Estimating hydraulic conductivity profiles using borehole resistivity logs

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Abstract

Measurements of aquifer resistivity are intuitively attractive for estimating aquifer hydraulic conductivity because of the fundamental relation between hydraulic conductivity and electrical conductivity; both of these properties depend on porosity, grain size and packing configuration ([1], [2]). In this study porosity and hydraulic conductivity profiles are estimated in three boreholes in Glafkos aquifer, located near the city of Patras in Western Greece. For this purpose, resistivity measurements, the law of Archie [1], the Kozeny-Carman model [2] and numerical simulations of pumping tests performed in the boreholes, have been used. It is shown that resistivity logs and pumping tests constitute a useful data set for the estimation of hydraulic conductivity profiles. The reliability of the results has been discussed. The relationships between porosity and hydraulic conductivity resulting for each of the three investigated boreholes have been compared to each other as well as with literature data. The comparison confirms that the value of the hydraulic conductivity for a given value of the porosity varies significantly.

1. Introduction

The coastal aquifer of Glaflkos River (Fig. 1a) is a very important groundwater reservoir for the water supply of the city of Patras. The aquifer covers an area of about 25km². Due to its importance, a network of seven observation wells shown in Fig. 1b has been constructed in the last years. The depth of the

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boreholes varies from 80 m to 120 m and their diameter is 12 in. Groundwater level data collected during the period from 2008 to 2012 have been used for the calibration of a groundwater model used for the investigation of management issues (Ziogas, [3]). In order to refine the estimation of the hydraulic properties of the aquifer, data collected during the construction of the boreholes, are used. In this study we focus on the analysis of the data collected in the boreholes G1, G4 and G5 (Fig. 1b). The analysis of the remaining wells is still in progress. The data collected in each of the aforementioned boreholes are: (a) a cuttings log, (b) a gamma ray (GR) log, (c) a spontaneous potential (SP) log, (d) two electrical resistivity logs, i.e. one short normal and one long normal (see below), and (e) water level measurements in the borehole during a pumping test of short duration (three to four hours). The logs (b), (c) and (d), which have been measured before the installation of the casing, have a vertical resolution 0.20 m.

The cuttings logs show that the aquifer consists of mixtures of coarse and fine gravel, sand and clay. The GR-logs show that the values of the radiation are smaller than 35 API units. According to [4] (see page 30 therein) such values correspond to clean formations, i.e. to formations with negligible clay content. Concerning the SP-logs, they add little to the investigation, because, due to the lack of clay layers in the formation, the clay base line cannot be established. Thus, concerning the structure of the formation at the location of the boreholes G1, G4 and G5, the logs (a), (b) and (c) provide only qualitative information.

Concerning the two types of the resistivity measurements, the difference between the short normal and the long normal log consists in the spacing of the electrodes of the measuring device. In the short normal device, which is characterized here as 16NR, the separation distance of the electrodes is 16 in (or 406 mm) whereas in the long normal, which is characterized here as 64NR, the separation distance of the electrodes is 64 in (or 1630 mm). The spacing of the electrodes determines the depth of the current penetration into the formation for a given borehole diameter ([4], [6]). Which of the aforementioned resistivity measurements are appropriate for the estimation of the hydraulic conductivity profiles, can be decided by considering the conditions, under which the law of Archie [1] that is used for the analysis of the resistivity measurements, is valid.

Fig. 1. The aquifer of Glafkos River: (a) location of the aquifer; (b) the constructed network of observation wells

2. The proposed method

The first step in in the estimation of the hydraulic conductivity profile is to estimate the porosity profile. This estimation is based on Archie’s law [1], which correlates the formation factor with the porosity. The formation factor \( F_a \) is defined as the ratio of the resistivity of the porous material \( R_o \) saturated with an electrolyte, to the bulk resistivity of the electrolyte \( R_w \):
Archie’s law is valid under the condition that the electrical resistivity of the pore fluid saturating the porous material is very low as to completely dominate the current flow in the formation [5]. Such conditions prevail in the zone closest around the borehole because the fluid saturating this zone, the so-called mud filtrate, is mainly drilling fluid and exhibits low resistivity (see Fig. 8.18 in [6]). Thus, for the analysis based on Archie’s law, resistivity measurements, which are representative for the area saturated with this low resistivity fluid, are required. Since the short normal resistivity device measures the resistivity in the area closer to the borehole than the long normal device, it is reasonable to assume that the resistivity values measured by means of the short normal device are representative for the aforementioned area. Therefore, we perform the estimation of the hydraulic conductivity profiles using the short normal resistivity logs. It should be noticed that for the analysis, no elimination of clay contamination effects has been performed (see [7]), since the gamma ray logs show that the clay content of the formation is not significant (see section 1).

The formation factor [Eq.(1)] is calculated from the resistivity values $R_{16NR}$ obtained from the 16NR-log, dividing them by the resistivity of the mud filtrate. In our investigations only the resistivity of the drilling mud has been measured. Concerning the relationship between the resistivity of drilling mud $R_m$ and that of the mud filtrate $R_{mf}$ there are contradictory opinions. Sherborne and Newton [8] found experimentally that the resistivity of the drilling mud in most cases closely approximates the resistivity of the mud filtrate. Patnode [9] concludes that it is erroneous to substitute drilling mud resistivity for mud filtrate resistivity and Lamont [10] found experimentally the relationship: $R_{mf} = 0.88 R_m$. Finally, Schneider [11] (see Fig. 4.177, page 304 therein) qualitatively indicates that $R_{mf}$ is slightly smaller than $R_m$. Due to the lack of data, we set in this analysis the resistivity of the mud filtrate equal to the measured resistivity of the drilling mud. It should be noticed that uncertainties in the resistivity of the mud filtrate significantly influence the resulting porosity and hydraulic conductivity profiles.

In order to calculate the porosity $\phi$ from the formation factor $F_a = R_{16NR}/R_{mf}$, we use Archie’s law in the form of Eq.(2), which has been proposed by Schneider [11] for unconsolidated sediments:

$$F_a = \frac{2}{\phi + \phi^2}$$

(2)

More usually an equation of the form: $F_a = \alpha/\phi^m$ is used (see [12]). Since there are no generally valid rules for the selection of the parameters $\alpha$ and $m$ in this equation, we preferred here to use Eq.(2).

For the estimation of the hydraulic conductivity from the porosity, functional relationships between porosity and hydraulic conductivity could be used. However, investigations on this issue are either performed for definite types of sediments (see [13]) or they provide results according to which the hydraulic conductivity varies over some orders of magnitude in relatively narrow ranges of the porosity ([13], [14]). This is due to the fact that the hydraulic conductivity does not depend only on the porosity but also on the grain size and the packing configuration [2]. From data presented in the literature (see for instance [15] and [16]), the relationship between porosity and grain size seems to be more unambiguous. Therefore, the procedure we follow in this study in order to estimate the hydraulic conductivity profile consists in the following steps: (a) we estimate the profile of the grain size by using the porosity profile, which has been estimated from the formation factor [see Eq.(2)], and a relationship between porosity and grain size (see below). (b) We use then a grain size–porosity-hydraulic conductivity relationship in order to estimate the hydraulic conductivity. In the literature, a large number of such relationships (see for instance [2] and [13]) has been proposed. In this study the Kozeny-Carman equation given in [2] has been used:

$$k_f = \frac{\gamma_w}{\mu_w 180} \frac{d^2 \phi^3}{(1 - \phi)^2}$$

(3)
\( \gamma_w \) is the specific weight of the water, \( \mu_w \) is the dynamic viscosity of the water and \( d_e \) is the effective grain diameter.

The relationship \( \phi = f(d_e) \) between porosity and effective grain size \( d_e \) for each of the three boreholes investigated here has been estimated adaptively, through a calibration procedure based on the pumping test data. We start for each borehole with a form of the function \( \phi = f(d_e) \), which results by approximating the data presented by Davis [15] and De Marsily [16] (see Fig. 2). From this initial form of the function \( \phi = f(d_e) \) and the previously estimated \( \phi \)-values [Eq.(2)], we calculate the hydraulic conductivity profile using Eq.(3).

![Fig. 2. Estimation of the porosity – grain size relationship for the observation well G1.](image)

This profile is then used for the numerical simulation of the pumping test performed in the borehole. Since the vertical discretization of the numerical model is coarser than the vertical resolution of the hydraulic conductivity profiles obtained from the resistivity logs, the hydraulic conductivity profiles used for the simulation have been respectively aggregated.

Depending on the deviations between the groundwater level measured during the pumping test in the borehole and that simulated, the function \( \phi = f(d_e) \) is respectively modified and a new hydraulic conductivity profile is calculated. Since the results of the simulation are more sensitive with respect to the hydraulic conductivity values at the screened sections of the borehole, the function \( \phi = f(d_e) \) is each time modified over its whole range, however, so that a higher or a lower value for the hydraulic conductivity at the screened section results, depending on the deviations between the measured and the simulated drawdown after each simulation. Thus, in this adaptive procedure the variation of the hydraulic conductivity of all the layers of the profile is not arbitrary but it is conditioned on the resistivity log.

Details concerning the simulations of the pumping tests are given in Ziogas [3]. The MODFLOW-2000 code [17] has been used. In order to minimize the computational effort, two-dimensional, cross-sectional aquifer models were used and the technique proposed by Langevin [18] for simulating axially symmetric (radial) flow in a 2D-model has been applied. The horizontal discretization is fine in the vicinity of the borehole and becomes logarithmically coarser toward the outer model boundary. The vertical discretization is fine in the screened parts of the casing and coarser in the rest of the model. Concerning the discretization in time, an initial time step of the order of 0.1ms has been used for the drawdown phase whereas for the recovery phase the initial time step was of the order of 1s. In both cases the time step was increased logarithmically. The borehole-column was simulated as a high conductivity zone and the pumping was assigned to the bottom cell of the borehole-column. The cells neighboring the borehole-column have been considered to be inactive, representing the casing of the wells, except of those corresponding to the screens. A number of columns surrounding the well casing were used to simulate the filter pack of the well. According to the grain size of the filter material, its hydraulic conductivity is
considered to vary between 500 m/d and 800 m/d. The columns surrounding the filter pack correspond to the aquifer. The top and bottom layers of the model are no flow boundaries. The outer model boundary is a constant head boundary with a value equal to the groundwater level, which was measured prior to the beginning of the pumping test. The distance of this boundary from the well column was set large enough, to ensure that the boundary does not affect the head drop around the well. To calculate the hydraulic head inside the well, observation points were set to all the cells in the screened part of the casing. The heads at the observation points were averaged using weights, which are related to the thickness of the layer that contains the corresponding observation point. These averaged heads were compared with the measured heads. The hydraulic conductivity profile providing the simulation results shown in Fig. 3 is considered to sufficiently approximate the water level variation measured during the pumping test in borehole G1 and is accepted as the final hydraulic conductivity profile for this location (see Fig. 4a).

Fig. 3. Comparison between the measured water level during the pumping test in borehole G1 and the water level simulated by using the hydraulic conductivity profile considered as the final one for this borehole: (a) drawdown period; (b) recovery period.

3. Results and discussion

Figure 4a shows the hydraulic conductivity profiles estimated for the thickness of the saturated zone of the aquifer penetrated by the boreholes G1, G4 and G5. The depth of the boreholes G1 and G4 is 120m. The difference in the aquifer thickness penetrated by each of them is due to the fact that the altitude at the location G1 is significantly larger than that at G4 whereas the groundwater level above the mean sea level in the two boreholes during the construction period differs only slightly. The depth of the borehole G5 is 80 m and it is located at even lower altitude than G4. The estimated profiles show that the aquifer at the locations G1 and G4 exhibits significant heterogeneity over the depth. At the location G5 the aquifer is more homogeneous.

Concerning the reliability of these results there are two indications that the estimated profiles are reliable. These are: (a) that the profiles simulate the reaction of the aquifer for the short duration pumping test performed in each borehole and (b) that the profiles are compatible with the resistivity logs. However, the analysis is based on a series of assumptions, the most important of which concern: (i) the functional relationship between the formation factor and the porosity [Eq.(2)], (ii) the functional relationship between porosity and hydraulic conductivity [Eq.(3)] and (iii) that clay contamination effects are not
significant (see section 1). Due to these assumptions, a sensitivity analysis is required for the final evaluation of the profiles.

Figure 4b shows the relationship between the porosity and the hydraulic conductivity resulting for the three boreholes investigated here, along with data presented in the literature (see Nelson [13] and Bush and Luckner [19]), which concern different materials. The hydraulic conductivity and porosity values of the materials of the Glafkos aquifer are within the wide range of these variables given in [13] but they are not compatible with the results presented in [19], particularly for the high hydraulic conductivity values. Further, the hydraulic conductivity-porosity relationships for the boreholes G1 and G5 are similar to each other but different from the corresponding relationship resulting for G5.

Fig. 4. Results for the analysis of the logs in boreholes G1, G2, G3: (a) Hydraulic conductivity profiles; (b) Comparison of the porosity – hydraulic conductivity relationships with literature data.

These results confirm that assessments of the value of hydraulic conductivity, which are based only on porosity values, are uncertain. This fact is emphasized also by the field experiments of Morin et al. [5], which show that there are aquifers, in which the correlation between porosity and hydraulic conductivity is not significant. Thus, for the estimation of the hydraulic conductivity profiles from the porosity profiles, additional information is required. Here has been shown that such information can be obtained from the pumping test performed in each borehole.

It should be noticed that hydraulic conductivity profiles can be estimated also from flowmeter measurements (Molz et al., [20], Kaleris et al., [21]). The difference between resistivity logs and flowmeter measurements is that the resistivity logs, which are always constructed before the installation of the casing, provide information over the whole depth of the aquifer. On the contrary, flowmeter measurements, which in unconsolidated sedimentary aquifers mostly cannot be performed in uncased boreholes, provide information over the whole depth of the aquifer only if the borehole is fully screened. For partially screened boreholes flowmeter measurements provide information mainly for the layers, which correspond to the screened parts of the borehole. Due to the fact that resistivity logs are low cost measurements, their combination with simple pumping tests, as described here, represent a cost effective method for the estimation of hydraulic conductivity profiles.
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