***Original Research Article***

# Assessment of groundwaterphysicochemicalquality in Gbêkêregion of Côte d'Ivoire using water quality indices and multivariateanalysis

## ABSTRACT

The large demand for drinking water in Gbêkêregion of Côte d'Ivoire issuppliedfromgroundwatersources. Thisstudyinvestigatedthegroundwaterphysicochemicalqualityin Gbêkêregionof Côte d'Ivoire basedonpreselected24 boreholes.Groudwaterevaluationindexandfocusedprincipal components analysiswereused toassesswaterphysicochemicalquality,whichisamajorfactorforcontrollingthegroundwaterqualityintermof drinkingpurposes. Most of the groundwaterwereacidicand presentedlowmineralization. Hydrochemical facies wasMg-Ca-Cl type. Groundwaterquality indexvalues rangedfrom 11.69 to 119.37. The analysis shows that about96%ofthesampleswerebelongingtoexcellentqualitywaterfordrinkingpurposes. Focusedprincipal components analysissuggeststhatgroundwaterqualitywasmainlyrelatedtogeogenic(rock–waterinteraction)andanthropogenicsource (agrogenicanddomesticsewage)inthestudyarea.Itisexpectedthatoutcomesofthestudywillprovideinsightsfordecisionmakerstakingpropermeasuresforgroundwaterqualitymanagement incentralCôte d'Ivoire.

**Keywords :**Hydrochemistry ; Groundwaterquality ;Chemical pollution ; Gbêkêregion.

## 1. INTRODUCTION

Groundwater has become the major source of watersupply for drinking, domestic, household, agricultural, industrial and environmental activities. This has led to anincrease in the demand of water supply which is met mostly from theexploitation of groundwater resources (Douagui et al. 2019, Selvakumar et al., 2017).Studies like Atwia et al. (2013); Jellalia et al. (2013), Anomohanran (2015) ; Abu Risha and Temamy (2016); AnabaOnana et al. (2017), Haj-Amor et al. (2018); Hamad et al. (2018); Boujghad et al. (2019) and El Baghdadi et al. (2019) showed that in many African cities, groundwater is a vital water source outside of surface water resources. The wise management of groundwater resources is fundamental for sustainable development for reliable water sources supply for urban and rural areas.

Determination of groundwater quality is important for assessing various usages. Variation in groundwater quality in an area is a function of physical and chemical parameters that are greatly influenced by naturalprocesses such as geological formations and anthropogenic activities (Selvakumar et al., 2017). The study of hydrogeochemical processes in groundwater helps to understand and distinguish between the rock-water interactions and anthropogenic influences. The geochemical processes occuring within the groundwater and the reaction with aquifer minerals have a profound effect on water quality (Srivastava, 2008 ;Goné et al., 2014). Groundwater chemically evolves by interaction with aquifer minerals or internal mixing of different groundwaters along subsurface flow-paths (Toth, 1984 ; Srivastava, 2008). Therefore spatial distribution of chemical species gives some idea about the direction of groundwater movement.

Evaluation of groundwater quality is a complex process that undertakesnumerous variablescapable of causingvariousstresses on general groundwaterquality. The integrated approachs that include drinking water indices and multivariate statistics are used to characterize thegroundwaterquality. Variousresearchershavetriedtodevelopawiderangeof WQIs forevaluationofgroundwaterquality;thechoiceofindexdependsonthegroundwaterinputparametersandthe desired results(Vasanthavigaretal.,2010;Singhetal.,2013;Tiwarietal.,2014;Shahidetal.,2014). Referring to recent works (Bodrud-Dozaetal., 2016, Bhuiyan et al., 2016 ; Douagui et al. 2019),waterqualityindex(WQI)isaneffectivetechniqueforassessingdrinkingwaterqualitysuitabilityinanyareaandtocommunicate theinformationonoverallwaterquality. Multivariate analysis methods such as focused principal component analysis are a sophisticated knowledge extraction and diagnosis tool that can provide the analysis and visualisation of multidimensional groundwater quality data. This is explained by the variety of variables observed as groundwater quality data, and uncertainty involved in transport and reaction mechanism into groundwater systems (Goné et al, 2014).

Gbêkê region in Côte d'Ivoire is located in an environment of crystalline rocks and is densely populated (Douaguiet al. 2018). Pressure on environment and on water resources is still tremendous. The quality of groundwater which is the main source of drinking water in rural and urban zones is threatened. However, few groundwater quality studies have been conducted in the region. Thus, there is a need to provide more insight into the groundwater quality in crystalline formations in this region to assist local authorities in developing plans and regulations and in implementing actions to reduce human health and environmental risks.
The objective of this work is to evaluate the physicochemical quality of groundwater in Gbêkê regionon suitability for drinking purposes.

## 2. MATERIALS AND METHODS

### 2.1. Study area

The study area is Gbêkê region, located in the center of Côte d'Ivoire. It covers the area between longitudes 4˚24' and 5˚43'N and latitudes 7˚12' and 8˚12'W (Fig. 1). The population is estimated at 1200000 inhabitants. This area is under the influence of the wet tropical climate with two distinct seasons: a long dry season (November-March) and a long rainy season (April-October). The study area covers 9136 km$^2$. The geological bedrock consists of the volcano-sedimentary and the granitoides, which are essentially constituted by granites (Fig. 1). On the one hand, the volcano-sedimentary includes meta-sediments mostly constituted of sandstone and schists intruded by severalgenerations of granitoids. On the other hand, the volcano-sedimentary is covered by metavulcanites which consist of amphibolites, meta-andesite, rhyolites, meta-basaltes, metagabbro and metadolerite.

Two aquifers exist in the study area for the groundwater extraction. The most important aquifers are the fractured aquifers of crystalline and schist rocks. Their permeability is conditioned by the presence of discontinuities such as faults and joints and, in some cases, by lithologic contacts. Over the fractured rocks, the weathered layer may constitute a porous aquifer.

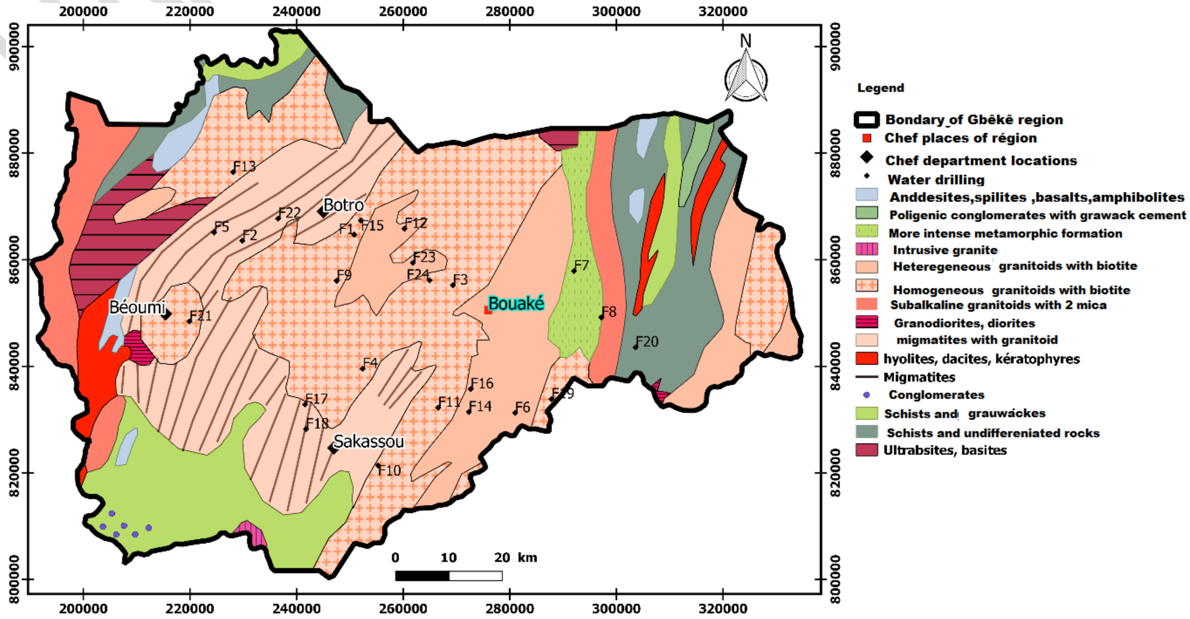

**Fig. 1. Study area**

## 2.2. Groundwater samples and data collection

Groundwater was sampled from 24 boreholes during the long dry season of 2015 (Fig. 1). Water sample collection from boreholes was carried out according to the procedures described by Lamrani et al. (2008) and Tayfur et al. (2008). Samples were taken after pumping for 5 min. The tap and the bucket were cleaned before sampling and caution was taken to avoid splashing. Samples were collected in 500 mL polyethylene bottles. Once collected, all samples were stored on ice and immediately transported to the laboratory. Chemical analyses were processed within 6 hours after collection.

## 2.3. Physico-chemical analyses

), Groundwater temperature (T), dissolved oxygen(DO), pH and electrical conductivity(EC)were measured in situ using the Hach Model 44600 Meter and the Multi 340i Handheld.

Chemical parameters were determined at the laboratory according to the methods presented in Table 1

Correlationstudieswerecarried out usingfocused principal components analysis (PCA) to determine the relationshipsbetweenphysicochemicalparameters. Focused PCA is a special type of PCA designed to describe and understandrelationshipsbetween a set of quantitative variables, with a particularinterest in the dependencies of one variable with the others. The relationshipsbetweennondependent variables are interpreted as in a PCA. Correlated variables are close or diametrically opposite (for negativecorrelations). Independent variables make a right angle with the origin. Focused PCA wasconductedusing R 3.4 software, module PSY.

**Table 1. Analysis methods of chemical parameters**

| Elements | Analysis methods |
|---|---|
| **$Ca^{2+}$. $Mg^{2+}$** | Atomic absorption spectrometry (NF ENISO 7980) |
| **K+** | Atomic emission spectrometry (AFNOR NF EN ISO 11885) |
| **$NO_3^-$** | Molecular absorption spectrometry (AFNO R standards NFT 90-045) |
| **$Cl^-$** | Liquid phase chromatography (AFNOR NF EN ISO 10304-3) |
| **$NH_4^+$** | Titrimetry method (AFNOR NF T90-015-1) |
| **$SO_4^{2-}$** | Chromatography of ions in the liquid phase (NF EN ISO 10304-1) |
| **$PO_4^{3-}$** | Molecular absorption spectrometry (AFNO R standards NFT 90-023) |
| **$Al^{3+}$** | Atomic absorption spectrometry (NF EN ISO 12020) |
| **Fe, $Mn^{2+}$, $Cu^{2+}$, $Zn^{2+}$** | Atomic absorption spectrometry (AFNO R standards FDT 90-112) |

## 2.4. Groundwater pollution evaluation

Groundwaterquality index (*GWQI*) methodreflects the composite influence of the different water qualityparameters on the suitability for drinkingpurposes.The standards for drinkingpurposes as recommended by WHO (2011) have been considered for the calculation of *GWQI*.For computing*GWQI*threesteps are followed as described by Vasanthavigar et al. (2010). In the firststep, Seventeenphysicochemicalparameters (pH, EC, Temperature, $NO_3^-$, $NO_2^-$ , $NH_4^+$, $SO_4^{2-}$, $PO_4^{3-}$, $K^+$, $Ca^{2+}$, $Mg^{2+}$, $Mn^{2+}$,$Cl^-$, $Fe^{2+}$, $Cu^{2+}$, $Zn^{2+}$, Fer total) has been assigned a weight(*wi*) according to itsrelative importance in the overallquality of waterfor drinkingpurposes (Table2). The maximum weight of 5 has been assignedto the parameterslike nitrate, nitrite and phosphate due to their major importance in water qualityassessment.Otherparameterswereassignedweightbetween 1 and

4depending on their importance in water qualitydetermination. In the second step, the relativeweight (*Wi*) iscomputedas follows (Equation 1) :

$$Wi = \frac{wi}{\sum_{i=1}^{n} wi} \tag{1}$$

Where$W_i$is the relative weight, ***wi***is the weight of eachparameter, ***n***is the number of parameters.

Inthethirdstep,a quality rating scale**(*$q_i$*)**for eachparameterisassigned by dividingits concentration in each watersample by its respective standard (Equation 3) according to WHO acceptability and health-based of drinking-water guidelines or limit values defined by Vasanthavigar et al. (2010) and Bhuiyan et al. (2016).

$$q_i = \left(\frac{C_i}{S_i}\right) \times 100 \tag{2}$$

Where, $q_i$is the quality rating ; $C_i$is the value or concentration of eachparameter in each water sample ; $S_i$is the drinking water standard for eachparameter.

For computing the *GWQI*, the ***SI***is first determined for eachparameter (Equation 3), whichisthenused to determine the *GWQI*. *GWQI*isdefined as (Equation 4):

$$SI_i = W_i \times q_i \tag{3}$$

$$GWQI = \sum SI_i \tag{4}$$

Where***SIi***is the sub-index of*i*thparameter ; $q_i$is the rating based on value or concentration of *i*thparameter ; ***n***is the number of parameters.

**Table 2. List of parameters, weightfactors, and limit values for the water quality index**

| **Parameters** | **WHO Standard (2011) (acceptability and health-based of drinking-water guideline values)** | **Weight (*wi*)** | **Relative weight(*$W_i$)*** |
|---|---|---|---|
| **pH** | 6.5 – 8.5$^b$ | 4 | 0.073 |
| **EC** | | 4 | 0.018 |
| **T** | 25 – 30°C$^c$ | 2 | 0.036 |
| **$NO_3^-$** | 50 mg.L$^{-1a}$ | 5 | 0.091 |
| **$NO_2^-$** | 3mg.L$^{-1a}$ | 5 | 0.091 |
| **$NH_4^+$** | 1.5 mg.L$^{-1b}$ | 3 | 0.055 |
| **$SO_4^{2-}$** | 250 mg.L$^{-1b}$ | 4 | 0.073 |
| **$PO_4^{3-}$** | 5 mg.L$^{-1c}$ | 5 | 0.091 |
| **$K^+$** | 12 mg.L$^{-1c}$ | 2 | 0.036 |
| **$Ca^{2+}$** | 100 mg.L$^{-1c}$ | 2 | 0.036 |
| **$Mg^{2+}$** | 50 mg.L$^{-1c}$ | 2 | 0.036 |
| **$Cl^-$** | 250 mg.L$^{-1b}$ | 3 | 0.055 |
| **$Fe^{2+}$** | 0.3 mg.L$^{-1b}$ | 4 | 0.073 |
| **$Fe_{total}$** | 0.3 mg.L$^{-1b}$ | 3 | 0.055 |
| **$Mn^{2+}$** | 0.4 mg.L$^{-1a}$ | 2 | 0.073 |
| **$Zn^{2+}$** | 3 mg.L$^{-1b}$ | 3 | 0.055 |
| **$Cu^{2+}$** | 2 mg.L$^{-1a}$ | 3 | 0.055 |
| | | ∑wi = 55 | ∑ ***Wi***= 1 |

[a] health-based ofdrinking-water guideline value

[b] acceptability and health-based ofdrinking-water guideline value

[c] limit values defined by Vasanthavigar et al. (2010) and Bhuiyan et al. (2016)

The *GWQI*range and type of water are classified as follows(Bhuiyan et al. 2016)(Table 3):

**Table 3. *GWQI* range and type of water**

| Range | Type of water |
|---|---|
| **< 50** | Excellent water |
| **50-100** | Good water |
| **100.1-200** | Poor water |
| **200.1-300** | Verypoor water |
| **> 300** | Water unsuitable for drinking purposes |

# 3. RESULTS AND DISCUSSION

## 3.1. Generalcharacteristicsofgroundwaterquality

General characteristics of groundwaterphysicochemicalparameters for the study area are summarized in Table 4. pH values variedfrom 3.06 to 8.36 withameanvalueof5.98±1.25. But 70.8% of all pH values of groundwatersampleshadtheir pH below 6.5 during the period of study, indicatingacidic nature of thesamples.This effectisexplained by the $CO_2$ production in the topsoilunder the actionof the biologicalactivities. Indeed, the study area aboundsmanyprimaryforests in protectedforest areas. The presence of theseforestspromotes the abundance of plant organicmatter. Itsmineralization releases $CO_2$whichisdissolved in groundwater as follows:

$$CH_2O + O_2 \longleftrightarrow CO_2 + H_2O \longleftrightarrow H^+ + HCO_3^-$$

For Goné et al. (2014) and Brindha et al. (2019), acidic water (pH below 6.5) is corrosive causingleaching of metalsfrompiped water supply and isdisagreeable in taste.Thoughhealth issues due to direct consumption of acidic water is notreported as the human body is capable of adjusting the acidic nature ofdrinking water, itincreases chances of heavymetal contaminant exposurethat leads to otherdiseases.

EC valuesrangedfrom105 to 632µS.cm$^{-1}$withameanvalueof266.9±129 µS.cm$^{-1}$ (Table 4).These values show that the prospectedboreholeswereweakly to fairlymineralised. In agreement withGoné et al. (2014), thismayberelated to the nature of silicate rocks within the groundwaterfrom the studiedaquifers. It isestablishedthat the geochemicalprocessesoccurringwithin the groundwater and the reactionwithaquiferminerals have a profond effect on water mineralisation.The lowmineralization of the groundwatersamplesobservedmaybeexplained by water in contact withhardlyalterableacid rocks.

Compared with the acceptability of drinking-water guideline proposed by WHO (2011), the groundwater samples presented low concentrations of major elements ($Ca^{2+}$, $Mg^{2+}$, $Cl^-$. $SO_4^{2-}$and $K^+$). According to WHO (2011), the health-based guideline for nitrate in drinking-water is 50 mg.L$^{-1}$. $NO_3^-$ concentrations of all the samples were below the permissible limit. The implication of this is thatthe water had very little contamination with landfill leachate, domestic sewage and other sources of pollution.

All the samples except three had the concentrations of iron within the suitable level of0.3 mg.L$^{-1}$. According to WHO (2011), there is usually no noticeable taste at iron concentrations below 0.3 mg/l, although turbidity may develop.The sampling sites that had concentrations of iron above 0.3 mg.L$^{-1}$ were F3, F4 and F8. At levels exceeding 0.3 mg.L$^{-1}$, iron in waters of these boreholes stains laundry and cause taste.

Health-based of drinking-water guideline value established by WHO (2011) for copperis 2 mg.L$^{-1}$ and all groundwatersampleswerewithinlimit. But, staining of laundry and sanitarywaremayoccurbelowguideline value (WHO, 2011).Aluminium concentrations of all the samples ranged from 0.001 to 0.011 mg.L$^{-1}$. There is no health-based of drinking-water guideline value established by WHO, but ahealth-based value derivedfrom the JECFA PTWI wouldbe 0.9 mg/l (rounded value), based on an allocation of 20% of the PTWI to drinking-water and assuminga 60 kg adultdrinking 2 litres of water per day.

Wenoted a dominance of the major ions $Cl^-$, $NO_3^-$, $Ca^{2+}$ and $Mg^{2+}$ in thesegroundwatersampleswhileother ions such as $K^+$and $SO_4^{2-}$ are comparativelylessrepresented. Concentrations of major cations and major anions wereclassified as :$Ca^{2+}$> $Mg^{2+}$>$K^+$and ($Cl^-$ + $NO_3^-$) > $SO_4^{2-}$. Thus, majority of groundwatersamplesfell in mixed Mg-Ca-Cltype.

**Table 4. Descriptive statistics of physicochemicalparameters in the study area**

| **Parameters** | **Unit** | **Min** | **Max** | **Mean** | **Std.Dev.** |
|---|---|---|---|---|---|
| **pH** | | 3.06 | 8.36 | 5.98 | 1.30 |
| **T** | °C | 27.40 | 31.00 | 29.05 | 0.87 |
| **DO** | $mg.L^{-1}$ | 6.60 | 7.10 | 6.81 | 0.09 |
| **EC** | $\mu S.cm^{-1}$ | 105.00 | 632.00 | 266.87 | 128.70 |
| **$NO_3^-$** | $mg.L^{-1}$ | 0.50 | 20.00 | 4.20 | 5.20 |
| **$NO_2^-$** | $mg.L^{-1}$ | 0.00 | 1.80 | 0.08 | 0.40 |
| **$NH_4^+$** | $mg.L^{-1}$ | 0.00 | 0.05 | 0.01 | 0.02 |
| **$SO_4^{2-}$** | $mg.L^{-1}$ | 0.00 | 30.00 | 2.1 | 6.6 |
| **$PO_4^{3-}$** | $mg.L^{-1}$ | 0.2 | 2.38 | 0.7 | 0.5 |
| **$Mn^+$** | $mg.L^{-1}$ | 0.00 | 0.20 | 0.03 | 0.05 |
| **$K^+$** | $mg.L^{-1}$ | 0.80 | 3.600 | 1.90 | 0.90 |
| **$Ca^{2+}$** | $mg.L^{-1}$ | 8.02 | 48.10 | 25.31 | 12.50 |
| **$Mg^{2+}$** | $mg.L^{-1}$ | 1.46 | 8.75 | 4.60 | 2.30 |
| **$HCO_3^-$** | $mg.L^{-1}$ | 11.100 | 2013.000 | 204.598 | 297.28 |
| **$Cl^-$** | $mg.L^{-1}$ | 3.50 | 60.30 | 13.70 | 12.80 |
| **$Fe^{2+}$** | $mg.L^{-1}$ | 0.00 | 0.40 | 0.02 | 0.08 |
| **$Fe_{TOT}$** | $mg.L^{-1}$ | 0.00 | 3.86 | 0.30 | 0.76 |
| **$Al^{3+}$** | $mg.L^{-1}$ | 0.001 | 0.01 | 0.004 | 0.003 |
| **$Cu^{2+}$** | $mg.L^{-1}$ | 0.00 | 0.08 | 0.015 | 0.02 |
| **$Zn^{2+}$** | $mg.L^{-1}$ | 0.00 | 0.10 | 0.03 | 0.033 |
| **$SiO_2$** | $mg.L^{-1}$ | 3.50 | 18.20 | 9.60 | 5.27 |

## 3.2. Groundwaterquality for drinkingpurposes

Table 5 shows groundwaterquality types determined on the basis of *GWQI* for assessing the suitability of groundwaterquality for drinkingpurposes. *GWQI* values variedfrom 11.69 to 119.37. The criticallimit (100) for drinking water purposeshas been proposed by Vasanthavigar et al. (2010) and Bhuiyan et al. (2016). Table 5shows thatallgroundwatersamplesdid not exceed the criticallimit (100) of *GWQI*s and belongedto excellent water qualityexcept for one sample (samplefromBorehole F8).

**Table 5. Pollution potential of groundwatersamples of the study area based on *GWQI***

| ***GWQI* values** | **Groundwaterquality types** | **Number of samples** | **% of samples** | **Samples** |
|---|---|---|---|---|
| **< 50** | Excellent water | 23 | 95.83 | 1-7 ; 9-24 |
| **50-100** | Good water | 0 | 0 | |
| **100.1-200** | Poor water | 1 | 4.17 | 8 |
| **200.1-300** | Verypoor water | 0 | 0 | |
| **> 300** | Water unsuitable for drinkingpurposes | 0 | 0 | |

## 3.3. Relationshipsbetweengroundwaterphysicochemicalquality

Statisticallysignificantrelationships($p < 0.05$) betweenphysicochemicalparameterswerefound in groundwaterboreholes (Fig. 2). $Ca^{2+}$$Mg^{2+}$, $K^+$, $Cl^-$, $NO_3^-$and $NH_4^+$concentrations showed a positive correlationwithEC.Theseparameterswerealsopositivelycorrelatedwitheachother. On the other hand, $Al^{3+}$ and DO showed a positive correlationwith $SiO_2$(Fig. 2). These associations indicate mixed sources of geogenic / anthropogenicorigin. $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Al^{3+}$, $Cl^{-}$ are the main constituents of groundwater as a result of interaction withminerals in aquifers and chemicalweathering of catchment rocks. The acidic nature of groundwaterwas due to leaching of altered rocks and anthropogenic sources.Anthropogenic pollutions werederivedfrom the useofchemicalfertilizersinagriculturalfields. Our findings are in agreement withthosereported byLigban et al. (2017) in Daloa (Côte d'Ivoire) and Bhuiyan et al. (2016) in Lakshimpur district of Bangladesh.

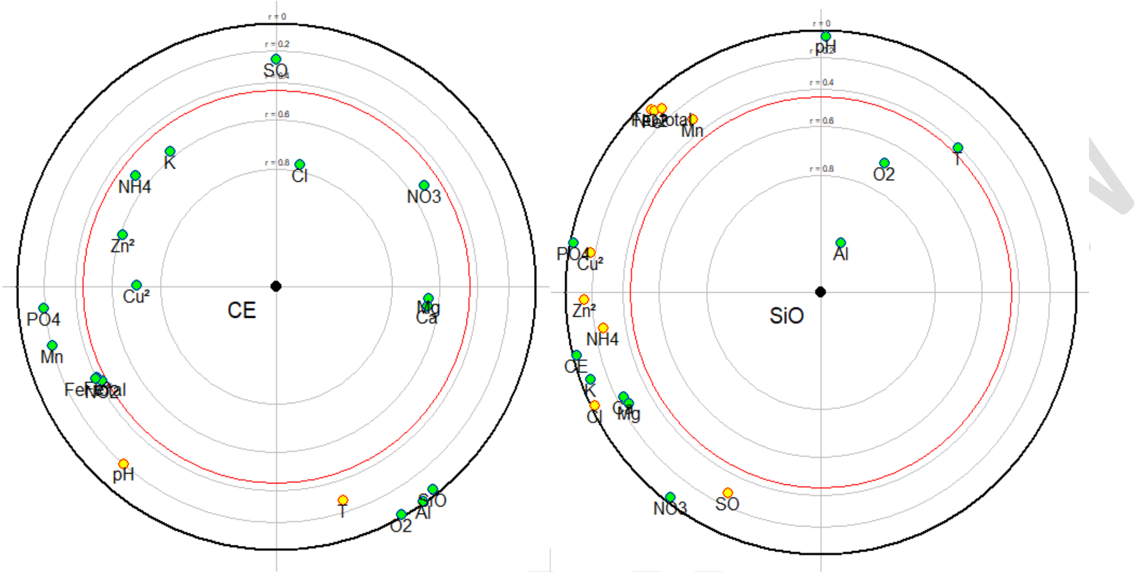

**Fig. 2. Focused principal components analysis ofphysicochemicalparametersand Electricalconducyivity and Silice ($SIO_2$). As the rings getcloser to the center theyreflect a highercorrelationwithEC and $SIO_2$**

## 4. CONCLUSION

Thisstudypresentedintegratedapproachesforcharacterizinggeochemistryandsuitabilityofgroundwaterquality inGbêkêregionofcentralCôte d'Ivoire. The groundwatersamplesfell in mixed Mg-Ca-Cl type. BasedonGWQI;about96%ofthesamples(23 sampling sites)belonged to excellent waterqualitytype,whereas4 % (1 location)exhibitedverypoor waterqualityfordrinkingpurposesinthestudyarea. The Focused PCA demonstratedthatanthropogenic andnatural/geogenicsources(rock–waterinteraction)wereresponsibleforvariationofphysicochemicalparametersingroundwateraquifer. Thispaperisexpectedtohelpwaterresourceplannerstakingadaptivemeasuresforgroundwaterqualitymonitoringin Gbêkêregion.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

## REFERENCES

1. Abu Risha, UA, Al Temamy, AMM, 2016. Comparative study of factors controlling the groundwater occurrence in BirKiseiba and Bir El Shab areas, south western desert, Egypt using hydrogeological and geophysical technique. Journal of African. Earth Sciences,117, 183-195. doi:10.1016/j.jafrearsci.2016.02.005

2. AnabaOnana, AB, NdamNgoupayou, JR, MvondoOndoa, J. 2017. Analysis of crystalline bedrock aquifer productivity: Case of central region in Cameroon. Groundwater fo Sustainable Development, 5, 66–74. http://dx.doi.org/10.1016/j.gsd.2017.05.003

3. Anomohanran, O., 2015. Hydrogeophysical investigation of aquifer properties and lithological strata in Abraka, Nigeria. Journal of African. Earth Sciences, 102, 247-253. https://doi.org/10.1016/j.jafrearsci.2014.10.006

4. Atwia, MG, Mohamed, M. Abu-Heleika, MM, El-Horiny, MM, 2013. Hydrogeochemical and vertical electrical soundings for groundwater investigations, Burg El-Arab area, Northwestern Coast of Egypt. Journal of African. Earth Sciences, 80, 8–20. https://doi.org/10.1016/j.jafrearsci.2012.11.001

5. Bhuiyan, HAM, Bodrud-Doza, M, Towfiqul Islam, ARM, Rakib, MA, Rahman, MS,Ramanathan,AL. 2016. Assessment of groundwater quality of Lakshimpur district of Bangladesh using water quality indices, geostatistical methods, and multivariate analysis. Environmental Earth Sciences, 75:1020, 1-23. DOI 10.1007/s12665-016-5823-y

6. Bodrud-Doza, M, Towfiqul Islam, ARM, Ahmed, F, Das, S, Saha, N, Rahman, SM. 2016. Characterizationofgroundwaterqualityusingwaterevaluation indices,multivariatestatisticsandgeostatisticsincentralBangladesh. Water Science 30, 19–40. http://dx.doi.org/10.1016/j.wsj.2016.05.001

7. Boujghad, A, Bouabdli, A, Baghdad, B. 2019. Groundwater quality evaluation in the vicinity of the DraaSfar Mine in Marrakesh, Morocco. Euro-Mediterranean Journal for Environmental Integration, 4 (12), 1-10. https://doi:10.1007/s41207-018-0096-3

8. Brindha K, Pavelic, P, Sotoukee, T. 2019. Environmental assessment of water and soil quality in the Vientiane Plain, Lao PDR. Groundwater for Sustainable Development 8, 24–30. https://doi.org/10.1016/j.gsd.2018.08.005

9. Douagui, GA, Kouassi, KA, Koumé, KB, Kouadio, AKS. 2018. Usinggeophysicalanomaliesforlocatingruralgroundwater suppliesincrystallinebasementenvironmentsofGbêkêRegion, center of Côte d'Ivoire Contributiondesanomaliesgéoélectriquespourlalocalisationdes aquifèresen milieu rural cristallindans la Région du Gbêkêau Centre de la Côte d'Ivoire. Environmental and Water Sciences, Public Health & Territorial Intelligence. http://revues.imist.ma/?journal=ewash-ti/

10. Douagui, GA, Kouadio, AKS, Mangoua, OMJ, Kouassi, KA, Koumé, BK, Savané, I. 2019. Using specific capacity for assessing of the factors controlling borehole productivity in crystalline bedrock aquifers of N'Zi, Iffou and Moronou regions in the eastern area of Côte d'Ivoire. Groundwater for Sustainable Development, 9. In press. https://doi.org/10.1016/j.gsd.2019.100235

11. El Baghdadi, M, Zantar, I, Jouider, A, Nadem, S, Medah, R. 2019. Evaluation of hydrogeochemical quality parameters of groundwater under urban activities. Case of BeniMellal city (Morocco). Euro-Mediterranean Journal for Environmental Integration, 4(6), 5-19. https://doi:10.1007/s41207-018-0087-4

12. Goné, DL, Douagui, GA, Bai, L, Kamagaté, B, Ligban, R. 2014. Using Graphical and Multivariate Statistical Methods for Geochemical Assessment of Groundwater Quality in Oumé Department (Côte d'Ivoire). Journal of Environmental Protection, 2014, 5, 1255-1265. http://dx.doi.org/10.4236/jep.2014.512119

13. Haj-Amor, Z, Hashemi, H, Bouri, S. 2018. The consequences of saline irrigation treatments on soil physicochemical characteristics. Euro-Mediterranean Journalfor Environmental Integration, 3 (22), 2-12. https://doi:10.1007/s41207-018-0064-y

14. Hamad, A, Baali, F, Hadji, R, Zerrouki, H, Besser, H, Mokadem, N, Hamed, Y. 2018. Hydrogeochemical characterization of water mineralization in Tebessa-Kasserine karst system (Tuniso-Algerian Transboundry basin). Euro-Mediterr. J. Environ. Integr. 3 (7), 1-15. https://doi.org/10.1007/s41207-017-0045-6

15. Jellalia, D, Lachaal, F, Andoulsi, M, Zouaghi, T, Hamdi, M, Bedir, M, 2013. Hydro-geophysical and geochemical investigation of shallow and deep Neogene aquifer systems in HajebLayoun-Jilma-Ouled Asker area, Central Tunisia. J. Afr. Earth Sci, 110: 227–244. https://doi.org/10.1016/j.jafrearsci.2015.06.016

16. Lamrani, AH, Oufdou, K, Mezrioui, N. 2008. Environmental pollution impacts on the bacteriological and physicochemical quality of suburban and rural groundwater supplies in Marrakesh area (Morocco). Environmental Monitoring and Assessment, 145 (1-3), 195-207.

17. Ligban, R, Mangoua, OMJ, Kouadio, ZA, Douagui, GA, Kouassi, KA, Goné, DL. 2017. Caractérisationchimique des eaux de sources naturellesdans le degrécarré de Daloa, au Centre-ouest de la Côte d'Ivoire. Afrique SCIENCE 13(2), 62 – 72.

18. Selvakumar, S, Chandrasekar, N, Kumar, G. 2017. Hydrogeochemical characteristics and groundwater contamination in therapid urban development areas of Coimbatore, India. Water Resources and Industry, 17, 26-33. http://dx.doi.org/10.1016/j.wri.2017.02.002

19. Shahid,SU,Iqbal,J,Hasnain,J.2014.Groundwaterqualityassessmentanditscorrelationwithgastro enteritisusingGIS:acasestudyofRawal Town,Rawalpindi,Pakistan.Environmental Monitoring and Assessment,186,7525–7537,http://dx.doi.org/10.1007/s10661-014-3945-9.

20. Singh,PK,Tiwari,AK,Panigarhy,BP,Mahato,MK. 2013.WaterqualityindicesusedforwaterresourcesvulnerabilityassessmentusingGIS technique:areview.InternationalJournal ofEarthSciences and Engineering,6(6–1),1594–1600.

21. Srivastava, KS, Ramanathan, LA. 2008. Geochemical Assessment of Groundwater Quality in Vicinity of Bhalswa Landfill. Delhi; India by Using Graphical and Multivariable Statistical Methods. Environmental Geology, 53, 1509-1528. http://dx.doi.org/10.1007/s00254-007-0762-2

22. Tayfur, G, Kirer, T, Baba, A. 2008. Groundwater quality and hydrogeochemical properties of Torbalı Region, Izmir, Turkey. Environmental Monitoring and Assessment, 146 (1-3), 157-169

23. Tiwari,AK, Singh,PK,Mahato,MK. 2014. GIS-basedevaluationofwaterqualityindexofgroundwaterresourcesinwestBokaroCoalfield, India.CurrentWorldEnvironment, 9 (3), 73–79

24. Toth, J. 1984. The Role of Regional Gravity Flow in the Chemical and Thermal Evolution of Groundwater. Proceedings of the First Canadian/American Conference on Hydrogeology, Banff,Alterta, Canada, 22-26 June 1984

25. Vasanthavigar, M.,·Srinivasamoorthy, K.,·Vijayaragavan, K.,·RajivGanthi, R, Chidambaram, S.,·Anandhan, P.,·Manivannan·R., Vasudevan, S. 2010. Application of water quality index for groundwater quality assessment: Thirumanimuttar sub-basin, Tamilnadu, India. Environmental Monitoring and Assessment, 171:595–609. DOI 10.1007/s10661-009-1302-1

26. WHO. 2011. Guidelines or Drinking-Water Quality. 4th Edition, World Health Organization, Geneva.