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Estimation of hydraulic parameters in a complex porous aquifer system using geoelectrical methods

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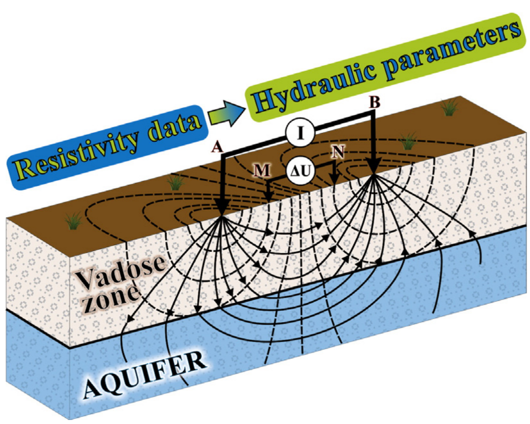
HIGHLIGHTS

- Cementation factor and alpha parameter were estimated using field data.
- Hydraulic characteristics of the aquifer were estimated from resistivity data.
- High correlation was observed between the geophysical method and pumping tests.
- The method is reliable for complex porous aquifer systems.
- A relationship between aquifer resistivity and hydraulic conductivity was produced.

GRAPHICAL ABSTRACT



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ABSTRACT

Geoelectrical methods have been widely used for the estimation of aquifer hydraulic properties. In this study, geoelectrical methods were applied in a lithologically and hydrochemically complex porous aquifer to estimate its porosity, hydraulic conductivity and transmissivity. For this purpose, the electrical resistivity of the aquifer as well as the electrical conductivity of the groundwater was measured in 37 sites and wells. Initially, the Archie's law was used to generate sets of cementation factor (m) and alpha (α) parameter from which the mode values of $\alpha = 0.98$ and $m = 1.75$ are representative of the studied aquifer. The transmissivity of the aquifer varies from 5.1×10^{-3} to 3.1×10^{-5} m^2/s, whereas the mean value of its porosity is 0.45.
The hydraulic conductivity of the aquifer which was calculated according to Archie's law varies from 2.08×10^{-6} to 6.84×10^{-5} m/s and is strongly correlated with the pumping test's hydraulic conductivity. In contrast, the hydraulic conductivity which was calculated using Dar-Zarrouk parameters presents lower correlation with the pumping test's hydraulic conductivity. Furthermore, a relation between aquifer resistivity and hydraulic conductivity was established for the studied aquifer to enable the estimation of these parameters in sites lacking data.

1. Introduction

The hydraulic parameters of an aquifer, such as hydraulic conductivity, transmissivity and porosity, constitute data essential for groundwater

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exploitation management and planning. The estimation of these parameters allows quantitative prediction of the exploitable amounts of groundwater and the hydraulic response of the aquifer to pumping. Field hydrogeological methods, such as pumping tests, have been used widely to estimate aquifer hydraulic parameters as they provide a high degree of reliability. However, various assumptions are required for the application of the methods' formulas, including aquifer homogeneity, isotropy, thickness, well storage, continuity, and the nature of the fluid flow to be valid under field conditions (Tizro and Singhal, 1993). In addition, these methods are costly, time-consuming and require a large data set to estimate an aquifer's hydraulic parameters (Tizro et al., 2010, 2012). Alternative methods to hydrogeological field procedure include hydrogeophysical methods that are based on the electric resistivity of the aquifer (Niwas and Lima, 2003). In these methods the geoelectrical equations are based on the assumption that electrical currents pass through the water/moisture contained in the pores of the rock matrix that is generally an insulator. The use of these equations presupposes available data on the lithology and geometrical characteristics of the aquifer, the vadose zone, groundwater level and electric conductivity. Geoelectrical methods are suitable for the estimation of hydraulic conductivity because they are relatively quick and inexpensive compared to pumping or slug tests and additionally the geophysical survey can be scaled by careful survey design (Slater, 2007). However, hydraulic conductivity is calculated indirectly from electrical measurements by using a mutual dependence of both on another petrophysical property (e.g. porosity) (Slater, 2007).

The attempt to correlate the electrical properties of the subsurface with the hydraulic characteristics of an aquifer began when Ungemach et al. (1969) established a relationship between transmissivity and transverse resistance. Thenceforth, a significant number of studies have been performed on the estimation of aquifer parameters using geoelectrical equations. A relation between a formation factor and an aquifer's intrinsic permeability was developed by Croft (1971) in order to estimate transmissivity from resistivity. Kelly (1977) proposed a semi-empirical relation between an aquifer's formation factor and hydraulic conductivity as well as an empirical formula between an aquifer's hydraulic conductivity and electrical resistivity. A relation between transmissivity and transverse resistance was proposed by Niwas and Singhal (1981). In addition, a modified transverse resistivity instead of transverse resistance was introduced by Niwas and Singhal (1985) to consider variations in groundwater quality. Kelly and Frohlich (1985) concluded that the relation between the hydraulic parameters and the resistivity of an aquifer is influenced by the position of the non-producing layers in regard to the aquifer layer. A linear relation between hydraulic conductivity and normalized aquifer resistivity and transmissivity was suggested by Yadav and Abolfazli (1998). The study of shaly sandstone aquifers by Lima and Niwas (2000) revealed that electrical resistivity and induced polarization parameters carry direct information about the volume conductivity of the sandstone matrix. Purvance and Andricevic (2000) confirmed theoretically and empirically the linear correlation between electrical and hydraulic conductivity whose slope is dependent on the geochemical and geological conditions of the environment. Geophysical methods were also used in India by Sinha et al. (2009) to estimate aquifer parameters suggesting that the estimation of aquifer's transmissivity is more accurate if the values are sorted by hydraulic unit. Tizro et al. (2010) estimated the transmissivity and hydraulic conductivity of an alluvial aquifer in western Iran using a direct relation between the aquifer's modified transverse resistance and its transmissivity. Soupios et al. (2007) estimated the hydraulic parameters of a shallow aquifer on the Greek island of Crete using Archie's (1942) law after calculating the formation factor from vertical electrical soundings and fluid resistivity. Geophysical methods were also applied to assess hydraulic conductivity in an alluvial aquifer of Pakistan (Sikandar and Christen, 2012) using the Kozeny equation for hydraulic conductivity and an empirical relationship between formation factor and hydraulic conductivity. In addition, Kozeny's equation in combination with Archie's law (Archie, 1942) was used to estimate the porosity and hydraulic conductivity of an alluvial aquifer in Germany (Niwas and Celik, 2012). The porosity of a porous aquifer can be estimated with Archie's (1942) law using the cementation factor (m) and alpha (α) parameter. The cementation factor (m) and alpha (α) parameter play a key role in the estimation of hydrological parameters, whereas the m factor cannot be quantified directly from any log or laboratory test (Kwader, 1985). However, when other factors such as water resistivity are known, m values can be obtained by trial and error methods (Kwader, 1985). Additionally, the cementation factor (m) can be calculated using a graphical method of a wide range of porosity and saturated resistivity measurements for a given formation (Pickett, 1973; MacCary, 1978). Olsen et al. (2008) established a semi-empirical formula to calculate the cementation factor (m) for sandstones from porosity and permeability. Additionally, Wang et al. (2014) established a model to estimate the cementation factor for hydrocarbon and water reservoirs. Lastly, Biella et al. (1983), performed a laboratory investigation in rounded sands and obtained the following values: $\alpha = 1.15$ and $m = 1.42$.

In the majority of the aforementioned studies, the values of m and α are based on the bibliography and laboratory measurements. Taking this into consideration, the present study aim to determine the representative cementation factor and alpha parameter of the porous aquifer system of Anthemountas basin in northern Greece. In addition, the resulting cementation factor and alpha parameter were then used to estimate the porosity, transmissivity and hydraulic conductivity of the aquifer using geoelectrical methods and a petrophysical equation. Therefore, available data from pumping tests (21 in total) were used and measurements of geoelectrical resistivity and the groundwater's electrical conductivity (37 sites) were also performed. The reliability of the results was examined by correlation analysis with field hydrogeological data. The study area was chosen due to the high availability of hydrogeological and geophysical data as well as the aquifer's complex hydro-chemical regime.

2. Study site

The study site is the porous aquifer of Anthemountas basin, which is located in northern Greece (Fig. 1). The porous aquifer covers an area of 181.5 km^2 and is developed in Quaternary and Neogene sediments (Kazakis et al., 2013). The aquifer in the western part of the basin is developed until the depth of 300 m. It is divided into the upper, unconfined, shallow aquifer with a mean thickness of 80 m and the deeper, confined aquifer below 150 m. The thickness of the unconfined porous aquifer, in the eastern part of the basin, does not exceed 120 m and is underlain by crystalline rocks (gneiss, schists, ophiolites, etc.). The geoelectrical structure of the central part of the basin was studied by Thanassoulas (1983) who recorded sediment thicknesses up to 1000 m. A more detailed geophysical survey by Vargemezis and Fikos (2010) mapped the depth of the bedrock surface under the sediments which varies from 100 m near Galarinos village to 800 m in the western part of Vasilika. The water demands of the area are met by the basin's porous aquifer, thus highlighting the importance of the area's groundwater. During the last decades groundwater overexploitation has caused a drop in the water table (Fikos et al., 2005; Theodossiou and Latinopoulos, 2006), seawater intrusion, and a decrease in groundwater quantity (Kazakis, 2014). The seawater intrusion in the coast combined with the mixing of geothermal fluids and the porous aquifer's fresh water in the inland (Kazakis, 2013), both result in a wide range of the groundwater's electrical conductivity values. The results of this survey can be used to estimate the hydraulic characteristics of the aquifer in areas lacking data. Hence, a large dataset of hydraulic data can be established for the aquifer and constitute the fundamental component for modeling groundwater flow processes.