

Discrimination in the Mineralization Processes of the Surface Water Table of the Senegal River Delta

Abdoul Aziz GNING*, Mansour GUEYE, Fatou NGOM DIOP, Raymond MALOU

Département de Géologie, Faculté des Sciences et Techniques/Université Cheikh Anta Diop, Dakar, Sénégal

*Corresponding author: gningabdoul@gmail.com

Received October 16, 2019; Revised December 02, 2019; Accepted December 11, 2019

Abstract Located in the north-west of Senegal, the Senegal River Delta (DFS) is a strategic region for the development of irrigated agriculture. Thus, with agricultural intensification, we are witnessing a salinization of the alluvial groundwater that could even lead to a degradation of the cultivated soils. The main objective of this study is to carry out a hydro-geo-chemical characterization of the alluvial groundwater and to discriminate between the different processes responsible for the mineralization of these waters in order to provide a model for acquiring the chemical composition of waters. To this end, two sampling campaigns were carried out, one in June 2011 during the dry season and another in December 2012. During these campaigns, 12 piezometers and 17 micro-piezometers were sampled. The river waters as well as the drainage waters were sampled. The results allowed a geochemical characterization of the waters of the DFS surface water table. Two groups of waters are individualized. These are fresh waters (rainwater and river water) of bicarbonate calcium facies ($\text{HCO}_3\text{-Ca}$) and salt waters (seawater and drainage water from irrigated areas) of chlorinated sodium facies (Na-Cl). The study of the origin of the mineralization showed that the dominant elements (Na and Cl) derive mainly from the old contamination of seawater. Their concentration under high evaporation explains their evolution towards brines. Marine pollution is the main factor in the acquisition of mineralization. The dissolution of minerals such as gypsum, calcite and to a lower extent dolomite contributes to the mineralization of water. These phenomena, as well as the basic exchanges, then constitute the evolutive factors of the chemical composition of the alluvial groundwater.

Keywords: mineralization, facies, pollution, brine, alluvial groundwater, salinization, irrigation

Cite This Article: Abdoul Aziz GNING, Mansour GUEYE, Fatou NGOM DIOP, and Raymond MALOU, "Discrimination in the Mineralization Processes of the Surface Water Table of the Senegal River Delta." *American Journal of Water Resources*, vol. 8, no. 1 (2020): 1-11. doi: 10.12691/ajwr-8-1-1.

1. Introduction

The Senegal River Delta (DFS) is the terminal part of the Senegal River basin. Two dams have been built on this river: the anti-salt dam of Diama (1986), located at 35 km upstream from Saint Louis, which prevents the rising of seawater and the Manantali dam (1988) located in Malian territory, which helps to store the excess rainfall recorded in the upper basin and releases it during stretching periods. The artificialization of the river regime through the water of these dams helped to ensure the sustainable practice of irrigated farming. Currently, it is estimated that 85,000 ha are cultivated by irrigation on the Senegalese side of the river [1]. This makes it one of the largest irrigation areas in West Africa [2]. As often, the development of irrigation is followed by soil degradation processes (salinization, alkalization, sodization) to varying degrees [3,4]. The practice of irrigated farming in the DFS is now seriously threatened by two closely related phenomena: the salinization of land that is leading to the abandonment of several developed areas [5] and the rise of the water table. Several soil and agronomic studies have followed one another in the delta

to try to understand the phenomenon of salinization and propose solutions [6-8]. In most of these studies, the alluvial groundwater is identified as the main cause of land salinization. Indeed, many authors explain this salinization of the land in the DFS by the presence of a shallow (2 m maximum) and saline groundwater [9-11] which, by capillary rise, would be at the origin of salt deposits on the soil surface.

Therefore, a hydro-geological and hydro-geochemical study of the alluvial groundwater is necessary to determine its hydro-geological properties, understand its functioning and replenishing mode in order to better appreciate its role in this salinization process.

In this context, the aim of this article is to carry out a hydro-geochemical characterization of the alluvial groundwater and to discriminate between the different processes responsible for the mineralization of these waters in order to provide a model for acquiring the chemical composition of waters.

2. Presentation of the Study Area

The DFS is located in the Saint Louis region of northwestern Senegal, at 260 km from the capital, Dakar.

Covering an area of 3500 km², it takes the form of a wide low land, limited to the north by the Senegal River, to the west by the Atlantic Ocean, to the east by the Lake Guiers system and to the south by the dunes (Figure 1). With potential irrigated land estimated at 150,000 ha [1], the DFS is an agro-economic area that hosts many agricultural development projects. The climate is of Sahelian type marked by low rainfall (on average 250 mm/year) and a strong evaporation recovery.

The hydrographic network includes the main branch of the Senegal River, which constitutes its northern and north-western limit and has many drifts, the main ones being the Gorom upstream, that takes its source in the village of RONKH, and the Gorom downstream, which passes through the Djoudji Park. Its two drifts join at the village of BOUNDUOM to give the Lampsar. We also note the presence of Lake Guiers, which is a 300 km² depression fed by the river through the Taoué canal.

These different branches of the river as well as the lake allow the irrigation of many agricultural areas through a complex system of open canals. The drainage water from these areas is discharged through canals and rejected into the natural depressions of NDIAEL, NOAR and KRANKAYE.

The geological context of the delta is part of that of the Senegalo-Mauritanian basin, whose formations are described in numerous studies [12-14]. The geological formations that outcrop in the DFS zone are mainly composed of quaternary deposits (Figure 2). Indeed, except the Eocene formations that are outcropping around Lake Guiers, the quaternary formations are the most important to understand the relatively recent history, on the geological scale of the DFS. The quaternary is characterized by alternation periods of marine transgressions and regressions that have allowed the installation of 60 meters thick deposits. From a hydro-geological point of view, various studies indicate

the presence of three aquifer systems [15-19]: the superficial aquifer represented by the Quaternary alluvial formations and the sandy or clay-sand deposits of the Continental Terminal, the intermediate aquifer of the Tertiary calcareous formations and the deep aquifer of the Maastrichtian sandstone formations.

The superficial aquifer of the Quaternary formations that contains the alluvial groundwater, the subject of this study, is complex and occupies the entire major bed of the river. Schematically, it is described as a single aquifer consisting of two superimposed reservoirs that can be separated, in places, by a discontinuous lenticular clay layer (Figure 3).

The upper reservoir is contained in the fine Nouakchottian sands. It can be captive or free depending on the presence or absence on the surface of semi-permeable, clayey layers belonging to the Post-Nouakchottian. The water table contained in this reservoir is generally between 1 and 3 meters under the ground, according to the period of year. This reservoir has an average thickness of 10 meters and is more important in the west (30 meters in St-Louis) than in the east (5 meters in Richard-Toll).

The lower reservoir is contained in the medium to coarse sands of the Inchirian. This reservoir can be separated from the previous one by a semi-permeable layer of clay or silt, belonging to the sediments of the Inchirian roof or the Nouakchottian base. The discontinuity of this semi-permeable barrier allows hydraulic communication between the two groundwater in some areas.

For hydrodynamic parameters, the synthesis of OMVS/USAID [20] summarizes the hydrodynamic characteristics of the superficial groundwater as follows: transmissivity (T) varies from 5.5 to 2.5×10^{-3} m²/s; hydraulic conductivity (K) from 2×10^{-4} to 3×10^{-4} m/s and the storage (S) from 5×10^{-4} to 2.5×10^{-4} .

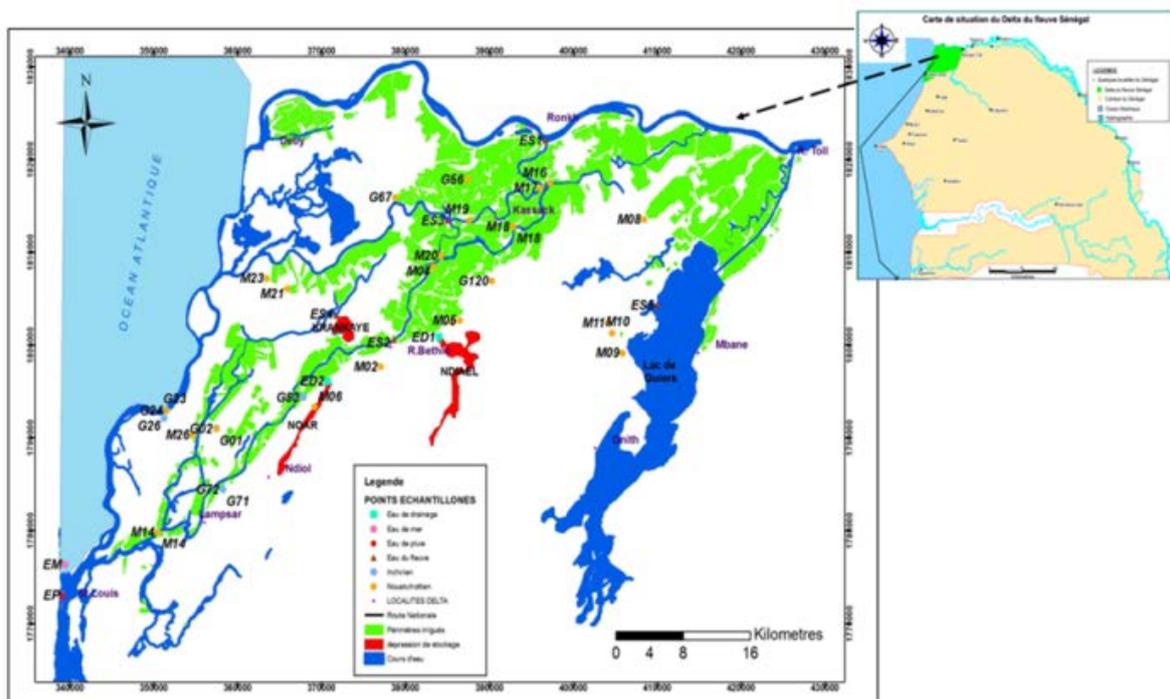


Figure 1. Situation map of the Senegal River Delta

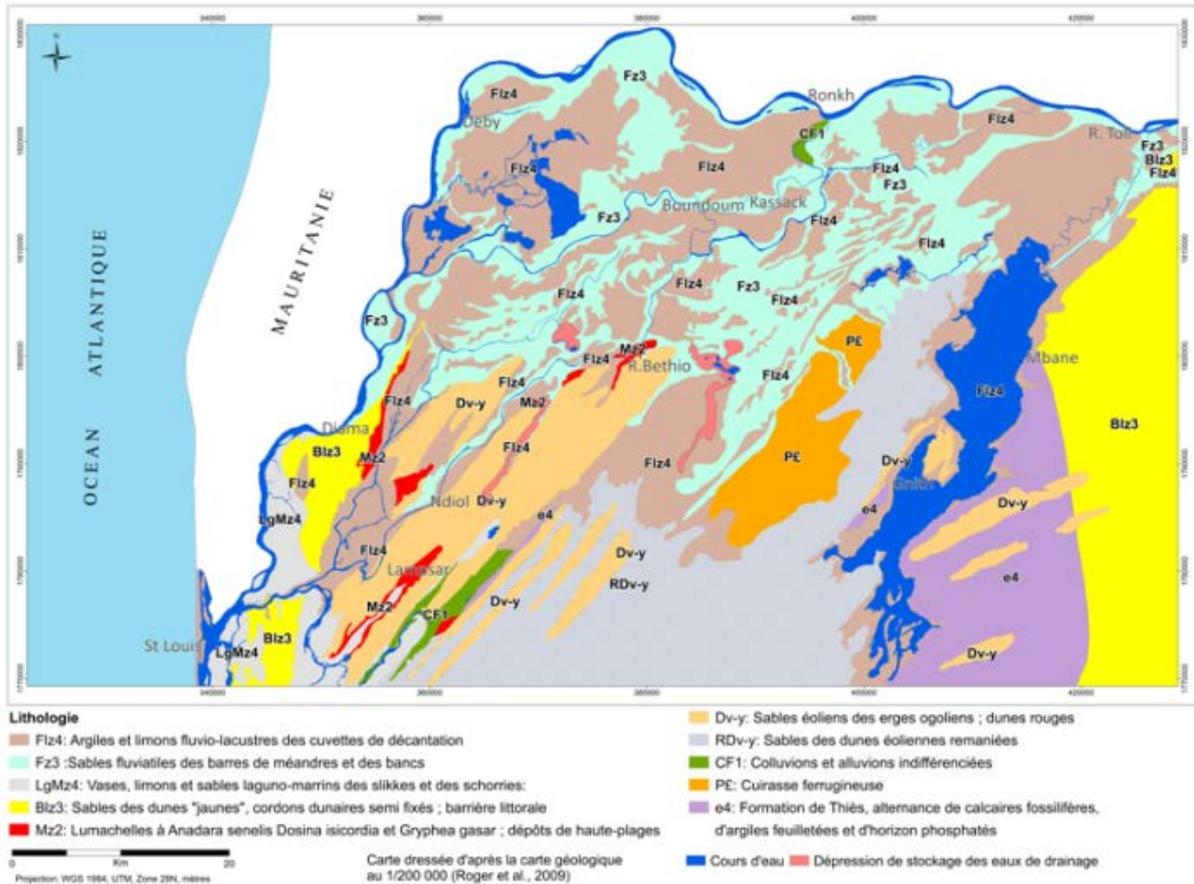


Figure 2. Map of geological formations outcropping in the Senegal River delta

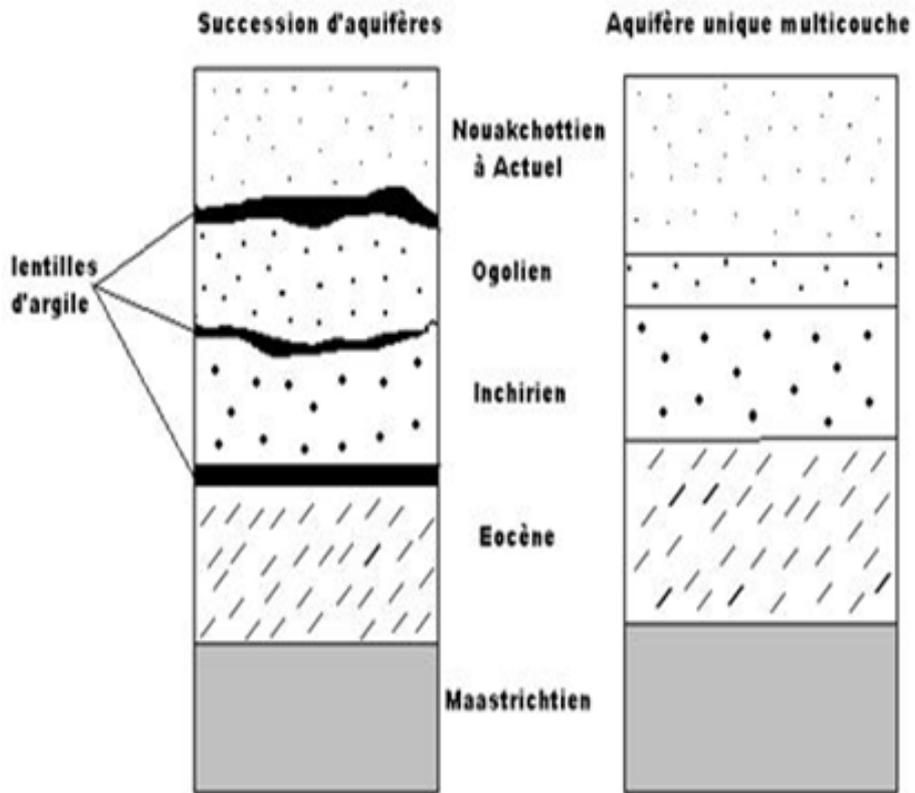


Figure 3. Schematic section of the variation of the aquifer system in the valley

3. Materials and Methods

3.1. Implementation of the Data Collection System

As part of this research program, a network for monitoring and sampling surface water has been set up. This network includes 23 piezometers belonging to the OMVS (Organization for the development of Senegal River) network established after the construction of the dams (1987). These piezometers, called GAXXX, have been renamed to GXX (for simplicity). Among the 23 remaining piezometers, 10 capture the Inchirian reservoir (G01, G23, G25, G26, G54, G71, G72 and G83). They are often in duplicate with those who capture the Nouakchottian. This network was completed by 30 micro-piezometers (designated by MXX) drilled by hand auger and named Mxx. Due to their shallow depth (6 m maximum), they all capture the upper reservoir of the Nouakchottian.

3.2. Water Sampling

Two sampling campaigns were conducted on this network, one in June 2011 during dry or low water periods and one in December 2012. During these campaigns, 12 OMVS piezometers (including 05 for the Nouakchottian and 07 for the Inchirian) and 17 micro-piezometers (which all capture the upper reservoir) were sampled.

The waters of the river were sampled at five points: Ronkh (ES1), Ross Béthio (ES2), Boundoum (ES3), the Krankaye Canal (ES4) and Lake Guiers (ES5). Drainage water was collected at the depressions of NDIAEL (ED1) and NOAR (ED2). A sea water (EM) sample was collected off the coast of the city of Saint Louis during the June campaign and four rainfall events (EP) were also sampled between August and September 2012.

3.3. Water Analysis

The samples were collected in 500 ml plastic bottles. They were filtered, transported and analysed at the chemistry laboratory of the Hydro-geology and Environmental Geology Group of the University of Liège. The physico-chemical parameters were measured in the field using an YSI multi-parameter probe. The analyses focused on major, minor ions and some trace elements. Ca^{2+} , Mg^{2+} , Na^+ , K^+ , ions and silica were dosed by flame atomic absorption. The Cl^- , NH_4^+ , and NO_3^- ions were dosed by potentiometry and the SO_4^{2-} ions by titration in return. Having a high electrical conductivity samples of the groundwater have been diluted up to 100 times, which may affect the detection limits of some elements such as nitrates or phosphates, which may not be properly measured. This is also the case for bromides, which are also a good indicator of the origin of groundwater salinity [21,22].

4. Results and Discussion

4.1. Identification of Chemical Facies

To determine the geochemical facies of the DFS water, the two periods cited above were considered: a period of low water (June 2011) and a period of high water (December 2012).

The representation of the results of the analyses of the low-water campaign on the Piper diagram (Figure 4A) shows two main facies: bicarbonate calcium and/or magnesium facies (HCO_3^- -Ca-Mg) and a sodium chloride facies (Cl-Na). The bicarbonate facies includes fresh water (river water). The analysis of the anion triangle shows that no cation is dominant.

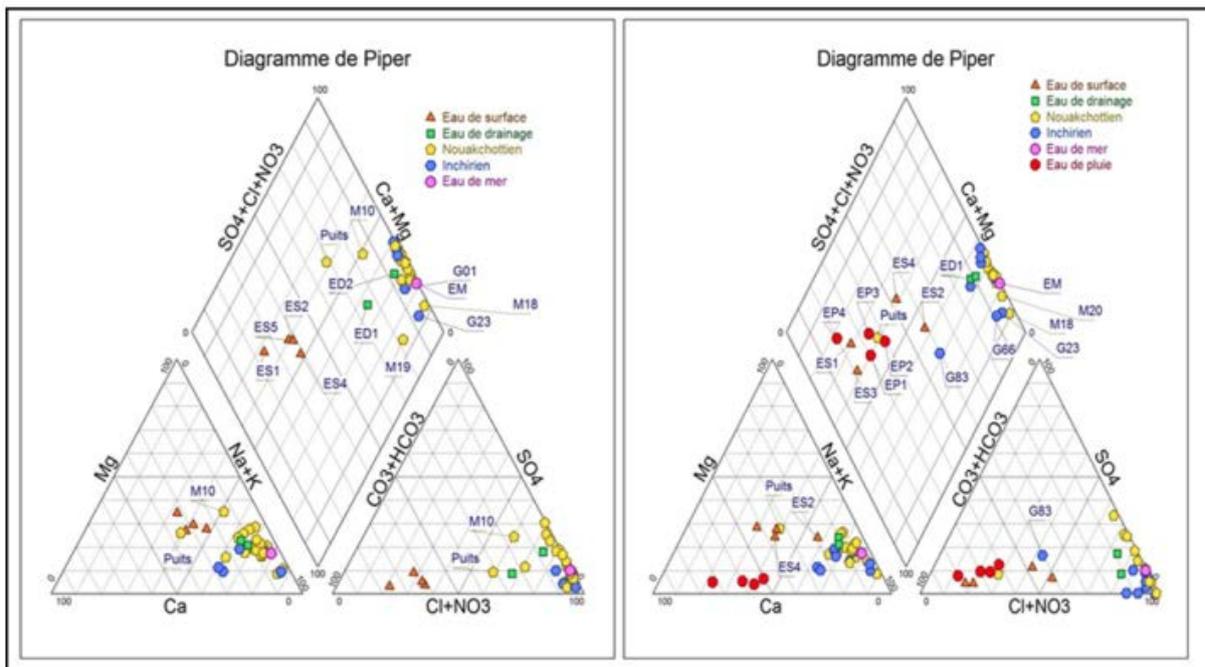


Figure 4. Piper diagram of water during low water (A) and high water (B) periods

Chlorinated sodium facies is represented by drainage waters, seawater and groundwater. This facies, typical of salt water, is characterized by Na^+ and Cl^- ions dominance. The well sampled at the village of Diamo has an intermediate chlorinated calcium and magnesium facies (Cl-Ca-Mg). It is closer to surface water.

The post-winter season (Figure 4B) retains these two main facies, but there is a migration of ES4 and ES2 points at surface water level, that correspond to the water of the river on the Krankaye Canal and at Ross Bethio level. The ES4 point becomes calcium and magnesium chlorinated due to chloride enrichment. Point ES2, on the other hand, is enriched with sodium (Na^+) and chloride (Cl^-) and becomes sodium chlorinated (Cl-Na). This migration can be explained by a communication between the river and the groundwater. Indeed, during this period, the valves that feed these branches of the river are closed; the level of the water body decreases and can lead to a water flow from the water table to the stream. The groundwater being rich in salt (Na^+ , Cl^-) contaminates the surface water at this area.

These observations were confirmed by SAED's water management officers who had noticed an increase in surface water salinity on some hydraulic axes after the valves were closed. The well migrates to the calcium bicarbonate pole. This suggests that the water table it receives is recharged by rain

4.2. Study of Groundwater Mineralization Processes

Piper diagram does not help to identify the geochemical processes responsible for groundwater mineralization. That's why we use binary diagrams to determine the origin and evolution of this mineralization. Binary diagrams aim to explain the probable origin of water as well as different chemical reactions that may alter its composition, such as cationic exchanges [23]. The chloride ion (Cl^-) is used as a reference element because it constitutes a conservative compound in the various processes likely to modify this composition [24]. The saturation indices of some minerals such as halite, calcite, dolomite and gypsum were calculated using the PhreeqC module of the Diagram software in order to assess the saturation of the water with respect to these minerals. The results are reported in Table 1.

4.2.1. Origin of Groundwater Mineralization

Groundwater has a chemical composition similar to that of seawater. Indeed, Na^+ and Cl^- ions are by far the dominant elements in the superficial groundwater of the DFS. They show a strong correlation ($r=0.94$) which proves their common origin and suggests their marine origin. The Na^+ vs Cl^- diagram is used to determine the origin of groundwater salinity [25-27]. Indeed, if the Na^+/Cl^- ratio is equal to 1, it indicates that the salinity comes from the dissolution of the halite. A $\text{Na}^+/\text{Cl}^- > 1$ ratio indicates a Na^+ enrichment due to a basic exchange with clays or the dissolution of silicate minerals [28]. A Na^+/Cl^- ratio = 0.86 (Na^+/Cl^- ratio of seawater) means that the groundwater is highly contaminated by sea water and when this Na^+/Cl^- ratio < 0.86 the salinity is due to seawater but that has evaporated to evolve towards brines

[29]. The deficit of Na^+ with respect to Cl^- can be explained by a replacement of the latter by Ca^{2+} following cation exchange.

Table 1. Results of saturation indices calculated with PhreeqC

Noun	Calcite	Dolomite	Gypse	Halite
M9	1.32	3.08	-0.13	-3.03
M10	0.48	1.50	-1.45	-5.44
M11	0.98	1.98	0.17	-2.55
M8	0.81	2.07	-0.34	-2.85
G120	1.26	3.43	-0.69	-2.14
M16	-1.25	-2.07	-0.23	-2.60
M17	1.66	4.00	-0.30	-2.45
M18	0.89	2.55	-1.41	-2.75
M19	1.20	2.73	-1.36	-4.17
M4	0.87	2.22	-0.01	-2.45
G56	-1.44	-1.90	-0.23	-2.34
G67	1.50	3.71	-0.96	-2.92
M5	-0.10	0.55	0.08	-2.39
M1	1.84	3.80	-0.16	-2.83
M2	-0.54	-0.54	0.07	-3.01
M6	1.48	3.30	0.11	-2.75
G72	1.50	2.72	0.05	-2.70
G71	1.31	2.41	0.11	-2.63
G01	2.02	4.67	-0.72	-2.57
G02	2.13	4.76	-0.80	-2.63
G23	1.06	2.64	-1.33	-3.75
G24	1.30	2.86	-0.48	-2.95
G26	1.02	2.30	-0.95	-3.21
M14	1.41	3.37	-0.10	-2.78
M21	1.37	3.18	-0.10	-2.38
M23	1.28	3.32	-0.23	-2.21
M26	0.70	2.11	0.13	-2.19

A careful analysis of the Na-Cl diagram shows the presence of two groups of water: a first group consisting of saline water (Na^+ and Cl^- content lower than that of seawater), most of which are close to hydraulic axes. (streams or irrigation canals) and which are much more aligned on the right of the seawater. The second group consists of brines with Na^+ and Cl^- content higher than those of seawater. These waters are found in piezometers, for the most part, far from the hydraulic axes and situated outside the agricultural installations. In these places, the groundwater is therefore subject to recharge by rain and evaporative recovery.

This marine origin of water has been confirmed by many previous studies and is explained by the geological history of the DFS which was established during the Quaternary following successive episodes of marine transgressions and regressions. In addition, there was the marine invasion that occurred on the river before the Diamo dam was built. The abundance of Mg^{2+} , K^+ , SO_4^{2-} ions can also be attributed to this marine origin. Indeed, its elements are abundant in seawater and have strong correlations with Na^+ and Cl^- ions, proving their common origin.

However, Ca^{2+} ions, relatively abundant in DFS groundwater, are not correlated with Na^+ and Cl^- ions. In addition, many points have higher $\text{Ca}^{2+}/\text{Na}^+$ ratios higher than seawater. This suggests that if seawater is probably

the source of water mineralization, it has evolved under the influence of other factors such as cationic exchanges or mineral dissolution.

4.2.2. Evolution of the Chemical Composition by Cationic Exchange

Cationic exchanges play an important role in the evolution of the chemical composition of water. It is a phenomenon that occurs between the groundwater and the casing (clays in general) when the chemical composition is unbalanced between these two environments [30]. The cationic exchange process is continuous but limited by the quantities of charge involved. This only affects the chemical composition of the water when the solution is not very concentrated. In case of highly mineralized water, its effect is reflected by a gradual modification of the ratios between ions by decreasing the proportion of monovalent to divalent ones. This can result in an evolution of the Na^+/Cl^- ratio in waters when they are concentrated. This ratio tends towards a constant value equal to 1 in case of sodium chlorinated water. We want to highlight this phenomenon as being the origin of the abundance of Ca^{2+} ions in the DFS groundwater.

The first source of Ca in groundwater in general is the dissolution of minerals such as dolomite or calcite according to the following equations 1 and 2.

$\text{CO}_2 + \text{H}_2\text{O} + \text{CaMgCO}_3 \rightarrow \text{Ca}^{2+} + \text{Mg}^{2+} + 2\text{HCO}_3^-$: dissolution of dolomite (1)

$\text{CO}_2 + \text{H}_2\text{O} + \text{CaCO}_3 \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^-$: dissolution of calcite (2)

These two reactions produce a release of HCO_3^- . However, Ca^{2+} is moderately correlated with Mg^{2+} ($r=0.53$) but not with HCO_3^- ions. In addition, the calcite dissolution diagram (Figure 6) shows a large imbalance in favor of Ca+Mg. This excess of Mg^{2+} and Ca^{2+} compared to HCO_3^- and CO_3^{2-} is much more marked in brines. The calculation of the saturation indices shows that only three points are saturated with respect to calcite and most of the structures

are supersaturated. This shows that the dissolution of calcite and dolomite does not control the presence of Ca^{2+} ions in the DFS groundwater.

Another possible source of Ca^{2+} ions is the dissolution of gypsum (CaSO_4). However, Ca^{2+} and SO_4^{2-} ions are moderately correlated although 60% of the points indicate a balance with gypsum, with IS values between -0.5 and 0.5. The correlation between SO_4^{2-} ions and gypsum IS shows that gypsum dissolution controls more the SO_4^{2-} content than Ca^{2+} .

The exchange process could then explain the relatively high levels of Ca^{2+} in groundwater. This phenomenon can be demonstrated from Ghebouli, Bencheikh [31] by the $\text{Ca}^{2+}/(\text{HCO}_3^- + \text{SO}_4^{2-})$ diagram as a function of Na^+/Cl^- (Figure 7). This diagram shows three main areas. A zone A where the Na^+/Cl^- ratio and the $\text{Ca}^{2+}/(\text{HCO}_3^- + \text{SO}_4^{2-})$ ratio are lower than 1. In this area, the Na deficit is not compensated by Ca. This area includes mostly salt water. A zone B where the deficit of Na is compensated by an excess of Ca. This area, which includes the brines, highlights the basic exchange phenomenon and shows that when water concentrates, the Na is exchanged with Ca. On the other hand, in zone C, there is an excess of Na corresponding to a deficit of Ca. These points, belonging to the group of salt water, are characterized by their proximity to Lake Guiers and the Senegal River. This suggests that the cationic exchange can take place in the opposite direction when there is fresh water recharge. This cationic exchange process can also be highlighted by the diagram $(\text{Ca} + \text{Mg}/\text{HCO}_3^- + \text{SO}_4^{2-})$ as a function of $(\text{Na} + \text{K}) - \text{Cl}$ [25,32]. When this basic exchange exists, the points are aligned on a -1 slope line. All our points (Figure 8) are aligned on this slope line-1. Two groups can still be identified, brines where the excess Ca+Mg corresponds to a deficit of Na+K and a second group where an excess of Na+K is noticed. These points correspond to the structures near the rivers mentioned above.

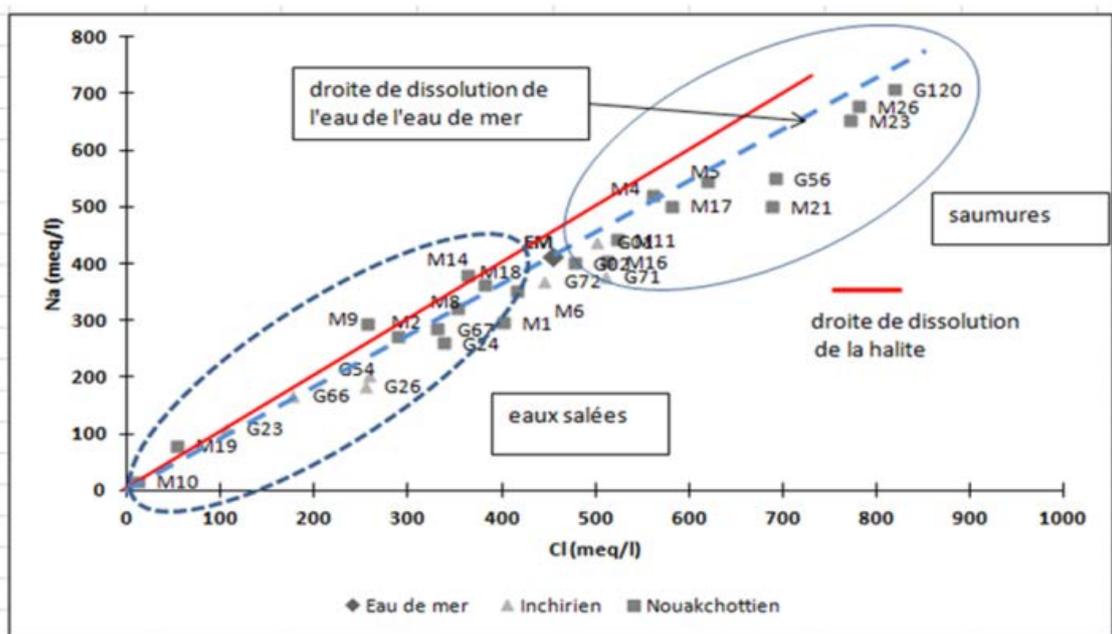


Figure 5. Correlation diagram between Na^+ and Cl^-

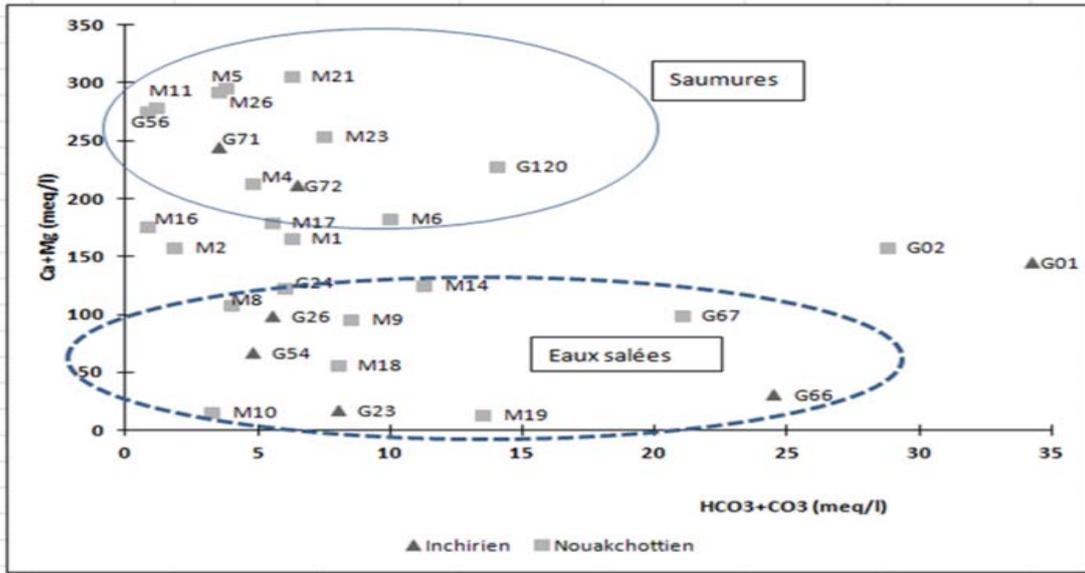


Figure 6. Dissolution diagram of calcite and dolomite

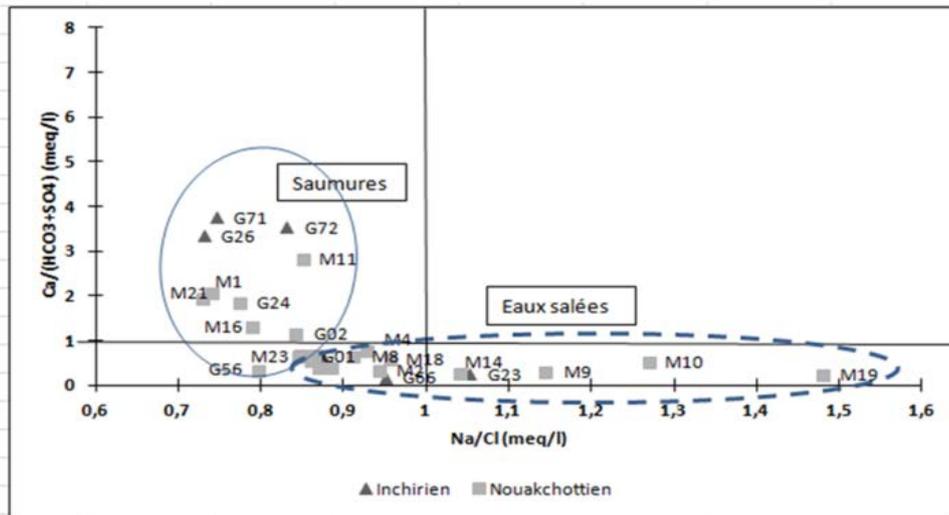


Figure 7. Ca / (HCO₃+SO₄) diagram as a function of Na/Cl

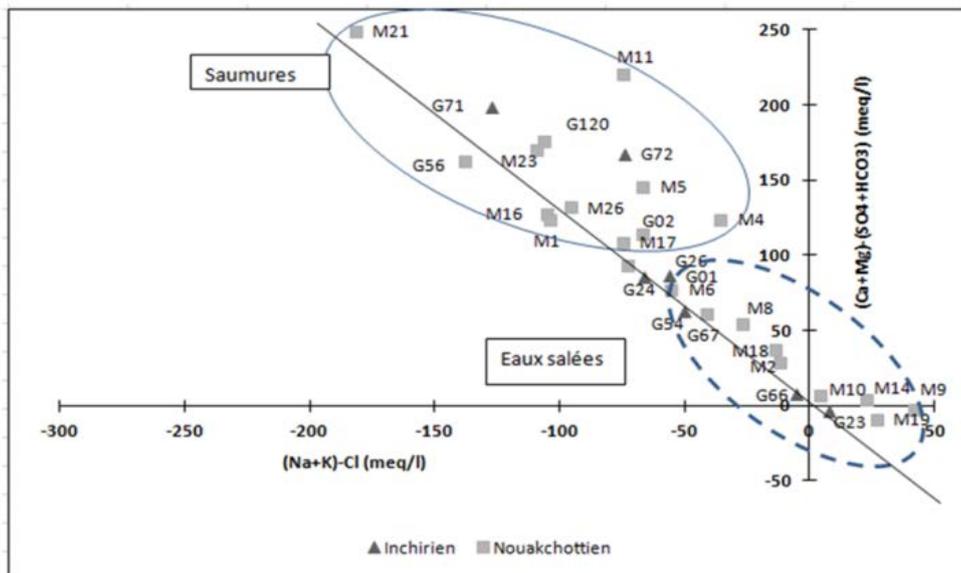


Figure 8. Diagram (Ca+Mg)-(HCO₃+SO₄) as a function of (Na+K)-Cl

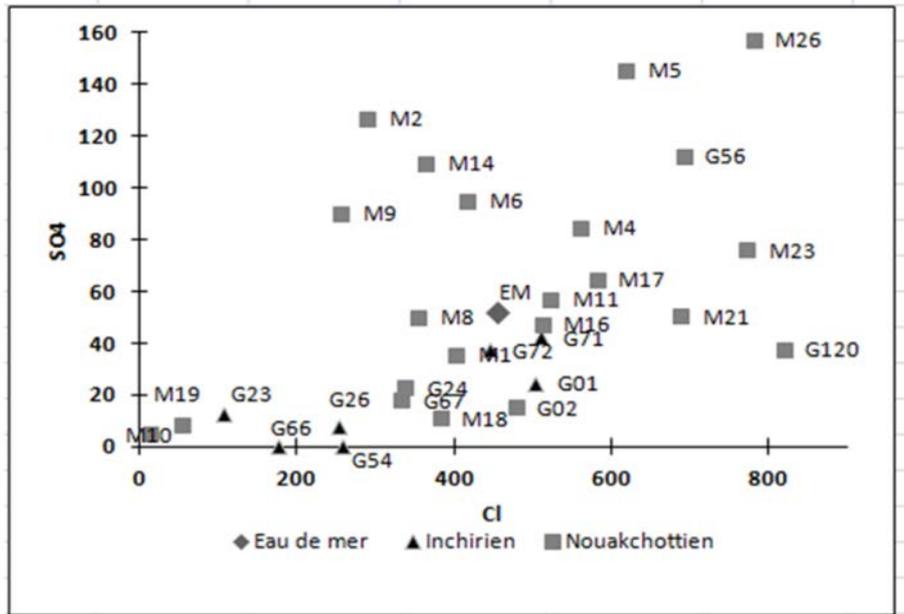


Figure 9. Correlation diagram between SO_4^{2-} and Cl^-

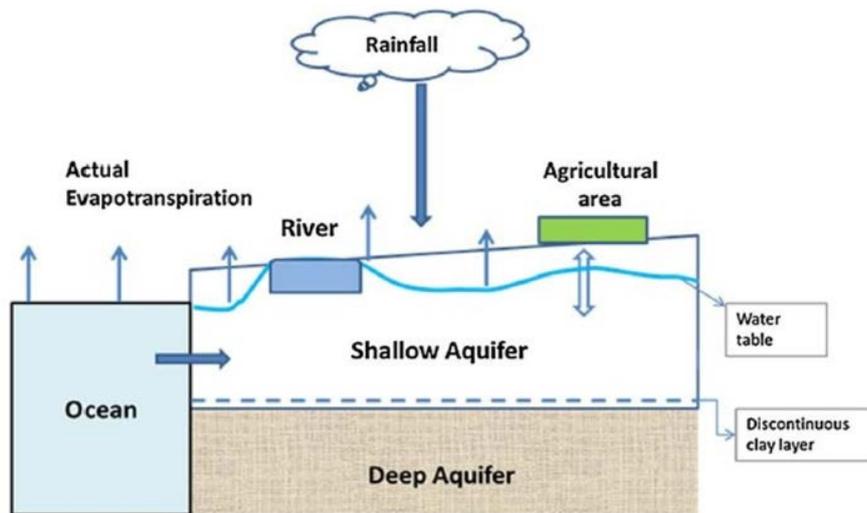


Figure 10. Conceptual diagram of the functioning of the DFS hydro-system

4.2.3. Increase in SO_4^{2-} Contents by Dissolving Gypsum

The sulphates in the DFS groundwater are basically of marine origin. This is evidenced by the correlation between SO_4^{2-} and Cl^- ions (Figure 9). However, many samples have higher $\text{SO}_4^{2-} / \text{Cl}^-$ ratios than seawater. This shows that sulphates have another source that can be gypsum dissolution. The saturation index values obtained with "PhreeqC" show that 60% of the samples are in balance with gypsum. The dissolution of gypsum is therefore a source of SO_4^{2-} ions for the DFS groundwater.

On the other hand, most samples from the lower reservoir (Inchirian) show a lower $\text{SO}_4^{2-} / \text{Cl}^-$ ratio than seawater. This depletion in SO_4^{2-} in the inchirian groundwater can be attributed to sulfate reduction through bacterial activities. This probably reflects reducing conditions, therefore of captive groundwater [33]. This phenomenon is widely observed in coastal aquifers subjected to marine intrusion [34,35] and may be related to the abundance of organic matter in Quaternary sediments and dissolved organic carbon.

4.3. Model for the Acquisition of Mineralization of the DFS Groundwater

The chemical composition of groundwater depends on a set of oxidation processes, hydrolysis, rainfall, dissolution [36], but also on mixtures and ionic exchanges that take place during its cycle in the various geological, biological and atmospheric reservoirs; processes that overlay the impacts of human activities [26]. Thus, in the DFS, the chemical composition of the superficial groundwater depends on the interactions that the aquifer may have with the different components of the hydro-system on the one hand and the reactions that may occur within the aquifer on the other.

Figure 10 represents a conceptual diagram of the operation of the DFS hydro-system. The main phenomena that may be at the origin of the evolution of the mineralization of the waters of the DFS superficial groundwater are described below.

Marine intrusion: it is the main factor affecting the quality of groundwater [34,37]. It is characterized by

seawater penetration into the aquifer following the rise of the fresh water-salt water interface. This is a phenomenon that occurs in almost all coastal aquifers, often caused by overexploitation of the aquifers, that favors the uplift of the bevel [38,39]. From a chemical point of view, marine intrusion can result in an alteration of the chemical composition or even salinization of groundwater.

In Senegal, the work of Diouf, Gomis [40] Gaye [41] has among other things confirmed the progress of the salt bevel in the northern coastal aquifer.

At the DFS level, most studies focused on the invasion of marine waters into the river before the Diama dam was built. This marine invasion was carried out on the major bed of the river but also in the settling tanks [42,43]. The infiltration of this marine water has contributed to the salinization of groundwater. High evaporation contributed to the evolution of these brine waters. However, geological studies describing the establishment of the delta have shown that it has been marked by successive phases of marine transgressions and regressions. This would mean that the chemical composition of groundwater will be affected by salt. The work of Le Brusq and Loyer [44] and Loyer Loyer and Diallo [45] has shown the brackish nature of the alluvial groundwater that has evolved into brine as a result of agricultural activities and high evaporation. Results obtained in this study confirm this marine origin of the DFS groundwater mineralization.

River/groundwater interaction: it reflects the drainage relationships between the river and the groundwater. The hydrographic network is very dense at the delta level. The river has many branches such as the upstream and downstream Gorom, the Lampsar, the Djeuss, the Kassack, which form an anastomotic network allowing the supply of water to the populations. They are also used to supply agricultural areas through a dense network of irrigation channels.

In most cases, the study of this river/groundwater relationship is based on the comparison between levels [46]. If the stream level is higher than the groundwater level, it feeds the groundwater, which occurs most often during the winter season. In the event that the groundwater level is higher, it is drained by the watercourse. However, more rigorously studying, the groundwater/river relationship is tantamount to quantifying the water flow exchanged between the two systems and the direction of these exchanges.

Geo-chemically, a supply of the groundwater by a stream results in a softening of the water.

In the DFS, the installation of dams and the high management of the river's coast at 1.5 m NGI make the river's level permanently higher than that of the groundwater. The river therefore probably feeds the superficial groundwater. This has been demonstrated in several areas of the DFS by Diao [18], Da Boit [16] and Cissé [47] and even in the medium valley [48,49].

The results of this study showed that piezometers located near the streams were mostly less mineralized, which is evidence of the river's influence on the chemical quality of the superficial groundwater. However, this influence is more felt in the piezometers of the Inchirian lower reservoir, which are less affected by the evaporative recovery.

Exchanges at irrigated perimeters: with an estimated developed area of 85,000 ha, the DFS is the largest irrigated cultivation area in Senegal. There are two types of interactions with the groundwater that can occur in the perimeters: the percolation of irrigation water and the rise of capillary groundwater. The first phenomenon is groundwater's recharge, usually accompanied by the mobilization of chemicals from fertilizers and agricultural inputs. This results into a chemical quality of the water through anthropogenic pollution that is marked by an increase in nitrates and phosphorus or other trace elements depending on the types of inputs used.

The capillary rise reflects an increase in the groundwater near the ground surface. In conditions of high evaporation, water leaves soluble elements on the ground surface, resulting in a degradation of soil quality.

In the DFS, percolation in rice fields is identified as the main source of groundwater recharge [50,51]. The work of Gning, Orban [52] et has shown that irrigation can induce a rise in groundwater level from 50 cm to 1 m in some areas.

Storage depressions recharging: at the DFS level, water from agricultural areas is discharged through a network of drainage channels. This network includes a tertiary canal that drains water from the plot, and a secondary canal that collects water from several tertiary channels and discharges it into a main canal. The electrical conductivity of the water measured in these depressions is about 5000 $\mu\text{S}/\text{cm}$. These highly contaminated waters also contribute to recharging the superficial groundwater.

Vertical draining: it reflects a communication between two superimposed aquifers. This hydraulic communication occurs when the two aquifers are not separated by a very low permeable layer. In the delta, the superficial groundwater can communicate with deep, Eocene and Maastrichtian aquifers in the absence of the low-permeable clay lenticular layer [48]. This communication results in a certain similarity of geochemical composition in the supposed exchange areas.

Ultimately, the evolution of the chemical composition of the DFS superficial groundwater will be guided by the degree of contamination by marine pollution, concentration by evaporation, softening by river water, the quality percolation water through agricultural areas and storage depressions, exchanges within the aquifer and communication with other aquifers.

5. Conclusion

These initial results made it possible to carry out a first geochemical characterization of the water in the DFS superficial groundwater. Two groups of waters seem to control the mineralization of the groundwater. These are fresh waters (rainwater and river) with calcium bicarbonate facies ($\text{HCO}_3\text{-Ca}$) and salt waters (seawater and drainage water from irrigated areas). The study of the origin of the mineralization showed that the dominant elements (Na and Cl) derive mainly from the old contamination of seawater. Their concentration under high evaporation explains their evolution towards brines. However, while marine pollution is the main factor in the

acquisition of mineralization, dissolution phenomena of minerals such as gypsum, calcite and to a lower extent dolomite have been demonstrated. These phenomena, as well as basic exchanges, are therefore the factors that determine the evolution of the chemical composition of water.

From a hydro-geological point of view, this study showed that the distinction between the two reservoirs seems to have a geo-chemical explanation. Indeed, there is a difference in the degrees of mineralization; the EC's are generally higher in the superficial reservoir. The relatively low levels of SO_4^{2-} in the lower reservoir reflect the containment conditions. Of course, all this is not to be generalized and more arguments will need to be made for a better decision, particularly by using decision-making statistical techniques such as factual discriminant analysis FDA [53].

References

- [1] DDAR/SAED. 2012.
- [2] Wopereis, M.C.S.e.a., "Preserving soil quality under irrigation in the Senegal River Valley", *Netherlands Journal of Agricultural Science*, vol 46(1). 97-107. 1998
- [3] Ghassemi, F., A.J. Jakeman, and H.A. Nix, *Salinization of lands and water resources*. Univ. of Newouth Wales. Press, Ltd, canberra, Australia, 1995.
- [4] Marlet, S., *Evolution des systèmes d'irrigation et gestion de la salinité des terres irriguées.*, in *Séminaire de modernisation de l'agriculture irriguée*. 2004; Rabat (Maroc).
- [5] Barbiéro, L. and C. Laperrousaz, *Cartographie de la salinité dans la vallée du Sénégal. Succès d'une démarche ascendante. Géophysique des sols et des formations superficielles* 1999.
- [6] Maynard, J. *Etude des sols pour leur aménagement en culture de décrue en zone aride : Vallée du Sénégal.* in *Conférence des Nations Unies sur l'application de la Science et de la Technique dans l'intérêt des régions peu développées* 1962.
- [7] Poussin, Wopereis, M. C. S., Debouzie, D., and Maeght, J. L., "Determinants of irrigated rice yield in the Senegal River valley", *Europ. J. Agronomy*, vol. 19.341-356. 2003
- [8] Zante, P., *Etude du comportement physique de sols argileux soumis à l'irrigation dans la moyenne vallée du fleuve Sénégal* ORSTOM, 1993.
- [9] Ceuppens, J. and M.C.S. Wopereis, "Impact of non-drained irrigated rice cropping on soil salinization in the Senegal River Delta", *Geoderma*, vol. 92. 125-140. 1999.
- [10] Loyer, J.Y., *Les sols salés de la basse vallée du fleuve Sénégal : caractérisation, distribution et évolution sous cultures*, ORSTOM, Editor. 1989; Paris p. 126 pages
- [11] Ndiaye, B., Molénat, J., Ndoye, S., Boivin, P., Cheverry, C., and Gascuel-Oudou, C., "Modelling water and salt transfer in rice plantations in the Senegal river delta", *Modélisation du transfert de l'eau et des sels dans les casiers rizicoles du delta du fleuve Sénégal*, vol. 21(3). 325-336. 2008.
- [12] Bellion, D. and T.P. Debenay. *Le bassin sédimentaire sénégal-mauritanien. Présentation générale.* in *Symposium International INQUA-ASEQUA*. 1986. Dakar.
- [13] Castelain, J., *Aperçu stratigraphique et micro-paléontologique du bassin du Sénégal. Historique de la découverte paléontologique.* Mém. Bur. Rech. Géol. Min., 1985. n° 32: p. 135-156.
- [14] Khatib, R., et al., *Rythmes sédimentaires liés aux variations eustatiques globales au Campanien et au Maastrichtien du Sénégal. Révision stratigraphique de la série du Crétacé terminal du Cap de Naze.* C.R. Acad. Sci. Paris., 1994. t. 311, série II: p. 1089-1095.
- [15] Audibert, M., *Delta du fleuve Sénégal : étude hydrogéologique. Projet hydro-agricole du bassin du fleuve Sénégal. Rapport projet AFR-REG-61. Généralités et rapport de synthèse* 1970, Organisation des Nations Unies pour l'alimentation et l'agriculture (FAO).
- [16] Da Boit, M., *Impact des aménagements hydro-agricoles sur la nappe superficielle de la basse vallée du fleuve Sénégal (Thiagar, Richard Toll, Dagana)*. 1993, FST-UCAD. 94 pages
- [17] Diagana, A., *Etude des paramètres hydrodynamiques des aquifères de la basse vallée du Sénégal entre Saint Louis et Podor*. 1990, FST-UCAD. 62 pages.
- [18] Diao, S.M., *Relation eau de surface/eau souterraine dans la région de Richard Toll/lac de Guiers.* . 1992, FST-UCAD. 71 pages
- [19] Illy, P., *Etude hydrogéologique de la vallée du fleuve Sénégal. Projet hydro-agricole de la vallée du fleuve Sénégal*. 1973, Rapport RAF/655061. 158 pages
- [20] OMVS/USAID, *Rapport de Synthèse hydrogéologique du delta du fleuve Sénégal*. 1990, Projet OMVS/USAID 625-0958. Eaux souterraines; Rapport final; Dakar/Sénégal. 73 pages + annexes
- [21] Faye, S. Maloszewski, P., Stichler, W., Trimborn, P., Cissé Faye, S., and Gaye, C. B., "Groundwater salinization in the Saloum (Senegal) delta aquifer : minor elements and isotopic indicators", *Science of the Total Environment*, vol. 343. 243- 259. 2005.
- [22] Sanchez-Martos, F., "Identification of the origin of salinization in groundwater using minor ions Ž Lower Andarax, Southeast Spain", *The Science of the Total Environment*, vol. 297. 43-58. 2002:
- [23] Demetriades, A., "General ground water geochemistry of Hellas using bottled water samples", *Journa of Geochemical Exploration*, vol. 107. 283-298. 2010.
- [24] Lenahan, M.J. and K.L. Bristow, "Understanding sub-surface solute distributions and salinization mechanisms in a tropical coastal floodplain groundwater system", *Journal of Hydrology* , vol. 390. 131-142. (2010).
- [25] Abid, K., et al., "Hydrologic and géologic facotors controlling groundwater geochemistry in the Turonian aquifer (Southern Tunisisa)", *Hydrogeology Journal*, vol. 19. 415-427. 2011.
- [26] Bourhane, A., *Discrimination de l'origine de la salinité dans les eaux souterraines : (contexte hydrogéologique et méthodes d'étude)*. 2010, Université de La Réunion. 109 pages
- [27] Magaritz, M., Nadler, A., Koyumdjiski, H., and Dan, J., "The Use of Na/Cl Ratios to Trace Solute Sources in a Semiarid Zone", *WATER RESOURCES RESEARCH*, vol. 17(3). 602-608. 1981.
- [28] Awni, T.B., "Wheathering process effects on the chemistry of the main springs of the Yarmouk Basin, North Jordan", *Journal of Environmental Hydrology*, Vol. 16 2008.
- [29] Kloppmann, W., Bourhane A., and F. Asfirane, *Méthodologie de diagnostic de l'origine de la salinité des masses d'eau. Emploi des outils géochimiques, isotopiques et géophysiques*. 2011, BRGM.
- [30] Appelo, C.A.J. and D. Postma, *Geochemistry, Groundwater and Pollution*. 2nd ed. ed. 2005, Rotterdam: A.A. Balkema.
- [31] Ghebouli, M.S., M. Bencheikh, and M. Elhocine, "Origine de la salinité des eaux souterraines- cas des hautes plaines Sétifiennes (Nord est algérien)", *Sciences & Technologie A*, N° 28 Décembre. 37-46. 2008.
- [32] Garcia, L.A. and A. Shigidi, "Using neural networks for parameter estimation in ground water", *Journal of Hydrology*, Vol. 318. 215-231. 2006.
- [33] Wang, Y. and J.J. Jiao, "Origin of groundwater salinity and hydrogeochemical processes in the confined Quaternary aquifer of the Pearl River Delta", *China Journal of Hydrology*, vol. 438-439. 112-124. 2012.
- [34] De Montety, V. and al., "Origin of groundwater salinity and hydrogeochemical processes in a confined coastal aquifer: Case of the Rhône delta (Southern France)", *Applied Geochemistry*, vol. 23 . 2337-2349. 2008.
- [35] Yamanaka, M. and Y. Kamagai, "Sulfur isotope constraint of the provenance of salinity in a confined aquifer system of the southwestern Nobi Plain, central Japan", *Journal of hydrology*, vol. 325 (1-4). 35-55. 2006.
- [36] Schoeller, H., *Hydrologie des régions arides - progrès recents*. 1959, Organisation des Nations Unies pour l'Education, la science et la culture (UNESCO): place de Fontenoy, Paris-70 Imprimeries Oberthur. p. 127.
- [37] Richter, B.C. and C.W. Kreitler, *Geochemical techniques for identifying sources of grounwater salintzation*. 1993, United States of America: Library of Congress Cataloging-in-publication Data.
- [38] Fedrigoni, L., et al., "Origine de la minéralisation et comportement hydrogéochimique d'une nappe phréatique soumise à des contraintes naturelles et anthropiques sévères : exemple de la

- nappe de Djebeniana (Tunisie)", *C. R. Acad. Sci. Paris, Sciences de la Terre et des planètes*, vol 332. 665-671. 2001.
- [39] Kouzana, L., A.B. Mammou, and N. Gaaloul, "Intrusion marine et salinisation des eaux d'une nappe phréatique côtière (Korba, Cap-Bon, Tunisie)", *Geo-Eco-Trop*, vol. 31. 57-70. 2007.
- [40] Diouf, S., R. Gomis, and J. Tchani, *Le contact eau douce-eau de mer entre Dakar et Saint-Louis (Sénégal). Une étude géoélectrique*. 1997.
- [41] Gaye, C.B., *La nappe des sables infrabasaltiques de la presqu'île du Cap-Vert (Sénégal)*. I. F. A. N. Dakar, série A. n° 1-2., 1986. Tome 45..
- [42] Cogels, F.X., *La qualité des eaux de surface dans le delta du fleuve Sénégal et le lac de Guiers* 1994.
- [43] Gac, J.Y., M. Carn, and J.L. Saos, "L'invasion marine dans la basse vallée du Fleuve Sénégal" *Revue Hydrobiol. trop.*, vol.19 (1). 3-17. 1986.
- [44] Le Brusq, J.Y. and J.Y. Loyer, *Evolution de la salinité des sols et des eaux en relation avec la riziculture submergée dans le delta du fleuve Sénégal (campagne (1981/1982)* ORSTOM, 1983.
- [45] Loyer, J.Y. and M.A. Diallo, *La cuvette de Pont Gendarme (Vallée ciu Lampar, Région du Fleuve Sénégal) Données sur les sols et sur les nappes. Recommandations pour la mise en valeur*. 1979, ORSTOM p. 47 pages
- [46] Paran, F., D. Graillot, and R. dechomets, *Caractérisation spatio-temporelle des échanges nappes/rivière à l'échelle de deux grands fleuves français : application aux secteurs de Donzère-Mondragon (Rhône) et Ecozone du Forez (Loire)*, in *Colloque Eau, Déchets et Développement Durable*, . 2010: 28 - 31 mars 2010, Alexandrie, Egypte.
- [47] Cissé, A., *Evolution des ressources en eau dans le delta du fleuve Sénégal ; influence du climat, des barrages et de l'irrigation climatique*. 2008, Université Cheikh Anta Diop de Dakar. Faculté des Sciences et Techniques
- [48] Diagana, A., *Etudes hydrogéologiques dans la vallée du fleuve Sénégal de Bakel à Podor : relations eaux de surface et eaux souterraines*, in *Département de Géologie*. 1994, Université Cheikh Anta Diop Dakar
- [49] Ka, O., *Géomatique appliquée à l'étude des eaux souterraines dans la vallée du fleuve Sénégal (Sénégal)*. . 2000, Université du Québec. INRS EAU.
- [50] Ceuppens, J., M.C.S. Wopereis, and K.M. Miézan, "Soil salinization processes in rice irrigation schemes in the Senegal River Delta" *Soil Science Society of America Journal*, vol. 61(4). 1122-1130. 1997.
- [51] Diaw, E.B., *Modélisation de la recharge des nappes dans les périmètres irrigués de la vallée du fleuve Sénégal* 1996, Université Louis Pasteur: Strasbourg.
- [52] Gning, et al., *Relation entre eaux agricoles et eaux souterraines : impact de l'irrigation sur la nappe alluviale du Delta du fleuve Sénégal.*, in *Colloque panafricain COPED/ANSTS 2012: Dakar*, du 30 octobre au 03 Novembre 2012
- [53] Madioune, D.H., *Etude hydrogéologique du système aquifère du horst de Diass en condition d'exploitation intensive (bassin sédimentaire sénégalais) : apport des techniques de télédétection, modélisation, géochimie et isotopie*, in *Faculté des Sciences Appliquées/Département ArGenCo (Architecture, Géologie, Environnement et constructions)/Secteur GEO³/Géotechnologies, Hydrogéologie, Prospection Géophysique*. 2012, Université de Liège (ULG): Liège.

