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A GEOSTATISTICAL APPROACH TO GROUNDWATER MODELLING FOR THIAROYE COASTAL AQUIFER

In this paper, we investigate a combination of geostatistical and mathematical methods for explaining the Thiaroye coastal aquifer groundwater dynamics and contamination by both seawater and Nitrates. The purposes of this investigation were to provide an overview of current groundwater hydraulic heads and quality spatial distributions in the study area. First we use GIS data to specify a model of hydraulic heads depending on both GPS coordinates and time using an ordinary least square estimation performed on Eviews. Then we use the governing partial differential equations for unconfined aquifers to calculate net recharge. In a second part, we specify geospatial models for explaining the variations of electric conductivity and for establishing relationships between nitrate and sodium concentrations. We find that throughout the study area, there is a weak monthly recharge rate certainly due to efforts aiming to prevent the area from flooding by controlling the water table level with pumping systems. Furthermore, correlations show that sodium and electric conductivity increase with depth and that nitrate and sodium concentrations are inversely correlated.

***Keywords*: Hydraulic heads; GIS data; Unconfined aquifer; Electrical conductivity; Groundwater quality; Statistical modelling; tests of hypothesis.**

1. Introduction:

The Thiaroye aquifer is an unconfined and coastal aquifer. Situated in the peri-urban part of Dakar, this region is located in an old dune network formed by hills and depressions. As schematized in figure 1, it concerns several areas like Guediawaye, Thiaroye, Pikine Yeumbel, Boune, Keur Massar, Malika, Tivavouane Peul. The water table is naturally close to the surface and without human intervention, the water table forms lakes in these depressions.

Almost 40% of the population has settled in these areas with potential risk of flooding, coastal erosion or sea level rise. This is the reason why Thiaroye groundwater resource evaluation and management still rise two main issues:

- What will be the effect of human intervention like pumping on the area water levels?
- Are there likely to be any undesirable side effects of development, such as seawater intrusion or any contamination that could serve to limit yields.

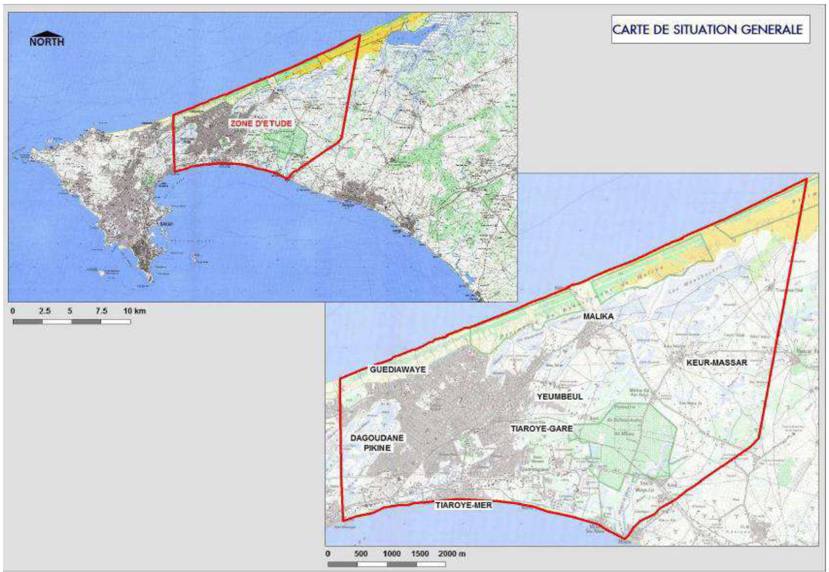

Figure 1. Thiaroye area (tire du PDD, rap. technique, Annexe 1, p. 9)

In 1950, the city of Dakar began pumping its groundwater for drinking with an average flow rate of 17,000 m^3 / d. This induced a lowering of the water table level. As water table is in contact with the sea, this drop in level has created a risk of sea water intrusion into the unsalted water of the groundwater. As this risk became major, the exploitation of the water table was stopped between 1959–1961 (Cabinet SGI-Merlin, 2010).

In 1961, pumping resumed. However, it is reduced to around 10,000 m^3/d to protect the groundwater from salt water intrusions (Cabinet SGI-Merlin, 2010). This pumping will last until 1988 and will cause a lowering of water table level along with drying up of naturally flooded land (ANAMS). In the same time the land drained by the drop in the water table was very quickly used to build new homes for welcoming people coming from rural areas. This area corresponds to the city of Pikine where approximately 900,000 people currently live.

This constant increase of the population of Dakar justifies the importation of water from Lake Guiers to meet drinking water needs. Part of this water is used in Pikine and is added to the natural recharge of this water table.

In this framework and for addressing the two key issues outlined earlier in the introduction, through modelling tools, we will study two problems using geostatistical models: one model simulating the distribution of heads and showing groundwater flownets and then, in a second part, we will study the contamination problem in order to find links that will be useful for a better understanding and management of this groundwater.

Geostatistics is a collection of statistical techniques for the analysis of spatial data. This technique can be used in a variety of groundwater modelling studies, such as mapping of spatial variables, estimation and simulation of piezometric heads and transmissivities, estimation of groundwater flow velocity based on observed heads, estimation of contamination volume based on point measurements, design of sampling and monitoring networks, etc (Sarkar B.C., 2019). Geostatistical methods are generally associated to interpolation techniques. Kriging is a linear interpolation method for which observation points are correctly re-estimated**.** Ordinary Kriging (OK) and lognormal Kriging were used to produce the spatial patterns of heavy metals and disjunctive Kriging was applied to quantify the probability of heavy metal concentrations higher than their guide values (Lui X et al. 2005). In the study conducted by Hu et al. (2005), spatial variability of grounwater quality and risk of NO3 pollution in groundwater in the central North China Plain were determined using the OK method. Geostatistical methods, Kriging and co-Kriging, were applied by Pozdnyakova and Zhang (1999) to estimate the sodium adsorption ratio (SAR) in a 3,375 ha agricultural field. The spatial distribution of nitrate concentration in the aquifer of central Italy (about 110 km^2) was investigated and co-Kriging and OK techniques were compared in another study by D'Agostino et al. (1998). In this present study, instead of interpolation methods, we will use Ordinary Least Square estimations. This method has the advantage of providing mathematically continous and regular functions that can be hanled easily and specifically that can accomodate to partial differential equations for function or parameter estimation. In this framework, after the OLS estimation step for getting an equation linking piezometric heads, geospatial coordinates and time, we use this equation to estimate the net recharge in the area using the governing equation in unconfined aquifers. In the second part, for assessing the ongoing groundwater contamination in the area, we use OLS estimation along with statistical tests.

2. Modelling of groundwater dynamics:

Three factors that are reduced pumping, increased recharge and precipitation can explain the rise of water table in Thiaroye area. This rise in water table level is a disaster for the inhabitants of Pikine since it induces a high risk of flooding. It was the reason why the senegalese government undertook an important project of rehabilitation of old boreholes and construction of new ones in 2014. The objective was to install sufficient pumping capacities throughout the Thiaroye zone that will make it possible to meet the water demand of farmers in the market garden area and fight floodings simultaneously. So in this present modelling work, we aim to assess the aquifer behavior with respect to these discharge wells and to calculate the net recharge within the area.

In general, a model should be calibrated against one period of the historical record, then verified against another period of record (Freeze, R. Allan, and John A. Cherry, 1979). In our case, for the calibration of the hydraulic heads, we will use a least square criteria (2) using the model expressed by equation (1):

$$h = \alpha_0 + P(t) + \varphi(x, y) . \quad (1)$$

Where h is the hydraulic head in meters, α_0 is a constant expressed in meters, $P(t)$ is a polynomial function of time t only and $\varphi(x, y)$ a polynomial function of space coordinates x and y only. So the calibration will consist in finding the best polynomial functions P and Q minimizing the residual R_h.

$$R_h = \frac{1}{n_{obs}} \left[\sum_{(i=1)}^{(n_{obs})} (h_{measured(i)} - h_{modelled(i)})^2 \right]^{1/2} . \quad (2)$$

Table 2 provides the values of $h_{measured}$ for three selected piezometers installed at Pikine, Boune and Tivavouane Peulh from May 2005 to April 2017.

In this table and the following mathematical model, the spatial coordinates are translated in order to handle relatively « small » numbers.

The real coordinates X_r and Y_r along with new X and Y coordinates obtained after translation by a vector $v = \binom{-244129}{-1636215}$ are presented in the below table 1.

Table 1

Spatial coordinates of the piezometers

Points	X_r	Y_r	X	Y
P25	244129	1636215	0	0
P26	247982	1633711	3853	-2504
P28	255065	1639393	10936	3178

Table 2

Hydraulic head of each piezometer as function of time

Points	Time (months)		1	3	5	7	9	39	43	44	144
	X	Y	Piezometric heights (m)								
P25	0	0	-1.36	-1.26	-2.22	-1.99	-1.77	-1.42	-1.97	-1.78	-3.48
P26	3853	-2504	-2.34	-2.35	-3.7	-3.61	-3.52	-3,7	-3.65	-3.84	-5.27
P28	-7650	-1244	0.37	0.45	-0.07	-0.08	-0.09	0.76	-0.1	-0.115	-1.615

The *water table* is best defined as the surface on which the fluid pressure *p* in the pores of a porous medium is exactly atmospheric. If *p* is measured in gage pressure, then on the water table, $p = 0$. Since $h = z + \psi$, *with* $\psi = \dfrac{p}{\rho g}$ this implies $\psi = 0$, and the hydraulic head at any point on the water table must be equal to the elevation z of the water table at that point.

$$h = z\,.$$

Meaning that the hydraulic head is given by only the knowledge of the altitude of the water table.

Groundwater flow in an unconfined aquifer is modeled by a parabolic PDE of the following form

$$S_y \frac{\partial h}{\partial t} - \nabla \cdot (T \nabla h) = \Delta R_N\,. \qquad (3)$$

With:

h – piezometric head (m);

ΔR_N – net recharge (m/s);

T – Transmissivity of the aquifer m^2/s;

s_y – Storativity or specific yield of the aquifer.

In table 3 below, we present the different values of the transmissivity T, hydraulic conductivity K and specific yield S_y considered for each of our three piezometers. Values of K and Sy are obtained from (Harold KOUKOUI et Ndéné NDIAYE, 2003). For the computation of transmissivities T, we will consider a mean deapth to substratum of 20 meters within the Thiaroye area (refer to SONYA CHAOUI, 1996).

Table 3

Values of K and Sy and T for each piezometer

Points	$K\ (m/s)$	$Sy\ (\%)$	$T\ (m^2/s)$
P25	$1.75.10^{-4}$	4.8	$3.5.10^{-3}$
P26	$1.85.10^{-4}$	2.1	$3.7.10^{-3}$
P28	$1.79.10^{-4}$	1.5	$3.58.10^{-3}$

These values are consistent with those in the report of CHAOUI, S. (1996). The hydrodynamic characteristics of the aquifer were also estimated by the MH / WHO study in 1972 where the values of transmissivity are between $1.6.\,10^{-3}$ and $6.75\ 10^{-3}\ m^2\ /s$. The highest values are found in the east and south of Retba Lake. In the Thiaroye basin, the transmissivity is of the order of $3\ .10^{-3}\ m^2\ /s$. The values of the storage coefficient are between 0.3% and 14%".

The unit time chosen in this study is the « month ». In this study, we will chose a polynomial function P of degree 4 in time and a polynomial function φ of degree 2 in space coordinates. After performing an OLS estimation using equation 1 and Eviews software, one obtains table 4 below.

Table 4

Results of the estimation of hydraulic heads h with Eviews

Dependent Variable: h

Method: Least Squares

Date: 10/05/20 Time: 13:14

Sample: 1 27

Included observations: 27

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-0.883432	0.217187	4.067613	0.0006
t	-0.235791	0.054611	4.317669	0.0003
t^2	0.014664	0.003798	-3.861182	0.0010
t^3	-0.000284	8.26E-05	3.440460	0.0026
t^4	1.34E-06	4.09E-07	-3.272134	0.0038
X^2	4.13E-08	2.50E-09	-16.50190	0.0000
Y^2	-3.59E-07	2.33E-08	15.39025	0.0000
R-squared	0.969468	Mean dependent var		1.841481

Continuation of the table 4

Adjusted R-squared	0.960309	S.D. dependent var	1.620609
S.E. of regression	0.322869	Akaike info criterion	0.795274
Sum squared resid	2.084888	Schwarz criterion	1.131232
Log likelihood	-3.736198	F-statistic	105.8423
Durbin-Watson stat	2.203092	Prob(F-statistic)	0.000000

According to the above table 4 and with student tests, one can see that all independent variables of the model are significative at an error threshold of at most 0.3%.

We therefore obtain the following equation.

$$h = -0.88343 - 0.23579 \cdot t + 0.01466 \cdot t^2 - 0.00028 \cdot t^3 + \\ +1.338 \cdot 10^{(-6)} t^4 + 4.131 \cdot 10^{(-8)} \cdot X^2 - 3.588 \cdot 10^{(-7)} \cdot Y^2 . \quad (4)$$

Note that P25 is located at Pikine, P26 at Boune and P28 at Tivavouane Peulh. A groundwater flownet is a 2D representation of a set of equipotential lines or flowlines. The construction of flow nets is one of the most powerful analytical tools for the analysis of groundwater flow (Freeze, R. Allan, and John A. Cherry, 1979). The flow net represented in figure 2 below shows that groundwater flows from Pikine to Boune and from Tivavouane Peulh to Boune. Moreover, in figure 3 below, we show the position of the three piezometers in a Dakar area map.

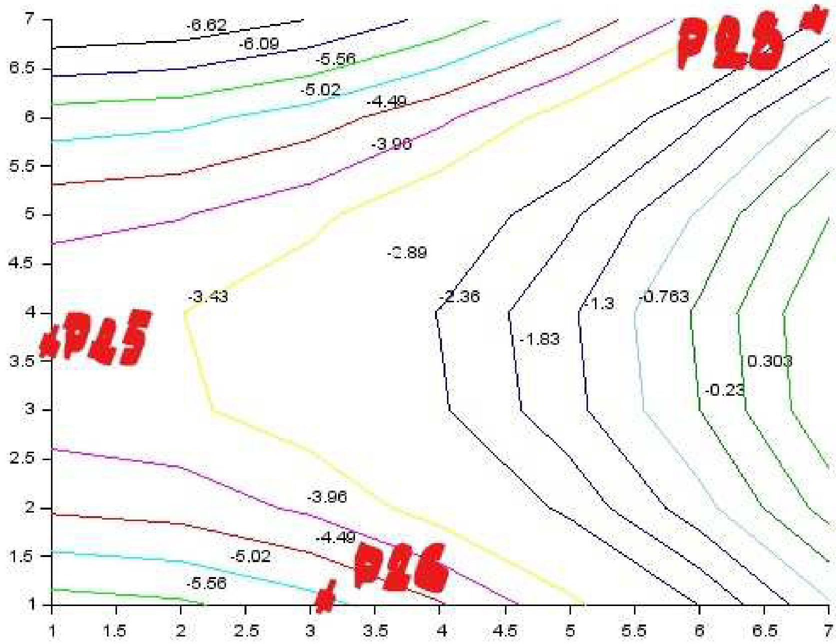

Figure 2. Flownets in the area delimited by P25, P26 and P28 piezometers

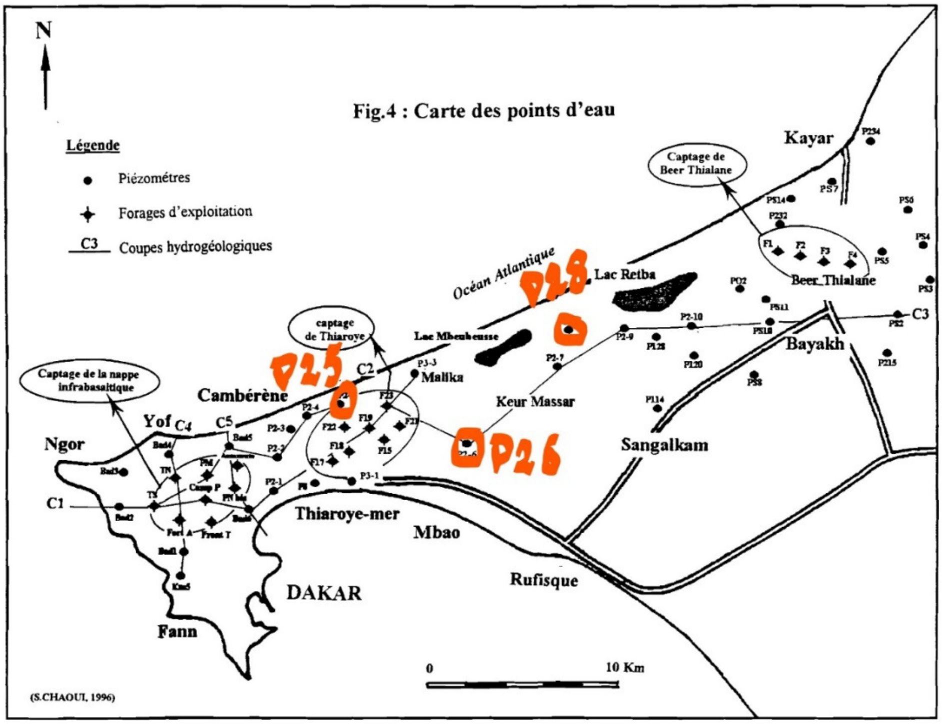

Figure 3. Map of the area showing piezometers P25, P26 and P28

From (3) and (4), one can infer the following equation (5) for the net recharge ΔR_N:

$$\Delta R_N = [-0.23579 + 0.02932.t - 0.00084.t^2 + 5.352.10^{-6}t^3]s_y - 6.3498.10^{-7}.T \tag{5}$$

The results of the calculations are summarized in table 5 below.

Table 5

Results of the estimation of net recharges

	Time (months)		1	3	5	7	9	39	43	44	144
	X	Y	Net discharges (m)								
P25	0	0	-0,010	-0,007	-0,005	-0,003	-0,002	-0,003	-0,005	-0,006	0,122
P26	3853	-2504	-0,004	-0,003	-0,002	-0,001	-0,001	-0,001	-0,002	-0,002	0,054
P28	-7650	-1244	-0,003	-0,002	-0,002	-0,001	-0,001	-0,001	-0,002	-0,002	0,038
Mean net discharge (m)			**-0,006**	**-0,004**	**-0,003**	**-0,002**	**-0,001**	**-0,001**	**-0,003**	**-0,003**	**0,071**

NB: If net recharges are negative, this corresponds rather to discharges.

One notice from the table 5 above that for each month within the area covered by the three piezometers, one has a mean recharge varying between -0.006 to +0.071 m/month. These values which are very near to zero can be explained by flooding fight strategies consisting mainly of pumping groundwater out of the concerned areas.

3. Modelling of groundwater contamination:

In Thiaroye partly irregular settlements, sanitation was and remains sparse and inefficient. The latrines are mainly connected to septic tanks which are not adapted to the hydrological situation. In fact, the wastewater from the septic tanks flows directly into the water table even when groundwater is pumped. The urbanization of the area therefore coincided with a significant increase of the level of nitrate in water. In the Thiaroye wells, for example, the nitrate concentration ranged from 5 to 40 mg/l in 1970 from 400 to 450 mg/l in 1997 (Diédhiou, M. et al. 2011). The resulting mineralization in the Thiaroye area is as result due to two main factors : saline invasion and high nitrate content of the water above the maximum allowable concentration of 50 mg/l defined by WHO. For this reason, we have chosen to specify two geostatistical models: First, we investigate the relationships between electrical conductivity, geospatial coordinates, depth to water table and an indicator of salt presence like TDS. This approach is justified by the fact that given that conductivity varies with water source like groundwater, water drained from agricultural fields, household waste water, rainfall, etc, and can therefore indicate groundwater seepage or a sewage leak. And as result, electrical conductivity can be used for water quality assessment.

We will use the least square method based on the minimization of R_{CE} in equation (7). Electric conductivity will be expressed using the below linear model (6):

$$CE = a_0 + a_1 X + a_2 Y + a_3 H + a_4 TDS. \quad (6)$$

In which model, the coefficients (a_i) are to be estimated, based on the minimization of the residue R_{CE} in equation (7) which expresses the mean difference between measured and simulated EC over the number of observations n_{obs}:

$$R_{CE} = \frac{1}{n_{obs}} \left[\sum_{i=1}^{n_{obs}} \left(CE_{measured\,(i)} - CE_{modelled\,(i)} \right)^2 \right]^{1/2}. \quad (7)$$

Furthermore, regression statistics, including parameter sensitivities and correlations are presented below. We obtain then the following specification for the Electrical conductivity function:

And in a second part, we specify a model which links mainly Nitrate and sodium concentrations through geospatial coordinates and depth to water table.

$$[Na] = b_0 + b_1X + b_2Y + b_3H + b_4[NO_3]^{-1}. \quad (8)$$

In this model, the coefficients (b_i) in equation (8) are to be estimated, based on the minimization of the residue R_{Na} in equation (9) which expresses the differences between measured and simulated Na:

$$R_{Na} = \frac{1}{n_{obs}}\left[\sum_{i=1}^{n_{obs}}\left(Na_{measured\,(i)} - Na_{modelled\,(i)}\right)^2\right]^{1/2}. \quad (9)$$

Fields measurements were performed in 2014 in the Thiaroye area at locations identified by their geospatial coordinates (X,Y) and consisted mainly of measuring the depth to water table (H) in meters, Electric conductivity (EC), the concentration of Total dissolved Solids (TDS), the concentration of Nitrates (NO_3) and the concentration of Sodium (Na). In table below, we present the results for 13 boreholes located in Thiaroye area.

Table 6

Physico-chemical parameters for 13 boreholes in Thiaroye area

Désignation	*xCoord UTM*	*yCoord UTM*	*Depth (m)*	*EC*	*TDS*	*NO3*	*Na*
THIAROYE F18	244144	1633165	42	3200	3602	-2	1295
THIAROYE Nord 1	243446	1635016	38	700	1942	112	280
THIAROYE F22	244094	1634118	38	3200	3320	-2	1221
THIAROYE F23	245475	1634503	46	4500	3330	3	1168
THIAROYE F11 bis	246082	1632468	43	4175	2499	7	900
THIAROYE F21 bis	245288	1633860	36	238	388	28	29
THIAROYE F19 bis	244782	1634080	37	263	570	40	36
THIAROYE F17 bis	243666	1633201	37	288	600	104	49
THIAROYE F2	243670	1633569	41	215	314	16	33
THIAROYE F4	244560	1632884	42	238	355	26	40
THIAROYE F5	245954	1634529	36	241	430	16	37
THIAROYE F6	246129	1634097	37	350	494	28	36
THIAROYE F8	248650	1631980	35	350	422	26	44

Table 7 below shows the results of the estimation of EC obtained with Eviews software using formula 6.

Table 7

Results of the estimation of Electric Conductivity with Eviews

Dependent Variable: CE
Method: Least Squares
Date: 09/28/20 Time: 21:32
Sample: 1 13
Included observations: 13

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	12311.79	332573.5	0.037020	0.9714
X	0.268896	0.119899	2.242692	0.0552
Y	-0.051579	0.194189	-0.265615	0.7973
H	154.0033	56.95678	2.703862	0.0269
TDS	1.007503	0.140831	7.153996	0.0001

R-squared	0.940006	Mean dependent var	1381.385
Adjusted R-squared	0.910010	S.D. dependent var	1694.561
S.E. of regression	508.3409	Akaike info criterion	15.58390
Sum squared resid	2067284.	Schwarz criterion	15.80119
Log likelihood	-96.29538	F-statistic	31.33691
Durbin-Watson stat	1.224776	Prob(F-statistic)	0.000062

This estimation leads to the following formula :

$$CE = 12311.78969 + 0.2688956516.X - 0.05157946738.Y + 154.0032841.H + 1.007503297.TDS. \quad (10)$$

Following the results provided by table, one can formulate the following remarks :

- The coefficient of determination $R^2 = 0{,}94$ indicates that 94% of the variations of CE are explained by the geostatistical coordinates, the depth to water table and dry residues.
- The values of probabilities the Student statistic associated to the variables "depth" and "TDS" show that the corresponding coefficients for these variables are significative at an error threshold of 2% max. EC does increase with an increase in depth and TDR. This is probably due to the increase of salinity with depth.
- The value of probability associated to the Fisher statistic (and the little value of the associated probability) shows that the model is significative at an error threshold of 0.01% max: there is globally a linear relation between EC and the other variables.
- An increase in water table depth of 1 meter yields an increase of

the EC by about 154 points.

- The gradient of the EC is in the direction of the vector: $T = (0{,}2688, -0{,}0515)$.

Table 8 below shows the results of the estimation obtained with Eviews software using formula 8.

Table 8

Results of the estimation of sodium concentration with Eviews

Dependent Variable: Na
Method: Least Squares
Date: 09/28/20 Time: 21:28
Sample: 1 13
Included observations: 13

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-369288.5	187204.2	-1.972651	0.0840
X	0.169939	0.073738	2.304622	0.0501
Y	0.197451	0.108016	1.827975	0.1050
H	139.3336	26.29919	5.298020	0.0007
$[NO_3]^{-1}$	-1730.496	396.4282	-4.365219	0.0024
R-squared	0.821446	Mean dependent var		397.5385
Adjusted R-squared	0.732169	S.D. dependent var		530.5531
S.E. of regression	274.5741	Akaike info criterion		14.35204
Sum squared resid	603127.3	Schwarz criterion		14.56933
Log likelihood	-88.28827	F-statistic		9.201083
Durbin-Watson stat	1.299730	Prob(F-statistic)		0.004356

This estimation leads to the following formula:

$$[Na] = -369288.5181 + 0.16994X + 0.19745Y + 139.33363H - 1730.4957.[NO_3]^{-1}. \quad (11)$$

Following the results provided by table, one can formulate the following remarks:

- The coefficient of determination $R^2 = 0{,}82$ indicates that 82% of the variations of $[Na]$ are explained by the geostatistical coordinates, the depth to water table and Nitates concentrations.
- The values of probabilities associated to the Student statistic for the variables "depth" and "$[NO_3]$" show that these variables are significative at an error threshold of 0.5%. $[Na]$ does increase with an increase in depth and decreases with a increase of salinity.
- The value of probability associated to the Fisher statistic shows

that the model is significative at a threshold of 0.5%: there is globally a linear relation between $[Na]$ and the other variables of the model.

- An increase in water table depth of 1 meter yields an increase of the $[Na]$ by about 139 points.
- The gradient of the $[Na]$ is in the direction of the vector: $T = (0{,}1699, -0{,}1974)$

Note 1:

The total dissolved solids concentration can be related to the conductivity of the water, but the relationship is not a constant. The relationship between total dissolved solids and conductivity is a function of the type and nature of the dissolved cations and anions in the water and possible the nature of any suspended materials.

$$TDS = \omega C, \tag{12}$$

where C is the conductance in: microsiemens or micromhos, TDS is expressed in g/m3 or *mg/t,* and ω is a conversion factor. For most groundwater, ω is between 0.55 and 0.75, depending on the ionic composition of the solution (Freeze, R. Allan, and John A. Cherry, 1979).

4. Conclusion:

This study shows that there is a monthly weak recharge rate ranging between -0.006 to +0.071 certainly due to efforts aiming to prevent the area from flooding by controlling the water table level with pumping systems. Concerning groundwater quality, we notice a high dependence of Electrical conductivity to geospatial coordinates, depth to water table and salinity as well as an inverse correlation between sodium and nitrates concentrations. If one moves deeper in the aquifer, seawater is predominant whereas at shallow depths, nitrates are more present.

Abreviations:

OLS – Ordinary Least Square

PDE – Partial Differential Equation

EC – Electric Conductivity

TDS – Total dissolved Solids concentration

$[Na]$ – sodium concentation

$[NO3]$ – nitrate concentration

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ГЕОСТАТИСТИЧНИЙ ПІДХІД ДО МОДЕЛЮВАННЯ ПІДЗЕМНИХ ВОД ДЛЯ ПРИБЕРЕЖНОГО ВОДОНОСНОГО ГОРИЗОНТУ ТІАРОЄ

У статті досліджено поєднання геостатистичних і математичних методів для пояснення динаміки підземних вод прибережного водоносного горизонту Тіаройе та забруднення як морською водою, так і нітратами. Цілями цього дослідження було надання огляду поточного гідравлічного напору підземних вод і якісного просторового розподілу на території дослідження. Спочатку ми використовуємо дані ГІС, щоб визначити модель гідравлічних напорів залежно від GPS-координат і часу, використовуючи звичайну оцінку найменших квадратів, виконану в

Eviews. Потім ми використовуємо керівні диференціальні рівняння в частинних похідних для необмежених водоносних горизонтів для розрахунку чистого поповнення. У другій частині визначені геопросторові моделі для пояснення варіацій електропровідності та для встановлення зв'язків між концентраціями нітратів і натрію. Встановлено, що по всій досліджуваній території спостерігається слабка місячна швидкість поповнення, що обумовлюється заходами спрямованими на запобігання затоплення території шляхом контролю рівня ґрунтових вод за допомогою насосних систем. Крім того, кореляції показують, що натрій і електропровідність збільшуються з глибиною і що концентрації нітратів і натрію обернено корелюють.

***Ключові слова*: гідравлічні напори; дані ГІС; безнапірний водоносний горизонт; електропровідність; якість підземних вод; статистичне моделювання; перевірка гіпотез.**