well productivity and thickness of covers and/or weathered layers indicates that, although they play an important role in the aquifer recharge, there is no direct correlation between them. Besides good recharge possibilities, it is necessary to present proper percolation conditions in the unaltered rock such as a net of interconnected and relatively open discontinuities. If these sites occur in places that favor groundwater recharge, good well productivity will remain.

The morphostructural compartments showed some influence on well productivity related to the presence or absence of pediments and/or sedimentary covers that increase the chances for recharge. The boundaries between compartments constitute favorable percolation zones, since they have a concentration of structures tectonically reactivated during geological evolution.

The fundamental structures for the obtaining of high well yields from crystalline rocks are the faults and joints that were originally open or those submitted to extensional stress during tectonic reactivations. The most important tectonic events that occurred in the area and were able to produce open structures included the extensional event related to the separation of South America and Africa—from the end of Mesozoic to Paleogene (NE–SW structures)—and the transtensional event related to neotectonics (NW–SE and E–W structures).

The percolation model presented at Fig. 14 summarizes the general picture of the conditions controlling well productivity in this scenario. The layers highlighted in grey might represent sedimentary covers or the weathered layer from the subjacent crystalline rock. The discontinuities of fractured rock are those found in the conditions described above.

Acknowledgements The authors thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq: National Council of Scientific and Technologic Development) for the financial support to carry out the PhD Thesis which was the basis of the present work. Thanks are also given to the Jundsondas Poços Artesianos for providing data about deep tubular wells, and to the reviewers and editors of the *Hydrogeology Journal*, whose suggestions were fundamental in improving the quality of this paper.

References

Banks D (1992) Optimal orientation of water-supply boreholes in fractured aquifers. Ground Water 30:895–900

Banks D, Robins N (2002) An introduction to groundwater in crystalline bedrock. Geological Survey of Norway, Trondheim

Banks D, Solbjorg ML, Rohr-Torp E (1992) Permeability of fracture zones in a Precambrian granite. Q J Eng Geol 25:377–388

Banks D, Odling NE, Skarphagen H, Rohr-Torp E (1996) Permeability and stress in crystalline rocks. Terra Nova 8:223–235

Bertachini AC (1987) Study of the hydrogeologic characteristics of crystalline terrain under humid climate in Jundiaí Region, São Paulo State (in Portuguese). PhD Thesis, Universidade de São Paulo, Brazil

Chilton PJ, Foster SSD (1995) Hydrological characterization and water-supply potential of basement aquifers in tropical Africa. Hydrogeol J 3:36–49

Chilton PJ, Smith-Carington AK (1984) Characteristics of the weathered basement aquifer in Malawi in relation to rural water supplies. IAHS Publ 144:57–72

Davis SN, Turk LJ (1964) Optimum depth of wells in crystalline rocks. Ground Water 22:6–11

Fernandes AJ, Rudolph DL (2001) The influence of Cenozoic tectonics on the groundwater production capacity of fractured zones: a case study in São Paulo, Brazil. Hydrogeol J 9:151–167

Gustafsson G, Krasny J (1994) Crystalline rock aquifers: their occurrence, use and importance. Appl Hydrogeol 2:64–75

Hasui Y (1990) Neotectonics and fundamental aspects of resurgent tectonics in Brazil (in Portuguese). In: Sociedade Brasileira de Geologia (ed) Proc of the Neotectonics and Cenozoic Continental Sedimentation in Southeastern Brazil Workshop, São Paulo, September 1990, pp 1–31

Hasui Y, Dantas ASL, Carneiro CDR, Bistrichi CA (1981) The Pre-Cambrian Basement and the Eopaleozoic in São Paulo (in Portuguese). In: Almeida FFM et al. (ed) Geologic Map of São Paulo State-1:500.000. Inst Pesquisas Tecnol Publ 1184 (1):12–45

Hasui Y, Haralyi NLE, Mioto JA et al (1989) Structural compartments and tectonic evolution of São Paulo State (in Portuguese). Inst Pesquisas Tecnol Publ 27.394

 DOI 10.1007/s10040-006-0112-6

Henriksen H (1995) Relation between topography and well yield in boreholes in crystalline rocks, Sogn og Fjordane, Norway. Ground Water 33:635–643
Henriksen H (2003) The role of some regional factors in the assessment of well yields from hard-rock aquifers of Fennoscandia. Hydrogeol J 11:628–645
Juliani C, Beljavskis P (1995) Lithoestratigraphic revision of the São Roque/Serra do Itaberaba belts (São Paulo State). Rev Inst Geol 16:33–58
Knopman DS, Hollyday EF (1996) Variation in specific capacity in fractured rocks. Ground Water 31:135–145
Lachassagne P, Wyns R, Berard P et al (2001) Exploitation of high yields in hard-rock aquifers: downscaling methodology combining GIS and multicriteria analysis to delineate field prospecting zones. Ground Water 39:568–581
LeGrand HE (1967) Groundwater of the Piedmont and Blue Ridge provinces in the southeastern states. US Geol Surv Circ 538:1–11
Lopes MFC (1994) Occurrence conditions of groundwater in the Piracicaba and Capivari River Catchments (in Portuguese). PhD Thesis, UNICAMP, Campinas, Brazil
Mabee SB (1999) Factors influencing well productivity in glaciated metamorphic rocks. Ground Water 37:88–97
McFarlane MJ, Chilton PJ, Lewis MA (1992) Geomorphological controls on borehole yields: a statistical study in an area of basement rocks in central Malawi. Geol Soc Spec Publ 66: 131–154
Morin RH, Savage WZ (2002) Topographic stress perturbations in southern Davis Mountains, west Texas: 2. Hydrogeologic implications. J Geophys Res 107:1–10
Morin RH, Savage WZ (2003) Effects of crustal stresses on fluid transport in fractured rock: case studies from northeastern and southwestern USA. Hydrogeol J 11:100–112
Naik PK, Awasthi AK, Mohan PC (2002) Springs in a headwater basin in the Deccan Trap country of the Western Ghats, India. Hydrogeol J 10:553–565
Neves MA (1999) Cenozoic evolution of the Jundiaí Region, São Paulo State, Southeastern Brazil (in Portuguese). PhD Thesis, Universidade Estadual Paulista, Rio Claro, Brazil
Neves MA (2005) Integrated analysis applied to groundwater exploration in the Jundiaí River Catchments, São Paulo State, Southeastern Brazil (in Portuguese). PhD Thesis, Universidade Estadual Paulista, Rio Claro, Brazil
Neves MA, Morales N, Borges MS, Ebert HD (2003) Morphotectonic compartments of Jundiaí Region, São Paulo State, southeastern Brazil (in Portuguese). Rev Bras Geociênc 33:167–176
Neves MA, Morales N, Saad AR (2005a) Facies analysis of Tertiary alluvial fan deposits in the Jundiaí region, São Paulo, southeastern Brazil. J South Am Earth Sci 19:509–520
Neves MA, Morales N, Saad AR (2005b) Cenozoic sedimentary coverings in the Jundiaí River Catchment, São Paulo State, southeastern Brazil (in Portuguese). Geociências 24:289–303
Nilsen B (1998) Norwegian sub-sea tunnels: a review with emphasis on water leakages. In: Serrano JM (ed) Proc international congress on tunnels and water. IAHS, Rotterdam, pp 913–918
Parizek RR, Siddiqui SH (1969) Determining the sustained yields of wells in carbonate and fractured aquifers. National Water Well Association Convention, San Francisco
Riccomini C (1995) Genetic and deformational tectonics of post-Gondwana sedimentary deposits in the middle-eastern part of São Paulo State and neighboring regions (in Portuguese). PhD Thesis, Universidade de São Paulo, Brazil
Saadi A (1993) Neotectonics in the Brazilian platform: outline and preliminary interpretation (in Portuguese). Geonomos 1(1):1–15
São Paulo (State) (2000) Water resources of Piracicaba, Capivari and Jundiaí River Catchments report: zero report (in Portuguese). Conselho Estadual de Recursos Hídricos, Piracicaba, 1CD
Setzer J (1966) Ecological and Climatic Atlas of São Paulo State (in Portuguese). Comissão Interestadual da Bacia Paraná-Uruguai, São Paulo
Singhal BBS, Gupta RP (1999) Applied hydrogeology of fractured rocks. Kluwer, Delft, The Netherlands
Stevaux JC, Souza Filho EE, Teixeira JA, Landim PMB (1987) Depositional systems of Itararé Sub-Group in the Capivari River Catchment, São Paulo State: a model for groundwater prospecting (in Portuguese). In: Proc Regional Geol Symp, vol 1, Sociedade Brasileira de Geologia, São Paulo, pp 355–374
Tam VT, De Smedt F, Batelaan O, Dassargues A (2004) Study on the relationship between lineaments and boreholes specific capacity in a fractured and karstified limestone area in Vietnam. Hydrogeol J 12:662–673
Tirén SA, Askling P, Wanstedt S (1999) Geologic site characterization for deep nuclear waste disposal in fractured rock based on 3D data visualization. Eng Geol 52:319–346
Vidal AC (2002) Hydrogeological study of the Tubarão Aquifer in Central Part of São Paulo State (in Portuguese). PhD Thesis, Universidade Estadual Paulista, Rio Claro, Brazil
Wise DU (1982) Linesmanship and the practice of linear geo-art. Geol Soc Am Bull 93:886–888
Yin Z-Y, Brook GA (1992) The topographic approach to locating high-yield wells in crystalline rocks: Does it work? Ground Water 30:96–102

 DOI 10.1007/s10040-006-0112-6