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EVALUATION OF AQUIFER TRASMISSIVITY IN KARST USING GEOPHYSICAL WELL LOGS

R. M. Valcarce Ortega
J. González Espinosa
Department of Geophysics
ISPJAE, La Habana, Cuba

R. Spandre
Department of Earth Sciences
University of Pisa, Italy

A hydrogeophysical model is presented for the South Havana Basin, Cuba, based on the processing of geophysical well logs, together with transmissivity data obtained from aquifer tests. The model provides clarification of the existing relationship between geophysical well log parameters and flow velocity, and demonstrates that longitudinal conductance is the best predictor of aquifer transmissivity.

INTRODUCTION

The effectiveness of geophysical methods in hydrogeologic investigations worldwide has resulted in an increasing volume of geophysical works in this field. The literature reports important results where geophysical methods, including well logging, are used to predict the behavior of hydrodynamic properties, (Jones and Bufford, 1951; Keys and MacCary, 1971; and Brown, 1988).

Mazac and Landa (1985) analyzed work carried out by other investigators, and defined the bases of the relationships between electric and hydraulic properties. They recognized the existence of direct and inverse relationships between these properties, depending on the type of aquifer, and highlighted the fact that correlations at the field scale depend on several factors, including the character of the correlations established at the laboratory scale. In general, a hydrogeophysical model should consider that:

- hydraulic conductivity is related to grain size and the effective porosity or total porosity for silts free of clay, and is related to the content of clay and the effective porosity in clayey silts,

- an inverse relationship exists between electric and hydraulic parameters when porosity controls the variations of hydraulic conductivity, and other factors like grain size and clay content are relatively constant, and

- direct relationships between electric and hydraulic parameters appear when there is an inverse correlation between clay content and hydraulic conductivity.

The majority of investigations in this field have been carried out in aquifers where primary porosity is prevalent. However, there are also numerous studies of the behavior of hydrodynamic properties based on geophysical methods in fractured and cavernous rocks.

Gómez Rivero (1979) introduced a methodology to estimate the permeability of rocks using only geophysical logs. He related the formation factor (obtained from an electrical log), the porosity (obtained from a porosity log), and the absolute permeability (obtained from laboratory data). He presented empirical equations obtained in carbonates and sands. The method could be applied to rocks with primary porosity and rocks with mixed porosity.

The methodology developed by Gómez Rivero has been successfully applied to study the permeability of volcanic-sedimentary rocks, where there is a prevalence of secondary or fracture porosity (García, 1996).

Katsube and Hume (1987) demonstrated that the relationship between the formation factor obtained from a log of focused current, and the formation factor obtained from a density log, could be used to estimate the hydraulic conductivity of fractured rocks. These authors established an equation of regression between transmissivity, obtained by hydrogeological tests in situ, and the ratio of the two formation factors for granitic intrusions in Canada.

There are also empirical correlations between the flow velocity of groundwater and geophysical well log parameters in three wells in the karstic aquifer of the South Havana Basin (Valcarce, 1995). This work established that porosity and clay content define the behavior of hydrodynamic parameters. Inverse correlations exist between the formation factor (obtained from the electrical log), and the velocity of the groundwater (obtained from the method of dilution of salt), and between the clay content (calculated from the natural gamma log), and flow velocity. In this paper, this analysis is expanded to 33 wells in the South Havana Basin aquifer, and includes other geophysical well parameters, and the results of aquifer tests.

The South Havana Basin aquifer is a coastal aquifer formed from rocks of Neogene age, mainly of the Güines formation. It contains a great variety of limestones, all with an elevated grade of karstification. Figure 1 shows the geographical location of the basin and the 33 wells studied.

The hydrogeological parameters of this aquifer have been studied for more than 50 years, since the first water supply and industrial use projects were established. Pumping tests give transmissivities between 1.15 x 10^{-1} m^2/sec and 5.78 x 10^{-1} m^2/sec, and in some places even greater. The great variation of values depends on the degree of karstification of the limestones. Great aquifer heterogeneity exists, with the only trend being a decrease in hydraulic conductivity with depth (López, 1991).

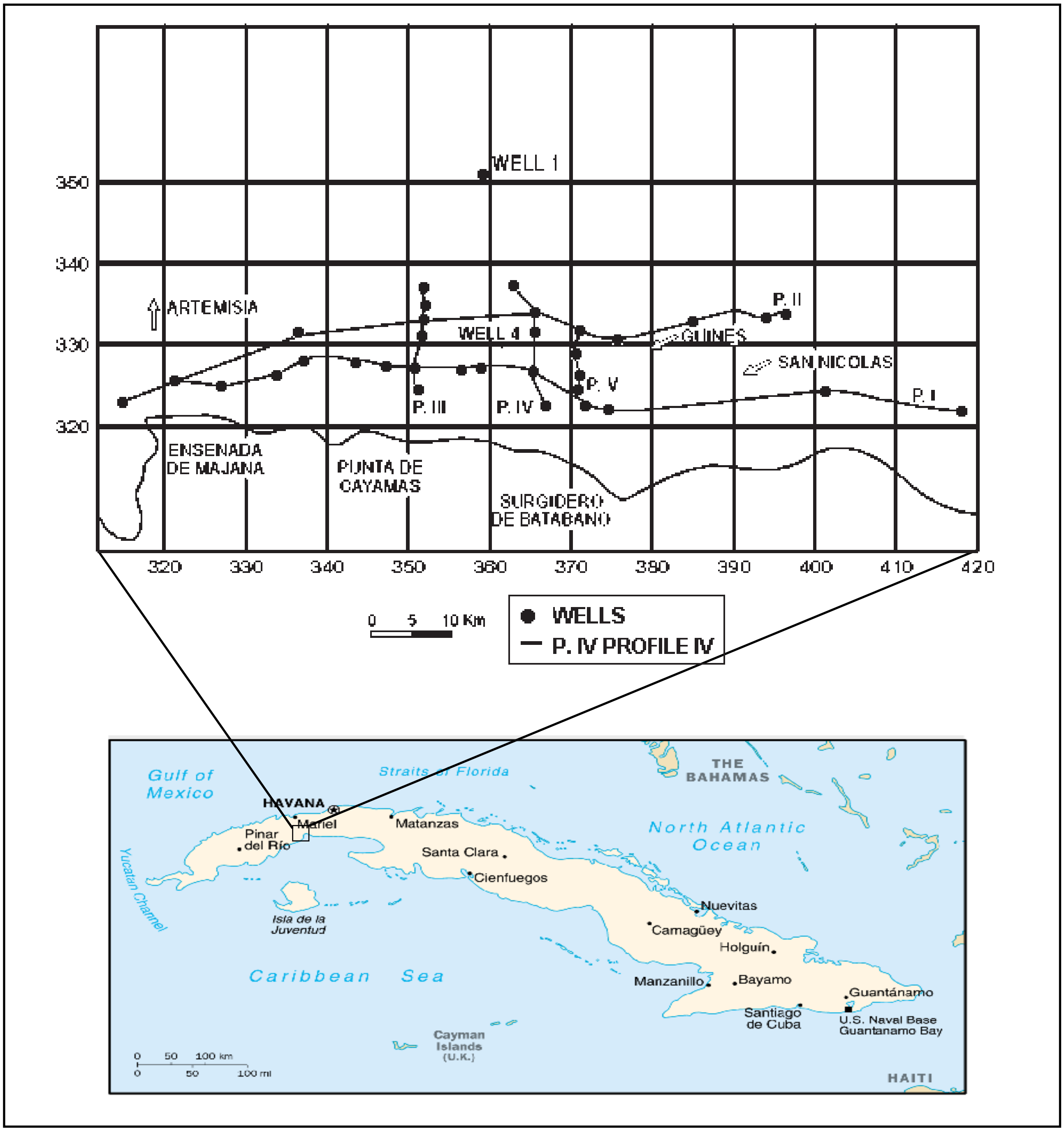

Figure 1. Location of study wells in the South Havana Basin, Cuba.

METHODOLOGY AND RESULTS

From the interpretation of the electric log (*Rt*) and natural gamma log (*Ig*) in 33 wells, parameters for each layer were calculated as follows (Ruiz and Kobr, 1989):

Formation factor (*F*):

$$F = \frac{Rt}{Rw} \tag{1}$$

where:

Rt : electric resistivity of the saturated rock, obtained from the electric log corrected by the corresponding factors.

Rw : electric resistivity of the water in the rock.

Porosity, according to the relationship of Archie:

$$\phi_{Archie} = \left(\frac{1}{F}\right)^{m} \tag{2}$$

where:

m : exponent of cementation of the rock. For the area of study, m = 1.3.

Clay content (*Car*), as follows:

$$Car = \frac{Ig - Ig_{\min}}{Ig_{\max} - Ig_{\min}} \tag{3}$$

where:

Ig : natural gamma intensity measurement in the well corrected by the corresponding factors.

Igmin : natural gamma intensity of the rock without clay.

Igmax : natural gamma intensity of the clay.

Transverse resistance (R_T) (Orellana, 1972):

$$R_T = hR_t \tag{4}$$

where:

h : thickness of layer.

Rt : electric resistivity of the layer, obtained from the electric log and corrected by the corresponding factors.

Longitudinal conductance (*S*) (Orellana, 1972):

$$S = \frac{h}{R_t} \tag{5}$$

In the 33 wells, 201 intervals were characterized using this methodology.

From the interpretation of the method of dilution of salt, the flow velocity of groundwater (*Vf*), the coefficient of filtration (*Kf*) and the transmissivity (*T*) were calculated (Kobr, 1992; Kobr et al., 1993).

Table 1 shows the linear correlation coefficients between the geophysical well parameters. This table shows a positive correlation between the longitudinal conductance (*S*) and the transmissivity (*T*); and a negative correlation between the clay content (*Car*) and the transmissivity (*T*). The ability of the longitudinal conductance (*S*) to estimate the transmissivity of the aquifer stands out.

Table 1. Linear Correlation Coefficients Between Geophysical Well Parameters, South Havana Basin

	Log Rt	*log R_T*	*log S*	*log Ig*	*log F*	*log f_{Archie}*	*log Car*
Log Vf	-0.27	-0.07	0.38	-0.43	-0.14	0.14	-0.39
log Kf	-0.27	-0.07	0.38	-0.43	-0.14	0.14	-0.39
log T	-0.19	0.26	0.58	-0.45	-0.01	0.01	-0.43

To identify and characterize groups of relatively homogeneous composition and to study the component structural of the system, a cluster analysis on these attributes was applied, (Alfonso, 1989; Samper and Carrera, 1990). For a classification model that considers the existence of 6 groups, and using the better results of the Fisher test, the correlation between geophysical well parameters and groundwater flow velocity was studied using the centroids of the defined groups. Table 2 shows the results.

Table 2. Linear Correlation Coefficients Between the Centroids of the Model of Classification with 6 Groups

	Rt	*R_T*	*S*	*F*	*ϕ1.3*	*Ig*	*Car*	*ηar*
Vf	-0.35	-0.29	0.83	-0.33	0.61	-0.80	-0.82	-0.85

These results show that:

- the relationship between longitudinal conductance and groundwater flow velocity is the best relationship between aquifer hydraulic and electrical properties, and

- increasing flow velocity of groundwater occurs with decreasing clay content in the aquifer.

From these results, the correlation was studied between longitudinal conductance (*S*), calculated from the electrical log, and transmissivity obtained from pumping tests, (T_{PUMPING}). A fundamental problem was encountered because the hydrogeological tests and the geophysical well log measurements did not coincide in time. For this reason, it was decided that conventional analysis could not be used, and instead the method of Uvarov was applied (Sacasas, 1987).

The method of Uvarov obtains the linear regression equation between two attributes, x and *y*, that are not necessarily a couplet. The method requires knowing if the correlation between both parameters is positive or negative.

These expressions are:

a) for normal distributions of x and y, and direct correlation between both variables:

$$y_i = \frac{R_y}{R_x}\left(x_i - x_o\right) + y_o \tag{6}$$

b) for normal distributions of x and y, and inverse correlation between both variables:

$$y_i = \frac{R_y}{R_x}\left(x_i - x_B\right) + y_B \tag{7}$$

where:

x_o, y_o: estimate of the minimal values of x and y.

x_B, y_B : estimate of the maximal values of x and y.

For a level of probability of 0.997, these maximum and minimum values are estimated as:

$$\begin{aligned} x_o &= \mu_x - 2.75\sigma_x \\ x_B &= \mu_x + 2.75\sigma_x \\ y_o &= \mu_y - 2.75\sigma_y \\ y_B &= \mu_y + 2.75\sigma_y \end{aligned}$$

where:

μ_x, μ_y: arithmetic mean of x and y respectively.

σ_x, σ_y : standard deviation of x and y respectively.

R_x, R_y : range of the x and y variables calculated as:

$$\begin{aligned} R_x &= x_B - x_o \\ R_y &= y_B - y_o \end{aligned}$$

If one of the variables, x or y, shows a logarithmic normal distribution, the same expressions can be applied using the logarithm of the variable in question.

The average thickness for the 26 aquifer tests was 24 m, and the values of longitudinal conductance (S) were calculated for 24 m of depth below the water level for the 33 wells.

To relate longitudinal conductance (S) and aquifer transmissivity (T) by means of the relationships of Uvarov, (T_{UVAROV}), it was assumed that:

- according to the information from well log geophysics, the correlation between these parameters is positive, and

- the longitudinal conductance and transmissivity have a logarithmic normal statistical distribution (Hoeksema and Kitanidis, 1985; Samper and Race, 1990).

The relationship of Uvarov between the longitudinal conductance calculated for 33 wells, and the transmissivity obtained from 26 pumping tests was the following:

$$\log\left(T_{i_{\mathrm{UVAROV}}}\right) = \left\{1.352\left[\log\left(S_i\right) + 1.215\right] + 2.361\right\} / 86400 \tag{8}$$

To evaluate the effectiveness of this methodology in the prediction of the transmissivity, results from 3 wells were analyzed where pumping tests and electric logs were available. Table 3 shows the results.

Table 3: Comparison Between Transmissivity Obtained from Pumping Test ($T_{\mathrm{PUMPING})}$ and Trasmissivity Calculated from the Relation of Uvarov (T_{UVAROV})

Well	**T_{PUMPING} (m^2/s)**	**T_{UVAROV} (m^2/s)**	**Error (%)**
A1	5.70×10^{-2}	5.67×10^{-2}	0.52
A2	5.33×10^{-2}	4.62×10^{-2}	1.30
A3	4.14×10^{-2}	3.60×10^{-2}	1.30

CONCLUSIONS

The applied data processing methodology allowed the definition of more general relations between geophysical and hydrodynamic parameters for the South Havana Basin. The effectiveness of geophysical well logs to evaluate the groundwater resources was demonstrated, including in karstic aquifers, where heterogeneity and anisotropy are fundamental hydrogeological properties.

In the karstic aquifers of the South Havana Basin, the longitudinal conductance is the geoelectric parameter that is the best predictor of aquifer transmissivity.

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ADDRESS FOR CORRESPONDENCE
Ing. Rosa Maria Valcarce Ortega
Directora de Relaciones Internacionales
Departamento de Geociencias
ISPJAE
Ciudad Habana
Cuba

Email: rosy@civil.ispjae.edu.cu