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Qualite des eaux souterraines riches en nitrates pour l'irrigation a Dakar, Senegal

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Using urban nitrate-rich groundwater for peri-urban irrigation in Dakar, Senegal: an evaluation of water quality concerns

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Contamination of urban groundwater from faecal effluent in sewered and unsewered areas is a widespread constraint to its use for water-supply provision. Here, we present the first multi-annual (2018–2024) assessment of the hydrogeochemistry and irrigation suitability of urban groundwater from the Thiaroye Aquifer. Groundwater samples (n = 225) were collected from 25 sites comprising boreholes, dug wells, hand pumps, and piezometers prior to, and following the monsoon over a seven-year period (2018–2024). Dominant facies groups are Na-K-SO4-Cl and Ca-Mg-SO4-Cl; chloride largely derives from anthropogenic sources including wastewater and on-site sanitation. Application of standard indices of water quality for irrigation (RSC, SAR, and %Na) reveal marked spatial heterogeneity, with 57% of groundwater samples classified as suitable for irrigation. Several wells (PD1, Pts 58, NP3, PAWS, F30), located in densely populated peri-urban areas with agricultural activity, exhibited elevated sodium concentrations limiting their suitability for use in irrigation. Recharge from monsoonal precipitation does not consistently result in the dilution of solute concentrations in shallow groundwater due, in places, to high pollutant loads from the surface and shallow subsurface, and impeded, lateral groundwater flow. Critically, nitrate concentrations reach up to 813 mg/L, significantly surpassing the agronomic thresholds for nitrate-sensitive crops like tomatoes, carrots, and onions cultivated in the Niayes. Coupled with the well-documented faecal contamination of the Thiaroye aquifer, this study suggests that pre-treatment methods such as biological denitrification or reverse osmosis are necessary before this urban groundwater can be safely utilized for irrigation at the most contaminated sites. These findings highlight the spatial heterogeneity of groundwater quality within the Thiaroye aquifer and suggest that targeted management strategies, combining controlled pumping with appropriate treatment and land-use planning, are essential to enhance irrigation potential while mitigating urban groundwater flooding in Dakar.

KEYWORDS
agriculture, groundwater management, hydrogeochemistry, Senegal, urban groundwater

1 Introduction

Groundwater remains a vital source of domestic water supply in many urban areas worldwide but is increasingly threatened by contamination through urbanization (Lapworth, 2017; WHO, 2022; Abascal et al., 2022; Howard, 2023). Rapid urban expansion in many low- and middle-income countries has led to higher population densities, an expansion of impervious surfaces, and inadequate sanitation infrastructure, which collectively contribute to the degradation of groundwater quality. These urban pressures facilitate the transport to groundwater systems of faecal pollutants such as nitrate and microbial pathogens, along with a growing range of emerging contaminants (Lapworth et al., 2012; Vystavna et al., 2017; Jurado et al., 2022; Pouye et al., 2023). Over the last few decades, numerous studies have reported that sanitation systems, unregulated waste disposal, and insufficient wastewater treatment exacerbate the contamination of urban aquifers (Kulabako et al., 2007; Nayebare et al., 2020; Pouye et al., 2023; Taylor et al., 2009; Etuk et al., 2025). Groundwater in many urban areas is increasingly at risk, requiring integrated urban planning and water resource management to ensure water security and the long-term sustainability of water use.

Urban groundwater contamination is a growing concern in the drylands of sub-Saharan Africa and other low- and middle-income countries around the world (Lapworth, 2017). One of the primary sources of contamination is low-cost, on-site sanitation systems that rely on the subsurface for the disposal and containment of human excreta (Kulabako et al., 2007; Nayebare et al., 2020; Pouye et al., 2023; Sorensen et al., 2020a, 2020b; Taylor et al., 2009). In the shallow unconfined aquifer of Quaternary sands underlying Dakar (Senegal), previous studies using faecal-indicator bacteria, geochemical and isotopic tracers have reported gross faecal contamination of shallow groundwater (Diédhiou et al., 2012; Re et al., 2010; Faye et al., 2019; Pouye et al., 2023). This insight is corroborated by additional research showing widespread contamination in which a strong relationship exists between the density of on-site sanitation facilities and elevated nitrate concentrations in shallow groundwater (Diaw et al., 2020; Pouye et al., 2022; Sorensen et al., 2020a, 2020b).

Rapid urbanization, coupled with increasing pollution of local water resources, has led many cities to reduce their dependence on on-site water supplies and increase their reliance on imported water (Dos Santos et al., 2017). Mounting groundwater contamination is particularly pronounced in low-income communities within rapidly expanding cities across tropical Africa and Asia, where infrastructure and governance mechanisms can lag behind population growth. These demographics highlight systemic challenges to integrated water management under increasing urbanization and climate variability (OECD et al., 2021). In Dakar, reductions in urban groundwater withdrawals on the Cap Vert peninsula for public water supplies (Figure 1) have led to the importation of water from: (1) surface water via a pipeline from Lake de Guiers 250 km away that currently represent 50% of the city's drinking water supply; and (2) groundwater from aquifers east of the Cap Vert peninsula that include deep Maastrichtian sands, Paleocene limestones, and northern coastal Quaternary sands (Diouf et al., 2020; Pouye et al., 2022).

Rising groundwater levels in urban aquifers have been reported in sub-Saharan tropical Africa over recent decades. Documented cases remain relatively limited and tend to occur in specific hydrogeological and urban settings. Beyond Dakar, where groundwater rise and recurrent flooding are well established (Faye et al., 2019; Diouf et al., 2020), similar dynamics have been reported in Niamey, Niger (Hado et al., 2021) and Abomey-Calavi in southern Benin, where rapid land-use change and increased recharge have led to groundwater flooding in several neighbourhoods (Houéménou et al., 2020). Two distinct mechanisms have been proposed to elucidate this trend. The first mechanism involves enhanced recharge due to the intensification of monsoonal rainfall under climate change, a phenomenon observed across tropical Africa (Faye et al., 2019; Kotchoni et al., 2019; Owor et al., 2009; Seddon et al., 2021; Taylor et al., 2013). The second mechanism pertains to reduced groundwater abstraction coupled with land-cover changes in urban areas, which has been demonstrated to facilitate water table rise in several Sub-Saharan African cities, including Niamey (Leduc, 2001; Favreau et al., 2009), Ouagadougou (Nakolendousse, 2018), and Bamako (Traoré, 2015). In the Cap Vert peninsula, progressive expansion of piped water supply from imported water sources lessened reliance on local wells and led to a reduction in groundwater abstraction from shallow aquifers. This shift favoured groundwater renewal, particularly in areas where pumping pressures had previously exceeded recharge rates.

Rising groundwater levels are not uniformly observed in cities across sub-Saharan Africa. Continued reliance on urban groundwater resources has led to groundwater depletion in some cities including Nairobi (Oiro et al., 2020) and Dodoma (Mndolwa et al., in review). In Dakar, the combination of limited drainage infrastructure, low-lying topography, and a shallow unconfined aquifer system underlying rapidly expanding low-income neighbourhoods makes the city particularly vulnerable to groundwater flooding during the rainy season (Faye et al., 2019; Diouf et al., 2020; Diop et al., 2019). In many peri-urban settlements such as Kampala (Tumwebaze et al., 2023), housing has encroached on former wetlands and natural depressions where the water table rises close to, or above, ground level during periods of intense rainfall. Groundwater flooding is particularly evident in the Cap Vert Peninsula where groundwater dynamics have been strongly influenced by historical water-supply practices. Between the 1950s and the 1980s, Dakar relied primarily on groundwater abstraction from the Thiaroye aquifer of Quaternary sands underlying the Cap Vert peninsula, supplying at times nearly half of the city's water demand. Rising nitrate contamination reduced the suitability of urban groundwater for public water supply. Consequently, the water supply for Dakar and its periphery increasingly depended from imported water sources. The subsequent cessation of pumping led to rising groundwater levels that today exacerbate urban flooding. Socio-economically, recurrent flooding disproportionately affects vulnerable populations who have limited ability to relocate or invest in protective infrastructure (Rezende et al., 2020). Urban flooding has long been recognised as one of the most significant climate-related hazards in Senegal. Reports from the national disaster management agency (DPC, 2008) highlight that a large portion of the population is exposed to flood risk, particularly in the eastern and peri-urban zones of Dakar where groundwater levels respond strongly to seasonal recharge.

In this context, the study offers three novel contributions. First, it presents the first multi-annual (2018–2024) record of hydrogeochemical monitoring for the Thiaroye aquifer, comprising 225 samples across 25 sites. This dataset allows for the characterization of temporal trends and inter-annual variability in groundwater quality. Second, it provides a systematic spatial assessment of irrigation suitability using three complementary indices (SAR, %Na, RSC) simultaneously, uncovering pronounced spatial heterogeneity not previously documented at this scale for this aquifer. Third, it explores two major

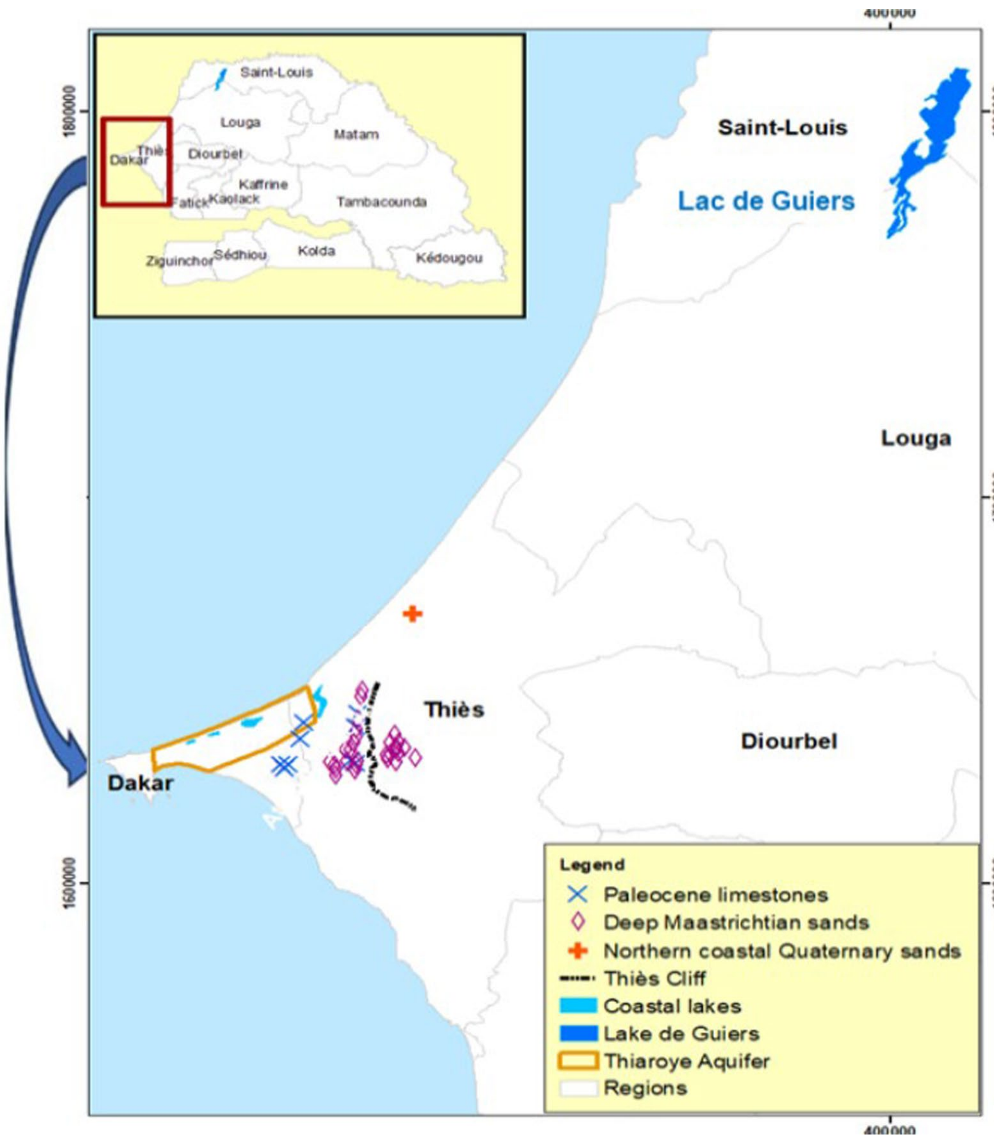

FIGURE 1
Location of Dakar and the Cap Vert peninsula as well as the sources of public water supplies on the peninsula imported from Lake de Guiers to the north (Louga Region) and aquifers (e.g., Deep Maastrichtian sands, Paleocene limestones, northern coastal Quaternary sands) to the east in Thiès Region. The inset map shows the location of the study area within Senegal in West Africa.

regional challenges: mitigating groundwater flooding through controlled pumping and facilitating the productive use of nitrate-contaminated groundwater for peri-urban agriculture, drawing on the Bengal Water Machine concept (Shamsudduha et al., 2022).

2 Study area

The Quaternary sand aquifer of Thiaroye underlies much of the Cap Vert Peninsula, the westernmost part of Senegal and Africa (Figure 1). It is located between the north latitudes 14°25′ and 15°05′ and west longitudes 16°55′ and 17°32′, and bordered to the north, south and west by the Atlantic Ocean, and to the east by the Thiès Plateau. The climate is semi-arid as mean annual precipitation and potential evapotranspiration are, respectively, 389 mm and 1950 mm/year. Rainfall is seasonal, with 80% of the precipitations recorded in July, August, and September. Recent observations highlight the magnitude of inter-annual variability as 296 mm rain fell in 2021 and 798 mm in 2022 (Pouye et al., 2023).

These climatic conditions, coupled with rapid urban expansion, have exerted significant pressure on local water resources and the overall hydrogeological balance (OECD et al., 2021). Historically, Dakar's drinking water was sourced, in part, from the shallow Thiaroye aquifer. In 1952, a wellfield in the Thiaroye aquifer contributing 15,000 m^3 per day to the urban water supply network was put into operation. Over time, the combination of inadequate sanitation infrastructure and increasing population density progressively degraded the groundwater quality in the Thiaroye aquifer, primarily due to nitrate contamination from domestic (faecal) wastewater. These factors significantly diminished the potability of water, with nitrate concentrations reaching up to 500 mg/L in parts of the wellfield (Faye, 2001; Mandioune et al., 2011). Consequently, a significant shift in water supply strategy was initiated in the late 20th century with the development of water transfer infrastructure from Lake de Guiers (Figure 1). The pipeline, which became operational in 1984, has been expanded multiple times to accommodate the increasing demand of the Dakar metropolitan area. Currently, about 50% of the drinking water supply is imported from the lake, which is located approximately 250 km away; the remainder comes from aquifers in Thiès (Figure 1), which include deep Maastrichtian sands, Paleocene limestones, and northern coastal Quaternary sands (Diouf et al., 2020; Pouye et al., 2022). The surface geology comprises unconsolidated sands of the Quaternary and Eocene marl and clay, which outcrop in the southern part of the Senegalese Mauritanian basin (Hébrard, 1966; Elouard and Hebrard, 1976; Barusseau and Gaye, 1983; Bellion, 1987; Sarr et al., 2008; Figure 2).

The Cap-Vert Peninsula contains several types of aquifers grouped into two large hydrogeological units, as originally outlined by Martin (1970); see also Henry (1972) and further corroborated by subsequent research (Chaoui, 1996; Faye et al., 2019). The first unit consists of Quaternary sands extending over the Peninsula tip and along the northern coast, forming a continuous and homogeneous layer subdivided into three aquifers: the Infra-Basaltic, Thiaroye, and Littoral Nord aquifers. The second unit, the Horst de Diass, comprises both Tertiary formations, including Paleocene limestones, marls, and Eocene limestone layers; and Secondary formations represented by the Maastrichtian layer.

This study focuses on groundwater within Quaternary sands that form the Thiaroye aquifer on the Cap Vert peninsula. The latter occupies an area of approximately 300 km^2 from Dakar to Kayar in the northeastern coastal zone of Senegal; deposits are mainly composed of clayey, coarse, and aeolian sands (Hébrard, 1966). Hydraulic conductivity (K) ranges from 10^{-3} to 10^{-5} m/s (OMS, 1972; Faye, 2001); specific yield (S_y) is ~20%, estimated from pumping tests and laboratory column tests (Martin, 1970; Diédhiou et al., 2012).

The study area is undergoing rapid land-use change driven by population growth and urban expansion. These transformations have progressively reduced the extent of the Niayes, a distinctive geomorphological zone consisting of interdunal depressions with shallow groundwater and fertile soils, historically used for intensive vegetable production. This contraction of the Niayes landscape reflects increasing pressure from urban development and has important implications for groundwater dynamics and land-based livelihoods. The Niayes constitute a significant employment area, specifically through market gardening, which produces more than 50% of the country's demand for fruits and vegetables (ANSD, 2023). Notably, this zone is also the main site where shallow urban groundwater, often affected by nitrate contamination, is extracted and reused for irrigation, directly linking groundwater management to agricultural practices in the Niayes.

3 Materials and methods

3.1 Groundwater sampling and analysis

Groundwater quality monitoring involved field testing (wellhead measurements) and the collection of 225 groundwater samples from 25 locations including boreholes, piezometers, dug wells, and hand pumps during pre-monsoon (April to May) and post-monsoon

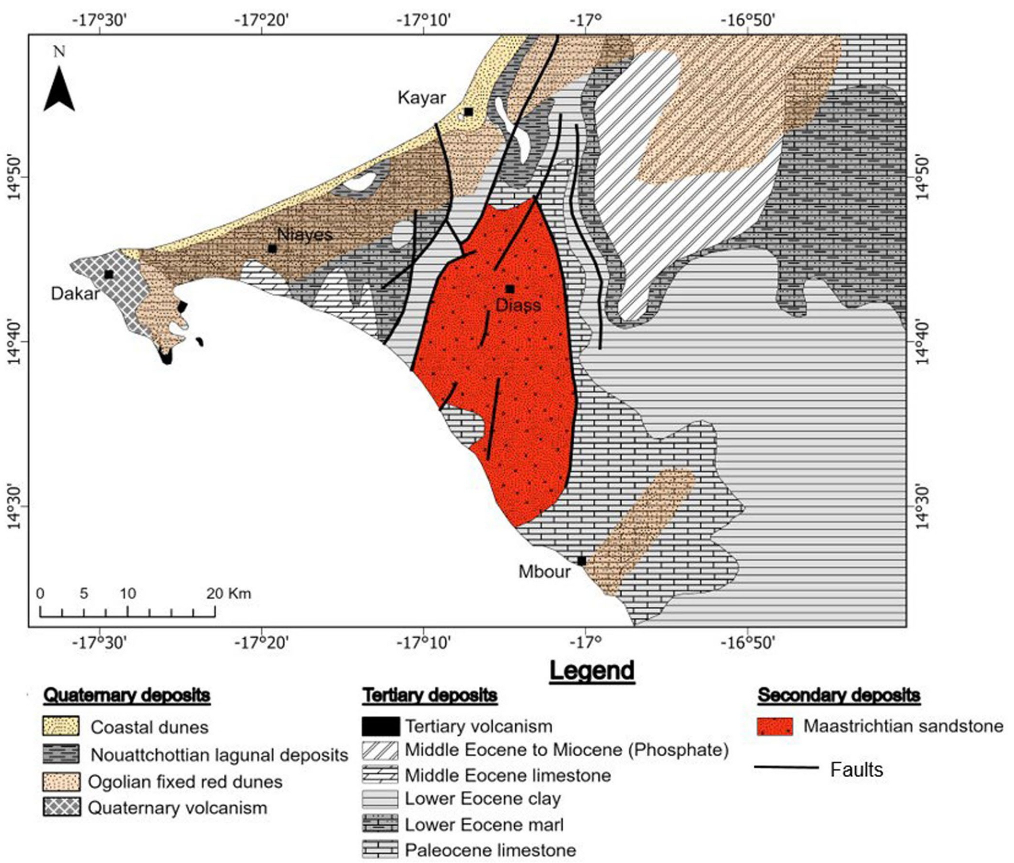

FIGURE 2
Geological map of the Cap Vert Peninsula (Elouard and Hebrard, 1976, modified).

(October to November) seasons from 2018 to 2024 (Figure 3). Electrical conductivity (EC), temperature (T°C), Total Dissolved Solids (TDS), pH, and Dissolved Oxygen (DO) were measured *in situ* using a Hydrolab Quanta© multiparameter probe. The samples were stored in high-density polyethylene bottles. Chemical analyses of pre-filtered water samples (0.22 µm) for major-ion concentrations were performed using a Dionex™ Aquion™ Ion Chromatography System (ThermoFisher Scientific, Waltham USA) in the hydrochemistry laboratory of the Cheikh Anta Diop University of Dakar (Geology Department). All 225 samples exhibited a Charge-Balance Error of less than ±5%.

3.2 Statistical analysis

Principal Component Analysis (PCA) was conducted on 9 hydrochemical variables (Ca^{+2}, Mg^{+2}, Na^{+1}, K^{+1}, HCO_3^{-1}, Cl^{-1}, SO_4^{-2}, NO_3^{-1}, and EC) using the Factor Analysis module of OriginPro software (OriginLab Corporation). This analysis was applied to the standardized correlation matrix, which included 225 samples. In accordance with the Kaiser criterion (eigenvalue >1; Kaiser, 1960), two factors were retained: Factor 1 (eigenvalue = 4.6, explaining 51% of total variance) and Factor 2 (eigenvalue = 1.6, explaining 18%), resulting in a cumulative, explained variance of 69%. Both eigenvalues exceed 1, meeting the Kaiser criterion. Varimax rotation was applied to enhance the interpretability of the factor loadings. To enhance the interpretability of the factor loadings, Varimax rotation was employed (Kaiser, 1958), a method commonly used in hydrogeochemical research (Helena et al., 2000; Cloutier et al., 2008; Hamzaoui-Azaza et al., 2017).

To assess seasonal variations in groundwater hydrochemistry, the Mann–Whitney *U* test (Mann and Whitney, 1947) was employed to analyze EC and NO_3^- concentrations at each sampling well, as well as the entire pooled dataset over the monitoring period (2018–2024). This test is a non-parametric, two-sided test with a significance level of $\alpha = 0.05$. The Mann–Whitney *U* test was selected over parametric alternatives due to the non-normal distribution of most hydrochemical variables and the unpaired nature of the pre- and post-monsoon sampling campaigns. The test statistics are given in Equations 1–3. For two independent samples of sizes n_1 (pre-monsoon) and n_2 (post-monsoon), all $n_1 + n_2$ observations are ranked together in ascending order, and two *U* statistics are calculated:

$$U_1 = n_1 n_2 + n_1 (n_1 + 1)/2 - R_1 \tag{1}$$

$$U_2 = n_1 n_2 + n_2 (n_2 + 1)/2 - R_2 \tag{2}$$

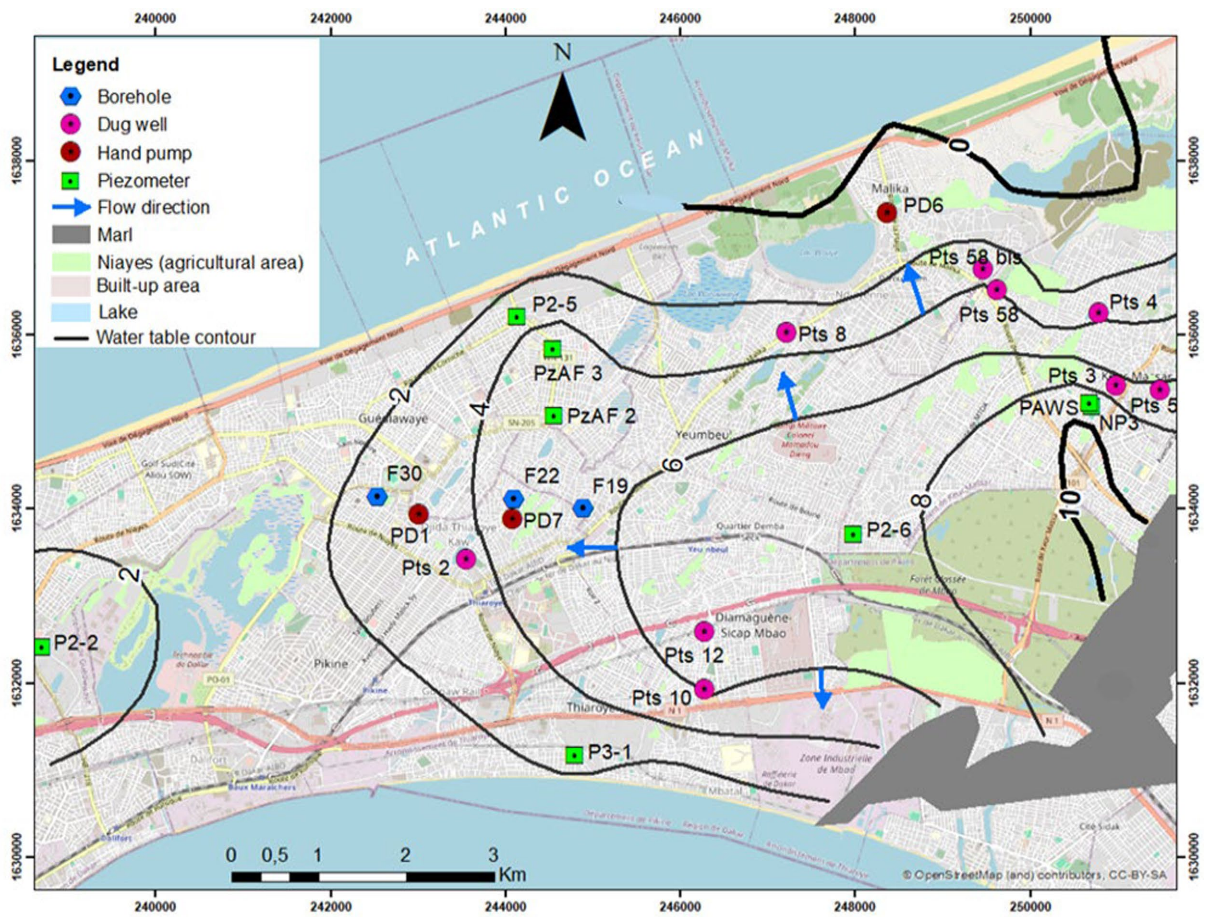

FIGURE 3
Map showing the location of sampled wells during 2024 dry-season measurements with Niayes and interpolated contours of hydraulic head (contour interval: 2 m; units: m a.m.s.l) in the Thiaroye urban aquifer of Quaternary sands in the central section of the Cap Vert peninsula; the location of an aquitard of marl limestone is indicated (grey shading) in the southeast corner of this map.

where R_1 and R_2 are the sum of ranks assigned to the observations of each group when all $n_1 + n_2$ observations are ranked jointly in ascending order. The test statistic is:

$$U = \min(U_1, U_2) \quad (3)$$

3.3 Irrigational quality parameters

In the study area, shallow groundwater is the primary source of crop irrigation. To characterize the suitability for irrigation, the sodium adsorption ratio (SAR; Richards, 1954), percentage of soluble sodium (%Na; Wilcox, 1955), and residual sodium carbonate (RSC; Eaton, 1950; McGeorge, 1954) indices were used.

3.3.1 Sodium adsorption ratio (SAR) and percentage of soluble sodium (%Na)

The sodium adsorption ratio (SAR) is an index used in soil science and water quality assessment to evaluate the amount of sodium (Na^+) relative to calcium (Ca^{2+}) and magnesium (Mg^2+) in water, particularly in irrigation water (Richards, 1954). It is expressed as:

$$SAR = Na^+ / \sqrt{\left(Ca^{2+} + Mg^{2+}\right)/2} \quad (4)$$

SAR indicates the potential for sodium accumulation in the soil, which can affect soil structure and plant growth (Todd, 1980; González et al., 2016). Its permissible value depends on the salinity of the environment (Table 1).

The percentage of soluble sodium (%Na) reflects the proportion of sodium and potassium ions relative to other major cations in water (Wilcox, 1955). It is expressed as:

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

Where all cationic concentrations are expressed in meq/L. %Na replaces the adsorbed calcium and magnesium. High concentrations of salt damage the soil structure, making it compact and impermeable (Vasanthavigar et al., 2011; Taloor et al., 2020).

3.3.2 Residual sodium carbonate

Residual sodium carbonate (RSC) indicates the amount of carbonate and bicarbonate relative to the calcium and magnesium ions in water (Eaton, 1950). It is expressed as:

$$RSC = \left(HCO_3^- + CO_3^{2-}\right) - \left(Ca^{2+} + Mg^{2+}\right) \quad (6)$$

Where all ion concentrations are in meq/L.

The RSC is important because an excess bicarbonate ion can deteriorate the soil structure by the deposition of sodium carbonate (Pivić et al., 2022). Groundwater is suitable for irrigation if the RSC is less than 1.25, marginal if the RSC ranges from 1.25 to 2.50, and unsuitable if it is higher than 2.50 (Li et al., 2012; Ravikumar et al., 2013).

TABLE 1 SAR classification for irrigation water (Richards, 1954).

SAR range	Interpretation
0 to 10	Suitable for irrigation
10 to 18	Low sodium hazard
18 to 26	Harmful to all types of soil
>26	Unsuitable for irrigation

4 Results

4.1 Typology of groundwater and hydrogeochemical processes

A summary of the physicochemical parameters measured during the pre- and post-monsoon seasons from 2018 to 2024 in the urban groundwater of Thiaroye is reported in Table 2. Results of the geochemical analyses are reported in Supplementary Table S1 of the Electronic Supplementary material. In the pre-monsoon, pH values varied from 3.8 to 8.1, with a mean of 6.7. This monitoring period also exhibits a higher standard deviation (*s*) in the mean (3.5), reflecting high spatial variability in pH across the sampled wells. In post-monsoon, the pH of sampled groundwater became more alkaline with values ranging from 6.2 to 9.6 and a mean value of 8.2; a lower standard deviation (*s*) in pH (0.7) suggests a more homogenized groundwater chemistry. The temperature of the collected groundwater samples ranged from 20.5 to 37.6 °C, with a mean value of 29.4 °C during the pre-monsoon. In post-monsoon, the values varied from 21.3 to 31.6 °C, with a mean value of 27.5 °C. EC values varied from 375 to 3,310 µS/cm in the pre-monsoon (mean: 1,928 µS/cm) and similarly from 336 to 3,180 µS/cm in the post-monsoon (mean: 1,925 µS/cm), highlighting consistently high and low mineralizations of groundwater across both seasons. Dissolved oxygen (DO) concentrations in the Thiaroye aquifer are also generally consistent in pre-monsoon and post-monsoon periods. Values ranged from 0.3/0.4 to 3.5/3.7 mg/L; the mean value during the post-monsoon (2.1 mg/L) exceeds that of the pre-monsoon (0.9 mg/L). These values reflect, in places, evidence of intense microbial degradation of organic matter and high biochemical oxygen demand.

Figure 4a presents a graphical representation of the hydrogeochemical facies (Langelier and Ludwig, 1942) based on the concentration of major ions in Supplementary Table S1 of the Electronic supplementary material. The plot reveals the predominance of the alkaline sulphate–chloride (Na-K-SO4-Cl) and the alkaline-earth sulphate–chloride (Ca-Mg-SO4-Cl) facies, with no significant variation from one season to the other. However, a few samples (Pts 01, Pts 10, Pts 12, PD6, and PD7) possess an alkaline-earth bicarbonate (Ca-Mg-HCO3) facies, specifically during the post-monsoon season. In Figure 4b, high salinity (TDS > 10 meq/L) can be observed in most groundwater samples during both the pre-monsoon and post-monsoon seasons from 2018 to 2024. Exceptions include wells (Pts 01, PD5, and PD7) that are characterized by low salinity (TDS < 10 meq/L). Only wells NP3 and PAWS 4 showed very high salinity (100 < TDS < 1,000 meq/L), specifically during the post-monsoon period of 2024, which is consistent with the dominance of chloride (Na-Cl) facies.

To explore correlations among geochemical variables, a Principal Component Analysis (PCA) was performed on all variables in samples from 2018 to 2024 (Ca^{+2}, Mg^{+2}, Na^{+1}, K^{+1}, HCO_3^{-1}, Cl^{-1}, SO_4^{-2},

TABLE 2 Summary of the physicochemical parameters measured during the pre- and post-monsoon seasons from 2018 to 2024 in the urban groundwater of Thiaroye (n = 225).

Parameters	Pre-monsoon				Post-monsoon			
	min	max	$\bar{x}$	s	min	max	$\bar{x}$	s
T°C	20.5	37.6	29.4	2.4	21.3	31.6	27.5	4.7
pH	3.8	8.1	6.7	3.5	6.2	9.6	8.2	0.7
EC (μS/cm)	375	3,310	1,930	717	336	3,180	1,925	708
DO (mg/L)	0.3	3.5	0.9	0.6	0.4	3.7	2.1	0.6

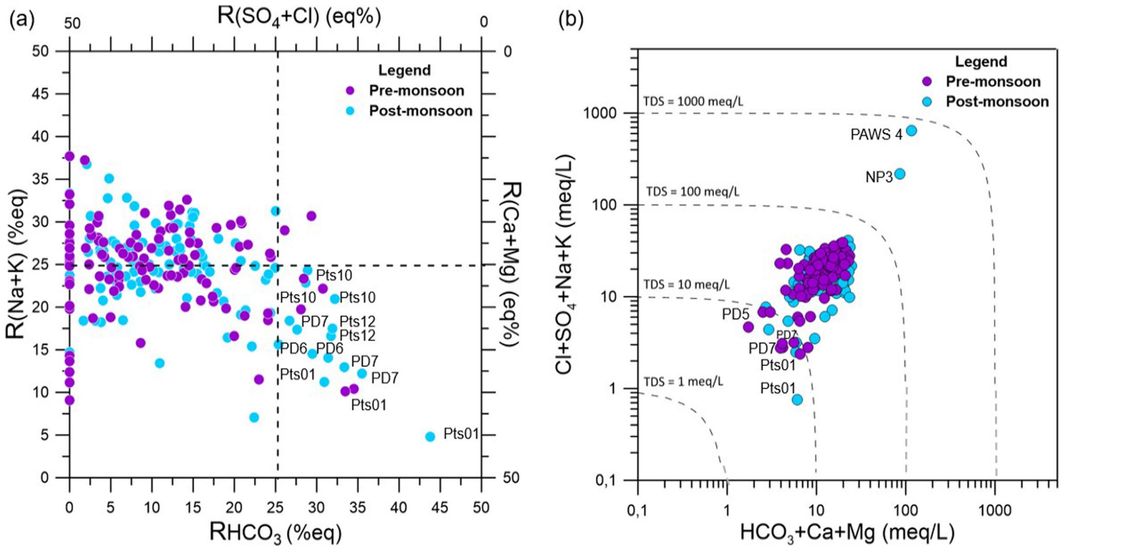

FIGURE 4
Langelier-Ludwig diagram **(a)** and Cl + SO_4 + Na + K versus HCO_3 + Ca + Mg diagram **(b)** for groundwater sampled from the urban Thiaroye aquifer from 2018 to 2024.

NO_3^{-1}, and EC). In Table 3 the results of the Varimax rotation are reported including the loadings, eigenvalues, amount of variance explained by each varifactor (VF). The results indicated a positive correlation between VF1 and EC, Cl^{-1}, NO_3^{-1}, Ca^{+2}, Mg^{+2}, Na^{+1}, and K^{+1}. However, VF2 was highly correlated only to HCO_3^{-1}. In Table 4 the correlation matrix for the PCA, which shows a good correlation between EC and major ions (Cl^{-1}, NO^{3-1}, Mg^{+2}, Na^{+1}, and K^{+1}) is presented. A strong correlation can be observed between Cl^{-1} and ions (Mg^{+2} and Na^{+1}); NO_3^{-1} and K^{+1}; Mg^{+2} and Na^{+1}.

To better evaluate the seasonal variations over the year on geochemical processes, bivariate plots were prepared during the pre- and post-monsoon seasons from 2018 to 2024 (Figures 5a–d). Figure 5a shows a strong correlation ($r \approx 0.89$) between Na^{+1} and Cl^{-1} values in groundwater. This pattern is consistent with previously established conceptual model for the region (Re et al., 2010; Diédhiou et al., 2012). We also noted a deviation of a few points from the 1:1 equiline and the freshwater–seawater dilution line, suggesting that part of the Na^{+1} may be derived from other processes (silicate weathering and/or cation exchange reactions). Figure 5b shows that most samples fall along the silicate degradation line. Figure 5c shows that most groundwater samples fall above the equiline with enrichment of $Ca^{+2} + Mg^{+2}$, a trend that indicates an excess of alkaline earths compared to the carbonates. Figure 5d shows an excess of chloride compared to sulphate in most groundwater samples. A few samples were characterized by an excess of sulphate (above the equiline), highlighting that part of the sulfate may be derived from natural contamination (evaporites dissolution) or anthropogenic pollution (wastewater, industrial, landfill or agricultural discharges).

TABLE 3 Factor loadings for PCA variables after varimax rotation. Values highlighted in bold represent relevant loadings for each varifactor (VF).

Variables	Factor1	Factor2
EC	**0.95**	0.1
HCO_3^{-1}	0.19	**0.86**
Cl^{-1}	**0.86**	−0.1
SO_4^{-2}	0.11	−0.82
NO_3^{-1}	**0.82**	0.02
Ca^{+2}	**0.60**	0.34
Mg^{+2}	**0.76**	0.13
Na^{+1}	**0.87**	−0.18
K^{+1}	**0.72**	0.14
Eigenvalue	4.61	1.59
Variance (%)	51.24	17.62
Cumulative (%)	51.24	68.86

Bold values indicate factor loadings ≥ 0.60, considered relevant contributions to each varifactor.

4.2 Urban groundwater suitability for irrigation

Groundwater suitability for irrigation was assessed using the RSC, SAR, and %Na indices (Equations 4–6). Table 5 shows that the residual sodium carbonate (RSC) values obtained during the pre- and

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TABLE 4 Spearman correlation matrix performed on the Thiaroye aquifer data collected between 2018 and 2024 (n = 225).

	EC	HCO_3^{-1}	Cl^{-1}	SO_4^{-2}	NO_3^{-1}	Ca^{+2}	Mg^{+2}	Na^{+1}	K^{+1}
EC	**1**								
HCO_3^{-1}	0.3	**1**							
Cl^{-1}	**0.8**	0.12	**1**						
SO_4^{-2}	0.03	−0.51	0.1	**1**					
NO_3^{-1}	**0.75**	−0.02	0.49	0.01	**1**				
Ca^{+2}	0.54	0.35	0.34	0	**0.63**	**1**			
Mg^{+2}	**0.72**	0.27	**0.72**	−0.06	0.54	0.32	**1**		
Na^{+1}	**0.86**	0.1	**0.89**	0.17	**0.57**	0.25	**0.62**	**1**	
K^{+1}	**0.63**	0.19	0.42	0.03	**0.71**	**0.57**	0.34	0.48	**1**
Color legend									
$r < 0$	$0 \le r < 0.2$	$0.2 \le r < 0.4$	$0.4 \le r < 0.6$	$0.6 \le r < 0.8$	$r \ge 0.8$				
Negative	Very weak	Weak positive	Moderate	Strong positive	Very strong				

Bold values indicate Spearman correlation coefficients $r \ge 0.6$ (strong to very strong correlation).

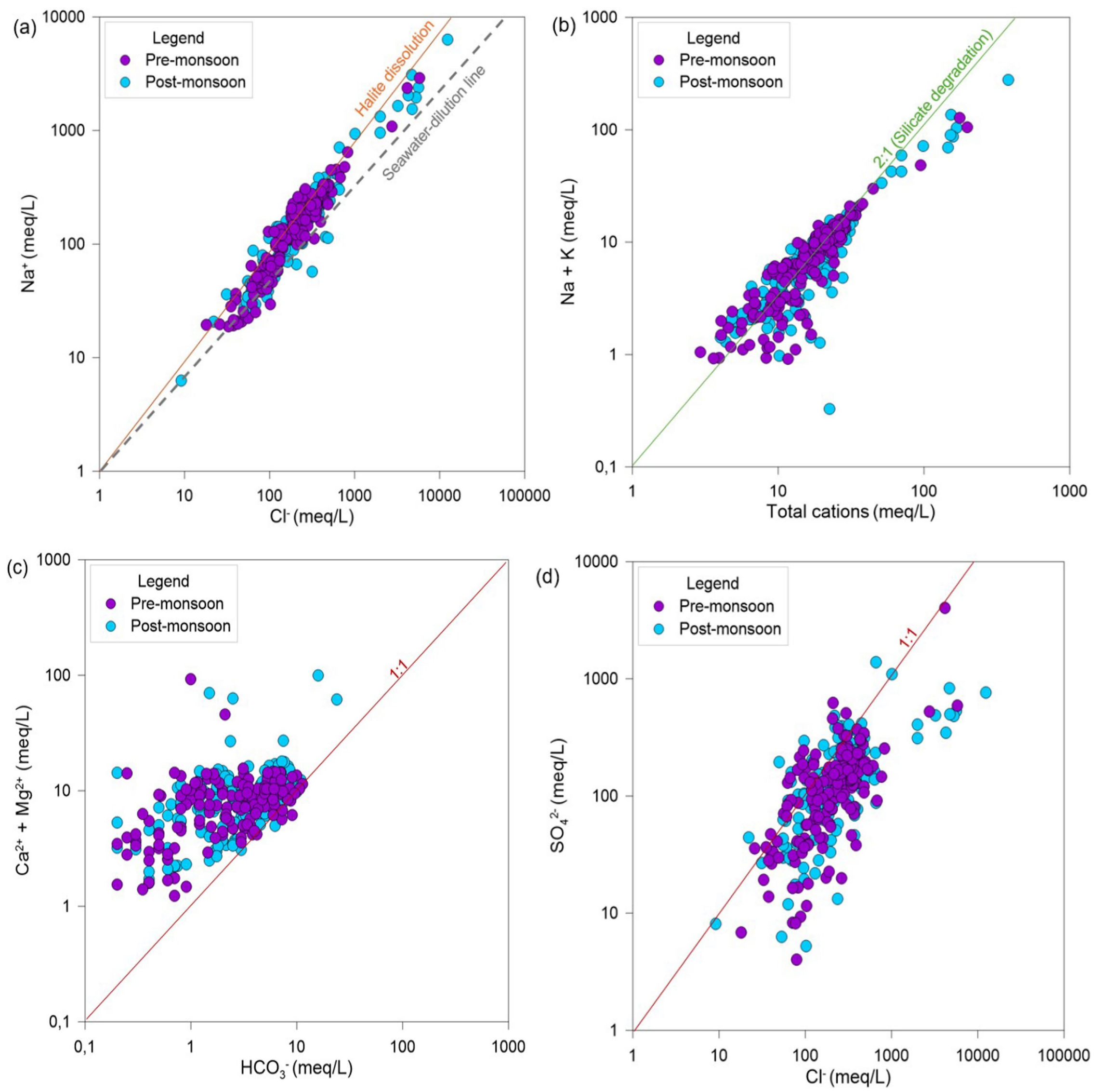

FIGURE 5
Bivariate hydrochemical plots of **(a)** Na^{+1} vs. Cl^{-1}, **(b)** Na^{+1} + K^{+1} vs. TC, **(c)** Ca^{+2} + Mg^{+2} vs. HCO_3^{-1}, and **(d)** SO_4^{-2} vs. Cl^{-1}.

post-monsoon periods from 2018 to 2024 in the Thiaroye urban aquifer are all negative, ranging from −0.1 to −13.6 meq/L. According to the classification adopted by Pivić et al. (2022), RSC values below 1.25 meq/L indicate suitability for irrigation. However, the strongly negative RSC values observed reflect a large excess of alkaline earth ions (Ca^{+2} and Mg^{+2}) over carbonates, which warrants a more nuanced agronomic interpretation. In the sandy Quaternary aquifer of Thiaroye, such excess may affect soil pH buffering capacity and interact with the high sodium concentrations indicated by SAR and %Na. RSC values should therefore be interpreted in conjunction with SAR and %Na rather than as a separate indicator of suitability.

Analytical results, plotted on the Riverside classification diagram (USSL) diagram (Rao et al., 2021), depict SAR versus electrical conductivity (Figure 6) to assess the suitability of sampled groundwater from the Thiaroye aquifer for irrigation purposes. When considering both the pre- and post-monsoon periods, ~10% of the 225 groundwater samples fall within the (C3-S1) class, which denotes a combination of low sodium content and low salinity hazard; these classes suggest good suitability for irrigation. Approximately 47 and 15% of the samples fall into the classes of (C4-S1) and (C4-S2), respectively, indicating high salinity to low and medium sodium content. These classes designate water acceptable for irrigation of salt-tolerant crops on well-drained soils or of good permeability, whose salinity must be controlled. 28% of the samples belong to the class of very high salinity to medium sodium content (C5-S2), which have limited applicability for irrigation purposes (Kawo and Karuppannan, 2018; Rawat et al., 2018).

As plants do not grow well in soils saturated with sodium, the classification of water points was carried out according to the Wilcox diagram (Wilcox, 1955), based on the electrical conductivity and sodium concentration in the water (Figure 7). Based on the Wilcox diagram, ~11% of the samples fell into the "excellent" class, ~32% were classified as "good," ~14% were categorized as "admissible," ~38% were "mediocre," and ~5% were "bad for irrigation purposes.

TABLE 5 Residual sodium carbonate (RSC) values in the Thiaroye urban aquifer of Dakar, Senegal.

Wells	Pre-monsoon	Post-monsoon	% difference
F19	−8.5	−7.8	8
F22	−4.9	−6.8	28
F30	−1.5	−3.4	56
NP3	−5.8	−5.9	2
P2-2	−10.9	−9.1	17
P2-5	−6.2	−2.9	53
P2-6	−9.2	−5	46
P3-1	−4.6	−3.9	15
PAWS 4	−4.5	−6.5	31
PzAF 2	−5.9	−4.9	17
PzAF 3	−8.2	−8.1	1
PD1	−3.9	−4.4	11
PD5	−2.6	−1.5	42
PD6	−2.4	−2.5	4
PD7	−3.2	−3.2	0
Pts 01	−2.2	−0.1	96
Pts 2	−12.4	−11.2	10
Pts 3	−2.3	−2.6	12
Pts 4	−8.8	−8.3	6
Pts 5	−8.2	−11	26
Pts 8	−8.3	−5	40
Pts 9	−10.6	−6.3	41
Pts 10	−0.2	−3.9	95
Pts 58	−13.6	−12	12
Pts 58 BIS	−6.1	−5.4	12

4.3 Groundwater quality and monsoonal recharge effect on solute concentrations

The Thiaroye Quaternary sands aquifer is mainly recharged by precipitation during monsoon (Faye et al., 2019; Pouye et al., 2023; Diouf et al., 2022). Results from Mann–Whitney U test indicate that pre-monsoon and post-monsoon distributions are not significantly different across the full pooled dataset (EC: $U = 1928$, $p = 0.9$, Table 6; NO_3^{-1}: $U = 2{,}390$, $p = 0.8$, Table 7). This result statistically demonstrates that monsoon rainfall recharge does not significantly dilute high solute concentrations in the Thiaroye aquifer. This is consistent with the high anthropogenic pollutant loads from on-site sanitation and the impeded lateral groundwater flow that characterize this urban aquifer. Localized visual differences observed in the box plots (Figure 8) at wells P2-5, Pts 01, Pts 4, Pts 9, and Pts 10 are not statistically significant, indicating that apparent dilution in less densely populated areas does not reach the threshold of formal statistical significance given the dataset's variability. Similarly, the apparent post-monsoon increase in NO_3^- concentrations observed visually at several wells is not confirmed as statistically significant by the Mann–Whitney U test ($p > 0.05$ at all wells), suggesting that inter-annual variability in nitrate loading masks any consistent seasonal signal.

5 Discussion

In the Thiaroye urban aquifer, the predominant hydrochemical facies are Na-K-SO_4-Cl and Ca-Mg-SO_4-Cl. The presence of Cl^{-1} and SO_4^{-2} in the groundwater is likely influenced by a mix of sources, such as wastewater, leaching from soils and landfills, and water-rock interactions through the dissolution of sulphate minerals like gypsum and anhydrite. Although halite or silicate weathering might locally contribute to Na^{+1} and Cl^{-1} enrichment in Na-K-SO_4-Cl water types, the Quaternary sands in the study area lack substantial evaporitic halite deposits, suggesting that anthropogenic sources may play a dominant role. Despite experiencing heavy to extreme rainfall events, the seasonal variation in water types remains low, reflecting relatively stable hydrochemical conditions.

In pre-monsoon, factor analysis revealed that VF1 (55% of the total variance) was highly correlated with EC, Cl^{-1}, Ca^{+2}, Mg^{+2}, Na^{+1}, K^{+1}, and NO_3^{-1} (Figure 9). This factor can be interpreted as the effect of aquifer salinization, related to waste and salts accumulated in the soil and unsaturated zone leached to groundwater by infiltrating recharge (urban runoff, residual streams, or residual rainfall). Salinization can also be explained by faecal effluent from on-site sanitation systems, wastewater, and agricultural inputs. NO_3^{-1} and K^{+1} are

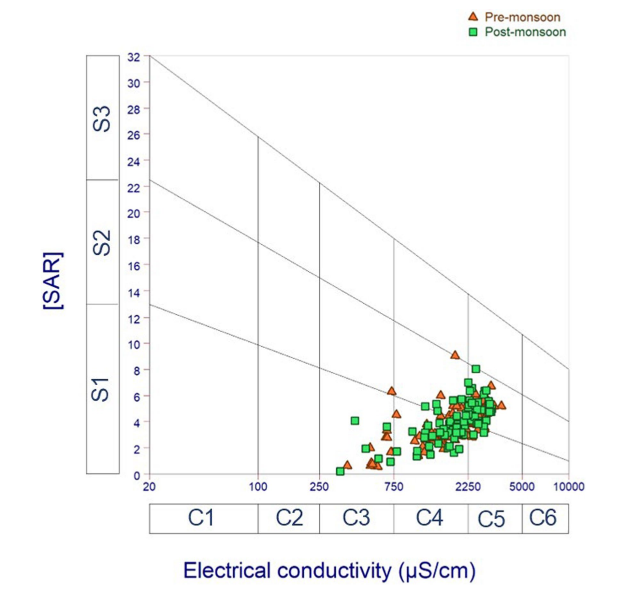

FIGURE 6
USSL diagram assessing the quality of pre- and post-monsoon sampled groundwater for irrigation from the Thiaroye aquifer in Dakar, Senegal.

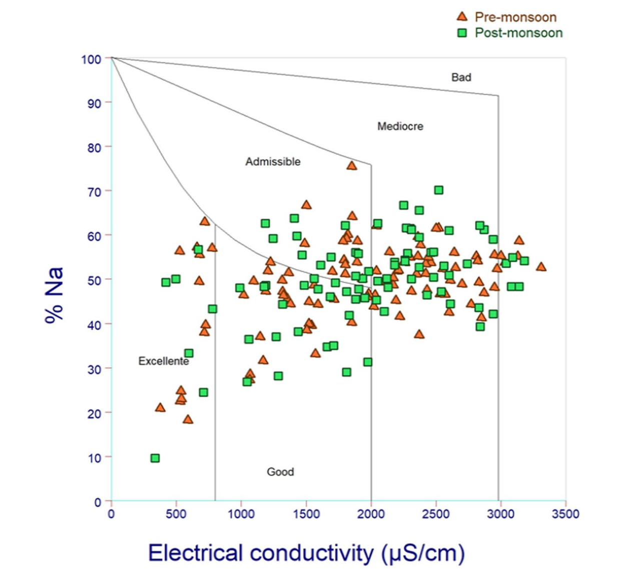

FIGURE 7
Wilcox diagram showing the suitability of groundwater from the Thiaroye aquifer in Dakar, Senegal for irrigation.

constituents of fertilizers and manure (Widory et al., 2004; Kendall et al., 2007; Gouaidia, 2017). The second factor, VF2 (16% of the total variance), was highly correlated with HCO_3^{-1} in pre-monsoon. This factor does not contribute to groundwater mineralization and can be interpreted as the effect of precipitation. Bicarbonate can also be generated in shallow groundwater from reactions with atmospheric CO_2 (Kump et al., 2014).

In post-monsoon, VF1 (46% of the total variance) was also highly correlated with Na^{+1}, Cl^{-1}, and Mg^{+2} (Figure 9c), resulting from natural geochemical processes. However, VF2 (28% of the total variance) was highly correlated with EC, NO_3^{-1}, Ca^{+2}, K^{+1}, and SO_4^{-2}. This factor may be attributed to faecal effluent from on-site sanitation systems, as recently highlighted by Pouye et al. (2025). The score plots (Figures 9b,d) indicate significant variability in mineralization across both seasons, with a pronounced effect in pre-monsoon. In both seasons, most samples exhibited high mineralization levels. However, peak mineralization was notably observed during the pre-monsoon season. These results support the hypothesis that in both seasons, the two main factors affecting groundwater chemistry are water-rock interaction processes and anthropogenic pollution. Both sources can negatively impact the overall quality of groundwater, making it less suitable for agricultural purposes.

No substantial dilution effect is observed on solute concentrations, particularly during the post-monsoonal period for NO_3^{-1} at wells F30, NP3, PD1, PAWS4, and Pts 58 (Figure 8b) during 7 years of groundwater quality monitoring. These observations can be explained by the combined effects of pollutant sources and recharge dynamics. In peri-urban areas of the Thiaroye aquifer, the high density of septic tanks and other anthropogenic sources generate a steady nitrate load to the unsaturated zone. As demonstrated by Pouye et al. (2023), intense monsoonal rainfall events can promote rapid vertical recharge that flushes accumulated nitrate from the soil and vadose zone towards the water table, resulting in sustained or increased NO_3^- concentrations after the rainy season rather than dilution. Similar observations have been made in Abuja, Nigeria by Etuk et al. (2025).

The near cessation of pumping from the urban aquifer on the Cap Vert peninsula led to a marked rise in groundwater levels, especially in the vicinity of production wells. As a consequence, comparatively steeper, lateral hydraulic gradients associated with the previous freshwater capture from pumping wells were replaced and reversed with gentler hydraulic gradient driving lateral groundwater flow towards coastal discharge zones. Combined with local drainage boundary conditions controlled by sea level, this weakening of lateral groundwater flow within the Cap Vert peninsula impedes groundwater drainage (Faye et al., 2019). As a result, groundwater flow is increasingly dominated by vertical recharge processes and longer residence times, which favour the persistence of nitrate in the predominantly sandy and granular Quaternary matrix where attenuation is limited.

In the coming years, renewed groundwater pumping for peri-urban irrigation could locally enhance freshwater capture in the Thiaroye aquifer by creating additional subsurface storage and inducing recharge from precipitation in a manner similar to the Bengal Water Machine (Shamsudduha et al., 2022). Pumping-induced drawdown may also temporarily mitigate urban flooding by increasing aquifer storage capacity. However, these potential benefits are dependent on land-cover conditions. The proliferation of impermeable surfaces associated with urbanization can constrain seasonal, diffuse recharge, restricting freshwater capture, and enhance surface runoff and the risk of flooding.

During the pre-monsoon and post-monsoon seasons from 2018 to 2024, all of the 225 groundwater samples were suitable for irrigation according to the RSC index, reflecting a predominance of alkaline earth ions over bicarbonates in the urban aquifer of Thiaroye. However, although RSC values remain within acceptable limits, continued long-term irrigation with these waters may progressively increase bicarbonate concentrations in soils, potentially leading to soil degradation, as highlighted by Pivić et al. (2022). The assessment of the suitability of water for irrigation using the SAR index yields results that differ from the RSC approach. The index shows that only 72% of groundwater samples are suitable for irrigation, a proportion that has similarly been observed in Senegal by Benam-Beltoungou et al. (2025). High SAR values reflect water unsuitable for irrigation and can affect soil structure and indirectly impact

TABLE 6 Mann–Whitney *U* test results comparing electrical conductivity (EC) between pre-monsoon and post-monsoon (2018–2024).

Well	*n* (pre)	*n* (post)	Median pre	Median post	Mean pre	Mean post	*U* statistic	*p*-value
F30	4	4	1,854	1,852	1,697	1,825	8	1
NP3	3	3	1,064	1,269	997	1,236	2	0.4
P2-2	4	3	2,315	2,300	2,325	2,320	5	0.9
P2-6	4	3	2,900	2,740	2,913	2,663	10	0.2
PAWS 4	4	3	1,440	1,410	1,556	1,656	5.5	1
PD1	4	3	1,820	1,900	1,708	1,901	5	0.9
PD 6	2	2	1,340	1,447	1,340	1,447	2	1
Pts 01	5	4	590	596	598	577	9	0.9
Pts 10	5	4	1,716	1,963	2,128	2,119	8	0.7
Pts 3	3	4	2,430	1,936	2,030	1,892	7	0.9
Pts 4	4	4	1,442	1,880	1,525	1,778	5	0.5
Pts 5	5	4	2,020	2,100	2,118	2,138	7	0.5
Pts 58	4	3	2,525	2,870	2,485	2,840	1	0.1
Pts 58 BIS	3	2	1,327	1,236	1,364	1,236	4	0.8
Pts 8	3	4	2,700	2,430	2,710	2,438	9	0.4
Pts 9	3	3	2,310	2,180	1,814	1,593	7	0.4
PzAF 2	3	3	2,300	2,370	2,390	2,363	4.5	1
PzAF 3	3	3	2,210	2,040	2,087	2,045	6	0.7
ALL WELLS (pooled)	66	59	1978	1951	1877	1903	1928	0.9

TABLE 7 Mann–Whitney *U* test results comparing nitrate concentrations between pre-monsoon and post-monsoon (2018–2024).

Well	*n* (pre)	*n* (post)	Median pre	Median post	Mean pre	Mean post	*U* statistic	*p*-value
NP3	3	4	67	263	102	327	2	0.2
P2-2	4	3	342	292	330	283	9	0.4
P2-5	4	4	315	156	326	169	15	0.1
P2-6	4	4	402	291	361	307	10	0.7
PAWS 4	4	4	22	33	63	106	6.5	0.8
PD1	5	4	302	334	306	326	9	0.9
PD 6	2	2	276	205	276	205	2	1
Pts 01	5	3	69	75	78	66	7	1
Pts 3	5	5	286	286	276	251	14	0.8
Pts 4	4	4	420	413	429	403	9	0.9
Pts 5	5	4	491	500	547	563	7	0.5
Pts 58	4	3	609	685	561	676	3	0.4
Pts 58 BIS	3	3	333	337	287	259	5	1
Pts 8	4	4	217	293	248	308	5	0.5
Pts 9	4	4	423	277	407	289	13	0.2
PzAF 2	4	3	203	217	223	223	6	1
PzAF 3	3	3	234	370	253	325	3	0.7
ALL WELLS (pooled)	72	65	287	286	289	287	2,390	0.8

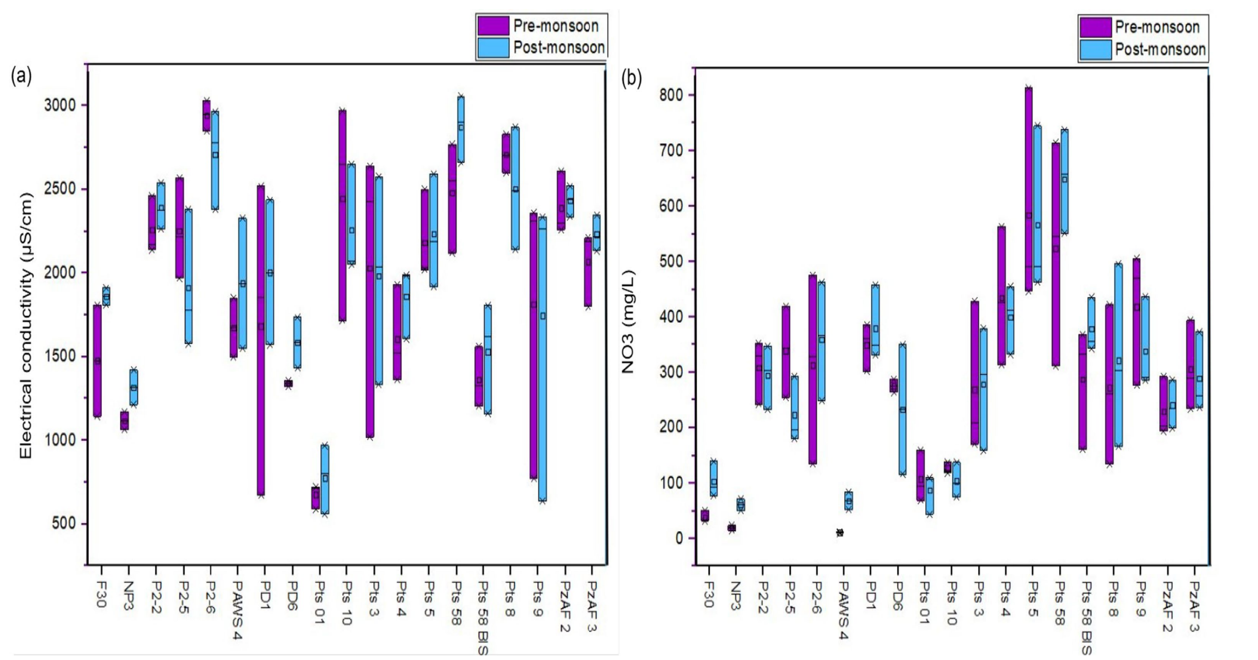

FIGURE 8
Box plots of **(a)** Electrical conductivity (EC) values and **(b)** $NO_3^{-}1$ concentrations in groundwater during pre- and post-monsoon periods showing variations from 2018 to 2024.

plant growth (Todd, 1980; González et al., 2016). The sodium percentage (%Na) showed that 57% of groundwater samples were good-to-acceptable for irrigation whereas 43% were mediocre-to-bad; the high proportion of sites unsuitable for irrigation can be attributed to significant mineralization, which reflects silicate weathering and/or cation exchange. The elevated percentage of sodium (%Na) in groundwater replaces the adsorbed calcium and magnesium ions, thereby compromising the soil structure and rendering it compact and impermeable (Vasanthavigar et al., 2011; Taloor et al., 2020).

Based on these three standard indices, the majority of the sampled groundwater (57%) can be considered suitable for agricultural use. Several wells (PD1, PD6, Pts58, NP3, PAWS, F30), located in Keur Massar and Malika (areas with high anthropogenic pressure), exhibit limited suitability, mainly due to elevated Na^{+1} concentrations. The reduced lateral groundwater flow and dominance of vertical recharge processes further limit solute dispersion, favouring the accumulation of Na^{+} in shallow groundwater. These findings highlight spatial constraints on the use of groundwater for irrigation in the Thiaroye aquifer and underline the need for site-specific management strategies when promoting groundwater-based peri-urban agriculture.

The three standard indices of water quality for irrigation show markedly different suitability rates (RSC = 100%; SAR = 72%; %Na = 57%), highlighting that each index captures a distinct aspect of water quality. In the Quaternary sands aquifer of Thiaroye, which has a low cation exchange capacity and is particularly vulnerable to sodium-induced structural degradation, SAR emerges as the most agronomically relevant index. The spatial interpolation of SAR and %Na values across the Thiaroye urban aquifer highlights spatial heterogeneity in irrigation suitability (Figures 10a,b). For the SAR index, most sampled wells fall within the "Doubtful" class ($6 < SAR < 9$), indicating a generally low sodium hazard across much of the Cap-Vert Peninsula. However, a localized zone of unsuitability ($9 \leq SAR < 14$) is identified in the western and central parts of the aquifer, centered around P2-2, F30, PD1, Pts 2, F22, F19 and Pts 9, as well as in the eastern part in well PAWS. This spatial pattern reflects the pronounced anthropogenic influence of on-site sanitation infrastructure in the densely populated peri-urban areas of Thiaroye and its surroundings, where sodium enrichment from domestic wastewater percolation is most intense.

The spatial distribution of %Na also reveals a "Good" class (<40%) located in the central and eastern parts of the Thiaroye urban aquifer, associated with well P2-5, F19, Pts 12, P2-6 and Pts 5, which benefit from relatively lower anthropogenic pressure and potential dilution by lateral inflow. A broad "Permissible" class (40–60%) encompassing the majority of the aquifer; and a "Doubtful" class (>60%) in wells F30 and PD1, confirming the spatial coincidence of sodium hazard identified by both indices. The spatial convergence of elevated SAR and %Na values at F30 and PD1 is particularly significant from a management perspective. These two wells are situated in densely populated urban areas characterized by high on-site sanitation density, limited natural recharge pathways, and restricted lateral groundwater flow. Their consistent identification as the least suitable sites for irrigation across both indices and multiple monitoring campaigns underscores the recommendation that groundwater from these locations should not be used for food-crop irrigation without prior treatment.

The Niayes region is one of Senegal's most crucial peri-urban agricultural zones, supplying over 50% of the country's vegetable needs (ANSD, 2023). Key crops such as tomatoes, carrots, and onions are particularly sensitive to high nitrate concentrations, with phytotoxicity thresholds significantly lower than the concentrations found in this study. Nitrate levels reaching up to 813 mg/L, approximately 16 times the WHO (2022) drinking water guideline of 50 mg/L greatly surpass agronomic thresholds and the nitrogen uptake capacity of crops in the Niayes. This situation poses risk to inadequate crop growth from the accumulation of nitrate in the matrix of the Quaternary sands of the

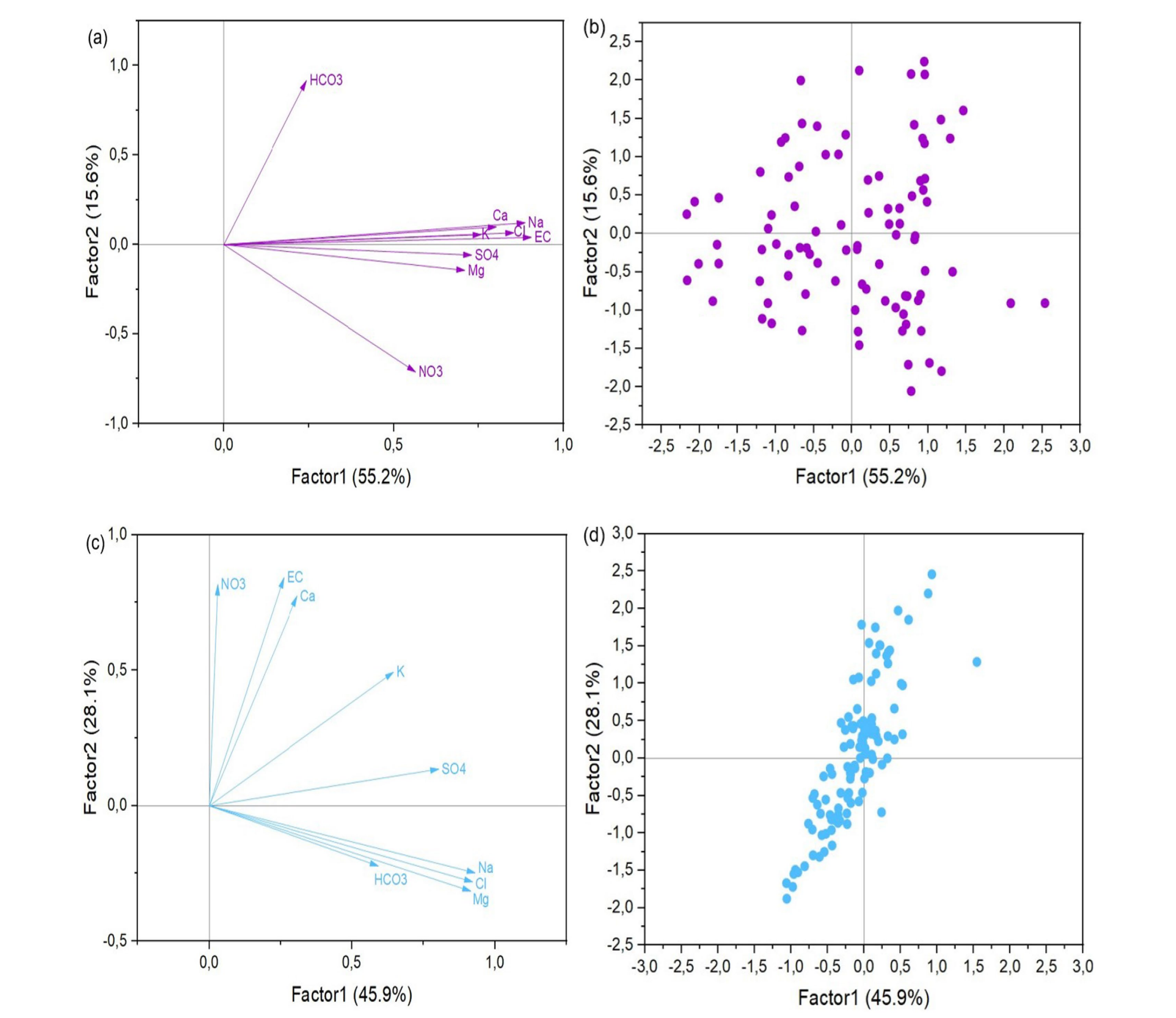

FIGURE 9
Loading plots **(a, c)** and score plots **(b, d)** in pre-monsoon (purple color) and post-monsoon (blue color).

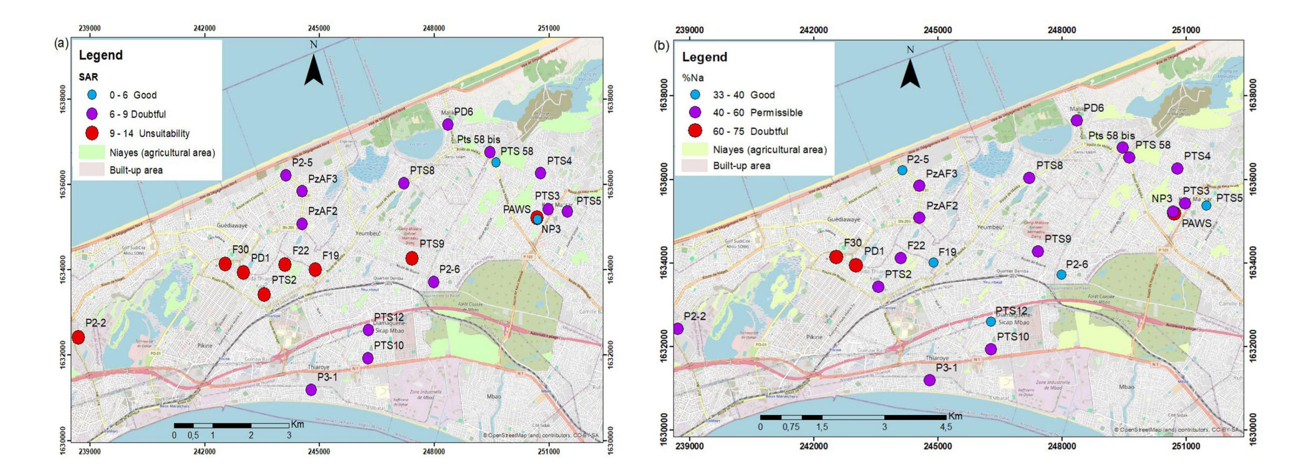

FIGURE 10
Spatial distribution of SAR **(a)** and %Na **(b)** irrigation suitability indices in the Thiaroye urban aquifer, Cap-Vert Peninsula, Dakar, Senegal (2018–2024).

Thiaroye aquifer, which is characterized by high hydraulic conductivity and limited attenuation capacity. If the use of this urban groundwater for irrigation is considered, pre-treatment options such as biological denitrification, ion exchange, or reverse osmosis would be necessary at the most contaminated sites before it can be safely used for food-crop irrigation (Neag et al., 2021; Barka et al., 2022).

The Thiaroye aquifer is known for its significant faecal contamination due to on-site sanitation (Diaw et al., 2020; Pouye et al., 2023). Although microbiological data were not gathered in this study, consistently low dissolved-oxygen levels (0.3–3.5 mg/L) observed throughout the monitoring network align with active microbial degradation of organic matter and ongoing faecal contamination, as confirmed by Sorensen et al. (2020a, 2020b) (Figure 11). Such microbiological risks are not captured by the SAR, %Na, or RSC indices evaluated in this study, and need to be addressed through dedicated microbiological monitoring before any irrigation scheme drawing on groundwater from the Thiaroye urban aquifer is implemented. Collection of site-specific microbiological data from the exploited aquifer are required to define appropriate treatment requirements for safe groundwater reuse in peri-urban agriculture.

The irrigation suitability findings from the Thiaroye aquifer can be contextualised against analogous studies on degraded groundwater and wastewater reuse for urban agriculture in West Africa and similar semi-arid settings. In the River Goulbi Maradi Basin, Niger, a semi-arid setting comparable to Dakar in terms of climate and agricultural context, only 76% of alluvial aquifer groundwater samples were suitable for irrigation based on SAR, %Na, and RSC (Issoufou Ousmane et al., 2023), similar to the 57% suitability observed in this study. In Burkina Faso, shallow groundwater assessed using SAR, %Na, RSC, and Kelly's ratio in the Karfiguéla paddy field was found to be 100% suitable for irrigation (Sauret et al., 2022). These comparisons highlight that the Thiaroye aquifer presents a significantly more challenging irrigation water quality context than comparable West African aquifers. This is largely due to the exceptionally high density of on-site sanitation infrastructure, impeded groundwater flow, and the absence of significant lateral recharge pathways in the Cap-Vert Peninsula.

While this study offers novel contributions, it is important to recognize several limitations. First, the sampling design exhibits irregularity throughout the monitoring period. Specifically, two seasons (pre- and post-monsoon) were sampled in 2018 and 2022, whereas only a single season was sampled in 2019, 2020, 2021, 2023, and 2024. This inconsistency restricts the systematic comparison of seasonal variability across all years, potentially introducing bias in the evaluation of inter-annual trends. Such bias should be considered when interpreting temporal patterns in groundwater quality. Second, the study did not include soil quality data, which hinders a direct assessment of the impact of groundwater irrigation on soil health, as well as potential salinization or sodification processes in the Niayes agricultural zone. Therefore, the integration of soil hydrochemical monitoring is strongly recommended for future research. Future research should include numerical groundwater flow modeling to facilitate the application of the Bengal Water Machine concept (Shamsudduha et al., 2022) in the Thiaroye aquifer. This approach, involving controlled pumping for irrigation, could concurrently alleviate groundwater flooding and enable the productive utilization of nitrate-contaminated water.

6 Conclusion

The suitability of urban groundwater from the Thiaroye Aquifer for peri-urban irrigation was assessed using a multi-tracer hydrogeochemical approach over a 7-year monitoring period (2018–2024). The findings suggest that while groundwater is conditionally suitable for irrigation, with 57% of the sampled wells meeting common chemical standards, a significant portion is unsuitable due to high sodium and salinity levels. Wells in densely populated and intensively cultivated peri-urban areas, such as Keur Massar and Malika, show hydrochemical characteristics that could threaten soil structure and crop productivity if not managed properly. Hydrochemical facies of groundwater, characterized by Na–K–SO_4–Cl and Ca–Mg–SO_4–Cl water types, reflect both natural geochemical processes and substantial anthropogenic inputs. High solute concentrations in some wells highlight the importance of vertical recharge pathways and prolonged groundwater residence times whereas areas benefiting from effective dilution exhibit improved water quality and greater irrigation suitability. These results underscore the pronounced spatial heterogeneity in groundwater quality across the aquifer, indicating that irrigation suitability cannot be uniformly assumed at the aquifer scale. Indeed, nitrate concentrations in the Thiaroye aquifer can reach up to 813 mg/L, 16 times the WHO drinking-water guideline concentration limit of

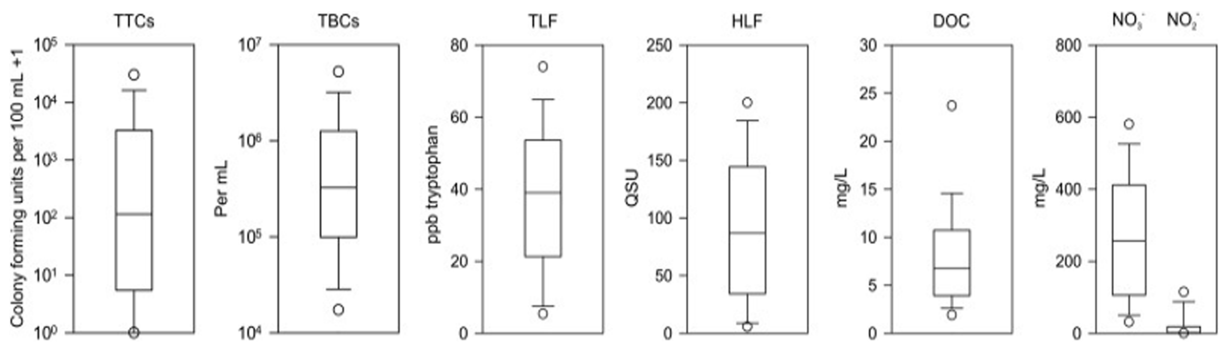

FIGURE 11
Boxplots of Thermotolerant Coliforms (TTCs), Total Bacterial Cells (TBCs), Tryptophan-Like Fluorescence (TLF), Humic-Like Fluorescence (HLF), Dissolved Organic Carbon (DOC), NO_3^- and NO_2^-. Box boundaries illustrate the 25th and 75th percentiles, the line within the box is the median, the whiskers are the 10th and 90th percentiles, and the circles are the 5th and 95th percentiles (n = 84; Sorensen et al., 2020).

50 mg/L. These high nitrate concentrations significantly surpass agronomic thresholds and the nitrogen uptake capacity of the main crops cultivated in the Niayes that include tomatoes, carrots, and onions. Use of groundwater with extreme nitrate concentrations poses substantial risks to crop growth of soil nitrate accumulation, nitrate leaching into the saturated zone, and potential runoff into urban lakes and coastal waters. The SAR, %Na, and RSC indices employed in this study do not account for nitrate risk, highlighting the necessity for a dedicated assessment of nitrate-specific irrigation risk. To safely utilize groundwater from highly contaminated sites for food-crop irrigation, pre-treatment methods such as biological denitrification, ion exchange, or reverse osmosis will be necessary. Beyond physicochemical parameters, the Thiaroye aquifer is known for significant faecal contamination from on-site sanitation, demonstrated by previous studies and consistently low dissolved oxygen levels (0.3–3.5 mg/L) observed in this study.

The proposed use of this urban groundwater for food-crop irrigation in the Niayes region raises critical microbiological risk concerns that are not addressed by inorganic hydrogeochemical indices employed here. Key exposure pathways include direct contact during irrigation, consumption of raw leafy vegetables, and aerosol inhalation during sprinkler irrigation. Future studies require site-specific microbiological data from the Thiaroye aquifer to determine appropriate treatment requirements and facilitate a formal microbial risk assessment before implementing any irrigation scheme based on this urban groundwater. Practically, these results offer a scientific basis for targeted, site-specific groundwater management rather than uniform aquifer-scale use or restriction. Controlled pumping of urban groundwater combined with protection of infiltration zones and land-use planning, can enhance freshwater capture, reduce solute accumulation, and mitigate urban groundwater flooding. However, the actual use of this groundwater for peri-urban agriculture will ultimately depend not only on hydrochemical suitability but also on the mitigation of nitrate and microbiological risks through appropriate treatment and, fundamentally, on the acceptance of treated groundwater by farmers and water managers in the Niayes.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MD: Writing – original draft, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Investigation, Methodology, Validation. AP: Formal analysis, Validation, Writing – review & editing, Investigation, Conceptualization, Methodology. VR: Conceptualization, Validation, Supervision, Writing – review & editing. CG: Conceptualization, Funding acquisition, Validation, Writing – review & editing. RT: Funding acquisition, Validation, Writing – review & editing. SF: Formal analysis, Data curation, Investigation, Conceptualization, Funding acquisition, Validation, Writing – review & editing, Supervision, Methodology.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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SUPPLEMENTARY TABLE S1
Full hydrochemical dataset (major ion concentrations, EC, pH, temperature, and dissolved oxygen) for all groundwater samples collected from the Thiaroye aquifer during pre- and post-monsoon campaigns, 2018–2024.

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