

# Evaluation of Groundwater Quality in the Deep Maastrichtian Aquifer of Senegal Using Multivariate Statistics and Water Quality Index-Based GIS

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#### Abstract

A regional groundwater quality evaluation was conducted in the deep Maastrichtian aquifer of Senegal through multivariate statistical analysis and a GISbased water quality index using physicochemical data from 232 boreholes distributed over the whole country. The aim was to 1) identify the water types and likely factors influencing the hydrochemistry, and 2) determine the suitability of groundwater for drinking and irrigation. Results showed that sodium, chloride, and fluoride are highly correlated with electrical conductivity (EC) reflecting the significant contribution of these elements to groundwater mineralization. The principal component analysis evidenced: 1) salinization processes (loaded by Na<sup>+</sup>, K<sup>+</sup>, EC, Cl<sup>-</sup>, F<sup>-</sup> and HCO<sup>-</sup><sub>3</sub>) controlled by water/rock interaction, seawater intrusion and cation exchange reactions; 2) dolomite dissolution loaded by the couple Ca<sup>2+</sup> and Mg<sup>2+</sup> and 3) localized mixing with upper aquifers and gypsum dissolution respectively loaded by  $NO_3^-$  and  $SO_4^{2-}$ . The hierarchical clustering analysis distinguished four clusters: 1) freshwater (EC = 594  $\mu$ s/cm) with mixed-HCO<sub>3</sub> water type and ionic contents below WHO standard; 2) brackish (Na-mixed) water type with moderate mineralization content (1310 µs/cm), 3) brackish (Na-Cl) water type depicted by high EC values (3292 µs/cm) and ionic contents above WHO and 4) saline water with Na-Cl water type and very high mineralization contents (5953 µs/cm). The mapping of the groundwater quality index indicated suitable zones for drinking accounting for 54% of the entire area. The occurrence of a central brackish band and its vicinity, which were characterized by high mineralization, yielded unsuitable groundwater for drinking and agricultural uses. The

approach used in this study was valuable for assessing groundwater quality for drinking and irrigation, and it can be used for regional studies in other locations, particularly in shallow and vulnerable aquifers.

#### **Keywords**

Groundwater Quality Index, Maastrichtian, Statistical Analysis, GIS

# 1. Introduction

Water is a critical resource for human health, economic development, food security, and ecological sustainability [1]. Groundwater constitutes a primary source and essential water supply in many regions, especially in arid and semi-arid areas [2]. However, most Sub-Saharan African countries have been affected by water quality degradation and drought [3] [4]. Natural processes and anthropogenic factors both have an impact on water quality, degrading groundwater sources and limiting their potential use for drinking, agriculture, recreation, and industry [5]. Indeed, the geological formations through which groundwater flows, as well as anthropogenic activities in a watershed basin, determine the spatial variation of groundwater quality [6] [7] [8] [9] [10]. Furthermore, the fast expansion of megacities raises competition for water supplies [11]. As a result, for many countries, a groundwater quality map is essential for water planning and allocations, as well as a warning of potential environmental health hazards.

The Maastrichtian aquifer is the largest groundwater reservoir in Senegal, covering nearly the entire country with an estimated potential of around 400 billion m<sup>3</sup> [12]. It is the most exploited aquifer, with approximately 1,300 boreholes producing 94.5 million m<sup>3</sup>/year [13]. Nevertheless, high mineralization content affects groundwater, with salt, fluoride, and chloride concentrations above World Health Organization (WHO) standards (1000, 1.5, and 250 mg·l<sup>-1</sup>, respectively), rendering the water unsuitable for drinking in some parts of the aquifer [14]. Furthermore, the aquifer is unconfined in the western part (Horst of Diass) and therefore susceptible to anthropogenic pollution from the surface. Numerous studies have been conducted in the Maastrichtian aquifer such as the identification of potential groundwater areas for borehole implementation, hydrochemistry and groundwater flow characterisation through geological and geophysical surveys, hydrochemistry studies and groundwater modelling [12] [14]-[19], but there is no up-to-date regional overview of the groundwater quality due to the lack of data covering the whole country.

Different techniques are commonly used to assess groundwater quality based on physicochemical parameters such as multivariate statistics analysis (MSA), Geographic Information Systems (GIS) and geostatistical modelling. Groundwater quality parameters that produce large data sets necessitate the interpretation of complex data matrices, as well as a better understanding of water quality and the interdependencies between parameters and sampling locations [20]. With regard to the present study, this is expected to happen in the context of a regional study involving hundreds of sampling sites. As a result, statistical tools such as principal components analysis (PCA) and hierarchical clustering (HCA) combined with correlation matrix analysis are useful in resolving this complex data set interpretation [21] [22]. Furthermore, GIS tools are widely used to generate groundwater quality maps and demarcate potential drinking-water suitability zones based on standards such as the water quality index (WQI) [23] [24] [25] [26]. In recent years, multi-criteria decision-making (MCDM) techniques such as the analytic hierarchy process (AHP) for water quality evaluation in GIS environments have been developed and implemented in water quality indexing [27] [28] [29]. Geostatistical modelling, on the other hand, is widely used for spatial variation of hydrochemical parameters in groundwater using various interpolation methods (e.g., Inverse Distance Weighted, Kriging, Akima). It can be used for identifying the proper zones for irrigation purposes through the mapping of hydrochemical indices such as sodium adsorption ratio (SAR), sodium percentage (Na%), and residual sodium carbonate (RSC) [30] [31] [32] [33].

The combinations of MSA, GIS-based AHP and geostatistical modelling in groundwater water quality indexing have been less investigated, especially in water-limited environments such as Senegal. Nevertheless, the combined use of such advanced techniques would provide guidelines for environmental managers, decision-makers, and water planners for future efficient uses of the groundwater.

In this regard, a set of original data is used in this present study to conduct a regional groundwater quality assessment of Senegal's deep Maastrichtian aquifer. The specific objectives are to 1) decipher the water type/composition and likely factors determining hydrochemistry through MSA and 2) ascertain the groundwater's suitability for human consumption and agriculture usage based upon GIS-based AHP and geostatistical modelling.

# 2. Study Area

Senegal is a semi-arid country, located in western Africa between longitude 11° - 18° West and latitude 12° - 15° North (**Figure 1(a)**). It is limited by Mauritania to the North and Northeast, Mali to the East, the Guinea Republic and Guinea Bissau to the South, and the Atlantic Ocean to the West. The relief is flat in a significant part of the continent, above 50 m. Maximum altitudes are recorded in the southeast of the country, on the border with the Guinea Republic, where the Bassari Mountains reach 581 m, and the Cap-Vert Peninsula with the Mamel hills, which reach 181 m. The climate is Sahelian, with a wet season from June to October and a long dry season the rest of the year. The highest precipitation amount occurs during the August-September period and varies spatially from 300 mm in the North to more than 1400 mm in the South.



**Figure 1.** Study area: (a) Sampling site location including groundwater head contours and flow direction (DGPRE, 2013); (b) Geological cross-section showing the hydrological units.

A subsident sedimentary basin extending from Guinea to Mauritania covers most of the country, except in the Southeast where Paleoproterozoic rocks outcrop (Kedougou-Kenieba inlier). Sediments of the Mesozoic age are thick (ca. 8 km) in the western part of the country, especially in the southern Casamance region, and thin towards the East and North. Most Mesozoic sediments (Senonian to Jurassic) are marine sandstone intercalated with clay and limestone of varying thicknesses [34]. The Late Cretaceous series (Maastrichtian) consists of homogenous sandy deposits that contain the deep aquifer. Because the groundwater is found within the Maastrichtian sands, this latter has been named the Maastrichtian aquifer. It is a confined aquifer, covered by Paleocene, Eocene, and Complex Terminal Formations, except in the Diass Horst where it outcrops (**Figure 1(b)**). It bears a vital water resource exploited at around 94.6 million m<sup>3</sup>/year. Computed residence times from the detectable <sup>14</sup>C isotopic data range from 10,000 to more than 30,000 years, evidencing paleowaters in the aquifer [16] [19]. The overall groundwater flow pattern occurs from the South-East (Palaeozoic bedrock border) towards the North-West and the West where groundwater has a negative head. This observed depression in the Diass Horst area is the result of the high abstraction for the drinking water supply of urban areas (**Figure 1(a)**).

# 3. Methodology

# 3.1. Water Sampling Collection

The water quality data, including 232 sampling locations across the country were obtained from Senegal's water planning department ("Direction de la Gestion et la Planification des Resources en Eau"). All water samples were collected in 250 and 500 ml polyethene bottles from 2013 to 2019. The chemical analyses, which included electrical conductivity (EC, measured in the field with a multi-parameter probe, HANNA, HI 9828), total dissolved solids (TDS) derived from EC (TDS =  $0.64 \times EC$ ), Cl<sup>-</sup>, SO<sup>2</sup><sub>4</sub>, NO<sup>-</sup><sub>3</sub>, F<sup>-</sup>, HCO<sup>-</sup><sub>3</sub>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup> and K<sup>+</sup> were conducted by the hydrochemistry laboratory of the Geology Department of Dakar University. The ion chromatography method with AQUION-DIONEX equipment was used for the chemical analyses. The exchange processes were carried out through AS14 A-AERS 500 columns for anions and CS12 A-CERS 500 for cations. The carbonate species were analyzed by titrimetry using a 0.05 N sulphuric acid solution. From more than 600 samples, ionic balances (IB) were used as cross-validation for chemical analysis. Samples with IB > 5% were removed from the database and 380 samples were retained for this present study.

#### **3.2. Statistical Analysis**

Descriptive statistics, correlation matrix and multivariate statistical models (PCA and HCA), together with classical hydrochemistry data visualization (e.g., Piper and Schoeller diagrams) were used to identify the potential factors influencing the water chemistry and to group the samples according to their water quality characteristics. The correlation matrix illustrates the relationship between all pairs of chemicals and is an effective tool for summarizing and visualizing patterns in large datasets. On one hand, PCA is typically used to locate the directions of maximum variance in high dimensional data in order to project them onto a reduced dimensional subspace while preserving most of the information. It is used in this study to identify likely factors that influence water chemistry based on chemical loads onto the principal components. All chemical parameters were included except for TDS which was derived from EC values. 214 water

samples (we removed missing values) were considered for the PCA and only components with eigenvalues  $\geq 1$  were considered significant following Kaiser criterion [35]. HCA, on the other hand, is a useful method for objectively arranging a large dataset into clusters based on a set of characteristics. Euclidean distances were used as a metric of dissimilarity between sets of observations, and Ward's criterion for the linkage rule [36]. All statistical analyses and data visualizations were carried out in Python using the scikit-learn machine learning and seaborn packages.

# 3.3. GIS Analysis and Geostatistical Modelling of Water Quality Parameters

All data sets used in this present study were compiled in a GIS environment by establishing a database geographically referenced to the UTM-WSG84 projection. The spatial distribution of groundwater quality parameters was computed using the inverse distance weighted (IDW) method with ArcGIS software's spatial analyst modules. IDW is a spatial interpolation technique that estimates values between measurements [37]. The prediction maps of TDS, EC, cations, and anions are classified according to [38] standards for drinking water. These raster data are then used to generate the groundwater quality index (GWQI) map, which represents the composite influence of different water quality parameters on overall water quality for drinking purposes.

#### 3.4. Groundwater Index for Drinking Purposes

The GWQI computation has been accomplished through two steps: 1) weighting assignment of each criterion by AHP, 2) quality rating scale and demarcation of GWQI. More details about the computation of the water quality index can be found in [31] [39] [40] [41].

#### 3.4.1. Weighting Assignment through AHP

Weighting is assigned to individual factors based on their relative relevance to drinking water quality as determined by standard values (e.g., WHO standard), which are then normalized using Saaty's scale [42]. Based on the relative relevance values, a pairwise comparison matrix is generated. A score of 1 shows equal prominence of the two themes, whereas a score of 9 indicates extreme prominence of one theme over the other. This threshold procedure includes the evaluation of all decision-makers into a final decision through pairwise comparisons of the alternatives [43] [44]. The consistency ratio ( $C_R$ ), which must be smaller than 0.1, is used to evaluate the comparison matrix consistency using the following equations:

$$C_R = \frac{C_I}{R_I} \tag{1}$$

$$C_I = \frac{\lambda_{\max} - n}{n - 1} \times 100 \tag{2}$$

where  $C_I$  is the consistency index;  $R_I$  is the ratio index; n is the number of factors and  $\lambda$  is the average value of the consistency vector.

# 3.4.2. Quality Rating Scale and Demarcation of Groundwater Quality Index

To delineate the GWQI map, a weighted linear combination aggregation of the raster dataset (derived from IDW interpolation) was performed using the weighted sum tools of ArcGis software, expressed as follows:

$$GWQI = \sum_{i=1}^{i=n} \left( \frac{C_i}{S_i} \times x_i \times 100 \right)$$
(3)

where  $C_i$  is the concentration of each parameter (mg·l<sup>-1</sup>);  $S_i$  is the WHO standard limit and  $x_i$  is the criterion score (relative weight of *i*) of chemical parameters *i* derived from AHP.

GWQI ranges were then classified according to [45] (Table 1).

#### 3.5. Water Quality Evaluations for Irrigation

The adequacy of the groundwater for irrigation purposes was evaluated using indicators including sodium percentage (*Na*%), sodium adsorption ratio (*SAR*), magnesium hazard (*MH*) and residual sodium carbonate (*RSC*) which are listed in **Table 2**. The rating was then based on standard value intervals following [46] [47] [48] [49].

# 4. Results and Discussions

#### 4.1. Hydrochemistry and Statistical Analysis

The statistical summary of the groundwater quality parameters in comparison with WHO standards are presented in **Table 3**. The electrical conductivity (EC) values of groundwater samples ranged from 19 to 6480  $\mu$ s·cm<sup>-1</sup>, with an average of 1764 (median of 1190  $\mu$ s/cm) which is slightly above the WHO standard (1500  $\mu$ s·cm<sup>-1</sup>). The high standard deviation value (1478  $\mu$ s·cm<sup>-1</sup>) revealed different water types ranging from fresh to saline water, suggesting different geochemical processes occurring in the aquifer. Cations and anions had average values below the WHO standards, except Na<sup>+</sup> and Cl<sup>-</sup> which mean values were well above (317 and 360 mg·l<sup>-1</sup>, respectively). The ionic dominance patterns were in the order of Na<sup>+</sup> > Ca<sup>2+</sup> > Mg<sup>2+</sup> > K<sup>+</sup> for cations and Cl<sup>-</sup> > HCO<sub>3</sub><sup>-</sup> > SO<sub>4</sub><sup>2-</sup> > NO<sub>3</sub><sup>-</sup> > F<sup>-</sup> for anions.

Table 1. Groundwater quality index (GWQI) intervals are used to classify water types.

GWQI	Water type
<25	Excellent water
25.1 - 50	Good water
50.1 - 75	Poor water
75.1 - 99.9	Extremely poor water
>100	Unsuitable for drinking purposes

Parameters	Formula	Rank Value	Water classification
	Na	0 - 6	Good
SAR	Ca + Mg	6 - 9	Doubtful
	$\sqrt{2}$	>9	Unsuitable
		<20	Excellent
	$(\mathbf{N} \to \mathbf{V})$	20 - 40	Good
Na%	$\frac{(Na + K)}{(Ca + Mg + Na + K)} \times 100$	40 - 60	Permissible
		60 - 80	Doubtful
		>80	Unsuitable
		<1.25	Good
RSC	$(CO_3 + HCO_3) - (Ca + Mg)$	1.25 - 2.4	Doubtful
		>2.5	Unsuitable
MII	$Mg_{\times 100}$	<50	Suitable
MH	$Ca + Mg^{-100}$	>50	Unsuitable

**Table 2.** Classification of water quality based on standard value intervals for irrigation. *SAR* is the sodium adsorption ratio, *Na%* is the sodium percentage, *RSC* is the residual sodium carbonate and *MH* is the magnesium hazard.

**Table 3.** Statistical overview of the water quality parameters in the Maastrichtian aquifer. N and Std are the sample size and the standard deviation. Electrical conductivity (EC) is in  $\mu$ s/cm and the ions are in mg/l units.

Parameters	N	Minimum	Maximum	Median	Mean	Std	WHO standard	
EC	377	19.00	6480.00	1190.00	1763.79	1478.09	1500	
$Ca^{2+}$	380	0.40	250.80	19.10	27.36	27.69	75	
$Mg^{2+}$	375	0.23	175.90	9.70 13.77		17.07	30	
Na <sup>+</sup>	380	1.59	1453.80	187.15 317.35		319.11	200	
$K^+$	378	0.13	39.56	9.40	10.78	8.99	12	
Cl-	380	0.60	2056.70	119.55 359.38		443.95	250	
$HCO_3^-$	379	2.00	768.70	304.40 294.46		136.76	300	
$\mathbf{SO}_4^{2-}$	375	0.03	656.00	55.47	71.41	77.20	200	
$NO_3^-$	218	0.02	181.90	2.10	7.50	21.15	50	
F <sup>-</sup>	252	0.02	4.49	0.63	1.13	1.16	1.5	

The correlation matrix (**Figure 2**) showed that EC has a strong positive correlation with Cl<sup>-</sup> (0.96), Na<sup>+</sup> (0.94) and K<sup>+</sup> (0.79), and a moderate correlation with  $F^-$  (0.60) and  $HCO_3^-$  (0.56) reflecting the significant contribution of these elements to the acquisition of groundwater mineralization such as 1/rock-water interaction, 2/ion exchanges, 3/salinization through actual or past marine intrusion in the coastal area and 4/freshening and mixing through leakage from upper aquifers (e.g., Paleocene and Eocene aquifers) and groundwater recharge in the unconfined area [16] [17] [19]. The Cl<sup>-</sup> gave a strong positive correlation with



**Figure 2.** Pearson correlation matrix of physicochemical parameters. Not significant parameters at p-value = 0.05 are highlighted in light grey color.

Na<sup>+</sup> (0.91) suggesting the same origin from either halite dissolution or salinization processes (e.g., seawater intrusion) as commonly reported in groundwater coastal areas [50] [51] [52] [53]. Since equal amounts of Na<sup>+</sup> and Cl<sup>-</sup> are mixed in groundwater as a result of halite dissolution, the ratio will be close to one. The Na<sup>+</sup>/Cl<sup>-</sup> ratios for the study area ranged from 0.33 to 28.75, with a mean value of 2.35, suggesting the possibility of additional mechanisms releasing sodium into the groundwater. Indeed, if the ratio is less than 1 and close to the marine ratio value (0.86) it may be due to seawater intrusion [54] [55]. Instead, a ratio greater than 1 suggests that sodium sources are from ion exchange reactions [51] [56] or Silicate weathering [57]. Furthermore, the Simpson ratio  $(Cl^{-}/HCO_{3}^{-})$  can also be used to classify the impacts of seawater intrusion on groundwater mineralization [58]. Generally, groundwaters that have not been contaminated by seawater intrusion have a Simpson ratio of less than 0.5. In this study, 27% of samples had a value greater than 0.5, which confirmed marine processes' occurrence in groundwater mineralization. Reference [59] suggested a paleowater origin of saline waters in the west part of the aquifer instead of actual seawater intrusion induced by over-exploitation. Na<sup>+</sup> showed a poor correlation with Mg<sup>2+</sup> (1.57) and nonsignificant (at p = 0.05) with Ca<sup>2+</sup>, due probably to the substitution of Mg<sup>2+</sup> or Ca<sup>2+</sup> in the groundwater with Na<sup>+</sup> in the aquifer reservoir which corroborated the cation exchange processes [17] [50] [60]. The significant correlation found between Ca<sup>2+</sup> and Mg<sup>2+</sup> (0.86) suggested the presence of magnesium calcareous minerals in the aquifer, such as dolomite  $(CaMg(CO_3)_2)$ , and their dissolution into groundwater. The positive high correlation between F<sup>-</sup> and Na<sup>+</sup> (0.75),  $HCO_3^-$  (0.72) and K<sup>+</sup> (0.70), and negative poor correlation between Ca<sup>2+</sup> (-0.30) indicated leaching of fluoride-bearing minerals such as apatite [59]. There was no significant correlation between  $NO_3^-$  and the other parameters, suggesting another source such as anthropogenic activities nearby the sampling site or leaking from upper aquifers as evidenced in the western and northern part of the study area by [14] [17]. Thus, rock-water interaction, residual/actual seawater water intrusion, cation exchange and localized mixing and pollution resulted in the hydrogeochemical evolution of groundwater quality in the Maastrichtian aquifer.

Results from PCA are presented in **Table 4**, which summarized the determined Principal Components (PC) loadings, their eigenvalues and the percentage of the variance contributed to each PC. Three components with an eigenvalue greater than 1 were sufficient to explain 81.5% of the variance in the correlation matrix as follows: 47.9% by PC 1, 22.9% by PC 2, and 10.6% by PC 3. The PCA loading circle plot and the contribution of each variable to the three principal components are presented in **Figure 3**. PC 1 was strongly loaded by Na<sup>+</sup>, K<sup>+</sup>, EC and Cl<sup>-</sup>, and by F<sup>-</sup> and HCO<sup>-</sup><sub>3</sub> to a lesser extent (**Figure 3(b)**), contributing to salinization processes mainly controlled by rock-water interaction (dissolution of halite and fluorite, silicate weathering) but also seawater intrusion and cation exchange reactions. PC 2 was loaded by the couple Ca<sup>2+</sup>/Mg<sup>2+</sup>, which comes primarily from dolomite dissolution (**Figure 4(c)**). PC 3 accounted for NO<sup>-</sup><sub>3</sub> and SO<sup>2-</sup><sub>4</sub> derived from localized pollution around boreholes and gypsum (CaSO<sub>4</sub>, 2H<sub>2</sub>O) dissolution as evidenced by [14] [59] (**Figure 4(d)**).

Due to the variability in ionic contents and involved hydrogeochemical processes deciphered with the correlation matrix and PCA, HCA was applied to identify the similarity between water samples.

	PC 1	PC 2	PC 3
EC	-0.955	-0.155	0.075
Ca <sup>2+</sup>	-0.185	-0.933	0.019
$Mg^{2+}$	-0.319	-0.889	0.021
$K^+$	-0.900	0.131	-0.038
Na <sup>+</sup>	-0.965	0.132	0.044
Cl⁻	-0.907	-0.246	0.111
$\mathrm{SO}_4^{2-}$	-0.334	-0.281	-0.564
$HCO_3^-$	-0.706	0.425	-0.097
$NO_3^-$	-0.101	-0.035	0.844
F⁻	-0.752	0.504	-0.025
Eigenvalue	4.821	2.305	1.067
% of Variance	47.984	22.944	10.617
cumulative % of the variance	47.984	70.929	81.545

 Table 4. Principal components (PCs) loadings for significant (in bold) chemical parameters.



**Figure 3.** Principal Component Analysis: (a) Correlation circle of the first two principal components (PC 1 and PC 2), and chemical parameter loading onto (b) PC 1, (c) PC 2 and (d) PC 3.



**Figure 4.** Hierarchical Cluster Analysis: (a) Identification of clusters based on the dendrogram; (b) Rectangular Piper diagram and (c) Schoeller diagram. Samples from each cluster are represented in (colored) circles and the cluster mean values are in squares.

The dendrogram distinguished four clusters (C1, C2, C3 and C4), with C3-C4 linked at higher distances (Figure 4(a)). Table 5 summarizes details on each cluster relative to the mean value of chemical parameters and the main water types based on the Piper (Figure 4(b)) and Schoeller (Figure 4(c)) diagrams. The first cluster, C1 (N = 148) was characterized by freshwater (average EC value of 594 µs/cm) with mean values of all ions below WHO standards and a mixed-HCO<sub>3</sub> water type. This cluster was mainly influenced by freshening, cations exchange reactions and mixing processes. Instead, C2 (N = 3) was mainly saline (Na-Cl) water type with higher mineralization compared to other clusters  $(EC = 5953 \,\mu\text{s/cm})$  and ionic contents well above WHO standards except for F<sup>-</sup> (0.6 mg·l<sup>-1</sup>) and HCO<sub>3</sub><sup>-</sup> (203.3 mg·l<sup>-1</sup>). C3 (N = 17) exhibited brackish water type (Na-Cl) but with lower ionic contents than C2 (EC =  $3247 \mu s/cm$ ), except for  $HCO_3^-$ ,  $F^-$  and  $NO_3^-$  which were higher compared to other clusters. C2 and C3 are mainly influenced by salinization processes and potentially by localized anthropogenic activities around boreholes. Finally, C4 (N = 46) presented similarities with C3, depicted by brackish water type (Na-mixed) with lower mineralization contents than C2 and C3.

#### 4.2. Spatial Variation of Groundwater Parameters

The spatial distribution of TDS values, cations, and anions concentration, classified in terms of WHO standards are shown in **Figure 5** and **Figure 6**. The TDS prediction map (**Figure 5(a)**) indicated an increasing gradient of mineralization from the East characterized by freshwater ( $<500 \text{ mg} \cdot l^{-1}$ ) towards a meridian band located in the centre part of the area where a significant rise in mineral contents is observed. Within this brackish central band, TDS is higher than the

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	
Water type name	Fresh	Saline	Brackish	Mixed	
water type name	N = 148	N = 3	N = 17	N = 46	
Dominant water type	Mixed-HCO <sub>3</sub>	Na-Cl	Na-Cl	Na-Mixed	
EC	593.8	5953.3	3291.8	1310.7	
Ca <sup>2+</sup>	35.7	235.9	14.9	9.0	
$Mg^{2+}$	14.8 128.8		7.8	5.7	
Na <sup>+</sup>	56.9	781.6	687.9	273.5	
$\mathrm{K}^{\scriptscriptstyle +}$	6.9	26.8	26.8	13.8	
HCO <sub>3</sub>	209.8	203.3	478.3	336.9	
Cl-	41.3	1892.4	781.3	212.7	
$\mathbf{SO}_4^-$	51.8	113.9	73.5	73.6	
$NO_3^-$	6.2	4.6	9.6	8.8	
$F^-$	0.5	0.6	3.2	1.9	

**Table 5.** Summary of groundwater characteristics of clusters based on average values. EC is in  $\mu$ s/cm and ions are in mg·l<sup>-1</sup> units.



**Figure 5.** Total Dissolved Solute (TDS) and cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup>, and K<sup>+</sup>) spatial variation.

WHO standards, ranging from 1.5 to 3.8 g·l<sup>-1</sup>. Reference [59] suggested that the high mineralization observed in this area is the result of past marine intrusion during the Eocene and Holocene periods but also rock interaction with paleowaters characterized by low transit time. As indicated by [16], apart from the Diass Horst, South and southeast borders, the most recent recharge episodes took place during the Holocene humid periods (between 12,000 and 3000 years BP). In addition, radiocarbon dating (<sup>14</sup>C) has shown that the Maastrichtian aquifer contains paleowaters in the brackish band that are over 125,000 years old [16] [59]. Towards the West, on the other side of the brackish band, TDS



**Figure 6.** Anions (F<sup>-</sup>,  $HCO_3^-$ ,  $SO_4^{2-}$ ,  $Cl^-$  and  $NO_3^-$ ) Spatial variation.

decreases again to reach values  $<500 \text{ mg} \cdot l^{-1}$  in the Diass Horst which constitutes the recharge zone of the aquifer [17]. The spatial distribution of Ca<sup>2+</sup> (**Figure 5(b**)) and Mg<sup>2+</sup> (**Figure 5(c**)) concentrations revealed that most of the study area has values less than 75 mg·l<sup>-1</sup>, except the northern part of the study area, which is higher than the WHO standards. This high concentration in the North, especially for Ca<sup>2+</sup> (241 mg·l<sup>-1</sup>), would come from the reverse cation exchange process with Na<sup>+</sup>, induced by the occurrence of the Guier dome (anticlinal structure of Lake Guier associated with faults) which allows mixing with the upper aquifer [61] [62]. Regarding Na<sup>+</sup> (**Figure 5(d**)) and K<sup>+</sup> (**Figure 5(e**)) concentrations, their spatial variations were relatively similar to TDS, especially for Na<sup>+</sup> whose concentration is higher compared to K<sup>+</sup>. From a few tens of milligrams in the East, the concentration gradually increases towards the West to reach, at the level of the brackish band; values higher than 12 and 200 mg·l<sup>-1</sup> for K<sup>+</sup> and Na<sup>+</sup> corresponding to the WHO threshold.  $F^-$  (Figure 6(a)) and  $Cl^-$  (Figure 6(d)) prediction maps were also similar to those of TDS and Na<sup>+</sup> with a high concentration greater than the WHO standard in the brackish band. According to [59], the high fluoride content does not come from residual seawater, as may be the case for chloride and Sodium. They would come from the interaction between groundwater and rock from fluoride minerals associated with phosphate sediments (e.g., apatite fluoride) as also evidenced in other studies [63] [64] [65]. The prediction map of  $HCO_{2}^{-}$  showed that most of the study area outside of the brackish band has values below WHO standard (<300 mg·l<sup>-1</sup>). Sulfate contents were lowest in the eastern and south-eastern parts of the country, where the concentrations were less than 100 mg· $l^{-1}$  (Figure 6(c)). While in the central and northern parts of the country, a higher concentration was observed exceeding 600 mg·l<sup>-1</sup> in some zones due to the dissolution of gypsum minerals. Nitrate contents were also low, less than 5 mg· $l^{-1}$  in most samples (Figure 6(e)). The only exceptions are a few samples collected in the central and the North-West part, where concentrations above 100 mg·l<sup>-1</sup> have been recorded. However, in this part of the country, the Maastrichtian is confined and covered with layers thicker than 200 m, therefore pollution from agriculture is not likely to occur. This nitrate would originate from the leaking and mixing of diverse types of water percolating from the upper aquifers, which are vulnerable to pollution.

#### 4.3. Groundwater Quality Index

Analytical hierarchical processes (AHP) have been used to compute suitable weights of the ten physicochemical parameters using a pairwise comparison matrix (**Table 6**). Fluoride and nitrate were given the highest weights, followed by EC,  $SO_4^{2-}$ , and Cl<sup>-</sup>. Instead,  $HCO_3^{-}$  has given the lowest weight.

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	Parameters	Ca <sup>2+</sup>	EC	Cl⁻	$\mathrm{HCO}_3^-$	$K^+$	$Mg^{2+}$	$Na^+$	$\mathrm{NO}_3^-$	$\mathrm{SO}_4^{2-}$	$\mathbf{F}^{-}$	Wi
	Ca <sup>2+</sup>	1										0.0447
	EC	3	1									0.1155
	Cl-	3	1	1								0.1155
	$HCO_3^-$	1/5	1/7	1/7	1							0.0149
	$K^+$	1/3	1/5	1/5	3	1						0.0275
	$Mg^{2+}$	2	1/5	1/5	3	1	1					0.0345
	Na <sup>+</sup>	1	1/3	1/3	5	3	3	1				0.0569
	$NO_3^-$	7	3	3	9	5	5	3	1			0.2305
	$\mathbf{SO}_4^{2-}$	3	1	1	7	5	5	3	1/3	1		0.1155
	$F^-$	5	3	3	9	7	7	5	1	3	1	0.2445

**Table 6.** Pairwise comparison matrix for criterion weightage and relative weights by Analytical Hierarchical Processes (AHP). The consistency ratio of the matrix is 0.04.

The spatial distribution of GWQI revealed that 20% of the study area falls in unfit water corresponding primarily to the brackish band, characterized by high TDS,  $F^-$ ,  $Cl^-$ ,  $Na^+$  and  $K^+$  contents (**Figure 7**). Poor to extremely poor water represents 26% of the study area and is located on both sides of the brackish band. Conversely, excellent, and good water types represent 25% and 29% of the study area situated in the East, southeast, and far Western parts of the country. Thus, the Maastrichtian aquifer has an essential reserve of high water quality standards, representing more than 54% of its total surface area in Senegal.

#### 4.4. Suitability for Irrigation Purposes

SAR, %Na, MH, and RCS indices were used to ascertain the suitability of the Maastrichtian aquifer for agriculture usage. For irrigated water, sodium hazard is a valuable tool to evaluate suitability. A significant increase in SAR at the root zone may influence soil permeability and cause the formation of progressively permeable layers, resulting in water logging [66] [67]. Furthermore, high Na<sup>+</sup> concentrations in irrigated water may cause absorption by clay particles, which is regulated by Ca<sup>2+</sup> and Mg<sup>2+</sup> ion exchange. In this present study, SAR varied between 0.09 and 115 (Figure 8(a)) and Na% ranged from 2.09 to 99.56 (Figure 8(b)). The suitable water types for irrigation based on these indices were observed in the East, Southeast and the western part of the country. Conversely, unsuitable, and doubtful water for irrigation was observed in the brackish band and its vicinity. Other, essential indices for irrigation water ratings are MH and RCS [68]. An excess of magnesium ions in groundwater degrades soil quality by increasing alkalinity, which may reduce agriculture productivity [26]. MH values of the study area ranged from 5.7% to 98% (Figure 8(c)) and RSC varied between -21 and  $12.4 \text{ meq} \cdot l^-$  (Figure 8(d)). Their spatial variation showed that most of the aquifer has suitable water for irrigation except in some parts in the brackish band and the South, West, and Southeast Regions to a lesser extent.



**Figure 7.** Water Quality Index spatial distribution map and pie chart of class proportions in the study area.



**Figure 8.** Spatial distribution of (a) Sodium Adsorption Ratio (*SAR*), (b) Sodium percentage (*Na*%), (c) Magnesium Hazard (*MH*) and (d) Residual Sodium Carbonate (*RSC*).

# **5. Summary and Conclusions**

This study employed multivariate statistical analysis, spatial modelling, and water quality index-based GIS to examine the hydrochemistry and ascertain the water suitability of Senegal's deep Maastrichtian aquifer for human consumption and irrigation. Overall, 232 sampling locations were considered and various hydrogeochemical parameters were analyzed from 2013 to 2019.

Results revealed a specific hydrochemistry pattern where sodium, chloride and fluoride are highly correlated with electrical conductivity (EC) reflecting the significant contribution of these elements to the acquisition of groundwater mineralization. The correlation matrix of parameters and also Na/Cl and HCO<sub>3</sub>/Cl ratios revealed various mineralization processes.

The Principal Component Analysis (PCA) evidenced three components:

- PC 1 strongly loaded by Na<sup>+</sup>, K<sup>+</sup>, EC and Cl<sup>-</sup>, and by F<sup>-</sup> and HCO<sub>3</sub><sup>-</sup> to a lesser extent, contributing to salinization processes controlled by water/rock interaction, seawater intrusion and cation exchange reactions;
- PC 2 loaded by Ca<sup>2+</sup> and Mg<sup>2+</sup> originated from dolomite dissolution;
- PC 3 which accounted for  $NO_3^-$  and  $SO_4^{2-}$  derived from localized mixing

with upper aquifers and gypsum dissolution.

Hierarchical Clustering Analysis (HCA) coupled with Piper and Schoeller diagrams distinguished four clusters:

- C1 (148 samples) characterized by freshwater with mean values of all ions below WHO standards and a mixed-HCO<sub>3</sub> water type;
- C2 (2 samples) depicted by Na-Cl (saline) water type with high mineralization and ionic contents well above WHO standards except for HCO<sub>3</sub><sup>-</sup> (203.3 mg·l<sup>-1</sup>) and F<sup>-</sup> (0.6 mg·l<sup>-1</sup>);
- C3 (17 samples) with brackish water type (Na-Cl) and lower EC values relative to C2 but higher HCO<sub>3</sub><sup>-</sup>, F<sup>-</sup> and NO<sub>3</sub><sup>-</sup> contents;
- C4 (46) characterized by brackish water type (Na-mixed) with lower mineralization contents than C2 and C3.

The spatial variation of groundwater parameters on one hand indicated high mineralization within a central brackish band with TDS values ranging from brackish to saline and ions contents well above WHO standards. On the other hand, the groundwater is fresh in the East and West parts of the country. Based on GWQI, poor to extremely poor water represented about 26%, unfit water for drinking corresponds to 20% of the total area, while good and excellent water represent 20% and 25%, respectively. Thus, the Maastrichtian aquifer means more than 55% of high-water quality for drinking purposes in Senegal. Relative to irrigation, the groundwater, in general, is suitable except in the brackish band and its vicinity, where unsuitable waters are observed according to *SAR*, *MH*, *Na%* and *RSC* values.

The approach used in this study was valuable for assessing groundwater quality for drinking and irrigation usages and can be used for regional studies in other sites, especially for shallow and vulnerable aquifers.

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# **Conflicts of Interest**

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

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