CALCULATION OF TRANSVERSE RESISTANCE TO CORRECT AQUIFER RESISTIVITY OF GROUNDWATER SATURATED ZONES : IMPLICATIONS FOR ESTIMATING ITS HYDROGEOLOGICAL PROPERTIES

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ABSTRACT

Serious difficulties are generally encountered during the interpretation of vertical electric sounding curves (VES). The purpose of this study is to correct the resistivity values of saturated aquifers by utilizing the conductivity and transverse resistance of the dry and saturated zones as revealed by resistivity well-logging technique. The true resistivity, ρ3, of the saturated zone, was calculated. The transverse resistance values were then corrected for all vertical electric sounding results. This procedure makes it possible to delineate and quantify underground water zones, based on the maps of hydrogeological and physical properties of aquifers.

Keywords: transverse resistance, transmissivity, resistivity, vertical electrical sounding

INTRODUCTION

The technique of transverse resistance has been applied in several studies in order to determine hydrodynamic parameters (Sinan & Rayack, 2006; El-Arbi *et al.*, 2008). Several methods of interpretation of vertical electric sounding have been developed. All of these interpretations present serious difficulties. In this study a synoptic review is given with special emphasis on such difficulties. This work also discusses the factors of influence that could be met in the following methods (which are used for all VES interpretation in the field of study):

a- Automatic correction method based on the Ghosh's filter .
b- Correction method based on transverse resistance.

The significance of these two methods will be emphasized in the determination of hydrogeological and physical parameters.

MATERIALS AND METHODS

Vertical electric sounding (VES)

Master curves interpretation method

Principle: in the interpretation of VES diagrams, the true resistivity of layers must be estimated from the apparent resistivity of the curves observed in the field. Their depths are also roughly estimated from the length of the configuration (distance between the current electrodes AB Schlumberger device). In fact, from these results it can be differentiated between a succession of conducting and resistant layers.

Historical views: many reference curves in the case of three or more layers have been published. The most known and used are those of the General Geophysical Company (C.G.G. 1964). The different types of theoretical curves are represented by four particular values of the third formation resistivity ρ3. $\rho 3 = 0$; $\rho 3 = 1$; $\rho 3 = \rho 2^2 / \rho 1$; $\rho 3 = \infty$ (ρ1 and ρ2 are the resistivities of the first and second layers). The use of these curves is simple.

Certain transfers are searched for, parallel to an axis, to make the observed curve obtained in the field coincide with one of the theoretical reference curves. In practice, there has never been a perfect coincidence between a field curve and a theoretical curve. The results have to be interpolated between the two curves. Among the theoretical curves, Cagniard's master curves are quoted. Whatever the method used, the manual calculus is very long and approximate, especially when the number of layers exceeds three (Cagniard, 1952). The utilization of a computer greatly facilitates the analysis and saves the time of long elaborate work (Jha *et al*., 2008).

Automatic interpretation

Direct method: the process consists of passing from an observed apparent resistivity curve to a conversion of resistivity in order to analyze the true resistivity and the formation depth corresponding to the vertical electric sounding curve. In practice, this method is very complicated because there is no single solution for the determination of these parameters *e.g.* Kunetz and Rocroi (1969) and Duprat *et al*. (1973). To obtain the transformation of the apparent resistivity curve, the coefficient of Ghosh's linear filter is used. Nine points are also chosen. Whenever this program is applied to a given curve certain errors arise, particularly when a conductive layer overlies a resistive one.

Program utilization procedure: it is sufficient to introduce the number of layers in the field, together with their resistivity and thickness, as given by the master curves (chart of Cagniard) in order to obtain the transformation curve. For this program, the distance between current electrodes as a unit, and nine observation points were chosen.

It is well known that the Ghosh's inverse method is more stable than the direct method (Ghosh, 1971).

Numerical analysis: Computer methods were utilized for analysis and interpretation of VES data. A program modified for use in a portable personal computer was utilized by the author in the field where the study was conducted (Harb, 1982) . This program presents an unusual advantage and the power to manipulate and analyse a great number of layers (Fig.1).

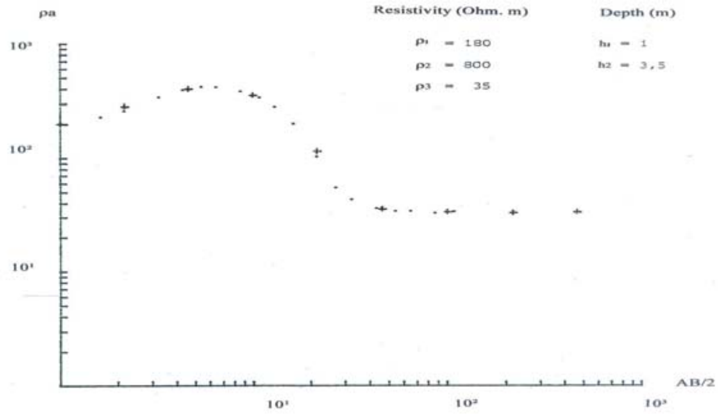


Figure 1. Example of the correction of electric sounding curves by using the modified program for the Ghosh filter method (Harb, 1982).

Function interpretation of electric sounding diagrams

```
          D =D/C1
Bucle  :  For j=0 to 8 do
              D=D*C2
              T=R(N)
              For i=N-1 to 1 do
                T=(1-T/R(i)/(1+T/R(i))
                T = R(i)(1-T)*E*P(E(i)/D)
              Next i
              V(j) = T
           Next j
           For L = 1 to 9 do
              T = 0
              T = T+K(L)*V(j+L-9)
           Next  L
           Print  (D,T/400)
           If (j<8+M) {goto Bucle}
```

Diagram : Computer interpretation of electric sounding diagrams (Harb, 1982)
K(1)……K (9) : Linear Coefficients ;
D : Distance AB/2 ;
N : Number of Layers ;
R (1)…………R (N) : True resistivity values ;
E (1)…….E (N-1) : thickness ;
M : Number of points.

Difficulties of interpretation

Whatever the method used of VES : master curves; Direct and Inverse method of Ghosh linear filter (Ghosh, 1971); computer method by numerical analysis (Harb, 1982), it presents a certain number of limitations:

1-It supposes that the bedding is horizontal.
2-Any two different layers must have a resistivity contrast of $\rho 2 / \rho 1 \neq 1$.
3-Every layer must have sufficient thickness with increasing values with depth. Consider a section having <u>n</u> layers, the electric contrast always varies, decreases or increases, *i.e.,*
$\rho 1 > \rho 2 > \rho 3$ ………………> ρn (Fig. 2a)
$\rho 1 < \rho 2 < \rho 3$ ………………< ρn (Fig. 2b)

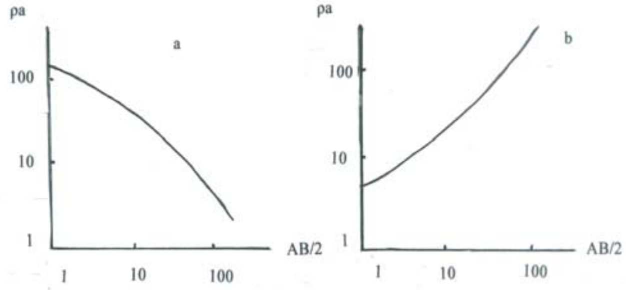


Figure 2. An example of VES showing non apparent intermediate layers.

When the thickness of each layer is almost equal, the apparent resistivity curve will have a diagram form of two or three layers. This aspect is referred to as the suppression phenomenon. In the case of a thin layer having an intermediate resistivity compared with that of the neighboring layers, it is not delineated on the VES curves. Otherwise, when its thickness increases, it deforms the diagrams. Prior to the identification of the thin layer, its effect could modify the thickness and the resistivity values of the neighboring layers. The interpretation of VES curves characterized by the "bell" form diagrams is very delicate. The use of master curves doesn't always allow the determination of the electric characteristics of the first layer ("Bell Form" of VES diagram).

The section which indicates strong resistivity in this type of diagram can be interpreted in many ways, because it can be superimposed on many theoretical curves. This phenomenon could be explained by the principle of equivalence. This principle applies to layers whose resistivity is between that of the neighboring -underlying and overlying -layers. In fact, a resistant layer confined between two more conductive layers is mostly revealed by its "transverse resistance" $Rt = \rho.h$, where h is the thickness of the layer.

On the other hand, a conductive layer confined between two more resistant layers will be essentially known by its "horizontal conductance" (C) (Dubois & Diament, 2001).

Therefore, it will be difficult or even impossible to distinguish these intermediate layers on the VES curves when they are situated between two layers of different resistivity and thickness as long as the values of Rt are close.

Because a lot of difficulties in VES curves such as the equivalence phenomenon, heterogeneities effects, topographic effects (among many others), the application of the transverse resistance is necessary to correct the aquifer resistivity of saturated zone in order to calculate the hydrogeological characteristics of underground water.

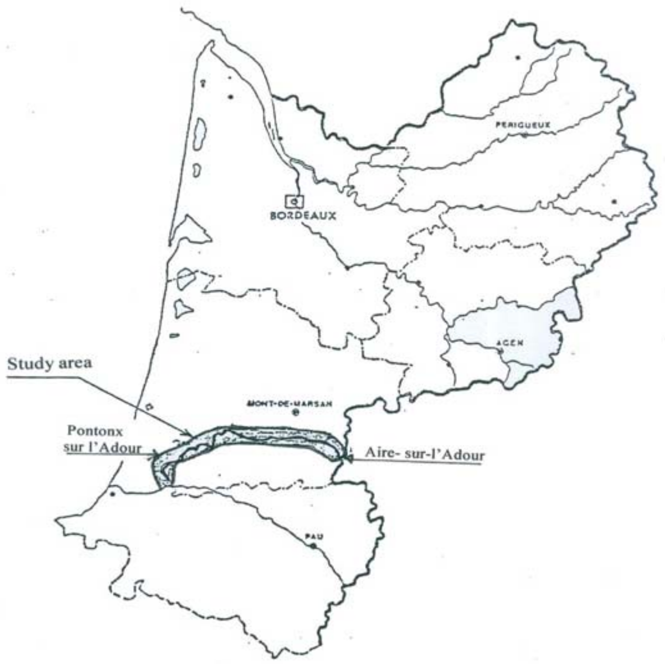
RESULTS AND DISCUSSION

Role of the transverse resistance in hydrogeology

The conductivity and transverse resistance of layers clarify a strong interpretation apart from any previous analysis of underground water (website ades). These applications are beyond the usual hydrogeological use of VES. These two factors (conductivity and transverse resistance) commonly yield the characteristics of aquifers (website BRGM). Instead of this approach, it is advantageous to consider the combination of the resistivity and the thickness of rock layers as a basis in evaluating some related properties such as the transmissivity and the capacity (S) of the aquifers. Ultimately, such approach could be oriented towards evaluating and protecting ground water resources (Guelala *et al*., 2009).

This method was applied on a 70 km long alluvial field in the Adour valley in France (map of study area) .

Map of Study Area in the Adour's Valley -France



350 VES distributed over 29 profiles were carried out. These soundings were spaced between 150 and 200 meters. Some 36 wells distributed over the above mentioned zone established a correlation between the depths or thicknesses given by VES and well-logging. The resultant regression line has a coefficient R= 0.87 (Fig 3).

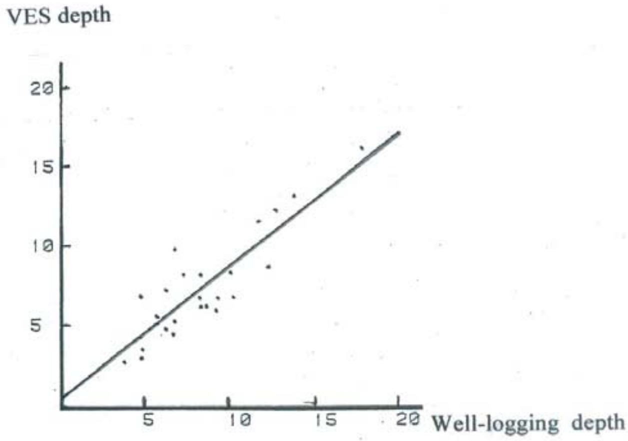


Figure 3. Correlation between the depth given by VES and well-logging.

Each geophysics profile has permitted the realization of geoelectrical sections based on the sensitivities and thicknesses of the layers in the Adour valley (Fig. 4).

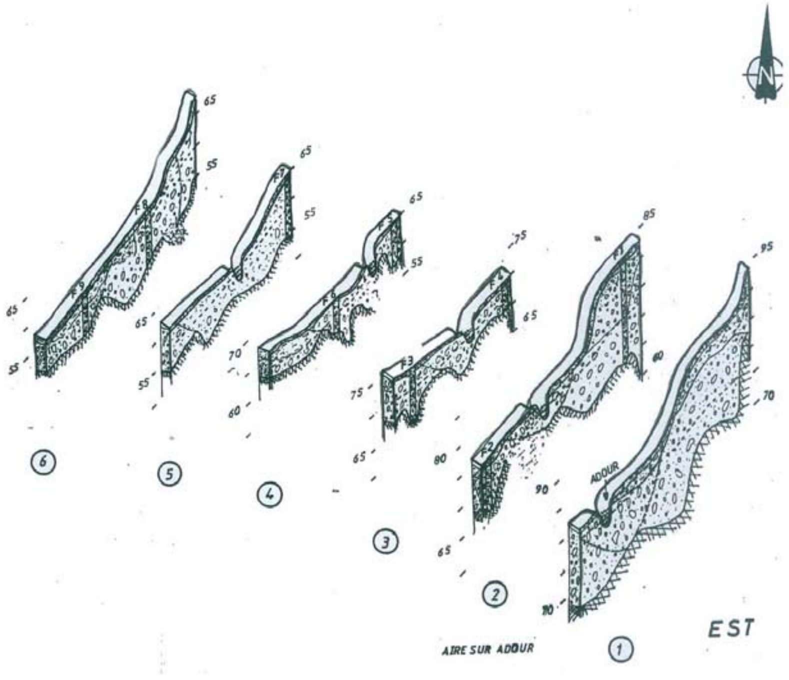


Figure 4. Geoelectrical profiles.

Definition of transverse resistance

Transverse resistance is the product of the layer's true resistivity and its thickness. The difficulties in the interpretation of resistivity curves for the saturated part of the aquifer led to use a correlation method referring to well-logging results. The transverse resistance parameter for the saturated zone of the aquifer makes it possible to delineate the most favorable zones, with the objective of hydrogeological exploration (Gilli *et al*., 2004).

Well-logging method for analysis

This method aims to correct the resistivity values of the aquifer's saturated part and recalculate the transverse resistance of the dry part. Knowing the physical and electrical parameters of electric sounding existing in the neighborhood of the well-logging borehole, the transverse resistances of the resistant part of the electrical sounding curve are calculated :

$$\begin{array}{c} R\ t = \rho(i+1).\ h\ (i+1) + \rho(i+2).\ h\ (i+2) \\ i=1 \end{array}$$

The total, Rt, is distributed over the dry and wet parts of the section's aquifer's well-logging. Then the resistivity $\rho 3$ of the saturated zone is calculated in terms of the correct thicknesses $h'2$ and $h'3$ by considering the first resistivity value, $\rho 2$, of the dry resistant part given by VES (Fig. 5).

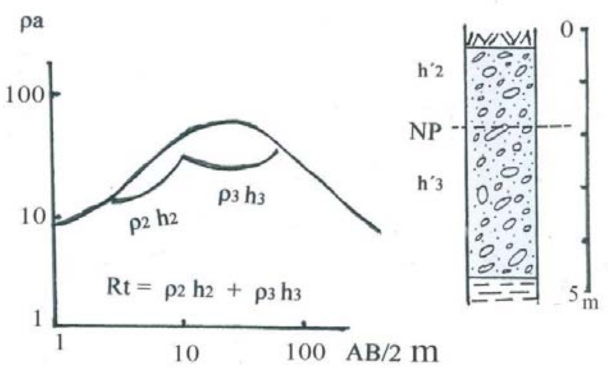


Figure 5. Analysis of saturated aquifer resistivity by transverse resistance of dry and saturated parts.

$\rho 3= Rt- \rho 2.h'2/h'3$ where $h'2$ and $h'3$ respectively represent the thicknesses of the saturated and non saturated zones of each borehole.

This technique was applied to all electric sounding near the well logging boreholes. It allowed the investigation of the resistivity of the saturated aquifer over the area of the entire field of study. This trial and error technique was used for all vertical electric sounding of the Adour field . The geoelectrical profiles allow one to distinguish between the depth of the saturated and the non saturated aquifers by means of the water table level.

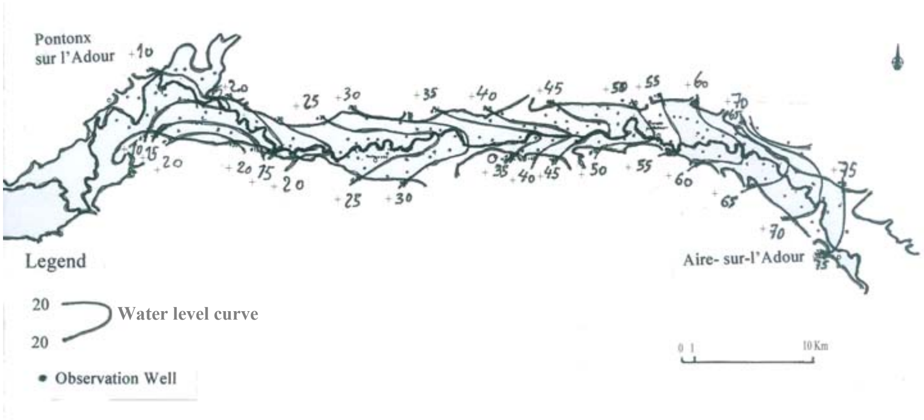


Figure 6. Water table map.

Since water level is an essential element for the analysis of vertical electrical sounding, it is important to map the general water level of the aquifers in the area of study.

Transverse resistances and determination of the saturated aquifer

In order to calculate the thickness of the aquifer's saturated zone, the surface of the water level was mapped by referring to the water table map (Fig. 6) as revealed on the geoelectrical sections (Fig. 4). The depth analysis of the saturated zone has been calculated, for every VES referring from the depth of electrical susbstratum and depth of the estimated water table level. Knowing the distribution of saturated and dry zones of the aquifer given by all VES, the procedure of analysis by well-logging was applied. Corrected values of the resistivity for the saturated zone were obtained. Referring to the corrected values, the transverse resistance of the saturated zone was recalculated over the study area. In order to demonstrate the variations of this parameter in the valley of Adour (study area), these results were mapped (Fig. 7).

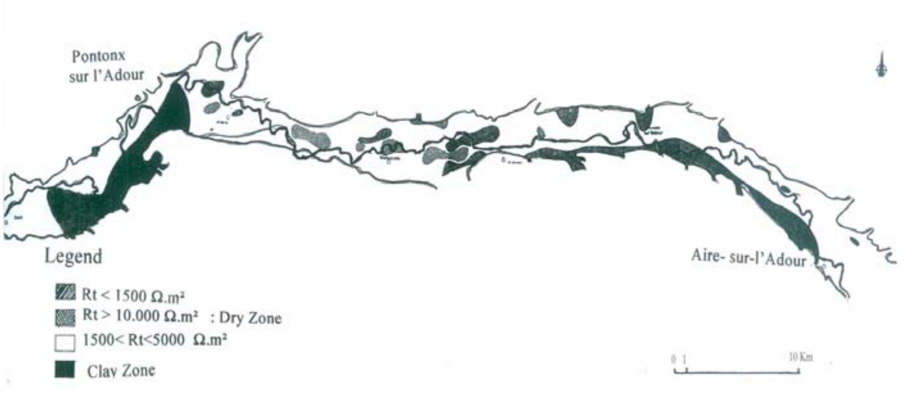


Figure 7. Transverse resistance map.

In the geographic distribution of results or values, a threshold of 1500 Ω.m^2 was chosen. In the upstream part of the Adour valley, the left bank of the river presents values up to 1500 Ω.m^2. However, in the right bank, they are higher. In the downstream part, most values exceed 1500 Ω.m2.

In conclusion, this map allows one to delineate favorable aquifer zones (Rt>1500 Ω.m^2., which have an important extension in the entire valley (investigated area). Then, the relationship between the transverse resistance and the transmissivity (T) characterizing the aquifers was searched for.

Correlation between Rt and T

The transmissivity (T) is a hydrogeological parameter, proportional to the permeability (k) and thickness (h) of the aquifer. The transverse resistance is a geophysical parameter, proportional to the resistivity (ρ) and thickness (h) of the aquifer.

$$T = k.h \text{ and } Rt = \rho.h$$

These two formulas are of the same type, because they characterize an aquifer formation. Consequently, in this alluvial formation it was found that the two factors (ρ & k) change in the same direction. A linear relationship was established between T and Rt by the experimental measurements executed in the field. The transmissivity values used were obtained by the pumping test based on the Jacob method. The transmissivity values were graphically drawn as a function of transverse resistances corresponding to the same aquifer's level for all pumping tests. The method of analysis used was the method of least squares. The equation of the straight line (Fig. 8) : $y = 2.9\ 10^{-6}\ x - 6.3\ .10^{-4}$ has a correlation coefficient R= 0.79.

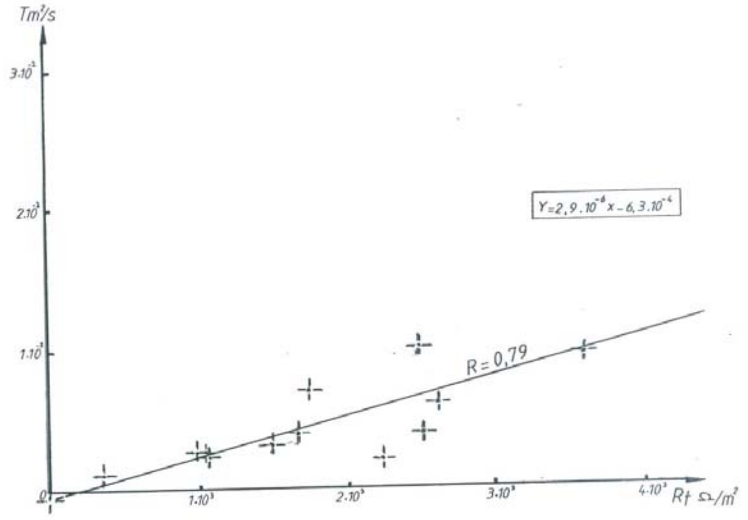


Figure 8. Correlation between the transmissivity and the transverse resistance in Adour valley.

This coefficient indicates that a linear relationship exists between the transmissivity and the transverse resistance of the aquifer. This correlation, based on twelve points, seems very reliable for an alluvial formation.

Analysis of the correlation between transmissivity and resistance T= f (Rt)

Knowing the corrected Rt for every VES, the values of the corresponding transmissivities were extrapolated based on the correlation straight line of correlation already established. The distribution of this data proves that the values vary between 10^{-2} and 10^{-3} m²/s. This type of variation corresponds to the validity field of the straight linear relationship. These results of transmissivities were mapped in order to localize the most productive zones of the underground water (Fig.9).

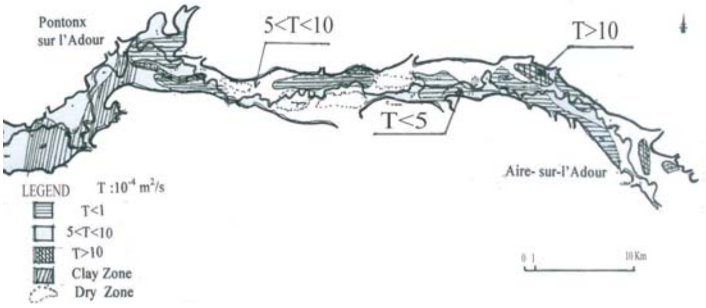


Figure 9. Map of transmissivity.

On the map of transmissivity (Fig. 9), the upstream part situated on the right bank of Adour's river has a strong transmissivity, whereas the left bank of the river has less transmissivity. The low valley is characterized by strong transmissivity. The terraces have transmissivities in the order of $0.3.10^{-2}$ m²/s representing dry zones.

Downstream of the study's area, the central zone of the valley has transmissivity values exceeding $0.5.\ 10^{-2}$ m²/s. In the lower part of valley the values decrease. The analysis of the aquifer's transmissivity allows one to calculate the permeability (k) of the whole section of the study area. The procedure is based on the relation : k = T/h. These values contributed to creation of a map of permeability (Fig. 10).

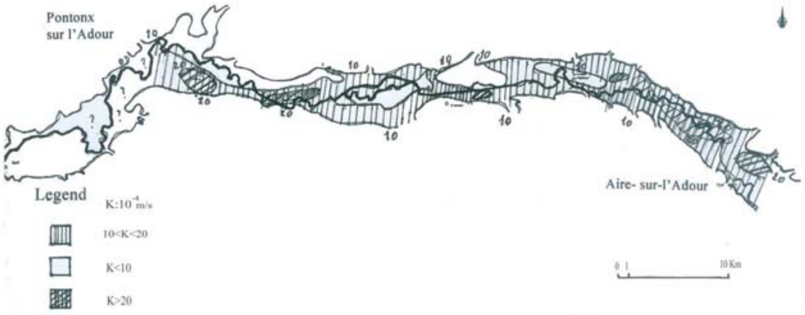


Figure 10. Map of permeability.

CONCLUSION

The study of these hydrogeological and physical parameters makes it possible to characterize the aquifer properties of the Adour valley, the geometrical extension of which has been defined previously. Likewise, the transverse resistance has shown the most favorable zones for hydrogeological exploitation. The transmissivity calculated by geoelectrical measurements corresponds to the hydrogeological data. It allows the estimation of the underground water potential of the study area.

The permeability extrapolated from the previous parameter characterized the flow in the saturated part of the aquifer.

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