

Hydrogeochemical Characterization of Aquifer Systems and Surface Water/Groundwater Relations in the Lower Senegal River Valley

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Abstract

This study assesses the chemical quality of water resources in the Lower Senegal River valley, based on 35 samples collected in November 2022. Major ion concentrations in surface water and groundwater were analyzed using classical geochemical interpretation diagrams (Piper, GIBBS, etc.) and multivariate geostatistical analyses, including hierarchical cluster analysis (HCA) and principal component analysis (PCA). The results revealed three types of facies: Ca-Mg-HCO₃-type facies, characteristic of poorly mineralized waters such as surface waters and groundwater from dune formations and the alluvial plain close to the hydraulic axis; Na-Cl type facies associated with well waters located in the alluvial plain that tap Inchirian or Nouakchottian shallow reservoirs and Maastrichtian deep borehole waters; and mixed Ca-Cl and Na-HCO₃ type facies observed in certain floodplain and dune reservoirs. The results showed a strong correlation between sodium, chlorides, bromides, and electrical conductivity, indicating a significant contribution of these ions to groundwater mineralization. The various sources of water mineralization include mixing processes between surface water or rainwater, or calcite or dolomite dissolution processes (for weakly mineralized waters), basic exchanges or inverse basic exchanges between the aquifer and the water table (for moderately mineralized waters), and evaporation processes, halite dissolution, and paleosalinity during periods of marine transgression and regression (for highly mineralized waters). The study also highlighted the high vulnerability of the alluvial aquifer to pollution from intensive irrigated agriculture, as significant quantities of sulfates and nitrates were measured in some samples. These results also highlight the importance of water quality management in the Lower Senegal Valley, particularly as concerns the protection of the alluvial aquifer against pollution from irrigated agriculture.

Keywords

Senegal River Valley, Groundwater, Pollution, Agriculture, Alluvial Aquifer

1. Introduction

The sustainable use of water resources in semi-arid and arid zones is a pressing societal issue (Qi et al., 2023). Consequently, monitoring and assessing the quality of water resources is essential to facilitate decision-making on health and environmental issues. Due to population growth, fast economic development and various human activities, the degradation of surface water and groundwater quality has increased, threatening their availability (Meybeck, 2003; Wu et al., 2023).

In Sahel, due to famine in the 1970s, a large-scale campaign of irrigated agriculture, based on total control of water in river valleys, was launched, particularly in the Senegal River valley (Bruckmann, 2016; Diop, 2008).

The study area, located in the lower Senegal River valley, is today a highly attractive agricultural zone with an estimated agricultural potential of 240,000 ha (SAED, 2021), making it one of the largest rice-growing areas in West Africa. Now that the Senegal river basin is well managed, agriculture is no longer dependent on the rainfall, and irrigation is practiced throughout the year. However, the salinity of the water and soil is still one of the main factors limiting productivity in this region (Loyer, Mougenot, & Zante, 1986; Abrol, Yadav, & Massoud, 1988). This salinity, due to the presence of an ancient marine gulf filled in by alluvial deposits, affects both land and groundwater. This salt is set in movement again by the intensification of irrigation and redistributed in the soil and groundwater (Da Boit, 1993; Diagana, 1990; Le Brusq, 1980; Loyer, 1989; Diaw, 2019). Water resources, especially surface water used for agricultural and industrial purposes, and even for supplying drinking water to the population, are increasingly threatened and affected by intensive farming (Camara, 2018), which has a major impact on groundwater. The management of water and soil resources is therefore one of the major challenges for achieving food security and sustainable development goals. The aim of this study is to characterize groundwater chemistry through studying the various processes (base exchange, precipitation/dissolution, water-rock interactions, evaporation/concentration) and factors (agricultural activities, geology, climate, etc.) that control water mineralization in the different hydrogeological entities of the lower Senegal River valley. The hydrogeochemical processes controlling water quality were determined through the integrated application of multivariate statistical methods: hierarchical cluster analysis (HCA) and principal component analysis (PCA), and the use of classic tools for interpreting hydrogeochemical processes, such as the Piper and Gibbs diagrams. Overall, this study provides a significant contribution to the understanding and management of water resources in semi-arid and arid zones and in massive irrigation context by highlighting the processes and factors controlling water quality in the lower Senegal River valley in order to make practical recommendations and warn users and decision-makers to improve water quality and preserve groundwater resources in the region, particularly regarding agricultural practices and soil management.

2. Study Area

The lower Senegal River valley is located in the northern part of Senegal, covering latitudes 15°51' and 16°35'N and longitudes 15°5' and 16°5'W. It is bounded to the north by the Senegal River, to the west by the delta, and to the east and south by the Ferlo (**Figure 1**). The climate is Sahelian, often strongly influenced by the Alizes, which bring coolness and humidity (Diaw, 2008; Dacosta, Kandia, & Malou, 2002). The area is characterized by two alternating seasons: a long dry season from October to May, and a rainy season from June to September. Maximum rainfall is recorded between August and September (400 mm), due to the maximum upwelling of the Intertropical Front towards the north.



Figure 1. Location of the study area and the sampling points.

Topography and geomorphology characterize the region as two entities with different altitudes, geology and physical environment. From an altimetric point of view, the lower altitudes (or lowlands) represent the major part of the alluvial plain, while the relatively higher altitudes are found in the dune formations. Analysis of **Figure 2** shows that almost 70% of the points sampled have altimetric slopes of less than 7 m, which means that this area is often submerged by surface water or run-off, which, with the presence of salts, is often responsible for the distribution of the soil types observed (clay, clayey silt and sandy silt) (van Lavieren & van Wetten, 1988; Boivin et al., 1995; Boivin et al., 2002). The dunes, with altitudes ranging from 10 to 30 m, are composed of red erg sand.



Figure 2. Drainage network and topography of the study area.

The lower Senegal River valley belongs to the Senegal-Mauritania sedimentary basin, the largest (approx. 340,000 km²) and westernmost of Africa's coastal basins (Roger et al., 2009a). Of Meso-Cenozoic age, it is a typical open basin with a structure characterized by a sedimentary fill that thickens towards the oceanic domain (Bellion & Debenay, 1986) (Figure 3).

Although earliest deposits date back to the Maastrichtian (Michel, 1973), the lower valley of the Senegal River was shaped during the Quaternary by continental facies interspersed occasionally with margino-littoral deposits. These were deposited during alternating periods of marine transgression and regression. The most important were formed during the Inchirian (40,000 - 31,000 years BP) and Nouakchottian (around 5500 years BP) periods. These quaternary alluvial deposits rest on a limestone (Eocene-Paleocene) or sandy-clay bedrock (Terminal Continental or Maastrichtian) (Diagana, 1994).



Figure 3. Geology map of the Senegal lower valley (Roger et al., 2009b, modified).

The subsurface sediments are originally marine and complex; they are composed of quartz, halite, montmorillonite, kaolinite, illite, gypsum, calcite as fossils (gastropods, lamellibranches), pyrite and ferruginous minerals resulting from the influence of the hydroclimatological factors of the fluvial deltaic lagoon and continental media. The geomorphology of the area derived from both erosion and depositional sequences was used by Audibert (1970) to differentiate aquifers present in the system.

The ancient ergs (vast NNE-SSW longitudinal dunes) edified during the Ogolian period, a period of strong marine regression (-100 m) and extreme aridity. The sediments are composed of isometric sand grain (0.2 mm) often coated with ferruginous clay. The whole system overlies an Inchirian semi-permeable sandy clay layer, which is generally used as a limit between the freshwater in the sand dunes aquifer and saline water in the Inchirian aquifer. The recent ergs

(marine terraces) induced by the Nouakchottian transgression (Illy, 1973), are composed of fine, white and isometric sand grains bearing some Anadara senilis shells and gravels overlaying argillaceous sand sediments. These are very characteristic in the lower valley zone and constitute the transition zone between the ancient erg and the flood plain.

From a hydrogeological point of view, two aquifer systems are present in the lower valley, represented from the bottom to the top by:

- the deep aquifers of the Maastrichtian sands and Paleocene-Eocene lime-stones and

- superficial Quaternary aquifers (Audibert, 1970; OMVS, 1972)

The complexity and heterogeneity of the shallow aquifer corresponds to the sandy-clay deposits of the Quaternary period which are associated with the Saloum Formation (ex-Terminal Continental) on the eastern edge of Lake Guiers. The alluvial aquifer occupies the entire major river bed, and the water has incorporated salt from geological formations whose marine origin has been mentioned in the valley's Quaternary morphogenesis. Their salt concentration exceeds that of seawater, and in some places, they are in communication with surface waters (Ngom, 2013). The organization of the surface aquifer in the study area is described by Audibert (1970) as that of a single aquifer formed by two overlaying reservoirs

- a relatively homogeneous upper reservoir, made up of fine Nouakchottian sands and sometimes the upper part of the Inchirian. Its width varies from 0 to 12 m. This aquifer compartment is geometrically captive or free, depending on the presence of a semi-permeable layer (clay and/or silt) on the surface belonging to current or sub-current sediments.

- a heterogeneous lower reservoir consisting of fine to coarse sands mixed with silts belonging to the Inchirian. Its width has not been determined. This reservoir is separated from the previous one by a semi-permeable layer (clay or silt): these are strata from the top of the Inchirian and sometimes from the base of the Nouakchottian. As this horizon is discontinuous, hydraulic communication exists between the two reservoir compartments that constitute the shallow aquifer in the lower river valley.

Before hydro-agricultural development, groundwater was recharged annually from the river floodwaters. Despite low rainfall, groundwater recharge is observed during the rainy season (from July to September), away from any influence from the river and irrigated fields. However, this recharge is very limited by the strong evaporative effect (Gning, 2015). At present, recharge by water from the natural hydrographic system (river, marigots and Lake Guiers) only concerns a small part of the aquifer, according to Saos and Zante (1985), recharge is essentially provided by water from irrigated areas, which have been expanding considerably since the impoundment of the Diama dam in 1987.

3. Methodology

In this article, 35 samplings were collected in this party of Senegal river lower

valley (Figure 1). Surface water samplings concerned the Senegal River and the Lake Guiers following a North-south profile. Groundwater samplings were collected through wells network distributed in the alluvial plain and dune formations and through boreholes of deep aquifers. In each site, geographical coordinates through GPS were taken. Measurements of the water's physico-chemical parameters (pH, temperature, electrical conductivity) were carried out in situ. Conductivity is measured using a multi-parameter instrument (WTW Multi-Line P4), which gives a corrected value at 25°C. Conductivity meter sensitivity is 000.1 µS·cm⁻¹. It also measures temperature and pH (with an accuracy of 0.1°C and 0.05 units). The sampled water was distributed in different 250 mL polyethylene bottles, adapted to the type of analysis to be carried out. Samples for anions analysis (HCO_3^- , NO_3^- , Cl^- , SO_4^{2-} , Br^- , F^-) were not acidified while those for cations (Ca^{2+} Mg²⁺, Na⁺, K⁺) were acidified with concentrated nitric acid and then stored at 4°C for analysis. Chemical analyses of waters were carried out by the hydrochemical and hydrology laboratory of the Department of Geology of Université Cheikh Anta Diop of Dakar. The concentrations of the major ions were examined by Ionic chromatography Dionex DX 120, fitted of AS4 column for anions and of CS12 column for cations.

Classical hydrochemical interpretation tools (e.g. Piper's diagram, Gibbs diagram), statistical methods, correlation matrix and binary diagrams were used to identify the main chemical facies of the waters and the factors that can influence water mineralization, and to group the samples according to their shared characteristics (Piper, 1953; Appelo and Postma, 2005; Abid et al., 2010; Gibbs, 1970). The correlation matrix and binary diagrams show the relationships between chemical elements.

Statistics are widely used in the evaluation of hydrogeochemical data, and have proved to be useful tools for the study of hydrogeochemical models of watersheds, contributing significantly to the classification of groundwater and to the discovery of the main mechanisms influencing its chemistry (Abdul-Wahab et al., 2022; Belkhiri & Narany, 2015; Usunoff & Guzmán-Guzmán, 1989; Stetzenbach et al., 2001; Güler et al., 2002; Güler and Thyne, 2004; Helstrup et al., 2007). In this study, hierarchical clustering analysis (HCA) and principal component analysis (PCA) were performed using R statistical software (R Development Core Team, 2007; Husson et al., 2017).

PCA is an effective tool for identifying the dominant hydrogeochemical processes controlling the chemical composition of groundwater, and for better understanding of the natural and anthropogenic sources influencing the spatial distribution of groundwater quality in the different aquifers of the lower Senegal River valley.

HCA was implemented in R using the stats package. Cluster analysis (CA) is a popular technique used to facilitate data interpretation. In our case, it was applied to sample data sets using the Ward. D method (Ward, 1963), using squared Euclidean distances as a measure of similarity. The main objective of HCA was to group together waters of similar mineralogical composition distributed over the entire sampling network.

4. Results and Discussions

The results of the major elements and in situ parameter analyses and their statistics are summarized in Tables 1-3.

 Table 1. Statistics of physico-chemical parameters by reservoir type.

	Во	oreholes				М	/ells		Surface water				
Variables	Min	Max	Med	Points	Min	Max	Med	Points	Min	Max	Med	Points	
T°C	32.30	37	33.90	5	27.1	35	29.9	21	24.6	30.6	27.30	9	
pН	7.27	8.15	7.89	5	6.74	8.09	7.35	21	7.18	7.79	7.32	9	
CE	692	3500	1865	5	210	9300	1107	21	80	294	133	9	

Table 2. Statistics of major ions by reservoir type.

	Bo	oreholes				We	Surface water					
Variables	Min	Max	Med	Points	Min	Max	Med	Points	Min	Max	Med	Points
HCO ₃	140.3	396.5	378.20	5	39.65	390.40	213.5	21	36.60	109.8	48.80	9
Cl	117.89	814.96	353.83	5	7.62	2660.54	205.40	21	3.38	33.73	11.35	9
Br	0.51	4.03	2.46	5	0	9.97	0.62	21	0	0.19	0	9
NO_3	19.79	167.15	69.45	5	1.99	521.53	68.40	21	1.47	8.83	3.27	9
SO_4	23.93	124.22	70.72	5	1.73	542.28	70.56	21	1.21	7.5	4.64	9
Na	36.85	671.66	347.71	5	15.83	1163.90	126.90	21	2.09	32.23	6.87	9
Κ	3.14	54.61	28.80	5	1.75	68.23	11.08	21	0.47	4.22	1.66	9
Mg	9.76	38.59	26.80	5	2.97	250.22	26.95	21	3.37	9.76	4.16	9
Ca	11.94	60.47	23.87	5	9.75	348.11	67.63	21	5.97	12.73	9.55	9
Fe	0.05	0.15	0.12	5	0.041	0.36	0.12	21	0.03	0.51	0.24	9
F	0.18	3.17	2.76	5	0.16	0.74	0.29	21	0.02	0.18	0.08	9

Table 3. Chemical composition in major ions $(mg \cdot L^{-1})$.

Id	Туре	T°C	pН	EC	HCO ₃	Cl	Br	NO ₃	SO ₄	Na	К	Mg	Ca	Fe	F	TDS
P0	S. W	24.6	6.82	134	48.8	12.64	0	3.23	5.14	11.55	2.83	4.64	5.97	0.47	0.15	95.42
P8	S. W	27.3	6.78	85	36.6	4.81	0	3.8	2.22	2.28	0.63	3.43	7.96	0.03	0.04	61.80
P11	S. W	27.3	7.1	80	36.6	3.76	0	1.47	2.37	2.51	0.59	3.37	6.37	0.09	0.02	57.15
P13	S. W	29	6.62	100	48.8	4.85	0	2.26	2.25	4.29	0.47	3.41	9.94	0.03	0.07	76.37
P19	S. W	25	6.45	90	48.8	3.38	0	2.03	1.21	2.09	0.49	4.11	9.55	0.51	0.03	72.20
P22	S. W	24.9	6.91	135	48.8	12.41	0	3.66	4.64	6.87	1.91	4.41	9.95	0.29	0.14	93.07
P24	S. W	26.9	7.8	133	48.8	11.35	0	3.27	6.07	8.76	2.04	4.16	9.95	0.45	0.08	94.93
P27	S. W	28.7	6.93	147	54.9	13.05	0	5.08	5.03	12.44	1.66	4.88	7.16	0.24	0.1	104.54
P32	S. W	30.6	7.59	294	109.8	33.73	0.19	8.83	7.5	32.23	4.22	9.76	12.73	0.21	0.18	219.38
P1	D	29.5	7.36	4220	256.2	1053.87	5.68	183.45	259.21	661.8	29.71	73.29	119.35	0.05	0.36	2642.98
P2	D	29	7.36	4200	347.7	1107.3	5.83	123.05	130.4	689.92	30.45	61.08	99.46	0.14	0.33	2595.66
P3	D	29.2	7.52	2350	320.25	524.09	2.98	68.4	91.46	377.77	20.3	26.95	67.63	0.14	0.56	1500.53
P4	D	28.6	7.43	480	237.9	21.02	0.19	3.77	17.54	15.83	1.89	20.54	47.74	0.04	0.18	366.64
P5	D	29.9	6.57	236	91.5	19.34	0.11	4.41	10.22	18.42	1.75	7.34	15.91	0.16	0.16	169.33

Conti	nued															
P6	D	30.6	7.42	2700	390.4	579.79	3.25	92.68	126.78	417.16	32.4	38.87	70.02	0.08	0.71	1752.14
P7	D	31.3	8.15	2680	256.2	523.66	3.17	124.4	271.07	429.02	31.79	36.65	59.68	0.06	0.74	1736.43
Р9	D	32	7.1	3850	219.6	1010.66	3.91	177.56	168.37	574.06	36.66	72.57	120.54	0.17	0.57	2384.68
P10	D	33.2	7.58	787	183	112.24	0.56	18.66	52.86	126.9	7.12	12.22	21.88	0.06	0.24	535.74
P12	PA	31.4	7.33	210	115.9	7.62	0	1.99	1.73	30.43	2.55	2.97	9.75	0.36	0.21	173.51
P14	D	27.1	6.33	659	134.2	95.22	0.48	62.53	25.16	87.38	7.39	6.19	35.81	0.09	0.21	454.65
P15	D	32	6.13	474	85.4	91.75	0.42	16.38	22.27	50.58	5.03	7.88	31.83	0.11	0.17	311.82
P16	D	31.4	5.69	756	39.65	205.4	0.62	47.69	20.04	85.12	6.81	14.74	47.74	0.16	0.22	468.18
P23	PA	29	6.54	2700	213.5	449.29	2.88	387.77	291.15	322.14	28.87	81.83	129.30	0.13	0.32	1907.18
P18	D	29.9	7.65	1107	359.9	154.15	0.59	18.48	9.09	68.77	6.05	33.12	95.48	0.16	0.23	746.03
P20	PA	29.4	6.9	479	140.3	67.54	0.35	9.06	22.28	48.22	4.16	8.86	33.42	0.05	0.19	334.42
P21	PA	29.4	7.15	955	286.7	139.07	0.56	22.1	24.12	43.91	6.78	10.14	127.31	0.06	0.16	660.90
P25	D	32	6.9	9300	347.7	2660.54	9.97	384.56	259.65	1163.9	68.23	250.22	348.11	0.12	0.41	5493.41
P28	PA	35	7.37	6050	152.5	1287.09	7.78	521.53	542.28	874.05	42.9	136.71	190.96	0.27	0.29	3756.36
P33	D	29.4	7.58	1060	131.15	172.38	0.61	80.22	70.56	112.09	11.08	20.82	49.73	0.05	0.45	649.14
P34	PA	31.3	6.65	1930	67.1	297.89	2.14	361.19	141.73	193.45	16.65	45.62	128.90	0.16	0.32	1255.15
P17	СТ	34.3	6.5	692	140.3	117.89	0.51	40.71	23.93	36.85	3.14	33.55	49.73	0.07	0.18	446.86
P26	Eoc	32.3	7.86	1190	378.2	127.16	0.57	19.79	48.13	96.65	8.18	38.59	60.47	0.15	0.26	778.15
P29	Maas	33.9	7.65	3240	396.5	814.96	4.03	111.47	95.23	657.77	51.7	17.09	23.87	0.05	3.17	2175.84
P30	Maas	37	7.67	3500	378.2	809.17	3.85	167.15	124.22	671.66	54.61	26.80	19.89	0.13	3.05	2258.72
P31	Maas	33.1	7.77	1865	366	353.83	2.46	69.45	70.72	347.71	28.8	9.76	11.94	0.12	2.76	1263.55

4.1. Physico-Chemical Parameters

pH are neutral to basic, with median values of 7.32 in surface water and 7.89 and 7.35, respectively, in boreholes and wells (**Table 1**). Acidic pH values have been measured in some wells tapping the alluvial aquifer. According to Deckers et al. (1996), this potential acidity is linked to the high pyrite concentration at shallow depths in the subsoil of many soils in the delta and, by extension, the lower valley. The oxidation of pyrite by rising groundwater causes the formation of sulfuric acid, which could reduce the pH of the water. On the other hand, on the marine terraces and in the dunes, the water samples show slightly basic values (pH = 8) due to the presence of shell clusters (Anadaris senilis) in the soils, whose dissolution can enrich the water with hydrogen carbonate ions (HCO₃) according to the reaction:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3$$
(1),

neutralizing soil acidity and forming gypsum

$$Ca^{2+} + SO_4^{2-} \rightarrow CaSO_4 + 2H_2O$$
⁽²⁾

which raises the pH

In surface waters, mineralization ranges from 80 to 294 $\mu\text{S/cm}.$ The lowest mineralized waters (80 - 100 μ S/cm) are found in samples taken from the main course of the river. Water samples taken from the river's tributaries, such as Lake Guiers, show higher conductivities ranging from 100 to 294 µS/cm. It should be noted that, at present, the saline charge in these tributaries is exclusively dependent on related human activities around these waterways (irrigation, domestic activities, livestock farming, etc.). In the wells, the electrical conductivity values of the groundwater sampled are fairly heterogeneous, ranging from 210 to 9300 µS/cm (Table 2). In general, the lowest mineralized waters are found in the Ogolian dune sediments and in the alluvial plain close to the hydraulic axes, or in the eastern part where the alluvial water table is semi-free. In the extension of the marine terraces and in the inter-dunes, well water often has higher concentrations. These saline waters, most of which are captured by piezometers, are contained in Nouakchottian or Inchirian sediments. They are unsuitable for human consumption and irrigation, and can considerably increase the salinization of under-irrigated land. Furthermore, the electrical conductivity values of water taken from boreholes are moderately to highly mineralized. They range from 692 to 3500 µS/cm. However, the lowest mineralized waters are found in boreholes tapping the Saloum Formation (ex-Continental Terminal) and in Eocene limestone. On the other hand, in boreholes tapping the Maastrichtian, the water is more highly mineralized. This high mineralization may be linked to the lithological nature of the tapped sediments and their position in relation to the saline central band, which contains ancient sedimentary brines (Travi, 1993).

4.2. Major Elements

Water chemistry in the study area is mainly characterized by Na-Cl, Ca-Mg-HCO₃ or mixed facies (**Figure 4**). The cations, classified as follows: Na > Ca > Mg > K > F > Fe, are largely dominated by Na ions, most of which exceed even the WHO standard norms (200 mg/L) for drinking water in groundwater (WHO, 2014). The order of abundance of anions is Cl > HCO₃ > NO₃ > SO₄ > Br. Chloride ions in groundwater also exceed WHO drinking water standards (250 mg/l) in over 50% of samples. In waters with low ion concentrations, the dominant ions are Ca²⁺, Mg²⁺ and HCO₃⁻. On the other hand, in samples with high total dissolved solutes, Na⁺ and Cl⁻ are the dominant ions (**Figure 5**).

4.3. Geochemical Mineralization Processes and the Contribution of Statistical Tools

The Piper's diagram (Piper, 1953) shows different types of chemical facies (**Figure 4**). Surface waters are dominated by Ca-Mg-HCO₃ facies. This type of chemical facies (around 20% of samples) has also been observed in the alluvial plain close to the hydraulic axis, in well water located at the foot of the limited-extension Ogolian dunes and in the high, fractured zone of the Guiers dome. It is also found in deep reservoirs that tap the water table of the Eocene limestone and the sandy-clay formations of the Continental Terminal. However,



Figure 4. Piper diagram for water samples.



Distribution of HCO₃, Cl, NO₃, SO₄, Na, K, Mg, Ca by water types

Figure 5. Standardized values of major elements.

groundwater collected from the dunes (P9; P10) as well as from the alluvial aquifer collecting Nouakchottian and Inchirien sediments, generally with a high mineral content, essentially shows sodium chloride chemical facies dominated by Na-Cl. This type of chemical facies Na-Cl dominates in boreholes tapping the deep Maastrichtian aquifer. In its central band, in some areas, these two main facies can migrate to mixed Ca-Cl or HCO₃-Na facies, reflecting the mixed character with surface waters and are mainly found on floodplains and dunes. These waters are associated with shallow wells with dilute chemistry and intermediate mineralization (TDS < 235 mg/l). These facies are probably the result of mixing processes in the floodplains and dune formations aquifer. Base exchange or reverse base exchange processes in freshwater systems tend to extract divalent ions such as Ca^{2+} from solution and replace them with monovalent ions such as Na⁺ (Hem, 1992).

On the other hand, in some locations such as ancient lagoon deposits, the presence of sulfate in the water is very frequent due to the dissolution of gypsum present as evaporites in the area. Dissolution processes of this gypsum lead to the release of sulfate ions in waters, explaining dominance of Na-Cl-SO₄ facies (Diaw, 2019). However, its origin could also be anthropogenic, as traces of gypsum used during soil desalting and, above all, polluting doses of nitrates from uncontrolled fertilizer spreading have been found in the water (Da Boit, 1993). High concentrations of nitrates and sulfates in water are a threat not only to human health but also to the ecological balance. Researches (Ward et al., 2005; Blaisdell et al., 2019; Elwood and van der Werf, 2022) have shown that many groundwater contaminants, such as nitrates (NO₃⁻), are suspected of affecting human health by causing, for example, cancers of the colon, rectum, ovary, bladder, gastrointestinal tract and mouth, as well as methemoglobinemia, while increasing the risk of birth anomalies. Previous studies have shown that the absorption of excessive amounts of sulfate by the human body causes a number of illnesses, including diarrhea, dehydration and gastrointestinal disorders (Man et al., 2014). Sulfate in the aquatic environment can be transformed into toxic substances under certain conditions, leading to the loss of essential metallic elements in aquatic plants and changes in the original eco-hydrological function (Geurts et al., 2009). Soucek et al. have shown that high concentrations of sulfate cause the death of freshwater invertebrates (Soucek and Kennedy, 2005).

Water-rock interaction, precipitation and dissolution are represented in the graphs TDS vs Na/(Na + Ca) and TDS vs Cl/(Cl + HCO₃). Samples located in the middle of the graph are mainly those affected by water-rock interaction. The Gibbs diagram (**Figure 6**) of aquifer data shows that groundwater mineralization is controlled by two processes: water-rock interaction and evaporation/crystallization. Water-rock interaction indicates that water chemistry is relatively linked to the aquifer's petrographic nature, but also to the degree of rock alteration that facilitates element solubility (Gibbs, 1970).

The position of the water in the evaporation range explains the high mineralization of this water, which even approaches the composition of seawater. Indeed, the superficial nature of the alluvial aquifers means that they are exposed to evaporation, especially in the dry season, which contributes to the concentration effect that tends to increase the mineralization of the water, especially in the late dry season. Paleosalinity linked to ancient deposits of marine sediments and terrasses (Lei et al., 2023), and the presence of ancient water conned in the Maastrichtian, are essentially responsible for the major contribution of Na and Cl to global mineralization. This is confirmed by the Br/Cl ratios (**Figure 8(b)**), which show a good correlation, suggesting a common marine origin for these two ions. Furthermore, these two phenomena explain the highly mineralized nature of the water in the lower valley, both in the alluvial aquifer and in the deep aquifers tapped by the boreholes. No samples were located in the precipitation field.



Figure 6. Gibbs diagrams.

Despite the low bromide ion concentration, binary diagrams and correlation matrices show a high correlation between EC and Na, Cl and Br ions (~0.90 in both wells and boreholes) and a fairly moderate correlation with HCO₃ ions. Cl and Br ions dissolved in natural water are close to ideal conservative tracers, due to their hydrophilic nature and small ionic size. The presence of bromide ions can be used to interpret the origin of salinity in a water table (Alcalá and Custodio, 2008; Fontes and Matray, 1993; Herczeg et al., 2001). It can be used to in-

terpret the phenomena responsible for the salinity of the water table: current water level, sedimentary paleosalinity, evaporites, recycling by irrigation (Davis et al., 1998, 2004).

In our study area, bromide, chloride and sodium ions show strong correlations (Figure 7, Figure 8(a), Figure 8(b)), indicating they are of the same origin and that the Na-Cl facies present in most groundwater is the consequence of paleosalinity established during the marine transgressions and regressions of the Nouakchottian and Inchirian periods, especially in the marine terraces where evaporation, crystallization or halite dissolution are predominant (Moussa et al., 2019; Tweed et al., 2011). The presence of sodium chloride facies (Na-Cl) in boreholes located along the axis of Lake Guiers is due to the presence saline water of Maastrichtian aquifer in its central band (Travi, 1993).



Figure 7. Pearson correlation matrix of physico-chemical parameters.

Furthermore, the strong correlation between Na and Cl ions and conductivity explains why these ions make such a significant contribution to groundwater mineralization. The higher their concentration in water, the higher the conductivity (**Figure 8(c)**, **Figure 8(d)**) which is the opposite of the case for bicarbonate ions. This is the consequence that conductivity is weakly controlled by HCO_3 (**Figure 8(e)**).

R statistical software was used for principal component analysis (PCA) and hierarchical cluster analysis (HCA). This analysis considers major ions (Ca²⁺, Mg²⁺, Na⁺, K⁺, HCO₃⁻, Cl⁻, NO₃⁻, SO₄²⁻, Fe²⁺). The PCA results presented in **Figure 9** show the PCA pie chart and the contribution of each variable to the three principal components. The principal component (PC) Dim1, which represents 60.6% of the samples, shows that Na⁺, K⁺, Cl⁻ and HCO₃⁻ ions, with a low contribution, are highly correlated, suggesting a common origin for Na, Cl and K ions, which would come from halite dissolution phenomena or water/rock interactions.



Relationship between CI and Br by water sources





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Relationship between EC and HCO₃ by water sources







Figure 9. Principal Component Analysis: Correlation circle of the first two principal components (PC 1 and PC 2) (left) and representativeness of each element in each PC (right).

The PC Dim2, representing 16.8% of the total variance, shows a positive correlation between Ca and Mg ions, nitrates and sulfates. Calcium and magnesium ions could originate from the dissolution of calcite (CaCO₃) or dolomite (CaMg(CO₃)) (Palmer & Cherry, 1984; Appelo and Postma, 2005) but also from mixtures between recharge waters (rainwater, waterlogging water or streams) as demonstrated by Diaw (2008, 2019).

The significant presence of sulphates may be of natural origin, due to the dissolution of gypsum, or anthropogenic, due to agricultural inputs or wastewater drainage. Nitrate, on the other hand, is anthropogenic, especially at wells (cattle troughs in the neighbourhood or near septic tanks: P28, P23, P32, P25, P9). Finally, Dim3, which contributes only 8% of the total variance, shows a negative correlation between Fe and the other ions, suggesting that this element has little or no role in water mineralization in the lower Senegal River valley.

Thus, the PCA could be subdivided into 3 water groups, namely:

• Na-Cl facies water encountered in wells located on marine terraces and in boreholes tapping the highly saline Maastrichtian in this zone,

• moderately mineralized Ca-Mg-Cl and Na-HCO₃ facies waters found in wells tapping dune formations or the alluvial plain.

• and the group of low-mineralized waters with HCO₃-Ca-Mg facies, which characterize surface waters and alluvial groundwater close to hydraulic axes or low-lying Ogolian dunes. This signature of groundwater close to hydraulic axes could suggest recharge of this alluvial aquifer by surface water.

The dendrogram (Figure 10) resulting from the HCA has highlighted 4 main groups (clusters) according to their dominant chemical composition, corresponding to the different facies in the Piper diagram. The first cluster (C1) is made up of surface waters with low mineral concentration and Ca-Mg-HCO₃ facies, with TDS values of less than 250 mg·L⁻¹. The second cluster (C2) represents Na-Cl, HCO₃-Ca and mixed (Na-HCO₃ or Cl-Ca) facies waters with TDS below 1000 mg·L⁻¹. This is the case for certain surface waters and groundwaters with moderate mineralization, with a codominance between HCO₃⁻ and Cl⁻ and Ca²⁺ and Na⁺ ions. This cluster includes wells tapping water from the alluvial aquifer close to the hydraulic axes or from the deep aquifers of the Saloum Formation or Eocene. Their facies are governed by exchange phenomena between surface water and groundwater in the alluvial aquifer, or by water/matrix interaction (Bouderbala & Gharbi, 2017; Zhang et al., 2021). Clusters 3 and 4 concern waters with sodium chloride Na-Cl facies, whose TDS even exceeds 2000 mg·L⁻¹. These samples represent water with high concentrations of Na and Cl ions, even exceeding WHO standard norms, and correspond to structures that tap the marine terrace aquifer and boreholes capturing the highly saline Maastrichtian aquifer in its central band (boreholes P28, P29, P30). These different aquifers owe their salinity to paleosalinity and the evaporation, crystallization and dissolution of halite in the marine terraces.



Figure 10. HCA of different water groups and piper diagram showing different facies.

5. Conclusion

By characterizing the various aquifer units in the lower Senegal River valley using geochemical and statistical tools for major ions, we were able to categorize the waters into three main facies: HCO₃-Ca/Mg, Na-Cl, and mixed (HCO₃-Na or Cl-Ca). Geochemical and geostatistical analysis confirmed these classifications, highlighting water/matrix interaction and evaporation/crystallization processes as the main influences on groundwater composition.

The results indicate the vulnerability of the alluvial aquifer to sulfate and nitrate pollution, due in particular to human activities such as irrigation and breeding. Such contamination could have adverse repercussions on public health and economic activities, underlining the need for regular monitoring and in-depth research to preserve the region's groundwater resources. As recommendations, these results demonstrate the need to 1) set up a regular water quality monitoring program to track levels of mineralization, nitrates, sulfates and other contaminants, to ensure effective management of water resources, 2) protect aquifers from potentially polluting activities, in particular alluvial groundwater, by implementing measures to protect aquatic ecosystems, 3) promote sustainable agricultural practices to reduce the use of fertilizers and limit the input of nitrates and sulfates into groundwater, thus helping to preserve water quality, 4) implement sustainable groundwater management practices to prevent overexploitation and maintain sustainable levels of abstraction, encouraging rational use of resources and finally, 5) raise awareness among local populations and stakeholders of the importance of preserving water quality and groundwater resources, to encourage participative and responsible management of water resources in lower Senegal river valley.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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