Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2026, 14(1), 371-385
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Comparative Study of the Hydrodynamic and Hydrochemical Characteristics of the Guitry and Zikisso Aquifers in the Gôh Region (Central-Western Côte D'Ivoire)

Omer Zephir De Lasme[1], Issouf Coulibaly[1,2], Kouassi Éric Germain Kouakou[1], Mohamed Kone[1], Lamine Touré[1]

[1]Department of Geosciences, Peleforo Gon Coulibaly University, Korhogo, Côte d'Ivoire
[2]Pan African University Institute of Water and Energy Science, including Climate Change (PAUWES), Tlemcen, Algeria
Email: issoufcoulibaly944@gmail.com

How to cite this paper: De Lasme, O. Z., Coulibaly, I., Kouakou, K. É. G., Kone, M., & Touré, L. (2026). Comparative Study of the Hydrodynamic and Hydrochemical Characteristics of the Guitry and Zikisso Aquifers in the Gôh Region (Central-Western Côte D'Ivoire). *Journal of Geoscience and Environment Protection, 14,* 371-385.
https://doi.org/10.4236/gep.2026.141020

Received: December 23, 2025
Accepted: January 24, 2026
Published: January 27, 2026

Abstract

This study focused on comparing the hydrodynamic properties and hydrochemical characteristics of groundwater in Guitry and Zikisso, in the Gôh region (central-western Côte d'Ivoire), in order to assess the sustainability of drinking water supplies. On the one hand, the drilling database was analyzed and processed using analytical solutions for determining hydrodynamic properties such as Theis and Cooper-Jacob. The data relating to the physical and chemical parameters were analyzed and then processed using the DIAGRAMMES hydrochemical software developed by the Hydrogeology Laboratory at the University of Avignon (France). This tool allows the chemical classification of groundwater to be represented graphically using standard diagrams (Piper), based on the mineral ion composition of the water. In Guitry, the aquifers are mainly confined (80%) and formed by several layers of fissures. In Zikisso, the aquifers are exclusively confined (100%) and have the same shape. The aquifers in Zikisso are more productive, with a specific yield of 1.24 m^2/h (compared to 0.44 m^2/h). The average depth of the boreholes reached 107.74 m and 99.10 m in Zikisso and Guitry, respectively. All groundwater samples were identified with the same facies: calcium with magnesium and bicarbonate type (Ca^{2+}, Mg^{2+}, HCO_3^-), indicating silicate hydrolysis as the only mineralization process that occurred and, probably, high connectivity of the fractured aquifers. These results highlight the importance of prior hydrodynamic and hydrochemical characterization to achieve sustainable groundwater management in the context of bedrock aquifers.

Keywords

Crystalline Aquifers, Hydrodynamics, Hydrochemistry, Guitry, Zikisso

1. Introduction

Like many West African countries, where crystalline rocks dominate much of the subsoil, the geological configuration of Côte d'Ivoire highlights two types of bedrock areas: a sedimentary domain (2.5%) near the sea and a domain of magmatic or metamorphic rocks (97.5%) inland. The drinking water supply for populations living in non-sedimentary areas is mainly provided by boreholes and wells that collect groundwater, in addition to treated vulnerable surface water (MacDonald et al., 2012; Lachassagne et al., 2021). According to numerous previous studies conducted by national researchers, the productivity of boreholes is generally linked to specific flow and transmissivity (Lasm, 2000). However, other parameters such as the thickness of weathered materials and petrographic nature can influence aquifer productivity (Baka, 2012; De Lasme, 2013). Consequently, the exploration of productive bedrock aquifers is increasingly focused on gaining a better understanding of the hydrodynamic functioning of aquifers. To achieve this in the Gôh region, five boreholes were installed in Guitry and four in Zikisso to increase the drinking water supply to the communities in these two localities. These are located in fractured layers of discontinuous aquifers. In order to improve our understanding of their hydrodynamic and hydrochemical characteristics, we first need to understand them thoroughly. The main objective of this study is to acquire the best possible knowledge of the subsoil and the hydrodynamic functioning of the aquifer based on the Guitry and Zikisso boreholes and sample analysis reports.

2. Location of the Study Area

The study area is located in two places in the central-western part of Côte d'Ivoire. The Guitry sub-area (**Figure 1**) is located between latitudes 5˚20 and 5˚24 north and longitudes −5˚23 and −5˚60 west. The Zikisso sub-area is located between latitudes 6˚0 and 6˚40 north and longitudes 5˚40 and 5˚45 west.

The geology of Guitry (**Figure 2(a)**) consists of several rock layers, such as granodiorites, andesites, granites, schists, and undifferentiated rocks. Based on the lithological view and geological map of the study site, the boreholes studied in Guitry are located on granodiorite-type formations, while those in Zikisso (**Figure 2(b)**) encountered various granitoid rocks, namely heterogeneous biotite and homogeneous biotite. This lithological context is consistent with recent geological and hydrogeological studies of the Ivorian basement, which show that aquifers in the central-western and central regions are often developed in granitoid and schistose formations, with their productivity depending on the degree of weathering and fracturing (De Lasme et al., 2021; Kouassi et al., 2012a; Baka et al., 2021; Ble Louan et al., 2022).

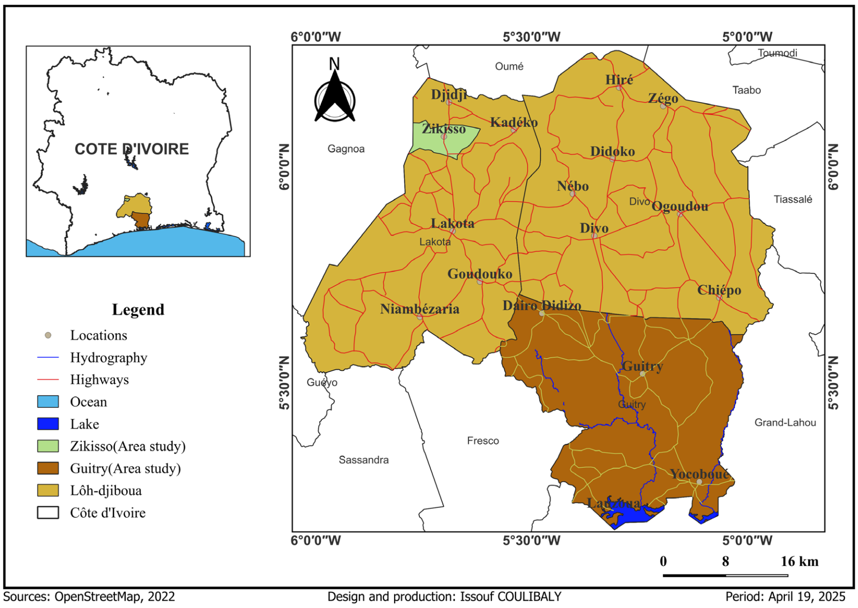
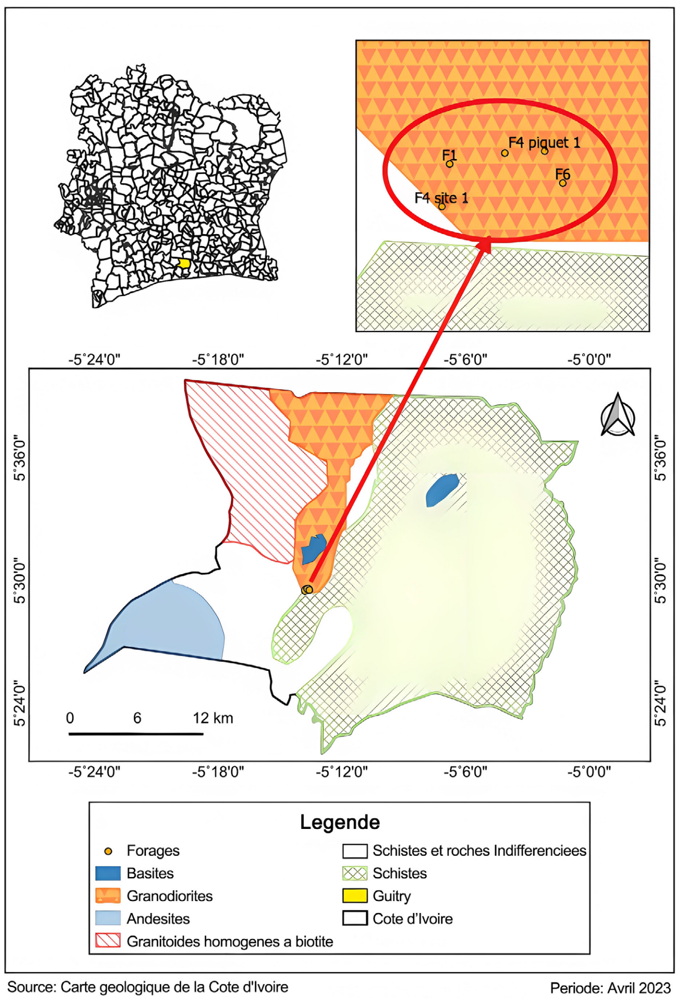
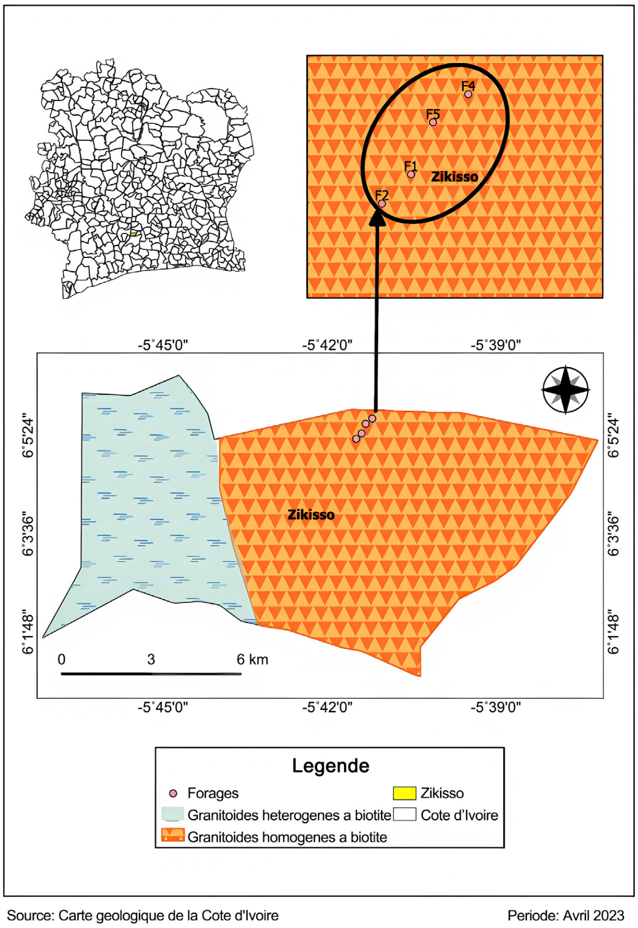


Figure 1. Area study map.



(a)



(b)

Figure 2. Geological map of Guitry (a) and Zikisso (b).

3. Materials

Most of the equipment used for this work consists of data from the technical data sheets of the pumping tests carried out on the nine boreholes located in the study area, including five (05) boreholes in the Guitry region and four (04) boreholes in Zikisso. The tool used to process this data is mainly equipped with the following specific software: GOOGLE EARTH to identify the localization of the boreholes studied; QGIS 3.18.2 to produce some maps; OUAIP 2.3 to interpret pumping test reports; STASTISTICA for descriptive statistical analysis; and as well as for principal component analysis and DIAGRAMMES 5.1, to determine hydrofacies from the PIPER diagram, designed by researchers and engineers at the Hydrochemistry Laboratory of the University of Avignon in France, which was used to perform the chemical classification of groundwater samples.

4. Methods

4.1. Determination of Hydrodynamic Parameters

A single methodology was adopted at two study sites. First, an analysis of the lithological profile and groundwater depth was carried out to identify the nature of the aquifer (confined or unconfined) and the type of aquifer (weathered materials or fractured layers) crossed by the equipped boreholes. Next, based on known hydrogeological characteristics, the conditions for using the analytical solution of Theis (1935) are satisfied with a reasonably estimated value set for the observation radius (≤10 m) between the piezometer and the well. The results of the hydrodynamic property values are generated automatically with the lowest associated error offset. The transmissivity value can be calculated by logarithmic approximation based on the simplification assumptions suggested by Cooper-Jacob (1946) according to Equation (1):

$$T = (0.183Q)/\Delta s \quad (1)$$

With: T: transmissivity expressed in (m^2/s);

Q: pumping flow rate of the first stage at (m^3/s);

Δs: variation of the drawdown (m) over one logarithmic cycle of time.

The variation of the drawdown (m) is expressed as follows (Equation (2)):

$$\Delta s = S_2 - S_1 \quad (2)$$

With:

S_1: drawdown at the beginning of the logarithmic cycle of time.

S_2: drawdown at the end of the logarithmic cycle of time.

4.2. Determination of Hydrochemical Parameters

4.2.1. Collection and Preparation of Hydrochemical Data

The hydrochemical data are derived from physicochemical analyses of groundwater samples collected in Guitry and Zikisso. They concern electrical conductivity and the main major ions (Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-), which are commonly used to characterize groundwater. Concentrations were expressed in $mg \cdot L^{-1}$ and then converted to $meq \cdot L^{-1}$ where necessary. The reliability of the data was ensured by consistency checks prior to statistical analysis, in accordance with recommendations in the literature (Freeze & Cherry, 1979; Appelo & Postma, 2005).

4.2.2. Hydrochemical Classification according to Piper's Diagram

The hydrochemical characterization of the waters was carried out using Piper's diagram. This diagram, commonly used with good results (Kouzana et al., 2007; Oga et al., 2009), made it possible to account for the distribution of water points in the hydrochemical facies. Groundwater classification was performed using Piper's diagram, based on the relative proportions of the main cations (Ca^{2+} and Mg^{2+}) and the main anions (HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-). This method allows hydrochemical facies to be identified and changes in the chemical composition of water along underground flow paths to be interpreted. The Piper diagram is widely used in studies of bedrock aquifers to distinguish between recent recharge, progressive mineralization, and surface influences according to (Piper, 1944; Back, 1966; Lasm et al., 2008).

4.2.3. Statistical Analysis and Correlation Matrix

A descriptive statistical analysis was followed by the calculation of Pearson's correlation coefficients between electrical conductivity (EC) and major ions. This approach allows linear relationships between parameters to be identified and groups of ions that evolve together to be highlighted. High correlations between certain cations and anions are interpreted as reflecting natural mineralization processes, while associations involving nitrates are used as indicators of anthropogenic influences related to surface inputs (Appelo & Postma, 2005; Ahoussi et al., 2011).

5. Results

5.1. Typology of the Aquifer Captured at Guitry and Zikisso

Analysis of the vertical lithological profiles (Table 1) of the boreholes revealed that the aquifers in Guitry are mainly confined (80%), while those in Zikisso are exclusively confined (100%). In Guitry, one borehole (F1) crossed a semi-confined aquifer. At two sites, the aquifers are structured as multi-layered fissures (60%) or a single fissured layer (40%), which may reflect the heterogeneity or anisotropy of the aquifers encountered in Zikisso and Guitry.

Table 1. Different types of aquifers encountered.

		BOREHOLE STAFFING		PERCENTAGE %	
		Guitry	Zikisso	Guitry	Zikisso
IDENTIFICATION OF THE WATER TABLE	Confined	4	4	80	100
	Confined and Permeable	1	0	20	0
AQUIFER TYPE	Multi-layer Cracked	3	4	60	100
	Double layer and single layer	2	0	40	0
	Total	5	4	100	100

5.2. Statistical Analysis of the Hydraulic and Hydrodynamic Parameters of Aquifers

5.2.1. Boreholes Depths

Statistical analysis of the hydraulic parameters (Table 2) of boreholes located in Guitry and Zikisso reveals significant differences in terms of depth, static level, critical flow rates, and operating yields. In Guitry, the depths of the boreholes ranged from 90 m to 110 m, with an average of 99.10 m and a standard deviation of 7.35 m, while in Zikisso, they ranged from 81.95 to 120 m, with an average of 107.74 m and a standard deviation of 17.96 m.

Static levels also show significant differences: from 1.85 to 5.45 m in Guitry, with an average of 3.62 m, compared to 2.87 to 10.82 m in Zikisso, with an average of 6.61 m. These higher levels in Zikisso suggest faster recharge and also reflect lower aquifer productivity.

Table 2. Statistical analysis of parameters.

		Average	Minimum	Maximum	σ
Guitry	Critical flow rate (m^3/s)	10.28	5.92	16	4.31
	Overall Depth (m)	99.1	90	110	7.35
	Transmissivity (m^2/s)	6.65E−05	2.24E−05	9.40E−05	1.58
	Permeability (m/s)	4.09E−06	9.28E−07	7.80E−06	1.58
	Specific storage coefficient (m^{-1})	1.64E−06	2.72E−08	4.22E−06	1.58
	Operating flow rate (m^3/h)	20.00	20.00	20.00	0.00
	Specific flow rate (m^3/h)	0.44	0.14	0.94	0.38
	Static Level (m)	3.62	1.85	5.45	1.38
Zikisso	Critical flow rate (m^3/s)	19.18	11.00	32.50	9.94
	Overall Depth (m)	107.74	81.95	120.00	17.96
	Transmissivity (m^2/s)	5.99E−05	3.05E−05	9.28E−05	1.29
	Permeability (m/s)	3.25E−06	8.75E−07	5.33E−06	1.00
	Specific storage coefficient (m^{-1})	1.46E−04	1.39E−06	4.31E−04	1.00
	Operating flow rate (m^3/h)	2.50E+01	2.50E+01	2.50E+01	1.29
	Specific flow rate (m^3/h)	1.24	0.24	3.27	1.39
	Static Level (m)	6.61	2.87	10.82	3.33

σ: Standard deviation.

5.2.2. Critical Flow Rate

In terms of critical flow rates (Table 2), the Zikisso boreholes show a higher range, between 11 and 32.50 m^3/h, with an average of 19.18 m^3/h and a standard deviation of 9.94 m, while those in Guitry vary from 5.92 to 16 m^3/h, with an average of 10.28 m^3/h and a standard deviation of 4.31 m. These values reflect the improved capacity of the Zikisso aquifers to withstand high pumping rates without disrupting the hydraulic functioning of the borehole, such as wall collapse, clogging, or sand suction. In both cases, operating flow rates were set uniformly at 25 m^3/h, which could prove excessive for some Guitry wells, where the critical threshold is often exceeded, thus risking compromising the sustainability of the structures if no regulation is applied.

Overall, these results reflect higher productivity in Zikisso wells compared to those in Guitry, which corresponds to the characteristics of the aquifers tapped, mainly deep fissured multilayer aquifers in Zikisso, compared to more heterogeneous structures (single layer, double layer, and multilayer) in Guitry. This qualitative and quantitative difference justifies differentiated management of the resource according to the area, with exploitation policies adapted to the fragility or robustness of the identified aquifers.

5.2.3. Hydrodynamic Parameters

The assessment of hydrodynamic parameters (Table 2), such as specific flow rate, transmissivity, and permeability, made it possible to evaluate the behavior of the aquifers exploited in the localities of Guitry and Zikisso. Specific flow rates, which are direct indicators of the productivity of the structures, vary in Guitry from 0.14 to 0.94 m^2/h, with an average of 0.44 m^2/h. These values highlight the productivity of the aquifers. In Zikisso, on the other hand, specific flow rates range from 0.24 to 3.27 m^2/h, with an average of 1.24 m^2/h, revealing productivity slightly higher than that of Guitry.

In terms of transmissivity, a key parameter defining an aquifer's capacity to transmit water, the two areas have similar values, but are slightly more homogeneous in Zikisso. In Guitry, the values range from 1.01×10^2 to 1.05×10^2 m^2/s, with an average of 1.03×10^2 m^2/s and a standard deviation of 1.58, while in Zikisso, they range from 1.01×10^2 to 1.04×10^2 m^2/s with an average of 1.03×10^2 m^2/s and a standard deviation of 1.29. This uniformity at Zikisso reflects a better-connected reservoir geometry, probably linked to a more favorable fracture density in the bedrock, as suggested by the observations of Faillat (1986) and Biémi (1992) on fractured aquifers in bedrock areas.

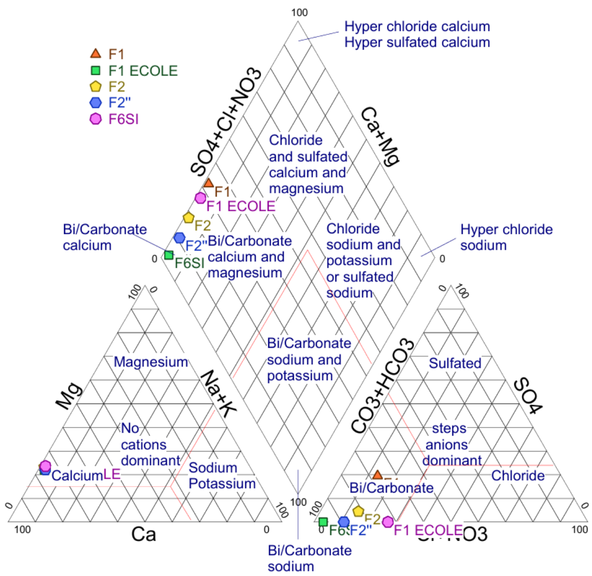
Permeability values, derived from transmissivity and estimated aquifer thickness, also confirm this trend. In Guitry, permeability coefficients range from 10^1 to 10^5 m/s, while in Zikisso they are slightly lower, ranging from 10^1 to 10^4 m/s. This difference suggests better hydraulic cohesion of the aquifers in Zikisso, reinforced by a homogeneous multilayer structure of deep fissures in all the boreholes studied.

These hydrodynamic parameters confirm the greater productivity of the Zikisso aquifers compared to those of Guitry. This finding corroborates the hydraulic data and reflects the more favorable nature of the fractured bedrock at Zikisso, which offers effective permeability and greater groundwater transmission capacities. This situation suggests a more sustainable exploitation potential at Zikisso, provided that rational pumping management respects the limits defined by the critical parameters observed.

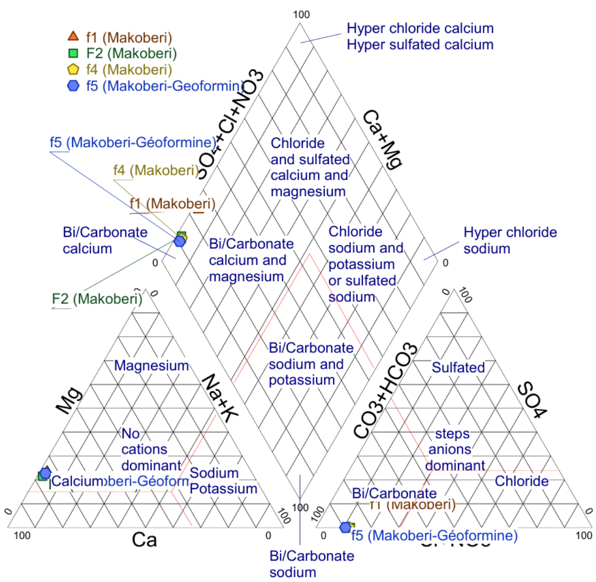
5.3. Hydrochemical Analysis

Analysis of the hydrochemical results obtained from Piper diagrams (**Figure 3**), principal component analysis (PCA), and the correlation matrix reveals a consistent structure in the chemistry of the Guitry and Zikisso aquifers studied. The hydrochemical facies obtained explain mineralization processes dominated by water-rock interaction, caused locally by anthropogenic surface inputs. Bedrock aquifers in West Africa are characterized by this organization, as several researchers have proven in previous studies.

Principal component analysis (PCA) was applied to reduce the size of the dataset and identify the dominant factors controlling groundwater chemistry. PCA was performed using the correlation matrix of normalized variables. The selected factor axes (F1 and F2) correspond to the components explaining the largest share of the total variance. The correlation circle and the projection of the samples onto the factorial planes made it possible to distinguish the natural mineralization processes linked to water-rock interaction and residence time from those associated with anthropogenic inputs, mainly marked by nitrates (Sielaff & Einax, 2007; Idris, 2008; Yao et al., 2023).



(a)



(b)

Figure 3. Piper's diagram of Guitry (a) and Zikisso (b).

Analysis of the results of the Piper diagrams shows several distributions by hydrochemical classes of Guitry groundwater, while also showing a gradual evolution of mineralization. Low mineralization of Class I waters, dominated by calcium and magnesium bicarbonate ions (Ca^{2+}, Mg^{2+}, and HCO_3^-), corresponds to recently recharged waters. These waters are characterized by a relatively short residence time and limited water-rock interaction. However, Classes II and III show more pronounced mineralization. A joint increase in Ca^{2+}, Mg^{2+}, SO_4^{2-}, and NO_3^- concentrations is observed, along with a longer residence time and an increased contribution from mineral dissolution processes. A comparable study was observed in the Afema mining environment, where facies differentiation reflects the hydrochemical evolution of underground flow paths (Yao et al., 2023).

In Zikisso, the results from the Piper diagram show a more homogeneous distribution of samples, dominated by calcium and magnesium bicarbonate facies. This homogeneity explains the relatively uniform lithological control and the predominant role of natural mineralization processes. Studies by Lasm et al. (2008) and Kouassi et al. (2012b), have shown that this type of facies is typical of fractured aquifers developed in crystalline basement formations, where silicate hydrolysis is the main mechanism for dissolving major ions.

Analysis of the correlation matrix (**Table 3**) highlights strong relationships between electrical conductivity (EC) and several major ions, notably Cl^- (r = 0.79), Mg^{2+} (r = 0.76), Ca^{2+} (r = 0.68), and HCO_3^- (r = 0.66). These correlations explain why the total mineralization of water is essentially controlled by dissolved ions resulting from the interaction between water and rock. Ca^{2+} and Mg^{2+} ions have a strong correlation (r = 0.99), as do these cations and bicarbonates (r ≈ 1). These results reflect a common origin linked to the hydrolysis of silicate minerals and the dissolution of CO_2 from the soil. The work of Yao et al. (2023) is similar to this hydrochemical behavior, attributing these ionic associations to the residence time of water in aquifers and the intensity of geochemical exchanges.

Table 3. Correlation matrix among major ions.

	CE	Cl^-	NO_3^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	HCO_3^-
CE	1						
Cl-	**0.79**	1					
NO_3^-	0.57	0.22	1				
SO_4^{2-}	0.57	0.22	**0.95**	1			
Ca^{2+}	**0.68**	0.19	**0.91**	**0.82**	1		
Mg^{2+}	**0.76**	0.33	**0.91**	**0.81**	**0.99**	1	
HCO_3^-	**0.66**	0.14	**0.89**	**0.8**	1	**0.98**	1

The results also show a strong correlation between nitrates and sulfates (r = 0.95), calcium (r = 0.91), magnesium (r = 0.91), and bicarbonates (r = 0.89). These strong correlations can be explained by the fact that they share a common origin linked to surface inputs, namely rainwater infiltration leaching soils and unsaturated horizons. Nitrates are therefore recognized as tracers of human origin. They are mainly associated with agricultural activities and the use of nitrogen fertilizers, as also shown by Ahoussi et al. (2011) and Yao et al. (2023) in comparable hydrogeological contexts.

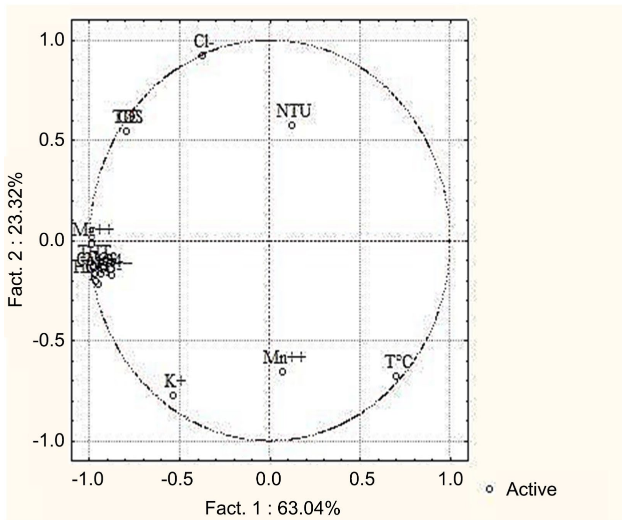
Geochemically, these processes correspond to the hydrolysis reactions of sodium and calcium feldspars, typically described by the following reactions (R.1) and (R.2):

$$2NaAlSi_3O_8 + 2CO_2 + 11H_2O \rightarrow Al_2Si_2O_5(OH)_4(\text{kaolinite}) + 4H_4SiO_4 + 2Na^+ + 2HCO_3^- \quad (R.1)$$

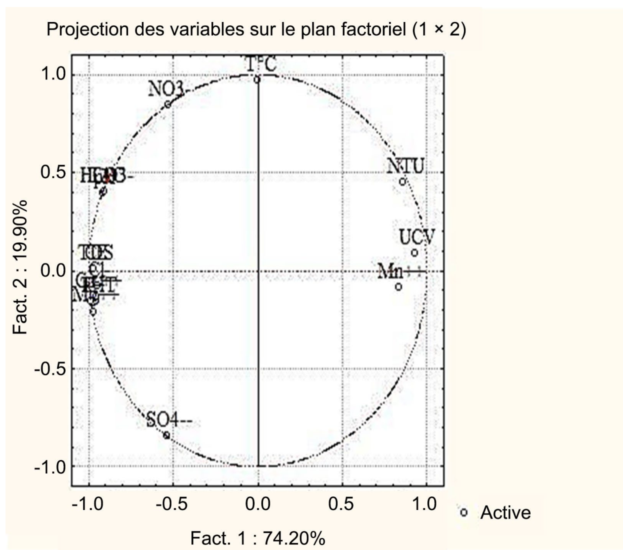
$$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Al2Si_2O_5(OH)_4(\text{kaolinite}) + Ca^{2+} + 2HCO_3^- \quad (R.2)$$

These minerals are abundant in rock formations, such as the alteration of albite and anorthite. These theoretical reactions lead to the gradual release of alkaline earth cations (Ca^{2+}, Mg^{2+}, Na^{+}) and the production of bicarbonate ions, while causing the neoformation of clay minerals. Although the altered minerals are not directly identified by the available data, the set of ionic associations observed, the PCA results, and the evolution of hydrochemical facies are consistent with this interpretative model, which is widely documented in the rock aquifers of West Africa (Lasm et al., 2008; Kouassi et al., 2012b; Yao et al., 2023).

To reinforce these results and their interpretations, Principal Component Analysis was performed. Factor F1, which includes EC, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, and Cl^-, represents the natural mineralization process linked to silicate hydrolysis and the residence time of water in the aquifer (**Figure 4**).



(a)

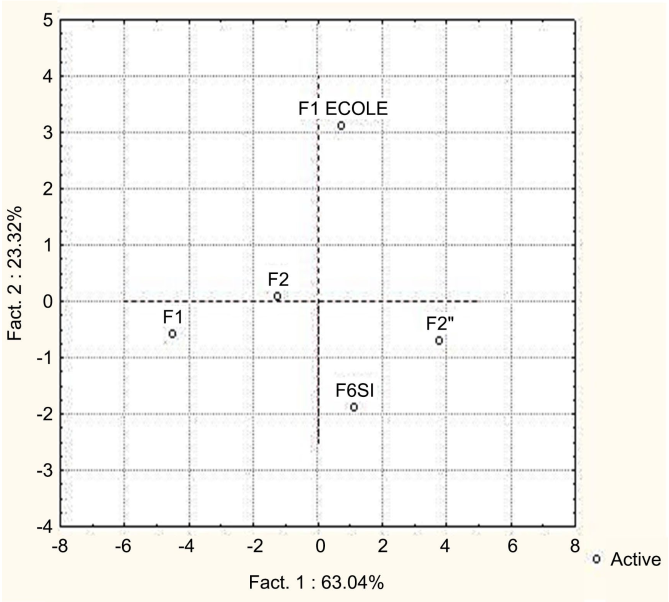


(b)

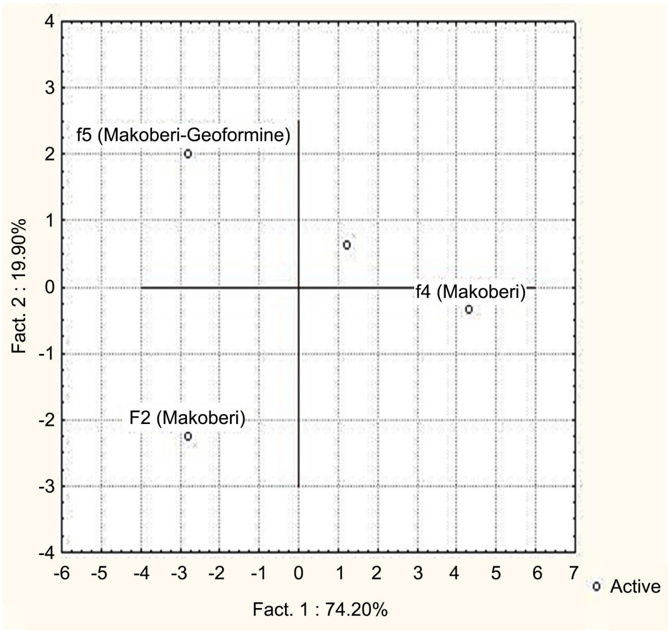
Figure 4. Community circle of the F1-F2 factorial plane of Guitry (a) and Zikisso (b).

This factor corresponds to the dominant mechanism controlling groundwater chemistry, as described in the bedrock aquifers of Côte d'Ivoire and other regions of West Africa (Lasm et al., 2011; Yao et al., 2023). Factor F2 is associated with nitrates and sulfates, reflecting the influence of surface inputs and human (anthropogenic) activities on water quality.

The projection of samples in factorial plans F1 and F2 highlights a clear contradiction between highly mineralized waters, due to a longer residence time, and waters influenced by nitrate-rich surface inputs (**Figure 5**).



(a)



(b)

Figure 5. Factor representation of samples of Guitry (a) and Zikisso (b).

This could be explained by the dual origin of mineralization: on the one hand, a non-anthropogenic process controlled by geology and underground flow. On the other hand, a human-induced process is caused by agricultural activities and land use. The study of the Afema mining environment reached similar conclusions, where Principal Component Analysis (PCA) further identified these two major mechanisms (Yao et al., 2023).

In summary, the hydrochemical results obtained show that the chemistry of the groundwater in Guitry and Zikisso is mainly governed by the hydrolysis of silicate minerals and the residence time of water in fractured aquifers, with a significant but secondary contribution from human inputs through surface infiltration. This hydrochemical mechanism is consistent with the conceptual models established for bedrock aquifers in West Africa and is fully in line with the interpretative framework proposed by (Yao et al., 2023). However, it is important to note that the small sample size in Guitry and Zikisso is a constraint imposed by the results of hydrogeophysical investigations, which led to the drilling of wells delivering a satisfactory flow rate for consumption. Consequently, these results are specific to the area studied and should not be generalized to neighboring areas without prior studies confirming the continuity of the hydrogeological context.

6. Conclusion

This comparative study highlights the variability of the hydrodynamic and hydrochemical characteristics of the Guitry and Zikisso aquifers. Although the two locations share the same hydrochemical facies of calcium and magnesium bicarbonate, their hydraulic performance differs considerably. Zikisso has an average critical flow rate of 19.18 m^3/h and an average specific flow rate of 1.24 m^2/h, which are higher than those of Guitry (10.28 m^3/h and 0.44 m^2/h, respectively). The greater average depths at Zikisso (107.74 m compared to 99.10 m at Guitry), as well as the exclusively confined nature of its aquifers, partly explain this higher productivity. Understanding these dynamics allows for better planning of the sustainable exploitation of groundwater resources in bedrock environments. It also highlights the need to integrate geophysical investigations and a territorial approach into water infrastructure development strategies. The groundwater in Guitry and Zikisso is mainly characterized by calcium and magnesium bicarbonate facies, typical of fractured rock aquifers. Mineralization is dominated by water-rock interaction, in particular the hydrolysis of silicate minerals and residence time. The strong correlations between electrical conductivity and major ions confirm this geochemical control. The Principal Component Analysis (PCA) also reveals an anthropogenic influence linked to agricultural inputs, as evidenced by nitrates. These results are consistent with the regional hydrochemical model for West Africa, particularly in Guitry and Zikisso, and validate the integrated Piper approach and principal component analysis (PCA).

Acknowledgements

The authors would like to thank the editorial team and the anonymous revierwers for their valuable comments and constructive suggestions, which helped improve the quality of this manuscript.

Conflicts of Interest

The authors of this article declare that they have no financial, professional, or personal conflicts of interest that could have inappropriately influenced this work.

References

Ahoussi, K. E., Oga, Y. M. S., Yao, B. F., Kouassi, A. M., Soro, N., & Biémi, J. (2011). Caractérisation hydrogéochimique et microbiologique des ressources en eau dans un contexte anthropisé: Cas du site d'un centre d'enfouissement technique en Côte d'Ivoire. *International Journal of Biological and Chemical Sciences, 5,* 2114-2132. https://doi.org/10.4314/ijbcs.v5i5.32

Appelo, C. A. J., & Postma, D. (2005). *Geochemistry, Groundwater and Pollution* (2nd ed.). Balkema.

Back, W. (1966). *Hydrochemical Facies and Groundwater Flow Patterns*. USGS Professional Paper, 498-A.

Baka, D. (2012). *Geometry, Hydrodynamics and Modelling of Fractured Reservoirs of the Proterozoic Basement of the Oumé Region (Central-Western Côte d'Ivoire)* (246 p.). Doctoral Thesis, Université Félix Houphouët-Boigny.

Baka, D., Soro, D., Yao, K. A., Kouadio, K. E., & Kouadio, K. L. (2021). Groundwater Resource Assessment in the Man Region (Western Côte d'Ivoire). *E-WASH Journal, 3,* 59-74.

Biémi, J. (1992). *Contribution to the Geological, Hydrogeological and Remote Sensing Study of the Sub-Saharan Watersheds of the Precambrian Basement of West Africa: Hydrostructural, Hydrodynamic, Hydrochemistry and Isotopic of the Discontinuous Aquifers of Furrows and Granitic Areas of the Haute Marahoué (Côte d'Ivoire)* (480 p.). Doctoral Thesis, University of Cocody-Abidjan.

Ble Louan, O., Soro, T., Yao, K. A., Kouassi, A. M., & Lasm, T. (2022). Influence of Lithology and Weathered Layers on Basement Aquifer Productivity in the Daoukro Region (Central-Eastern Côte d'Ivoire). *Revue des Sciences de l'Eau, 35,* 23-36.

Cooper, H. H., & Jacob, C. E. (1946). A Generalized Graphical Method for Evaluating Formation Constants and Summarizing Well-Field History. *Transactions American Geophysical Union, 27,* 526-534.

De Lasme, O. Z. (2013). *Contribution à une meilleure connaissance des aquifères fissures du socle précambrien: Cas de la région de San Pedro (Sud-Ouest de la Côte d'Ivoire)* (176 p.). Thèse de doctorat Hydrogéologie, Université Félix Houphouët Boigny.

De Lasme, O. Z., Kouamé, K. F., Soro, N., & Lasm, T. (2021). Characterization of the Hydrodynamic Properties of Basement Aquifers in Some Localities of Northern Côte d'Ivoire. *European Scientific Journal, 17,* 78-95.

Faillat, J. P. (1986). *Fissured Aquifers in the Humid Tropics: Structure, Hydrodynamics and Hydrochemistry (West Africa)* (534 p.). Doctoral Thesis, University of Languedoc.

Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Prentice Hall.

Idris, A. M. (2008). Combining Multivariate Analysis and Geochemical Approaches for Assessing Groundwater Quality. *Microchemical Journal, 90,* 159-163.

Kouassi, A. M., Ahoussi K. E., Yao K. A., Ourega W. E. J. A., Yao, K. S. B., & Biemi, J.

(2012a) Analyse de la productivite des aquiferes fissures de la region du N'Zi-Comoe (centre-est de la Cote d'Ivoire). *Larhyss Journal, No. 10,* 57-74.

Kouassi, M. A., Ahoussi, E. K., Koffi, B. Y., Ake, Y. A., & Biemi, J. (2012b). Caractérisation hydrogéochimique des eaux des aquifères fissurés de la zone Guiglo-Duekoué (Ouest de la Côte d'Ivoire). International Journal of Biological and Chemical Sciences, 6, 504-518. https://doi.org/10.4314/ijbcs.v6i1.45

Kouzana, L., Ben Mammou, A., & Gaaloul, N. (2007). Intrusion marine et salinisation des eaux d'une nappe phréatique côtière (Korba, Cap-Bon, Tunisie). *Geo-Eco-Trop, 31,* 57-70.

Lachassagne, P., Dewandel, B., & Wyns, R. (2021). Review: Hydrogeology of Weathered Crystalline/Hard-Rock Aquifers—Guidelines for the Operational Survey and Management of Their Groundwater Resources. *Hydrogeology Journal, 29,* 2561-2594. https://doi.org/10.1007/s10040-021-02339-7

Lasm, T. (2000). *Hydrogéologie des réservoirs fracturés de socle: Analyse statistique de la fracturation et des propriétés hydrodynamiques. Application à la région des montagnes de Côte d'Ivoire (domaine archéen)* (274 p.). Thèse de doctorat, Université de Poitiers.

Lasm, T. et al. (2011). Hydrodynamic and Hydrochemical Functioning of Fractured Aquifers in West Africa. *Journal of African Earth Sciences, 5,* 642-662.

Lasm, T., Yao, K. T., Oga, M. S., Kouamé, K. F., Jourda, P., Kouadio, K. E., & Baka, D. (2008). Analysis of the Physico-Chemical Characteristics of Groundwater in Proterozoic Land Region of the Tiassalé Area (Southern Côte d'Ivoire). *European Journal of Scientific Research, 20,* 526-543.

MacDonald, A. M., Bonsor, H. C., Dochartaigh, B. É. Ó., & Taylor, R. G. (2012). Quantitative Maps of Groundwater Resources in Africa. *Environmental Research Letters, 7,* Article ID: 024009. https://doi.org/10.1088/1748-9326/7/2/024009

Oga, M. S., Lasm, T., Yao, K. T., Soro, N., Saley, M. B., Kouassi, D., & Gnamba, F. (2009). Caractérisation chimique des eaux des aquifères de Fracture: Cas de la région de Tiassalé en Côte d'Ivoire. *European Journal of Scientific Research, 31,* 72-87.

Piper, A. M. (1944). A Graphic Procedure in the Geochemical Interpretation of Water Analyses. *Transactions, American Geophysical Union, 25,* 914-928.

Sielaff, K., & Einax, J. W. (2007). Application of Multivariate Statistical Methods for Groundwater Evaluation. *Journal of Soils and Sediments, 7,* 45-52.

Theis (1935). The Relation between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of the Well Using Ground-Water Storage. *Transactions of the American Geophysical Union, 16,* 519-524.

Yao, K. A. F., Ahoussi, K. E., Tivoli, L. M. S., Salze, D., & Lopez-Ferber, M. (2023). Caractérisation hydro-chimique et évaluation de la qualité des eaux souterraines de l'environnement minier du canton Afema (Sud-Est de la Côte d'Ivoire). *European Scientific Journal, 19,* 248. https://doi.org/10.19044/esj.2023.v19n6p248