The Noordbergum Effect and Characterization of Aquitards at the Rio Maior Mining Project

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ABSTRACT

The planned exploitation of the Rio Maior lignite deposits will require a major dewatering program involving a thick leaky sand aquifer, and a heterogeneous and anisotropic aquitard complex. Diatomite, lignite, and clay are the main lithologies found in this aquitard complex. Characterization of the sand aquifer was accomplished by performing pumping tests with interpretations for steady-state and nonsteady-state conditions. Aquitards were characterized by using both laboratory and field tests to determine hydraulic conductivity. Field methods were either those commonly adapted to leaky aquifers using water-level data taken from observation wells tapping the underlying sand aquifer or those using water-level data taken from piezometers located at the same distance from the pumping well and screened in the aquitard and in the aquifer. Field values of hydraulic conductivity are greater than laboratory values. In several piezometers the Noordbergum effect was observed during pumping tests. Redistribution of the loads originated by the pumping in the underlying sand aquifer is considered to be responsible for the reverse water-level response in the overlying lignite-diatomite complex. The Noordbergum effect has some influence in the application of the ratio method. On a practical basis, it seems reasonable to use the Noordbergum effect to compute drawdowns in the aquitards, and this leads to somewhat higher values for vertical hydraulic conductivities.

INTRODUCTION

The Rio Maior basin is located near the village of the same name approximately 80 km north of Lisbon on the border of the Portuguese Tagus Cenozoic basin. The Rio Maior basin has two major points of economic interest: the occurrence of large amounts of very pure siliceous sand used by the glass and ceramic industries and the occurrence of approximately 35 million tons of lignite coal.

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The Rio Maior basin is a small graben-like depression of Pliocene and Quaternary age. It is roughly rectangular in shape and runs northwest to southeast. The depression contains sands which are overlaid in the most depressed region by a very heterogeneous sequence of lignites, clays and sands.

The lignite deposits are planned to be mined to a depth of 120 m. In order to mine the coal at this depth, it will be necessary to depressurize the artesian water levels in the underlying sand aquifer which stand some 70 m above the future mine floor and to dewater the pores in the lignite-diatomite complex itself.

Dewatering the lignite diatomite complex and depressurizing the sand aquifer are two important considerations in the design of the open-cast mine and have decisive implications with respect to the economic feasibility of the project. Previous hydrologic studies carried out in the Rio Maior area were aimed at the determination of hydrologic parameters for the design of the dewatering system, and were presented in an unpublished internal report (LNEC, 1980).

Pumping tests were performed both in the sand aquifer and in the lignite-diatomite complex. During the tests, water-level measurements were taken simultaneously in the sand aquifer and in the lignite-diatomite complex. The results of hydrologic studies and analysis of potentiometric surface maps were used to develop a regional flow model of the basin and to estimate the amount of recharge from precipitation. The amount of water to be discharged by the dewatering systems also was calculated.

This paper presents results obtained from pumping tests which are not very often available in literature, namely as regards field-checking of the Noordbergum effect, the determination of aquitard characteristics by the ratio method, and its comparison with the characteristics obtained by laboratory and other field methods.

GEOLOGY AND HYDROLOGY OF THE RIO MAIOR BASIN

Figure 1 is a regional geologic map of the study area. Figure 2 shows a cross section along the central part of the Rio Maior basin along line AB in Figure 1.

The basin contains medium to fine-grained, well-sorted, siliceous white sands with a minor amount of kaolinitic clay (about 10 percent). In the deepest part of the basin, the sand thickness reaches about 100 m. The sands are terrestrial in origin and contain some aeolian. They are characterized by remarkable horizontal homogeneity with only minor vertical anisotropy. On a large scale, the sand complex seems to have a homogeneous behavior as suggested by the outcrops of this sand formation in large sand quarries existing in the area.

The basin is about 5 km long and 2.5 km wide and is bordered by normal faults. The Cidral fault in the northeasternmost part of the basin is the most prominent fault. It has over 200 m of vertical displacement. The rock formations beyond the

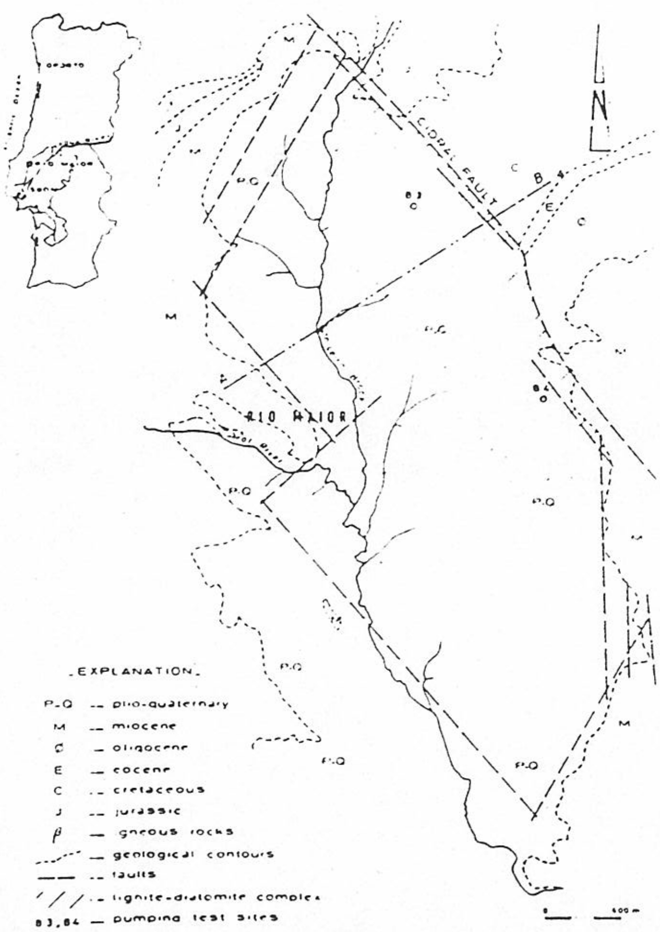

Fig. 1. Geologic map of the Rio Maior lignite basin with location of cross section and test sites.

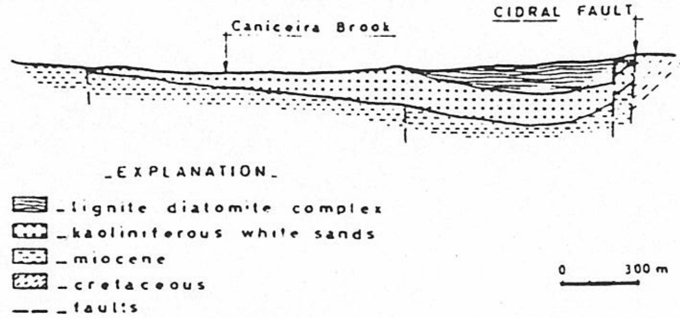

Fig. 2. Simplified geologic cross section of the Rio Maior basin along line AB in Figure 1.

Cidral fault are less permeable than the sand aquifer, but presumably as permeable as the lignite-diatomite complex. So far, no pumping tests have been performed beyond Cidral fault.

A lens-shaped lignite-diatomite deposit about 3 km long and 0.7 km wide occurs in the deepest part of the basin and overlies the sand complex (see Figure 2). It is composed predominantly of lignite and diatomite with large amounts of sand, sandy clays, clays, and some impure lignite and diatomite layers. The deposit has a very pronounced lenticular shape (see Figure 2), and reaches a thickness of about 120 m in its deepest part. The deposit thins to the southwest and terminates abruptly to the northeast against the Cidral fault.

Because of some layers with low permeability, the lignite-diatomite complex is highly anisotropic and serves as an aquitard to the underlying leaky sand aquifer.

The boundaries of the basin are made up of Jurassic to Miocene formations that have a considerable range of lithology. Clayey siltstones and sandstones predominate in the Jurassic and Cretaceous formations, whereas sandstones, limestones, marls and clays predominate in the Miocene formations. Based on previous studies, the boundary formations are considered to have low permeabilities and in their present undisturbed condition, they are recharging the basin mainly on the northwest and northeast boundaries (see Figure 1).

The main hydrological studies consisted of pumping tests performed in either the sand aquifer or the lignite-diatomite complex. Simultaneous water-level measurements were made in piezometers located in both formations at distances of about 30, 80 and 140 m from the pumping wells. Two piezometers made of rigid PVC with 5 cm diameters were installed in the same borehole, one tapping the sand aquifer and the other the lignite-diatomite complex.

Across the screened intervals, sand and gravel packs were installed and the piezometers developed by air lifting. Between the piezometers a seal of portland cement was used to avoid hydraulic connection between them.

Interpretation of test data was made by using traditional hydrological methods for steady-state and nonsteady-state conditions.

The average values of transmissivity and storativity and respective standard deviations for the sand aquifer at the B4 pumping-test site obtained from a dozen different determinations were calculated to be:

$$T = 540 \pm 43 \text{ m}^2/\text{day, and}$$

$$S = 1.2 \times 10^{-3} \pm 0.5 \times 10^{-3}.$$

Three pumping tests performed in the sand aquifer used discharge rates of 43, 49 and 57 liters per second (lps) during a five-day pumping period. After pumping stopped, a five-day period of recovery was monitored in the same piezometers used for monitoring the pumping tests. Graphs constructed with data obtained during drawdown and recovery times show an extremely good agreement.

Careful execution of the field tests, particularly in discharge control, ensured the results to be accurate enough to be used in a more detailed analysis of the Noordbergum effect and to determine aquitard characteristics by using the ratio method (Neuman and Witherspoon, 1972).

The lignite-diatomite complex was also characterized by means of pumping tests in two different sites. The northwestern part of the lignite-diatomite complex was tested with a discharge rate of 4 lps, and gave the following results:

$$T = 31 \pm 8 \text{ m}^2/\text{day, and}$$

$$S = 3 \times 10^{-4} \pm 1.2 \times 10^{-4}.$$

In the southeastern part, a discharge rate of 8 lps could be used. The following results were obtained:

$$T = 91 \pm 22 \text{ m}^2/\text{day, and}$$

$$S = 4.6 \times 10^{-4} \pm 0.7 \times 10^{-4}.$$

Besides the higher transmissivity found in the southeastern part, it is important to note the small values obtained for the storage coefficient. The five-day pumping tests were only able to depressurize the interstratified aquifers, which reacted as leaky aquifers. The storage coefficient therefore will not be useful for computations of the long-term dewatering of the complex. A long-term pumping test is scheduled for this complex to obtain an estimate of a long-term specific yield.

THE NOORDBERGUM EFFECT

The Noordbergum effect consists of a reverse water-level response in aquitards or in aquifers separated from the pumped aquifer by aquitards during early times of pumping and recovery tests. The apparently paradoxical behavior of a piezometric surface due to ground-water pumping is similar to other effects obtained in problems in three-dimensional consolidation. In this domain, it is also called the Mandel-Cryer effect (Mandel, 1953; Cryer, 1963). The observed drawdowns in an aquitard during the pumping of an overlying aquifer near Noordbergum (The Netherlands) agreed with predicted behavior (Verruijt, 1969). This author considers that the pumping of the upper layer will attract water from the lower layer and promote a decrease in volume with a tendency to compression in this lower layer. Since pore water opposes volume compression of the soil, this results in an increase of the pore-water pressure.

In Rio Maior, reverse water-level responses were observed in two pumping test sites on piezometers located in the lignite-diatomite complex during pumping on the underlying sand aquifer. Figure 3 shows the array used at one of

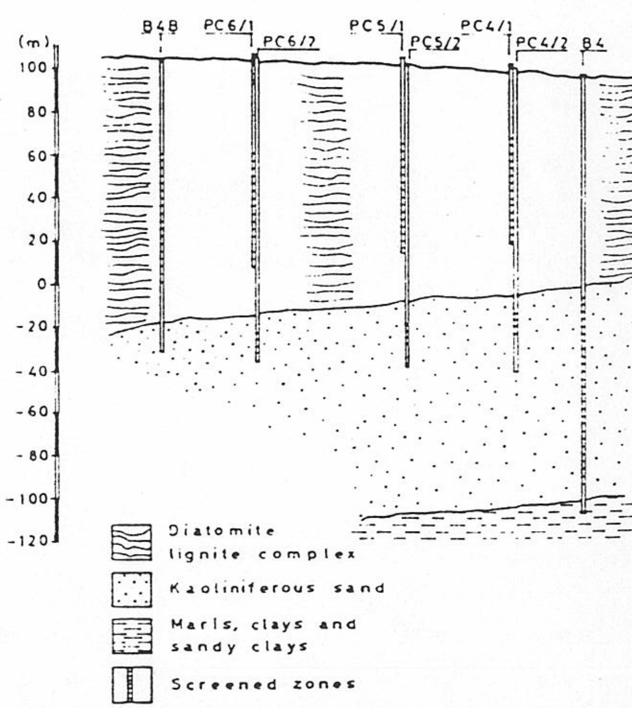

Fig. 3. Observation well layout for monitoring B4 and B4B pumping wells.

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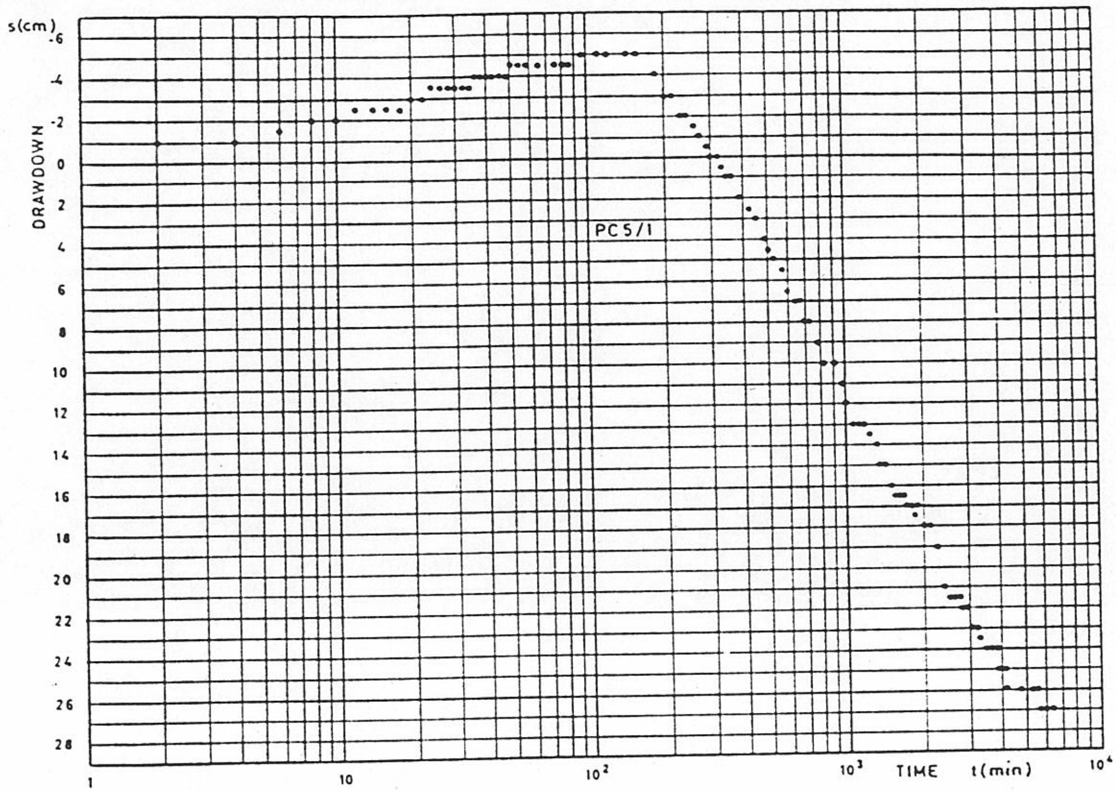

Fig. 4. Noordbergum effect at PC5/1; B4 pumping well taps the sand aquifer and the observation well is screened in the aquitard.

these two pumping test sites. The piezometers were situated at 30, 80 and 140 m from the pumping well. Figure 4 shows the water-level response in the piezometer located 80 m from the pumping well. This was the strongest reverse response recorded. In the other two piezometers located at distances of 30 and 140 m, the response was less marked, the rising height being less than 2 cm.

At B3, the pumping test site located approximately 2,000 m away from the B4 site, a remarkable but somewhat different behavior was detected. In Figure 5 it can be observed that the water level rises in the first two hours of pumping. After that time the water levels fall as far as the initial water level with no further water-level decline until the fifth day of pumping. The rise in the water level was similar in the piezometers located 30 and 80 m from the pumping well, reaching a value of 4.5 cm, and was smaller in the piezometer located at 140 m with a maximum value of 3.0 cm.

The permanence of the water level around its initial value suggests that no significant leakage has taken place at this particular area. Thus, it seems reasonable to infer a very low vertical hydraulic conductivity for the overlying confining layers and also that the transmission of pressure has overcome the zone of low permeability. It seems also that there is no need for a water attraction from the confining layer as postulated by Verruijt (1969). Instead, it seems more adequate to assume that pore-water pressure increases below a pumped aquifer because of rock matrix compression caused by the three-dimensional effect (Gambolati, 1974).

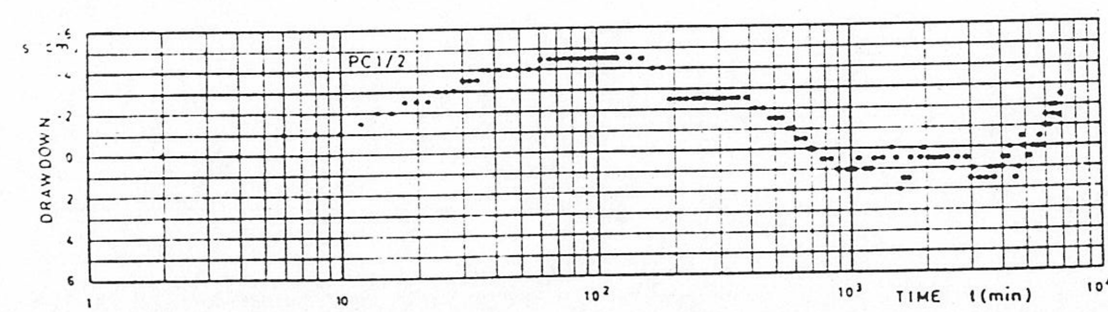

Fig. 5. Noordbergum effect in the aquitard at the B3 pumping test site.

Wolf (1970) states that if appreciable strain occurs in the pumped aquifer, it is not difficult to visualize the transfer of this deformation across confining beds and/or adjacent aquifers that have the proper physical characteristics for allowing such a transfer. This transfer would account for some of the previously observed reverse water-level fluctuations.

This type of mechanism seems well adapted to the reverse water-level response in the Rio Maior pumping tests. The deformation caused in the aquifer by the water discharge is transmitted to the confining layers with an increase in total loads. The redistribution of stresses in a constant effective stress basis originates the increase of pore-water pressure and as a consequence the rise of water levels in the piezometers. This type of response also could be found even when confining layers are completely impermeable.

DETERMINATION OF AQUITARD CHARACTERISTICS

Data collected from observation wells tapping the aquifer and the aquitard at the same radial distance from the pumping well make it possible to use the ratio method for determining aquitard characteristics (see Neuman and Witherspoon, 1972).

The principle of the method states that if measurements of (s) and (s') which represent drawdown in an aquifer and an aquitard respectively, are made at the same radial distance (r) from the pumping well at time (t) after pumping starts, it is possible to use the ratio (s'/s) to compute the vertical diffusivity of the aquitard (K'/S'_s), and consequently to compute the vertical hydraulic conductivity of the aquitard provided the specific storage coefficient (S'_s) is known.

Figures 6, 7 and 8 display data collected during a five-day pumping test at the B4 pumping test site. B4 is the pumped well.

Using the procedure mentioned above, the following values of diffusivity (α') were computed

$\alpha' = 61.7\ cm^2\ s^{-1}$ at PC 4,

$\alpha' = 93.8\ cm^2\ s^{-1}$ at PC 5, and

$\alpha' = 154.8\ cm^2\ s^{-1}$ at PC 6.

Vertical hydraulic conductivity (K') was computed using laboratory tests to determine the coefficient of compressibility (a_v) in order to make

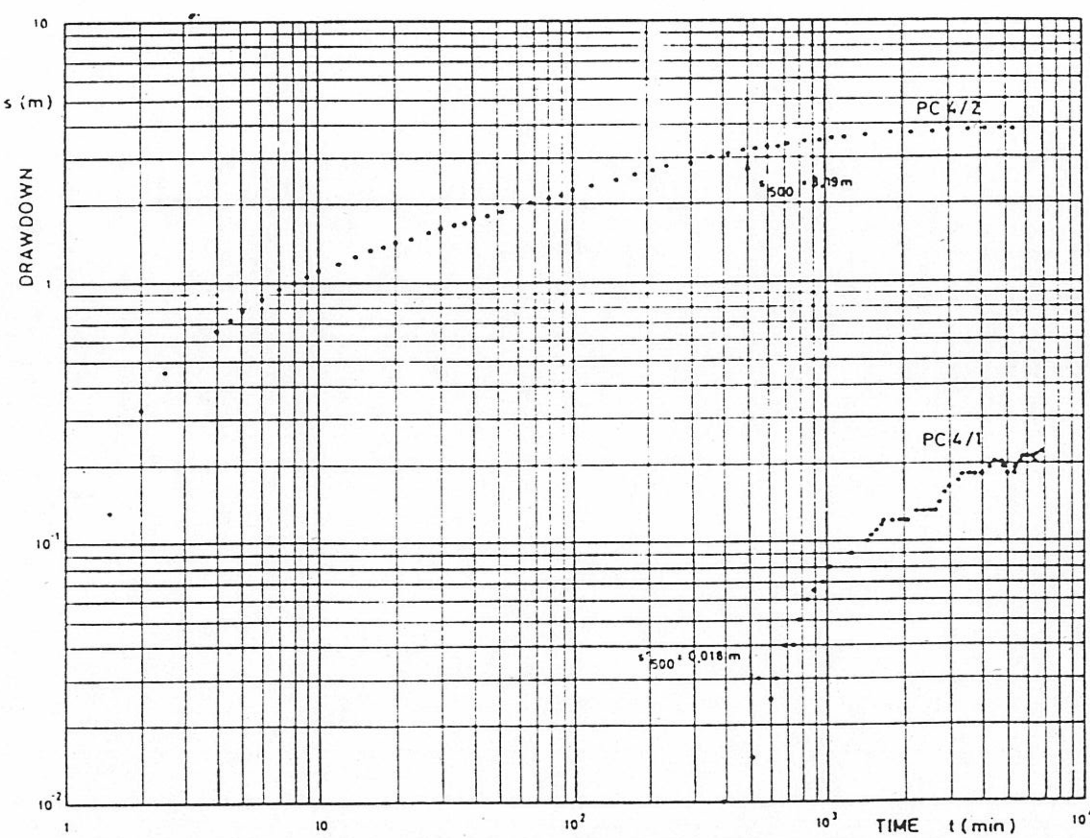

Fig. 6. Drawdown versus time graph in the aquifer and in the aquitard measured at a distance of 30 m from the pumping well.

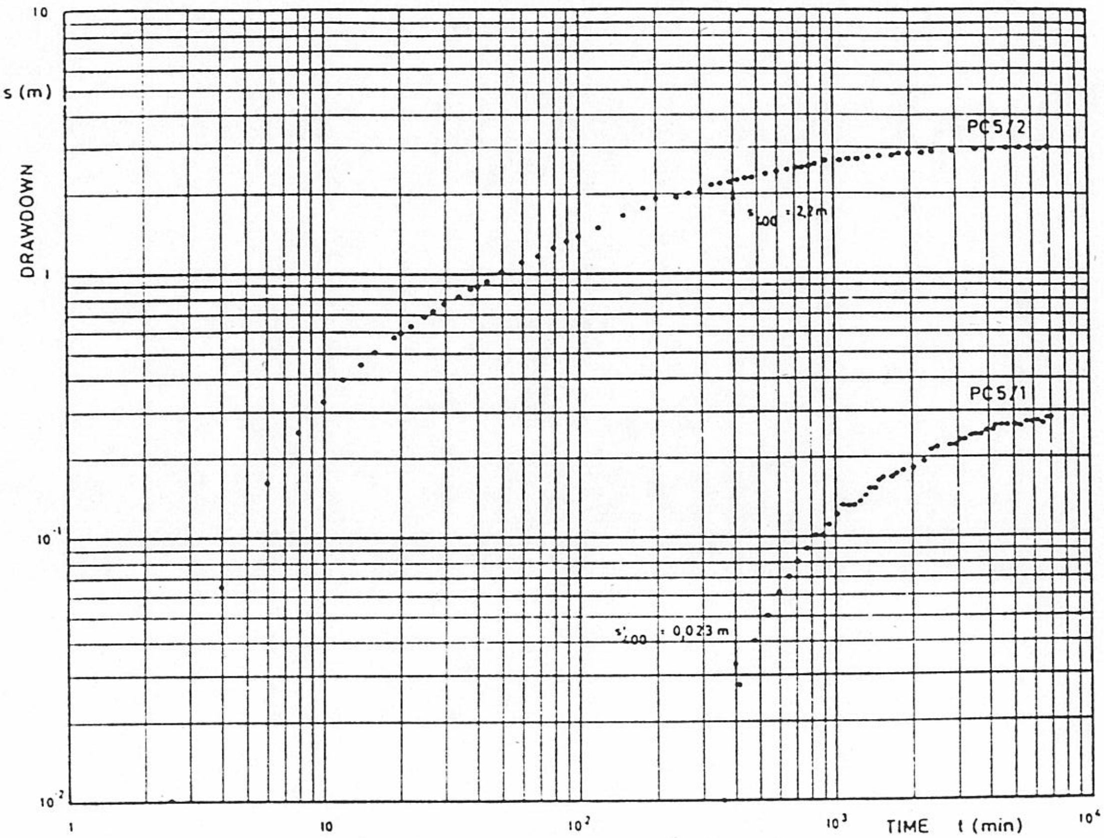

Fig. 7. Drawdown versus time graph in the aquifer and in the aquitard measured at a distance of 78 m from the pumping well.

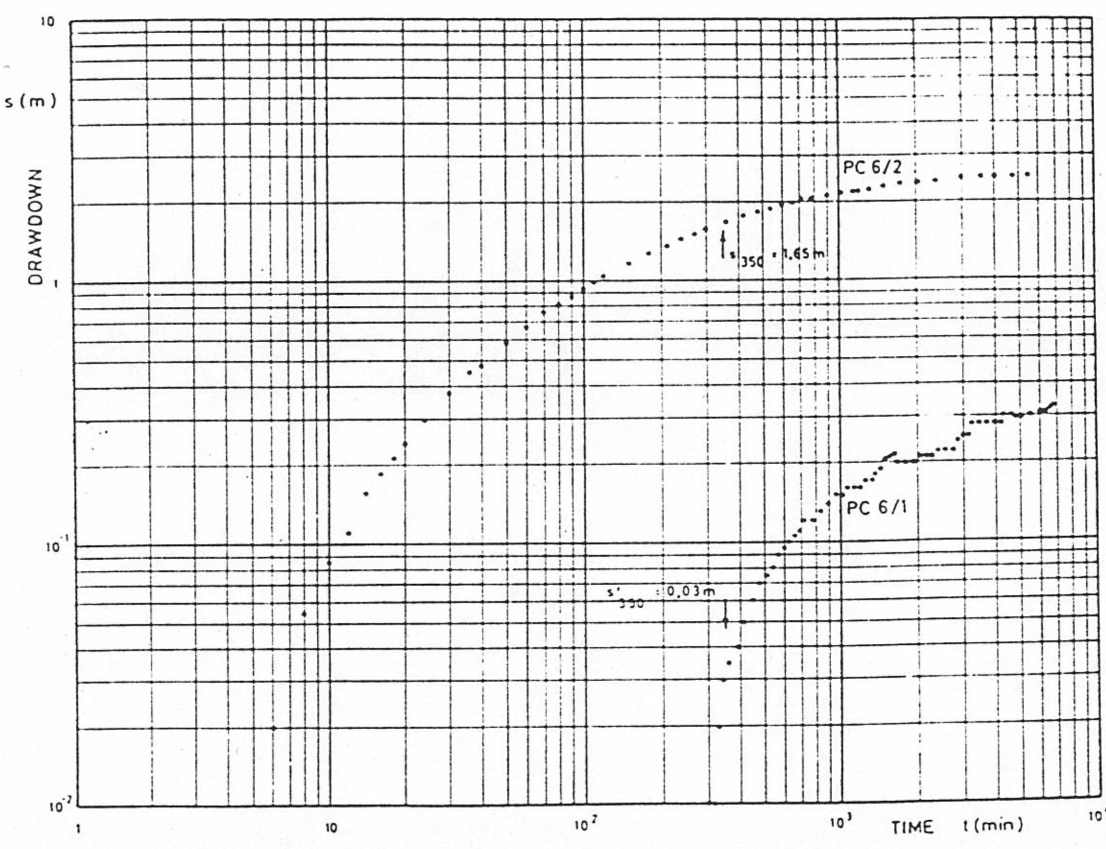

Fig. 8. Drawdown versus time graph in the aquifer and in the aquitard measured at a distance of 144 m from the pumping well.

Table 1. Vertical Hydraulic Conductivity of Aquitard Determined by Various Methods

	Observation Wells					
Method	*PC4*	*PC5*	*PC6*	*PR10*	*All*	
Ratio	4.0×10^{-5}	6.3×10^{-5}	10.0×10^{-5}	—	—	—
Walton	1.6×10^{-5}	0.6×10^{-5}	1.3×10^{-5}	1.4×10^{-5}	—	—
Hantush	3.6×10^{-5}	—	2.0×10^{-5}	1.5×10^{-5}	—	—
De Glee	—	—	—	—	1.5×10^{-5}	—
Laboratory	—	—	—	—	—	7.4×10^{-9} to 7.3×10^{-6}

Note: Values in cm s^{-1}.

it possible to compute (S_s') according to the formula

$$S_s' = a_v \gamma_w / (1 + e) \qquad \text{(Neuman \& Witherspoon, 1972)}$$

where

a_v = coefficient of compressibility,

γ_w = specific weight of water, and

e = void ratio.

From laboratory determinations in undisturbed diatomite and lignite samples,

$$a_v = 8 \times 10^3 \text{ cm}^2 \text{ kg}^{-1}, \text{ and}$$

$$e = 2.$$

Therefore,

$$S_s' = 2.67 \times 10^{-6} \text{ cm}^{-1}$$

Finally, the vertical hydraulic conductivity for the aquitard was determined to be

$K' = 1.6 \times 10^{-4}$ cm s^{-1} at PC 4,

$K' = 2.5 \times 10^{-4}$ cm s^{-1} at PC 5, and

$K' = 4.1 \times 10^{-4}$ cm s^{-1} at PC 6.

These values of K' were computed assuming Z = 50 m. As the screened zone is very long, it is questionable to use this value of Z. Therefore, the same calculations were repeated using the distance to the deepest screened interval. In this case, values for K' at Z = 25 m would be four times smaller:

$K' = 4.0 \times 10^{-5}$ cm s^{-1} at PC 4,

$K' = 6.3 \times 10^{-5}$ cm s^{-1} at PC 5, and

$K' = 10.0 \times 10^{-5}$ cm s^{-1} at PC 6.

Other methods also have been used to compute the hydraulic conductivity of the aquitard. The method for steady-state conditions (De Glee, 1951), the type-curve method (Walton, 1962), and the inflection-point method (Hantush, 1956). See Kruseman and De Ridder (1976) for all these methods. The values obtained by these methods are intermediate between the values obtained by the ratio method and by laboratory testing of undisturbed specimens.

Table 1 presents the results obtained by different methods, taking Z = 25 m for the thickness of the aquitard in all the field methods used. In the same table, maximum and minimum values obtained in the laboratory on undisturbed samples are presented. Tested samples which would have aquitard behavior were taken from lignite, diatomite, and clay layers by adequate drilling techniques using rotary drilling with borehole stabilization with bentonite mud and cutting devices adapted to soft rocks. Samples were tested in the laboratory by traditional soil mechanics procedures using variable head permeameters.

An analysis of Table 1 shows that field values are higher than laboratory values. It is also shown that values obtained by the ratio method were systematically higher than values obtained by the other methods.

Values obtained by the ratio method were 5 to 15 times higher than the highest values obtained at the laboratory. According to the opinion of one of the authors of the method (Neuman, personal communication, 1981) values of one to two orders of magnitude higher than laboratory values are the most commonly found.

The values determined for the lignite-diatomite complex agree fairly well. The presence of some sand layers within the aquitard and the presence of fractures and fissures in the lignite and diatomite layers may explain the higher field values obtained.

CONCLUDING REMARKS

During the characterization of the formations occurring in the Rio Maior basin, it was possible to use the ratio method and other field methods to determine aquitard characteristics. The values obtained by these methods were compared with

values obtained in the laboratory. This comparison showed that field methods gave values systematically higher than the laboratory methods and that the ratio method gave the highest values.

Recorded water levels in the aquitard formations showed reverse water-level response when pumping the underlying sand aquifer. This behavior was considered to represent the Noordbergum effect. The deformations originated in the aquifer by the pumping were transmitted to the confining layers originating an increase in the loads acting in these layers. The redistribution of loads with constant effective stresses originated the increase in pore-water pressure and the rising of water levels.

The drawdown values used in the ratio method have been computed with reference to the water level measured when pumping started; that is to say, the Noordbergum effect was not considered in the computations because it was intended to use the ratio method as proposed by the authors.

Nevertheless, the observation of field data shows that the use of the highest water level caused by the Noordbergum effect as the reference level for drawdown computations seems acceptable because leakage seems to start at this point as suggested by the straight line in the graphs. This procedure would introduce some slight adjustments in the values obtained because drawdown in the aquitard would be somewhat larger with a consequent increase in the computed vertical hydraulic conductivity of the aquitard.

Two different discharge systems will be needed for dewatering and depressurizing the formations connected with the future opencast mine. One system will depressurize the leaky sand aquifer by means of a few deep wells with high discharge rates and another system will dewater the lignite-diatomite complex by means of a larger number of low discharge rate wells screened in the entire saturated thickness of the lignite-diatomite complex.

Forecast drawdowns were obtained by using a finite-element model of the basin. Storage coefficient of the lignite-diatomite was considered too low; therefore, a value for the specific yield was assumed. Transmissivities were considered reliable for both systems. Vertical hydraulic conductivities determined by the ratio method were considered the most adequate for characterizing the aquitard behavior when modeling the underlying sand aquifer.

The total amount of water to be discharged was estimated taking into account the recharge by precipitation and by ground-water flow from the boundary formations. The depressurization of the sand aquifer and the dewatering of the lignite-diatomite complex and of a narrow zone in the adjacent boundary formations will account for the remaining water needed to be pumped.

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