

Hydrochemical Characterization of the Continental Terminal Aquifer in Cap Skirring Area, Southwestern Senegal

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Abstract: Cap Skirring area is located in the southwestern part of Senegal, where groundwater is the only resource for drinking water supply. The present study helps to assess and determine the most dominant hydrogeochemical processes controlling the groundwater quality in the Cap Skirring area in Southwestern Senegal. For these purposes, 23 groundwater samples have been collected and analyzed for pH, Ca^{2+} , Mg^{2+} , Na^+ , K^+ , SO_4^{2-} , Cl^- , HCO_3^- and NO_3^- concentrations and the indices total hardness (TH) as well as total dissolved solid (TDS) were calculated based on the analytical results. The analysis indicated that the groundwater in the study area is generally soft. Comparison of these chemical data with the WHO drinking water standards showed that WHO standards were exceeded mainly in wells D30 (Ca^{2+} , HCO_3^-) and PD122 (Cl^- , NO_3^- , Na^+ and K^+), both located in the eastern part of the area. The Piper, Shadha, and other bivariate diagrams presenting the geochemical facies of the groundwater showed the HCO_3^- – Ca – Mg as the dominant water type (65.2 %) followed by the Cl – Na – K water type (21.7 %), and the Cl – Ca – Mg water type (13.0 %). This hydrogeochemical characterization indicates that the groundwater is mainly recharged by the high seasonal rainfall that occurs in the area. Salinization conditions and reverse ion exchange reactions were also observed in the some groundwater samples. This salinization process was mainly found along the eastern part (“belong”) of the study area in samples taken at PD 122, PD 144, PD 55, and Marie Diatta or near the Atlantic coast (PD 154).

Keywords: Major Ions, Hydrochemical Characterization, Cap Skirring Area, Southwestern of Senegal

1. Introduction

Coastal zones located between marine and continental domains are generally characterized by large biodiversity of the ecosystems but also face strong impacts of human activities. It is estimated that nearly 70 % of the world's population lives in coastal areas [1, 2] and fresh groundwater is a very important resource for the future development of the coastal regions. In the past decade, these groundwater's are susceptible to salinization due to overexploitation and sea level rising, both having a significant impact on the water resources and more particularly on water quality [3-7]. Therefore, climate change and sea level rising are the main concerns for most coastal areas. However, the local geological

contexts and specifications of the different aquifer systems (porous, fissured, karstic, unconfined or confined) in coastal area are greatly related to precarious equilibrium between fresh- and saltwater.

Semi-arid countries, like Senegal, draw most of the water demand for populations and livestock, but also for the tourist and agricultural sector from the groundwater. This situation is mainly linked to surface water scarcity, its vulnerability to pollution, and the non-sustainability of this resource, but also to climate change, which affects the quality and quantity of available surface water resources [8, 9]. Additionally, coastal areas have experienced major economic growth in recent years, associated with a strong increase in population. On the other hand, groundwater pumping in these areas is often problematic,

as excessive groundwater extraction, accompanied by a significant decrease in recharge, can induce saltwater intrusion. Recently, observation by the populations of the Diembering municipality located in the study area of Cap Skirring, reported an increase in the exploitation of water resources especially by hotels and industry, which has aroused concerns at the local level. In addition, one of the largest bottled water producers, SODECA ("Société d'embouteillage de la Casamance"), exploits the Continental Terminal (CT) aquifer in this area for human consumption. Faced with this problematic, the Directorate of Management and Planning of Water Resources of Senegal has started a study aiming to understand the groundwater pumping and climate change impacts on the CT aquifer in the Cap Skirring area. In this context piezometric and hydrochemistry measurements have been performed to better understand the behavior of the aquifer under current conditions. Therefore, the aim of this study is to determine the suitability of the groundwater for human consumption and to identify processes responsible for the mineralization of Cap Skirring coastal aquifer. For this purpose, hydrochemical data sampled from the wells in the study area were compared to WHO drinking water standard and correlation between chemical ion were also performed since those correlations can be used as indicators for the interaction between the ground- and seawater in the coastal aquifers.

2. Materials and Methods

2.1. Study Area

The Cap Skirring area is located in the southwestern part of Senegal between 16° 41' 20" to 16° 48' 08" W and 12° 20' 03" to 12° 28' 44" N and is administratively situated in the Ziguinchor region, in the Oussouye department, and in the rural municipality of Diembering. It is a coastal strip of width varying between 4.5 km on either side of Boucotte to less than 600 m at the height of the tip of Cap Skirring at the level of the isthmus. It has a stretched shape in the NW-SE direction and covers approximately 50 km², which is 22 % of the total area of Diembering municipality (Figure 1). The study area is bound to the north by the Nikine-Diembering dune system, to the south by the Bissau-Guinean border, to the east by the salty marshy areas called "bolongs", and to the west by the Atlantic Ocean (Figure 1).

Casamance region, particularly the Cap Skirring area, is characterized by a Sudano-Guinean climate with a dry season between November to May and a rainy season from June to October. Climatic data collected from the Senegal National Civil Aviation and Meteorological Agency (ANACIM) show that annual rainfall varies strongly between the years (826.5 mm in 2003 and 1803 mm in 1989) with a long-term annual mean of 1218 mm (1979–2019). Maximum air temperature is on average 31°C (1979–2019) and occurs from March to October corresponding to the beginning and the end of the rainy season. Minimum air temperature is observed from January to February (21.4°C). Potential evapotranspiration is in general negatively correlated to precipitation.

Geologically, the Senegalese territory, with the exception of its eastern part, belongs to the sedimentary domain, which is part of the Senegalese-Mauritanian sedimentary basin. This latter is the most western and largest (340,000 km²) meso-cenozoic basin of the African Atlantic margin [10]. Its formation started with the opening of the Atlantic Ocean in the Lower Jurassic and its evolution followed the expansion of this ocean. With a length of 1400 km, the Senegalese-Mauritanian basin is limited to the north by Mauritania Republic, to the south by Guinea Bissau Republic, to the east by the Hercynian chain of the Mauritians and the Taoudeni basin and is largely open to the Atlantic Ocean to the west.

The basin has a low and sandy coast, which leads to four estuaries which are from north to south: the estuaries of Senegal, Sine Saloum, Gambia, and Casamance [11]. It consists of an essentially marine sedimentary formation ranging from the Trias-Lias to the Quaternary period. The geological description of the study area is based on the studies published by Sarr, S. [10], Ngom, F. D. [11], Tessier, F. [12] and Bellion, Y. J. C. [13] carried out in the Senegalo-Mauritanian basin. According to these studies, the Cap Skirring area belongs to the Casamance sedimentary basin, which constitutes the most southern part of the Senegalese sedimentary gulf. In this basin, oil and hydraulic drilling boreholes showed, that the Cretaceous is characterized by marine deposits with fossiliferous levels. Gorodiski, A. [14] reported that these deposits are overlain by marine formations ranging from the Tertiary to the Middle of Miocene at Ziguinchor region. This latter formation is capped by the Continental Terminal formations made up of sandstone or clay, all azoic. These formations contain the superficial aquifer that is subject of this study.

Various hydrogeological, hydrodynamic, and geophysical studies carried out in the Senegalese sedimentary basin [15-20] revealed four aquifer systems with different characteristics: the superficial or "terminal complex" aquifer system, the intermediate or semi-deep aquifer system, and the deep aquifer system.

The superficial aquifer system or "complex terminal" includes predominantly sandy-clayey and sandy formations formed during the Quaternary, the Continental Terminal and the Oligo-Miocene age. This "complex terminal" contains throughout the Senegalese territory the Continental Terminal and the alluvial sandy aquifers of the Senegal River in the north, the northwestern coast aquifer from Saint-Louis to Dakar, the infrabasaltic aquifer in Dakar area, and the sweet water lenses from the Saloum Islands. The top aquifer in Cap Skirring area belongs to the Continental Terminal age, which is currently the only aquifer exploit in this area for drinking water due to its good water quality and shallow depth.

The intermediate or semi-deep aquifer system is characterized by karstic limestone formations and marly-limestone from the Eocene and Paleocene age. In the Casamance region, the semi-deep aquifer is characterized by sandy clayey material of post-Lutetian age (Upper Eocene to Pliocene). These formations were deposited in huge dug

basins in the marly-limestones of the Middle and Lower Eocene. Therefore, this system is a multi-layered aquifer made up of fine, medium or coarse sandy or clayey deposits alternating with clay lenses. Its thickness varies between 130 m on Average Casamance and 200 m in the Lower Casamance. In Cap Skirring area, this aquifer is not exploited due to its very high salinization.

The deep aquifer system contains exclusively the sandy to sandy-clayey formation of the Maastrichtian. It is a vast reservoir (estimated between 300 and 500 km³) which extends almost over the entire Senegalese basin. In Casamance, the top limit of this aquifer plunges towards the southwest and takes the form of a basin whose bottom is located in Lower

Casamance between -500 and -600 m IGN elevations [16-18]. In the Kolda region (Upper Casamance), it occurs between -140 and -200 m. The thickness of this aquifer decreases from west to east and vary between 25 m at Dabo in Upper Casamance and 95 m at Kartiak in Lower Casamance. In a hydrodynamic point of view, water quality of these aquifer decreases from upstream to downstream due to the increase in the fine particles towards the west. Transmissivity values ranged between 1×10^{-2} and $3 \times 10^{-2} \text{ m}^2 \text{ s}^{-1}$ in upstream location [15]. In the middle and lower Casamance, it is less than $1 \times 10^{-2} \text{ m}^2 \text{ s}^{-1}$ and its average storage coefficient value is equal to 2.5×10^{-4} . In the study area, the Maastrichtian aquifer is not exploited due to its high mineralization.

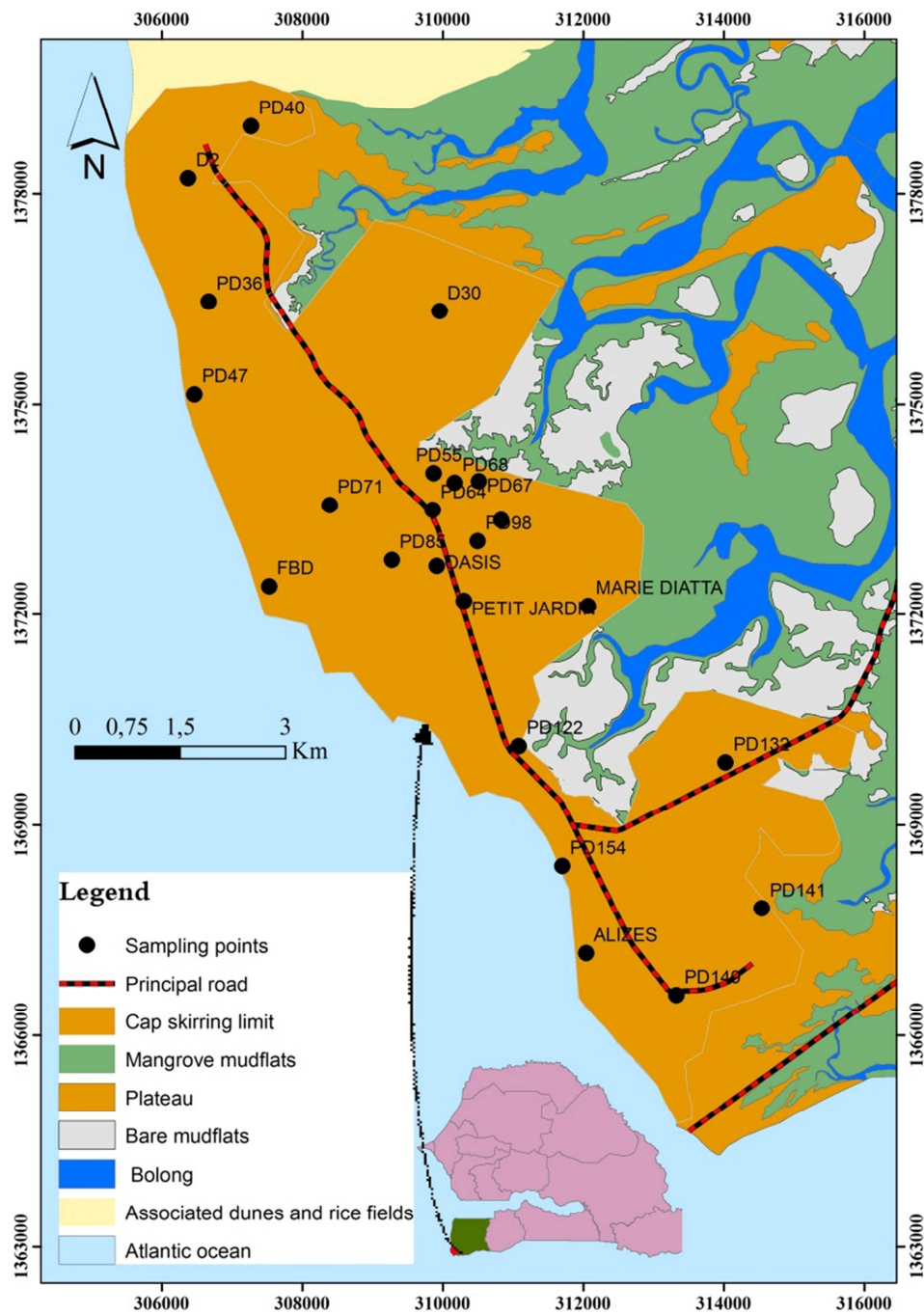


Figure 1. Localization of the study area and the 23 groundwater sampling points.

2.2. Sample Collection and Laboratory Analysis

In order to characterize the chemistry of the groundwater system, sampling was carried out in January 2020 in 23 boreholes used for drinking or agricultural water supply (Figure 1). A GPS system was used to locate the exact coordinates of the sample collections. At each sampling point, two water samples were collected in 250 ml polyethylene bottles and kept cool at 4 °C. Subsamples for cation analyzes were acidified to pH-values below 2 by adding HNO₃ and the non-acidified samples were used for anion analyzes. Water samples were analyzed at the chemistry laboratory of the Geology Department of the Cheikh Anta Diop University of Dakar (UCAD). Major anions (Cl⁻, SO₄²⁻, HCO₃⁻, and NO₃⁻) and cations (Ca²⁺, Mg²⁺, Na⁺, and K⁺) were determined by ion chromatography using the Dionex DX120 chromatograph (ThermoFischer Scientific). Physicochemical parameters such as pH-value, temperature, total dissolved solid and electrical conductivity were determined in situ with a multi-parameter probe (WTC multi 3430 Set G).

For the interpretation of the hydrochemical characteristics of the sampled water, different indices were used.

Total dissolved solutes (TDS) who represents the water salinity [21, 22] was calculated using Water Software Quality Hydrochemistry diagrams.

Total hardness (TH) is defined by the hydrotimetric title, which corresponds to the presence of calcium and magnesium ions. Water hardness associated with its acidity defines its aggressiveness: soft water associated with an acid pH is thereby aggressive water [23]. Total hardness (TH) was calculated from the values of the Ca²⁺ and Mg²⁺ ion concentration in the groundwater samples according to Todd, k. [24].

$$TH = 2.497 \times Ca^{2+} + 4.115 \times Mg^{2+} \quad (1)$$

where Ca²⁺ and Mg²⁺ were expressed in mg L⁻¹. TH values for water can be distinguished into four classes according to Sawyer, et al. [25]. TH values less than 75 feature class I

characterized by soft water, class II shows TH values between 75 and 150 and is characterized by moderately hard water, hard water have TH values between 150 and 300 (class III). Very hard water (class IV) exceeds TH values of 300.

In addition, to determine the suitability of water for human consumption, the average values of the physicochemical parameters (pH, EC, TH, and TDS) and the major and trace ions of the water sampled were compared to the WHO. [26] drinking water standards. In this study, the major ions Ca²⁺, Mg²⁺, Na⁺, K⁺, SO₄²⁻, Cl⁻, HCO₃⁻, NO₃⁻ were assessed to analyze the Continental Terminal groundwater quality. On the other hand, some important relationship such as Na⁺ versus Cl⁻ and (Ca²⁺ and Mg²⁺)-(Na⁺ and K⁺) versus HCO₃⁻ (SO₄²⁻ and Cl⁻) were explored, since those could be used as indicators for an interaction between the ground- and seawater in the coastal aquifers [26-29].

3. Results and Discussions

3.1. Drinking Water Quality

The pH values of the groundwater system vary between 4.02 and 7.91 with a median of 7.24. Data analysis showed that 13.0 % of the water samples had acid pH values between 5 to 6.5, 82.6 % had a pH value that meets the WHO standards (6.5 – 8.5) and 4.4 % had a highly acidic pH value between 4 to 5. The electrical conductivity (EC) is a parameter expressing the mineralization of water and high water EC values refer to significant mineralization. The measured EC values of the Cap Skirring CT aquifer vary between a minimum of 108 and a maximum of 1538 µS cm⁻¹ with a median of 338 µS cm⁻¹. This EC values show, that the groundwater samples are slightly mineralized. Nevertheless, a value of 1538 µS cm⁻¹ is observed in well PD122, which slightly exceeds the WHO standard. Saxena, et al. [30] and Mondal, et al. [31] classified water on the basis of EC into three categories: freshwater (<1500 µS cm⁻¹), brackish water (1500 – 3000 µS cm⁻¹), and saline water (>3000 µS cm⁻¹).

Table 1. Summary statistics of the Continental Terminal aquifer groundwater quality parameters sampled in January 2020.

Variables	Unit	Mean	Median	Minimum	Maximum	Ecart-type	WHO international standards (2017)	% of wells above WHO limit
pH	-	6.98	7.24	4.02	7.91	0.82	6.5 – 8.5	
CE	µS cm ⁻¹	450.78	338.00	108.00	1538.00	327.90	1500	4.3
TH	mg L ⁻¹	136.41	109.91	47.95	379.79	83.32	500	0
TDS	mg L ⁻¹	321.00	239.00	78.00	1040.00	222.79	1500	0
HCO ₃ ⁻	mg L ⁻¹	128.50	122.00	0.00	402.60	94.65	250	8.7
Cl ⁻	mg L ⁻¹	62.89	32.43	14.42	252.26	65.22	250	4.3
SO ₄ ²⁻	mg L ⁻¹	9.88	5.72	1.83	46.07	10.69	250	0
NO ₃ ⁻	mg L ⁻¹	28.88	1.55	0.44	447.02	93.40	50	8.7
Ca ²⁺	mg L ⁻¹	44.06	34.96	15.89	111.23	25.70	100	4.3
Mg ²⁺	mg L ⁻¹	6.41	4.23	2.01	32.01	6.83	50	0
Na ⁺	mg L ⁻¹	36.58	21.89	2.44	190.87	45.24	150	4.3
K ⁺	mg L ⁻¹	3.38	2.12	0.63	14.07	3.37	12	4.3
F ⁻	mg L ⁻¹	0.22	0.21	0.08	0.36	0.08	1.5	0
Fe	mg L ⁻¹	0.22	0.13	0.03	1.31	0.28	-	-

Based on this classification, nearly all water samples (95.7 %) fall within the fresh water class, except the sample

from well PD122 with the extreme EC value of 1538 µS cm⁻¹, which is classified as being brackish water. Total Dissolved

Solid values observed are lower than the WHO drinking water standards and vary between a minimum of 78 and a maximum of 1040 mg L⁻¹ with a median of 239 mg L⁻¹. Total Hardness (TH) values in water sampled vary between a minimum of 48 and a maximum of 330 mg L⁻¹ with a median of 110 mg L⁻¹ (Table 1). These values are all below the WHO standards for TH, which is set to 500 mg L⁻¹. Classification according to TH values shows that soft, moderately hard, and hard waters were represented by 13, 60.9 and 26.1 % of the groundwater samples, respectively.

3.2. Major Ion Chemistry and Chemical Processes

The chemical data analysis on the Continental Terminal aquifer showed that the concentration of the chemical elements analyzed are generally lower than the WHO drinking water standards at most of the sampled points. The Cl⁻ values range between a minimum of 14.4 and a maximum of 252.3 mg L⁻¹ with an average of 62.9 mg L⁻¹ (median = 32.4 mg L⁻¹). Only 4.3 % of the sampled waters exceed the WHO threshold for drinking water set to 250 mg L⁻¹ (PD 122). HCO₃⁻ concentrations vary between 0.0 and 402.6 mg L⁻¹ with an average value of 128.5 mg L⁻¹ (median = 122.0 mg L⁻¹),

whereby slightly more (8.7 %) of all water sampled exceeded the WHO threshold (D 30; PD 47). The Ca²⁺ concentrations were between 15.9 and 111.23 mg L⁻¹ (mean = 44.1 and median = 35.0 mg L⁻¹) and the Na⁺ concentration ranged from 2.4 to 190.9 mg L⁻¹ (mean = 36.6 and median = 21.9 mg L⁻¹), whereby for both elements 4.3 % of the samples were above the WHO limits. All other element concentrations and percentage of samples exceeding the WHO thresholds for drinking water can be looked up in Table 1, whereby in general less than 9 % of all samples exceeded the drinking water limits.

The concentrations of other ions exceeded the WHO drinking water standards such as for HCO₃⁻ in well D30 and PD47, Cl⁻ in well PD122, NO₃⁻ in PD122 and Alizes, Ca²⁺ in well D30 as well as Na⁺ and K⁺ in well PD122. Chemical data (expressed in meq L⁻¹) of the groundwater sampled in the Cap Skirring aquifer indicate a general order of magnitude as follows: HCO₃⁻ > Cl⁻ > SO₄²⁻ > NO₃⁻ for the anions and Ca²⁺ > Na⁺ > Mg²⁺ > K⁺ for the cations.

To explore potential correlation between the measured element concentrations or derived indices such as TH or TDS the Pearson correlation coefficient (*r*) was calculated and the results are listed in Table 2.

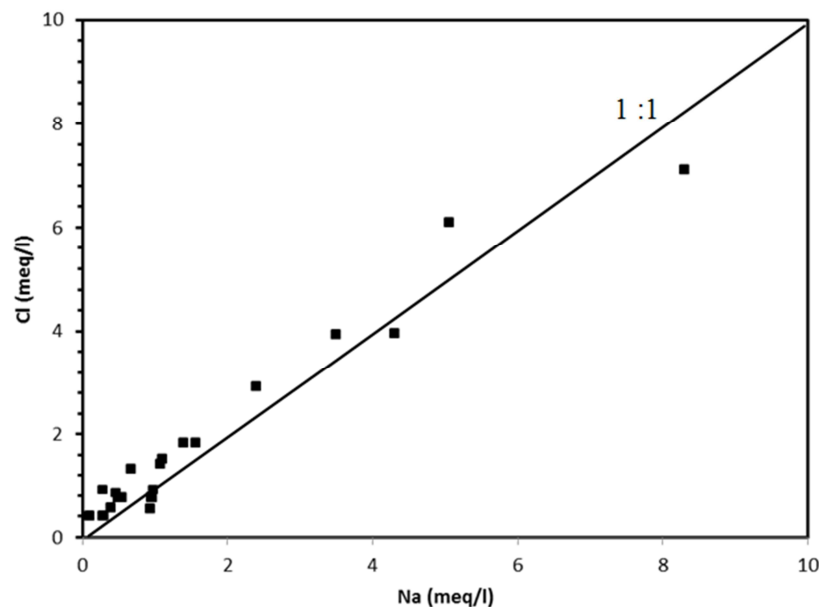


Figure 2. Relationship between Na⁺ and Cl⁻ of the Continental Terminal groundwater samples.

Table 2. Correlation matrix of hydrochemical parameters of Continental Terminal groundwater samples with Pearson correlation coefficient *r*. High correlation (*r* > 0.7) are highlighted in bold. All elements are expressed in mg L⁻¹, except EC in (μs cm⁻¹) and pH (-).

	TDS	pH	EC	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻
TDS	1										
pH	-0.35	1									
EC	0.99	-0.42	1								
Ca ²⁺	0.79	0.11	0.71	1							
Mg ²⁺	0.70	-0.07	0.68	0.56	1						
Na ⁺	0.84	-0.65	0.89	0.35	0.42	1					
K ⁺	0.82	-0.63	0.88	0.32	0.44	0.99	1				
HCO ₃ ⁻	0.30	0.69	0.20	0.74	0.45	-0.22	-0.22	1			
Cl ⁻	0.79	-0.61	0.86	0.33	0.41	0.97	0.98	-0.20	1		
SO ₄ ²⁻	0.56	-0.12	0.53	0.50	0.76	0.30	0.30	0.36	0.23	1	
NO ₃ ⁻	0.76	-0.79	0.79	0.34	0.39	0.85	0.81	-0.32	0.75	0.35	1

As can be seen, the Total Dissolved Solid correlates well with Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , and NO_3^- with correlation coefficients exceeding 0.70 in all cases. On the other hand, there is only a weak correlation with SO_4^{2-} ($r = 0.56$) and HCO_3^- ($r = 0.30$). This weak correlation indicates that bicarbonate and iron are not involved in the mineralization process of the CT groundwater. The strong correlations with the other elements provide strong evidence that these main elements are involved in the mineralization of the groundwater samples. In coastal area, Na^+ and Cl^- are often highly positively correlated and representing the dominant ions in the majority of coastal groundwater samples indicating the increased mixing effect of seawater into the groundwater [32]. In the groundwater samples of the studied aquifer, very strong correlations between the ions concentrations of Na^+ vs Cl^- ($r = 0.97$) was found (Figure 2), pointing to the fact that both ions have the same origin either caused by seawater intrusion or dissolution of halite.

In general, the dominant cations and anions in fresh groundwater are Ca^{2+} and HCO_3^- or SO_4^{2-} . However, in groundwater samples affected by seawater intrusion the order of magnitude of cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) and anions (Cl^- , SO_4^{2-} , HCO_3^-) will change [33, 34]. In these coastal aquifers, salinity is considered as the most contamination form and major ion ratios were sometime used to identify the origin of salinity [28, 35].

The Chadha's plot (Figure 3) shows that majority of groundwater samples (65.3 %) fall in the recharge water zone (Ca-HCO_3 water type) indicating fresh groundwater. The rest of the water samples are located in the zones of seawater (21.7 %) (Na-Cl water type) and reverse ion exchange water (13 %) (Ca/Mg-Cl water type), respectively.

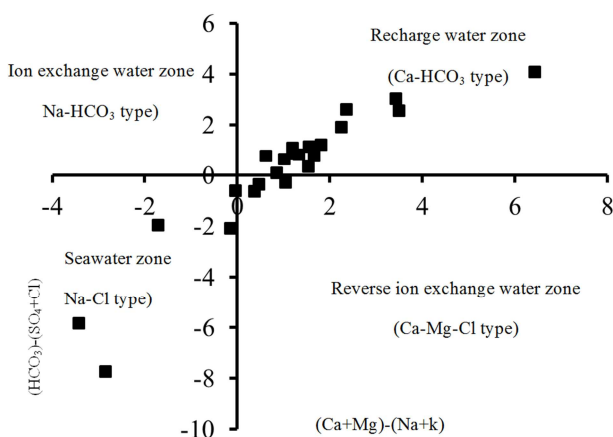


Figure 3. Chadha diagram of Continental Terminal groundwater samples.

The hydrogeochemical characteristics of the CT groundwater samples based on Chadha's diagram [36] show significant groundwater recharge due to the high seasonal rainfall but also saline groundwater conditions in some boreholes located mainly along the “bolong” (eastern limit) (PD 122, PD 144, PD 55, and pumping well Marie Diatta) or the Atlantic ocean (PD 154), which can be attributed to saltwater intrusion and the reverse ion exchange reactions into

the aquifer. Saltwater impact from the “bolong” can be due by the high concentration of this saline surface water, whereby concentrations measured in October 2021 showed 11,465 and 4,959 mg L^{-1} for Cl^- and Na^+ , respectively. Chemical ion values plotted in the Piper trilinear diagram [37] identified the same water type with the dominance of $\text{HCO}_3-\text{Ca}-\text{Mg}$ water type (65.2 %) followed by the $\text{Cl}-\text{Na}-\text{K}$ water type (21.7 %) and the $\text{Cl}-\text{Ca}-\text{Mg}$ water type (13.0 %) (Figure 4).

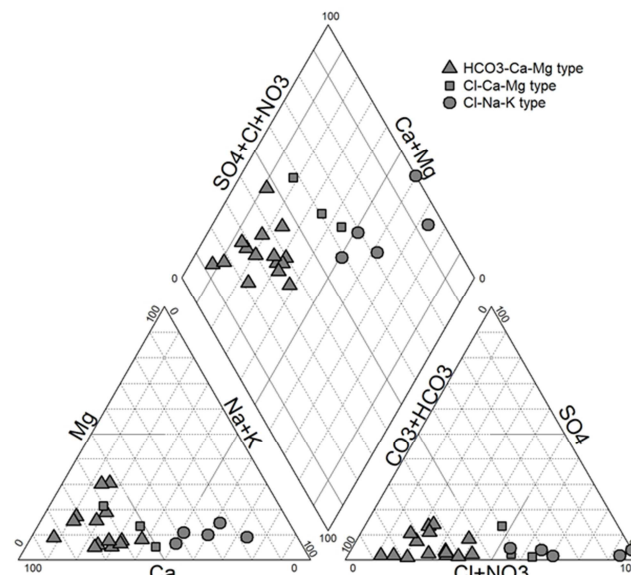


Figure 4. Piper diagram of the groundwater sampled from the Continental Terminal aquifer.

4. Summary and Conclusion

The characterization of the Continental Terminal aquifer in the Cap Skirring area according to the hydrochemical analysis showed, that most of the water sampled in this area has ion concentration, EC and pH values below the WHO drinking water standards. Overall, for all ions analyzed less than 9 % of the samples exceeded those limits (2 boreholes), meaning that the aquifer water is in general suitable for drinking purpose. A detailed analysis showed, that the WHO standards were exceeded in wells D30 for Ca^{2+} and HCO_3^- , PD47 for HCO_3^- , PD122 for Cl^- , Na^+ and K^+ , and PD 122 and Alizes for NO_3^- . The chemical analysis results as well the assessment of water quality revealed that the abundance of the major ions is in the following order: $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{NO}_3^-$ for the anions and $\text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+$ for the cations reflecting $\text{HCO}_3-\text{Ca}-\text{Mg}$ water type. The Piper and Chadha diagrams show mainly $\text{HCO}_3-\text{Ca}-\text{Mg}$ water type (65.2%) followed by the $\text{Cl}-\text{Na}-\text{K}$ water type (21.7%) and by the $\text{Cl}-\text{Ca}-\text{Mg}$ water type (13.0%). Hydrogeochemical characterization shows that significant recharge due to the high seasonal rainfall, salinization conditions and reverse ion exchange reactions occur in the groundwater aquifer. The protection of the continental terminal aquifer in order to ensure the drinking water supply to Cap Skirring region requires maximum control of pumping to avoid overexploitation as this aquifer is

only the one exploited in this area for water supply.

Consent for Publication

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

- [1] Bear, J., Alexander H. D. C., Shaul S., et al. (1999). Seawater intrusion in coastal aquifers: concepts, methods and practices, 1st ed. Boston: Kluwer Academic.
- [2] De Montety, V., Radakovitch, O., Vallet-Coulomb, C., Blavoux, B., Hermitte, D., Valles, V. (2008). Origin of groundwater salinity and hydrogeochemical processes in a confined coastal aquifer: case of the Rhône delta. *Applied Geochemistry* 23 (8): 2337-2349. <https://doi.org/10.1016/j.apgeochem.2008.03.011>.
- [3] Isa, N. M., Aris, A. Z., & Sulaiman, W. N. A. W. (2012). Extent and severity of groundwater contamination based on hydrochemistry mechanism of sandy tropical coastal aquifer, *Science of the Total Environment*, vol. 438, pp. 414–425.
- [4] Werner, A.; Bakker, M.; Post V. E. A.; Vandenbohede, A.; Lu, C.; Ataie-Ashtiani, B.; Simmons, C. T.; Barry, D. A. (2013). Seawater intrusion processes, investigation and management: recent advances and future challenges. *Advances in Water Resources* 51: 3–26.
- [5] de Caritat, P.; Bastrakov, E. N.; Jaireth, S.; English, P. M.; Clarke, J. D. A.; Mernagh, T. P.; Wygralak, A. S.; Dulfer, H. E.; Trafford, J. (2019). Groundwater geochemistry, hydrogeology and potash mineral potential of the Lake Woods region, Northern Territory, Australia. *Australian Journal of Earth Sciences* 66 (3): 411–430.
- [6] Rajendiran, T.; Sabarathinam, C.; Chandrasekar, T.; Keesari, T.; Senapathi, V.; Sivaraman, P.; Viswanathan, P. M.; Ganesh Nagappan, G. (2019). Influence of variations in rainfall pattern on the hydrogeochemistry of coastal groundwater - an outcome of periodic observation. *Environmental Science and Pollution Research*, <https://doi.org/10.1007/s11356-019-05962-w>
- [7] Adimalla, N., Li, P. (2019). Occurrence, health risks, and geochemical mechanisms of fluoride and nitrate in groundwater of the rock-dominant semi-arid region, Telangana State, India. *Human and Ecological Risk Assessment* 25 (1–2), 81–103. <https://doi.org/10.1080/10807039.2018.1480353>.
- [8] Eissa, M.; De-Dreuzy, J.; Parker, B. (2018). Integrative management of saltwater intrusion in poorly-constrained semiarid coastal aquifer at Ras El-Hekma, Northwestern Coast, Egypt. *Groundwater for Sustainable Development*, Volume 6, pp 57-70. <https://doi.org/10.1016/j.gsd.2017.10.002>.
- [9] Batarseh, M.; Imreizeeq, E.; Tilev, S.; Al Alaween, M.; Suleiman, W.; Al Remeithi, A. M.; Al Tamimi, M. K.; Al Alawneh, M. (2021). Assessment of groundwater quality for irrigation in the arid regions using irrigation water quality index (IWQI) and GIS-Zoning maps: Case study from Abu Dhabi Emirate, UAE. *Groundw. Sustain. Dev.* 2021, 14, 100611. <https://doi.org/10.1016/j.gsd.2021.100611>.
- [10] Sarr, R. (1995). Biostratigraphic and paleoenvironmental study of the Terminal Cretaceous to Middle Eocene series of Western Senegal. Systematics and migration of ostracods. Doctorate Thesis in Sciences, Cheikh Anta Diop University of Dakar, 335 p+ annexes.
- [11] Ngom, F. D. (2000). Characterization of water transfers in the Nema basin in Sine Saloum. Doctorate Thesis, Cheikh Anta Diop University of Dakar, 130p.
- [12] Tessier, F. (1952). Contribution to the stratigraphy and palaeontology of western Senegal (Cretaceous and Tertiary). *Newsletter of the AOF Mining Directorate* 14, 1-267.
- [13] Bellion, Y. J. C. (1987). Post-Paleozoic geodynamic history of West Africa from the study of some sedimentary basins (Senegal, Taoudenni, Iullemmeden, Chad). PhD thesis, University of Avignon (Paris, France).
- [14] Gorodiski, A. (1958). Miocene and phosphate index of Casamance. *C. R. Sem. Geol. Fr.* of 3 Nov. 1958.
- [15] Debuissou J., Gagnire G. (1969). Campaign of 133 wells 1967/68. Casamance and Eastern Senegal Region. *B. R. G. M.* 69 DAK5.
- [16] Kruger A. S. (1980). Hydrogeological study of the Casamance 1979/1980. General Report. General Division and Rural Equipment of Dakar. Vol. 1 - 124 p. 33 fig. 17 tabl. 3 maps h. t.
- [17] Le Priol J. (1983). Hydrogeological synthesis of the Casamance sedimentary basin. 3 vols. DEH Dakar.
- [18] Sustract G. (1984). Mineral Plan of the Republic of Senegal. BRGM. 3 vols. 725 P; 50 maps.
- [19] Bellion, Y. J. C. et Guiraud, R. (1984). The Senegal sedimentary basin. Synthesis of current knowledge in Mineral Plan of the Republic of Senegal, B. R. G. M. and D. M. G., Dakar ed. vol. 1 p. 4-63.
- [20] Roger, J., Barusseau, J. P., Castaigne, P., Duvail, C., Noël, B. J., Nehlig, P., Serrano, O., Banton, O., Comte, J. C., Travi, Y., Sarr, R., Dabo, B., Diagne, E., Sagna, R. (2009). Explanatory note for the 1/200 000 geological maps of the Senegalese sedimentary basin. Mining sector support program, sedimentary basin mapping project, Department of mining and geology.
- [21] Li, P. Feng, W., Xue, C. T., Tian, R., Wang, S. (2017). Spatiotemporal variability of contaminants in lake water and their risks to human health: a case study of the Shahu Lake tourist area, Northwest China. *Expo Health* 9 (3): 213–225. <https://doi.org/10.1007/s12403-016-0237-3>
- [22] Wu, J., Zhou, H., He, S., Zhang, Y. 2019. Comprehensive understanding of groundwater quality for domestic and agricultural purposes in terms of health risks in a coal mine area of the Ordos basin, north of the Chinese Loess Plateau. *Environ Earth Sci* 78: 446. <https://doi.org/10.1007/s12665-019-8471-1>
- [23] Miquel, G. (2022). La qualité de l'eau et assainissement en France 74 p + annexes; rapport l'OPECST n° 2152.
- [24] Todd, K. (1980). Ground water hydrology, 2nd edn. John Wiley & Sons, New York.
- [25] Sawyer, G. McCarthy, L. (1967). Chemistry of sanitary engineers, 2nd ed. McGraw Hill, New York, p-518.

- [26] WHO. (2017). Guidelines for drinking-water quality: Fourth edition Incorporating the First addendum. World Health Organization, Geneva, Switzerland, 541 p.
- [27] Fadili, A., Mehdi, K., Riss, J., Najib, S., Makan, A., Boutayab, K. (2015). Evaluation of groundwater mineralization processes and seawater intrusion extension in the coastal aquifer of Oualidia, Morocco: hydrochemical and geophysical approach. *Arabian Journal of Geosciences*: DOI 10.1007/s12517-015-1808-5.
- [28] Abdalla, F. (2016). Ionic ratios as tracers to assess seawater intrusion and to identify salinity sources in Jazan coastal aquifer, Saudi Arabia. *Arabian Journal of Geosciences* 9: 40; DOI 10.1007/s12517-015-2065-3.
- [29] Sunkari, E. D.; Abu, M.; Bayowobie, P. S; Dokuz, E. U. (2019). Hydrogeochemical appraisal of groundwater quality in the Ga west municipality, Ghana: Implication for domestic and irrigation purposes. *Groundwater for Sustainable Development* 8 pp 501–511. <https://doi.org/10.1016/j.gsd.2019.02.002>.
- [30] Saxena, V. K., Mondal, N. C., Singh, V. S. (2004). Evaluation des paramètres hydrogéochimiques pour délimiter les zones d'eau douce dans les aquifères côtiers. *Journal of Applied Geochemistry* 6: 245–254.
- [31] Mondal, N. C., Singh, V. S., Rangarajan, R. (2009). Aquifer characteristics and its modeling around an industrial complex, Tuticorin, Tamil Nadu, India: a case study. *Journal of Earth System Science* 118 (3): 231–244.
- [32] Bouwer, H. (1978) *Groundwater hydrology*. McGraw-Hill, New York.
- [33] Hoyle, B. L. (1990). Ground-water quality variations in a silty alluvial soil aquifer, Oklahoma. *Ground Water* 27: 540–549.
- [34] Bouderbala, A. (2015). Groundwater salinization in semi-arid zones: an example from Nador plain (Tipaza, Algeria). *Environmental Earth Sciences* 73: 5479–5496; DOI 10.1007/s12665-014-3801-9.
- [35] ElMoujabber, M., Bou Samra, B., Darwish, T., Atallah, T. (2006). Comparison of different indicators for groundwater contamination by seawater intrusion on the Lebanese coast. *Water Resource Management* 20: 161–180.
- [36] Chadha, D. K. (1999). A proposed new diagram for geochemical classification of natural waters and interpretation of chemical data. *Hydrogeol Journal* 7, 431–439.
- [37] Piper, A. M. (1944). A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Transactions American Geophysical Union*, 25 (6); 914–928.