



Assessment of the physicochemical and isotopic suitability of groundwater for irrigation at the agricultural site of N'Djili Cecomaf, Kinshasa-DR Congo

[Evaluation de l'aptitude physico-chimique et isotopique des eaux souterraines à l'irrigation dans le site agricole de N'Djili Cecomaf, Kinshasa-RD Congo]

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Abstract

The objective of this study was to assess the physicochemical and isotopic quality of groundwater used for irrigation at the N'Djili Cecomaf agricultural site. The mixed approach used was based on hydrochemical and isotopic analyses combined with multivariate statistical analyses. The groundwater samples from the wells were collected during the rainy and dry seasons of 2023 for hydrochemical and isotopic analyses. The results showed that the groundwater is characterized by a dominant chemical facies of the chloride-calcium and magnesium type. PCA revealed weak positive correlations between Ca^{2+} , Mg^{2+} , NO_3^- , HCO_3^- , SO_4^{2-} , Cl^- and EC ions in both seasons. Furthermore, the waters are poorly mineralized, with a very low degree of salinity. Nitrate concentrations exceed 50mg/l and are an indicator of the pollution of these waters because of fertilizers and various manures used on the site, but also of contamination by the waters of the N'Djili River, which carry suspended solids, especially during the rainy season. The Oxygen-18/Deuterium and deuterium excess (d-excess) relationships showed that the water captured by these wells comes from meteoric waters resulting from the infiltration of rainfall during the rainy season and/or from interactions with the waters of the N'Djili River, which drain the lowland. These waters are beneficial for plant nutrition. Based on the sodium adsorption ratio, permeability index and magnesium absorption rate, these waters are excellent for irrigation.

Keywords : Assessment, physicochemical, isotopic, groundwater, irrigation.

Resumé

L'objectif de cette étude était d'évaluer la qualité physico-chimique et isotopique des eaux souterraines à l'irrigation dans le site agricole du N'djili Cecomaf. L'approche mixte utilisée était basée sur les analyses hydrochimiques et isotopiques combinées aux analyses statistiques multivariées. Des échantillons d'eau souterraine des puits ont été prélevés pendant la saison de pluie et la saison sèche en 2023. Les résultats obtenus montrent que ces eaux souterraines sont caractérisées par un faciès chimique dominant du type chloruré calcique et magnésien. L'ACP a révélé des faibles corrélations positives entre les ions Ca^{2+} , Mg^{2+} , NO_3^- , HCO_3^- , SO_4^{2-} , Cl^- et la CE pendant les deux saisons. Ces eaux sont peu minéralisées, avec un degré faible de salinité. La concentration en nitrate dépasse 50mg/l et constitue un indicateur de la pollution des eaux de suite de fertilisants et diverses fumures utilisées, mais aussi de la contamination par les eaux de la rivière N'Djili qui transporte de matières en suspension, au cours de la saison de pluie. Les relations Oxygène-18/Deutérium et de l'excès de deutérium ont montré que les eaux captées par ces puits proviennent des eaux météoriques issues de l'infiltration des précipitations pendant la saison de pluie et/ou des interactions avec les eaux de la rivière N'Djili qui drainent le bas-fond. Ces eaux sont bénéfiques pour la nutrition des plantes. Sur base du rapport d'adsorption de sodium, de l'indice de perméabilité, et du taux d'absorption de magnésium, il se dégage que ces eaux sont excellentes pour l'irrigation.

Mots-clés: Evaluation, physico-chimique, isotopique, eaux souterraines, irrigation.

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1. Introduction

The Democratic Republic of Congo (DRC) has a very dense hydrographic network occupying a surface area of almost 77810 km² compared with the surface area of the mainland, estimated at 2,267600 km² (Tshimanga et al., 2022). The land exploited annually covers only 10% of the 80 million hectares of arable land. In addition to surface water, groundwater is an important resource for the population of the DRC, particularly in areas where surface water resources are limited. It is estimated that groundwater from wells accounts for around 10% of the country's drinking water supply, and groundwater represents almost 47% of renewable water resources (Nkaba et al., 2022; Nsiala, 2012; Ndembo, 2009).

Of an estimated irrigation potential of 7 million hectares, only 65.000 hectares are irrigated (ANAPI, 2015; Banza, 2020 ; FAO, 2005). Groundwater can be a resource to capitalize on for irrigation, given the polluting nature of surface water, which is often used to irrigate crops. Unlike surface water, groundwater is less sensitive to seasonal and climatic fluctuations, making it more reliable for year-round irrigation.

The N'Djili river watershed, which covers part of the city of Kinshasa and the surrounding area, is a zone where peri-urban agriculture is highly developed. In this watershed, surface waters are subject to various forms of pollution, as it is an area of high demographic pressure, where various household wastes, wastewater, human excreta from latrines, industrial effluents and various wastes from car garages contribute to surface water pollution (Nsiala, 2012). The use of surface water for irrigation does not provide good-quality

agricultural produce for consumption by the general population of Kinshasa. Also, the soils of Kinshasa's agricultural perimeters have, for the most part, a low water retention capacity due to their sandy texture and particulate structure (Shomba, et al., 2015).

In this context, the use of groundwater for irrigation may be a viable solution, given certain natural, non-polluting qualities of this water. However, it is necessary to evaluate this possibility in order to reassure ourselves that groundwater from the N'Djili Cecomaf agricultural site can be used for irrigation in peri-urban agriculture. Groundwater studies using environmental isotopes currently offer unique and additional information on the origin and movement of groundwater and dissolved elements; this also enables a quantitative assessment of ionic mixtures in water.

The objective of this study was to evaluate the physico-chemical and isotopic characteristics of groundwater from the N'Djili Cecomaf agricultural site for irrigation, taking into account the nature of the minerals and their chemical facies, as well as the nature of its stable isotopes.

2. Material and methods

2.1. Study area

The study area is located in the urban part of the N'Djili river watershed in the city-province of Kinshasa, precisely in the agricultural site of the marketing center for vegetable and fruit products (Cecomaf, in French). It lies between 15°9' and 15°39' longitude East and 4°22' and 4°59' latitude South, at an altitude of 300m. Figure 1 shows the location of the study site on the map in the city of Kinshasa.

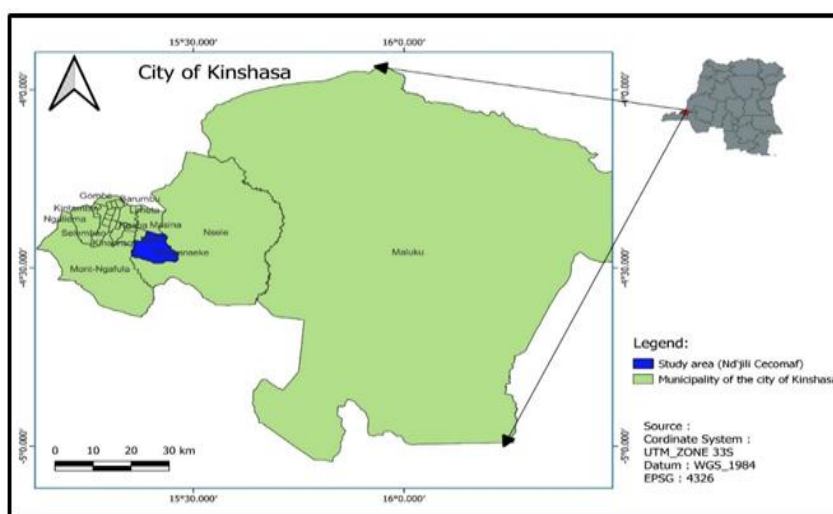


Figure 1. Location of the study site in the City of Kinshasa

The terrain's topography is divided into two morphological zones: the plain and the hills (Ndembo, 2009). The plain is located around the Malebo pool, at a mean of altitude of between 280 and 350m. It is the site of heavy sedimentation, with large deposits of sediment from the upper reaches. This results in siltation and flooding in the lower reaches (Falasi, 2018 ; Luboya, 2002).

Aquifer recharge in the N'djili watershed depends on seasonality and the topographical pattern of its terrain. Higher-lying areas generally receive more precipitation and have a greater recharge capacity

(Ndembo, 2009). Aquifer productivity also depends on the permeability of geological formations, the presence of fractures and water quality (Nsiala, 2012).

In the north-south part of Kinshasa, the geological data presented by Caillie (in Lateef et al., 2010) show superficial terrains consisting mainly of sands (fine, medium and coarse), gravels, clays and polymorphous sandstone debris. Fine sands and clayey sands, up to 20m thick, cover the lowland area and occasionally contain polymorphous clays and sandstone debris in much localized areas. Figure 2 shows the geological cross-section of the study area.

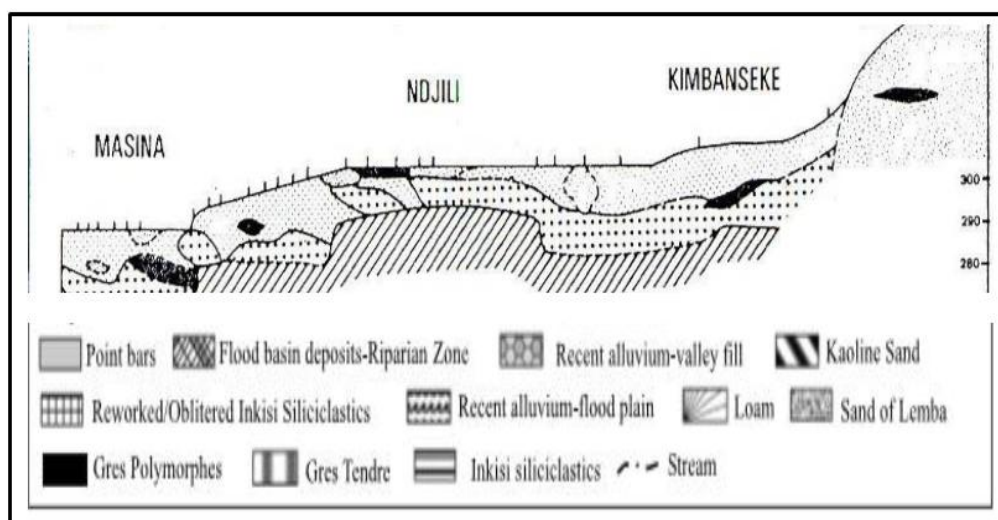


Figure 2. Geological cross-section of the N'Djili region in the north-south part of Kinshasa (source: Lateef et al., 2010)

The hydrogeological studies had shown that this water table generally flows in a gravitational manner, from south-west to northeast, due to the slope of the bedrock. In this area, data from the last 10 years collected at the N'Djili meteorological station show a mean of annual temperature of around 26°C. The years 2015, 2016, 2018, 2019, 2020 and 2021 were characterized by high average temperatures (26°C), compared with the other years, which recorded low mean of annual temperatures (25°C) over the last ten years.

The rainfall coefficient showed that 2015, 2016, 2017, 2018 and 2020 were the surplus years ($H > 1$). These years were characterized by abundant precipitation that contributed to groundwater recharge, while 2013, 2014, 2019, 2021 and 2022 were the deficit years ($H < 1$). During these years, precipitation was low, with a similarly low contribution to groundwater recharge. Figure 3 shows the evolution of the rainfall coefficient over the years 2013 to 2022.

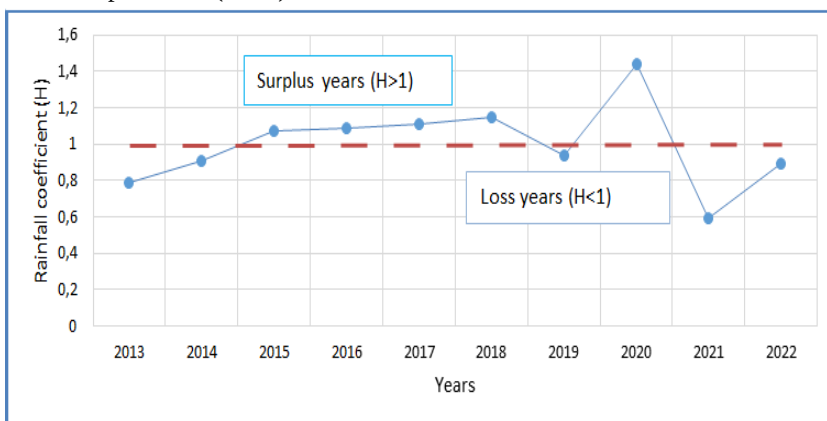


Figure 3. Rainfall coefficient for the years 2013 to 2022 (Source: N'Djili Station, 2023)

2.2. Methods

2.2.1. Sampling techniques

The agricultural site of N'Djili Cecomaf (Kinshasa) was chosen, and 10 wells were selected for groundwater sampling. Sampling was carried out in two campaigns corresponding to the rainy season in May (1ère campaign) and the dry season in July 2023 (2e campaign). The choice of these two periods is justified by the fact that during these times, the water table is not recharged in the same way, and the piezometric level of the water table is different from one period to the next, as hydrological fluctuation has a major influence on groundwater quality. Figure 4 below shows the spatial distribution of the various wells selected for groundwater sampling.

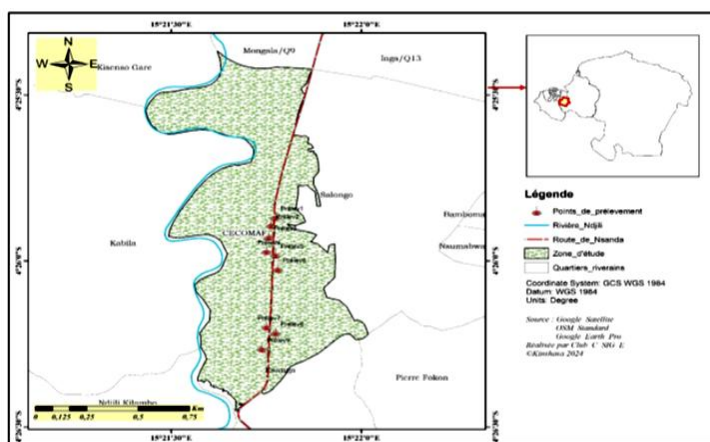


Figure 4. Groundwater sampling points at N'Djili Cecomaf

2.2.2. Physicochemical characterization of groundwater

The physicochemical analysis methods used were those recommended by AFNOR standards (NF-T 90-10, 1997), Rhajaoui et al. (2021) and Rodier (2009). At each sampling point, temperature, pH and electrical conductivity were measured in situ; and in the laboratory, the following parameters were analyzed: bicarbonate (HCO_3^-), calcium (Ca^{2+}), chlorides (Cl^-), ammonium (NH_4^+), nitrates (NO_3^-), phosphates (PO_4^{3-}), sulfates (SO_4^{2-}), sodium (Na^+) and potassium (K^+).

2.2.3. Isotopic characterization of groundwater

The groundwater samples collected were packaged in 250 ml polyethylene vials before being sent to the laboratory of the nuclear energy research center of Alger for analysis of Oxygen-18 (^{18}O) and Deuterium (^2H). Stable isotope contents (^{18}O and ^2H) were measured by Laser Picarro-L2110i mass spectrometry and are expressed in per thousand with

respect to the international standard V-SMOW (Vienna Standard Mean Ocean Water).

The stable water isotope contents (Oxygen-18 and Deuterium) obtained were plotted in a $\delta^{18}\text{O}/\delta^2\text{H}$ ratio diagram, with reference to the input function (rainwater) which is represented by :

- The right of global oceanic waters, equation: $\delta^2\text{H} = 8 \delta^{18}\text{O} + 10$ ($r^2 = 1$) (Madène, 2021; Benadela, 2023).

- The right of local meteoric water for the Kinshasa area, equation: $\delta^2\text{H} = 7.9 \delta^{18}\text{O} + 14$ ($r^2 = 0.96$) (Ndembo, 2009).

2.2.4. Determining the suitability of groundwater for irrigation

The study of the suitability of groundwater from the N'Djili Cecomaf agricultural site for irrigation was based on several criteria that control the quality of water intended for agricultural use. We analyzed a number of parameters, including sodium adsorption ratio (SAR), electrical conductivity (EC), sodium content (%Na), permeability index (PI%) and magnesium adsorption ratio (MAR). These methods describe the potential risk of soil salinization and the negative effects of irrigation water on soils and plants (Madene, 2021; Medouri & Sekfali, 2021; Singh et al., 2019 ; Fedrigoni et al., 2001).

3. Results

3.1. Physicochemical characteristics

The results of the physicochemical characteristics of groundwater from the N'Djili Cecomaf agricultural site are presented in table I.

table I. Physicochemical characteristics of groundwater at the agricultural site of N'Djili Cecomaf.

Parameters	unit	Standards WHO	Dry season				Rainy season			
			Min	Max	Average	CV	Min	Max	Average	CV
pH	-	6.5 - 9.2	6.10	7.20	6.54±0.36	5.50	4.50	4.90	4.74±0.11	2.21
T	°C	27	18.4	18.8	18.61±0.12	0.69	31.2	31.7	31.44±0.21	0.69
CE	µS/cm	1500	512	649	599.3±38.57	6.44	201	289	248.8±33.86	13.61
Ca^{2+}	mg/l	200	9.13	26.28	16.95±6.49	38.30	7.02	50.09	28.94±16.25	56.15
Mg^{2+}	mg/l	150	0.32	13.59	6.18±3.86	62.44	0.06	10.15	5.19±3.92	75.55
Na^+	mg/l	200	0.03	8.14	1.91±2.96	54.49	0.32	17.71	6.13±5.57	90.94
K^+	mg/l	12	0.02	2.28	1.12±0.01	90.70	0.14	4.09	1.71±1.15	67.28
HCO_3^-	mg/l	250	18.28	81.12	52.60±24.34	46.27	31.09	137.04	71.00±37.04	53.43
Cl^-	mg/l	250	0.71	20.12	9.61±8.50	87.70	5.26	9.62	6.94±1.35	19.45
PO_4^{3-}	mg/l	250	0.05	0.07	0.06±0.01	10.71	0.31	2.01	1.06±0.43	40.82
NO_3^-	mg/l	50	49.83	151.24	86.97±32.15	36.97	71.02	172.12	107.34±27.81	25.90
SO_4^{2-}	mg/l	250	7.29	8.46	7.42±0.42	5.40	14.23	19.09	16.80±1.66	9.89

The data in this table show that the physicochemical characteristics of the groundwater change with the season. Mean pH values are higher in the dry season (6.54 ± 0.36) than in the wet season (4.74 ± 0.11). The mean temperature value is 18.61 ± 0.12 in the dry season and 31.44 ± 0.21 in the rainy season. The same applies to mean electrical conductivity values ($599.3 \pm 38.57 \mu\text{S/cm}$) in the dry season and ($248.8 \pm 33.86 \mu\text{S/cm}$) in the rainy season. Mean cation and anion values, on the other hand, showed the opposite trend.

3.1.1. Ionic dominance and hydrochemical facies

Among the cations, the most dominant are Ca^{2+} with a concentration varying between $1.44 \pm 0.23 \text{ meq/L}$ in the rainy season and $0.84 \pm 1.09 \text{ meq/L}$ in the dry

season, and Mg^{2+} with a concentration varying between $0.49 \pm 0.81 \text{ meq/L}$ in the dry season and $0.41 \pm 0.12 \text{ meq/L}$ in the rainy season.

Among the anions, the most dominant are NO_3^- with concentrations varying between $1.71 \pm 0.81 \text{ meq/L}$ in the wet season and $1.39 \pm 0.45 \text{ meq/L}$ in the dry season, HCO_3^- with concentrations varying between $1.13 \pm 0.24 \text{ meq/L}$ in the wet season and $0.84 \pm 0.12 \text{ meq/L}$ in the dry season, Cl^- with $0.27 \pm 0.15 \text{ meq/L}$ in the dry season and $0.19 \pm 0.02 \text{ meq/L}$ in the wet season, and SO_4^{2-} with $0.17 \pm 0.03 \text{ meq/L}$ in the wet season and $0.07 \pm 0.02 \text{ meq/L}$ in the dry season.

All these chemical characteristics are plotted in the Piper diagram to determine the chemical facies of the groundwater as follows:

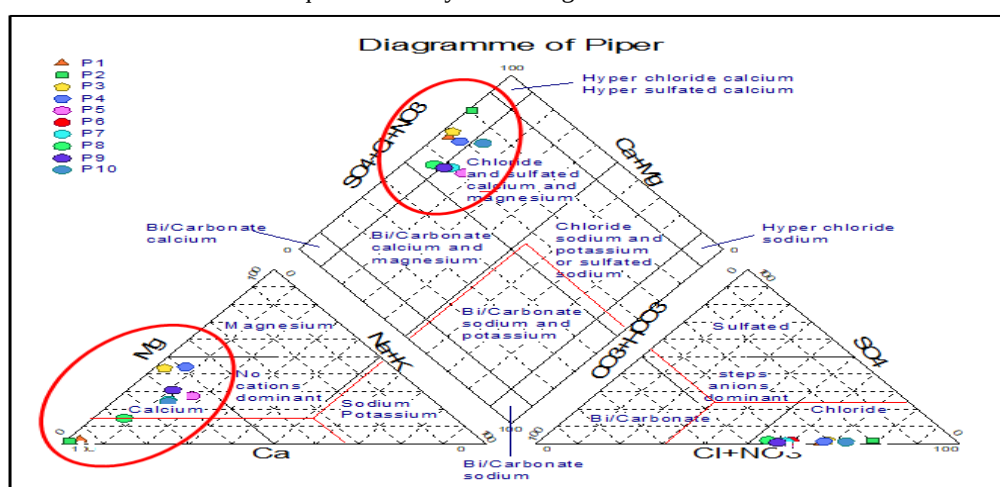


figure 5. Piper diagram and chemical facies of groundwater at the N'Djili Cecomaf agricultural site.

These elements make it possible to identify a single group of waters with a common behavior that reflect these chemical facies. These are waters of the chloride-calcium and magnesium type.

- The chloride-calcium complex, which accounts for at least 78% of the samples, comes from anthropogenic activities, notably potassium fertilizers (KCl) used by market gardeners, the weathering of

carbonate rocks (CaCO_3), landfill leachates, some industrial wastes and open-water evaporites (NaCl).

- The chloride-magnesium complex, which accounts for at least 22% of the samples, comes from the dissolution of inorganic salts such as magnesium chloride (MgCl_2).

3.1.2. Correlation matrix between chemical elements

The correlation between the various chemical elements is shown in table II.

Table II. Correlation of Bravais Pearson

Variables	pH	T	CE	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	PO_4^{3-}	NH_4^+	NO_3^-
pH	1.00												
T	-0.96	1.00											
CE	0.94	-0.98	1.00										
Ca^{2+}	0.37	-0.36	0.39	1.00									
Mg^{2+}	0.33	-0.36	0.33	-0.03	1.00								
Na^+	0.56	-0.45	0.48	0.11	0.29	1.00							
K^+	0.26	-0.28	0.34	0.12	-0.05	0.34	1.00						
HCO_3^-	0.36	-0.30	0.33	0.32	-0.05	0.45	0.59	1.00					
SO_4^{2-}	0.50	-0.42	0.45	0.52	-0.07	0.13	0.19	0.54	1.00				
Cl^-	-0.22	0.22	-0.22	-0.12	-0.24	-0.25	0.30	0.13	-0.03	1.00			
PO_4^{3-}	0.80	-0.86	0.82	0.27	0.38	0.35	0.24	0.33	0.19	-0.19	1.00		
NH_4^+	0.84	-0.85	0.85	0.04	0.35	0.50	0.27	0.12	0.27	-0.20	0.66	1.00	
NO_3^-	0.36	-0.34	0.39	0.18	-0.42	0.33	0.29	0.45	0.40	0.30	0.21	0.28	1.00

The elements listed in this table highlight significant positive correlations between pH and EC ($r=0.94$), phosphate ($r=0.80$) and ammonium ($r=0.84$); between EC and phosphate ($r=0.82$) and ammonium ($r=0.85$). Ammonium is thought to result from the solubilization of nitrogen fertilizers and other anthropogenic activities. These positive correlations suggest that these elements contribute to the mineralization of groundwater. However, some ions showed weak correlations with electrical conductivity ($r < 0.5$), indicating their very limited contribution to overall salinity. It is assumed that the waters of this nappe are fed by water from the infiltration of surface water and water from the N'djili River. They provide important insights into the hydrochemical processes that influence the mineral composition of groundwater at this site. The results of the chemical principal component analysis are shown in figure 6.

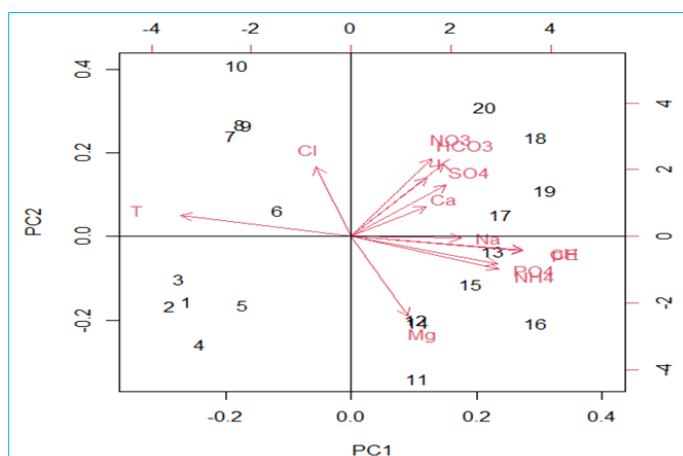


Figure 6. PCA of groundwater at the N'Djili Cecomaf agricultural site

Principal component analysis shows a positive correlation between nitrate, bicarbonate, potassium, sulfate and calcium. This correlation suggests the leaching of compound fertilizers used in market gardening at this site. EC is correlated with sodium, pH, phosphate, magnesium and ammonium.

These chemical elements either determine the mineralization of these waters, as they originate from precipitation, or from anthropogenic activities, notably fertilizer inputs and other atmospheric deposits of various kinds, during which ion exchange plays a significant role.

3.2. Isotopic characteristics

3.2.1. Relationship between Oxygen-18 and Deuterium

The relationships between oxygen-18 and deuterium in groundwater collected at the N'Djili Cecomaf agricultural site during the wet and dry seasons are shown in figure 7.

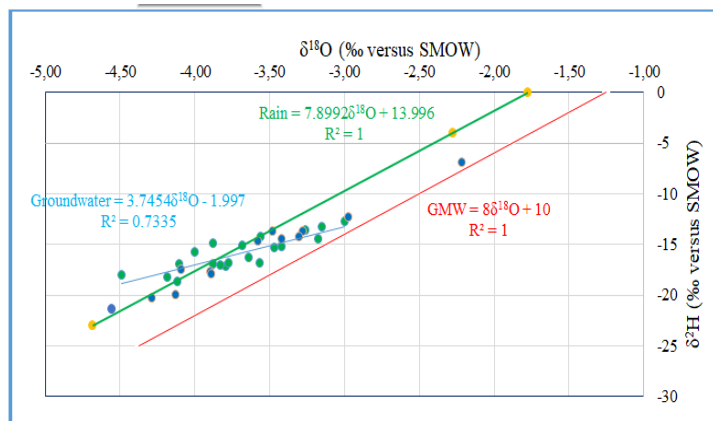


Figure 7. Oxygen-18 and deuterium relationships in groundwater

It turns out that water from different wells aligns well around the straight line with equation $\delta^2\text{H} = 3.7454 \delta^{18}\text{O} - 1.997$. This straight line is different from that for global meteoric waters (GMW) defined by Craig (1961). The Oxygen18-Deuterium relationship over all sampled waters shows a very good correlation for both periods ($R^2 = 0.73$).

In the light of this graphical representation, groundwater from the N'djili Cecomaf agricultural site is grouped together. They represent evaporated water located above the global meteoric waters (GMW). These water points, deviating from the GMW, attest to isotopic fractionation due to evaporation.

They thus explain the relative enrichment in stable isotopes (^{18}O and ^2H), which would be linked to the evaporation of rainwater before its infiltration, as revealed by the intercession observed between the local meteoric water line and that of the water table.

3.2.2. Seasonal variability of groundwater isotopic composition

Results for seasonal variability in groundwater isotopic composition at the Cecomaf agricultural site in the N'Djili watershed are shown in figures 8, 9 and 10.

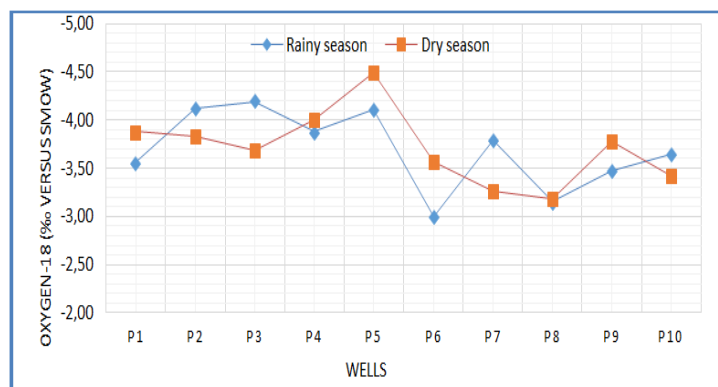


Figure 8. Seasonal variability of Oxygen-18 in different wells

The data recorded in figure 8 show that the seasonal evolution of $\delta^{18}\text{O}$ allows these groundwaters to be categorized into a single group according to the values of their respective averages ($-3.7 \pm 0.38\text{‰}$). This shows that during both seasons, $\delta^{18}\text{O}$ concentration evolves in the same way despite small variabilities observed in some wells.

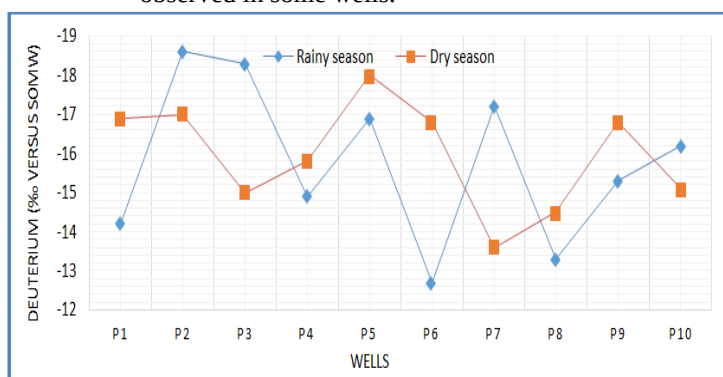


Figure 9. Seasonal variability of deuterium in different wells

This graph shows that during the two seasons, $\delta^2\text{H}$ values do not evolve in the same way in the different wells. During the rainy season, water from wells P2, P3, P7 and P10 have higher values than the other wells, while during the dry season, water from wells P1, P4, P5, P6, P8 and P9 have higher deuterium values than the other wells. This confirms that during the dry and rainy seasons, $\delta^2\text{H}$ does not have the same concentration in the groundwater of this aquifer, due to climatic variability in the oceanic air mass.

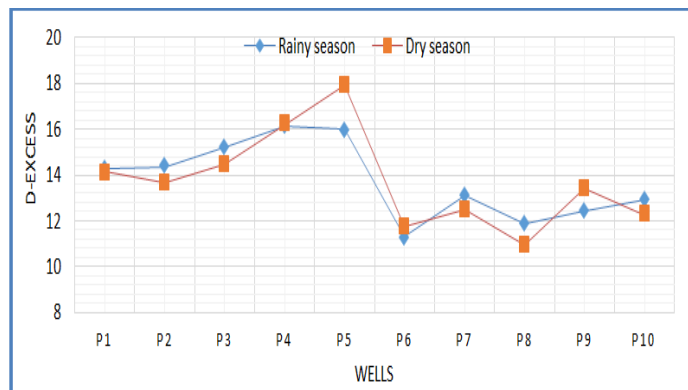


Figure 10. Seasonal variability of d-excess in different wells

The excess deuterium value varies as a function of water vapor, i.e. relative humidity and temperature at the ocean-atmosphere interface. This value is equal to 10 when water vapor condensation is of oceanic origin. Values above 10 indicate that the water is of atmospheric origin (meteoric water), coming from precipitation and is enriched. Values below 10 show that the water is connate, originating from deep geological formations, and is depleted. Figure 10 shows that deuterium excess values range from 10.94 to 17.92‰ during the dry season, and from 11.03 to 16.2‰ during the rainy season. It can be seen that all these values are above 10‰, consequently, they are meteoric waters from rainfall and are enriched in stable isotopes.

3.2.3. Relationship between EC and oxygen-18

The result of the relationship between EC and oxygen-18 in groundwater at the Cecomaf agricultural site in the N'djili watershed is shown in figure 11.

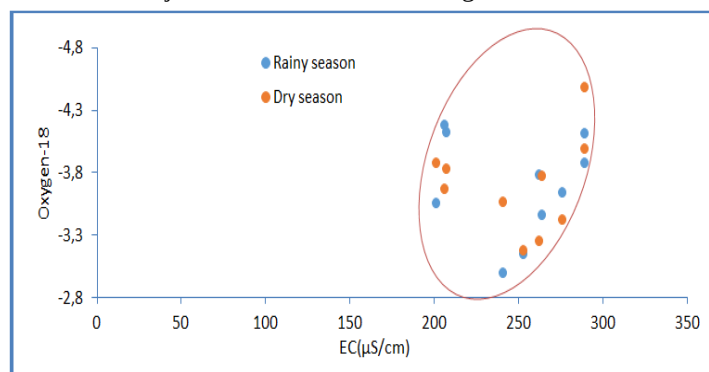


Figure 11. Relationship between CE and Oxygen-18

The figure 11 shows that these groundwaters have electrical conductivity values ranging from 200 to 300 $\mu\text{S}/\text{cm}$ and Oxygen-18 enriched contents ranging from -3 to -4.49‰ during all two seasons. These water points would reflect an isotopic signature of waters with low salinity levels and whose dissolution would

be due to groundwater evaporation phenomena before their infiltration into the water table.

3.2.4. Relationship between nitrate and oxygen-18

A relationship between nitrate ions (NO_3^-) and oxygen-18 (^{18}O) is very important for identifying the

various potential sources of nitrogen contamination and determining the origin of water pollution. The result of the relationship between nitrate and oxygen-18 in groundwater in the N'djili basin is shown in figure 12.

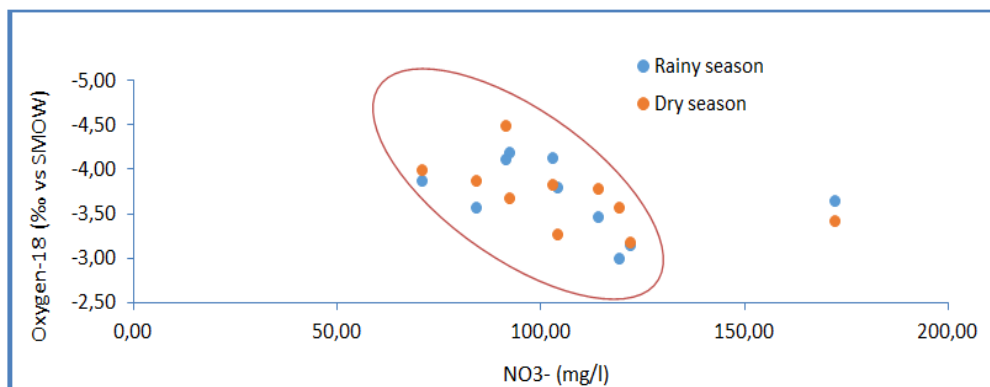


Figure 12. Relationship between oxygen-18 and nitrate

Water sampled in both dry and rainy seasons showed nitrate levels well above 50mg/l (WHO standards for drinking water), and levels enriched in stable isotopes (from -3.0 to -4.49‰ vs SMOW for Oxygen-18). This is already evidence of nitrate pollution. Pollutants drained by infiltration water reach their maximum concentration during the rainy season as soon as the first infiltration flows arrive rapidly, i.e. during the direct recharge of nitrate-containing water from organic fertilizers and wastewater. However, these levels are highly beneficial for plant nutrition, due to their need for mineral nitrogen. It should be

noted that nitrate-laden waters are rich in $\delta^{18}\text{O}$, which implies that nitrates originate from surface water infiltration (rainwater or groundwater river exchange).

3.3. Groundwater suitability for irrigation

3.3.1. Sodium adsorption ratio (SAR)

Analysis of the data shown in figure 13. reveals that the alkalizing power of water from all wells is <10 meq/l. This shows that these waters are excellent for irrigation. There is less risk of sodium adsorption, which can increase water salinity.

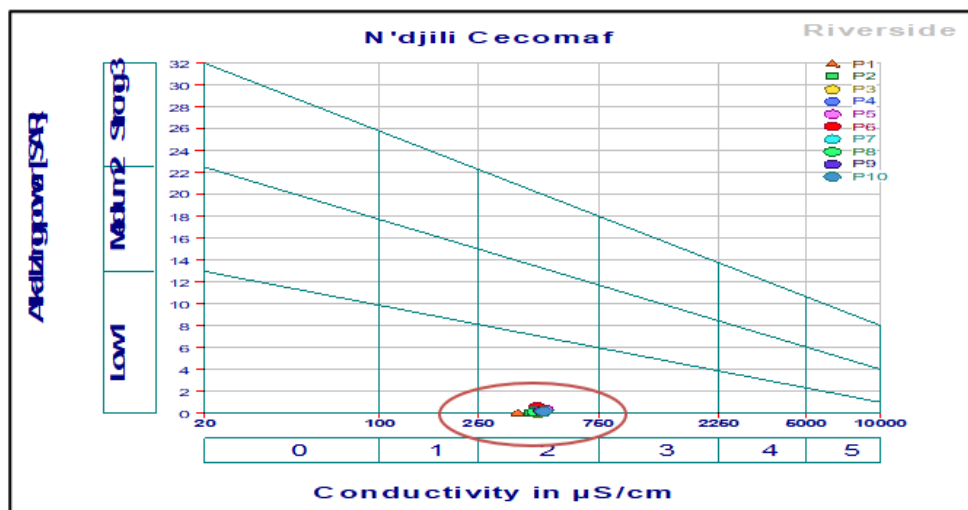


Figure 13. Sodium adsorption ratio (SAR)

The EC of the groundwater in these wells ranges from 250 to 750 $\mu\text{S}/\text{cm}$, which places them in the C2-S1 category of Richard's diagram. Consequently, these

waters are good, and can be used without special controls for irrigating salt-tolerant plants on soils with good permeability.

3.3.2. Sodium content (%Na)

The data in figure 14. show that the relationship between EC and sodium content classifies these waters as excellent for irrigation. This shows that sodium

content will have sufficiently no effect on soil permeability and water infiltration during agricultural activities.

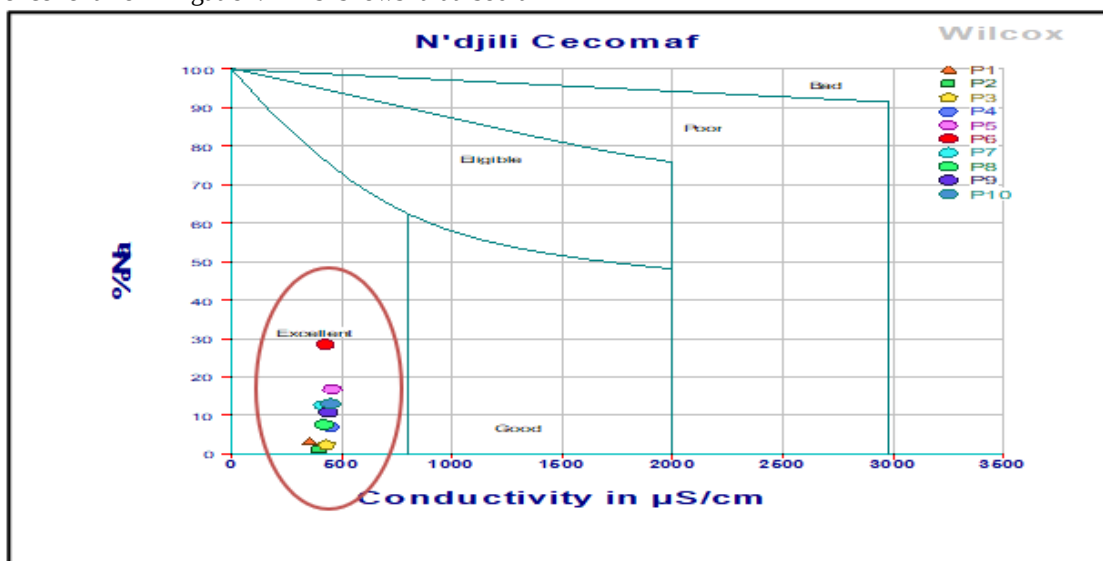


Figure 14. Ratio of sodium content to EC

3.3.3. Permeability index (PI)

The permeability index is obtained using the Doneen (1964) equation as follows:

$$PI = \left(\frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \right) \times 100$$

The criteria for classifying irrigation water quality according to the permeability index are shown in table III.

Table III. Irrigation water quality classification criteria according to PI

Water class	Permeability index (%)	Water quality
Class I	>75	Excellent
Class II	25 - 75	Good
Class III	< 25	Inappropriate

(Source: Madene, 2021)

Table IV. Averages of some chemical elements used to calculate the permeability index

Chemical elements	Average values (meq/L)
Na ⁺	0.16
HCO ₃ ⁻	0.99
Ca ²⁺	1.14
Mg ²⁺	0.45

$$PI = \left(\frac{0.16 + \sqrt{0.99}}{1.14 + 0.45 + 0.16} \right) \times 100 = 65.7\%$$

According to the Doneen classification (table III), the permeability index of the groundwater collected at the agricultural site of N'Djili Cecomaf corresponds to class II, with 65.7%. This class corresponds to water of good quality for irrigation.

3.3.4. Magnesium absorption ratio (MAR)

The magnesium absorption ratio (MAR) is calculated from the following formula:

$$MAR = \frac{Mg^{2+}}{(Ca^{2+} + Mg^{2+})} \times 100$$

The criteria for classifying irrigation water quality according to the magnesium absorption ratio are shown in table V.

Table V. Irrigation water classification criteria according to MAR

Water class	MAR (%)	Water quality
1	< 50	Adapted
2	50 - 65	Marginal
3	>65	Inappropriate

(Source: Madene, 2021)

Table VI. Averages of some chemical elements used to calculate the magnesium absorption ratio

Chemical elements	Average values (meq/L)
Ca ²⁺	2.28
Mg ²⁺	0.45

$$MAR = \frac{0.45}{(2.28 + 0.45)} \times 100 = 16.4\%$$

The magnesium absorption ratio is 16.4%, classed as category 1 water suitable for irrigation.

5. Discussion

This investigation showed that the seasonal rhythm (dry season and rainy season) and the regime of the N'Djili River, combined with anthropogenic activities, affect the geochemical composition of these waters. Water pH ranged from 4.74 (rainy season) to 6.54 (dry season) for all wells sampled. These results

are justified by the fact that the acidity of the water is more related to the dissolution of bicarbonate from atmospheric carbon dioxide, which is solubilized in rainwater. During the dry season, the degradation of organic matter, which releases humic acids into the environment, pushes water pH towards neutrality. [Nsiala \(2012\)](#) and [Luboya \(2002\)](#) in the same study area found similar results. Water temperature, on the other hand, follows an opposite trend. During the rainy season, it rises to 31.4°C in all sampled wells.

It turns out that there are significant concentrations of ions in this groundwater. These concentrations follow the following order: $\text{NO}_3^- > \text{HCO}_3^- > \text{Ca}^{2+} > \text{SO}_4^{2-} > \text{Cl}^- > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+ > \text{PO}_4^{3-}$. This classification can be explained by the various origins of the chemical elements, including granite dissolution, domestic wastewater infiltration, fertilizer inputs, etc. Work by [Ndembo \(2009\)](#) had already shown that nitrate, bicarbonate and calcium account for more than half of the ionic load of groundwater in the Kinshasa region.

The isotopic study provided a better understanding of the hydrogeochemical functioning of the water table in the study area, including the origin of these waters, and how they are recharged. The interpretation of this study was supported by previous work ([Ndembo, 2009](#); [Sandao, 2013](#); [Benadela, 2023](#); [Madene, 2021](#); [Abou Zakhem et al. 2017](#)). The isotopic results of oxygen-18/deuterium relationship analysis generally showed the existence of a single water group represented by evaporated waters that are located above the global meteoric right (GMW). These slopes are lower than that of global meteoric waters, which is 8, and that of local meteoric waters, which is 7.9. This reflects the evaporation of raindrops during the fall, in an unsaturated environment before infiltration into the water table, and the infiltration of water from the Ndjili River, given the distance of the wells from the river. Isotopic contents are close to those of well water in the Kinshasa plains area. These results are similar to those found by [Bekkousa et al. \(2018\)](#) in northwest Algeria, [Ndembo \(2009\)](#) in the Kinshasa area, [Sandao \(2013\)](#) in Niger and [Trabelsi \(2016\)](#) at Tunis. These authors had found that groundwater with slopes below the global meteoric waters right and local meteoric waters right had a meteoric origin and were poorly mineralized.

The relationship between oxygen-18 and electrical conductivity clearly shows that these waters

are enriched in stable isotopes and have a very low salinity level. Nitrates (NO_3^-) are present in the N'djili Cecomaf groundwater at levels ranging from 86.97 mg/l in the dry season to 172.12 mg/l in the wet season. These values are well above the standard set for drinking water, which is 50mg of nitrate per liter of solution. These results are similar to those found by [Ferdigoni et al. \(2001\)](#) in Tunisia, and [Bekkoussa \(2009\)](#) in Algeria. [Mfumu \(2016\)](#) had revealed that groundwater in the plain and hill area of Kinshasa had high nitrate levels above the standard set by the WHO. [Kamenan \(2020\)](#) found also similar results in his study on the fissured aquifers of the Lobo watershed in the Ivory Coast.

The sodium adsorption rate (SAR) is considered the best measure of sodium (alkaline) risk in irrigation water, as it is directly related to the adsorption of Na^+ in the soil and is an important criterion for estimating water suitability for irrigation ([Medouri & Sekfali, 2021](#); [Andreo et al., 2004](#)). The results obtained show that the alkalizing power of water from all wells is <10 meq/L, and EC values range from 250 to 750 $\mu\text{S}/\text{cm}$, according to Richard's diagram. These waters are excellent for irrigation, with less risk of sodium adsorption leading to increased salinity. These results corroborate those found by [Nagaraju et al. \(2014\)](#) who had shown that excess salt content is one of the main concerns with water used for irrigation. High salt concentration in water or soil will negatively affect crop yields, cause soil degradation and pollute groundwater.

The permeability index for these waters is 65.7%. This value ranges from 25 to 75%, in class II according to Doneen's categorization. The waters are good and can be used for irrigation without any constraints. The magnesium content of the water is considered one of the most important qualitative criteria for determining the quality of irrigation water. The Mg^{2+} content obtained after analysis was 16.4%. The water is classified as suitable for irrigation. According to [Medouri & Sekfali \(2021\)](#), Ca^{2+} and Mg^{2+} maintain a state of equilibrium in most groundwater and [Dhirendra et al. \(2009\)](#) add that high levels of Mg^{2+} in groundwater will adversely affect soil quality by making it alkaline, resulting in lower crop yields.

6. Conclusion

The objective of this study was to assess the physicochemical and isotopic suitability of

groundwater for peri-urban agricultural irrigation in the city of Kinshasa. The results showed that the waters sampled are chloride-calcium and magnesium. There are positive correlations between chemical elements in the dry and rainy seasons. The Oxygen-18/Deuterium relationship showed that there is only one type of water (meteoric water) which is recharged by the rapid infiltration of precipitation during the rainy season, and/or by contact with the waters of the N'Djili River, which feed the wells during the dry season. The relationship between oxygen-18 and EC shows that these waters are enriched in stable isotopes (Oxygen-18 and Deuterium) and have a very low salinity level; and with nitrate, pollution is noted with levels exceeding 50mg/l in these waters. However, the groundwater at the N'Djili Cecomaf agricultural site is excellent for irrigation, as it does not have the high salinity levels that can hinder crop nutrition.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work of this article.

Ethical Considerations

The study involved environmental groundwater sampling and laboratory analyses only. No human participants or animals were involved; therefore, ethical committee approval and informed consent were not required.

Contribution of the authors

P.B.I.: participated in the design, sample collection, data analysis, and writing ;

M. M. supervised this study and the search for funding ;

A.K.M. participated in the analysis and validation of the results ;

B. S. B. participated in the correction and validation of the results ;

G.-S. L. participated in project design and data collection ;

R.M.T.: participated in the correction, supervision, and search for funding.

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