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Geostatistical Approach for Mapping the Transmissivity and Static Level of the aquifer of the continental terminal of Lower Casamance (Senegal)

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Abstract: The groundwater contained in the formations of the Continental Terminal (CT) of Lower Casamance (South-West of Senegal) is the main source of water supply for the populations. Found at shallow depths (less than 30 m), that groundwater, with proven hydraulic performance, coexists with a dense hydrographic network characterized by the estuary of the Casamance River and the Kamobeul, Bignona, Diouloulou's backwaters (bolons) where salinities exceed those of the ocean (inverse estuary). This environment associated with the deficient rainfall conditions challenges us on a real need to understand the superficial aquifer system from both a qualitative and a quantitative point of view. This article presents the results of a hydrodynamic characterization of the CT aquifer system. The model implemented with the ArcGIS software made it possible to map the transmissivity and the static level of the groundwater of the low Casamance CT slick by using the geostatistical method.

Key words: Mapping, Transmissivity, Aquifer, Static level, geostatistical method

INTRODUCTION

In low Casamance, the population's drinking water supply is mainly based on the exploitation of wells and drillings that capture the surface aquifer of the Continental Terminal (CT)[1]. This aquifer coexists with the Casamance River, which has a hypersaline estuary (river water three times as salty as ocean water)[2-3-4]. Various studies carried out in the area have contributed to improving knowledge of the estuarine environment of low Casamance and its ecosystem. They have shown that, in addition to the saline intrusion that manifests itself more than 100 km from the mouth, the considerable increase in the salinity of the river's water also contributes to the contamination of the superficial groundwater in this region.[5-6-7-8]. As a result of these studies, questions remained unresolved, namely the long-term availability of groundwater from the CT, the impact of the river's salinity on this aquifer, the vulnerable zones to pollution, the mechanisms and the degree of salinisation of the groundwater of the lower Casamance region in low and medium-term. In order to meet the growing water needs of the population and ensure the preservation of the resource, it is necessary to build a rational and sustainable management plan for the exploitation of the groundwater. This requires a good knowledge of the aquifer system both qualitatively and quantitatively. This article aims to map, by the geostatistical method, two parameters indicating the availability of groundwater and its accessibility namely the Transmissivity and the static level of the aquifer.

MATERIALS AND METHODS

Présentation of the study area: Our zone is located in the south western part of Senegal and occupies an area of 7,339 km^2. It is located between latitudes 11° and 15'5° N and longitudes 14° and 17° W. In terms of administrative division, our study area corresponds to the Ziguinchor region whose departments are: Ziguinchor, Oussouye and Bignona **(Figure 1).**

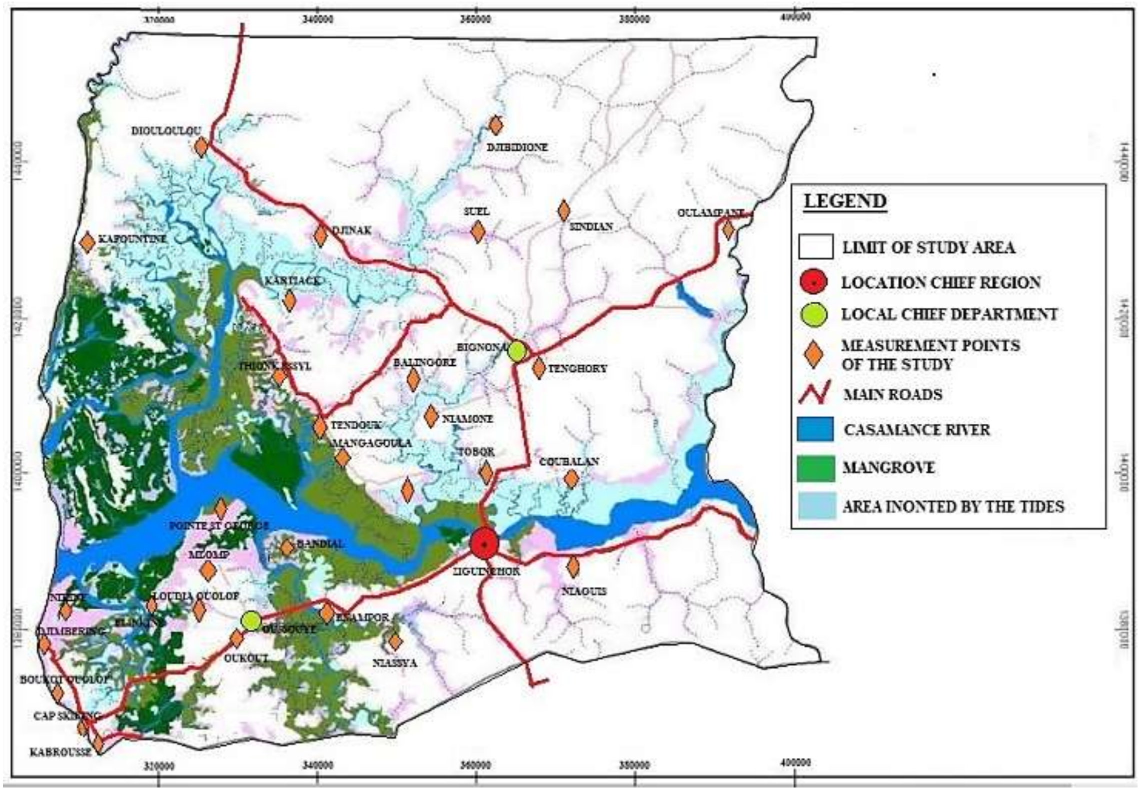

Figure 1: Location of the study area

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A description of the morphological elements shows that in the north west, the area is formed by a plateau dissected by a series of cuts, most of which are clogged. It is on its rim, especially in the areas of low topography (around the bolons) mangrove mud flats and shallows are located; the southwestern zone is particularly incised by the ancient rivers[9-10]. The Hydrological System consists mainly of the Casamance River formed by the meeting of several small marriages at an altitude of 50 m midway between Fafakourou and Ve1ingara in Upper Casamance (Kolda Region)[11]. In lower Casamance, at the Adeane level, the Casamance River enters into a confluence with Soungrougrou, its most important tributary, formed by the meeting of several small tributaries that originated in the vast Pata forest. Downstream from Ziguinchor, the tributaries of Casamance, known as Bolons, dissect deeply the sandstone plateau of the Continental Terminal. These are the Bignona, Baila and Diouloulou on right bank, and the Kamobeul on the left bank[11]. The climate of the region is of the sub-Guinean type with rainfall ranging between 800 and 2000 mm for the period from 1987 to 2017 with a rainfall of 1524.5 mm in 2017[12]. This region is characterized by a wet season that runs from June to October with most of the precipitation in August and September and a dry season from November to May. The average temperature is 30° C. The vegetation cover is characterized by the formation of a forest domain consisting of dense dry forests and gallery forests located mainly in the southern part. Mangrove and palm groves colonize the river-sea zone.

Description of the aquifer system: The Casamance basin is an integral part of the entire Senegal-Mauritanian sedimentary basin of which it represents the southern part. The geological formations that are the subject of our study are those of the Continental Terminal of Lower Casamance (**Figure 2).**

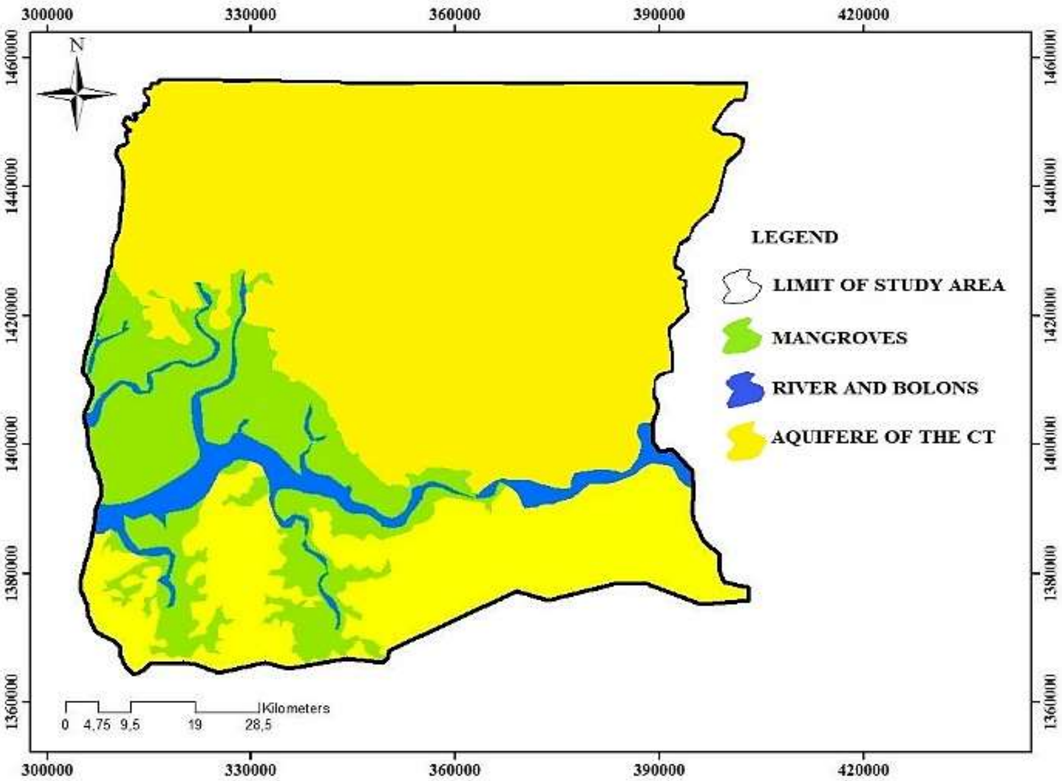

Figure 2: Aquifer of the CT of Lower Casamance

They are made of sandy clays and red, yellow and variegated ocher clay sands, interlayered with a lateritic cuirass and zones of concretion from the late Miocene to Quaternary age[13]. In the area, there

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are three main superimposed aquifers, from bottom to top, the Maastrichtian deep aquifer, the semi-deep Miocene aquifer and the Continental Terminal superficial aquifer, which provides the essential (95%) of the drinking water supply of the populations[1]. The continental terminal groundwater generally has a free surface with a static level averaging 10 m under the trays and less than 1 m at the shallows, the thickness of the saturated aquifer is in the range [20 m; 30 m][13]. The few hydrodynamic parameters available at the the Water Resources Management and Planning Directorate (DGPRE) come from the particle size analysis of the samples taken during 26 recognitions surveys carried out under the 1979 and 1983 of Lepriol FED project. This is the permeability K (5.10^{-5} to $1.5.10^{-4}$ m/s), the Transmissivity T ($1.5.10^{-4}$ m^2/s) and the effective Porosity (an average value of 10%)[14]. It is important to note that, for this study, the data set that we have for the continental terminal concerns more about the departments of Ziguinchor and Oussouye. Most of the existing drillings in the Bignona Department capture Oligo-Miocene even though the traditional wells exploit the continental terminal.

Materials and DATA: In this article, the data used are drawn from a descriptive and cartographic database. The hydrogeological data (descriptive) are collected from the database of DGPRE and include the monitoring records of various drillings. The latter give some chemical and hydrodynamic characteristics of the aquifer formations captured by drillings or piezometers. Data processing for this article was done using software such as:

- The Excel software for the realization of the different calculations and tables;
- ArcGIS 10.2.2 GIS for the localization of the various water points (geo referencing), the statistical study of the various parameters, the geostatistical study and the realization of the maps. The use of GIS software is essential for the regional hydrogeological mapping project[15].

Methodology of géostatistiques analysis: Geostatistics refers to probabilistic analysis methods for studying spatially correlated phenomena called regionalised phenomena. The term "regionalised" has been proposed to describe a phenomenon unfolding in space (and/or time), and showing a certain structure. Almost all the subsoil descriptive variables, Transmissivity, for example, can be considered regionalized variables.

From a mathematical point of view, a regionalised variable is simply a function z (x) giving the value at the point x of the space (at one, two or three dimensions) of a characteristic z of the natural phenomenon studied. Generally, these functions have a spatial (or temporal) behaviour that is far too complex to be described with analytical expressions[16-17]. Of the existing geostatistical methods, Kriging remains the most optimal and the most precise statistical method of interpolation and extrapolation.

Unlike all other methods, it also allows us to calculate the estimation error[18-19]. Nevertheless, to be able to apply the results of the theory of random functions, it is necessary to be able to reconstitute the law of the random function in question, or at least its first moments: this is called statistical inference. Statistical inference then requires the introduction of additional hypotheses on the random function to overcome the impossibility[20]. This hypothesis is second-order stationarity, which has resulted more broadly in the intrinsic hypothesis.

The intrinsic hypothesis assumes that, for any vector, the growth $Z(x+h)-Z(x)$ has a zero mathematical expectation and an independent variance of the point.

$$\begin{cases} E[Z(x+h)-Z(x)]=0 \\ Var[Z(x+h)-Z(x)]=2\gamma(h) \end{cases} \qquad (1)$$

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The function is called "semi variogram" (according to an established habit, we will use a "variogram" language abuse).

The Kriging method is always preceded by the estimation of a variographic function. It is this function that will take into account both the geometry of the data, the characteristics of the regionalization and the precision of the estimation[20]. The variogram of an intrinsic random function is thus by definition:

$$\gamma(h) = \frac{1}{2} Var[Z(x+h) - Z(x)] \quad (2)$$

Assuming the intrinsic hypothesis is satisfied, the theoretical variogram is estimated by the experimental variogram from the available experimental point pairs on the single accessible realization:

$$\gamma^*(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [z(x_i + h) - z(x_i)]^2 \quad (3)$$

After Kriging by different models, we make a choice of the best adapted model by cross validation. It makes it possible to compare the impact of the different models and to choose one for the estimation. Its principle is to re-estimate the Transmissivity values for sampled points through the fitted models. The operation is carried out for all the points, and the quality of the estimate is calculated on the basis of five statistical criteria used by the ArcGis software[21-22].

- the average error:

$$\frac{1}{n}\sum_{i=1}^{n}[Z^*(x_i) - Z(x_i)] \quad (4)$$

- The standard deviation of errors:

$$\sqrt{\frac{1}{n}\sum_{i=1}^{n}[Z^*(x_i) - Z(x_i)]^2} \quad (5)$$

- the average of the standard deviation:
- $\sqrt{\frac{1}{n}\sum_{i=1}^{n}\hat{\sigma}\,(x_i)}$ (6)
- - middle of the reduced error:
- $\frac{1}{n}\sum_{i=1}^{n}[Z^*(x_i) - Z(x_i)]/\,\hat{\sigma}(x_i)$ (7)

-the standard deviation of the reduced error:

$$\sqrt{\frac{1}{n}\sum_{i=1}^{n}[[Z^*(x_i) - Z(x_i)]/\hat{\sigma}(x_i)]^2} \quad (8)$$

Verification conditions:

- The average of the estimation errors and that of the reduced (standardized) errors are close to zero,
- the standard deviation of the reduced error close to 1
- The standard deviation of the errors is close to the mean of the Kriging standard deviation.

RESULTS AND DISCUSSIONS

We have characterized two hydrodynamic parameters of the groundwater namely Transmissivity and the static level. Indeed, Transmissivity is the flow per unit width of an aquifer under a unit load gradient. It makes it possible to quickly calculate the flow rate Q crossing a cross section of a ply of width L under a gradient H.

$$Q = T.L.gradH \text{ with } T = Ke \quad (9).$$

T is transmissivity (m^2/s); ***K*** is the hydraulic conductivity (m/s) and ***e*** is the aquifer thickness (m).

Thus the cartographic prediction of Transmissivity can constitute a basic document for an efficient choice of drilling sites in Lower Casamance. Coupled with a prediction of the static level of the aquifer, the study will optimize the investment costs for the realization of productive boreholes.

Mapping of transmissivity: The input data is a sample of more than 51 points. The **figure 3** shows the distribution of Transmissivity values on the drillings studied. This distribution is quite random and meets the requirements of statistical sampling.

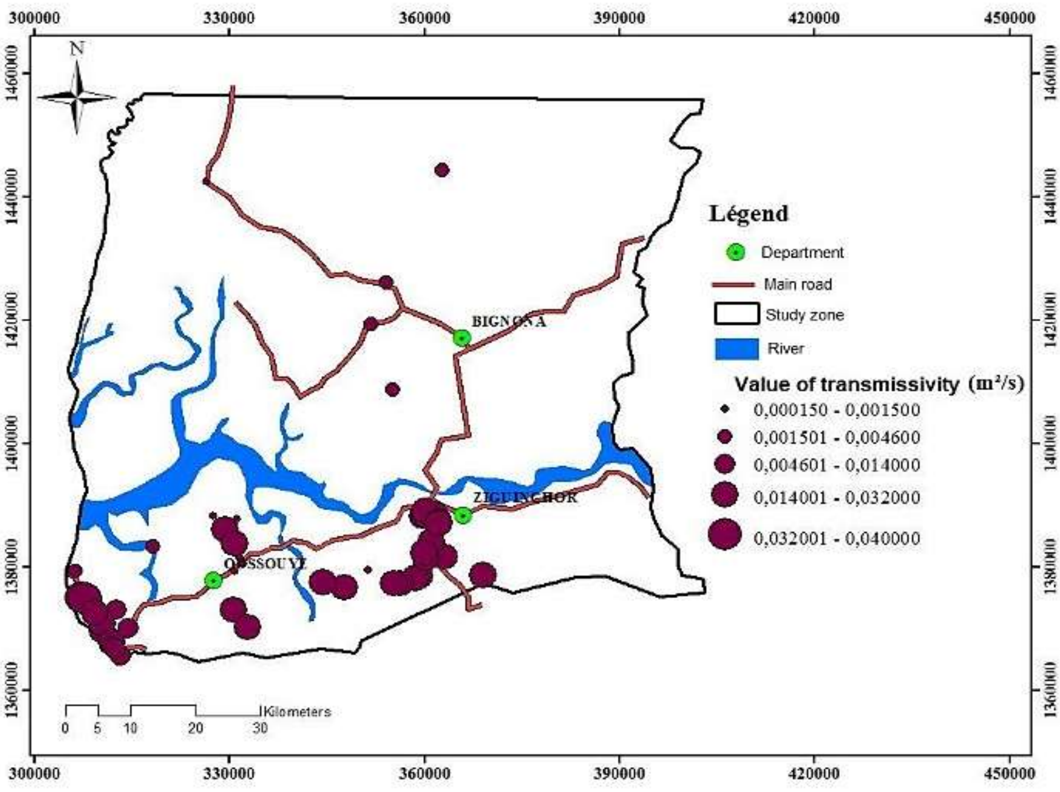


Figure 3: Distribution of sample values

The map of these data, traced with symbols proportional to the value of the transmissivities, shows that the latter have a certain spatial irregularity with low values located in the Bignona's department. The table 1 gives us some statistical characteristics of the sample.

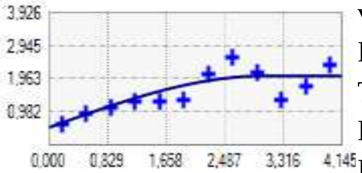
Table 1: Some statistical characteristics of the sample

Characteristics	Values
Sample size	51
Average	0,01928
Minimum	0,00015
Maximum	0,04
Median	0,028
Standard deviation	0,012

The analysis in Table 1 shows that in Lower Casamance, Transmissivity values at the CT level are in the range [$1.5.10^{-4}$ m^2/s; 4.10^{-2} m^2/s] for an average of $1.9.\ 10^{-2}$ m^2/s.

Construction of the experimental variogram: The analysis in Table 2 shows that the variogram of the transmissivity values present a discontinuity at the origin testifying to the local irregularity of the transmissivity with a pure nugget effect of the order of 0.00005211.

Table 2: Characteristics of the variogram

Variogram plot	Properties of the variogram[1]
$\gamma(10^{-4})$  **Distance (km). h.10^{-1}**	Spherical model/isotropic variogram Range: 304m Tier: $2,0410^{-4}$ Not (m): 34.54 Number of class: 12 Nugget effect: 0.0000521

The nugget effect is due to two main causes namely measurement errors (ie poor quality of data) and micro-regionalization (ie the existence of a scale much smaller than that explored[18]. We will retain for our study, the spherical model which presents a better calibration.

Kriging and Estimation of Transmissivity: The figure 4 shows the spatial distribution of Transmissivity values of the aquifer CT system obtained by this geostatistical modelling. The values range from $4.43.10^{-4}$ to $2.897.10^{-2}$ m^2/s. They are strong in the part of the aquifer system localized in the department of Ziguinchor on the border with Guinea Bissau and in the department of Oussouye near the coast but remain weak in the department of Bignona with values less than 0.02 m^2/s

Recall the estimated value in one node is the most likely value calculated from the statistical model calibrated and optimized compared to experimental data. And that the number of data points determines the accuracy of the estimate. The estimation errors calculated by ordinary Kriging are shown in Figure 5. This figure shows that the low values of the estimation error are still in the Ziguinchor and Oussouye departments and in the center of Department of Bignona. This is related to the high number of observed values existing in these areas of the aquifer. In contrast, the error becomes more and more important on the rest of the groundwater, especially towards the periphery by going towards Sedhiou and at the level of the mudflats where the values of the Transmissivity remain unknown because of the small number of hydraulics works tested in these places.

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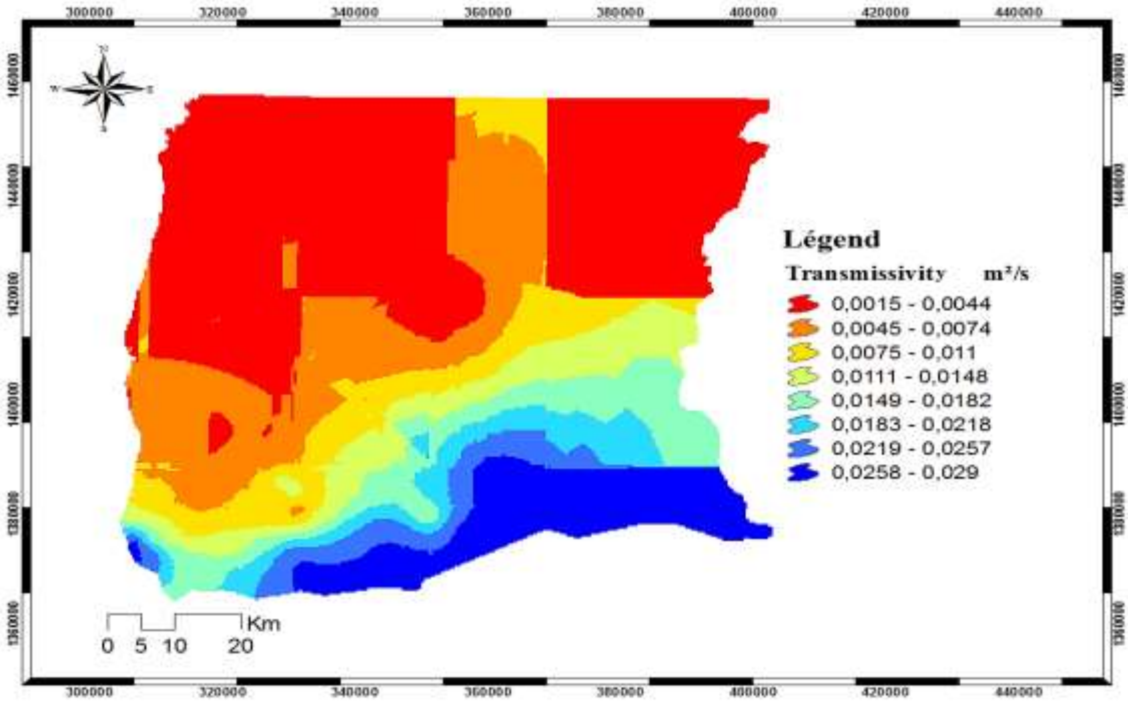


Figure 4: Map of Transmissivity values (in m²/s)

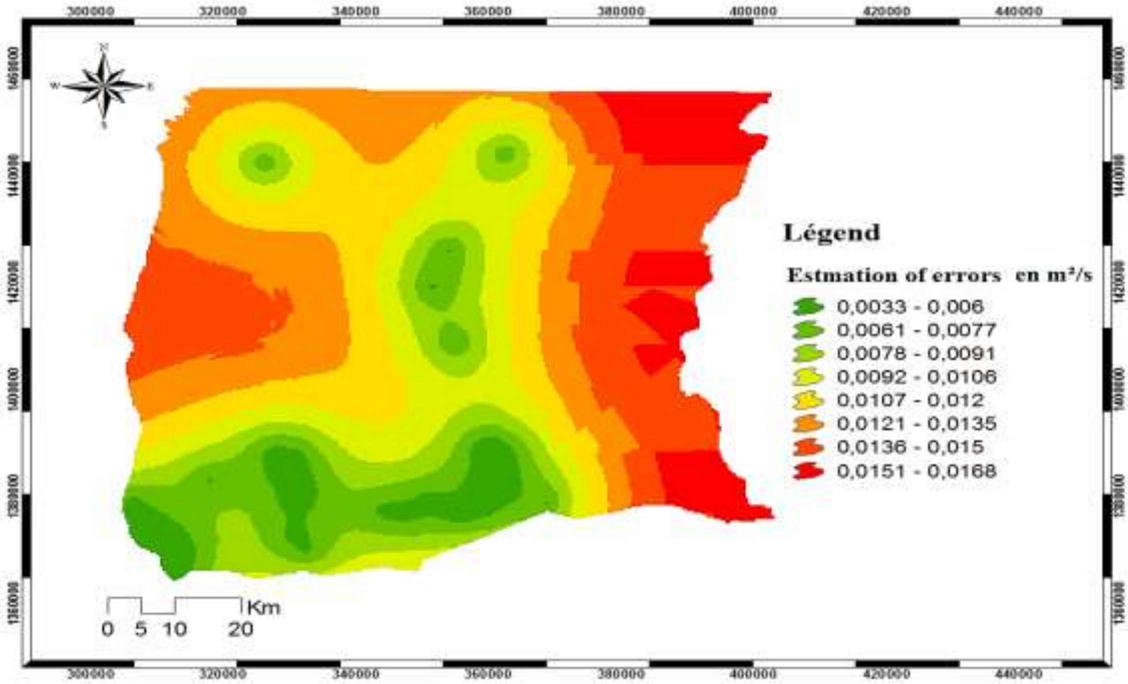


Figure 5: Map of Estimation errors of Transmissivity (m²/s)

Validation of the Model: The results of the cross-validation show that the variogram model constructed for Kriging assessment and mapping of the Transmissivity fields is satisfactory **(figure 6).** Indeed, all established conditions have been verified **(Table 3)**

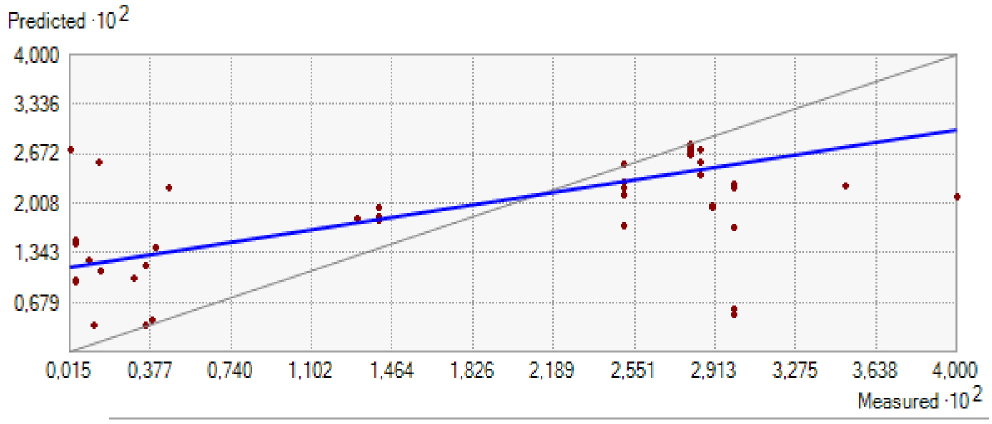


Figure 6: Cross validation results.

Verification of cross validation Conditions: The conditions of validity of the model are respected in the **table 3**

Table 3: Summary of results

Statistical Parameters	Values	Vérification
Average estimate errors	0.000672	Checked
Average Error Reduced	0.039247	Checked
Standard Deviation for Reduced Error	1.087405	Checked
Standard deviation of estimation error	0.010002	Checked
Mean of the standard deviation	0.0096608	

Static Level Mapping (NS): The input data is a sample of 40 points. The **figure 7** shows the distribution of static level values over the study area.

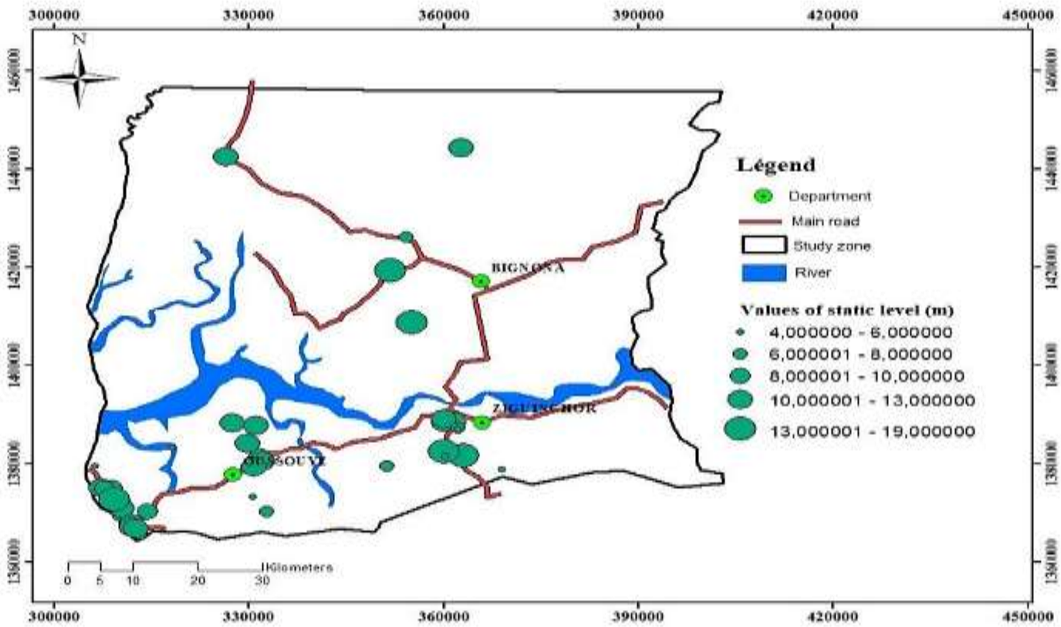


Figure 7: Statistical characteristics of the sample

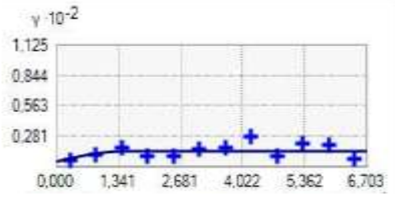
Table 4: Some statistical characteristics of the sample

Characteristics	Values
Sample size	40
Average	10.27
Minimum	4
Maximum	19
Médian	10.5
Standard deviation	3.609

The analysis in **Table 4** shows that in Lower Casamance, the static level of the CT is between 4 and 19 m. The average is 10.27 m on all the low Casamance.

Construction of the experimental variogram : Table 5 shows the characteristics of the variogram

Table 5: Characteristics of the variogram

Tracé du variogramme	Valeurs du modèle
$\gamma(10^{-3})$  **Distance (km). h.10^{-1}**	Model Spherical model/isotropic variogram Range : 144m Tier : $1,610^{-3}$ Not (m) : 55,8 Number of class: 12 Nugget effect: 9,43

The analysis in Table 5 shows that the behaviour of the variogram is very close to the origin reflects the degree of continuity and spatial regularity of the regionalized variable. The nugget effect of this variable is significant 9.43 because of micro-regionalization (that is to say the existence of structures on a much smaller scale than the one explored). Measured data is concentrated at points.

Kriging and Estimation of the Statistical Level: Figure 8 shows the spatial distribution of the values of the static level of the aquifer system CT obtained by this geostatistical modelling. The values are between 6 and 18 m. The NS of the aquifer is less than 12 m in the part of the aquifer system located in the department of Ziguinchor on the border with Guinea Bissau and in the Oussouye department near the coast, whereas in the center of the studied zone they remain higher than 14 m.

The estimation errors of the NS are given in **Figure 9.** The figure shows that the errors are less than 2 m in the areas at the capturing fields and their surroundings (Ziguinchor, Oussouye, Kabrousse, Cap skiring, Oussouye, Oukout, Mlomp, Bignona). We also note isolated values showing low errors such as those recorded in Diouloulou and Djibidione. Apart from that, the error becomes more and more important on the rest of the water table, especially towards the periphery by going towards Sédhiou and the level of the mudflats and remains higher than 3 m.

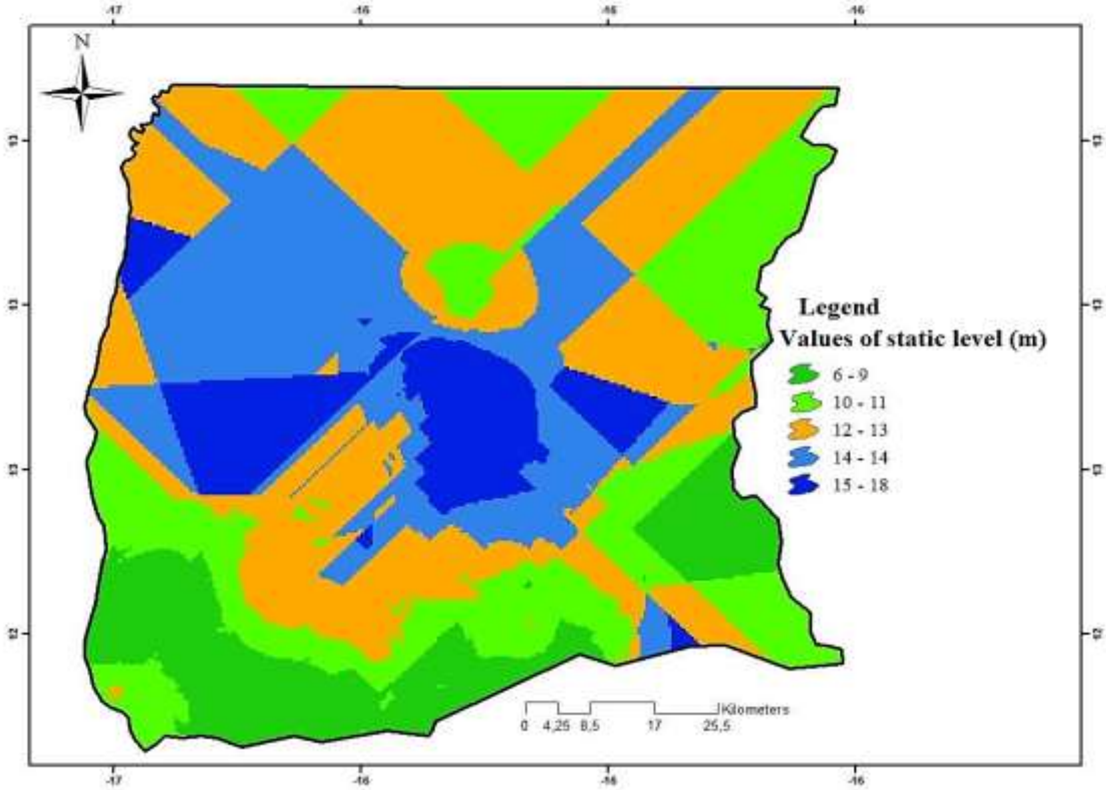


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Figure 8: Map of Static Level Values (m)

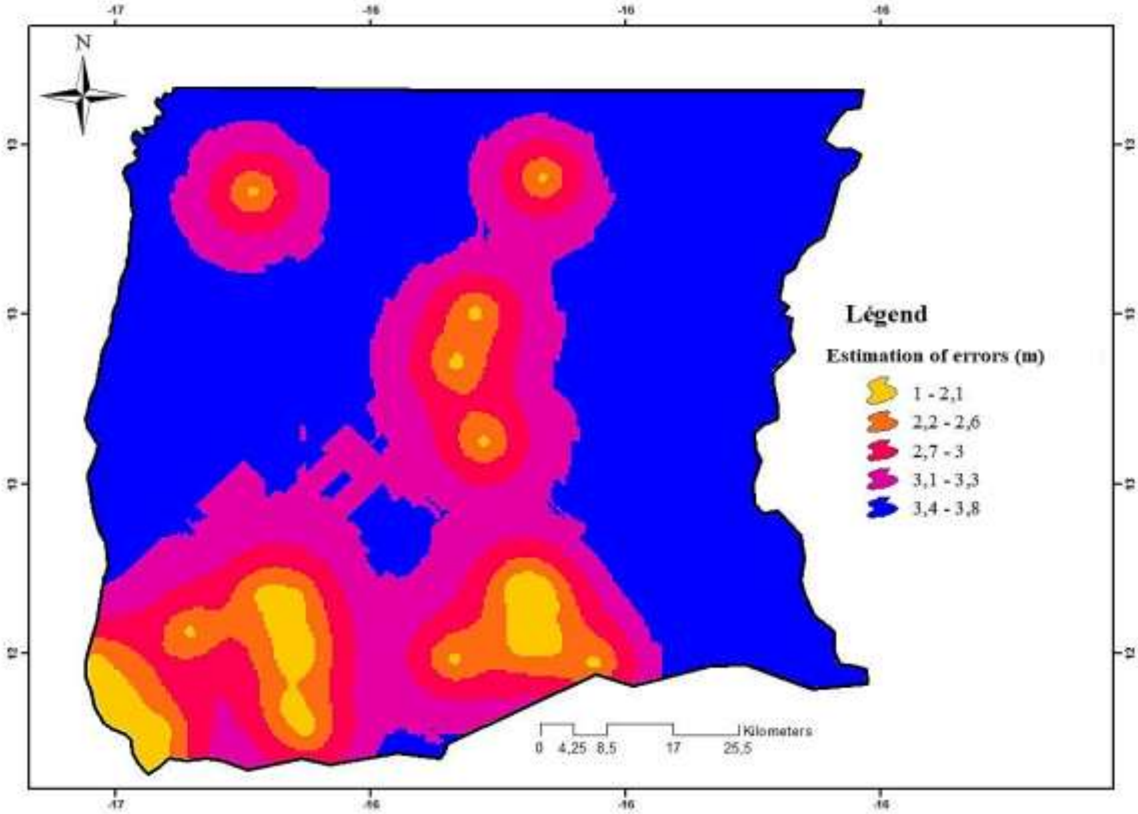

Figure 9: Estimation error of Static level (m)

Validation of the model: The results of the cross-validation show that the variogram model constructed to evaluate and map by Kriging the NS fields is satisfactory. Indeed, all established conditions have been verified **(Table 6).**

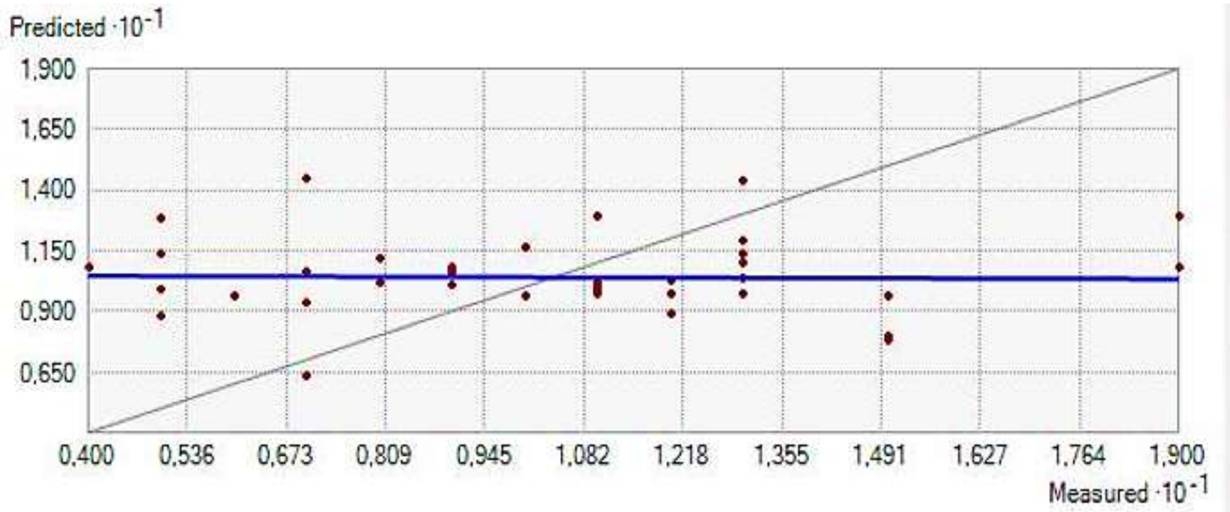

Figure 10: Cross validation results.

Table 6 below shows the verification of cross validation conditions.

Table 6: Summary of results

Statistical Parameters	Values	Vérification
Average estimate errors	0,233	Checked
Average Error Reduced	0,041	Checked
Standard Deviation for Reduced Error	1,19	Checked
Standard deviation of estimation error	3,12	Checked
Mean of the standard deviation	3,85	

CONCLUSION

Given that the drinking water supply of the populations of the lower Casamance, rests mainly on the exploitation of the wells and drilling capturing the aquifer of Continental Terminal. And that the production of aquifers and their accessibility depend on the Transmissivity and the static level. It was then necessary to study the distribution of these two variables in the area to help in the choice of sites for future settlements. The results obtained are satisfactory with the data used, although it should be noted that a larger data series at the level of the Bignona department and the periphery (towards Sédhiou) would give more precision to the model.

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