HYDROGEOLOGICAL STUDY OF THE RIVER CONNECTED AQUIFERS IN GREATER SAO PAULO

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ABSTRACT

A cooperative research project between our two institutions began in May of 1989. Some of its objectives are: (i) the characterization of the contaminant source(s), stratigraphy, transport phenomena and geochemical processes in effect at three or more sites, representing different geological environments, along the Rio Tiete and Rio Pinheiros on their course through greater Sao Paulo; (ii) determination of the usefulness of drive-point piezometer installation technology for installing piezometers at these sites; (iii) using all available geochemical techniques (organic, inorganic, and isotopic), to understand the nature of contamination and the transport processes within the river connected aquifers; (iv) to recommend how the experience gained in Sao Paulo might be applied to the broader problems of highly urbanized, humid tropical environments in general.

During the first year of field work sites have been selected and geophysically surveyed, and the drive-point technology has been extensively tested. The results will be presented.

KEYWORDS

Groundwater; aquifer; river-connected aquifer; contamination; drive-point piezometers; coring; geophysics; electromagnetic induction.

INTRODUCTION

The city of Sao Paulo, Brazil is the largest city in South America with approximately 15 million inhabitants. Sao Paulo is considered to be the industrial centre of Brazil by virtue of its large and diversified industrial sector. Industries worldwide generally locate near rivers which serve both as a source of water and as a means of waste disposal. This is also the case in Sao Paulo where many industries are situated along the Tiete and Pinheiros Rivers which run through the city.

These rivers have been extremely contaminated by industrial and domestic liquid wastes. In some sections of the city, groundwater is extracted from shallow aquifers to provide municipal drinking water and industrial process water. Water wells located near the rivers may be inducing downward vertical flow gradients under the rivers resulting in the potential downward migration of contaminants. These contaminants may reach the production well, seriously threatening the quality of the groundwater supply.

A collaborative research project was undertaken by personnel from the University of Sao Paulo and the University of Waterloo to investigate the hydrogeological conditions along the Tiete and Pinheiros Rivers. The main objectives of the research project were to determine the stratigraphy of the shallow sediments adjacent to the rivers, to monitor the distribution of groundwater contamination in the sediments and to measure the hydraulic gradients in the shallow subsurface near the rivers.

The hydrogeological field work involved both the installation of piezometer nests and the collection of continuous cores at several sites along the river. For the most part, techniques used to install the piezometers and obtain the core samples employed hand-operated equipment. These techniques were recently developed at the University of Waterloo and are described in Starr and Ingleton (1990). A small drill rig was also used to install deeper multilevel piezometers at one of the sites.

Portable electromagnetic geophysical instruments were used to conduct both surface and borehole geophysical surveys. The techniques used included the electromagnetic induction instruments EM-31, EM-34, and the borehole EM-39 all developed by Geonics Inc. Standard surface resistivity techniques were also employed. The geophysical surveys were conducted in an attempt to characterize the stratigraphy near the rivers and to observe geophysical anomalies that may be associated with groundwater contamination, similar to the observations made Greenhouse et al. (1988).

Field investigations were carried out at three principle study sites along the Tiete and Pinheiros Rivers. In this paper we will discuss the physical characteristics of each site, outline the investigation methodology and present results and conclusions based on the analysis of the field data collected to date. This project is on-going and the results presented here should be considered preliminary. Additional data analysis on the geochemistry and the isotopic content of the groundwater is currently underway.

SITE SELECTION

Considering the enormity of the Sao Paulo area, it was necessary to focus the field investigations on a series of sites that would be representative of the general conditions along various sections of the river system. To this end, three independent sites were chosen each characterized by distinctly different hydrogeological conditions.

The study sites were selected primarily to represent different geological environments along the two rivers. Secondly, the attempt was made to locate sites where downward vertical flow gradients might already exist near the rivers. This choice was based on the proximity of production wells to the candidate study area and the potentiometric map of the Sao Paulo area constructed by Rocha et al. (1989). In addition, the site selection criteria included consideration of accessibilites and the long-term security of the instrumentation. It was also necessary to choose sites that were in areas of low electromagnetic interference to facilitate the collection of geophysical data.

Each of the three study sites chosen will be discussed below. Their general location with respect to the Sao Paulo area is indicated in Figure 1.

METHODOLOGY

To measure the hydraulic gradients in the sediments near the rivers, nests of piezometers were installed with piezometer tips placed at different depths in the shallow sediments. Hydraulic head measurements were made in the piezometers and in some cases water samples were collected for future geochemical and isotopic

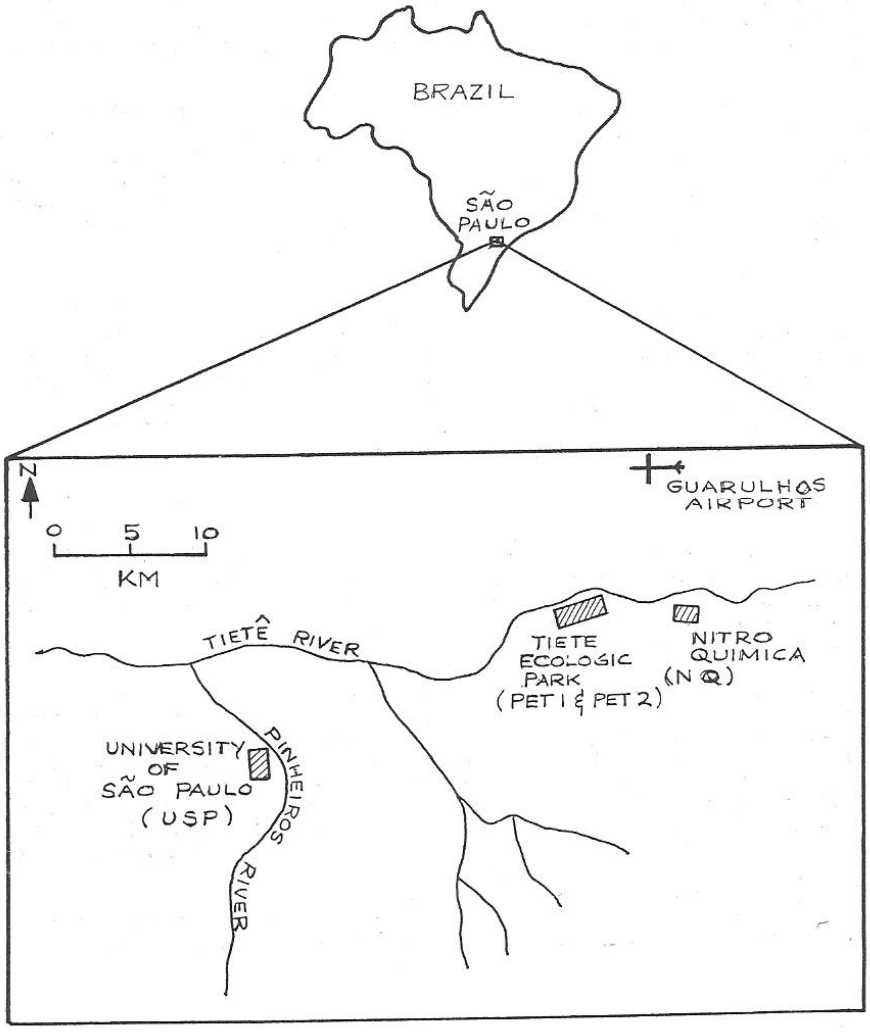

Fig. 1. Location map of the study sites

analysis. The hydraulic head data was used to determine whether recharging or discharging conditions prevailed at each site.

Continuous 2 inch diameter core samples were collected at each site with a hand-operated drive-point piston sampler. These core samples permitted the detailed examination of the stratigraphic sequence. Samples from the cores were also collected for pore water extraction to be completed at a later date.

Surface geophysical surveys were conducted using the electromagnetic induction instruments EM-31 and EM-34. These surveys permitted the measurement of the subsurface electrical conductivity. The spatial variability of electrical conductivity is assumed to be a measure of the inhomogeneity of the sediment sequence. Variation in electrical conductivity in the subsurface may also arise as the pore water chemistry changes. For example, as the concentration of dissolved ions increases the electrical conductivity of the pore water and subsequently the subsurface materials may increase. In this way the electromagnetic induction techniques can be used to map high conductivity pore water which may be indicative of groundwater contamination.

Borehole geophysical surveys were conducted at one of the sites to determine the subsurface stratigraphy and to observe possible groundwater contamination near the river. An EM-39 logging unit was used to conduct the borehole geophysics. Boreholes were logged with an electrical conductivity probe and a natural gamma probe. The electricity conductivity probe is similar in principle to the surface electrical induction instruments. The probe measures the vertical variability of electrical conductivity surrounding a 5 centimetre or larger diameter plastic cased borehole. The natural gamma probe measures the natural gamma emissions, generally from potassium decay, which is a function of the clay content (Telford et al., 1976).

SITE 1: NITRO QUIMICA (NQ)

The Nitro Quimica site (NQ) is located along the Tiete River in the Municipality of Guarulhos and borders on the region of Sao Miguel Paulista (Figure 1). The area is located on the meander belt of the Tiete River where the river along this section has been artificially straightened (Figure 2A). Historically, these meander belts have been a source of industrial minerals, usually sand, for building purposes. After the sand has been removed the excavated area is generally backfilled with domestic and industrial waste. Visible mounds of garbage which contain a large portion of industrial waste are evident in the study area.

This study site was selected because the area is proposed to be developed into a recreational park and to date no detailed examination of the area has been conducted to observe the degree of soil and groundwater contamination. The sediments are fluvial in origin and believed to be of Quaternary age. Figure 2B illustrates the shallow subsurface geology near the Tiete River based on coring observations.

The contaminated level of the river is thought to be low owing to the fact that only a few industries and urban centres which could be discharging contaminated effluent into the river are located upstream. The hydrogeologic flow regime of NQ is not believed to be influenced by pumping.

Geophysical surveys were conducted over a two week period. The location of these surveys is illustrated on Figure 2A. Electromagnetic induction surveys and standard resistivity soundings employing the Schlumberger electrode array were conducted. The main purpose of the geophysical surveys was to determine the lateral variability of the subsurface stratigraphy. The results indicate that subsurface materials are laterally and vertically inhomogeneous. Electrical conductivities varied by approximately 60 mS/m suggesting that the stratigraphy

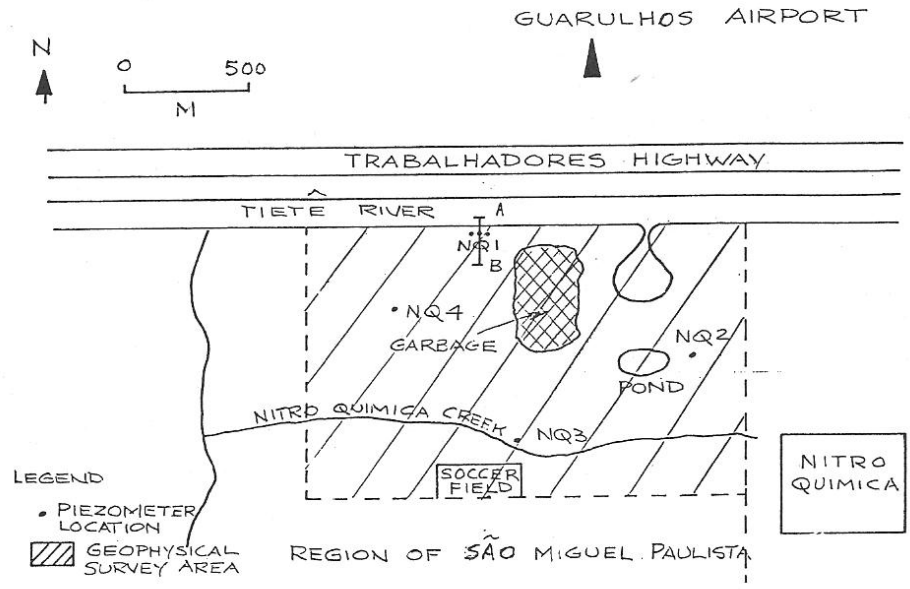

Fig. 2A. Plan view of Nitro Quimica (NQ)

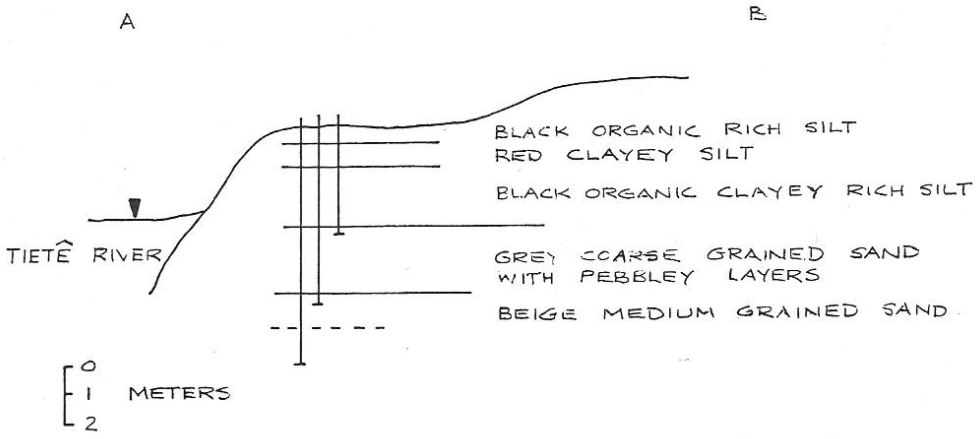

Fig. 2B. Cross-section of NQ illustrating the piezometer depths and stratigraphy

of the area is complex which would be anticipated with a fluvial deposit.

Electromagnetic techniques can identify, in certain circumstances, areas where the groundwater is contaminated. However, at NQ the lateral variability of the subsurface materials masks any change in the groundwater quality that might exist.

SITE 2: PARQUE ECOLOGICAL DO TIETE

Parque Ecological Do Tiete (PET) is located approximately 10 kilometres west of NQ (Figure 1). This area, like site 1 described earlier, is located on a meander belt of the Tiete River (Figure 3A). The sediments within the park are of fluvial origin and believed to be of Quaternary age. Coring was conducted at this site near the river and the coring observations are illustrated on the cross-section in Figure 3B.

The park itself has been extensively modified by the straightening of the river's course and by the dumping of fill material to provide a wildlife reserve and a recreational area. An old municipal landfill is located within the park boundaries.

Two separate areas were selected to be studied within PET. The locations of the areas known as Parque Ecological Do Tiete 1 (PET1) and Parque Ecological Do Tiete 2 (PET2) are illustrated on Figure 3A. PET1 is located at the eastern edge of PET far from any industries which may be influencing the hydrogeological flow regime by the pumping of production wells. Conversely, PET2 is thought to be influenced by production wells based on a piezometer map by Rocha et al. (1989). Neither of these sites is located on natural subsurface material. The subsurface material at PET1 is sand and gravel deposited during dredging operations of the Tiete River in the early 1980's. PET2 is located on fill material which was deposited to reclaim land from the river. Each of these sites is suitable for geophysical surveys. Along this portion of the Tiete River's course has been artificially straightened and the contamination level is believed to be higher than at site 1.

The two sites within PET were geophysically surveyed with the electromagnetic induction tools EM-31 and EM-34 as well as standard surface resistivity soundings using the Schlumberger electrode array.

Each of the two sites was instrumented with piezometers to collect water samples and to observe hydraulic heads. A nest of five piezometers at PET1 was installed approximately 30 metres from the edge of the Tiete River to depths of 10.1, 8.5, 5.8, 4.5, and 3.5 metres below ground level. At PET2 three piezometers were installed 15 metres from the river to depths of 6.0, 4.5, and 3.5 metres below ground level. The elevation of the river was approximately 3 metres below the elevation of the ground at each of the sites at PET.

The results of the geophysical surveys at PET are similar to those at NQ. The background electrical conductivities across PET1 and PET2 are variable, indicating that the stratigraphy is laterally inhomogeneous. As a result, the weak anomalies due to groundwater contamination could not be detected.

This was the first site where the drive-point piezometer installation technology was attempted. The problems encountered with the drive-point technology were the same at each of the sites and will only be discussed in this section. Through the installation of piezometers at PET the limitations of the technology became obvious. For example, at PET2 piezometers could not be installed deeper than 6.0 metres below ground level due to an extremely compacted green clay layer. Additionally, care had to be exercised when driving the piezometer tips through fine grained materials which had a tendency to clog the piezometer tip and render it inoperable. This problem of the piezometer tip being clogged was solves by hand auguring a hole through the fine grained material at surface to a depth where

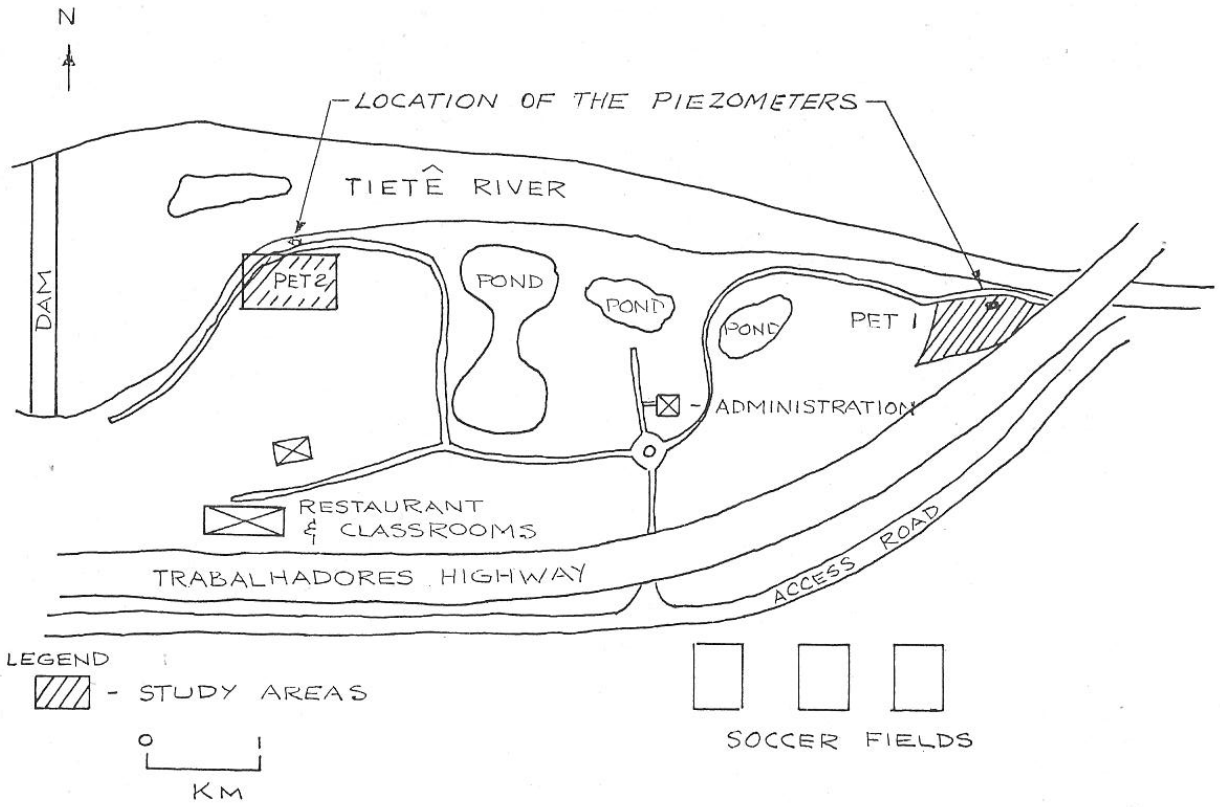

Fig. 3A Plan view map of Parque Ecological Do Tiete (PET) showing sites 1 and 2

coarser materials were encountered. An alternative would be to design a better piezometer tip that would be more resistant to clogging by fine grained materials.

At both PET1 and PET2 hydraulic head measurements from the drive-point piezometers indicate that a groundwater discharge zone exists near the river. Figures 3B and 3C illustrate the static water levels in each of the piezometers; where water levels are absent the piezometer had not reached equilibrium.

This discharge zone is currently containing the contaminated river water. However, these conditions may change in the future if more production wells are located nearby.

Analysis of the geochemistry and isotopic data of the groundwater and river water is currently underway.

SITE 3: UNIVERSITY OF SAO PAULO

The third study area is located on the campus of the University of Sao Paulo (Figure 1). The geology beneath the university is typified by weathered Precambrian bedrock in the southern portion and sediments of Tertiary age in the northern area of the campus (Iritani, M., personal communication). The study area is located on Tertiary sediment near the Pinheiros River (Figure 4A). Figure 4B illustrates the geology at this site based on drillers logs. The highly contaminated Pinheiros River flows on permeable sands and gravels and therefore could pose a problem if river water was infiltrating into the shallow aquifer system. As with the other two sites, the course of the Pinheiros River through the area has been artificially straightened.

Recently, three production wells have been installed near the Pinheiros River by the University of Sao Paulo to provide water for the university sporting complex and hospital. One of these production wells was chosen to conduct a pumping test to observe the aquifer response to pumping. To monitor the pumping of the aquifer a series of observation wells was installed; their locations and screen depths are shown in Figure 4B. The analysis of the pumping test data is currently underway.

Borehole geophysical surveys were conducted at the USP site to observe the stratigraphy. Measurements were made in six existing 7.5 centimetre diameter, plastic-cased piezometers which were installed by the Centro De Pesquisas De Agua Subterraneas (CEPAS) to classify the hydrogeology of the USP campus. The piezometers, which are approximately 30 metres in depth, were surveyed with the EM-39 using an electrical conductivity probe and a natural gamma probe.

Logging results indicate that 20 to 25 metres of predominately sand materials overly a 1 to 3 metre thick, clay-rich unit. This clay rich unit was not identified from drilling. The thick water bearing sand and gravel zones appear to be almost clay free.

Hydraulic head measurements in the multilevel observation wells indicate that the hydraulic gradients are downward to a depth of approximately 25 metres and below 25 metres to 40 metres depth the gradients are upward. This implies that the highly contaminated Pinheiros River is probably infiltrating into the subsurface seriously effecting the quality of the groundwater.

Isotopic and geochemical analysis of the groundwater and river water is currently being undertaken.

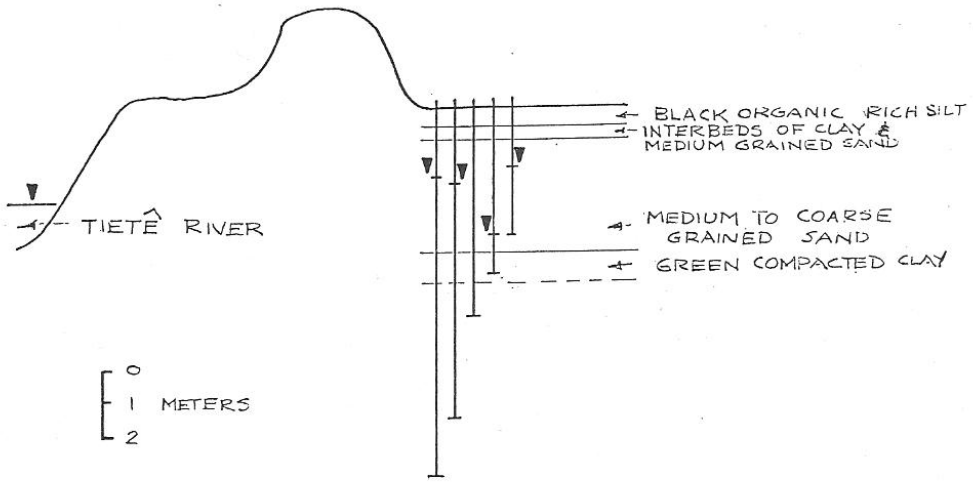

Fig. 3B Cross-section of PET1 illustrating piezometer depths and stratigraphy

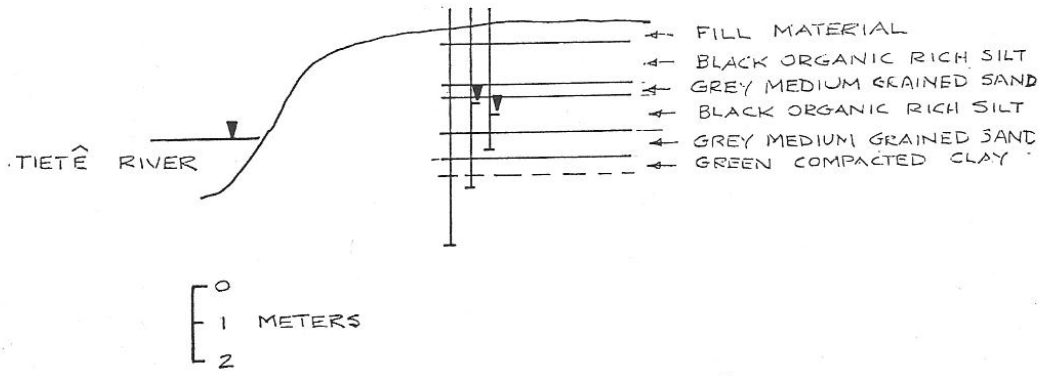

Fig. 3C Cross-section of PET2 illustrating piezometer depths and stratigraphy

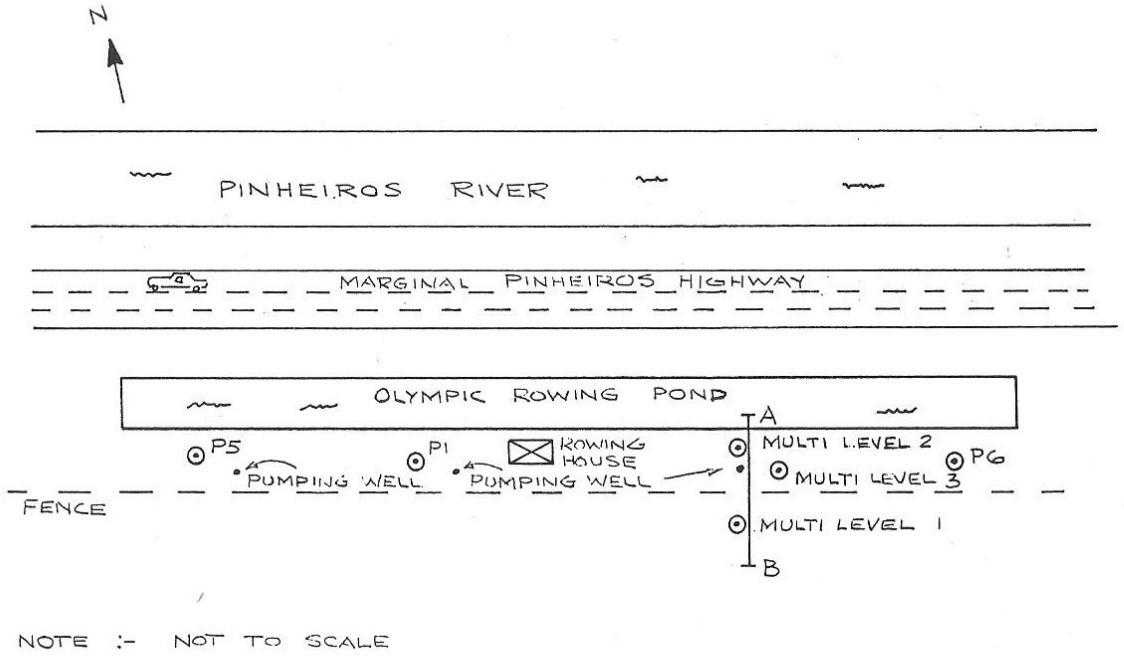

Fig. 4A Plan view of map of the University of Sao Paulo (USP) site

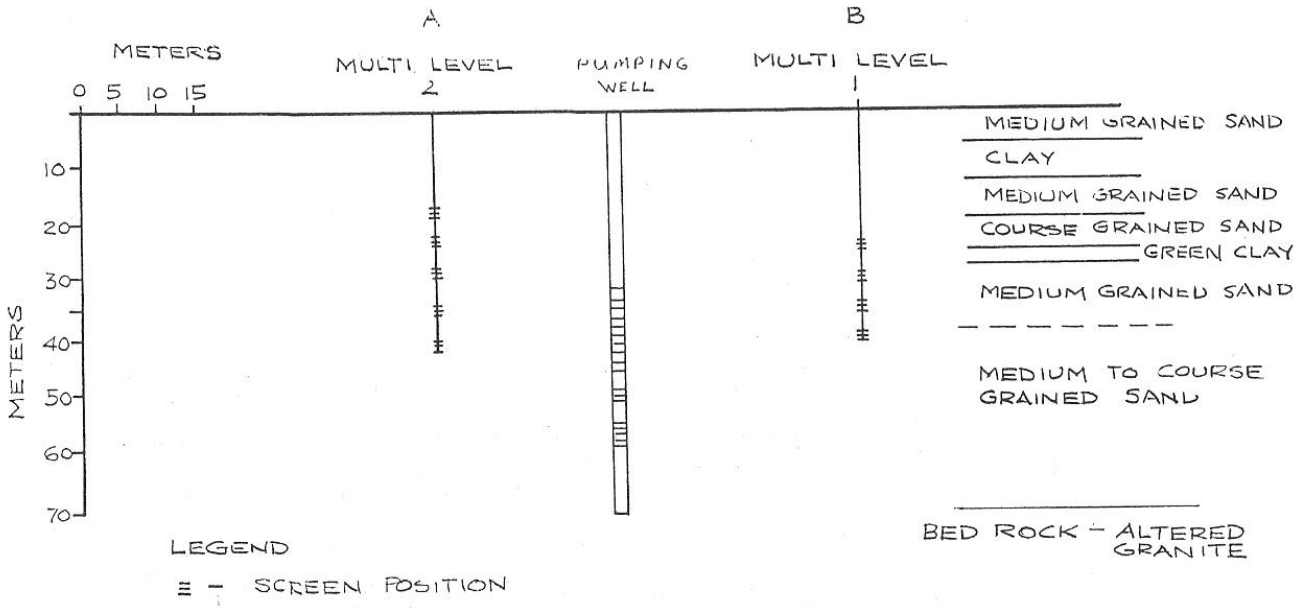

Fig. 4B Cross-section of the USP site

CONCLUSIONS

Discharging conditions prevailed at PET beside the river during the period when the studies were conducted. A discharging zone at the rivers will effectively contain the contaminated river water from infiltrating into the shallow aquifer system. However, a recharge zone exists in the shallow subsurface at the USP site. The implications of recharging conditions near the highly contaminated Pinheiros River are serious. The infiltrating river water could seriously affect the quality of groundwater of the newly installed production wells which are to supply some of the campus.

Drive-point installation technology was effectively used to install piezometers at all sites. However, this technology had its limitations in the subsurface environment near the rivers. Piezometers could not be installed through very resistant materials and the piezometer tip could not be driven through clayey material where the tip would become clogged and rendered inoperable.

The stratigraphy of the subsurface near the rivers was successfully characterized through hand coring and by geophysics.

ACKNOWLEDGEMENTS

This project was funded by the International Development Research Centre, project #3-P-85-1033. Many individuals have provided help and support. We particularly acknowledge the assistance of M. Iritani, S. Hassuda, V. Liete, B. Tito and A. Da Silva, and also M. Rodrigus at Cia Tecnologia de Saneamento provided support and laboratory facilities.

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