Groundwater Flow Modelling: A Decision-making Tool for Water Resource Management in Coastal Areas - Case Study of the Oussouye Plateau (South Senegal)

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Abstract Hydrogeological and hydrochemical investigations were used to develop a conceptual model of the Continental Terminal (CT) aquifer functioning in the Oussouye plateau (South Senegal). Two field campaigns were carried out in June and October 2017 to measure physicochemical parameters and groundwater sampling. The geometry of the CT was established using geophysical technics (electrical methods) and the drilling logs from previous studies carried out in Oussouye region. These investigations led to build the mathematical model under the Visual modflow interface with the Modflow-2000 code developed by USGS. The results show a general trend of groundwater flow towards the Casamance River and its tributaries from piezometric mounds in the central area of the plateau which represent the potential recharge zones. Regarding chemical quality, electrical conductivity varies from 28 to 1314 µs/cm with high variance and standard deviation values reflecting variable sources, geochemical and dilution processes occurring in the plateau. The analysis of water samples shows an excellent groundwater quality. Major ions contents do not exceed WHO standards except Iron (Fe) which are relatively high in some wells. The mathematical model was calibrated in steady state. The average difference between simulated and observed head is 0.009 m and the root mean squared is less than 0.2m. Simulations under transient conditions showed that the groundwater is vulnerable to high pumping rate due to the drawdowns at the catchment wells, which can reach 7 m for 300 m^3/d. This significant drawdown should be avoided for this type of piezometric configuration where the maximum hydraulic head is around 5 m. However, the model revealed a sustainable groundwater potential for the needs of local and neighboring populations by 200m^3/d.

Keywords: *shallow aquifer, Casamance, costal area, continental terminal, groundwater management, Modflow*

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1. Introduction

Groundwater resources are used for drinking water production because of their many advantages: high-quality, small-quality variations (seasonally), low-storage costs (relatively small surface facilities) and easy exploitation [1]. Due to the increased population in coastal zones, many communities are faced with water shortage problems. The shortfall in water supply is often met by pumping groundwater [2], which sometimes copes with some difficulties [3] such as: (1) evolving distribution between fresh and salt water [4], (2) lowering of the hydraulic heads influencing general groundwater flow patterns and the water balance [1], (3) land subsidence [5], and (4) in

worst circumstances sea water intrusion occurs and salt water reaches exploitation wells.

The Continental Terminal (CT) aquifer in Casamance (Southern Senegal) is the main sources of fresh water for agricultural activities, livestock and drinking water supply of the region. Over pumping of groundwater wells especially in the Oussouye Plateau (OP), bounded largely by salt brackish water (locally called bolongs) and the Casamance River is a major risk of the groundwater quality degradation in this particular area. Therefore, to combat the potential threats, it is necessary to undertake a scientific study that focuses on the behavior of this coastal groundwater system under anthropic pressures.

One of the best tools available to help groundwater hydrologist to overcome challenges of prediction is usually by a groundwater flow modelling [6,7,8]. Modular

finite-difference flow model (MODFLOW) by the U.S Geological Survey (USGS) is widely used for groundwater flow and contaminant transport modelling among softwares. Some contexts such as agriculture, airfields, constructed wetlands, climate change, drought studies, landfills, mining operations, river and flood plain monitoring, salt water intrusion, soil profile surveys, watershed analyses, are the areas where the software has been reportedly used this last decade [9].

The aim of this paper is to develop a rational management and decision-making tool for resource managers based on groundwater flow modelling under Visual Modflow.

2. Study Area

The OP is located in southwestern Senegal and includes the localities of Mlomp, Oukout and Santhiaba Manjack. It is part of the left estuary of the Casamance River, which is completely occupied by marine waters. The hydrological system is dominated by the Casamance River and its many tributaries, which are characterized by very winding paths that frame the OP in its northern, western and eastern parts and bring it into contact with sea water. It is bordered in its southern part by the Republic of Guinea Bissau (Figure 1).

The weather in Oussouye as in the Casamance region is Sudano-Guinean, characterized by warm with an average wet temperature of 27°C. The climate has a seasonal cycle with a rainy season of 5 to 6 months from May to October (average of 1200 mm/year) and a dry season from November to April/May. Evapotranspiration is estimated at 1659 mm per year with a maximum at April (189 mm).

The OP belongs to the western southern part of the Senegalo-mauritanian basin which extends about 1400 km from Mauritania in the north to Guinea Bissau in the south. This coastal basin with a passive margin accumulates a powerful sedimentary series of mainly marine origin, beginning in the Triassic-Lias and ending in the Miocene. However, it is largely covered by recent Plio-Quaternary deposits that mask the oldest Mesocenozoic sediments. Regarding hydrogeology, the Oussouye area contains a shallow (Continental Terminal), a semi-deep (Oligo-Miocene) and a deep (Maastrichtien) aquifers separated by relatively thick impermeable levels (clays). However, most of the boreholes drilled in this area tap the shallow groundwater because of high salinity content of the deep and semi deep aquifers. The permeability of the CT formation varies from 5.10^-5 to 1, 5.10^-4 m/s and the transmissivity give values from 5.10^-5 to 10^-4 m^2/s according to pumping tests [10].

3. Methodology

3.1. Data Acquisition

Two field campaigns were carried out in June and October 2017 to measure physicochemical parameters and groundwater depth. The water points were then surveyed by differential GPS to define the piezometric map and thus the groundwater flow. Water samples from the first campaign were collected for chemical analysis (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, CO_3^{2-}, HCO_3^-, SO_4^{2-}, NO_3^-, Fe and PO_4^{3-}) performed at the hydrochemistry laboratory of Geology department (University of Dakar).

The geometry of the CT was established using geophysical technics (electrical sounding), drilling reports from previous studies [11] and 30 m SRTM resolution (digital elevation model) from USGS in addition to GPS surveying. All these basic data were used to define the morphology of the top and the bottom of the aquifer in order to build the 3D model of the CT.

3.2. Modelling Method

The mathematical model was built under the Visual modflow interface with the Modflow-2000 code developed by USGS [12]. The governing equation for groundwater flow of constant density through porous media in terms of freshwater head, which is solved by MODFLOW routines may be described by the partial differential equation (Equation 1).

$$\frac{\partial y}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial y}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial y}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)-W=-S_s\left(\frac{\partial h}{\partial t}\right) \quad (1)$$

Where K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y and z coordinate axes which are assumed to be parallel to the major axes of hydraulic conductivity; h is piezometric head; W is a volumetric flux per unit volume and represents sources and/or sinks of Water; S_s is the specific storage of the porous material and t is time.
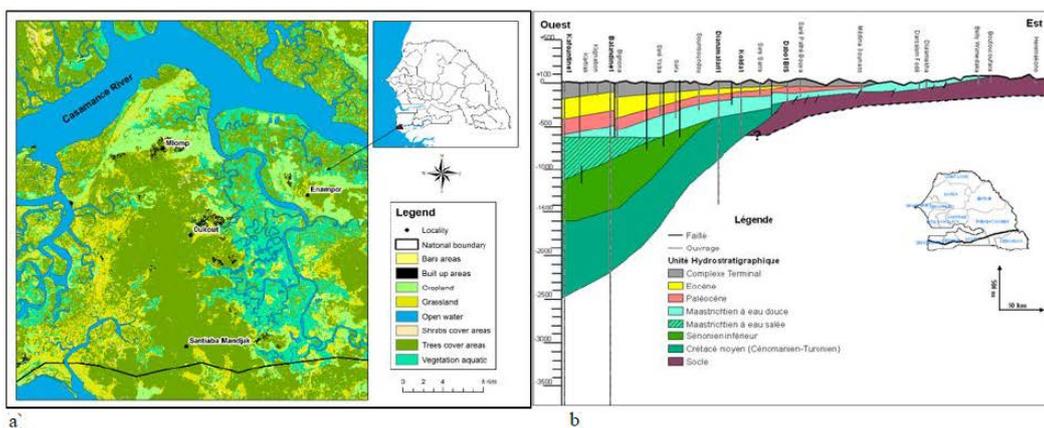

Figure 1. (a) Land use of OP, (b) Hydrogeological setting in the south of Senegal

In the lack of continuous piezometric monitoring over time, the model is calibrated in steady-state using the October 2017 flow state, which is more representative because of high abstraction from wells (dynamic level at water point) leading to a transient regime of the system during the dry season (June). Moreover, the October's flow state considers infiltration after the rainy season (July-September).

The model is subsequently operated in a transient simulation with same boundaries condition to evaluate the future impact of new pumping over a period of 50 years. For each simulated scenario, the impact of abstraction was assessed according to the modeled drawdown inside the borehole. It is deducted from the drawdowns calculated by the model at the meshes where the boreholes are located, using the Dupuit formula [13] to consider the difference in size between the mesh (500 m) and the borehole (diameter of 200 mm) by the Equation 2:

$$h_{mesh} - h_{well} = \frac{Q}{2\pi T}\left(\ln\left(\frac{a}{r_p}\right) - \frac{\pi}{2}\right) \qquad (2)$$

Where h_{mesh} is the simulated head in the mesh; h_{well} the simulated head after correction, Q the pumped flow rate; T the transmissivity of the aquifer; the side of the mesh, and r_p the radius of the well.

3.3. Conceptual Model

The CT is represented by a single layer with a mesh size of 500 m (69 rows and 57 columns) (Figure 2). Natural boundaries (water bodies) were used to define the extension of the model. Therefore, the boundaries conditions applied for the aquifer are:
- Constant head limits in areas where water bodies are present, such as to the north with the Casamance River; in the West and East with the bolongs.
- Non-flow limit in the South corresponding to the border with Bissau Guinea has been pushed relatively far from the area of interest so that it does not have a particular impact.
- Inside conditions for recharge rate and abstractions from the borehole catchment and traditional wells where rate was surveyed.

4. Results

4.1. Geometry

The topographic map highlights the plateau area in the center of the region, which rises from 25 to 30 m except for the northern part, where it is lower. Above and on either side of the flanks, the topography becomes lower with +5 m IGN (Figure 3a). The substratum's depth was evaluated from the resistivity data of vertical electrical soundings [11]. In fact, the resistivity values which vary greatly from one point to another depend on the lithology encountered and the conductivity of the imbibed water. The high values in this granular media context indicate a poorly conductive setting and can be interpreted as dry or wet (low clay proportion) frank sands. On the other hand, the gradual decrease at depth or laterally indicates a more clayey sand. The low resistivity values (1 to 5 Ω.m) identify the clayed substratum that separates the CT and the Oligo-miocene aquifer. Thus, the morphology of the substratum shows low areas between -25 and -30 m in the center and west, except for the parts located in the south-east and the far north-east (Figure 3b) The corresponding layer are relatively thick in the central parts with a thickness of 50 m, decreasing to 10 m at the extreme South-East (Figure 3c).
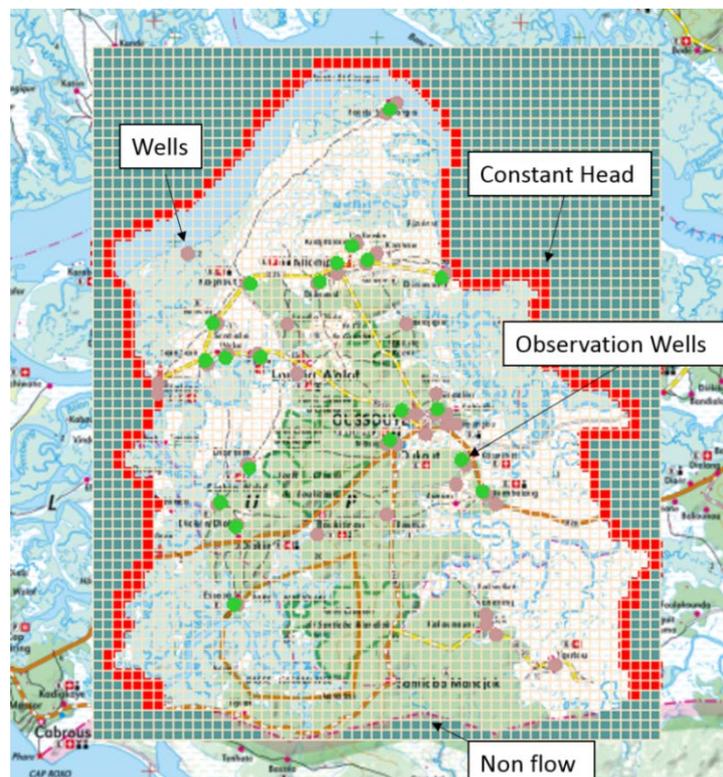

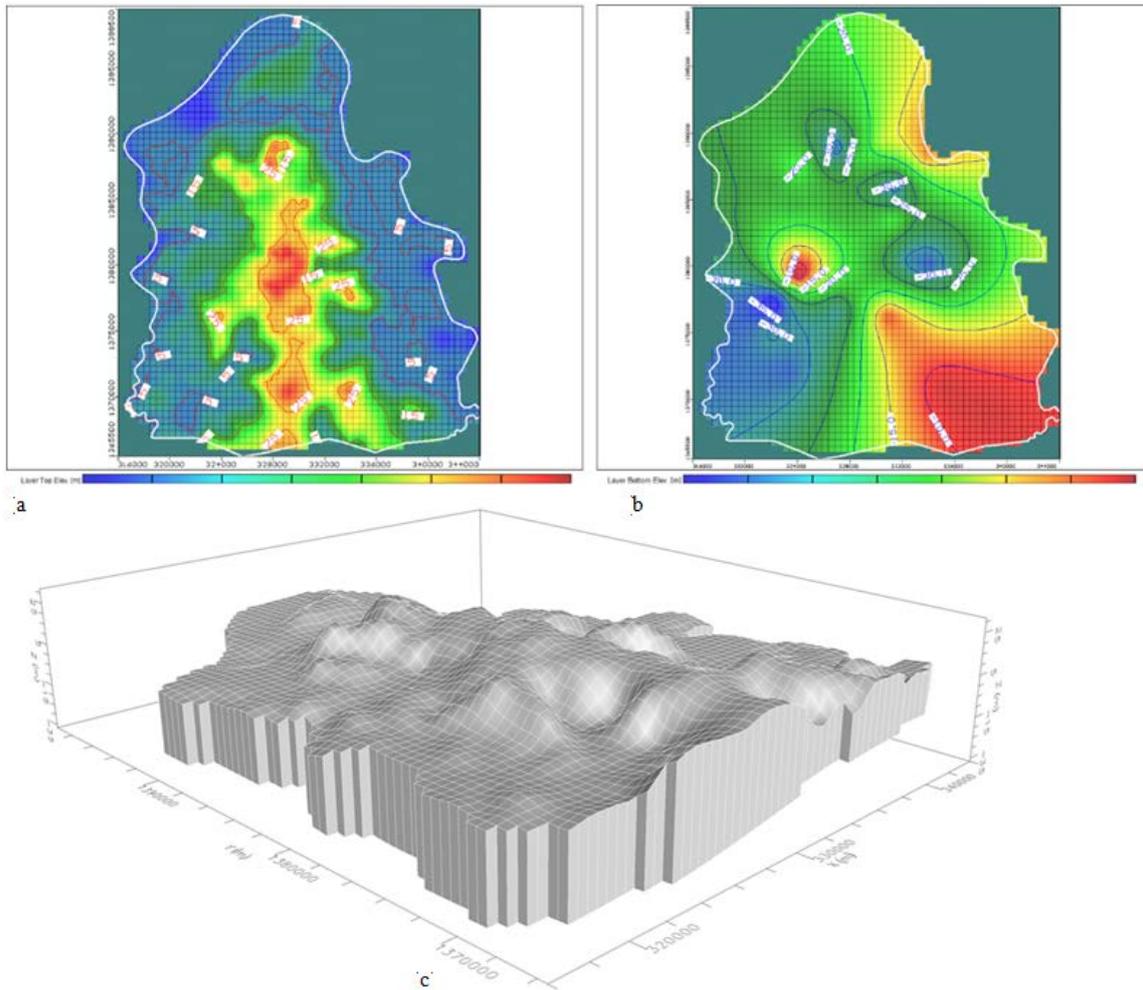**Figure 2.** Boundaries conditions of the CT model

Figure 3. (a) Topographic map, (b) morphology of the substratum of CT, (c) 3D model of the CT in the Oussouye plateau
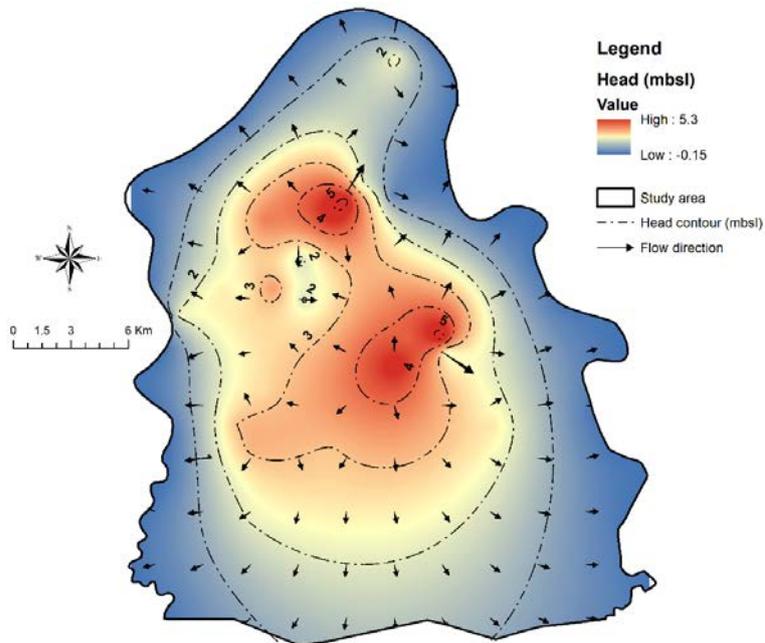

Figure 4. Groundwater flow of the CT aquifer in the Oussouye plateau (October 2017)

4.2. Groundwater Flow

The groundwater depth measured after the rainy season (October 2017) was used as basic data to calculate the piezometric level. The piezometric map obtained by kriging interpolation (Figure 4) shows a piezometric mound located in central part of the OP which control the groundwater flow. General flow pattern from

this mound at +5m (considered as the preferential recharging area) occurs in all directions toward the water bodies suggesting that groundwater drains into the Casamance River and the bolongs. The tightening of the head contours in the North-East as well as the lower hydraulic gradient would suggest lower hydrodynamic parameters such as transmissivity values (T) at this area. Also, their spacing in the west and the south suggests higher T.

4.3. Groundwater Quality and Mineralization Processes

Physico-chemical characteristics of groundwater from the two campaigns were evaluated according to a descriptive statistical analysis (Table 1). The temperature values range between 25.0 and 33.0°C reflecting the shallow character of the CT groundwater where heat exchanges are easily achieved through ambient temperature. The pH values, revealed the slightly acidic to basic character of the CT waters. They vary from 4.7 to 8.2 with averages and medians of 6.1 and 7.6 depending on the season. The electrical conductivity (EC) goes from 28 to 1314 µs/cm with very high variance and standard deviation values reflecting variable sources, geochemical and dilution processes depending on zones. The lowest EC values observed in the central part (corresponding to the mound) indicates the preferential recharge zones as suggested with the piezometric map. Mean and median EC values between 168 and 342 µs/cm indicate low mineralized waters that tend to become charged during high water periods. This process is well known in shallow groundwater where the acquisition of mineralization is achieved by dissolving salts in the unsaturated zone and mobilization ions through geochemical reactions during infiltration [14].

Table 1. Descriptive statistic of the physic-chemical parameters

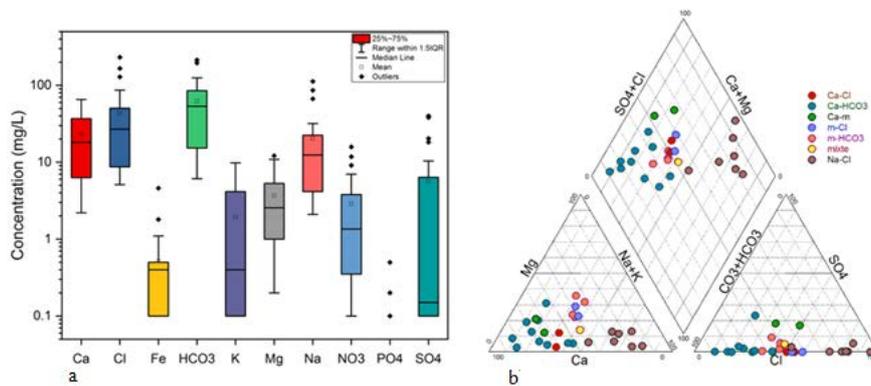| Parameters	CE	pH	T	CE	pH	T
Units	µs/cm	-	°C	µs/cm	-	°C
Sampling Date	June			October		
Min	28.0	4.7	25.0	28.0	6.1	26.3
Max	1218.0	8.2	33.3	1314.0	8.2	29.7
Mean	258.8	6.1	29.3	342.2	7.5	27.7
Median	168.6	6.1	29.4	315.0	7.6	28.0
Dev.Stand	238.9	0.6	1.8	260.9	0.6	0.9
Variance	57050.6	0.4	3.3	68075.3	0.3	0.8

Figure 5. (a) Box plot of major ions, (b) Piper diagram of samples during wet season (June 2017)
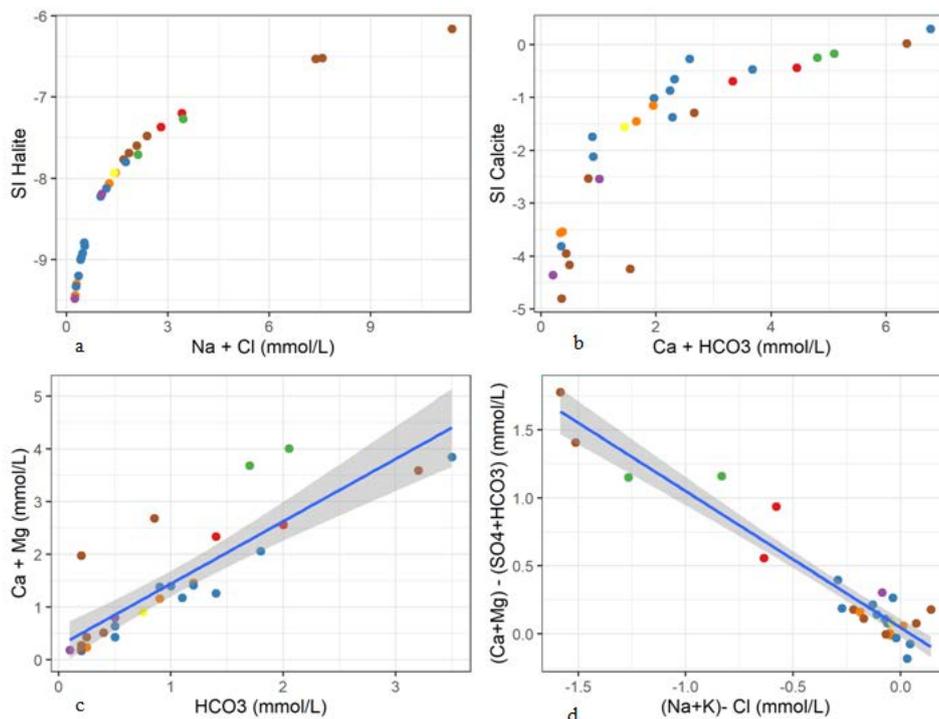

Figure 6. Biplots diagrams indicating mean geochemical processes. The legend is the same as in the Figure 5b

The box plot of ions content shows fresh and drinking water, except of the Iron (Fe) with an average and median values higher than the WHO standard (Figure 5a). The occurrence of Ion in the CT comes mainly from alteration products of the Pliocene or Mio-Pliocene ferruginous-clayey in composition [15].

According to Piper diagram [16] there are 7 water-type unevenly distributed in the OP mainly Na-Cl, Ca-HCO3, Ca-Cl and mixed facies (Figure 5b). However, there is a predominance of Ca-HCO3 and m-HCO3 facies in the central zone (potential recharge area) that could result from of carbonate mineral dissolution during infiltration. This process is exhibited by the positive correlation between Ca+Mg and HCO3 close to [1:1] equilibrium line (Figure 6c). Moreover, the freshest waters (Ca-HCO3 and m-HCO3 facies) are bellow calcite saturation index, indicating the possible calcite dissolution (Figure 6b). Na-Cl facies is largely due to inverse ionic exchange exhibited in the graph [(Ca+Mg) - (HCO3+SO4)] vs [(Na+K)-Cl] (Figure 6d) by linear negative trend [17].

4.4. Groundwater Modelling

4.4.1. Steady State Calibration
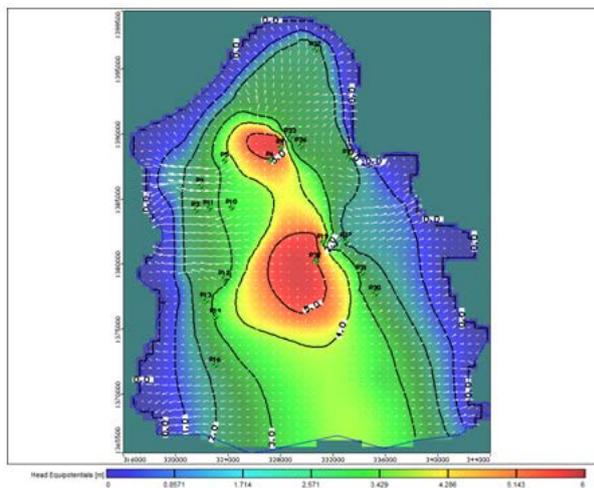
a
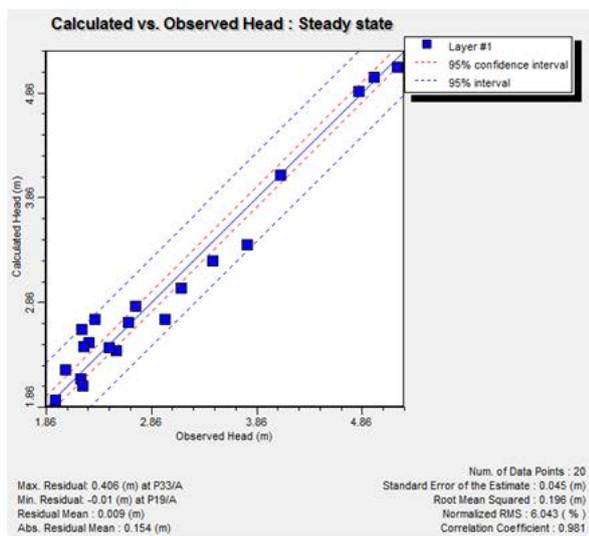
b

Figure 7. (a) Calibrated head by steady-state model, (b) Correlation between measured and calculated values with statistical analysis

The model was calibrated with the October's data on a set of 20 representative observation wells. The adjusted permeability values through manual trials and PEST optimization are between 10^{-6} and 10^{-4} m/s. These values are consistent with those derived from pumping test in the CT aquifer [10], as well as the sandy-clayey nature of the reservoir. The calibrated recharge values still respect a flow gradient with rates of 80 to 20 mm/year in the central part and 5 mm/year on the sides of the flow (more runoff toward the surface waters).

Difference between simulated and measured head values shows a fair match (Figure 7a) with computed Mean Absolute Error, Standard Error of Estimate and Root Mean Squared Error less than 0.2 m together with the square of Pearson correlation of 0.98 (Figure 7b).

The computed water budget for October 2017 (Table 2) evidenced the following characteristics:

- Inflows exclusively through recharge is 13,062 m^3/d
- Outflows to the Casamance River and the bolong is 11,271 m^3/d and pumping community need of 1,880 m^3/d.

Table 2. Water Balance in steady state model (October 2017)

Terms	Inflow (m3/jour)	Outflow (m3/jour)
Constant Head	0	11270.5
Abstraction	0	1880
Recharge	13062.5	0
Total	13063	13150

4.4.2. Simulation and Model Prediction

The objective of the simulation is the predicted the possibility of providing suitable drinking water in terms of the quantity and quality by evaluating the likelihood impact of future abstractions. The number of boreholes and their pumping rates were calculated on the basis of population sizes using the standard consumption for rural water supply recommended by [18].

• Scenario 1

For the first scenario, 5 new boreholes were established in the plateau where the CT is thicker with the best permeability values. For each borehole, a pumping rate of 200 m^3/d has been computed to meet the rural water supply needs (35 liters per person per day). The results of simulation show a decrease of piezometric level in the plateau (Figure 8). However, everywhere else on the flanks, the flow regime remains stable showing that the groundwater is draining towards the surfaces water. The simulated drawdowns are low in borehole FN1 and FN5 located in areas of higher permeability. However, for the FN3, FN4 and FN6, it reaches 5 m (Table 3).

In transient simulation, the steady state head (stable regime) is reached after 10 years of simulation (Figure 9). This period gives an indication of the stabilization time in case of permanent pumping at 200m^3/day with recharges and boundary conditions that do not change over time.

Table 3. Piezometric levels and drawdowns in boreholes (1st Scenario)

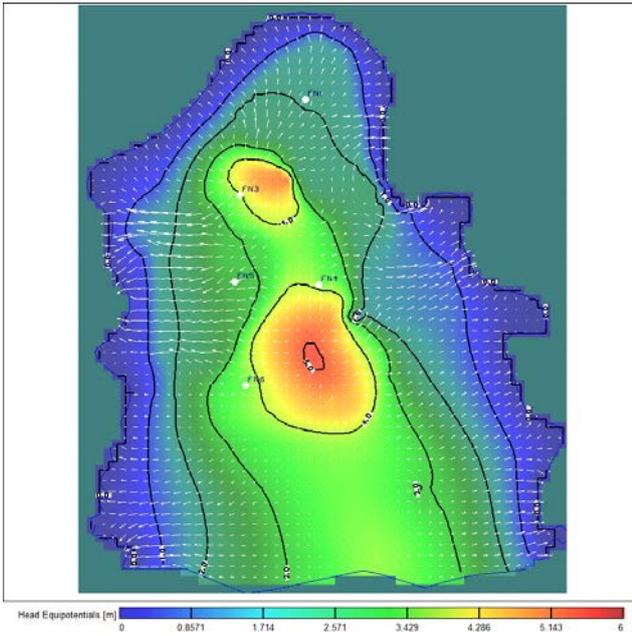| Borehole	Simulated Head in mesh (m)	Simulated head inside the Borehole (m)	Simulated drawdown inside the Borehole (m)
FN1	2.00	0.69	1.31
FN3	3.39	-1.83	5.22
FN4	3.32	-1.77	5.09
FN5	2.38	0.57	1.81
FN6	3.59	-1.38	4.97

Figure 8. Groundwater flow and simulated Head after additional abstractions (1er Scenario)

To assess the sensitivity of the model to abstraction, a need of urban consumption (65L per person per day) in case of urbanization of the study area over time are computed by increasing the pumping rate to 300m³/d for all borehole. The time series shows high decline especially for FN4, FN3 and FN6 up to -0.7m at mesh (Figure 10).

• **Scenario 2**

In a second scenario, 5 new boreholes are considered in addition to those of the scenario 1. In all 10 boreholes, a rate of 300m³/d are computed the take account other future needs such as irrigation and livestock. The simulated head shows that groundwater flow remains stable in the flanks as in the first scenario except in the center area where the simulated head is lower due to additional boreholes.

In addition, an increase in drawdowns simulated in boreholes is observed at all water point (Table 4). The borehole more affected by are FN3, FN4 FN6 and FN11 with a maximum drawdown of 7.8m (FN3) and a stationary state reached after 20 years. For other boreholes, the decline is not significant as in scenario 1 (Figure 10).
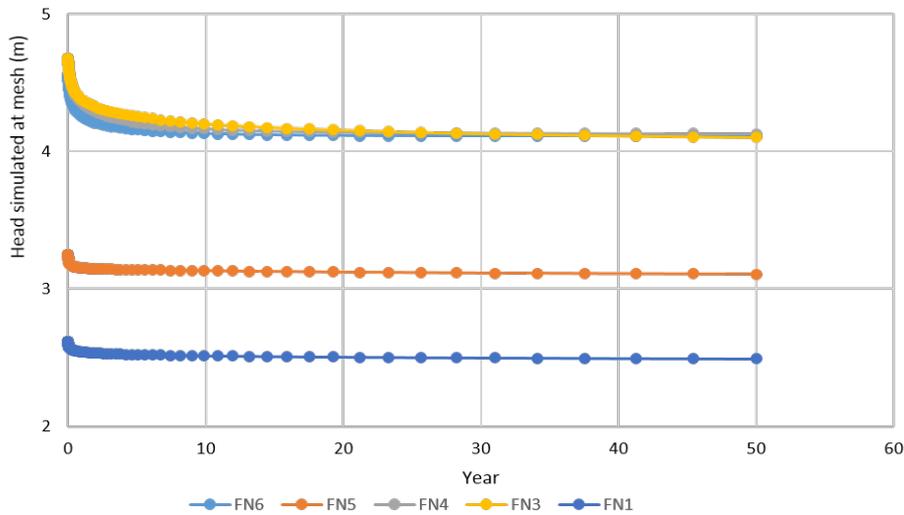

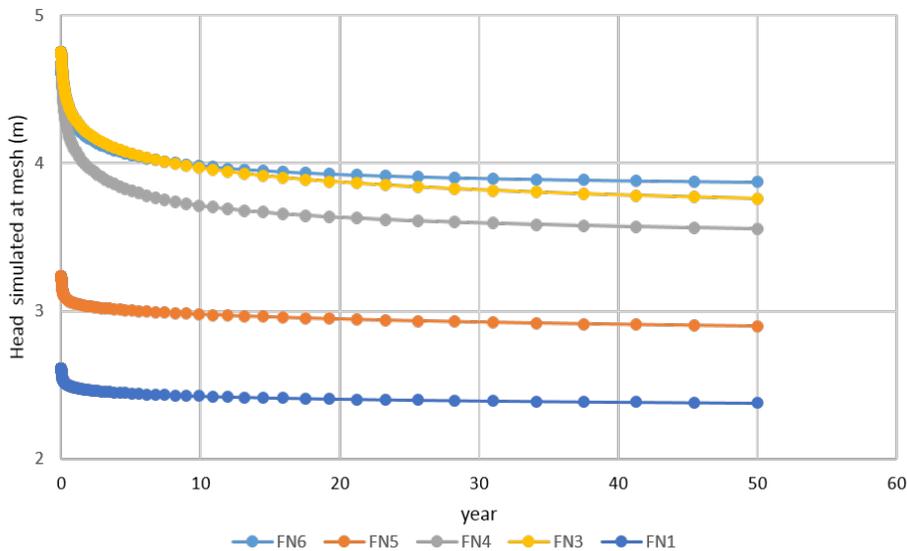**Figure 9**. Head time series over 50 years (200m³/d)

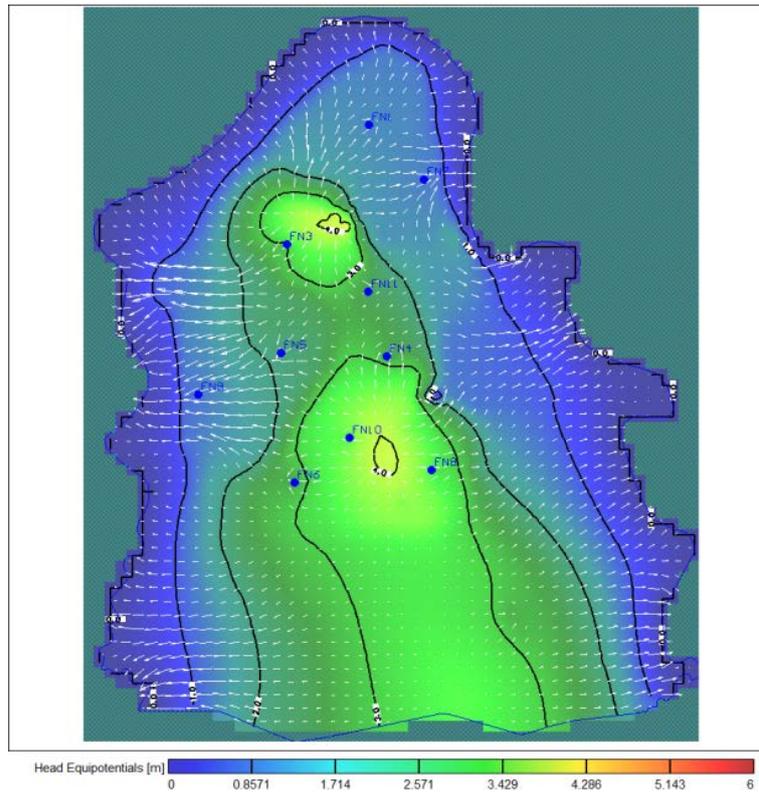**Figure 10**. Head time series over 50 years for (300m³/d)

Figure 11. Groundwater flow and simulated Head after additional abstractions (2em Scenario)

Table 4. Piezometric levels and drawdowns in boreholes (2nd Scenario)

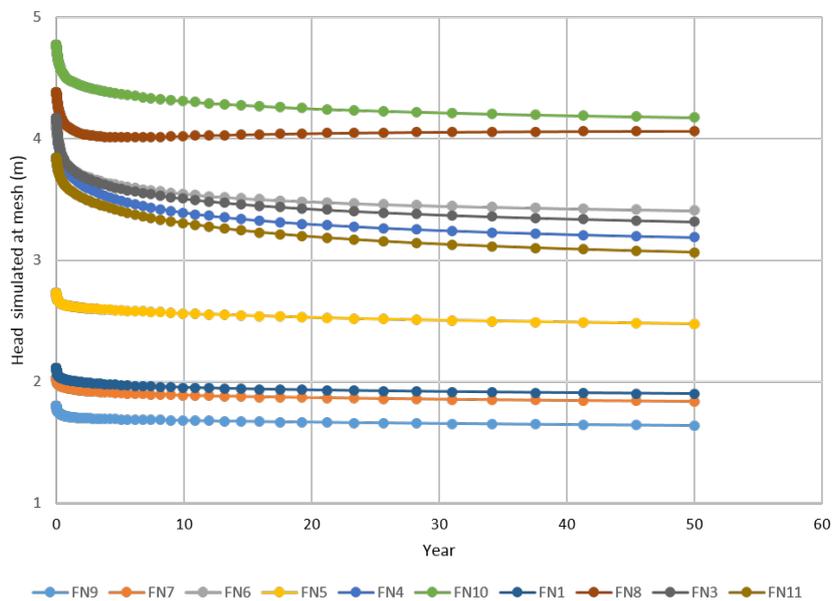| Borehole	Simulated Head in mesh (m)	Simulated head inside the Borehole (m)	Simulated drawdown inside the Borehole (m)
FN1	1.57	-0.39	1.96
FN3	2.65	-5.13	7.78
FN4	2.289	-5.32	7.61
FN5	1.79	-0.88	2.67
FN6	2.62	-4.78	7.40
FN7	1.484	0.17	1.32
FN8	3.202	-1.43	4.63
FN9	1.220	-1.22	2.44
FN10	3.340	-0.92	4.26
FN11	2.280	-3.16	5.44

Figure 12. Head time series over 50 years

5. Conclusion

The modelling of the Continental Terminal in OP led to the estimation of the potential of this groundwater with the establishment of new boreholes in addition to those already operational in the study area. The model was calibrated based on well and borehole data collected in the field and the calibration results were satisfactory despite their number. The simulation showed that the groundwater is very sensitive to heavy pumping due to the drawdowns at the catchment wells, which can reach 7 m. This high drawdown is especially to be avoided for this type of piezometric configuration where the maximum head at the mound is around 6 m. However, for the needs of local and neighboring rural water supply, the model revealed an exploitable potential of 200 m^3/d.

Acknowledgements

References

[1] Vandenbohede, A., Van Houtte, E., & Lebbe, L. (2009). Sustainable groundwater extraction in coastal areas: a Belgian example. *Environmental geology*, 57(4), 735-747.

[2] Bear, J., Cheng, A. H. D., Sorek, S., Ouazar, D., & Herrera, I. (Eds.). (1999). *Seawater intrusion in coastal aquifers: concepts, methods and practices* (Vol. 14). Springer Science & Business Media.

[3] Essink, G. H. O. (2001). Improving fresh groundwater supply-problems and solutions. *Ocean & Coastal Management*, 44(5-6), 429-449.

[4] Van Meir, N., & Lebbe, L. (1999). Simulations of evolution of salt-water distribution in young dunes near the French-Belgian border. Natuurwetenschappelijk Tijdschrift, 79(1-4), 105-113.

[5] Aguilar-Pérez, L. A., Ortega-Guerrero, M. A., Lugo-Hubp, J., & Ortiz-Zamora, D. D. C. (2006). Análisis numérico acoplado de los desplazamientos verticales y generación de fracturas por extracción de agua subterránea en las proximidades de la Ciudad de México. Revista mexicana de ciencias geológicas, 23(3), 247-261.

[6] De Rosnay, J. (1975). *Le macrocosme: vers une vision globale*. Éditions du Seuil.

[7] Aracil. J (1968). Introduction à la dynamique de système. Lyon, P.U.L, 412p.

[8] Benhachmi, M. K., Ouazar, D., Naji, A., Cheng, A. H. D., & Harrouni, K. (2003, March). Pumping optimization in saltwater intruded aquifers by simple genetic algorithm-Deterministic model. In 2nd International Conference on Saltwater Intrusion and Coastal Aquifers–Monitoring, Modelling and Management.

[9] Hariharan, K. S., Tagade, P., & Ramachandran, S. (2017). Mathematical Modeling of Lithium Batteries: From Electrochemical Models to State Estimator Algorithms. Springer.

[10] FED (1983). Étude Hydrogéologique du basin de la Casamance. Rapport de synthèse hydrogéologique du bassin sédimentaire casamançaise.

[11] DGPRE (2018). Étude d'évaluation des potentialité du plateau d'Oussouye. Rapport des investigations hydrogéologique

[12] McDonald, M. G., & Harbaugh, A. W. (1988). A modular three-dimensional finite-difference ground-water flow model. US Geological Survey.

[13] Dupuit, J. (1863). Theoretical and practical studies on the movement of running water: Paris, Carilion-Goery et V

[14] Faye, S., Faye, S.C., Ndoye, S. and Faye, A. (2003) Hydrogeochemistry of the Saloum (Senegal) Superficial Coastal Aquifer. Environmental Geology , 44, 127-136.

[15] Faye, S., Maloszewski, P., Stichler, W., Trimborn, P., Faye, S.C. and Gaye, C.B. (2005) Groundwater Salinization in the Saloum (Senegal) Delta Aquifer: Minor Elements and Isotopic Indicators. Science of the Total Environment, 343, 243-259.

[16] Piper, A.M. (1944) A Graphic Procedure in the Geochemical Interpretation of Water Analyses. American Geophysical Union Transactions, 25, 914-923.

[17] Fisher, R. S., & Mullican III, W. F. (1997). Hydrochemical evolution of sodium-sulfate and sodium-chloride groundwater beneath the northern Chihuahuan Desert, Trans-Pecos, Texas, USA. Hydrogeology journal, 5(2), 4-16.

[18] Howard, G., Bartram, J., Water, S., & World Health Organization. (2003). Domestic water quantity, service level and health (No. WHO/SDE/WSH/03.02). World Health Organization.