

PHYSICOCHEMICAL TYPOLOGY OF WATERS FROM WEATHERED AQUIFERS IN THE MAN DEPARTMENT, WESTERN COTE D'IVOIRE

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Abstract

A hydrogeochemical study conducted in the Man Department (western Côte d'Ivoire) aims to characterise the physicochemical quality of well water in relation to the local geological formations. The investigation was carried out on 56 wells evenly distributed across the department. The physical parameters considered include temperature, pH, turbidity, redox potential, total dissolved solids (TDS), and electrical conductivity (EC). The chemical parameters include the major cations and anions. The hydraulic structures are mainly underlain by three lithological units: anorthosites, norites, and charnockites, which correspond to heterogeneous biotite-bearing granitoids and migmatites covering nearly 88% of the study area. These crystalline rocks, characterised by low permeability, host discontinuous aquifers whose waters exhibit generally low mineralisation (mean EC = 129.98 ± 123.56 $\mu\text{S/cm}$) and slightly acidic to neutral pH values (5.11 ± 0.56). Multivariate statistical analysis (Principal Component Analysis, PCA) indicates that the chemical variability of the groundwater is mainly controlled by electrical conductivity, NO_3^- , HCO_3^- , Cl^- ions, and redox potential. Two main groups of waters were identified: oxidising, weakly mineralised waters, and more reducing waters enriched in oxidised anions. The high conductivities observed in the Logoualé area, along with moderate nitrate levels (up to 40 mg/L), suggest a localised anthropogenic influence, probably linked to domestic and agricultural activities. The dominant hydrochemical facies is of the calcium-bicarbonate type, typical of tropical crystalline basement aquifers. Overall, the well waters of the Man Department comply with WHO drinking-water standards; however, certain areas, particularly in the north and within the municipality of Man, show signs of diffuse contamination. Regular monitoring of electrical conductivity and nitrate concentrations is recommended to prevent future degradation of the water resource.

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Introduction

Water resources are increasingly under pressure worldwide due to the combined effects of growing demand (driven by rapid population growth and the expansion of irrigated areas) and the reduction of available resources. Integrated Water Resources Management (IWRM) appears to be the only sustainable alternative to the global water crisis. This holistic approach to water management is based on the guiding principles of the Dublin–Rio Conference, which states that freshwater is a finite and vulnerable resource, essential to economic development and sustainable environmental well-being (McCammon, 1992). The widespread use of phytosanitary products since the end of the Second World War has led to a remarkable increase and stabilisation of agricultural yields. However, this progress has not been without environmental consequences, particularly regarding water quality (Lopez et al., 2015; Réal et al., 2005). In addition to pesticide use in agriculture, mining activities whether artisanal (gold panning) or industrial represent a significant source of land and water pollution. It is now well established that the influence of land use on water quality is multifactorial. In a review of the literature, Baker (2005) highlighted the complexity of the relationships between land use and water quality.

The impact of land use on water quality is modulated by the physical and chemical characteristics of the landscape through complex processes that vary in space and time. Infiltration is the main driver of solute percolation into aquifers, while temperature and rainfall govern the processes controlling contaminant mobility. Moreover, the influencing factors are anthropogenic, hydrological, geological, and edaphic in nature (Johnson et al., 1997). In industrialised countries, groundwater and surface water contamination by domestic effluents causes serious public health issues. In addition, agriculture through the extensive use of fertilisers is a major aggravating factor. Several studies worldwide (Girard, 1993; Groen et al., 1988; Mariotti, 1986) and those cited by Bolduc et al. (2006) demonstrate a strong correlation between agricultural activity and elevated nitrate concentrations in groundwater. Developing countries such as Côte d'Ivoire are not exempt from this situation. Water resources in these regions are severely affected by industrial and agricultural effluents. Surface waters are increasingly eutrophic, and groundwater exhibits nitrate enrichment as a result of anthropogenic activities. Nitrate pollution is a global issue, particularly in regions of intensive agricultural production. Agricultural lands act as diffuse sources of nitrate infiltration into the environment. Unlike point sources (such as domestic effluents), diffuse sources can only be managed effectively through an integrated approach. Once nitrogen from any source enters the environment, it undergoes a series of chemical transformations culminating in the production of nitrate. Unlike the ammonium ion (N-NH_4^+), the nitrate ion (N-NO_3^-) is highly soluble in water and is not retained by organic matter (humus) or clay complexes. It is therefore highly mobile and easily leached by infiltrating water into the underlying aquifers. Existing literature indicates that water sources with high nitrate levels can cause infant mortality due to methaemoglobinemia. The World Health Organization (WHO, 2017) recommends that water containing more than 10 mg/L of N-NO_3^- should not be used for preparing infant food. Under high pH conditions, nitrates can also lead to the formation of nitrosamines, which lower stomach pH; many of these compounds are carcinogenic in animals and potentially in humans. These chemical characteristics of nitrate its solubility and mobility make it a significant threat to water resources.

Located in a highly agricultural region and within a mountainous crystalline basement setting, the Man Department in western Côte d'Ivoire faces multiple environmental challenges. Interest in groundwater stems from its use via village wells to meet daily domestic needs. However, access to potable water in these areas is limited by the type of aquifers present (fractured and weathered zones) and by increasing demand (Savané, 1997). A gradual deterioration in water quality has been observed, resulting from intensive agricultural practices and uncontrolled urban expansion (Faillat, 1990; Lévêque et al., 1983). In such a context, nitrate remains one of the principal pollutants. Several hypotheses have been proposed regarding the origin of nitrates in Ivorian groundwater. According to Faillat (1990), in the Bandama watershed, this contamination partly results from extensive deforestation in favour of urban and cultivated land. Deforestation releases nitrogen stored in root systems, which is then leached into aquifers. Ouattara (2009) showed that several groundwater abstraction structures in central Côte d'Ivoire are contaminated by nitrates, with maximum concentrations of 37.5 mg/L and 23 mg/L in weathered and fractured aquifers, respectively. Although these concentrations remain below the WHO guideline value for drinking water (50 mg/L), shallow wells may be at greater risk of future contamination, especially as anthropogenic pressures persist. Therefore, the present study aims to assess the physicochemical status of groundwater from the weathered-zone aquifers in the Man Department. Specifically, it seeks to (i) identify the lithologies tapped by the sampled wells, (ii) discriminate the physicochemical quality of well water according to depth and electrical conductivity, and (iii) provide a diagnostic framework for prioritising the most affected water points requiring intervention.

Materials and methods

Study area

Located approximately 600 km from Abidjan, Man is the administrative capital of the Tonkpi Region and the principal city of the Montagnes District, which also includes the Guémon and Cavally regions. The city is often referred to as the "City of 18 Mountains" because of the numerous mountain ranges that encircle it, positioning Man within a natural basin. It lies between 7°20' and 7°35' N latitude and 7°25' and 7°45' W longitude (Figure 1). Geographically, the region represents the eastern extension of the Guinean Mountain Chain, most of which lies

within Guinea, and it is located near the Liberian border. The area includes several villages that have been absorbed by the city's expansion, where traditional housing types coexist with modern urban dwellings (RGPH, 2014). Recent geochemical investigations by Kouamélan (1996), along with petrological, petrographic, and geochronological studies by Camil (1984), have contributed to a better understanding of the geological formations of the region. From a lithological perspective, two major geological units can be distinguished, located on either side of the Danané–Man fault (N70°), which divides the area into three main domains: the northern granulitic domain, the intermediate granulitic and migmatitic domain, and the southern biotite-bearing migmatitic domain. The latter two domains together form what is referred to as the anatectic complex.

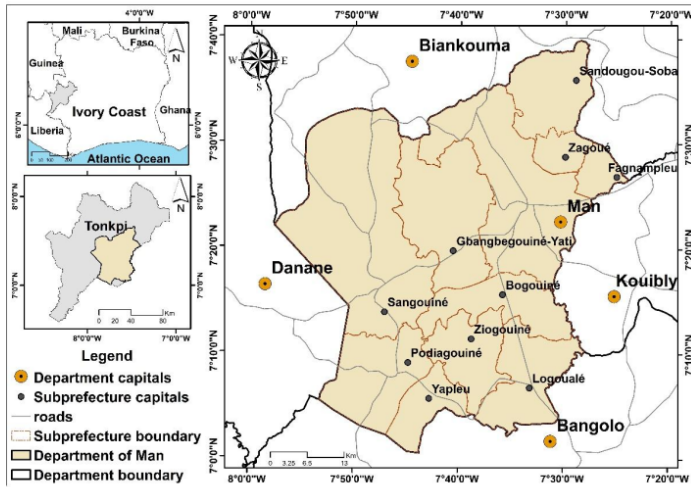


Figure 1. Location of the Man department

Sampling strategy

As part of this study, 56 wells tapping unweathered-zone aquifers were sampled over a three-day period, from 4 to 7 April 2022. Prior to fieldwork, various sampling sites (localities) were selected based on the administrative map of the Man Department. During the field campaign, the following operations were carried out:

- Measurement of water level and wellhead height using a piezometric probe and a measuring tape;
- Water collection from each well using a bailer, with sample transferred into polyethylene bottles;
- Description of the immediate environment of each well and recording of its geographical coordinates using a GPS device.

Figure 2 shows the spatial distribution of the sample points, which is relatively homogeneous and covers the entire Man Department. After sampling, all water samples were stored in a cool box and transported to the laboratory of the University of Man for analysis. The physical parameters, sulphates, and nitrates were measured at the Central Laboratory of the University of Man (LC-UM), while cations and other major anions were analysed at the Institut

85 National Polytechnique Houphouët-Boigny (INPHB). The analytical methods used for the determination of the
86 various parameters are summarised in Table 1.

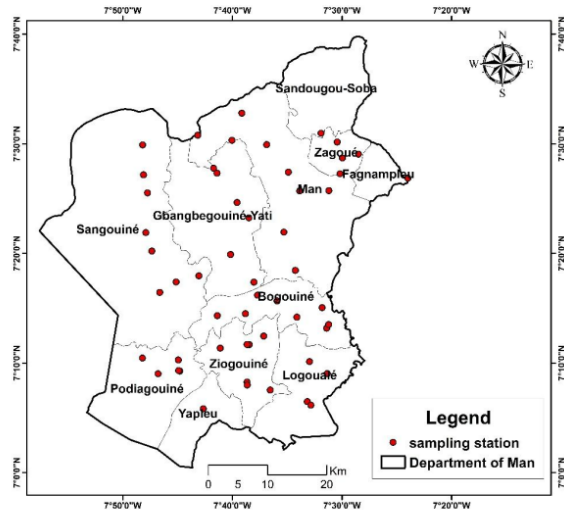


Figure 2. Spatial distribution map of the sampling points

Table 1. Analytical methods used for the determination of chemical parameters

Chemical parameters	Analytical methods	Standards / References
Nitrites (NO_2^-)	Molecular absorption spectrophotometry	NF EN 26777
Nitrates (NO_3^-)	Molecular absorption spectrophotometry	NF EN 26777
Sulphates (SO_4^{2-})	Molecular absorption spectrophotometry	NF T 90-040
Orthophosphates (PO_4^{3-})	Molecular absorption spectrophotometry	NF 17 ISO 15681-2
Calcium (Ca^{2+})	Titrimetry	NF T 90-003
Magnesium (Mg^{2+})	Titrimetry	NF T 90-003
Bicarbonate (HCO_3^-)	Titrimetry	NF EN ISO 9963-2
Chloride (Cl^-)	Titrimetry (silver nitrate method)	NF ISO 9

Electrical conductivity classes of well water

Table 2 presents the electrical conductivity (EC) classes based on World Health Organization (WHO) standards. According to this classification, waters with EC values below $200 \mu\text{S}/\text{cm}$ are considered low-mineralised, whereas those with EC values above $600 \mu\text{S}/\text{cm}$ are regarded as highly mineralised. This classification was used to group the wells of the Man Department according to their total dissolved solids (TDS) content (WHO, 2017).

Table 2. Electrical conductivity classes of well water according to WHO standards (OMS, 2017)

Electrical Conductivity ($\mu\text{S}/\text{cm}$)	Mineralisation class	Interpretation
< 200	Low mineralisation	Soft, weakly mineralised water
200 – 600	Moderate mineralisation	Moderately mineralised water
> 600	High mineralisation	Hard, strongly mineralised water

Inverse Distance Weighting (IDW) interpolation method

Interpolation predicts the values of raster cells from a limited number of sampled points. It allows the estimation of unknown values for any type of geospatial point data, such as elevation, rainfall, or chemical concentrations. One of the most widely used barycentric interpolation techniques is the Inverse Distance Weighting (IDW) method, in which the influence of each sampling point decreases with increasing distance, controlled by a power parameter (d) (Pingale et al., 2014). Using this method, the predicted value at a point s_0 is expressed as follows:

$$Z(s_0) = \sum_{i \in V(s_0)} \frac{1/|s_i - s_0|^d}{\sum_{i \in V(s_0)} (1/|s_i - s_0|^d)} Z(s_i), \text{ with } d > 0(1)$$

Let $V(s_0)$ represent the set of observations located within a certain neighbourhood of s_0 . The weighting is a function of the inverse distance. The formula defining the weighting is given in Equation 2:

$$\lambda_i = \frac{d_i^{-p}}{\sum_{i=1}^N d_i^{-p}}(2)$$

The IDW method requires the selection of a power parameter and a search radius. The power parameter (p) controls the influence of measured values on the interpolated value according to their distance (d) from the prediction point (Erdogan, 2009). A relatively high power parameter assigns greater weight to nearby points, resulting in a surface that captures more local detail (Yavuz & Erdoğan, 2012). In this study, the IDW method was employed to generate the spatial distribution maps of electrical conductivity (EC) and nitrate concentrations in well waters.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) allows the summarization and visualization of information contained in a dataset composed of individuals or observations described by multiple inter-correlated quantitative variables. Each variable can be considered a separate dimension. When a dataset contains more than three variables, visualizing this multidimensional space becomes very challenging. PCA is therefore used to extract the most important information from a multivariate data table and to express it as a set of new variables called principal components. These new variables correspond to linear combinations of the original variables. The number of principal components is less than or equal to the number of original variables. The information contained in a dataset corresponds to the total variation it exhibits. The goal of PCA is to identify directions (or principal components) along which the variation in the data is maximized. In other words, PCA reduces the dimensionality of a multivariate dataset to two or three principal components that can be graphically represented, with minimal loss of information (Abdi & Williams, 2010; Kassambara, 2017). PCA is a multidimensional statistical method that enables the synthesis of information to compare different systems. It is particularly suitable for: (i) explaining chemical similarities between different waters and/or between different points of mineralization measurement, and (ii) identifying the variables governing these mechanisms.

Results

Lithology of the investigated wells and descriptive statistics of in-situ parameters

The water supply structures (wells) in the Man department are predominantly located on three major geological units: anorthosites, norites, and charnockites; heterogeneous biotite-bearing granitoids; and migmatites on heterogeneous biotite-bearing granitoids (Figure 3). Approximately 88% of the wells are situated within these formations, while the remaining 12% are distributed across other geological units. Anorthosites, norites, charnockites, and heterogeneous biotite-bearing granitoids are the most widespread lithologies in the department, covering roughly 80% of the territory. Being crystalline rocks, they exhibit medium to low permeability, hosting aquifers whose water resources are modest compared to porous aquifers (sands, gravels, sandstones, etc.). Overall, waters in contact with these rocks are weakly to moderately mineralized and are potentially enriched in Ca^{2+} , Mg^{2+} , Fe^{2+} , K^+ , Na^+ , and

HCO₃⁻, with a neutral to slightly basic pH. In contrast, waters in contact with migmatites over heterogeneous biotite-bearing granitoids tend to be slightly acidic to neutral.

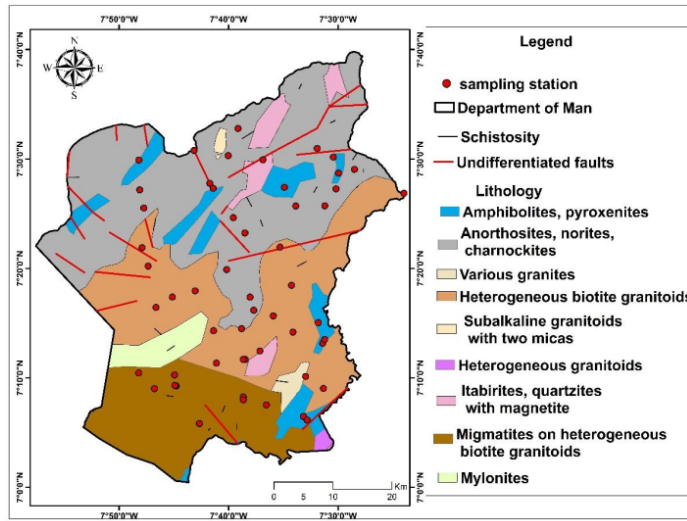


Figure 3. Spatial distribution of the sampled points across the lithological units

The waters of the Man department have an average pH of 5.11 ± 0.56 , indicating that the well waters are slightly acidic to neutral. Regarding the redox potential, values range from 114.40 mV to 308.30 mV, with a mean of 220.01 ± 45.93 mV. Dissolved oxygen, electrical conductivity, TDS, and turbidity exhibit standard deviations that are high or close to the mean (Table 3), reflecting the presence of wells with extreme or exceptional values of these parameters compared to the average. The waters have an average dissolved oxygen content of 2.57 ± 5.44 mg/L, indicating that most are poorly oxygenated. The average electrical conductivity of 129.98 ± 123.56 μ S/cm suggests that the wells in the Man department are weakly to moderately mineralized. However, some wells exhibit conductivity values approaching those of highly mineralized waters. Based on lithology, the waters would be expected to be weakly to moderately mineralized. Wells exhibiting these elevated conductivity values warrant particular attention regarding potential contamination.

Table 3. Descriptive statistics of in-situ physicochemical parameters

Parameter	pH	Redox (mV)	DO (mg/L)	EC (μ S/cm)	Depth (m)
Mean	5.11	220.01	2.57	129.98	6.92
Standard Deviation	0.56	45.93	5.44	123.56	2.44
Minimum	3.24	114.40	1.09	16	2.20
Maximum	6.55	308.30	42.43	806	12.45

Typology of wells according to depth

The depths of the wells were classified into three arbitrary categories to assess the relationship between depth and the concentrations of chemical elements (Figure 4). The wells are generally low in chloride, orthophosphate, and, to a lesser extent, sulfate. The electrical conductivity (EC) of the wells ranges between 0 and 400 μ S/cm, while nitrate

concentrations vary from 0 to 40 mg/L. Regarding chloride, orthophosphate, and sulfate concentrations, the scatter plots according to depth classes remain highly heterogeneous, indicating that the chemical characteristics of the water are generally similar regardless of well depth and EC. Differentiation is observed only for nitrate concentrations (0–20 mg/L and 20–40 mg/L) and EC values (0–200 $\mu\text{S}/\text{cm}$ and 200–400 $\mu\text{S}/\text{cm}$). Wells with higher conductivity tend to have higher nitrate concentrations. Therefore, EC is used as a distinguishing parameter to differentiate wells based on their nitrate content.

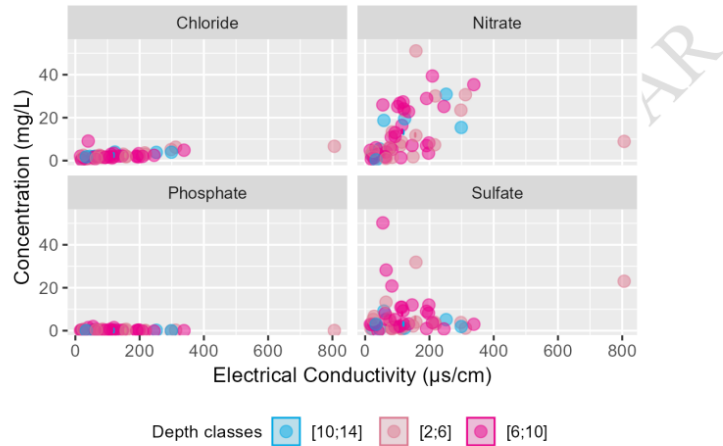


Figure 4. Concentrations of nitrate, chloride, orthophosphate, and sulfate in wells according to depth and electrical conductivity (EC)

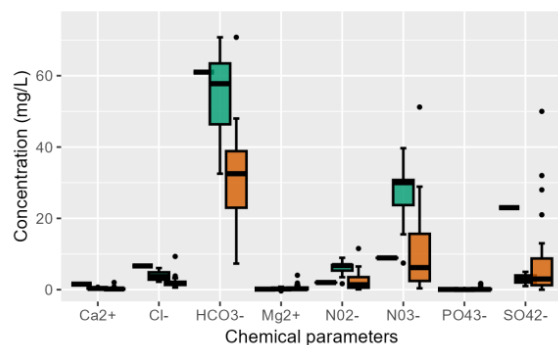
Typology of wells based on electrical conductivity

Distribution of Major Ion Concentrations

Figure 5 illustrates the distribution of the main ion concentrations in wells from the Man department. Overall, the most representative anions are bicarbonate (HCO_3^-) and nitrate (NO_3^-).

- For wells with low electrical conductivity, HCO_3^- concentrations range from 22 to 38 mg/L, with a median NO_3^- concentration of 5 mg/L.
- For wells with moderate conductivity, HCO_3^- ranges between 48 and 62 mg/L, and the median NO_3^- concentration is 30 mg/L.

Other ions exhibit nearly identical distributions regardless of the conductivity class, indicating that their concentrations do not vary significantly with electrical conductivity. The dominant hydrochemical facies in the region is therefore calcium-bicarbonate, irrespective of whether mineralisation is low or moderate. The secondary facies is characterised by magnesium as the dominant cation and nitrate as the dominant anion.



EC classes High Moderate Weak

Figure 5. Distribution of major ion concentrations according to electrical conductivity classes

Principal component analysis

• Distribution of inertia

This dataset comprises 56 individuals (or wells) and 16 variables, with one qualitative variable used illustratively. The inertia of the factorial axes indicates whether the variables are structured and also suggests an appropriate number of principal components to consider. The first two axes of the analysis account for 40.96% of the total inertia of the dataset, meaning that 40.96% of the overall variability of the cloud of individuals (or variables) is represented in this plane (Figure 6). This is a relatively moderate percentage, indicating that the first plane captures only part of the total variability contained within the active dataset. This value exceeds the reference value of 27.2%, implying that the variability explained by this plane is significant. Consequently, it may be necessary to consider higher dimensions, such as the third axis or beyond, in the analysis.

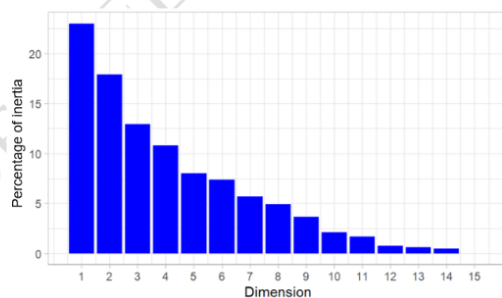


Figure 6. Decomposition of total inertia

An assessment of the relevant number of axes to be interpreted suggests restricting the analysis to the description of the first four axes. These components exhibit an inertia rate higher than the 0.95 quantile of random distributions (64.73% compared to 47.36%). This observation indicates that only these axes carry meaningful information. Consequently, the interpretation of the analysis will be limited to these axes alone. For improved readability of the plots resulting from the PCA, the names of the localities where the wells were investigated have been replaced with

codes (P1 to P56). Table 4 provides the correspondence between the well names and their respective codes, as well as their geographical coordinates.

Locality	Code	Latitude	Longitude	Locality	Code	Latitude	Longitude
Saguipleu	P1	7.26972	-7.6284	Logoulé 1	P29	7.10256	-7.5472
Podiougouiné 1	P2	7.15439	-7.7466	Logoulé 2	P30	7.1505	-7.5223
Podiougouiné 2	P3	7.15517	-7.7483	Koulinié	P31	7.16875	-7.5493
Gouépleu	P4	7.17411	-7.8034	Saopleu	P32	7.21944	-7.5233
Douleu	P5	7.15028	-7.7797	Glolé 1	P33	7.22508	-7.5203
Kpankepleu	P6	7.09706	-7.7109	Glolé 2	P34	7.25078	-7.5301
Yapleu	P7	7.17122	-7.7488	Glégouiné	P35	7.23642	-7.5686
Gotongouiné-B.	P8	7.27392	-7.7771	Lepkepleu	P36	7.30753	-7.5709
Sangouiné	P9	7.36494	-7.7983	Botongouiné	P37	7.38733	-7.6417
Gotongouiné	P10	7.49828	-7.8031	Tiaképleu	P38	7.41058	-7.6595
Ligbalé	P11	7.45289	-7.8018	Lamapleu	P39	7.45536	-7.6900
Drangouiné	P12	7.42525	-7.7957	Biakalé	P40	7.46286	-7.6952
Damakoupleu	P13	7.33678	-7.7891	Biakalé	P41	7.51297	-7.7193
Gotongouiné 2	P14	7.28986	-7.7522	Gblé	P42	7.50514	-7.6673
Zoba	P15	7.29914	-7.7175	Kié	P43	7.54647	-7.6523
Gouagounompleu	P16	7.33156	-7.6695	Mélapleu	P44	7.49869	-7.6144
Gbangbéguiné	P17	7.28969	-7.6339	Guepleu	P45	7.45683	-7.5816
Mlonguiné	P18	7.261	-7.5987	Yébégouin	P46	7.42839	-7.5643
Bogouiné	P19	7.24169	-7.6468	Blauckauss	P47	7.42869	-7.5200
Gouékangouiné	P20	7.23858	-7.6895	Godegouin	P48	7.45436	-7.5030
Gouégolé	P21	7.20758	-7.6189	Goualepleu	P49	7.50272	-7.5072
Trinlé-Diaplé	P22	7.19472	-7.6411	Déoulé	P50	7.51592	-7.5318
Zogouiné	P23	7.18917	-7.6851	Gbatta	P51	7.47833	-7.4993
Gouéguiné	P24	7.19481	-7.6444	Zagoué	P52	7.48414	-7.4750
Zogouiné	P25	7.13764	-7.6444	Singouin	P53	7.44767	-7.3997
Goulé 1	P26	7.13319	-7.6442	Gboné	P54	7.44767	-7.3997
Goulé 2	P27	7.12558	-7.6091	Fagnamleu	P55	7.36558	-7.5883
Gbloalé	P28	7.10794	-7.5528	Zélé	P56	7.36558	-7.5883

• Description of the plane 1:2

The critical probability of the Wilks test ($p\text{-value} = 5.34 \times 10^{-10}$) identifies the variable whose categories best discriminate among individuals on the plane (i.e. the one that best explains the distances between them). Only one qualitative variable can account for the separation of individuals: the *Electrical Conductivity (EC) Classes*. Individuals are therefore coloured according to their membership in the modalities of the EC Classes variable (figure 7). Dimension 1 separates individuals such as P47, P35, P54, P18, P25, P50, P29, P46, P37, and P31 (located on the right-hand side of the plot, characterised by strongly positive coordinates on the axis) from individuals such as P30, P28, P10, P2, P56, P33, and P6 (on the left-hand side, characterised by strongly negative coordinates). The group including individuals P35, P25, P31, and P22 (with positive coordinates) is associated with high values of PO_4^{3-} , *Turbidity*, SO_4^{2-} , and *Dissolved Oxygen* (from most to least extreme). The group including P47, P54, P18, P50, P29, P46, P37, and P9 (also with positive coordinates) is characterised by high values of *Electrical Conductivity (EC)*, HCO_3^- , NO_2^- , NO_3^- , and Cl^- (from most to least extreme), and by low *Redox potential* values. Conversely, the group including P30, P28, P10, P2, P56, P33, and P6 (with negative coordinates) shows high *Redox potential* values and low values for NO_2^- , NO_3^- , Cl^- , HCO_3^- , *EC*, and Ca^{2+} (from most to least extreme).

215 Dimension 2 contrasts individuals such as P35, P25, P31, and P22 with individuals like P47, P54, P18, P50, P29, P46,
 216 P37, and P9 (located at the bottom of the plot, characterised by strongly negative coordinates on the axis). The group
 217 comprising P35, P25, P31, and P22 exhibits high values of PO_4^{3-} , *Turbidity*, SO_4^{2-} , and *DissolvedOxygen*. The group
 218 comprising P47, P54, P18, P50, P29, P46, P37, and P9 is associated with high *EC*, HCO_3^- , NO_2^- , NO_3^- , and Cl^-
 219 values, and low *Redox potential* values.

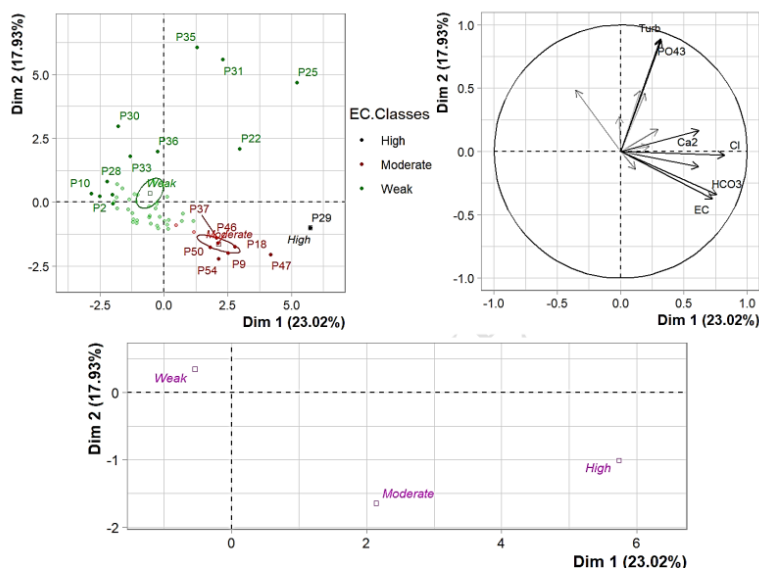


Figure 7. Plot of individuals, variables, and categories on the 1:2 plane

• Description of the plan 3:4

224 Dimension 3 separates individuals such as P24, P22, P16, P43, P44, and P46 (located on the right-hand side of the
 225 plot, characterised by strongly positive coordinates on the axis) from individuals such as P40, P38, P19, P8, P23, and
 226 P25 (Figure 8). The group including P24, P22, P16, P43, P44, and P46 is associated with high values of NO_2^- and
 227 NO_3^- (from most to least extreme). In contrast, the group including P40, P38, P19, P8, P23, and P25 shows high
 228 values of *pH* and *depth*, but low values of NO_2^- , NO_3^- , and *Electrical Conductivity (EC)*.

229 Dimension 4 contrasts individuals such as P40, P38, P19, P8, P23, and P25 with individuals such as P9, P37, P10,
 230 and P36. The group comprising P40, P38, P19, P8, P23, and P25 is characterised by high *pH* and *depth* values and
 231 low mineralisation, with low concentrations of NO_2^- and NO_3^- . Conversely, the group including P9, P37, P10, and
 232 P36 exhibits high *DissolvedOxygen (DO)* and *EC* values, and low *pH*, *Temperature*, and *depth* values.

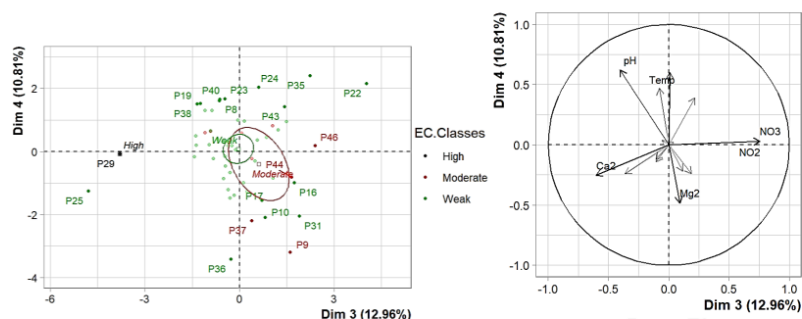


Figure 8. Plot of individuals and variables on the 3:4 plane

Spatial distribution of electrical conductivity and nitrate concentrations

Across the entire Man Department, electrical conductivity values are generally low, with an average of $129.98 \mu\text{S}/\text{cm}$, indicating that the well waters are weakly mineralised (Figure 9). The Logoulé area shows the highest conductivity values, ranging from 280 to $804 \mu\text{S}/\text{cm}$. The southern part of the department is weakly mineralised, with electrical conductivity values ranging between 16 and $103 \mu\text{S}/\text{cm}$. In the northern zone, conductivity also remains low. The municipality of Man and the localities of Sandougou-Soba (in the north-east) and Sangouiné (in the north-west) display intermediate conductivity values, between 192 and $279 \mu\text{S}/\text{cm}$ (Figure 9).

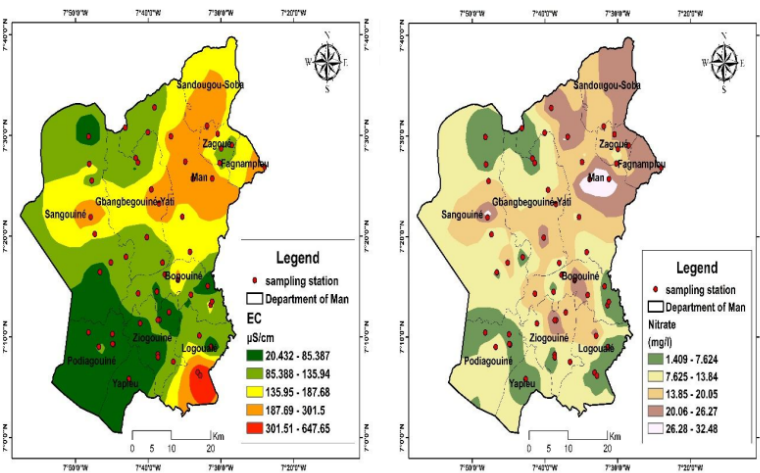


Figure 9. Spatial distribution of electrical conductivity and nitrate concentrations in the Man Department

Overall, in almost all wells across the Man Department, nitrate concentrations are below $15 \text{ mg}/\text{L}$. The Podiagouiné and Yaple localities show the lowest nitrate concentrations ($0.9\text{--}5 \text{ mg}/\text{L}$). The municipality of Man and the Bogouiné locality presents slightly higher concentrations, ranging between 10 and $26 \text{ mg}/\text{L}$ in certain areas. These

results indicate that the sampled wells do not show nitrate contamination relative to the WHO standards. However, wells located in the northern part of the department deserve particular attention.

Discussion

The distribution of hydraulic structures in the Man Department is strongly influenced by the geological substratum, which is composed predominantly ($\approx 88\%$) of anorthosites, norites, charnockites, biotite-bearing granitoids, and migmatites. These crystalline formations, being low in porosity and permeability, allow only limited water infiltration. Consequently, the associated aquifers are discontinuous, of low productivity, and possess limited storage capacity, which explains the low average mineralisation observed ($EC \approx 130 \mu S/cm$). The chemical composition of the groundwater is consistent with this geological context. The dominance of a calcium–bicarbonate facies indicates that mineralisation mainly results from the weathering of silicate minerals (feldspars, biotite, amphiboles), rather than from evaporitic processes or saline intrusions. Waters in contact with these rocks typically exhibit slightly acidic to neutral pH values ($\approx 5.11 \pm 0.56$), linked to the limited dissolution of carbonates and the acidic nature of the host rocks (Appelo & Postma, 2004; Faillat & Blavoux, 1989; Freeze & Cherry, 1979). Comparable studies conducted in crystalline basement areas of Côte d'Ivoire have reported similar patterns of low mineralisation with localised peaks related to diffuse pollution and the vulnerability of shallow aquifers (Kouassi, 2007; Lasm et al., 2011; Rashrash et al., 2015).

The relatively low average electrical conductivity (EC) values confirm the absence of high concentrations of dissolved salts. However, the high standard deviation suggests local variability influenced by factors such as point-source contamination, variation in groundwater depth, and fracture heterogeneity within the substratum. The high EC values observed in Logoualé ($280\text{--}804 \mu S/cm$) may result from prolonged water circulation in open fracture zones, which promotes ion exchange, or from local domestic or agricultural pollution. A particularly strong relationship between EC and nitrate concentrations is observed: wells with higher EC values also show higher NO_3^- concentrations (up to 40 mg/L). This correlation likely reflects anthropogenic inputs (domestic wastewater, latrines, fertilisers), compounded by the shallow depth of wells and the absence of sanitary protection around wellheads. The EC– NO_3^- correlations are consistent with global observations in groundwater from urbanised or intensively farmed areas (Dassargues, 2020; WHO, 2017). Nevertheless, the measured concentrations remain below the WHO limit (50 mg/L), indicating moderate contamination. The spatial distribution of EC and nitrate shows low mineralisation across most of the department, with localised increases in the Man municipality and Logoualé. These areas also correspond to zones of intense human activity, supporting the hypothesis of anthropogenic influence on groundwater chemistry. In contrast, the southern ($16\text{--}103 \mu S/cm$) and northern sectors, characterised by low mineralisation, indicate younger waters with limited interaction with host rocks. The low nitrate concentrations in Podiagouiné and Yapleu ($0.9\text{--}5 \text{ mg/L}$) further confirm the low anthropogenic impact in these zones.

The Principal Component Analysis (PCA) results show that the first two axes explain 40.96% of the total variance, revealing a moderate but meaningful data structure. The main discriminating variables are electrical conductivity, nitrate, bicarbonate, chloride, and redox potential. This structure highlights two main groundwater groups: oxidising, weakly mineralised waters (low NO_3^- , NO_2^- , Cl^- , high redox values), representing recent and uncontaminated recharge waters and more mineralised, reducing waters, rich in oxidised anions, indicative of anthropogenic influence or longer residence times within the porous or fractured medium. This duality is consistent with the presence of populations exposed to varying anthropogenic pressures and different groundwater flow regimes within fractured networks (Appelo & Postma, 2004). The third and fourth PCA axes, which explain an additional proportion of variance, distinguish shallow, mineralised waters from deeper, more basic, and weakly mineralised waters, suggesting a hydrogeochemical stratification with depth, although less pronounced than the stratification associated with EC. Although most wells in the Man Department meet drinking-water quality standards, the elevated nitrate and EC values observed in some localities warrant enhanced monitoring. These parameters, being indicators of diffuse pollution, can evolve rapidly under increasing demographic and agricultural pressures. The low dissolved oxygen content ($DO \approx 2.6 \pm 5.4 \text{ mg/L}$) observed in several samples suggests stagnant conditions or

moderate organic pollution, as reported in other Ivorian studies (N'Guettia et al., 2019; Ouattara et al., 2016; Sodomon et al., 2024). This underlines the need for targeted sanitation measures, such as well sealing and the protection of water points from nearby contamination sources.

Conclusion

This study aimed to characterise the hydrogeochemical typology of well waters in the Man Department. The results indicate that the groundwater is slightly to moderately mineralised, with an acidic pH averaging around 5.11. The dominant hydrochemical facies (HCO_3^- - Ca^{2+} and HCO_3^- - Mg^{2+}) are typical of tropical crystalline aquifers, and the observed spatial variability results from the combined effects of lithology, well depth, and land use. Regarding the Principal Component Analysis (PCA), four relevant axes were retained to construct the model. Among the four factorial classifications performed, two (axes 1:2 and 3:4) validated the model. In other words, these axes encompass the chemical parameters influencing electrical conductivity classes, namely nitrate (NO_3^-) and bicarbonate (HCO_3^-). While bicarbonate concentrations have a natural origin, linked to the lithological composition of the host rocks, the higher nitrate levels likely have an anthropogenic source. Some localities show elevated nitrate concentrations, although still below the drinking-water limit. This is notably the case in Bogouiné and Man, where concentrations reach around 20 mg/L. It is therefore recommended to raise community awareness about activities conducted near wells, in order to reduce contamination risks. Overall, the findings confirm that the crystalline basement geology plays a fundamental role in controlling groundwater quality, but that anthropogenic factors are becoming increasingly significant in certain areas. A periodic monitoring programme focusing on nitrate, electrical conductivity, and redox potential, combined with aquifer vulnerability mapping, is necessary to anticipate future changes in groundwater quality within this environmental and socio-economic context.

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