APPRAISAL OF GEOSTATISTICAL METHODS TO ESTIMATE HYDRAULIC PROPERTIES OF A COMPLEX BASALTIC RESERVOIR. THE GULF BASALTIC AQUIFER, DJIBOUTI, HORN OF AFRICA.

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ABSTRACT

Estimating hydraulic properties of highly heterogeneous reservoirs is still a problem difficult to solve, especially when available data are few and poorly distributed. Such an estimate is still necessary to develop numerical models for resource management of these reservoirs. In the Republic of Djibouti, the basaltic reservoirs are the main source of water supply. Djibouti, the capital city, is especially supplied with water from the Gulf basaltic aquifer. The sustainable management of this reservoir is currently a priority, since its resources are overexploited. The objective of this work is to analyze several geostatistical methods (ordinary kriging, cokriging and kriging with external drift) and compare their performances to estimate the properties of highly heterogeneous reservoirs.

The Gulf basaltic aquifer is strongly heterogeneous. The transmissivity (T, m²/h) data are few and clustered mainly along the coastline. However, several geophysical surveys were undertaken over this basaltic reservoir. At present, a great deal of geoelectric data (transverse resistance, R ohm.m²), almost uniformly distributed, are available. Performances of the geostatistical methods are assessed using the cross-validation procedure. The results show that ordinary kriging, which is a univariate method, is the least suitable method to assess the transmissivity of the basaltic aquifer. The use of the transverse resistance (R), as an auxiliary variable, much more densely sampled than the principal variable (T), can significantly improve the estimation of T. Comparing the cokriging and the kriging with external drift, shows that KED is the best estimation procedure of the transmissivity of this highly heterogeneous reservoir.

INTRODUCTION

Basaltic volcanic rocks form aquifers which can contain significant groundwater resources and represent the major water supply source (Krivochieva and Chouteau, 2003). The structure of these aquifers can however be strongly heterogeneous and show high variability in reservoir properties (Livet et al., 1999 . Sruoga et al., 2003 ; Jalludin and Razack, 1994), which actually constitutes a real difficulty when one aims at the identification of these aquifers. The resources of these aquifers can accordingly be wrongly exploited, resulting in overexploitation and quality deterioration.

This situation prevails in the Republic of Djibouti, a country of 23000 km² and 650000 inhabitans located in the Horn of Africa at the crossing of the Red Sea and the Indian Ocean (Fig.1). The territory of Djibouti is mainly covered by volcanic rocks (more than 75%) as a result of the Red Sea, Gulf of Aden and East African rifts spreadings. The country undergoes an arid climate and does not possess perennial surface waters. Thus water resources are almost solely provided by aquifers located in volcanic rocks.

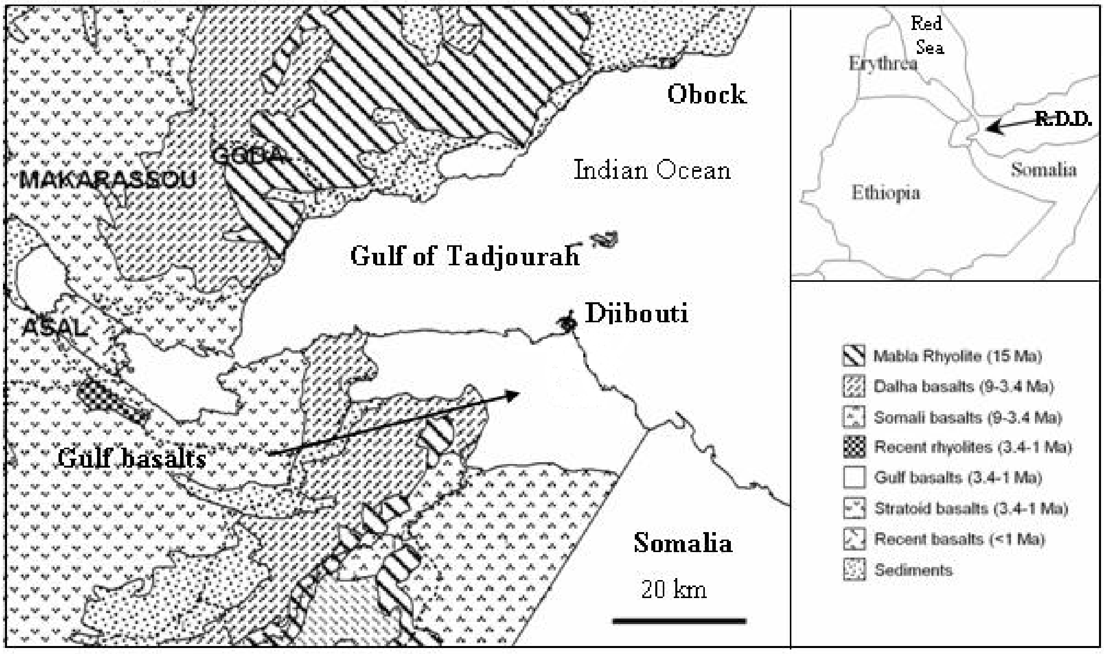

Figure 1: Geological setting of the Gulf basaltic aquifer.

The city of Djibouti, capital of the Republic, is supplied with drinking water, abstracted from the Gulf basaltic aquifer. The steady and drastic increase in water demands, due to the rapid development of the capital particularly during the last two decades, has led to an intensive exploitation of this aquifer and has severely depleted its reserves and deteriorated its quality (Houssein and Jalludin, 1996 ; Jalludin and Razack 1997). An optimal and sustainable management of this aquifer must be undertaken in order to prevent an irreversible deterioration of its resources. The evaluation of this aquifer hydrogeological properties and the elaboration of a management numerical model are the principal objectives of a large research program launched by the authorities. All the transmissivity data available since the Sixties were assembled in a database (Jalludin & Razack, 2004). However, transmissivity data of the Gulf aquifer are still few and irregularly distributed (Fig.2). Upscaling these few data at the scale of the aquifer is a prerequisite, before undertaking a valuable modeling task.

This paper is focused on the estimation of the transmissivity of this strongly heterogeneous aquifer, with the use of geostatistical methods (Isaak and Srivastava, 1989; Kitanidis, 2000). A noteworthy advantage of geostatistics is that these estimation procedures take into account the spatial variability of the data. This propriety is essential when dealing with very highly heterogeneous medium such as the Gulf basaltic aquifer. Three methods are compared, ordinary kriging (OK), cokriging (COK) and kriging with external drift (KED). OK is a univariate estimation method, which uses only the available data of the principal variable to estimate. COK and KED are multivariate estimation methods as they use the principal variable but also one or more secondary variables which are sampled at much more locations over the study area. In the latter case, the principal and secondary variables should display significant correlations.

In this study, the availability of a large number of geoelectrical data covering the aquifer system was exploited as secondary data in the COK and KED procedures. The Gulf basaltic aquifer was subjected to a number of geoelectric surveys in the Sixties. Accordingly, geoelectric data are quite numerous and are distributed almost over the whole area of the aquifer (Fig.3). Comparison of the different estimation methods, (OK, COK, KED) is made using the cross-validation procedure (Isaak and Srivastava, 1989; Clark, 1986). The following points will be developed : statistical analysis of available transmissivity (T, m^2/h) and transverse resistance (R, $ohm.m^2$) data; statistical regression between T and R data ; variographic analysis of T and R data; comparison of the three geostatistical estimation methods ; estimation of the transmissivity using the best geostatistical method. .

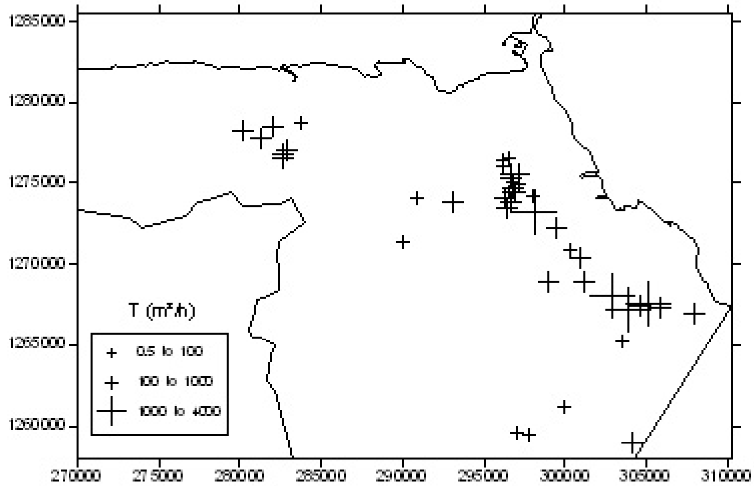

Figure 2: Distribution of the transmissivity data

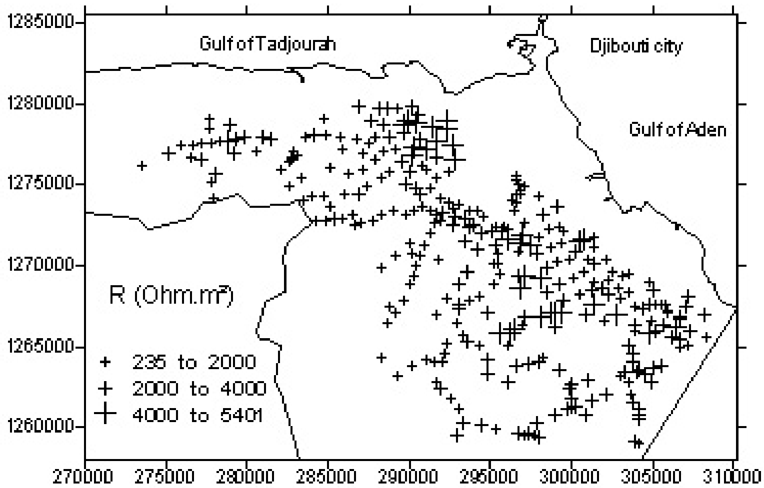

Figure 2 – Distribution of the transverse resistance (R, ohm.m²) data

Summary of univariate and bivariate geostatistical analysis

A few noteworthy features regarding the geostatistical methods used in this study are highlighted hereunder. A detailed presentation can be found in basic geostatistics references (Isaaks and Srivastava, 1989 , Kitanidis, 2000; Clark and Harper, 2000).

A geostatistical estimation procedure is twofold. When the variable of interest is unique (say Z), the first objective is to describe the spatial correlation between sample points. This is achieved by calculating the variogram, which is defined by the following equation:

$$\gamma_Z(h) = \frac{1}{2} E\left[\left(Z(x+h) - Z(x)\right)^2\right] \quad [1]$$

where $h=x_i-x_j$; E: mathematical expectation. The variogram is the basic tool for geostatistical analysis. It shows the spatial variability of the regionalized variable. The second objective is to provide the best estimation of the variable Z at unsampled points. Contrary to other estimation techniques, Geostatistics takes into account the observable spatial correlation between sample points to predict the variable at unsampled points. The geostatistical univariate estimation method used in this study is the ordinary kriging (OK). The kriging estimator (Eq.2) at a point x_0 is written:

$$Z^*(x_0) = Z_0^* = \sum_{i=1}^{N} \lambda_i Z(x_i) \quad [2]$$

Z_0^* is a linear weighted estimator, N is the number of values involved in the estimation within the searching neighbourhood and λ_i are weights. The OK estimator should satisfy two major conditions, called the unbiasedness and optimality conditions. These conditions stipulate that the errors of estimate (differences between the true values and the estimated values) should have a mean equal to zero and a minimum variance. They are written, respectively:

$$\mathrm{E}\left(\mathrm{Z}^* - \mathrm{Z}_0\right) = 0 \quad [3]$$

$$\mathrm{Var}\left(\mathrm{Z}^* - \mathrm{Z}_0\right) \text{ minimum} \quad [4]$$

In many cases, the principal variable Z is undersampled, whereas one (or more) secondary variables are available at much more sample points. In such cases, the secondary variables, which should be correlated with the principal one, can be used to improve the estimation of the principal variable Z. Two bivariate geostatistical methods, which use one secondary variable densely sampled, are implemented in this study : cokriging (COK) and kriging with external drift (KED).

Cokriging requires the variogram of the principal variable Z (Eq.1), the variogram of the secondary variable Y (Eq.5) and the cross variogram (eq.6) of both variables Z and Y :

$$\gamma_Y(h) = \frac{1}{2} E\left[\left(Y(x+h) - Y(x)\right)^2\right] \quad [5]$$

$$\gamma_{ZY}(h) = \gamma_{YZ}(h) = \frac{1}{2} E\left[\left(Z(x+h) - Z(x)\right)\left(Y(x+h) - Y(x)\right)\right] \quad [6]$$

The variogram, $\gamma_Z(h)$ or $\gamma_Y(h)$, as stated above, shows the spatial variability of one variable, whereas the cross variogram, $\gamma_{ZY}(h)$, shows the spatial covariability of one variable with the other.

Cokriging is the multivariate extension of kriging that allows the inclusion of more readily available and inexpensive attributes in the prediction process. The cokriging estimator is also a linear estimator of weights λ_i (principal variable) and β_i (auxiliary variable) and is written:

$$Z^*(x_0) = \sum_{i=1}^{N} \lambda_i Z_i + \sum_{j=1}^{M} \beta_j Y_j \qquad [7]$$

where Z_i and Y_j are the values of variables Z and Y measured at points i and j respectively ; N and M are the number of points of measurement of variables Z and Y within the searching neighbourhood ; λ_i and β_i are unknown. The COK estimator should also satisfy the unbiasedness and optimality conditions.

Developing equations [3, 4] leads to a system of kriging (or cokriging) equations written in terms of the variograms and cross-variogram. Solving these systems yields the N weights λ_i to be used for OK estimation [eq.2] or the N weights λ_i and and M weights β_j to be used for COK estimation (Eq. 7). The kriged estimate (Eq.2) or cokrigged estimate (Eq.7) can be calculated.

The variance of the errors of estimate (kriging variance) is given as:

$$\sigma^2(x_0) = Var(Z^* - Z_0) = \sum_{i=1}^{N} \lambda_i \gamma(x_i - x_0) + \mu_0 \qquad [8]$$

where μ_0 is the Lagrange multiplier. The expression of the co-kriging variance can be found in geostatistical basic references.

The variance of the errors of estimate is an indicator of the confidence to be granted to the kriging or cokriging estimates. The lower the variance, the higher the confidence.

One should note that OK and COK takes well into account : i) the spatial positions of the point to be estimated and the known points; and ii) the spatial variability of the variables through the variograms and the cross-variogram.

Kriging with external drift (KED) is an alternative to co-kriging. In this case, the auxiliary variable Y(x) is considered as a second random variable and is interpreted as a drift or trend that may follow the principal variable Z(x) throughout the study area. Z(x) may thus be expressed as (Wackernagel 1995):

$$Z(x) = a + b\,Y(x) + R(x) \qquad [10]$$

where a and b are constants, Y(x) is the auxiliary variable (or drift function), R(x) is a residue.

To be useful the drift function either need to be everywhere known or can be easily and precisely interpolated throughout the study area. KED assumes that, rather than being constant, the mean E[Z(x)] is a function of location, specifically a linear combination of one drift function which varies according to location :

$$E[Z(x)] = a + b\,Y(x) \qquad [11]$$

The residue R(x) is assumed to be an intrinsic residue :

$$E[R(x)] = 0 \qquad [12]$$

The principal variable Z(x) is then modeled as a nonstationary variable whose non-constant average is locally equal to the external drift. The KED estimator should, as the OK and COK estimators, satisfy the unbiasedness (Eq.3) and the optimality (Eq.4) conditions.

Cross validation

The performances of the estimation methods are assessed using the cross-validation procedure (Isaaks and Srivastava, 1989 ; Clark, 1986). This procedure compares actual values with estimates and comprises the following steps : i) eliminate a single value from the data set, ii) estimate a new value at this location vs. the surrounding values using OK, COK or KED, iii) calculate the actual error using (Z_i* - Z_i) (actual value-estimated value), and iv) find out the theoretical error using the estimation variance (or its square-root, the standard deviation). This procedure is repeated for all the data set. If the estimation is accurate, the following results should be obtained : i) the average of the actual errors should be zero (Eq.3) ; ii) their variance should be a minimum (Eq.4) ; iii) the ratio of the variance of the actual errors to the average estimation (kriging or cokriging) variance (Eq.13) should be one :

$$\left\{\frac{1}{N}\sum_{i=1}^{N}(Z_i^* - Z_i)^2\right\} / \frac{1}{N}\sum_{i=1}^{N}\sigma_i^2 = 1 \qquad [13]$$

A standardised W statistic can also be calculated as follows (Clark, 1986) : each actual error is divided by the appropriate estimation standard error. This W statistic should then average zero and have a standard deviation of one.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING OF THE GULF BASALTIC AQUIFER

The regional geodynamic framework is related to the expansion of the tectonic plates of Africa, Arabia and Somalia since 30 My, during which the principal volcanic series, basalts and rhyolites, that are found in the area of Djibouti, were laid down (Jalludin, 1993). Basalts of the Gulf (2.8-1 My), which are the subject of this study, are located close to the town of Djibouti (Fig. 1). They cover a surface of 560 km2 until the town of Arta and the massif of Bour Ougoul towards the West, and until Hindi and Loyada towards South-west. They are presented in the form of a plateaus which go up to 200 meters in altitude. Several principal wadis (temporary rivers), Ambouli, Atar, Damerdjog and Douda, cross this formation and sometimes sculpt canyons whose cliffs exceed several tens of meters. Many volcanic cones of different sizes strew the plateaus, in particular in the Southern part.

The Gulf basalts are composed of basaltic flows with intercalation of sedimentary layers, scoria and paleosoils. They are characterized on the surface by a significant weathering in balls. The thickness of this formation is very variable because of the play of the normal faults and the paleoreliefs highlighted by geophysics (CGG, 1965-1987) and drillings. It must reach 200 meters at least, in particular near the well PK20.

Basalts of the Gulf lie in discordance on Somalis basalts (7.1-3 My) in the South and on Dalha basalts (9-3.4 My) and Mabla rhyolites (15 My) in the West. This contact is well determined by the geomorphological criteria in the West and South-west.

Several networks of fractures affect the Gulf basalts. The East-West fracturing direction is the most significant and results probably from the first deformations linked with the pouring of the basaltic formation and which would have been reactivated until recently. The other directions of fracturing are N140°-150° and NS-N040°. The outcrops are characterized by weathering and hydrothermalism. Their effects are all the more marked as the formation is older. The hydrothermal activities result in secondary mineral deposits and accordingly reduce the permeability of the basalts.

The Gulf basaltic aquifer is prone to an intense exploitation for the drinking water supply of the town of Djibouti. This exploitation has increased regularly with the social and economical development of the Capital and amounts to about 35 000 m^3 per day (12.7 millions m^3 per year) provided by 32 wells. The abstraction rate of the wells is included between 20 and 100 m^3/h. One notes a regular degradation of the quality of water highlighting the overexploitation of the aquifer.

Because of the arid climate, annual precipitations reach only 150 mm on average. The surface of basalts being impermeable because of surface weathering, the recharge of the aquifer occurs exclusively in the stream beds occupied by alluvial deposits which represent an intermediary aquifer before basaltic aquifer recharge (Jalludin and Razack 2004). Recharge of the aquifer has been estimated by BGR (1982) as the equivalent of 5 % of the precipitations (150 mm). The annual average recharge is estimated between 10 and 15 millions cubic meters per year indicating that there might be overexploitation of the aquifer.

Transmissivity data. Statistical and variographic analyses

Jalludin & Razack (2004) elaborated a database of all the transmissivity data available regarding the Gulf basaltic aquifer and other basaltic aquifers in the Republic of Djibouti. Since then this database has constantly been kept updated. At present, 42 (forty two) data of transmissivity characterizing the Gulf basaltic aquifer are available (Fig.2). The summary statistics of these transmissivity values deduced from these tests are provided in Table 1. The transmissivity values of the Gulf basaltic aquifer range between 0.5 m^2h^{-1} and 3600 m^2h^{-1}. The average is 402 m^2h^{-1}, the standard deviation is 676 m^2h^{-1} and the variation coefficient is 168 %. These statistics emphasize the strong heterogeneity of this aquifer.

Table 1. Summary statistics of the transmissivity (T, m²/h) database for the Gulf basaltic aquifer including T values deduced from pumping test data and estimated from corrected specific capacity.

maximum	**minimum**	**average**	**Standard deviation**	**Coefficient of variation (%)**
3 600,0	0,5	402	676	168

The frequency distribution of the transmissivity data set is reported on a log-probability diagram (Figure 4). Most of the data are plotted along a line, which indicates that the data are lognormally distributed. No fitting test is provided here. However lognormality of the transmissivity has widely been demonstrated in the literature (Delhomme, 1979 ; Neumann, 1979) and is at present accepted as an intrinsic property of heterogeneous media.

The experimental variogram of the log-transmissivity (logT) is reported in figure 5. It is characterized by no drift, a sill and an autocorrelation between the points for low distances It shows that logT has a regionalised variable behaviour. No nugget effect was depicted which means that there is no lower scale structure. The theoretical model fitted to the experimental logT variogram is an exponential model, whose general equation is :

$$\gamma(h) = C_0 + C_1 [1 - \exp(-\frac{3h}{a})] \qquad (14)$$

where C_0 is the nugget effect, C= C_0 + C_1 is the sill, a is the practical range (distance at which 95% of the sill has been reached) , h is the distance between sampling points. The nugget effect represents any small-scale data variability or possible sampling (measurement and/or location) errors. The sill indicates the total variance. The range is the distance between sampling points at which the sill is reached. Beyond the range, the variance measured between the data points is independant from the respective data points and there is no longer a correlation between the points.

The expression of the exponential variogram of log(T) is :

$$\gamma(h) = 0.0 + 0.63 \ [1 - \exp(-\frac{3h}{5160})] \qquad (15)$$

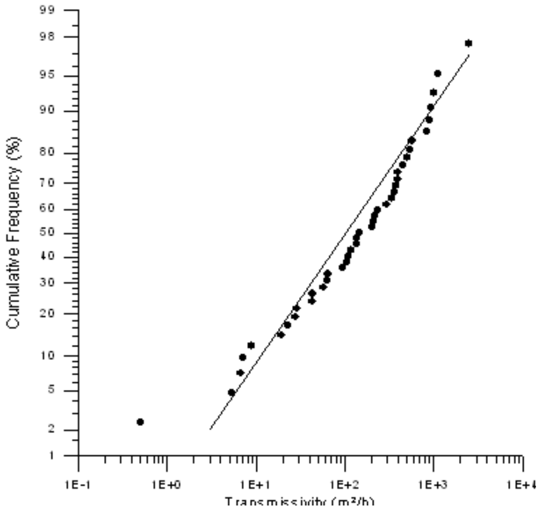

Figure 4: Frequency distribution of T(m²/h)

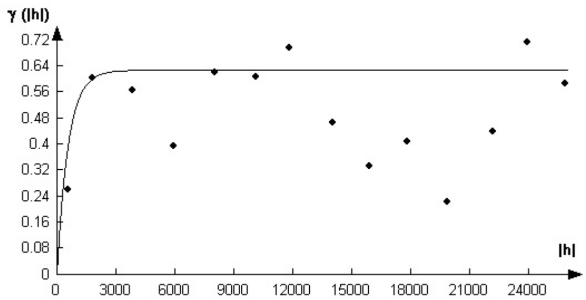

Figure 5: Experimental variogram of logT and fitted exponential model.

Geophysical prospection and transverse resistance data

Several geophysical studies were undertaken on the Gulf basaltic aquifer in order to develop the groundwater resources supply for Djibouti town (BGR 1982, 1996; CGG 1965-1987; ARLAB 1984; ISERST 1997). Progressively, these geophysical surveys covered almost the whole Gulf basaltic aquifer. The Schlumberger electrical method (Astier 1971) has been almost exclusively applied. For the present study, all the available transverse resistance (R, Ohm.m²) data were collected, as they are reported in these surveys. The raw electrical soundings were not reinterpreted. A number of 322 transverse resistance data were thus collected. They are quite homogeneously scattered over the aquifer surface (Fig.3).

Statistics on the transverse resistances data are given in Table 2. The average is 2265 ohm.m² and a coefficient of variation of 55%.Transverse resistance values vary between 235 ohm.m² and 5400 ohm.m². Low values are generally significant of the presence of clay material, while high values would result from impervious basalts.

Table 2. Summary statistics of the transverse resistance (R, Ohm.m²) database for the Gulf basaltic aquifer .

maximum	minimum	average	Standard deviation	Coefficient of variation (%)
5400	235	2168	1257	58

The frequency distribution of the transverse resistance is plotted on a log-probability diagram (Figure 6). As for transmissivity, this diagram shows that the transverse resistance data are lognormally distributed. This result is consistent with those previously published in the litterature (Razack and Sinan, 1988 ; Ahmed et al., 1988)

The experimental omnidirectional variogramme of the logarithm of transverse resistance (logR) is presented in figure 7. It is characterized by no drift, a sill and an autocorrelation between the points for low distances showing that the transverse resistance has a regionalised variable behaviour. It also indicates the presence of a second-order stationnarity for an h of about 6 km.

The theoretical model fitted to the experimental logR variogram is an exponential model, whose equation is :

$$\gamma(h) = 0.0 + 0.081 \ [1 - \exp(-\frac{3h}{10080})] \quad (16)$$

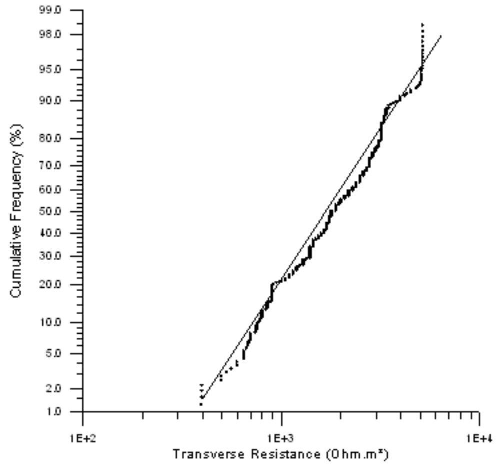

Figure 6: Frequency distribution of R(Ohm.m²)

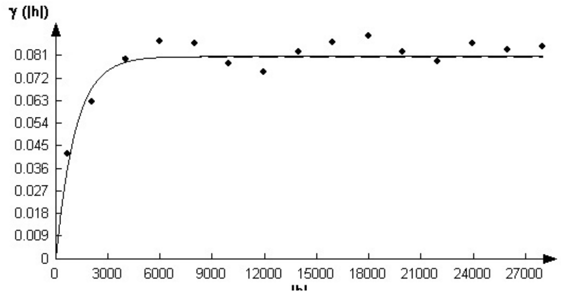

Figure 7: Experimental variogram of logR and fitted exponential model

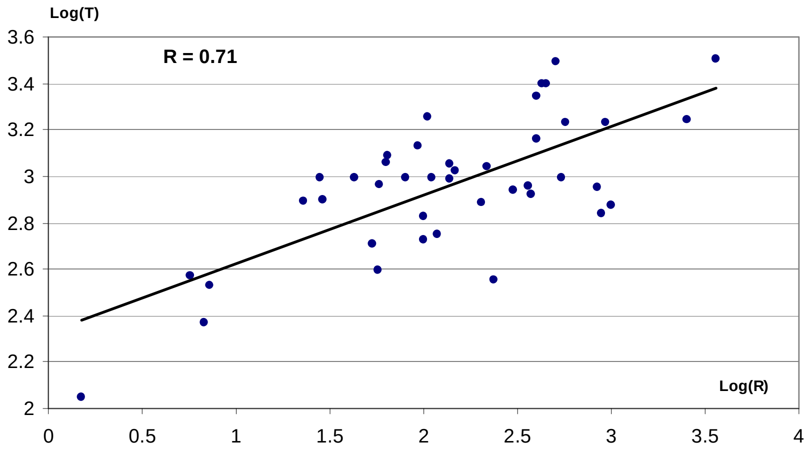

Figure 8: Correlation diagram between log(T) and log(R)

REGRESSION ANALYSIS OF LOG (TRANSMISSIVITY) VS. LOG(TRANSVERSE RESISTANCE)

Previous studies on the relationship between transmissivity and transverse resistance investigated three types of statistical relationships : linear form T = a + bR, exponential form $T = ab^R$ and log-log form logT = a+blogR (i.e. geometrical) (Razack and Sinan 1988 ; Kosinski and Kelly 1981; Heigold et al., 1979 ; Mazac et al., 1985). However when the variables are lognormally distributed, a log-log regression yields the best estimates (Huntley, 1986 ; Razack and Huntley, 1991).

The log(T) data vs. log(R) data are reported in figure 8. The diagram shows that both variable are linearly correlated. The value of the coefficient of correlation is R = 0.71, which is quite significant. Such a significant correlation between log(T) and log(R) allows thus to undertake estimation of the undersampled principal variable (log transmissivity) using the widely sampled auxiliary variable (log transverse resistance).

Cross validation results and discussion.

The cross validation results are summarized in Table 3. The following comments can be drawn :

- The errors average (Eq.2) is close to zero. The lowest values are provided by OK and KED.
- The errors variance (Eq.3) is the lowest for KED.
- The average of the Wi statistics is close to zero and its standard deviation close to one for the 3 methods. Best values are however related to OK and KED.
- The ratio Errors variance/estimation variance (Eq.13) is close to 1 for the 3 methods.

The correlation coefficients between observed and predicted values of log(T) are not significant for OK [R_{OK}(obs, pred) = 0.10] and COK [R_{COK}(obs, pred) = 0.13]. The highest correlation is provided by the KED procedure [R_{KED}(obs, pred) = 0.50].

Table 3: Comparison of the cross-validation performances using the OK, COK and KED estimation procedures

	OK	**COK**	**KED**
R(obs, pred)	0.1	0.1	0.5
W Average	0.04	0.34	0.08
W SD	1.05	1.16	1.08
Error Average	0.04	0.24	0.06
Error SD	0.78	0.79	0.69
Error Variance (1)	0.61	0.62	0.48
Estimation Variance (2)	0.52	0.46	0.41
(1)/(2)	1.2	1.3	1.2

Accordingly, the cross validation clearly demonstrates that OK and COK are the least performing estimation methods. Cokriging, though using a densely sampled auxiliary variable, does not provide in this study, the best estimation, contrary to what was observed in previous studies (Aboufirassi & Marino, 1984).

The best estimation of the logT is provided by the KED procedure. The use of logR data, as auxiliary variable, proved quite useful when performing estimation using KED.

Estimation of the logT of the Gulf basaltic aquifer using KED

Estimation of the Gulf basaltic aquifer log(transmissivity) using KED has been carried out on a grid with a mesh size of 1 km x 1 km. As transmissivity is assumed isotropic, the KED is performed with a moving neighbourhood that uses a circle radius search. The KED procedure produces an unbiased estimation of logT. This is the best estimation of logT that can be presently achieved, on the basis of the available transmissivity and transverse resistance data.

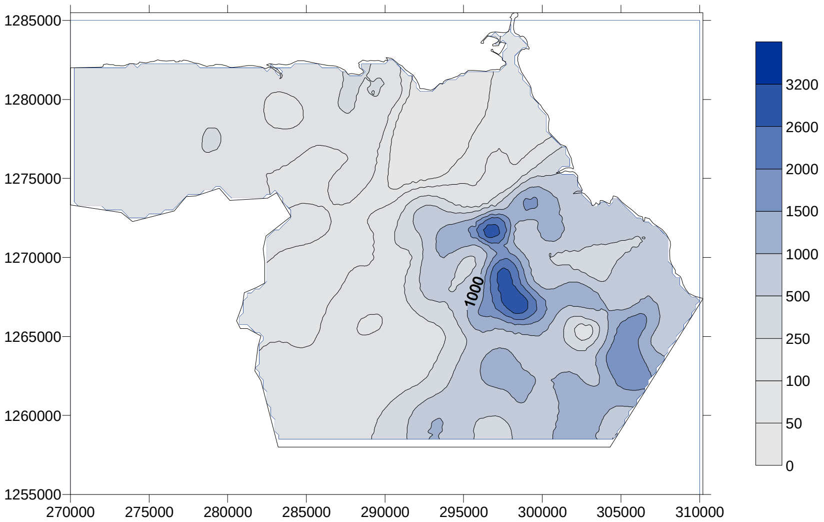

Figure 9: Distribution of the transmissivity (T, m²/h) of the Gulf basaltic aquifer, obtained by backtransform of the estimated logT using KED

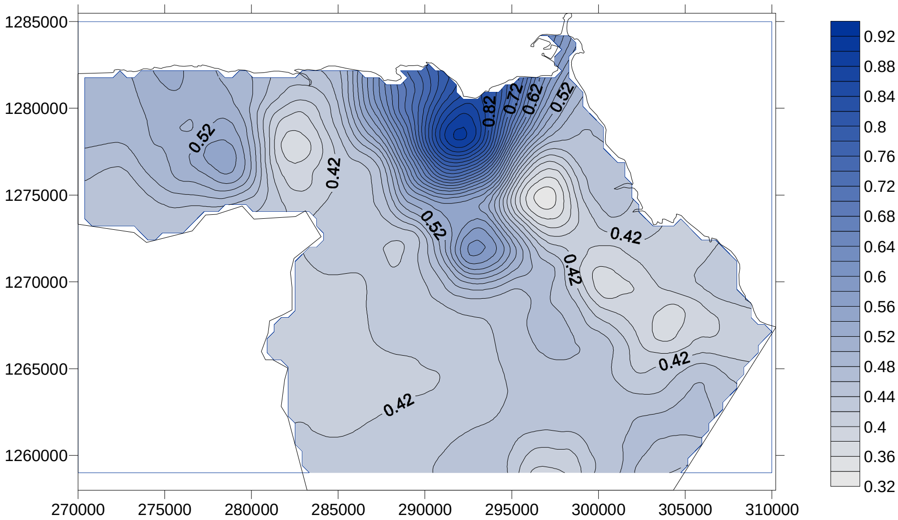

Figure 10: KED variance associated with the estimation of logT

Figure 9 shows the distribution of the transmissivity (T, m²/h) throughout the Gulf basaltic aquifere. This distribution is obtained by backtransform of the estimated logT distribution using KED. This estimation will be used in forthcoming numerical modeling works of the Gulf basaltic aquifer.

Figure 10 shows the estimation variance associated with the estimation of logT. The higher the variance, the more uncertain the estimation of logT. The figure reveals however that the places where the estimation is highly uncertain, are rather few. This might be due to the densely sampled auxiliary variable (transverse resistance, R ohm.m²) used with KED.

CONCLUSION

The determination of the transmissivity fields is one of the most critical issue to which the hydrogeologists are faced. An attempt has been undertaken on the basis of geoelectrical properties to estimate the transmissivity field of the Djibouti basaltic aquifer using geostatistical procedures. Three estimation procedures have been compared, ordinary kriging (OK), cokriging (COK) and kriging with external drift (KED). OK is a univariate method, as it uses only the data of the principal variable, while COK and KED are bivariate method as they use the data of an auxiliary variable, which can be much more densely sampled than the principal variable. The auxiliary variable used in this study is the transverse resistance.

The main findings of this study are summarized as follows :

1. Transmissivity (T, m^2/d) and transverse resistance (R, ohm.m^2) are lognormal variables.
2. Both variables are spread over several orders of magnitude, revealing the strong heterogeneity of the aquifer.
3. A significant statistical relationship was found between logT and logR, along with a correlation coefficient R=0.71.
4. The geostatistical procedures estimation performances were assessed using cross-validation. This test showed that the best logT estimates are provided by KED.
5. An estimation of the logT of the Gulf basaltic aquifer was performed on a regular grid of 1 km x 1 km using KED.

The geostatistical approach proved useful to provide a reliable estimation of the log(transmissivity) of the Gulf basaltic aquifer. This approach incorporates all the available data on transmissivity and transverse resistance. This transmissivity estimation will be used as an input in forthcoming modelling of this important aquifer, the water resources of which need to be optimally managed.

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