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Groundwater Quality for Irrigation Purposes in the Diass Horst System in Senegal

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Abstract: Due to surface water scarcity and variability in rainwater events in the Thies region, Senegal, farmers mostly rely on groundwater resources to improve yield production, although water quality in the hydrosystem and its suitability may be an issue. The objective of this study is to evaluate suitability of the Maastrichtian and Paleocene aquifers located the central western part of Senegal in the Thies region for irrigation purposes. For this purpose, chemical analyses were carried out on the major ions on the Maastrichtian and Paleocene aquifers through a network of 62 sample locations (39 from the Maastrichtian and 23 from the Paleocene) sampled in June 2019. Different water suitability assessment indices were used to evaluate the potential for irrigation, including sodium absorption ration (SAR), percentage of sodium (Na%), permeability index, Kelly ratio (RK), and salinity potential (SP) together with Wilcox and USSL diagrams as methods. The results indicate, that the Ca-Mg-HCO_3 water type is dominant in the Maastrichtian aquifer, while in the Paleocene aquifer, HCO_3-Ca-Mg and Cl-Ca-Mg are the main water types. The combination of these computed index values indicates that the percentage of suitable water for irrigation purposes accounts for 89.7% and 86.9% of the samples for the Maastrichtian and the Paleocene aquifers, respectively. On the other hand, water samples unsuitable for irrigation purposes range between only 10.3% and 13.1% for the two aquifers.

Keywords: groundwater; irrigation; water quality index; hydrogeochemistry; western Senegal

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1. Introduction

Worldwide, cultivated lands for agricultural crop production cover 1.6 billion ha, which accounts for about 12% of the global land area [1]. Fertile land is therefore a crucial natural resource for all sorts of agricultural production, including livestock farming. In Western Africa, the available agricultural land varies between 62 and 95% of the individual countries [2], where crop production through irrigation practices may reach two to four times the yield compared to rainfed agriculture yields [3,4]. In arid and semi-arid regions, where surface water occurrence is scarce and rainwater events are variable, groundwater constitutes the unique resource for drinking and socio-economic development, including agriculture [5,6]. The contribution of groundwater for irrigation purposes has increased steadily over the years from about 40% during the early 1980s to about 80% in recent years [7–10]. In the study region, irrigated agriculture using groundwater resources has increasingly developed over the past two decades by individual private farmers to agrobusiness due to arable and fertile soils. In addition to agriculture practices, the mining sector needs as well as urban and rural drinking water needs represent other pressures on the groundwater potential. As a consequence, high groundwater extraction rates occur, which may even increase in the future in this area to meet the competing domestic, agricultural, and industrial demand, leading to a continuous groundwater level decline and deterioration of the groundwater quality through salinization, e.g., by salt water intrusion [11,12].

In this paper, we focus mainly on the suitability of groundwater for agricultural irrigation, which takes into account the effects of the dissolved minerals on both soil and plants [13,14]. In fact, salt-rich irrigated waters can lead to: 1/ salt precipitation at the soil surface, causing inherent losses in crop production [15]; 2/ high salt concentrations in the top soil profile as well as physico-chemical soil characteristics which may directly interfere with crop productivity (as pore water salinity becomes too high for growing plants) [16–18]. For example, the increase in the sodium concentration in the soil pore water can lead to the dispersion of clays, causing degradation of the soil structure [19]. In addition, soil degradation changes the hydraulic characteristics of the soils, such as water and air permeability and water retention [20–23], which can lead to reduction in the root zone aeration [24] and crop productivity. In general, the soil's vulnerability with regard to salinization depends not only on the chemical quality of the irrigated water but also on the physico-chemical characteristics of the soil itself, in addition to inadequate anthropogenic drainage systems [25–30]. In the region, farmers currently use pumped groundwaters from boreholes with limited knowledge of their quality and suitability with regards to irrigated crops. Thereby, an assessment of the water quality oriented to suitability in agriculture is of prime importance to promote best agricultural yield and appropriate management strategies.

In this prospect, water quality indices are effective tools [4,13,30–33] to evaluate water quality for drinking and irrigation purpose, and they constitute key parameters for the assessment and management of groundwater reservoirs. In this present work, we estimate the suitability of groundwater for irrigation purposes by measuring, e.g., the electrical conductivity (EC), sodium adsorption ratio (SAR), salinity potential, permeability index (PI), and relative proportions of Na^+ expressed by Na% in the Maastrichtian and Paleocene aquifers in order to assess the possible risks to crops production and soil degradation through use of unsuitable water for irrigation.

2. Materials and Methods

2.1. Study Area

The Thies region is one of the fourteen administrative regions of Senegal. It is located in the western part of Senegal between 14°02′15″–15°26′09″ N and 17°08′58″–16°29′44″ W and covers an area of 6601 km^2. It is bound to the north, south, and east by the Louga, Fatick, and Diourbel–Fatick regions and to the west by the region of Dakar and the Atlantic Ocean. It has two maritime coasts, one in the north (called "Grande Cote"), where the main market gardening area of the "Niayes" area is located, and the other one in the south (call "Petite Cote"), which is one of the most touristic areas in Senegal (Figure 1).

The region is characterized by a semi-arid climate with a rainy season between 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 (234.9 mm in 2014 and 664.4 mm in 2010) with a long-term annual mean of 445.7 mm (1989–2019). Maximum air temperature is on average 35 °C (1989–2019) 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 (18.5 °C).

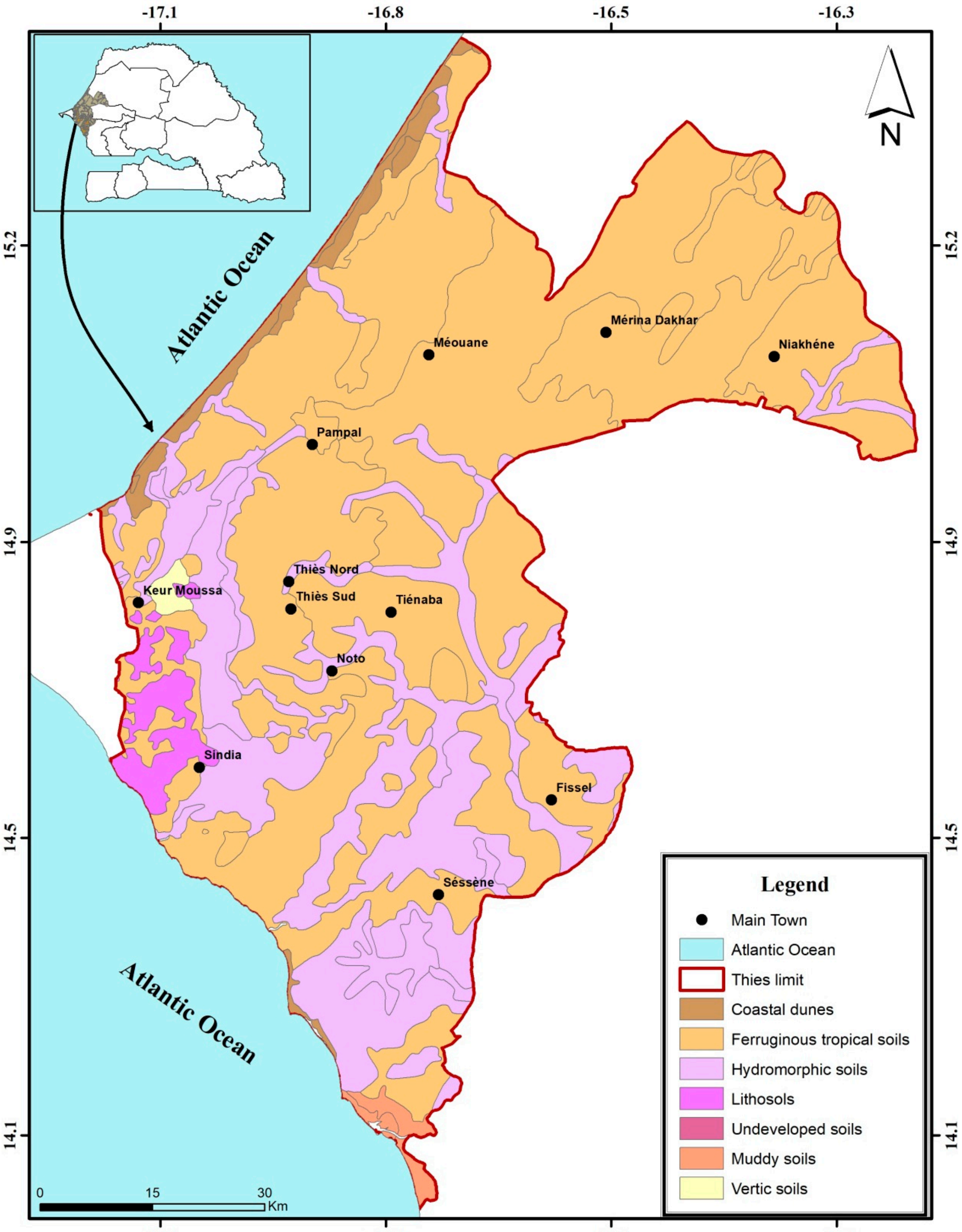


Figure 1. Localization of the study area and distribution of the different soil types [34] modified.

Geologically, the Thies region belongs to the Senegalese-Mauritanian basin, whose sedimentary formations start from the Trias–Lias to the Quaternary without interruption. The lithostratigraphic description of this region begins from the Upper Cretaceous with the Maastrichtian formations until the late Quaternary deposits. This description is essentially based on data from geological profiles, water and especially hydrocarbon exploration, and on the synthesis of published studies by [11,35–39].

The Maastrichtian formation is observed throughout the Senegalese basin and outcrops at the Diass horst under sandy and clayey facies. Composed mainly of clayey to coarse sands, the Maastrichtian aquifer is exploited by more than 1500 boreholes in most parts of the country. Its thickness increases towards the west quite rapidly from 60 m at Dendoudi in the Est, reaching 85 m at Dioumanan, 310 m at Sagata located at the center of the basin, 405 m at Mbour, and more than 2000 m at the longitude of Dakar [35]. The Paleocene is known to outcrop in the peninsula of Dakar, around the horst of Diass. It is a transgressive formation and slightly in unconformation with variable facies and is thin over the Maastrichtian in the horst zone. In the system, the sedimentation was predominantly terrigenous during the Cretaceous. However, it became through a trangressive phase during the Paleogene a chemical characteristic [36] with predominance of clay-marly and limestone facies [38,40].

The tectonics of the region is very complex, especially in the Diass featured by the William Ponty, Sebikhotane, Pout, Fouloume, and Thies faults.

From a hydrogeological point of view, the study area includes two major aquifers, namely, the Maastrichtian and Paleocene aquifers, which play an important role in the water supply of households, industries, agriculture, market gardening, and mining. Due to major faults, the hydraulic system is configured into three compartments: 1/ the Sebikotane compartment at the West between the Ponty–Kayar and Sebikotane faults featured by the Paleocene limestone aquifer; 2/ the horst compartment at the center where the Maastrichtian sandstone aquifer is outcropped; 3/ the Pout compartment at the East where the Paleocene aquifer underlies the Maastrichtian sandstone aquifer. (Figure 2) [11,35–37,39].

The soil map of the study area (Figure 1) was extracted from the soil map at 1:50,0000 compiled by [34]. The most important soil classes include ferruginous, hydromorphic, and alluvial-colluvial soils occurring in the low plains. These soils are characterized by a grey humus topsoil horizon of few centimeters thick, followed by a clay and light brown iron nodules horizon. They are composed of fine sand on the surface and sandy-clayey in deep zones.

2.2. Sample Collection and Analysis

The sampling campaign was carried out in June 2019 in a network of boreholes tapping the Maastrichtian and Paleocene aquifers. A total of 62 boreholes were sampled, with 39 boreholes in the Maastrichtian and 23 boreholes in the Paleocene (Figure 3). These boreholes are used for the drinking water supply of the Dakar region and for irrigation in the area. Electrical conductivity (EC), temperature (T°), and pH were measured in situ. Samples were collected in plastic bottles which were thoroughly rinsed three times prior sampling. The bottles were then carefully sealed, labeled, and stored at low temperature during the transport and at the laboratory before analyses. Water samples were analyzed at the chemistry laboratory of the Geology Department of the Cheikh Anta Diop University of Dakar (UCAD). Major anions (Cl^-, SO_4^{2-}, HCO_3^-, and NO_3^-) and cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) were determined by ion chromatography using the Dionex DX120 chromatograph (ThermoFischer Scientifics, Waltham, MA, USA).

2.3. Water Quality for Irrigation Purposes (Water Indices)

In this study, five indices were used to evaluate the water quality for irrigation purpose, namely the sodium absorption ratio (SAR), the salinity potential (SP), the Kelly ratio (KR), the permeability index (PI), and the percentage of Na^+ (Na%). In addition to these indices, USSL diagrams (SAR versus EC) [41] and Wilcox diagrams (Na% versus EC) [14] were used to assess the soil salinization and sodium hazard, whereby the USSL diagram describes the alkalinizing power of the water. These tools were combined to assess the potential risk of soil salinization and to control their negative effects on soils and plants.

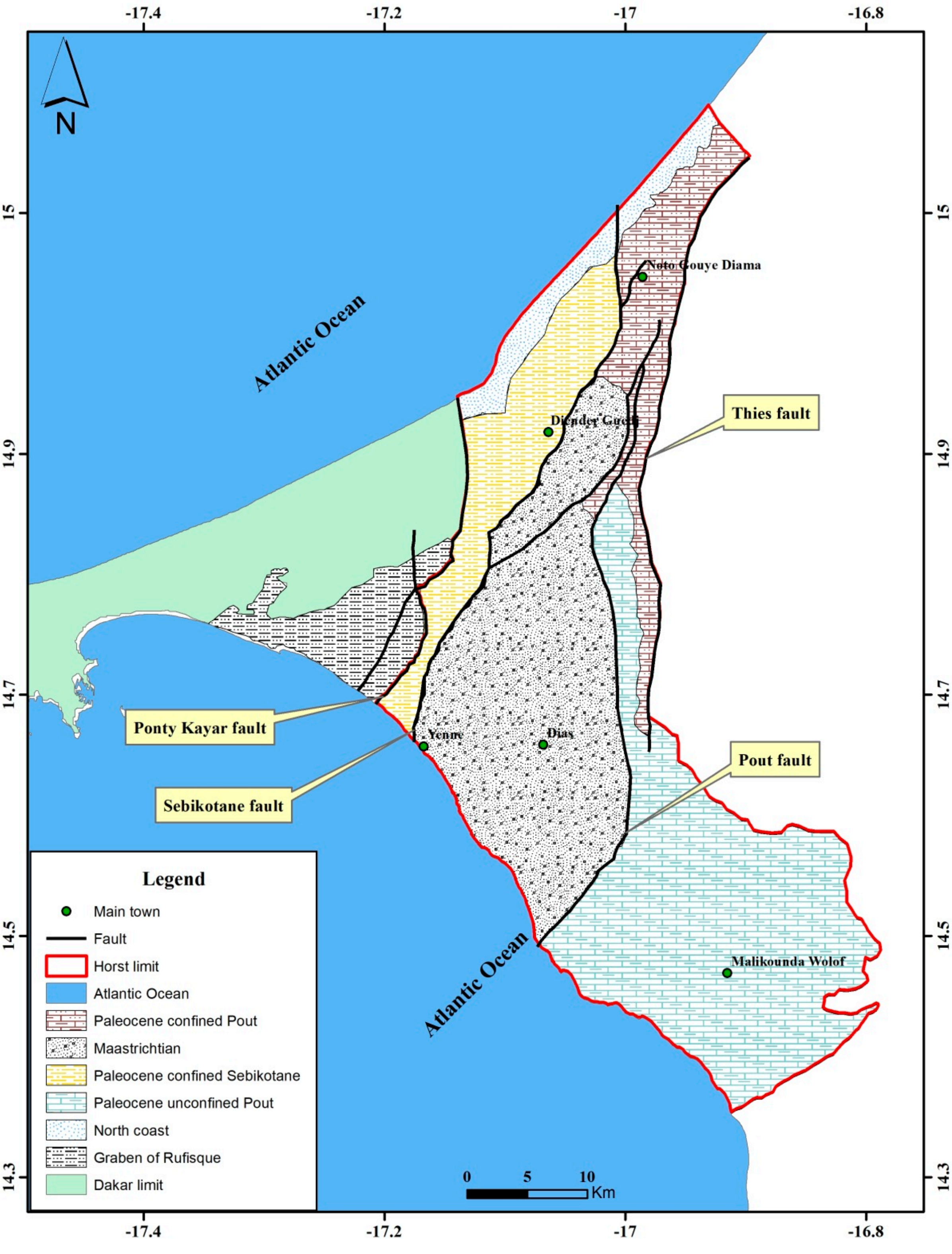


Figure 2. Aquifer formations in the Peninsula of Dakar (modified from [39]).

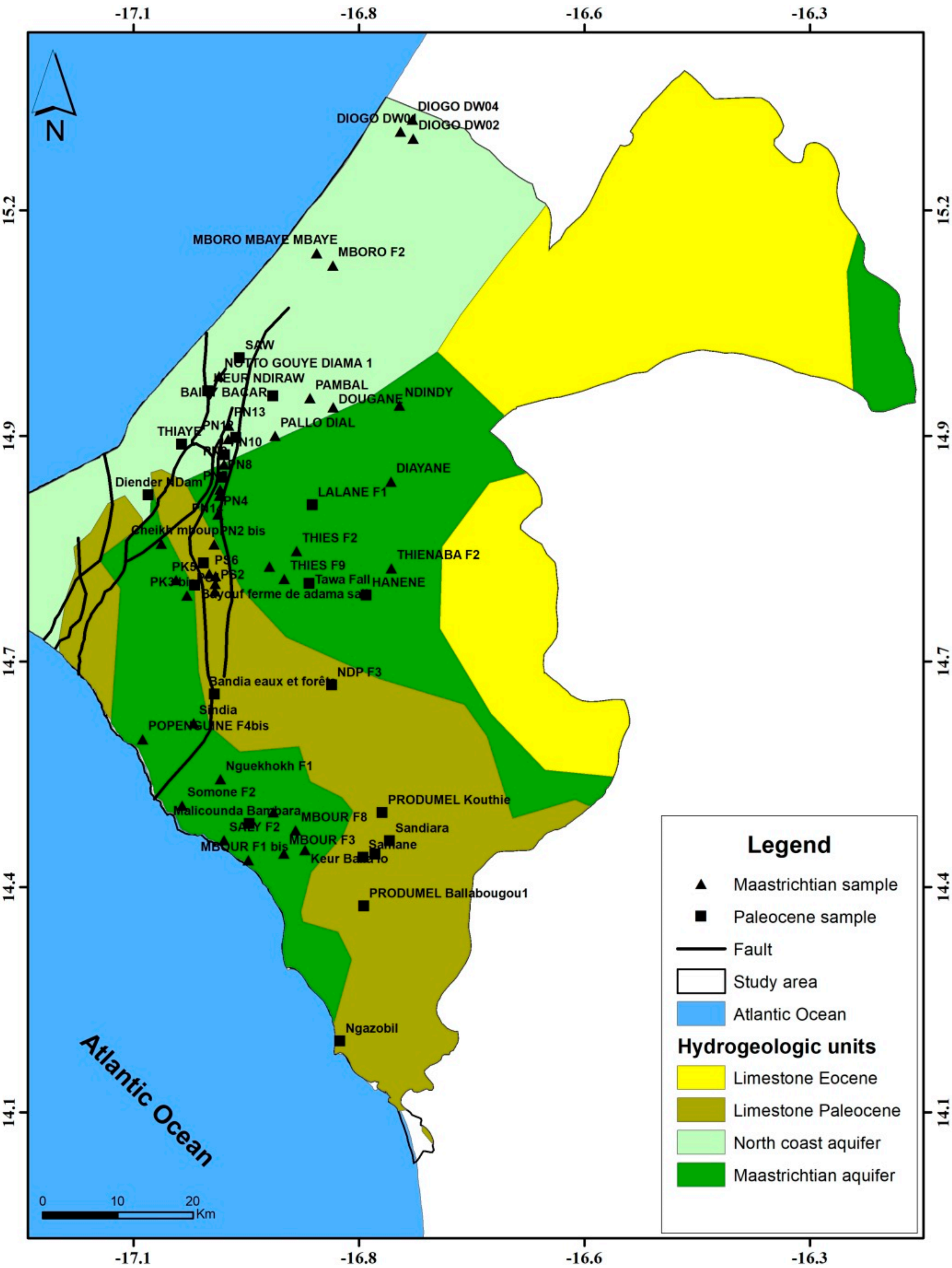


Figure 3. Location of the boreholes for groundwater sampling in the Thies region in 2019.

Salinity hazard of irrigation water based on the electrical conductivity (EC) discriminates four classes [14,42]. Water with EC values ≤ 250 μS cm^{-1} characterizes low salinity water suitable for all types of crops and soils, EC values between 250 and 750 μS cm^{-1}

indicate medium salinity waters, which can be used if a moderate amount of leaching occurs, range values between 750 and 2250 µS cm^{-1} characterizes high salinity which is unsuitable for soil with restricted drainage, and values between 2250 and 5000 µS cm^{-1} represent very unsuitable high salinity water for irrigation.

The sodium absorption ratio (SAR), which generally provides information on the risk of alkalinity, is a parameter which computes the proportion of sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) ions in a water sample. As mentioned priorly, high Na^+ concentrations may impact the soil negatively through the degradation of aggregates and increase in the concentration of free clay particles which can clog fine soil pores [30,43]. The SAR is expressed by Equation (1) according to [13]:

$$\mathrm{SAR} = \frac{\left(\mathrm{Na}^{+}\right)}{\sqrt{\left(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}\right)/2}} \quad (1)$$

whereby all ions are expressed in meq L^{-1}.

Classification of irrigation water based on SAR distinguishes four classes [13]. Waters with SAR values between 0 to 10 (S1) are low in sodium and are suitable for all types of crops and soil, except for those crops which are sensitive to sodium. Values ranging between 10 and 18 (S2) characterize waters exhibiting medium sodium suitable for coarse texture or organic soil with high permeability but is relatively unsuitable for fine textured soil. Values ranging between 18 and 26 (S3) represent waters with high sodium content, which are harmful for almost all type of soils. These latter require good drainage and additionally high leaching of gypsum. Finally, SAR values exceeding 26 (S4) are associated with very high sodium content waters, which are unsuitable for irrigation purposes.

Soluble salts in waters can be expressed by either EC or by the salinity potential, SP. The SP also controls the suitability of water for irrigation. Hereby, it is assumed that low soluble salts accumulate in the soil and are therefore beneficial for irrigation [30,31]. Salinity potential values for irrigation water can be distinguished into tree classes in soil of medium permeability [30,44]. SP values less than 5 are class I, characterized by good to excellent water for irrigation. Values between 5 and 10 are related to class II, characterized by a medium water type, and class III has SP values exceeding 10, characterized by poor water for irrigation.

The salinity potential is calculated by Equation (2) [44]:

$$\mathrm{SP} = \mathrm{Cl}^{-} + \frac{1}{2}\left(\mathrm{SO}_4^{2-}\right) \quad (2)$$

where, again, Cl^- and $SO_4{}^{2-}$ ions are expressed in meq L^{-1}.

Kelly et al. (1940) suggested that the sodium problem in irrigation water can be conveniently described by a ratio of Na^+ and Ca^{2+} + Mg^{2+} ions. The so-called Kelly's ratio is provided by Equation (3) [45]:

$$\mathrm{KR} = \frac{\mathrm{Na}^{+}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}} \quad (3)$$

where, again, Na^+, Ca^{2+}, and Mg^{2+} are expressed in meq L^{-1}.

A Kelly's ratio higher than one indicates an excess of sodium contents in waters, which is unsuitable for irrigation, while a Kelly's ratio smaller one indicates suitable waters for irrigation [30].

The permeability index (PI) is an important factor inferring information on the quality of irrigation water with respect to changes in the arable soils, as the soil permeability can be impacted by an excess of ions such as Na^+, Ca^{2+}, $HCO_3{}^-$, and Mg^{2+} [46,47]. The PI is calculated by Equation (4) according to [44], who classified the water into Class I, Class II, and Class III. Class I and II waters are categorized as good for irrigation with

75% or more of maximum permeability and class III water is unsuitable with 25% of maximum permeability.

$$PI = \frac{(Na^{+} + \sqrt{HCO_3}) * 100}{\left(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}\right)} \quad (4)$$

A high Na^+ percentage (Na%) in irrigation water can lead to degradation of the soil structure, hence causing low aeration and poor water infiltrability. The classification of groundwater according to the Na% allows the definition of five classes: excellent (Na% < 20), good (20 < Na% < 40), permissible (40 < Na% < 60), doubtful (60 < Na% < 80), and unsuitable (Na% > 80) [14]. The Na% can be calculated by Equation (5) [48,49], whereby all ion concentrations are in meq L^{-1}.

$$Na\% = \frac{(Na^{+} + K^{+})}{\left(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}\right)} * 100 \quad (5)$$

3. Results and Discussions

3.1. General Characterization of the Aquifer Waters

The statistics of the chemical composition of Maastrichtian and Paleocene groundwater samples of the Thies area are summarized in the Tables 1 and 2. In general, the pH-value influences the form and availability of nutrients in waters essential for crop development is optimal [50], and the pH of irrigation water should be between 6.5 and 8.54 [51]. In the Maastrichtian aquifer, pH values vary between 6.98 and 7.8 with a median of 7.51 (Table 1), indicating suitable water for irrigation purpose. In the Paleocene aquifer (Table 2), neutral to basic pH values are observed with a minimum of 6.96 at the sampling location Baba Diaw F1 and a maximum of 8.11 at Produmel Ballabougou (median = 7.50).

Electrical conductivity (EC), which expresses dissolved salt contents in the groundwater, plays an important role in assessing the suitability of water for irrigation. The United States Department of Agriculture Salinity Laboratory uses EC values to classify irrigation water into four salinity classes. From measured data in the system, groundwater samples showed range EC values of 274–1403 µS cm^{-1} with a median of 462 µS cm^{-1} and between 204 and 2860 µS cm^{-1} (median of 823 µS cm^{-1}) for the Maastrichtian and the Paleocene aquifers, respectively.

Table 1. Summary statistics of the Maastrichtian groundwater quality parameters sampled in June 2019.

Chemical Parameters of the Maastrichtian Aquifer							
Variables	**Unit**	**Number ofSamples**	**Mean**	**Median**	**Minimum**	**Maximum**	**Ecart-Type**
pH	-	39	7.50	7.51	6.98	7.8	0.17
Temperature	°C	39	32.8	31.7	28.2	40.9	3.5
EC	(µS cm^{-1})	39	557.9	462.0	274.0	1403.0	253.6
HCO_3^-	(mg L^{-1})	39	204.27	183.0	134.20	366.0	61.95
Cl^-	(mg L^{-1})	39	50.95	32.78	10.55	193.7	43.88
SO_4^{2-}	(mg L^{-1})	39	29.50	27.67	7.89	70.90	15.85
NO_3^-	(mg L^{-1})	39	8.50	2.43	0.81	164.7	25.98
Na^+	(mg L^{-1})	39	48.97	27.35	4.31	211.9	50.89
K^+	(mg L^{-1})	39	4.71	3.57	1.38	17.7	3.69
Ca^{2+}	(mg L^{-1})	39	34.99	34.35	7.96	71.8	14.07
Mg^{2+}	(mg L^{-1})	39	16.42	14.55	4.82	44.9	8.76

Table 2. Summary statistics of the Paleocene groundwater quality parameters measured in June 2019.

Chemical Parameters of the Paleocene Aquifer							
Variables	**Unit**	**Number of Samples**	**Mean**	**Median**	**Minimum**	**Maximum**	**Ecart-Type**
pH	-	23	7.53	7.50	6.96	8.11	0.64
Temperature	°C	23	29.61	29.6	24.5	33.3	2.2
EC	(μS cm^{-1})	23	1025.7	823.0	204.0	2860.0	579.4
HCO_3^-	(mg L^{-1})	23	238.56	244.0	0.00	530.70	130.08
Cl^-	(mg L^{-1})	23	132.83	72.6	10.52	537.65	132.62
SO_4^{2-}	(mg L^{-1})	23	67.02	36.02	3.33	302.19	77.09
NO_3^-	(mg L^{-1})	23	10.03	6.88	1.19	49.73	11.76
Na^+	(mg L^{-1})	23	69.45	34.42	5.11	441.07	95.09
K^+	(mg L^{-1})	23	5.86	4.27	1.52	15.52	4.26
Ca^{2+}	(mg L^{-1})	23	52.11	48.29	8.14	108.19	27.17
Mg^{2+}	(mg L^{-1})	23	37.73	25.47	1.86	87.53	27.56

Chemical data (expressed in meq L^{-1}) of the groundwater sampled in the two aquifers indicate a general order of magnitude as follows: HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- for the anions and Na^+ > Ca^{2+} > Mg^{2+} > K^+ for the cations. Values plotted in the Piper trilinear diagram [52] identified dominant HCO_3-Ca-Mg water type in the Maastrichtian aquifer, while in the Paleocene aquifer, both HCO_3-Ca-Mg and Cl-Ca-Mg water types occur (Figure 4).

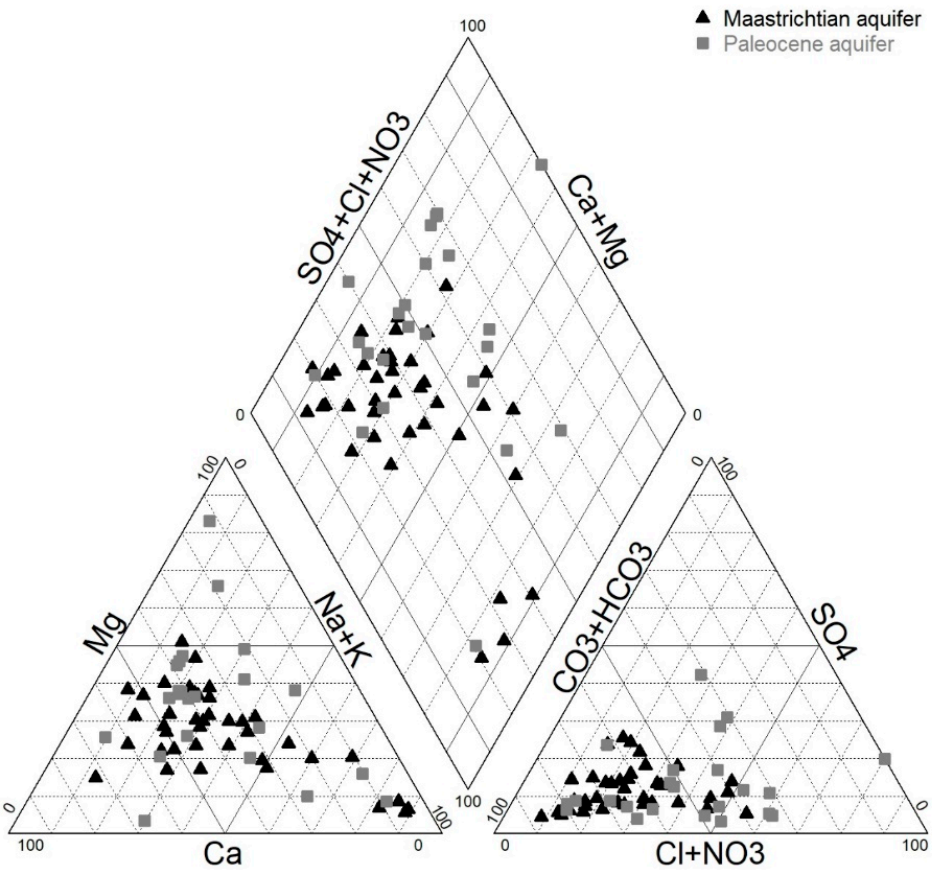


Figure 4. Piper diagram of the Paleocene and Maastrichtian aquifers.

3.2. Suitability of the Aquifer Water for Irrigation Purposes

In the horst area, the two main aquifers are heavily exploited to meet demands for drinking water supply, industries, mining, and agriculture. Many factors affect the quality of irrigation water, including temperature, pH, salinity, and alkalinity. Irrigation water requirements depend essentially on temperature and the pH value of the groundwater.

However, the water quality for irrigation water is generally evaluated using salt and alkali damage [32]. For this evaluation of the suitability of the groundwater for irrigation, the electrical conductivity (EC) and the sodium absorption ratio (SAR), Kelly ratio (RK), salinity potential (SP), permeability index (PI), and the percentage of sodium (Na%) were calculated. Additionally, the risks of soil salinization and sodium hazard were assessed using USSL and Wilcox diagrams.

3.2.1. Electrical Conductivity (EC)

The electrical conductivity (EC), which represents a measure of the total dissolved ions, is the most widely used water quality index for irrigation water control as it measures the water salinity hazard. High EC in groundwater samples may be inferred by leaching or dissolution of the aquifer minerals, mixing with saline sources, or a combination of these processes [51,52]. The EC values of the Maastrichtian aquifer vary between 274 (piezometer PS4 bis) and 1403 μS cm^{-1} (Mbour F1 bis) with a median of 462 μS cm^{-1}, while for the Paleocene aquifer, EC values vary between 204 (Toude Ndiop) and 2860 μS cm^{-1} (Ngazobil) with a median of 823 μS cm^{-1} (see Table 3 and Figure 3). Classification of the sampled Maastrichtian and Paleocene aquifers according to EC values shows four classes. Overall, 79.5% of the sampled Maastrichtian groundwater presents a moderate risk of salinization corresponding to class C2 (located around Thies F9, F6, Pout sud 4 bis), and 20.5% of the water is of high risk of salinization and corresponds to class C3 (at Mbour F1 bis, Mbour F3, and Diogo DW04) (see Table 3). On the other hand, for the sampled Paleocene groundwater, 65.4% presents high risk of class C3 (Produmel Ballabougou 1, Produmel Kouthie, and Baity Bacar), 26.0% of moderate risk (C2) (at Bandia, Baba diaw, F1, and F2 Pout), 4.3% without risk (C1) around Toude Ndiop, and 4.3% of very high risk (C4) of salinization (at the Ngazobil) (Table 3).

Table 3. Classification of groundwater aquifer by measured electrical conductivity (EC).

Aquifer	Classes	Electrical Conductivity (μS cm^{-1})	Water Quality	% of Samples
Maastrichtian	C2	250 < EC < 750	Moderate risk of salinization	79.5
	C3	750 < EC < 2250	High risk of salinization	20.5
Paleocene	C1	EC < 250	No risk of salinization	4.3
	C2	250 < EC < 750	Moderate risk of salinization	26.0
	C3	750 < EC < 2250	High risk of salinization	65.4
	C4	2250 < EC < 5000	Very high risk of salinization	4.3

3.2.2. Sodium Absorption Ratio (SAR)

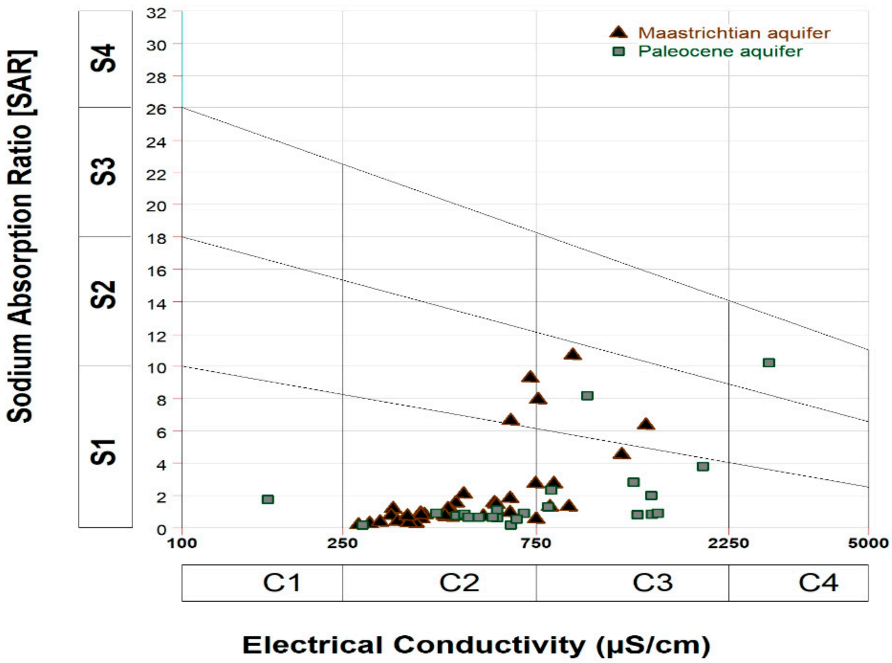
Groundwater salinity and SAR can be used to evaluate water quality for irrigation purposes. In general, the salinity in groundwater originates from salt leaching from soils, anthropogenic sources (e.g., fertilizer salts, waste water infiltration), weathering of the evaporate minerals, mixing of saline sources, or a combination of these processes [53–55]. The SAR values of the Maastrichtian aquifer samples vary between 0.24 and 15.1 meq L^{-1} with a median of 1.38 meq L^{-1} (Table 4). For the Paleocene aquifer, the SAR values exhibit the same range as for Maastrichtian aquifer. Minimum and maximum SAR are 0.23 and 14.5 meq L^{-1} with a median of 1.27 meq L^{-1} (Table 4). As noticed, from Table 4, more than 90% of the sampled groundwaters from the two aquifers belong to class S1 and are therefore suitable for irrigation if only the SAR values are considered.

Table 4. Classification of the groundwater quality according to the sodium adsorption ratio (SAR).

Aquifer	Classes	SAR (meq L^{-1})	Water Quality	% of Samples
Maastrichtian	S1	<10	Excellent with low alkalinization hazard	92.30
	S2	10 < SAR < 18	Good without special control	7.70
Paleocene	S1	<10	Excellent with low alkalinization hazard	91.30
	S2	10 < SAR < 18	Good without special control	8.70

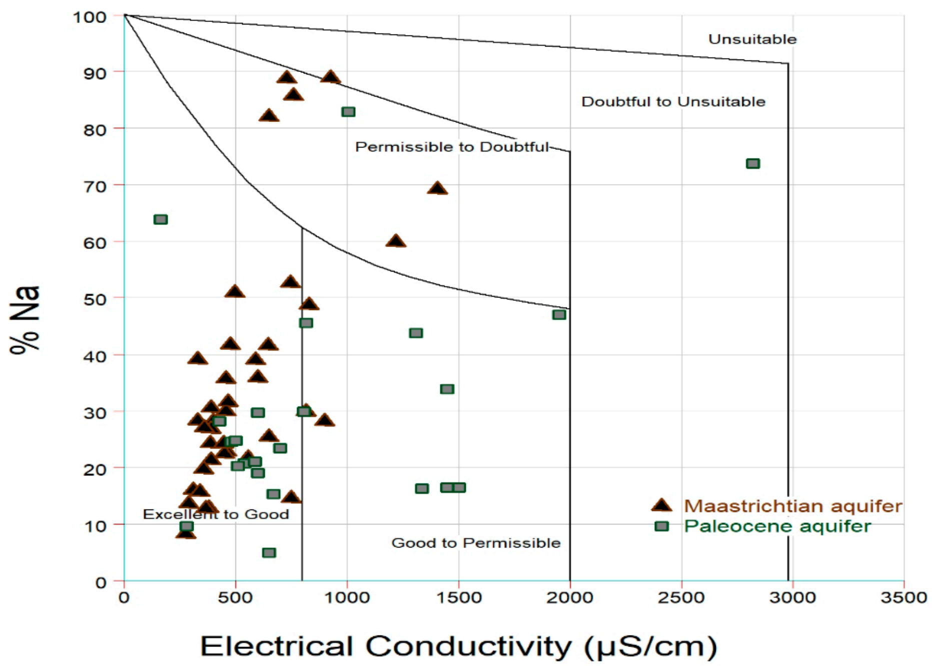
3.2.3. USSL Diagram

The United States Department of Agriculture Salinity Laboratory diagram (USSL) shows a detailed analysis of groundwater with respect to irrigational suitability [41]. Based on this classification, the Maastrichtian and Paleocene groundwaters of the study area can be grouped into classes C2S1, C2S2, C3S1, and C3S2 and C1S1, C2S1, C2S2, C3S1, and C4S3, respectively (Figure 5a). For this classification, C and S values ≤ 3 indicate lower EC and lower SAR. Overall, 87.2% of the sampled Maastrichtian groundwater and 87.0% of the sampled Paleocene groundwater indicate low to medium salinity and medium alkalinity, which can be used for irrigation in almost all types of soils with no danger of exchangeable sodium. C3S1 (which characterizes highly saline–low sodic hazard) and C3S2 (for highly saline–medium sodic type) occur in the Maastrichtian groundwater located in the north part of the horst at Diogo and in the south of the study area. These types are considered as acceptable water for the irrigation of salt-tolerant crops on well-drained or high-permeability soils whose salinity must be controlled. C4S3, which depicts very highly saline–high sodic type soil, is encountered in the Paleocene aquifer with EC values ranging between 2250 and 5000 µS cm^{-1}. This salty water type found towards Ngazobil is not recommended for irrigation due to its harmful effects on plants and soils (Figure 5a).



(**a**)

Figure 5. *Cont.*



(**b**)

Figure 5. USSL diagram (SAR versus EC plot) (**a**) and Wilcox diagram (Na% versus EC plot) (**b**) of the Maastrichtian and Paleocene groundwater samples (June 2019).

3.2.4. Percentage of Sodium (Na%)

In the study area, the Na% values range between 8.24 and 88.9%, with an average of 35.8% and median of 28.33% for the Maastrichtian aquifer and between 4.95 and 82.8% (mean = 30.9% and median = 24.54%) for the Paleocene aquifer (Tables 5 and 6). Using this index parameter to evaluate suitability, samples from the Maastrichtian aquifer are classified into three quality classes (C1 to C3), with 51.3% exhibiting good water quality for irrigation, followed by class C3 with 28.2% of permissible water quality for irrigation. Among the good quality classes, 20.5% of the samples are qualified as excellent in quality (see Table 5). On the other hand, sampled Paleocene groundwaters exhibit four classes (C1 to C4), where 30.4% represent excellent water quality class C1 and 43.5% of class C2 with good water quality.

Table 5. Classification of the water samples according to the percentage of Na (Na%).

Aquifer	Classes	Na%	Water Quality	% of Samples
Maastrichtian	C1	<20	Excellent water quality for irrigation	20.5
	C2	20 < Na% < 40	Good water quality for irrigation	51.3
	C3	40 < Na% < 60	Permissible water quality for irrigation	28.2
	C4	60 < Na% < 80	Doubtful water quality for irrigation	0
	C5	Na% > 80	Unsuitable water quality for irrigation	0
Paleocene	C1	<20	Excellent water quality for irrigation	30.4
	C2	20 < Na% < 40	Good water quality for irrigation	43.5
	C3	40 < Na% < 60	Permissible water quality for irrigation	13
	C4	60 < Na% < 80 Na% > 60	Doubtful water quality for irrigation	13.1
	C5	Na% > 80	Unsuitable water quality for irrigation	0

Table 6. Summary of geochemical classification of irrigation indices.

Variables	Unit	Mean	Median	Minimum	Maximum	Ecart-Type
Maastrichtian Aquifer						
Variables	**Unit**	**Mean**	**Median**	**Minimum**	**Maximum**	**Ecart-Type**
SAR	(meq L^{-1})	2.85	1.38	0.24	15.09	2.25
Kelly ratio (KR)	(meq L^{-1})	1.07	0.37	0.08	7.55	1.85
Salinity potential (SP)	(meq L^{-1})	2.19	1.82	0.70	6.38	1.36
Na%	(meq L^{-1})	35.76	28.33	8.24	88.89	21.81
Paleocene Aquifer						
Variables	**Units**	**Mean**	**Median**	**Minimum**	**Maximum**	**Ecart-Type**
SAR	(meq L^{-1})	2.67	1.27	0.23	14.50	3.52
Kelly ratio (KR)	(meq L^{-1})	0.68	0.30	0.05	4.58	1.04
Salinity potential (SP)	(meq L^{-1})	4.77	2.85	0.70	16.87	4.08
Na%	(meq L^{-1})	30.88	24.54	4.95	82.83	20.08

The samples falling into C3 with permissible water quality and C4 with doubtful water quality are 28.2% and 13%, respectively, for the Maastrichtian and the Paleocene. This evidences that the groundwater in the Maastrichtian aquifer is overall more suitable for irrigation than that of the Paleocene.

The Na% versus EC graph is also an important tool to evaluate the irrigation water suitability [23,56]. These two parameters plotted in Wilcox diagram (Figure 5b) are based on the Na%–EC relationship, where water quality can be distinguished into five classes: (i) excellent to good, (ii) good to permissible, (iii) permissible to doubtful, (iv) doubtful to unsuitable, and (iiv) unsuitable [14]. Figure 5 shows that 84.61% and 91.3% of the Maastrichtian and Palecene water samples are classified as excellent to good for irrigation purposes, respectively.

3.2.5. Salinity Potential (SP)

Assessing salinity is important because excess of salt in the irrigation water. In fact, salinity increases the soil water osmotic pressure and infers on roots soil water uptake [57] and plants physiological water stress [28,30]. Additionally, high salt contents in the root zone caused by salty irrigation water can directly damage the plant root system through so-called "root burns" [50]. The SP parameter, which sums up the chloride and sulfate concentrations in the water, is a widely accepted salinity indicator [15,42]. The computed SP values in the Maastrichtian aquifer vary between 0.7 and 6.38 meq L^{-1} with a mean of 2.19 meq L^{-1} and median of 1.82 meq L^{-1}. On the other hand, for the Paleocene aquifer, the SP values vary between 0.7 and 16.64 meq L^{-1} (mean = 4.44 meq L^{-1} and median = 2.85 meq L^{-1}) (see Table 6). As for the EC and SAR values, the SP values can be also classified according to [28,42] into three classes in soil of medium permeability. Most of the sampled Maastrichtian waters (97.4%) are classified as good to excellent quality, with SP values less than five, and 2.56% are of medium quality (SP values between 5 and 10). The medium quality class waters are located at Dougane and Mbour F1 Bis. For the Paleocene aquifer, 13.0% of the sampled waters are of poor quality and are located around Produmel Ballabougou1 (SP = 10.53 meq L^{-1}), Produmel Kouthie (SP = 12.28 meq L^{-1}), and Ngazobil (SP = 16.87 meq L^{-1}), while 69.6% of the samples are of good to excellent quality (Table 7).

Table 7. Classification of water according to their salinity potential (SP).

Aquifer	SP	Classes	% of Samples
Paleocene	<5	Good to excellent	69.6
	5 < SP < 10	Medium	17.4
	>10	Poor	13.0
Maastrichtian	<5	Good to excellent	97.4
	5 < SP < 10	Medium	2.6

3.2.6. The Kelly Ratio (KR)

The KR values of the Maastrichtian aquifer vary between 0.08 and 7.55 meq L^{-1} (mean = 1.07 meq L^{-1} and median = 0.37 meq L^{-1}) and those of the Paleocene between 0.05 and 4.58 meq L^{-1} (with a mean of 0.68 meq L^{-1} and a median of 0.30 meq L^{-1}). Table 8 shows the classification of Maastrichtian and Paleocene sampled waters according to the KR, whereby the majority of the sampled points in the Maastrichtian aquifer (82%) are classified as good for irrigation. However, 18% of the samples have poor quality water. These points are located at Diogo DW01 (KR = 4.35 meq L^{-1}), Diogo DW04 (KR = 7.54 meq L^{-1}), Cheikh mboup (KR = 5.61 meq L^{-1}), and the Diayane point (KR = 7.31 meq L^{-1}). For the Paleocene aquifer, 87% of the water samples are of good quality, and only 13% are not suitable for irrigation according to the KR. The latter are found in Ngazobil (KR = 2.74 meq L^{-1}) and Keur Ndiraw (KR = 4.58 meq L^{-1}).

Table 8. Water classification according to the Kelley ratio (KR).

Aquifer	RK	Water Quality	% of Samples
Maastrichtian	<1	good for irrigation	82
	RK > 1	not good for irrigation	18
Paleocene	<1	good for irrigation	87
	RK > 1	not good for irrigation	13

3.2.7. Permeability Index (PI)

The permeability index (PI) of the Maastrichtian aquifer varies between 44.4 and 118%, with a mean of 73.77% and a median of 70.1%. As shown in Figure 6 and Table 6, 90% of the Maastrichtian sampled waters are suitable for irrigation according to PI and only 10.2% of the samples belong to class III. Among the suitable water, 79.5% belong to class I, 10.3% to class II. For the Paleocene aquifer, the PI ranges between 31.2 and 115% with a mean of 58.27% and median of 54.73%. Class I and class II represent up to 91.3% of the sampled waters (Figure 6).

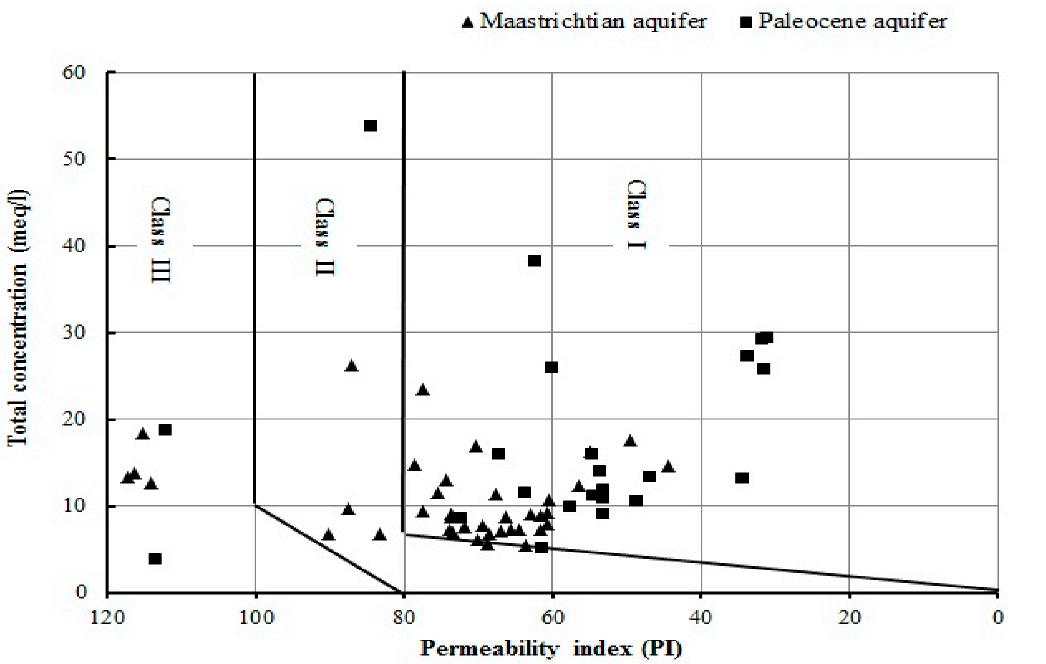


Figure 6. Doneen's chart for the permeability index for the Maastrichtian and Paleocene samples.

Water samples were classified by combining all the indices in order to determine an average water quality suitable for irrigation. Thus, the samples were grouped into three classes according to the water suitability for irrigation. Classes 1 and 2 include samples that are good to excellent (≥50% classified as suitable for indices) and permissible (25–50% classified as suitable for indices) for irrigation purposes, respectively. Class 3 was classified as unsuitable for irrigation, representing ≤25%. Based on this combined classification, most sampled Maastrichtian waters are considered as good to excellent (84.6%), especially from the region Pout North and Pout South; 5.1% as permissible class; and 10.8% as the unsuitable class. These latter samples are located around Diogo DW, Cheikh Mboup, and Diayane points (Figures 7 and 8).

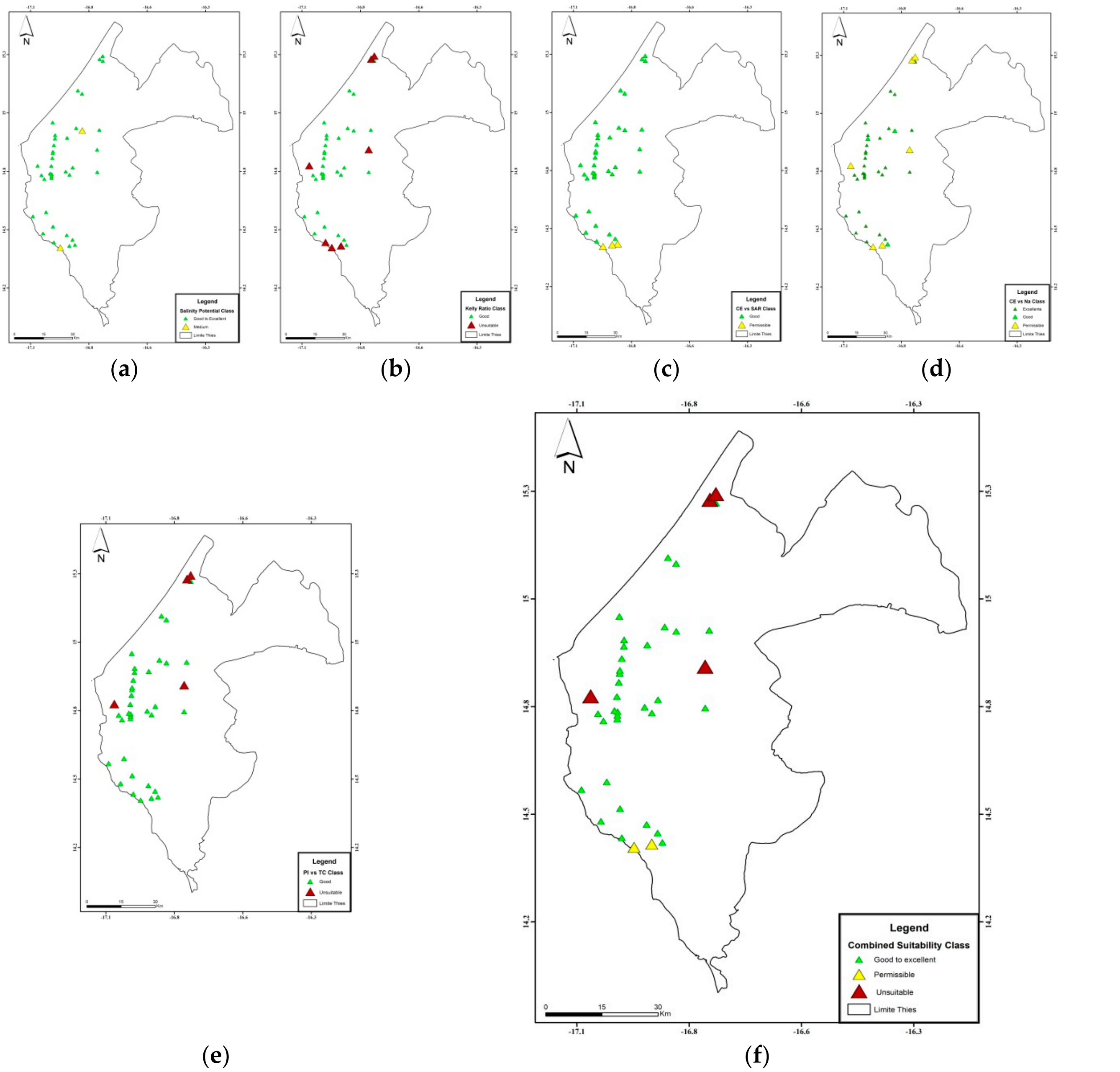


Figure 7. Salinity potential (**a**), Kelly ratio (**b**), CE vs. SAR (**c**), CE vs. Na% (**d**), PI vs. TC (**e**), and combined (**f**) suitability maps of Maastrichtian aquifer for irrigation purpose.

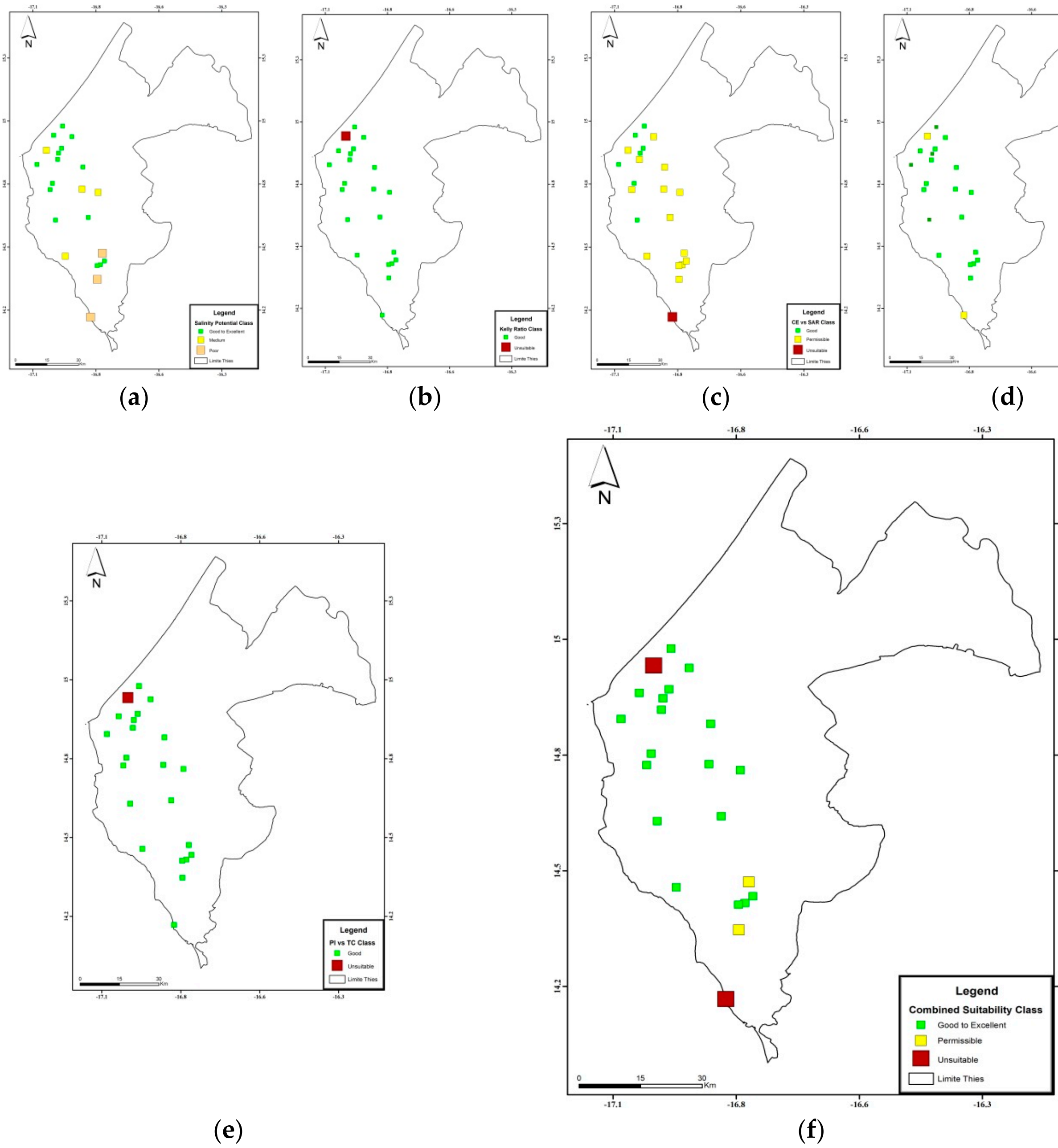


Figure 8. Salinity potential (**a**), Kelly ratio (**b**), CE vs. SAR (**c**), CE vs. Na% (**d**), PI vs. TC (**e**), and combined (**f**) suitability maps of Paleocene aquifer for irrigation purpose.

In the Paleocene aquifer, the majority of samples are considered as good to excellent class (78.3%) and are found in the central and southern part of the study area, whereas 8.7% are classified as permissible and 13.0% as unsuitable water quality (located in around Ngazobil, Keur ndiraw, and Toude Diop areas) (Figure 8).

4. Summary and Conclusions

Groundwater is the major source of drinking water in most parts of Senegal, including the study area. In this latter area, groundwater is also used to meet the irrigation, industrial, and mining sector demands. This study focused on the water suitability assessment for irrigation of the Maastrichtian and Paleocene aquifers in the Thies area in western Senegal. Piper diagrams indicate the dominancy of the HCO_3-Ca-Mg water type in the Maastrichtian aquifer and both the HCO_3-Ca-Mg and Cl-Ca-Mg water types in the Paleocene aquifer. Five water quality indices were used for the assessment, namely, the sodium absorption ratio (SAR), the salinity potential (SP), the Kelly ratio (KR), the permeability index (PI), and the percentage of sodium (Na%). Additionally, Wilcox and USSL diagrams were used to illustrate the quality of groundwater and its suitability for irrigation in the study area. The Electrical conductivity (EC), which expresses the degree of mineralization of water samples, is relatively high in the Maastrichtian aquifer, where 20.5% of the water sampled represents high risk of salinization corresponding to class C3. In the Paleocene aquifer, the risk of salinization is higher with the presence of classes C3 (high risk of salinization) and C4 (very high risk of salinization). The report of the chemical data in the USSL diagram shows that the Maastrichtian water samples do not present a significant risk for irrigation purpose (C3S1 and C3S2). However, waters of C4S3 class, which present a very high risk of salinization, are observed in the Paleocene aquifer. Potential salinity water values show that most of the Maastrichtian water samples (97.4%) are considered as good to excellent quality and only 2.6% as medium quality. For the Paleocene aquifer, 69.6% of the water has Sp values between 5 and 10, revealing good quality for irrigation. The percentage of sodium (Na%) shows that the Maastrichtian groundwater samples are of excellent to acceptable quality, while Paleocene Na% values range from excellent to unsuitable for irrigation. The combination of PS, KR and Na% indices and USSL, Wilcox, and Doneen classification reveals that the percentage of water samples suitable for irrigation purposes is 89.7% and 86.9% of the samples for the Maastrichtian and the Paleocene aquifers, respectively. However, due to the high groundwater extraction rates and agricultural and mining activity in the study area, an evaluation of the spatial and temporal evolution of groundwater quality is required to ensure effective and sustainable management of the water resource.

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