Quantitative Use of Surface Resistivity Data for Aquifer Hydraulic Parameter Estimation. A review

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Abstract

It is well recognized that the classical technique of acquiring hydraulic conductivity from pumping test, is extremely costly and time consuming and that an interrelationship between resistivity and permeability is expected to exist if the medium is the same. Since resistivity method is based on the equation of conservation of charges and Ohm's law; the hydrodynamics on the equation of conservation of mass and Darcy's law, there is a need for combined effort to sharpen means of estimation, to improve confidence, based on the physics of the problem. By reviewing the extensive literature on this subject, some interesting results pointing out the presence of different physical behaviour controlling the relationship between hydraulic conductivity, K, and electrical resistivity, ρ are made known.

1. Introduction

The objective of aquifer characterization is to create hydrogeologic maps of the geometries of aquifers and aquitards and their flow properties, such as porosity and hydraulic conductivity. Without characteristic hydrogeologic maps, hydraulic flow and contaminant transport cannot be accurately modeled. Historically, hydrogeologic maps have been created by qualitatively interpolating flow properties between wells using hydraulic, chemistry and lithologic well data. However, over the past few decades, geostatistical techniques and geophysical data have been used in addition to traditional data analysis techniques to quantitatively interpolate flow properties throughout the well columns and away from wells where data do not exist. These innovative techniques have proven to be more cost-efficient and less subjective than traditional ones.

The relationship between hydraulic conductivity and electric resistivity is one of the most difficult and challenging approaches in the field of hydrogeophysics. The promising side of this relation is the analogy between electric current flow and water flow, whereas the grand ambiguity is the non-dimensionality between both two quantities. The purpose of this article is to review issues related to using electrical resistivity for quantitative estimation of hydraulic parameter for aquifer characterization and to facilitate the collation of information resident in various hydrogeophysical sub disciplines.

2. What electrical resistivity sounding measures and what is require for aquifer characterization

The parameter measurable from resistivity data are;

- Resisitivity of different layers (or conductivity of different layers)
- Thickness of the layers
- Depth to the layers

From this information it is often possible to infer:

- Thickness of aquifer
- Resistivity of the aquifer

From this information, we often compute

- Formation factor – aquifer resistivity (and water resistivity information)
- Porosity – formation factor
- Longitudinal conductance – layer resistivity and thickness
- Transverse resistance – layer resistivity and thickness
- Transmissivity – electric conductivity, transverse resistance (and hydraulic conductivity information)

- Protective capacity – longitudinal conductance.

3. Electric resistivity – hydraulic conductivity relationship

The following review is not addressed to the experienced hydrologist, but to those geoscientist and hydrologist who still have not been exposed to some of the basic theory on electrical resistivity and hydraulic conductivity. We need to know what information is contained in the resistivity data and how to extract it before trying to use it quantitatively in estimation of hydraulic parameters for aquifer characterization

Mathematically, electrical current flow (J) in a conducting medium is governed by Ohm's law

$$J = -\sigma \frac{dV}{dr} \qquad (1)$$

and groundwater flow in a porous medium by Darcy's law.

$$q = -K \frac{dh}{dr} \qquad (2)$$

where, J is the current density (amps per unit area), σ is electrical conductivity (Siemens/m), V is electrical potential (volts), r is distance (metres), q is specific discharge (discharge per unit area), K is hydraulic conductivity (or permeability; m/s) and h is the hydraulic head (m). The analogy is widely accepted [11], [12]. Thus, the electrical method provides a powerful analogue and tool for groundwater exploration and modeling.

For homogeneous and isotropic medium, both electric current and groundwater flow satisfy the Laplace equation: for electrical flow,

$$\frac{d^2V}{dr^2} + \frac{2\,dV}{r\,dr} = 0 \qquad (3)$$

and

$$\frac{d^2h}{dr^2} + \frac{1\,dh}{r\,dr} = 0 \qquad (4)$$

for groundwater flow.

For a point current source, the solution of equations in a semi-infinite, homogeneous medium for (hemispherical earth) electrical flow can be written as

$$V = \frac{\rho I}{2\pi} \frac{1}{r} \qquad (5)$$

and for hydraulic flow a similar equation can be written as:

$$h = \frac{Q}{2\pi T} \ln r \qquad (6)$$

If the transmissivity of an aquifer of saturated thickness b is expressed by

$$T = Kb \qquad (7)$$

then:

$$V = \frac{Q}{2\pi Kb} \ln r \qquad (8)$$

In general terms, since larger connected pores make for better flow characteristics for both water and electric currents it is expected that at the very least there should be some relationship between electrical and hydraulic parameters

[2] found empirically that the true resistivity R of a fully brine-saturated system of insulating grains increased linearly with varying brine resistivity R_w.

$$R = F_i R_w \qquad (9)$$

The proportionality constant that relates the material's true resistivity and brine resistivity is the formation resistivity factor F_i $(F_i \geq 1)$.

The intrinsic formation factor (F_i) combines all properties of the material influencing electrical current flow like porosity ϕ, pore shape, and digenetic cementation.

$$F_i = a.\phi^m \qquad (10)$$

Different definitions for the material constant (m) are used like porosity exponent, shape factor, and cementation degree. Factors influencing (m) are, e.g., the geometry of pores, the compaction, the mineral composition, and the insolating properties of cementation. The constant (a) is associated with the medium and its value in many cases departs from the commonly assumed value of one. The quantities (a) and (m) have been reported to vary widely for different formations.

Equation (9) is called Archie's first law, where it is valid only in fully saturated clean formations (the grains are perfect insulators). When the medium is not fully saturated, water saturation plays an important role, where the changing in degree of saturation changes the effective porosity (accessible pore space). It became Archie's second law.

$$R = F_i R_w S_w^{-n} \qquad (11)$$

When the amount of clay is considered negligible when using Archie's Law and the Kozeny-Carman Law [3], it is possible to obtain the aquifer hydraulic conductivity (K). In fact K (m s^{-1}) will be:

$$K = \left[\frac{g\rho_w}{\mu_w}\right]\frac{d_{10}^2 F^{-3/m}}{180\,(1-F^{-1/m})^2} \qquad (12)$$

Where, ρ_w is water density (kg m^{-3}), μ_w is the water dynamic viscosity (Pa s), g is the acceleration due to gravity (m s^{-2}), d_{10} is the equivalent diameter where 10% of the particles' mass has a smaller diameter (mm), and F is the formation factor.

It is standard practice to use resistivity data to solve for F using Equation (9), so that F – ϕ relationships can be determined for each formation using Equation (10). However, Equation (9) is only valid for systems of fully saturated insulating grains; it is not valid for systems of neither partial saturation nor conducting minerals($F \neq R/R_w$). Therefore, F values published as R/R_w do not describe the material's flow characteristics unless in a clay-free and fully saturated systems. Solving for F correctly is particularly important when using F to solve for hydraulic conductivity (K).

Therefore, Archie's law breaks down in three cases: (1) partially saturated aquifer [6], [25], (2) fresh water aquifer [1], [16], and (3) clay contaminated aquifer [29], [35], [38]. In Archie condition (fully saturated salt water clean sand), the apparent formation factor equals the intrinsic formation factor [2]. Whereas in non-Archie condition the apparent formation factor is no longer equals to the intrinsic formation factor. [35] concluded that Archie's empirical equations have provided the basis for the fluid saturation calculations. In shaly sands, however, exchange counter ions associated with clay minerals increase rock conductivity over that of clean sand, and the Archie relations is no longer valid. [16] showed that at low groundwater salinities, surface conduction substantially affects the relation between resistivity and hydraulic conductivity and, with even low clay contents, the relation between hydraulic conductivity and resistivity becomes more a function of clay content and grain size and less dependent (or independent) of porosity.

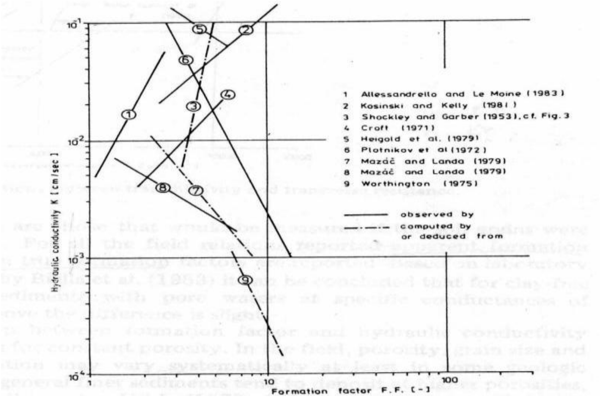

Figure 1: Reported relation between hydraulic conductivity and aquifer formation factor (from [26]).

3.1. When the Aquifer is contaminated with clay

Clay content influence on filtration coefficient was mentioned in [21], [24] as an important factor in the relationship between geophysical parameters and hydraulic conductivity for unconsolidated sediments. [4] showed, that in a heterogeneous mixture of different grains, hydraulic conductivity is controlled by the component with the finest pore system, in other words, by clay content.

The Waxman-Smits model [36] assumed two parallel conductances in shaly sand, one associated with the bulk electrolyte and the other resulting from the clay exchange cations . For fully water-saturated sands, their equation was given as

$$\frac{1}{R_o} = \frac{1}{F^*}\left[\frac{1}{R_w} + BQ_v\right] \qquad (13)$$

where F*, by analogy with Archie's equation, was called the shaly sand formation resistivity factor and Q_v, is the cation exchange capacity per unit pore volume of the rock (meq/ml). It describes the number of cations available for conduction that are loosely attached to the negatively charged clay surface sites. The ions, which can range in concentration from zero to approximately 1.0 meq/cm^3, are in addition to those in the bulk pore fluid. Q_v varies with porosity according to the following equation [38]:

$$\log Q_v = -3.56 - 2.74\log\phi \qquad (14)$$

The parameter B represents the average mobility of cations near the grain surfaces. It is the equivalent ionic conductance of clay exchange cations (mho-cm^2/meq) as a function of C_w (specific conductivity of the equilibrating electrolyte solution (mho/cm)). It describes how easily the cations can move along the clay surface. It varies with water resistivity according to the equation [38]:

$$B = 3.83[1 - 0.83\exp(-0.5/R_w)] \qquad (15)$$

According to [38], the Waxman-Smits model relates the apparent formation factor (F_a) and intrinsic formation factor (F_i):

$$F_a = \frac{F_i}{1 + BR_wQ_V} \qquad (16)$$

where, the term (BQ_v) reflects the effect of surface conduction due to clay particles. When no clay particles exist, the apparent formation factor is equal to the intrinsic formation factor. When clay particles exist, the term (BQ_v) will have a considerable value and there will be a large difference between the apparent formation factor and the intrinsic formation factor.

Re-arranging the terms, a linear relationship between $\frac{1}{F_a}$ and R_w

$$\frac{1}{F_a} = \frac{1}{F_i} + \left[\frac{BQ_v}{F_i}\right] R_w \qquad (17)$$

where, $\frac{1}{F_i}$ is the intercept of the straight line and $\frac{BQ_v}{F_i}$ represents the gradient. Thus, by plotting $\frac{1}{F_a}$ vs. fluid resistivity R_w ,we should, in principle, obtain a value for the intrinsic formation factor, which will subsequently enable us to estimate porosity.

The hydraulic conductivity calculation can be achieved through the use of the Kozeny–Carman–Bear equation,

$$K = \left[\frac{g\rho_w}{\mu_w}\right] \frac{d^2}{180} \left[\frac{\phi^3}{1-\phi^2}\right] \qquad (18)$$

3.2. Saturated and Non Saturated Aquifer

Archie's first and second laws show the relation between bulk resistivity and formation factor. Formation factor could be linked to hydraulic conductivity by Kozeny-Carman equation. One of the most recent modifications of this equation is made by [7]. They obtained the following expression for the estimation of hydraulic conductivity of unconsolidated sediments (sand, gravel, silt) [23]:

$$K_s = \frac{a}{FS^c_{p(el)}} = \frac{a}{F\left(10^5 \sigma''_{1HZ}\right)^c} \qquad (19)$$

Where K_s is the hydraulic conductivity in m/s, F is the apparent formation factor, $S_{p(el)}$ is the electrically estimated specific surface area per unit volume (μm^{-1}), σ '' is the imaginary conductivity component measured at 1 Hz (S/m), a is a constant equals 10^{-5} and C is a constant ranges between 2.8 and 4.6 depending on the material type and the method used to measure K_s. Accordingly, the modified Kozeny-Carman equation and Archie's first and second laws should control the relationship between hydraulic conductivity (K) and formation resistivity (R) in both saturated and non-saturated sediments.

4. Estimation of hydraulic conductivity from electric resistivity

Estimation of hydraulic conductivity from electric resistivity measurements can offer the following advantages:

- measurements are indirect and minimally invasive,
- resistivity data are densely sampled, repetitive, spatially continuous information can be obtained,
- Evaluation of the groundwater potentiality of new areas before well drilling. It gives advantage to select the most productive zones for drilling new wells,
- potential estimation of many hydraulic parameters through hydraulic conductivity and
- It can provide a new and important hydrogeologic trend for the application of resistivity measurements.

Practical analytical equation for estimating the hydraulic conductivity from surface electrical measurement is essential because all the inputs that use equation 12, 18 and 19 may not be readily available. [33], derived two analytical equations

$$T = (K\rho)C = \frac{KC}{\sigma} \qquad 20$$

for lateral direction current and fluid flows and

$$T = \left(K/_\rho\right)R = KR\sigma \qquad 21$$

for lateral hydraulic flow and current flowing transversely.

T is the transmissivity, K is the hydraulic conductivity, C is the longitudinal conductance and R is the transverse resistance of the aquifer material.

If the aquifer is saturated with water of uniform resistivity, then either the product $K/_\sigma$ or the product $K\sigma$ would remain constant, and T can be estimated from either C or R, respectively.

$$R = \sum_{i=1}^{n} h_i\, \rho_i \qquad 22$$

and

$$C = \sum_{i=1}^{n} h_i/_{\rho_i} \qquad 23$$

Where ρ_i and h_i are the layer resistivity and thickness of ith layer respectively.

There are many hydrogeophysical approaches that have been used to estimate hydraulic conductivity from surface resistivity measurements. These approaches are classified as follows:

4.1. The use of interpreted geophysical and hydrogeological data

- The of used vertical electrical sounding and pumping tests to provide analytical relationship to estimate the aquifer transmissivity from transverse resistance in an area of the same geological situation, if hydraulic conductivity of the aquifer at any point therein is known, considering that (K.σ) is a constant factor [10], [18], [28], [33]. This method resulted in a fairly good correlation with the measured data.

- The use of normalized aquifer resistivity instead of aquifer resistivity [34]. In this method an analytical relationship between normalized transverse resistance and aquifer transmissivity has been developed for estimating transmissivity from resistivity sounding data taking into consideration the variation in groundwater quality [9], [39], [40].
- The use of groundwater resistivity (R_w) measured from boreholes samples and apparent formation factor (F_a), estimated using formation resistivity from Vertical Electrical Sounding to estimate intrinsic formation factor. Intrinsic formation factor is used to estimate porosity. Estimated porosity is then, used in Kozeny-Carman equation to estimate hydraulic conductivity [32].

4.2. Empirical and semi-empirical relationship

- [37], correlated between the values of groundwater resistivity (Rw) determined from the chemical analysis of borehole water samples, with the formation resistivity (Ro) as deduced from the interpretation of geoelectric soundings measured nearby boreholes. He concluded that, geoelectric determination of groundwater salinity would be most exact at lower salinities and where porosity is relatively high.
- [17], carried out a correlation between resistivity values of six schlumberger VES and pumping test data of the wells. He got a good direct relation between aquifer resistivity and measured hydraulic conductivity, good direct relation between aquifer resistivity and specific capacity, and good direct relation between formation factor and measured hydraulic conductivity.
- [15], used Wenner sounding resistivity and hydraulic conductivity data from pumping test to show an inverse relation between hydraulic conductivity and resistivity due to that poorly sorted sediments are responsible for reduced porosity and thus less hydraulic conductivity.
- [22] presented data showing a direct relation between permeability and apparent formation factor and another direct relation between transmissivity and normalized aquifer resistance.
- [13], showed a direct empirical relation between hydraulic conductivity and transverse resistivity, and empirical relation between hydraulic conductivity and transverse resistivity.
- [26], studied the Factors influencing relations between electrical and hydraulic prosperities of aquifers and aquifer materials. A general hydrogeophysical model was used to demonstrate that at the aquifer scale a variety of relations might be expected.
- [14], studied the relationship between hydraulic conductivity and aquifer resistivity in fractured crystalline bedrock, Rhode Island. Reverse relation between hydraulic conductivity and aquifer resistivity has been found. This result agree with theoretical calculations by [8], laboratory sample measurements by [27], and field data relationship by [15].

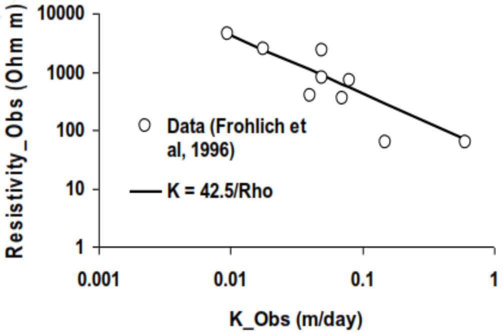

Figure 2: Direct relationship between electrical resistivity and hydraulic conductivity.

5. Probability of observing a false correlation

Most of us are familiar with the correlation co-efficient r, which is a measure of the strength of the relationship between two or more variables. But we must remember that for a given correlation co-efficient, we should make some estimate of its validity. For example, is a correlation of 0.91 good or bad? The praticioners should be aware that the smaller the samples, the greater the uncertainty about the true value of correlation. The strength of the correlation alone is not necessary an indication of whether it is an important correlation: the significant value should normally be considered. With a small sample size this is crucial, a strong correlation may easily occur by chance. With large to very large sample sizes, however, even a small correlation can be highly statistically significant. For example, a correlation with a sample of 100 and obtain r of 0.2, it is significant at the 0.05 level, yet 0.2 is only a weak correlation. So significance alone cannot be used as guide, instead the effect size and proportion of variation explained may be more important.

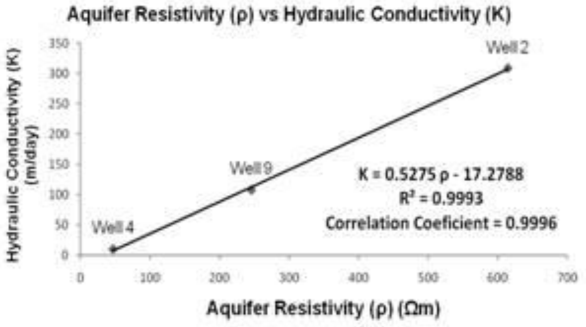

Figure 3: Graph of Aquifer Resistivity (ρ) Vs Hydraulic Conductivity (K).

Summary

Surface resistivity data can be important quantitative estimator of aquifer hydraulic parameter and geometries when correctly used in aquifer characterization studies. It is needful when using surface resistivity data to consider: 1) the nature of the aquifer (clay content); 2) the saturation; 3) the physical basis of the correlation; 4) the possibility of false correlation.

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