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Assessment of the Physico-Chemical Quality of Surface Waters in the Casamance Estuary

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Abstract

The study establishes a baseline for the physicochemical quality of the surface waters of the Casamance Estuary (Senegal). Seasonal sampling (2022-2023) at six stations involved taking *in situ* measurements of temperature, salinity, dissolved oxygen and pH, as well as sampling the surface water. These samples were analysed using spectrophotometry to determine the concentrations of sulphates, nitrates, nitrites, ammonium and phosphates. Results show marked seasonal but limited spatial variability; most parameters meet Water Framework Directive (WFD) "good" thresholds except for consistently high sulphate. The work provides initial reference values for future impact tracking of oil exploitation in Senegal.

Keywords

Casamance Estuary, Physico-Chemical Parameters, Water Quality, Nutrients

1. Introduction

In natural aquatic ecosystems, nutrients are typically present in low and regulated concentrations, playing a fundamental role in maintaining ecological balance [1]. However, increasing anthropogenic pressures, including rapid urbanization, industrial expansion, agricultural intensification, and irrigation have significantly altered nutrient dynamics, often leading to contamination levels that exceed natural tolerable thresholds [2] [3]. Recent studies highlight that these pressures have exacerbated water quality degradation globally, particularly in coastal and estuarine environments [4]-[6].

The assessment of physico-chemical water quality is a crucial tool for evaluating the health of aquatic ecosystems, especially in estuaries, which serve as biodiversity hotspots and vital breeding grounds for numerous marine species [7]. This assessment relies on key parameters such as temperature, salinity, dissolved oxygen, pH, and nutrient concentrations (e.g., phosphates, nitrates, nitrites, and ammonium), which collectively determine the ecological and chemical status of water bodies [8] [9]. Recent research underscores the importance of continuous monitoring, particularly in regions experiencing growing anthropogenic pressures [10] [11].

Although nutrients themselves are not directly toxic to marine life, their excessive accumulation in estuarine and coastal environments can trigger harmful ecological imbalances, notably eutrophication. This phenomenon, characterized by excessive algal blooms, oxygen depletion, and biodiversity loss, is primarily driven by nutrient inputs from urban wastewater, agricultural runoff, and domestic effluents [12] [13]. Recent findings indicate that climate change and increasing human activities further exacerbate eutrophication risks by altering hydrological cycles and nutrient transport [14] [15]. Moreover, high levels of mineral enrichment can disrupt water transparency, hinder primary production, and modify trophic interactions, with cascading effects on ecosystem resilience [9] [16] [17].

Against this backdrop, human-induced pressures including urban, agricultural, and industrial activities, are intensifying along the Senegalese coastline, raising concerns about the degradation of marine and coastal ecosystems. Of particular concern is the increasing risk of contamination associated with hydrocarbon exploitation near Senegal's shores, which could exacerbate existing environmental challenges [18] [19]. Despite its ecological and socio-economic significance, the Casamance estuary remains insufficiently studied, with the last comprehensive research dating back to the 1980s, conducted by ORSTOM (now IRD) [20]. Currently, a detailed assessment of the physico-chemical quality of its waters is lacking.

This study aims to fill this knowledge gap by evaluating the physico-chemical quality of the Casamance estuary's waters. To this end, key environmental parameters including temperature, salinity, dissolved oxygen, and pH will be analyzed alongside nutrient concentrations (sulfates, nitrates, nitrites, ammonium, and phosphates). Establishing a baseline for these indicators is crucial for monitoring future environmental changes and guiding conservation efforts in the region.

2. Materials and Methods

2.1. Study Area

The sampling campaigns were conducted along the Casamance River, located in the southwestern region of Senegal. The Casamance basin extends between 12˚20' and 13˚21' north latitude and 14˚17' and 16˚47' west longitude. Its hydrographic network is dominated by the Casamance River, a semi-permanent watercourse that generally flows from June to March at the Ziguinchor station [21]. The Casamance River follows an east-to-west trajectory, forming a 220 km-long estuary. It originates in the Kolda region and is fed by the confluence of several small rivers, which typically dry up during the dry season [22]. The river basin spans approximately 14,000 km^2 [23]. This region plays a crucial role in Senegal's economy, supporting key activities such as tourism, small-scale fishing, and fish processing. Additionally, significant efforts have been made to preserve biodiversity and marine ecosystems, notably through the creation of Marine Protected Areas (MPAs). The Niamone-Kalounaye MPA (N-K MPA) and the Kassa-Balantacounda MPA (K-B MPA) have been established to safeguard the ecological integrity of the estuary (**Figure 1**).

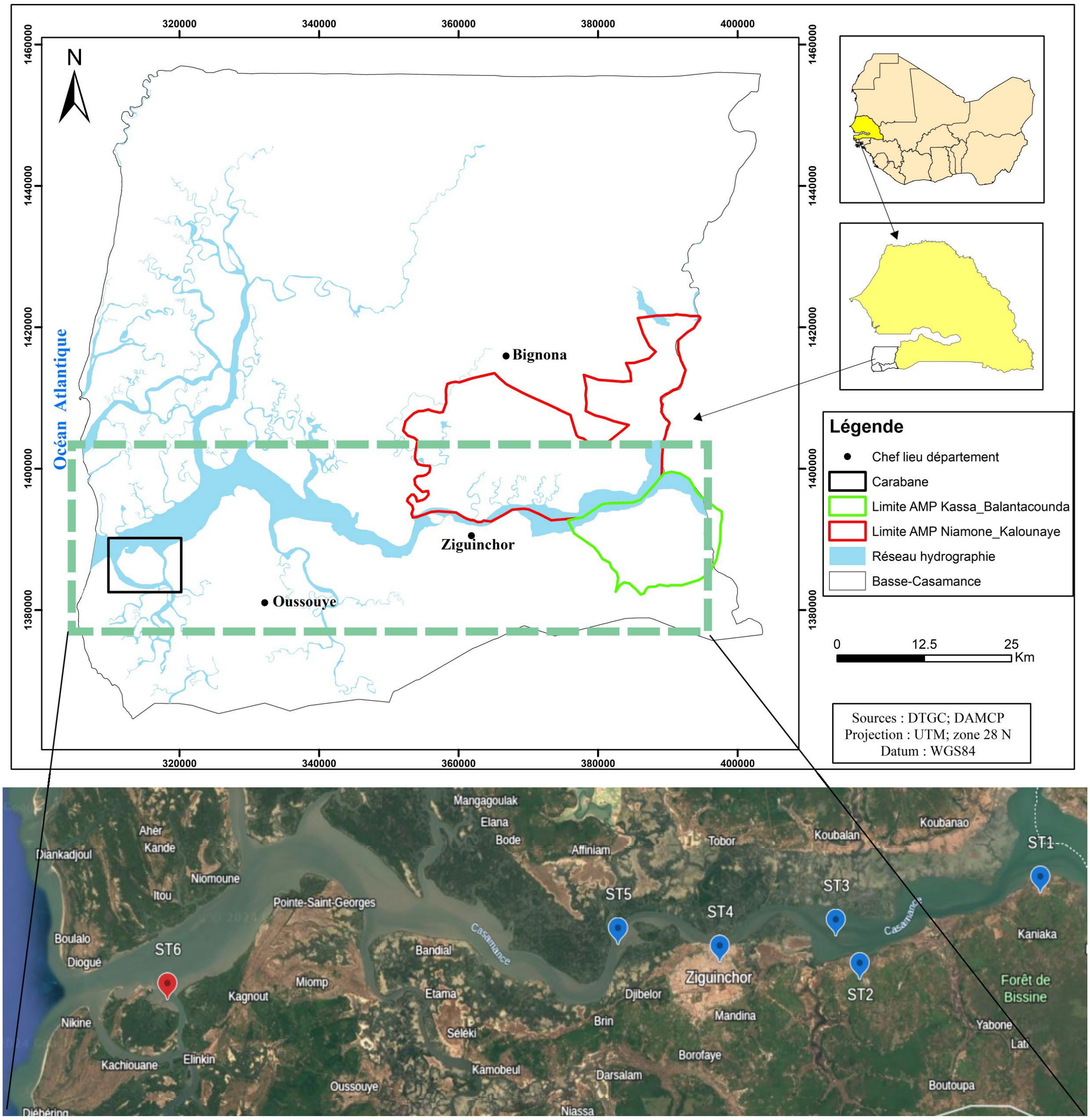


Figure 1. Location of study area and Geographical location of water sampling stations.

2.2. Sampling Protocol

Physico-chemical parameters, including temperature, salinity, dissolved oxygen, and pH, were measured simultaneously at six (6) fixed stations, geolocated using GPS (**Table 1**, **Figure 1**). Measurements were taken at depths ranging from 0 to 1 m using a CTD probe (WiSens CTDS) for temperature and salinity, a miniDOT logger for dissolved oxygen, and a multi-parameter probe (HANNA HI9829) for pH. Additionally, water samples were collected at each station using polystyrene bottles, which were pre-rinsed three times with environmental water before sampling. To ensure sample integrity, the bottles were stored on ice in a thermostat-controlled container before being transported to the Laboratoire d’Analyse et de Traitement de l’Eau (LATE) at the Université Assane Seck de Ziguinchor (UASZ) for analysis. Sampling was conducted between 2022 and 2023, covering four successive hydroclimatic seasons: Warm season (WS), Warm-to-cold transition (WCTS), Cold season (CS) and Cold-to-warm transition (CWTS).

Table 1. Coordinates (longitude and latitude) of the various water and sediment sampling stations. *Coordonnées* (*longitude et latitude*) *des différentes stations de mesure d’échantillonnage de l’eau et des sédiments.*

AMP	AMP K-B		AMP N-K			Carabane
Stations	ST1 (Adéane)	ST2 (Niaguiss)	ST3 (Bolong-Coubalan)	ST4 (Port de Ziguinchor)	ST5 (bolong-Affiniam)	ST6 (river mouth)
Coordinates (longitude/latitude)	16.02˚W/12.63˚N	16.16˚W/12.58˚N	16.17˚W/12.61˚N	16.26˚W/12.59˚N	16.35˚W/12.6˚N	16.69˚W/12.55˚N

2.3. Analysis of water samples

The determination of the concentrations of sulfate (SO_4^{2-}), phosphate (PO_4^{3-}), nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) followed a standardised protocol in accordance with the recommendations of the American Public Health Association [24] and the manufacturer’s guidelines. For each parameter, a defined volume of the water sample was introduced into a clean cuvette. The appropriate reagent (**Table 2**) was then added according to the instructions provided with the analysis kit. The cuvette was thoroughly mixed to ensure complete homogenisation of the sample.

Table 2. Methods and reagents used for each nutrient researched.

Element required	Method	Reagents used
sulfate (SO_4^{2-})	Sulfaver 4	Sulfaver 4 Reagents
phosphate (PO_4^{3-})	Ascorbic acid	Ammonium Molybdate
nitrate (NO_3^-)	Chromotropic acid	Test Tubes N Tube, Nitraver × Reagent
nitrite (NO_2^-)	Diazotization	Nitriver 3 reagent
ammonium (NH_4^+)	Salicylate	1-Sachet of powder for ammonia salicylate 2-Sachet of powder for cyanurate salicylate

After the specified reaction time, the sample was placed in the spectrophotometer and the concentration (expressed in mg/L) was automatically measured using the READ function of the DR 900. The wavelengths used for each nutrient were: 880 nm for phosphates, 507 nm for nitrites, 410 nm for nitrates, 450 nm for sulphates and 655 nm for ammonium. HACH reagent kits were used for all analyses based on methods relying on the formation of coloured complexes, enabling the precise and reliable detection of nutrients in water. Nutrient concentrations are expressed as ion mass.

2.4. Data Processing and Analysis

Statistical tests were carried out to illustrate the spatial and temporal variability of the parameters measured in the estuary: Statistical tests (Shapiro-Wilk test followed by Kruskal-Wallis test or ANOVA) with R software to check the normality of the data; Correlation matrices to interpret the bivariate relationships between the different parameters; Principal Component Analysis (PCA) to determine the multivariate relationships between the different parameters studied and identify groups of stations that are similar or dissimilar in terms of the characteristics of physico-chemical parameters and nutrient levels in the estuary.

3. Results

3.1. Spatial and Temporal Variability of Physico-Chemical Parameters

Temperature generally increases from the mouth of the estuary (ST6) toward the interior (ST1) (**Figure 2(a)**). The lowest temperatures are recorded during the dry season (25.48˚C ± 1.28˚C) and the transition to the cold season (25.21˚C ± 1.25˚C), while the highest values occur in the warm season (31.21˚C ± 0.83˚C) (**Figure 3(a)**).

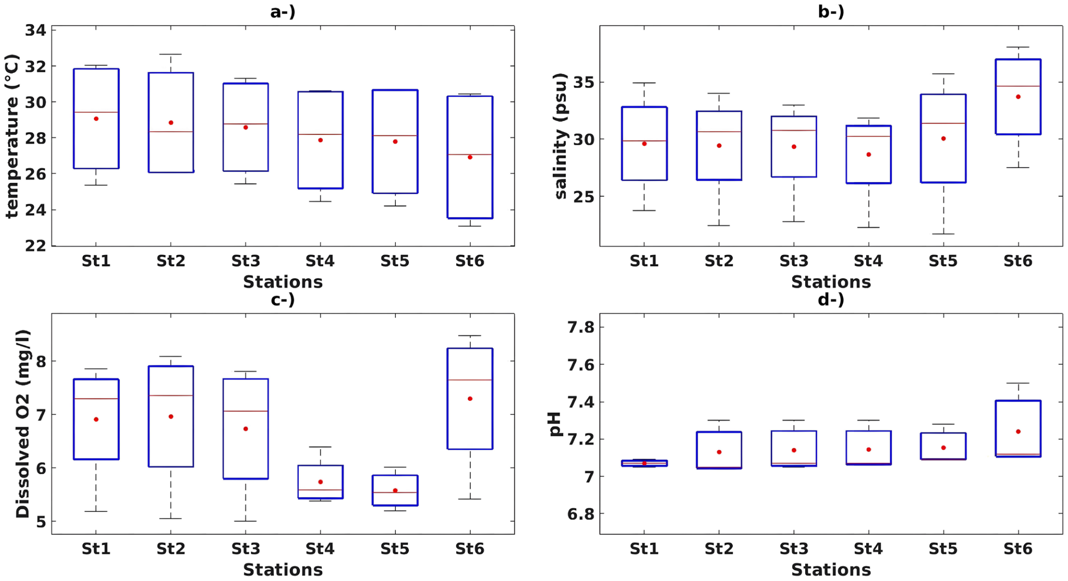


Figure 2. Spatial variation of environmental parameters: (a) temperature, (b) salinity, (c) dissolved oxygen, (d) pH) measured during the different sampling periods.

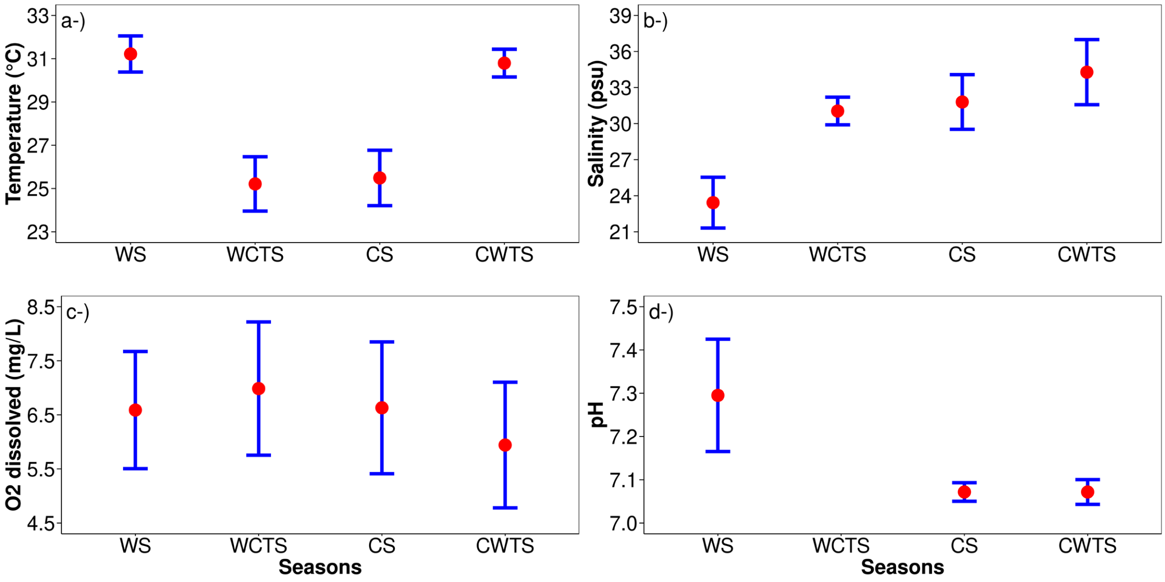


Figure 3. Seasonal variation of environmental parameters: (a) temperature, (b) salinity, (c) dissolved oxygen, (d) pH) measured during the different sampling periods: warm season (WS), warm-cold transition (WCTS), cold season (CS) and cold-warm transition (CWTS).

Salinity remains relatively uniform across stations, with a notable peak at ST6 (Figure 2(b)). However, it exhibits strong seasonal variations, reaching its highest levels in the dry season (34.28 ± 2.71 PSU) and dropping to a minimum during the rainy season (23.42 ± 4.2 PSU) (Figure 3(b)).

No distinct spatial trends were observed for dissolved oxygen (Figure 2(c)). However, a clear seasonal variation was evident (Figure 3(c)), with river waters being more oxygenated during WCTS (6.98 ± 1.23 mg/L) and less oxygenated during CWTS (5.94 ± 1.16 mg/L).

A slight upward trend in pH was observed (Figure 2(d)), indicating increased alkalinity closer to the sea. However, pH measurements could not be recorded during WCTS campaigns due to probe failure.

Statistical analyses revealed no significant spatial variation in these environmental variables ($p > 0.05$), but significant seasonal differences were detected ($p < 0.05$).

3.2. Spatial and Temporal Variation of Mineral Elements

Sulphate concentrations in the river are consistently high and relatively uniform, with a mean value of 1756.66 ± 763.96 mg/L (Figure 4(a)). However, strong seasonal variation was observed, peaking during CWTS (2666 ± 595 mg/L) and reaching a minimum during WCTS (933 ± 366 mg/L) (Figure 5(a)).

Phosphate concentrations showed slight variation between stations, with the highest recorded value (0.24 mg/L) at station ST2 (Figure 4(b)).

Nitrate exhibited a moderate upward trend, with a mean concentration of 0.114 ± 0.055 mg/L (Figure 4(c)). Strong seasonal variation was observed, with the highest concentration recorded during CWTS (0.383 ± 0.231 mg/L) and the lowest

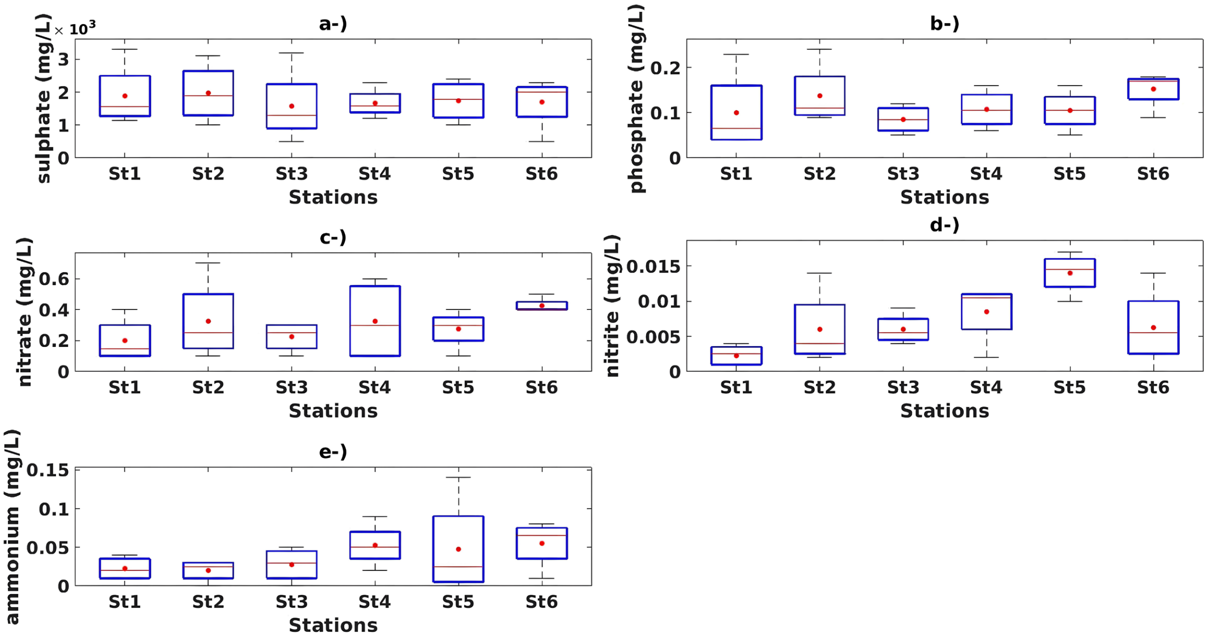


Figure 4. Boxplot of nutrient concentrations by station, with mean values represented by red dots: (a) sulphate, (b) phosphate, (c) nitrate, (d) nitrite and (e) ammonium.

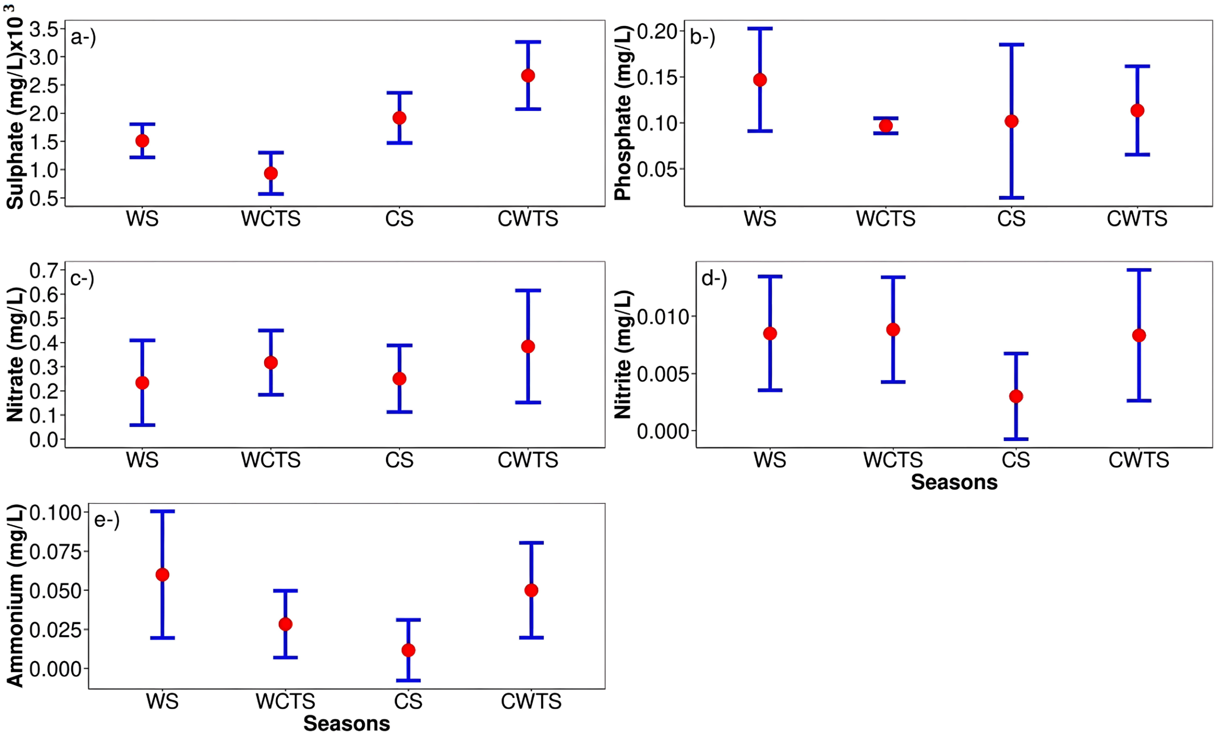


Figure 5. Seasonal variability of mean concentrations (red dots) and standard deviations (blue lines) of: (a) sulphate, (b) phosphate, (c) nitrate, (d) nitrite and (e) ammonium.

during winter (0.233 ± 0.175 mg/L) (Figure 5(c)). Nitrite concentrations increased significantly from ST1 (0.002 ± 0.001 mg/L) to ST5 (0.014 ± 0.002 mg/L) before decreasing at ST6 (0.006 ± 0.005 mg/L) (Figure 4(d)). Seasonally, nitrite levels remained relatively stable, with a slight decrease observed in CS (**Figure 5(d)**). Ammonium showed a moderate increase from 0.020 ± 0.014 mg/L at ST2 to 0.055 ± 0.031 mg/L at ST6 (**Figure 4(e)**). The highest concentrations were recorded during the rainy season (WS) (0.06 ± 0.04 mg/L), while the lowest occurred in CS (**Figure 5(e)**).

Statistical analysis indicated that, except for nitrite ($p < 0.05$), none of the other mineral elements exhibited significant spatial variation ($p > 0.05$). In terms of seasonal variability, all elements showed significant seasonal differences ($p < 0.05$), except for phosphate ions ($p > 0.05$).

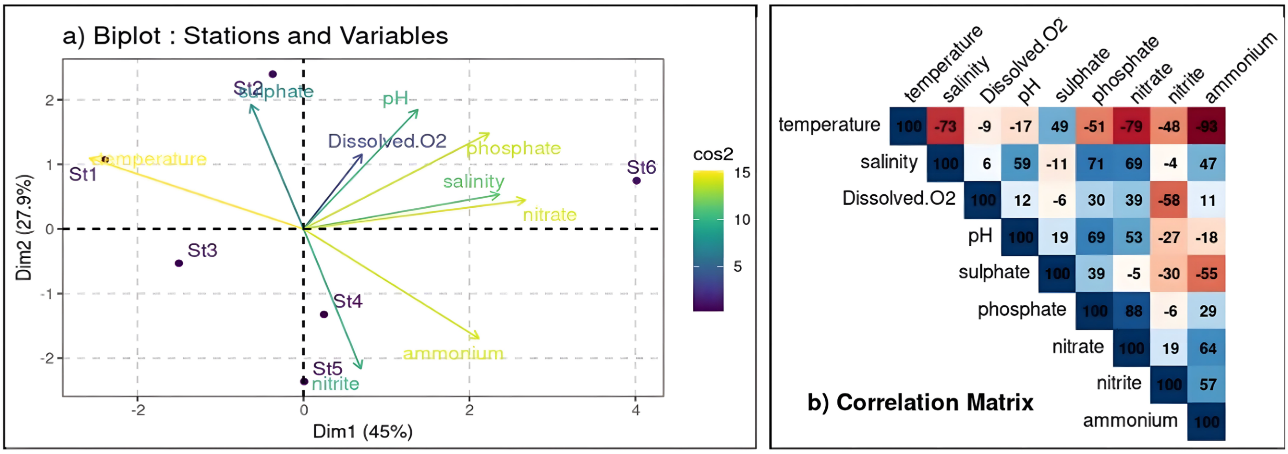
3.3. Multivariate Analysis

1) Spatial relations between environmental variables

Figure 6(a) shows that the two principal axes, explaining over 72.9% of the variance, effectively represent the studied variables. Most variables are well represented on the correlation plan (**Figure 6(a)**). Except for sulphate, phosphate, nitrite, and dissolved oxygen, the remaining variables are correlated with the primary (horizontal) axis, which accounts for 45% of the variance.

The correlation matrix (**Figure 6(b)**) illustrates relationships between environmental variables and mineral elements. Analysis reveals a significant antagonistic relationship between temperature and both nitrate and ammonium. Salinity and pH are positively correlated with the spatial variation of phosphate and nitrate. Dissolved oxygen shows a significant negative correlation with nitrite.

Additionally, a negative correlation is observed between sulphate and ammonium, while phosphate follows a spatial pattern similar to nitrate. Nitrate and nitrite are positively correlated with ammonium.



	temperature	salinity	Dissolved.O2	pH	sulphate	phosphate	nitrate	nitrite	ammonium
temperature	100	-73	-9	-17	49	-51	-79	-48	-93
salinity		100	6	59	-11	71	69	-4	47
Dissolved.O2			100	12	-6	30	39	-58	11
pH				100	19	69	53	-27	-18
sulphate					100	39	-5	-30	-55
phosphate						100	88	-6	29
nitrate							100	19	64
nitrite								100	57
ammonium									100

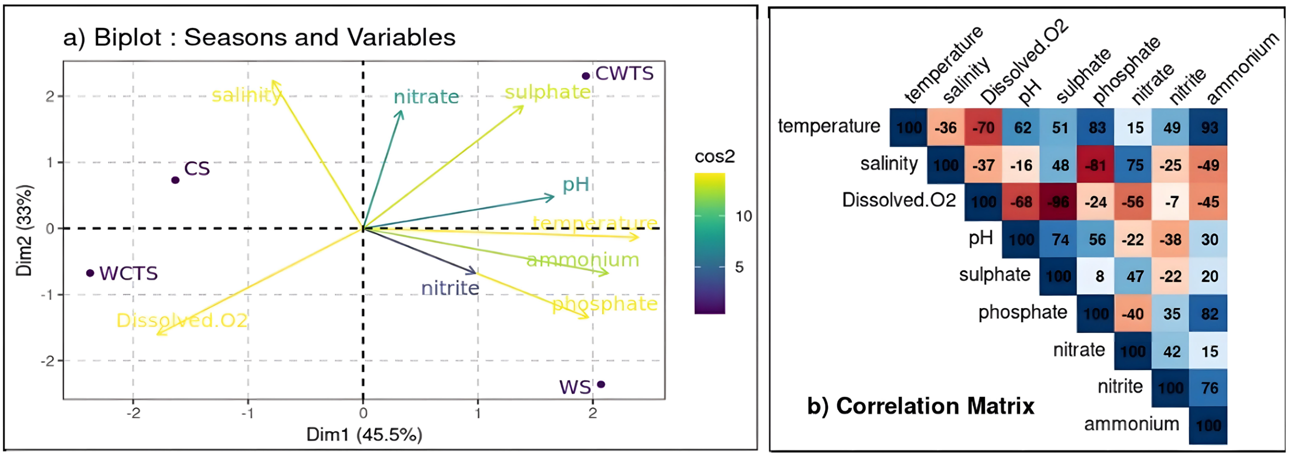
Figure 6. Multivariate analysis of spatial variations in physico-chemical parameters and mineral elements: (a) biplot of stations and parameters on the factorial plane and (b) correlation matrix.

A projection of the sampling stations and studied variables (**Figure 6(a)**) reveals that station ST6, located near the river mouth at Carabane, exhibits the highest concentrations of nitrates and phosphates, as well as the highest salinity values.

Stations ST1 and ST3, situated upstream of Ziguinchor, record the warmest water temperatures, while ST2 shows the highest sulphate concentrations. Stations ST4 and ST5, located near the town of Ziguinchor, display elevated levels of nitrites and ammonium.

2) Seasonal relations between mineral elements

The seasonal relationships between the different parameters studied are analyzed in Figure 7. The first two principal axes of the PCA explain 78.5% of the total variance, indicating a good representation of the variables involved (Figure 7(a)).



a) Biplot : Seasons and Variables

b) Correlation Matrix

	temperature	salinity	Dissolved.O2	pH	sulphate	phosphate	nitrate	nitrite	ammonium
temperature	100	-36	-70	62	51	83	15	49	93
salinity		100	-37	-16	48	-81	75	-25	-49
Dissolved.O2			100	-68	-96	-24	-56	-7	-45
pH				100	74	56	-22	-38	30
sulphate					100	8	47	-22	20
phosphate						100	-40	35	82
nitrate							100	42	15
nitrite								100	76
ammonium									100

Figure 7. Multivariate analysis of seasonal variations in physico-chemical parameters and mineral elements: (a) biplot of stations and parameters on the factorial plane and (b) correlation matrix.

The projection of seasons and studied parameters onto the factorial plane reveals distinct seasonal patterns (Figure 7(a)). The rainy season (WS) is characterized by high temperatures, elevated pH, and increased ammonium and phosphate concentrations. CWTS records average salinity, nitrate, and sulphate values, while CS and WCTS exhibit the highest salinity and dissolved oxygen levels.

4. Discussion

4.1. Analysis of the Spatial and Seasonal Variability of Environmental Parameters

The seasonal variation of surface temperatures in the estuary exhibits minimum values between the transitional warm-cold season (WCTS) (25.21˚C ± 1.25˚C) and the dry season (CS) (25.48˚C ± 1.28˚C), with maximum values reaching 31.21˚C ± 0.83˚C during the warm season (WS). This temperature gradient aligns with fluctuations in air temperature within the lower atmospheric layers, which are in direct contact with the surface water masses.

The Lower Casamance region experiences relatively low temperatures during the boreal winter, with a pronounced cool period between December and March encompassing the WCTS and CS periods. In contrast, higher temperatures prevail during the summer months, corresponding to the CWTS and WS periods. These air temperature variations significantly influence the observed seasonal changes in the estuary's water temperature. Additionally, the measured temperatures indicate a gradual cooling of the water masses as one approaches the estuary's mouth. This observation is consistent with findings from previous studies, such as those by [25], which analyzed temperature patterns across Senegal and observed similar cooling trends in coastal regions. These temperature dynamics are further influenced by regional climatic patterns. For instance, research by [26] highlighted the impact of sea surface temperature anomalies on atmospheric conditions over the Tropical Atlantic, affecting coastal regions like Casamance. The temperature values obtained during the present study (October 2022 to December 2023) are comparable to those reported by [27] in the Niamone-Kalounay Marine Protected Area (MPA), encompassing stations ST3, ST4, and ST5. In their study, conducted from July 2020 to June 2021, temperatures ranged from 20˚C to 33.5˚C, with an average of 27.39˚C ± 3.15˚C. This consistency in temperature ranges between the two studies suggests a stable thermal environment in the region over the past few years.

Salinity levels in the Casamance estuary exhibit significant seasonal variability, with minimal values during the warm season (WS) (23.42 ± 42 psu) and relatively uniform values during other seasons. This decrease in WS can be attributed to freshwater influx from rainfall runoff during the rainy period, which coincides with October 2022 measurements. In contrast, during the dry season, salinity levels rise, peaking at 34.28 ± 2.71 psu during the transitional cold-warm season (CWTS, May-June). This increase is accompanied by a longitudinal salinity gradient, primarily due to marine water intrusion and intense evaporation characteristic of this period [28]. The Casamance River functions as an inverse estuary, with salinity increasing upstream during the dry season. This phenomenon results from limited freshwater inputs and high evaporation rates, leading to saltwater intrusion [29]. Studies have documented this inverse salinity gradient, noting that salinity increases with distance from the mouth during the dry season [28] [30]-[32]. This dynamic explains the relatively high salinity observed at station ST1 (34.9 psu in CWTS), located upstream. However, the highest salinity values are found at station ST6, near the estuary mouth, where marine influence is more pronounced.

Dissolved oxygen concentrations measured at the surface during the different seasons were all greater than or equal to 5 mg/L. These values suggest a favorable ecological status for aquatic fauna, in line with the critical dissolved oxygen thresholds below which adverse effects on aquatic life may occur [33]-[35]. Moreover, the elevated dissolved oxygen concentrations observed during the WCTS and CS periods at station ST6 (**Figure 2(c)**) can be attributed to the drop in water temperature during these periods (**Figure 2(a)**). Colder water has a higher capacity to retain dissolved oxygen [36].

Regarding pH, the recorded values ranged from 7.04 to 7.5, with the exception of WCTS (where no measurements were taken). These results indicate a slightly neutral environment, consistent with the criteria for natural water, which should typically have a pH between 6 and 8.5 [37].

Principal component analysis (PCA) applied to the different parameters studied revealed correlations that varied both spatially and seasonally. Spatially (**Figure 6**), the results indicate that cold water bodies near the estuary (ST6) generally have higher salinity and contain elevated concentrations of phosphates and nitrates. Seasonally, the PCA (**Figure 7**) shows that during the warm season (WS), dissolved oxygen (O_2) concentrations are relatively low, while concentrations of phosphate, nitrite, and ammonium are high. In contrast, the transitional cold-warm season (CWTS) is characterized by saltier waters with increased concentrations of sulphates and nitrates [28] [30].

4.2. Analysis of the Chemical and Ecological Quality of Water in the Estuary

Mineral elements are essential parameters for evaluating the ecological and chemical quality of surface waters. This quality can be assessed according to criteria defined by various organizations and regulatory frameworks, notably the Water Framework Directive [38], which establishes a framework for the management and protection of water resources at the European level [39].

The sum of mineral nitrogen elements (MNE) analyzed in this study (nitrate + nitrite + ammonium) shows concentrations in the estuary ranging from 0.264 ± 0.132 mg/L in the cold season (CS) to 0.441 ± 0.243 mg/L during the cold-warm transition saison (CWTS). These values indicate good water quality, according to the thresholds defined by the WFD (in mg/L) for transitional water bodies (very good: [0 - 0.252], good:]0.252 - 0.756], moderate: > 0.756) [40]. Additionally, all nitrate and nitrite concentrations recorded in this study remain well below the chronic thresholds for aquatic life, set at 3.60 mg/L [41].

Phosphates (PO_4^{3-}) originate mainly from phosphate fertilisers used in agriculture, domestic wastewater, and the decomposition of organic matter. Excessive quantities can lead to eutrophication, promoting the growth of harmful algae and reducing the concentration of dissolved oxygen [12]. Run-off during the rainy season increases the input of phosphates into aquatic ecosystems, which could explain the observed increase in their concentration in SC. The measured values (ranging between 0.096 ± 0.008 mg/L and 0.146 ± 0.055 mg/L) indicate moderate water quality, according to the WFD (very good: [0 - 0.028], good:]0.028 - 0.094], moderate: >0.094) [39]. These concentrations are also close to the natural levels observed in surface waters, generally ranging between 0.1 and 0.2 mg/L PO_4 [42].

Sulfate ions originate from the dissolution of marine salts, notably sodium sulphate and magnesium sulphate, as well as from anthropogenic sources such as industrial effluents and agricultural activities. these ions play a key role in maintaining the ionic balance of living organisms. However, high concentrations in aquatic environments can have adverse effects on plants and animals. In particular, they can disrupt the osmoregulation of organisms (*i.e.* sodium osmotic imbalance), which can have consequences for the survival, growth and/or reproduction of individuals and populations [43]. The average concentrations observed in this study (with the exception of WCTS) exceed the critical threshold of 1000 mg/L, beyond which adverse effects may be observed in certain aquatic ecosystems [44].

The Casamance estuary has been relatively understudied in recent decades. The bibliographic review conducted as part of this study did not reveal any specific research assessing mineral element concentrations in this estuary. However, water quality studies have been carried out in other regions of Senegal, particularly along the northern coasts and in the Senegal River. A recent study in the Sangomar Protected Area (Senegal) shows that concentrations of mineral elements, particularly nitrates, phosphates and ammonium, vary seasonally but remain below international water quality standards [45].

In Dakar, the concentrations of phosphates (1.1 to 30 mg/L), ammonium (9.80 to 12.90 mg/L), nitrates (0.8 to 19.7 mg/L), and nitrites (0.01 to 0.07 mg/L) reported by [46] are significantly higher than those measured in the Casamance estuary. This difference can be explained by the high level of anthropogenic activity in the Dakar coastal zone, where large amounts of wastewater and organic waste are discharged into the marine environment [47].

In the Senegal River, [37] observed nitrate concentrations significantly higher than those measured in the Casamance estuary, especially during the rainy season (3.1 to 5.5 mg/L). In contrast, the nitrite concentrations recorded by [37] (0.01 to 0.019 mg/L) are comparable to the results obtained in this study.

5. Conclusion

This study provides insights into the physico-chemical quality of the Casamance estuary waters, emphasizing the spatial and seasonal dynamics of key environmental parameters, including temperature, salinity, pH, dissolved oxygen, and mineral elements. The results generally align with the environmental standards set by the Water Framework Directive (WFD), indicating the overall good ecological status of the estuary. However, elevated sulphate concentrations were observed, exceeding thresholds that could potentially harm certain aquatic ecosystems. These findings highlight the importance of continued and regular monitoring to ensure the preservation of ecological balance and to mitigate any potential environmental risks in the future.

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Conflicts of Interest

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

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