

Integrated Assessment of Physicochemical Characteristics and Health Risks of Groundwater from Wells in the Continental Terminal Aquifer of Bonoua (Southeastern Côte d'Ivoire) Using WQI, HI, and PCA during the Rainy Season

Tohouri Privat^{1*}, Anongba Braphond Rodrigue Vincent Benjamin¹, Orou Kotchi Rodrigue², Adja Miessan Germain¹

¹Department of Sciences and Technology, Ecole Normale Supérieure d'Abidjan, Abidjan, Côte d'Ivoire

²Department of Agriculture and New Technology, Université de San Pedro, San Pedro, Côte d'Ivoire

Email: *privatohouri@gmail.com

How to cite this paper: Privat, T., Benjamin, A. B. R. V., Rodrigue, O. K., & Germain, A. M. (2025). Integrated Assessment of Physicochemical Characteristics and Health Risks of Groundwater from Wells in the Continental Terminal Aquifer of Bonoua (Southeastern Côte d'Ivoire) Using WQI, HI, and PCA during the Rainy Season. *Journal of Geoscience and Environment Protection*, 13, 212-235.

<https://doi.org/10.4236/gep.2025.1312012>

Received: October 24, 2025

Accepted: December 6, 2025

Published: December 9, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Groundwater in Côte d'Ivoire is increasingly exposed to contamination from both natural and anthropogenic sources. This study evaluates the physicochemical characteristics and potential health risks of well water from the Continental Terminal aquifer in Bonoua, southeastern Côte d'Ivoire, during the rainy season. Thirty groundwater samples were collected and analyzed for 28 parameters, including major ions and heavy metals. Results revealed low mineralization (mean electrical conductivity: 161.85 $\mu\text{S}/\text{cm}$) and acidic conditions (mean pH: 5.16). Concentrations of aluminium (504 $\mu\text{g}/\text{L}$), manganese (998 $\mu\text{g}/\text{L}$), iron (1023 $\mu\text{g}/\text{L}$), and cadmium (78 $\mu\text{g}/\text{L}$) exceeded the World Health Organization drinking-water guidelines. The Water Quality Index (WQI) ranged from 7.08 to 758.40 (mean: 136.55), indicating that most wells (77%) were unsuitable for direct consumption. Non-carcinogenic health risk assessment revealed higher vulnerability among children (mean Hazard Index, HI: 19.50) compared with adults (mean HI: 8.49), with most wells exceeding the safety threshold (HI > 1). Principal Component Analysis (PCA), explaining 79.29% of the total variance, identified three main pollution sources: natural mineralization, acid-driven metal mobilization, and anthropogenic contamination. These findings highlight the urgent need for strengthened groundwater monitoring and sustainable management strategies in the Bonoua region.

Keywords

Groundwater, Heavy Metals, Water Quality Index, Health Risk Assessment, Principal Component Analysis, Côte d'Ivoire

1. Introduction

Access to safe drinking water is a major public health concern, particularly in sub-Saharan Africa, where many rural populations rely on wells (WHO, 2017). Shallow well waters are highly vulnerable to anthropogenic pressures such as wastewater infiltration, insufficient sanitary protection, uncontrolled use of fertilizers and pesticides, and proximity to unregulated dumpsites (Traoré et al., 2006). These pressures can deteriorate water quality by introducing pollutants such as nitrates and heavy metals (Pb, Cd, Cr, Fe, etc.), which may pose health risks when their concentrations exceed internationally established thresholds (USEPA, 2004; WHO, 2017). Several studies have emphasized the importance of monitoring well water during the rainy season, when contamination risks are heightened due to increased surface runoff and leaching (Ouattara et al., 2016; Hounsounou et al., 2018). In Bonoua (Côte d'Ivoire), surface water analyses revealed elevated concentrations of cadmium, iron, and manganese, suggesting a potential transfer of these contaminants to groundwater (Tohouiri et al., 2017). The combination of high population density and intensified agricultural, domestic, and industrial activities further increases pressure on local water resources, making seasonal water quality assessments essential. Traditionally, physicochemical parameters are used to evaluate water quality. However, composite indices such as the Water Quality Index (WQI) provide a more integrative and accessible approach to assessing overall water suitability (Abbasi & Abbasi, 2012; Tyagi et al., 2013). Non-carcinogenic health risk assessment, based on Hazard Quotients (HQ) and Hazard Indices (HI), is used to estimate potential exposure risks for various population groups, including sensitive categories such as children (USEPA, 1989; Wu et al., 2009). Additionally, Principal Component Analysis (PCA) has proven effective for identifying pollution sources and distinguishing between natural and anthropogenic contributions to water composition (Reghunath et al., 2002; Shrestha & Kazama, 2007). Despite the existence of several studies on groundwater quality in Côte d'Ivoire, very few have focused specifically on the Continental Terminal aquifer in Bonoua, particularly during the rainy season when contamination risks are highest. Therefore, this study provides new insights into the seasonal variability, health implications, and pollution sources affecting well water quality in this coastal region. In this context, the present study aims to: 1) assess the physicochemical quality of well water, 2) evaluate potential health risks, and 3) identify the main pollution sources using PCA. These objectives seek to improve understanding of groundwater vulnerability and to support the implementation of appropriate management and protection measures.

2. Materials and Methods

2.1. Study Area

The study area is located in southeastern Côte d'Ivoire, between latitudes 5°10' N and 5°33' N and longitudes 3°12' W and 3°50' W, covering approximately 1864 km² and including the departments of Alépé, Bonoua, Aboisso, and Adiaké (**Figure 1**).

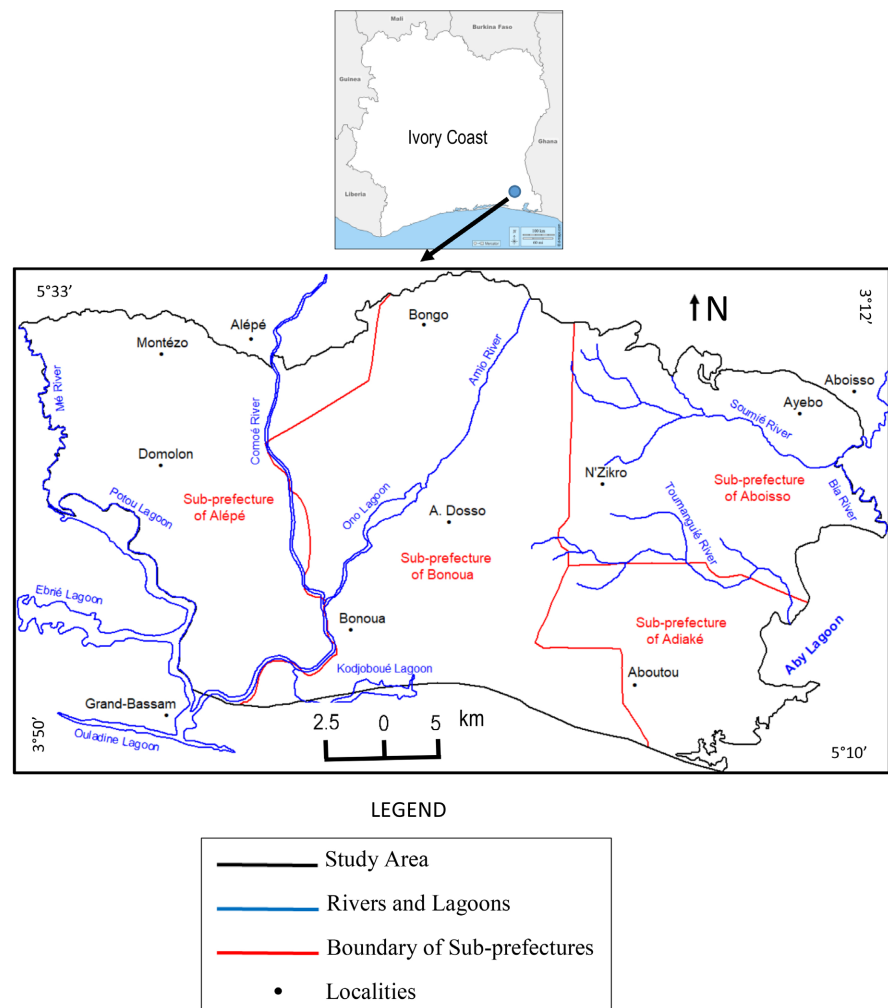


Figure 1. Geographic location of the study area.

It overlies the Continental Terminal aquifer of Bonoua, a strategic groundwater resource exploited through wells and boreholes for drinking water supply and agro-industrial activities. Dating from the Mio-Pliocene, the aquifer consists of sands, sandstones, clays, and conglomerates with high permeability and represents one of the major groundwater reservoirs in Côte d'Ivoire (Loroux, 1978).

The region experiences a transitional equatorial climate with two rainy and two dry seasons, and annual rainfall varies from 800 to 2000 mm. The original vegetation (dense evergreen forests and littoral psammo-hygrophilous formations) has

been largely modified by agricultural expansion, including industrial crops (rubber, oil palm, pineapple) and subsistence crops (cassava, yam, and plantain) (Roose & Chérourx, 1965). The hydrographic network includes the Comoé, Bia, and La Mé rivers, as well as the Soumié and Toumanguié tributaries, which feed the Aby, Potou, and Ébrié lagoons. The Comoé River, with an average discharge of approximately 300 m³/s, plays a central role in regional hydrological dynamics (Halle & Bruzon, 2006).

2.2. Data Collection

A water sampling campaign was carried out in July 2014, during the rainy season, targeting 30 wells. The selection of wells was based on several criteria, including accessibility, proximity to agricultural activities, and the presence of potential pollution sources such as latrines or septic tanks. Each water sample was collected using a dedicated dipper previously sterilized by rinsing to avoid contamination. Samples were transferred into pre-cleaned polyethylene bottles and stored under appropriate conditions. Sampling coverage was limited by the presence of non-functional wells and access difficulties caused by road conditions. Additional site information (including UTM coordinates and elevation) was recorded for each sampled well (Table 1).

Table 1. Location and geographic coordinates of sampled wells in the Bonoua area (Continental Terminal aquifer, southeastern Côte d'Ivoire).

Locality	Well Code	UTM X (m)	UTM Y (m)	Well Altitude (m)	Locality	Well Code	UTM X (m)	UTM Y (m)	Well Altitude (m)
Adiaké	P1	467648.53	584286.04	10	Kimoukro	P16	440162.13	600495.53	21
Ahoutoué	P2	409273.74	605114.42	30	Memni	P17	418418.49	609426.90	61
Akouré	P3	417181.75	594697.71	32	Monga 1	P18	426784.79	605465.02	10
Akroaba B (1)	P4	442527.87	596788.38	25	Monga 2	P19	426758.85	605391.34	29
Akroaba b (2)	P5	444036.31	598852.45	34	Motobé	P20	429433.70	587310.37	9
Andou M'bato	P6	427152.40	597164.35	16	Ngokro 1	P21	429043.96	592368.17	18
Béniakré	P7	453134.00	602552.36	62	Ngokro 2	P22	429163.78	592368.17	19
Bongo V1	P8	439163.62	609015.79	98	Ono Salci 1	P23	437300.63	594992.99	25
Bonoua	P9	433175.76	582103.61	16	Ono Salci 2	P24	437224.83	594899.10	30
Campement Ono	P10	446747.03	601394.60	32	Ono Salci 3	P25	436901.63	594838.59	26
Campement Opi	P11	438845.49	596257.31	21	Ono Salci 4	P26	436853.50	594713.36	15
Djiminikoffikro	P12	449241.49	584149.75	108	Samo	P27	442370.12	584925.27	71
Grand-Alépé	P13	415344.74	605251.97	42	Soumié	P28	467189.77	598035.73	23
Huit kilos	P14	427892.94	577939.47	12	Obrou Cõmon	P29	444038.97	602032.44	42
Ingrakon	P15	425725.68	601088.50	12	Yaou	P30	430371.49	579615.41	16

Samples were preserved on dry ice and subsequently stored at +4°C before la-

laboratory analysis at the CIAPOL laboratory within 24 hours of collection. During the field campaign, several physicochemical parameters were measured *in situ*, including pH, redox potential, temperature, electrical conductivity, salinity, total dissolved solids, dissolved oxygen, and turbidity. These measurements were performed using a portable multiparameter probe (HANNA HI9828). Laboratory analyses focused on major ions (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , SO_4^{2-} , HCO_3^-), heavy metals (Pb^{2+} , Cd^{2+} , Fe^{2+} , Mn^{2+} , Al^{3+} , Cu^{2+} , Zn^{2+}), and nutrient species (NO_3^- , NO_2^- , NH_4^+ , PO_4^{3-}), along with selected physical parameters (suspended solids, hydrotimetric titre). All analyses were conducted following standardized protocols (AFNOR, 1997; Rodier et al., 2009) (Table 2).

The dataset, although collected in 2014, remains relevant for the present study. Since the sampling period, land use, industrial activities, and population density in the Bonoua region have remained relatively stable. No major environmental or anthropogenic changes have occurred that could significantly affect groundwater quality. In the context of limited recent data in West Africa, these historical records provide a reliable basis for evaluating water quality and supporting sustainable resource management.

Table 2. Analytical methods used for the determination of chemical parameters.

Parameter	SI units	Analytical method	Reference Standard
Magnesium (Mg^{2+})	mg/L	Flame atomic absorption spectrometry	NF T 90 - 112
Calcium (Ca^{2+})	mg/L	Flame atomic absorption spectrometry	NF T 90 - 005
Potassium (K^+)	mg/L	Flame atomic absorption spectrometry	NF T 90 - 020
Sodium (Na^+)	mg/L	Flame atomic absorption spectrometry	NF T 90 - 019
Bicarbonate (HCO_3^-)	mg/L	Acid titration	NF T 90 - 003
Phosphate (PO_4^{3-})	mg/L	Molecular absorption spectrometry	NF T 90 - 023
Nitrate (NO_3^-)	mg/L	Molecular absorption spectrometry	NF T 90 - 012
Nitrite (NO_2^-)	mg/L	Molecular absorption spectrometry	NF T 90 - 013
Ammonium (NH_4^+)	mg/L	Ion chromatography	NF T 90 - 015
Chloride (Cl^-)	mg/L	Ion chromatography	NF T 90 - 014
Sulfate (SO_4^{2-})	mg/L	Ion chromatography	NF T 90 - 040
Zinc (Zn)	$\mu\text{g/L}$	Inductively coupled plasma emission spectrometry (ICP)	NF T 90 - 112
Copper (Cu)	$\mu\text{g/L}$	Inductively coupled plasma emission spectrometry (ICP)	NF T 90 - 112
Lead (Pb)	$\mu\text{g/L}$	Inductively coupled plasma emission spectrometry (ICP)	T 90 - 119
Manganese (Mn)	$\mu\text{g/L}$	Inductively coupled plasma emission spectrometry (ICP)	NF T 90 - 119
Cadmium (Cd)	$\mu\text{g/L}$	Inductively coupled plasma emission spectrometry (ICP)	T 90 - 119
Aluminium (Al)	$\mu\text{g/L}$	Inductively coupled plasma emission spectrometry (ICP)	T 90 - 119
Iron (Fe)	$\mu\text{g/L}$	Inductively coupled plasma emission spectrometry (ICP)	NF 90 - 017
Suspended solids (SS)	mg/L	Filtration through a 0.45 μm membrane, drying at 105°C, and weighing	NF T 90 - 105
Total hardness (TH)	°F	EDTA titration	NF T 90 - 003

2.3. Study Methodology

The assessment of well water quality was conducted using an integrated analytical approach combining several tools:

- comparison of measured concentrations with World Health Organization (WHO, 2017) guideline values;
- calculation of the Water Quality Index (WQI) for a synthetic evaluation of water suitability;
- estimation of non-carcinogenic health risks using Hazard Quotient (HQ) and Hazard Index (HI); and
- application of Principal Component Analysis (PCA) to identify potential sources of contamination.

2.3.1. Comparison with WHO Drinking Water Standards

The concentrations of the analyzed physicochemical parameters (physical, major ions, trace metals, and nitrogen compounds) were compared with the WHO (2017) drinking water quality standards—this comparison aimed to evaluate the suitability of well water for human consumption.

2.3.2. Calculation of Water Quality Index (WQI)

The WQI was calculated using the weighted arithmetic method of Brown et al. (1972), commonly applied in hydrogeochemical studies (Sahu & Sikdar, 2008; Tyagi et al., 2013). This approach integrates multiple water quality parameters into a single index that reflects the overall potability status. The relative quality (Q_i) of each parameter was determined using Equation (1):

$$Q_i = \left[\frac{V_{\text{actuel}} - V_{\text{ideal}}}{V_{\text{standard}} - V_{\text{ideal}}} \right] \times 100 \quad (1)$$

where:

- V_{actuel} : measured concentration of the parameter;
- V_{standard} : WHO guideline value (WHO, 2004);
- V_{ideal} : optimal value (7 for pH, 14 mg/L for DO, and 0 for all other parameters) (Ramakrishnaiah et al., 2009; Tyagi et al., 2013; Abbasnia et al., 2018).

The relative weight (W_i) is defined by Equation (2):

$$W_i = K/S_i \quad (2)$$

with $K = 1/\sum(1/S_i)$.

Where S_i is the WHO standard for the parameter and K is a normalization constant.

The overall WQI was then calculated using Equation (3):

$$WQI = \sum(Q_i \times W_i) / \sum W_i \quad (3)$$

In this study, nineteen parameters were incorporated into the analysis (pH, EC, TDS, Cl^- , NO_3^- , SO_4^{2-} , NH_4^+ , Ca^{2+} , Mg^{2+} , Na^+ , K^+ , HCO_3^- , Fe^{2+} , Zn^{2+} , Cu^{2+} , Al^{3+} , Mn^{2+} , Pb^{2+} , Cd^{2+}) because of their potential impact on human health (WHO, 2004; Sahu & Sikdar, 2008; Tyagi et al., 2013), and their relevance to groundwater quality assessment in tropical regions affected by both geogenic and anthropo-

genic inputs.

The classification of WQI values followed the criteria proposed by Tyagi et al. (2013) in Table 3.

Table 3. Classification of water quality based on the weighted arithmetic WQI method.

WQI value	Water quality	Interpretation	Grade
0 - 25	Excellente	Suitable for use without treatment	A
26 - 50	Good	Slightly affected	B
51 - 75	Medium	Acceptable quality, requires treatment	C
76 - 100	Poor	Not potable without advanced treatment	D
>100	Very poor/Polluted	Dangerous for any use	E

2.3.3. Health Risk Assessment

The health risk assessment related to the ingestion of contaminated water was performed following USEPA guidelines (USEPA, 1989; USEPA, 2004; USEPA, 2011) to quantify non-carcinogenic effects from chronic exposure. The main indicators are the Chronic Daily Intake (CDI), Hazard Quotient (HQ), and Hazard Index (HI). This approach differentiates between adults and children, accounting for distinct ingestion behaviors and physiological characteristics.

1) Chronic Daily Intake

The CDI expresses the amount of contaminant ingested over a prolonged period and is calculated using Equation (4):

$$CDI = (C \times IR \times EF \times ED) / (BW \times AT) \quad (4)$$

where:

- C: contaminant concentration (mg/L);
- IR: ingestion rate (L/day);
- EF: exposure frequency (days/year);
- ED: exposure duration (years);
- BW: body weight (kg);
- AT: averaging time (days), calculated as $ED \times 365$ for non-carcinogenic risk.

The parameter values used, obtained from USEPA (2004), are given in Table 4.

Table 4. Typical exposure parameters used for health risk assessment (USEPA, 2004).

Parameter	Children	Adults
IR (Ingestion rate)	1 L/day	2 L/day
BW (Body weight)	15 kg	70 kg
ED (Exposure duration)	6 years	30 years
EF (Exposure frequency)	365 days/year	365 days/year
AT (Averaging time, non-carcinogenic)	2190 days	10,950 days

2) Hazard Quotient (HQ)

The Hazard Quotient (HQ) measures the non-carcinogenic risk of a specific contaminant and is calculated using Equation (5):

$$HQ = CDI/RfD \quad (5)$$

where *RfD* is the reference dose (mg/kg/day), defined as the exposure level below which no adverse effects are expected.

The interpretation criteria are as follows:

- HQ < 1: negligible risk;
- HQ ≥ 1: potential health risk.

Only contaminants with available RfD values (**Table 5**) were considered, namely Cu²⁺, Zn²⁺, Cd²⁺, Mn²⁺, Al³⁺, Fe²⁺, NO₃⁻, NO₂⁻, and NH₄⁺. Pb²⁺ and Cu²⁺ were excluded due to concentrations below detection limits.

Table 5. Reference doses (RfD) of the parameters considered.

Parameter	Chemical formula	RfD (mg/kg/day)
Copper (Cu)	Cu ²⁺	0.04
Zinc (Zn)	Zn ²⁺	0.3
Cadmium (Cd)	Cd ²⁺	0.001
Manganèse (Mn)	Mn ²⁺	0.14
Aluminium (Al)	Al ³⁺	0.0004
Iron (Fe)	Fe ²⁺ /Fe ³⁺	0.7
Nitrate (NO ₃ ⁻)	NO ₃ ⁻	1.6
Nitrite (NO ₂ ⁻)	NO ₂ ⁻	0.1
Ammonium (NH ₄ ⁺)	NH ₄ ⁺	0.3

RfD: reference dose expressed in milligrams per kilogram of body weight per day.

3) Hazard Index (HI)

The Hazard Index (HI) represents the overall non-carcinogenic risk from simultaneous exposure to multiple contaminants and is computed as the sum of individual HQs, Equation (6):

$$HI = \sum HQ_i \quad (6)$$

The interpretation is based on the same principles as above:

- HI < 1: no combined effect expected;
- HI ≥ 1: potential for synergistic or cumulative toxic effect.

2.3.4. Principal Component Analysis (ACP)

Principal Component Analysis (PCA) was applied to the hydrochemical dataset to identify latent structures, reduce variable redundancy, and detect potential sources of contamination. This multivariate approach is particularly effective in analyzing complex environmental systems where multiple parameters interact simultaneously (Liu et al., 2003; Shrestha & Kazama, 2007). The data were stand-

ardized (mean-centered and scaled to unit variance) to eliminate the influence of differing measurement units. The adequacy of PCA was tested using the Kaiser-Meyer-Olkin (KMO) index and Bartlett's sphericity test. Principal components were retained according to Kaiser's criterion (Kaiser, 1960), selecting only those with eigenvalues greater than 1. Interpretation was based on the correlation matrix, total variance explained, and component loadings. The analysis included all physicochemical parameters contributing to the determination of WQI and HI, namely Cl^- , HCO_3^- , SO_4^{2-} , K^+ , Na^+ , Ca^{2+} , Mg^{2+} , NO_3^- , NO_2^- , NH_4^+ , EC, Cd^{2+} , Mn^{2+} , Al^{3+} , and Fe^{2+} . All statistical analyses were performed using SPSS version 29.0, a widely used software package for environmental multivariate analysis.

3. Results

3.1. Hydrochemical Characteristics of Well Water

The statistical summary of the physicochemical parameters, major ions, nutrients, and heavy metals measured in situ and in the laboratory is presented in **Table 6**. These results are expressed through standard statistical descriptors (minimum, mean, maximum, median, standard deviation, and coefficient of variation (CV)).

Overall, the measured parameters exhibit wide variability, reflecting the influence of both natural and anthropogenic factors on groundwater composition within the Continental Terminal aquifer of Bonoua.

Table 6. Physicochemical characteristics of well water from the Continental Terminal aquifer of Bonoua during the rainy season (July 2014), compared with the (WHO, 2017) guideline values.

Parameter	SI unit	Min	Mean	Max	Median	SD	CV (%)	WHO (2017)
Physical parameters								
Temperature (T)	°C	25.10	27.09	28.70	27	0.69	2.53	25°C
MES	mg/L	17.25	27.92	52.78	26.62	8.65	30.97	-
Turbidity (Turb)	NTU	0.20	1.97	11.70	0.99	2.45	124.27	5 NTU
Redox potential (Eh)	mV	-39	63.51	122	66.90	47.31	74.50	-
Physicochemical parameters								
pH	-	4.04	5.16	6.87	5.09	0.83	91.56	6.5 - 8.5
Electrical conductivity (CE)	µS/cm	28.81	161.85	420.65	109.67	115.88	71.60	1500
Salinity (Sal)	-	0.01	0.08	0.20	0.06	0.06	70.40	-
Total Dissolved Solids (TDS)	mg/L	10	86	220	60	60.53	70.38	1000
Total Hardness (THT)	°F	0.93	3.09	5.39	3.10	1.02	33.12	35
Dissolved Oxygen (DO)	mg/L	0.45	4.14	6.57	3.98	1.78	42.91	≥ 5
Major Ions								
Chloride (Cl^-)	mg/L	0.40	14.79	36.80	11.57	9.83	66.48	250
Bicarbonate (HCO_3^-)	mg/L	1.20	21.19	54.70	14.49	15.98	75.38	120
Sulfate (SO_4^{2-})	mg/L	1	7.27	18	5	4.70	64.74	250

Continued

Potassium (K ⁺)	mg/L	0.37	6.62	17.12	3.87	5.24	79.14	12
Sodium (Na ⁺)	mg/L	1.10	6.14	15.80	3.74	4.47	72.81	200
Calcium (Ca ²⁺)	mg/L	1.86	8.09	13.50	7.83	2.76	34.06	100
Magnesium (Mg ²⁺)	mg/L	1.22	2.56	4.84	2.12	1.19	46.53	50
Nutrients								
Nitrate (NO ₃ ⁻)	mg/L	1.70	14.33	21.87	14.35	3.97	27.73	50
Nitrite (NO ₂ ⁻)	mg/L	0	0.04	0.24	0.02	0.05	131.08	0.1
Ammonium (NH ₄ ⁺)	mg/L	0.01	0.27	1.24	0.13	0.33	123.78	0.5
Phosphate (PO ₄ ³⁻)	mg/L	0.02	0.18	0.91	0.14	0.17	91.56	0.5
Heavy metals								
Zinc (Zn ²⁺)	µg/L	0	93.90	782	5	167.13	177.99	3000
Cooper (Cu ²⁺)	µg/L	ND	ND	ND	ND	ND	ND	1000
Lead (Pb ²⁺)	µg/L	ND	ND	ND	ND	ND	ND	50
Cadmium (Cd ²⁺)	µg/L	0	5.10	78	0	15.10	296	3
Manganese (Mn ²⁺)	µg/L	2	350	998	323	283.29	80.93	50
Aluminium (Al ²⁺)	µg/L	1	111.53	504	56	130.84	117.31	200
Iron (Fe ²⁺)	µg/L	0	203	1023	65	290.65	143.18	300

ND = not detected; SD = standard deviation; CV = coefficient of variation.

3.1.1. Physical Parameters

The water temperature ranged from 25.10°C to 28.70°C, with a mean of 27.09°C, which is slightly above the WHO guideline of 25°C, consistent with typical tropical aquifer conditions. Suspended solids (SS) varied from 17.25 mg/L to 52.78 mg/L (mean: 27.92 mg/L), suggesting moderate turbidity associated with surface infiltration. Turbidity displayed substantial variability (CV = 124.27%), remaining below the WHO limit of 5 NTU for most wells, although some reached up to 11.70 NTU.

The oxidation-reduction potential (Eh) ranged from 39 mV to +122 mV (mean: 63.51 mV), indicating heterogeneous redox conditions across wells, with both reducing and oxidizing environments. Such variability often reflects differences in organic matter content, recharge rate, and microbial activity within the aquifer.

3.1.2. Physicochemical Parameters

pH values (4.04 - 6.87; mean = 5.16) indicate pronounced acidity in most wells, below the WHO acceptable range (6.5 - 8.5). This acidity may result from the oxidation of organic matter or the leaching of lateritic soils rich in iron and aluminium oxides. Electrical conductivity (EC) (28.81 - 420.65 µS/cm; mean = 161.85 µS/cm) and total dissolved solids (TDS) (10 - 220 mg/L; mean = 86 mg/L) are well

below WHO limits (1500 $\mu\text{S}/\text{cm}$ and 1000 mg/L, respectively), confirming low mineralization and limited ionic enrichment. Salinity remained low (mean = 0.08), and total hardness (THT) averaged 3.09° F, classifying the water as very soft. Dissolved oxygen averaged 4.14 mg/L (slightly below the 5 mg/L guideline), suggesting occasional oxygen depletion due to microbial activity in shallow wells.

3.1.3. Majors Ions

Major ion concentrations were generally low (**Table 6**). Mean concentrations were 14.79 mg/L for Cl^- , 21.19 mg/L for HCO_3^- , and 7.27 mg/L for SO_4^{2-} , all well below WHO limits. Cation concentrations also remained moderate: K^+ = 6.62 mg/L, Na^+ = 6.14 mg/L, Ca^{2+} = 8.09 mg/L, and Mg^{2+} = 2.56 mg/L.

The high coefficients of variation (34% - 79%) for most ions indicate localized inputs, possibly linked to variations in lithology or anthropogenic activities (fertilizers, domestic wastewater). The dominance of bicarbonate and chloride suggests mixed sources, with groundwater influenced by both mineral weathering and infiltration of surface runoff.

3.1.4. Nutrients

Nitrate (NO_3^-) concentrations (1.70 - 21.87 mg/L; mean = 14.33 mg/L) remained below the WHO threshold (50 mg/L), suggesting limited fertilizer leaching during the rainy season. Nitrite (NO_2^-) (mean = 0.04 mg/L) and ammonium (NH_4^+) (mean = 0.27 mg/L) showed very high CVs (> 120 %), implying sporadic contamination from local sanitation sources or decomposing organic matter.

Phosphate (PO_4^{3-}) (mean = 0.18 mg/L) also remained within permissible limits (0.5 mg/L) but indicates occasional domestic or agricultural inputs. Overall, nutrient concentrations confirm moderate anthropogenic influence with spatial heterogeneity across wells.

3.1.5. Heavy Metals

Among the analyzed trace metals, several exceeded WHO guidelines (**Table 6**). Cadmium (Cd^{2+}) (mean = 5.10 $\mu\text{g}/\text{L}$; max = 78 $\mu\text{g}/\text{L}$) surpassed the permissible limit (3 $\mu\text{g}/\text{L}$), indicating possible inputs from industrial or agricultural sources. Manganese (Mn^{2+}) showed particularly high levels (mean = 350 $\mu\text{g}/\text{L}$; max = 998 $\mu\text{g}/\text{L}$), exceeding the 50 $\mu\text{g}/\text{L}$ guideline by up to sevenfold. Iron (Fe^{2+}) concentrations (mean = 203 $\mu\text{g}/\text{L}$; max = 1023 $\mu\text{g}/\text{L}$) often surpassed the 300 $\mu\text{g}/\text{L}$ limit, consistent with natural leaching of lateritic soils. Aluminium (Al^{3+}) (mean = 111.53 $\mu\text{g}/\text{L}$) occasionally exceeded the 200 $\mu\text{g}/\text{L}$ threshold, while zinc (Zn^{2+}) (mean = 93.9 $\mu\text{g}/\text{L}$) remained far below the 3000 $\mu\text{g}/\text{L}$ limit.

Copper (Cu) and lead (Pb) were below the detection limit of 1 $\mu\text{g}/\text{L}$, indicating minimal industrial contamination. These results reveal that metal enrichment primarily arises from geochemical weathering and soil leaching, aggravated by acidic pH that promotes metal mobility. Due to their concentrations being below the detection limit, Pb and Cu were excluded from the health risk calculations to ensure methodological transparency.

3.2. Water Quality Index (WQI)

The computed WQI values for the thirty (30) sampled wells (**Table 7**) exhibited substantial spatial variability, ranging from 7.08 (P1) to 758.40 (P10), with a mean of 136.55 ± 142.80 ($CV = 104.57\%$), indicating pronounced heterogeneity in groundwater quality across the study area. The lowest WQI (7.08) recorded in well P1 falls within the “excellent” category, suggesting suitability for human consumption without treatment, whereas well P10 exhibited an “inferior” quality (758.40), reflecting significant contamination. The classification of wells according to WQI categories revealed that 10% were excellent ($WQI < 25$), 13.33% good ($26 \leq WQI \leq 50$), 20% medium ($51 \leq WQI \leq 75$), 16.67% poor ($76 \leq WQI \leq 100$), and 40% very poor ($WQI > 100$). Overall, 76.67% of wells recorded WQI values exceeding 50, implying that most groundwater samples do not fully meet WHO drinking-water standards without prior treatment.

Table 7. Calculated WQI values and water quality classification for the 30 sampled wells.

Well code	WQI	WQI range	Quality class	Grade	Well code	WQI	WQI range	Quality class	Grade
P1	7.08	0 - 25	Excellent	A	P16	20.56	0 - 25	Excellent	A
P2	210.08	>100	Very poor	E	P17	49.98	26 - 50	Good	B
P3	121.73	>100	Very poor	E	P18	76.41	76 - 100	Poor	D
P4	80.42	76 - 100	Poor	D	P19	71.25	51 - 75	Medium	C
P5	49.17	26 - 50	Good	B	P20	70.03	51 - 75	Medium	C
P6	236.82	>100	Very poor	E	P21	103.72	>100	Very poor	E
P7	281.86	>100	Very poor	E	P22	97.67	76 - 100	Poor	D
P8	21.94	0 - 25	Excellent	A	P23	279.82	>100	Very poor	E
P9	52.74	51 - 75	Medium	C	P24	257.80	>100	Very poor	E
P10	758.40	>100	Very poor	E	P25	57.97	51 - 75	Medium	C
P11	200.05	>100	Very poor	E	P26	63.87	51 - 75	Medium	C
P12	77.91	76 - 100	Poor	D	P27	258.14	>100	Very poor	E
P13	67.79	51 - 75	Medium	C	P28	239.87	>100	Very poor	E
P14	46.98	26 - 50	Good	B	P29	42.36	26 - 50	Good	B
P15	84.20	76 - 100	Poor	D	P30	109.93	>100	Very poor	E

WQI = Water Quality Index. Classification based on the weighted arithmetic method (see **Table 3**).

3.3. Health Risk Assessment

The detailed HQ and HI values by parameter and by well are presented in Appendix A (**Table A1** and **Table A2**). The summary of non-carcinogenic risk indices (HI) for children and adults is shown in **Table 8**, while **Figure 2** provides a graphical representation of these indices on a linear scale. HI values range from 0.87 to 84.68 for children and from 0.37 to 36.29 for adults, with mean values of 19.50 and 8.49, respectively. These results indicate considerable variability in risk levels

among wells, with children systematically exhibiting higher HI values than adults.

Table 8. Non-carcinogenic hazard index (HI) values for children and adults in groundwater samples from the Continental Terminal aquifer in Bonoua (Southeastern Côte d'Ivoire). HI values greater than 1 indicate potential non-carcinogenic health risks, while values below 1 suggest negligible risk levels.

Well Code	HI (Children)	Non-carcinogenic risk (Children)	HI (Adults)	Non-carcinogenic risk (Adults)
P1	3.51	Potential health risk	1.5	Potential health risk
P2	28.10	Potential health risk	12.04	Potential health risk
P3	84.68	Potential health risk	36.29	Potential health risk
P4	53.49	Potential health risk	22.92	Potential health risk
P5	43.49	Potential health risk	18.64	Potential health risk
P6	37.08	Potential health risk	15.89	Potential health risk
P7	4.85	Potential health risk	2.08	Potential health risk
P8	1.15	Potential health risk	0.49	Negligible risk
P9	1.05	Potential health risk	0.45	Negligible risk
P10	19.57	Potential health risk	8.39	Potential health risk
P11	43.05	Potential health risk	18.45	Potential health risk
P12	1.80	Potential health risk	0.77	Negligible risk
P13	16.32	Potential health risk	7.00	Potential health risk
P14	7.82	Potential health risk	3.35	Potential health risk
P15	12.90	Potential health risk	5.53	Potential health risk
P16	0.87	Negligible risk	0.37	Negligible risk
P17	1.80	Potential health risk	0.41	Negligible risk
P18	18.35	Potential health risk	7.86	Potential health risk
P19	9.17	Potential health risk	3.93	Potential health risk
P20	1.76	Potential health risk	0.75	Negligible risk
P21	4.37	Potential health risk	1.87	Potential health risk
P22	15.22	Potential health risk	10.81	Potential health risk
P23	62.80	Potential health risk	26.92	Potential health risk
P24	33.78	Potential health risk	14.48	Potential health risk
P25	1.23	Potential health risk	0.53	Negligible risk
P26	2.08	Potential health risk	0.89	Negligible risk
P27	52.85	Potential health risk	22.65	Potential health risk
P28	3.73	Potential health risk	1.69	Potential health risk
P29	11.25	Potential health risk	4.82	Potential health risk
P30	6.89	Potential health risk	2.95	Potential health risk
Minimum	0.87		0.37	
Mean	19.50		8.49	
Maximum	84.68		36.29	
SD	21.76		9.34	
CV (%)	112		110	

Based on the risk classification, most wells present *potential health risks* ($HI > 1$) for both children and adults, whereas only a few wells (P8, P9, P12, P16, P17, P20, P25, and P26) show *negligible risk*. The graphical comparison confirms this pattern, clearly highlighting the predominance of elevated HI values, particularly among children. The highest HI values, observed in wells P3, P4, P5, P11, P23, and P27, identify priority sites for monitoring and potential mitigation measures. Overall, 97% of the wells exceed the threshold value of 1 in children, and 73% in adults, revealing a significant non-carcinogenic health risk in the study area.

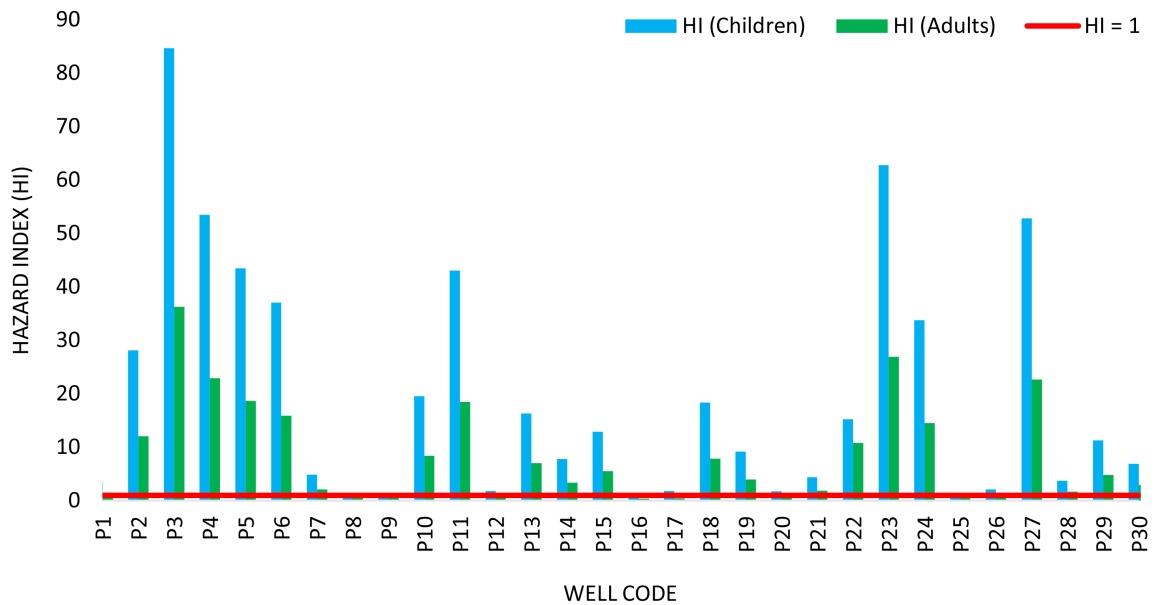


Figure 2. Variation of the non-carcinogenic hazard index (HI) for children and adults (linear scale). The red horizontal line represents the threshold limit ($HI = 1$) separating negligible from potential health risk levels.

3.4. Principal Component Analysis (PCA)

The Kaiser-Meyer-Olkin (KMO) index (0.733) confirmed the adequacy of the dataset for multivariate analysis, while Bartlett's test of sphericity ($\chi^2 = 689.187$; $df = 105$; $p < 0.001$) indicated significant inter-variable correlations (**Table 9**).

These statistical results validated the application of Principal Component Analysis (PCA) to the dataset.

Table 9. Kaiser-Meyer-Olkin (KMO) index and Bartlett's test of sphericity.

Statistic		Value
Kaiser-Meyer-Olkin (KMO) Index		0.73
Approx. Chi-square		689.187
Bartlett's Test of Sphericity	df	105
	Significance	< 0.001

The correlation matrix (**Table 10**) showed very strong positive associations

among the major ions (Cl^- , SO_4^{2-} , Na^+ , K^+ , HCO_3^- , Mg^{2+} , and EC; $r > 0.95$), reflecting a common geogenic origin mainly related to mineral dissolution and ion exchange processes. Moderate correlations between NH_4^+ , NO_2^- , and dissolved ions ($r \approx 0.30 - 0.50$) indicate possible agricultural inputs. In contrast, NO_3^- exhibited negative correlations with most major ions ($r \approx -0.45$ to -0.55), suggesting distinct anthropogenic contamination pathways, likely from domestic or agricultural effluents. Transition metals such as Mn^{2+} , Fe^{2+} , and Al^{3+} displayed moderate to strong correlations (up to 0.60), implying joint mobilization under reducing and acidic conditions.

Table 10. Pearson correlation matrix among physicochemical parameters.

Variables	Cl^-	HCO_3^-	SO_4^{2-}	K^+	Na^+	Ca^{2+}	Mg^{2+}	NO_3^-	NO_2^-	NH_4^+	CE	Cd^{2+}	Mn^{2+}	Al^{3+}	Fe^{2+}
Cl^-	1.00														
HCO_3^-	0.96	1.00													
SO_4^{2-}	0.99	0.95	1.00												
K^+	0.95	0.98	0.95	1.00											
Na^+	0.96	0.98	0.97	0.98	1.00										
Ca^{2+}	0.67	0.53	0.62	0.49	0.49	1.00									
Mg^{2+}	0.95	0.94	0.95	0.94	0.97	0.48	1.00								
NO_3^-	-0.48	-0.54	-0.45	-0.51	-0.47	-0.03	-0.37	1.00							
NO_2^-	0.52	0.57	0.52	0.48	0.54	0.38	0.47	-0.29	1.00						
NH_4^+	0.42	0.47	0.40	0.44	0.38	0.28	0.27	-0.55	0.34	1.00					
CE	0.98	0.96	0.99	0.95	0.97	0.63	0.94	-0.45	0.57	0.41	1.00				
Cd^{2+}	-0.37	-0.25	-0.35	-0.23	-0.26	-0.47	-0.30	-0.01	0.03	-0.13	-0.32	1.00			
Mn^{2+}	-0.09	-0.16	-0.12	-0.16	-0.20	0.28	-0.22	0.16	-0.20	0.11	-0.12	-0.32	1.00		
Al^{3+}	0.17	0.15	0.12	0.13	0.08	0.32	0.06	-0.15	0.17	0.31	0.12	-0.11	0.42	1.00	
Fe^{2+}	-0.24	-0.30	-0.22	-0.29	-0.29	0.07	-0.28	0.31	-0.07	-0.08	-0.22	-0.14	0.58	0.60	1.00

Values represent Pearson correlation coefficients (r). All correlations are significant at $p < 0.05$.

According to Kaiser's criterion (eigenvalues > 1), three principal components (F1-F3) were extracted, cumulatively explaining 79.29% of the total variance (**Table 11**).

Beyond the third component, eigenvalues dropped below unity, justifying the retention of three main factors. The component matrix (**Table 12**) details the loadings of each variable on these three factors:

1) Factor 1 (F1), explaining 54.06% of the total variance, was strongly associated with Cl^- , HCO_3^- , SO_4^{2-} , Na^+ , K^+ , Mg^{2+} , Ca^{2+} , and EC, and negatively correlated with NO_3^- . This factor represents natural mineralization and ion exchange processes, with minor anthropogenic input. The strong negative correlation between F1 and NO_3^- suggests a spatial separation between geogenic and anthropogenic influences: wells with high natural mineralization tend to exhibit low nitrate con-

centrations, whereas those with elevated nitrate levels are likely affected by human activities such as domestic wastewater infiltration and agricultural runoff. 2) Factor 2 (F2), accounting for 16.08% of the variance, showed high positive loadings for Mn^{2+} , Fe^{2+} , and Al^{3+} , indicating metal mobilization from lateritic horizons under variable redox and pH conditions, and 3) Factor 3 (F3), explaining 9.15% of the variance, presented positive loadings for NH_4^+ and Cd^{2+} and a negative loading for NO_3^- , corresponding to localized anthropogenic contamination from agricultural runoff and domestic wastewater.

Overall, the integration of results from **Table 9**, **Table 10**, **Table 11**, and **Table 12** confirms that groundwater chemistry in the Bonoua aquifer is governed by three dominant processes: 1) natural mineral dissolution and ion exchange, 2) redox-controlled mobilization of metals, and 3) anthropogenic pollution linked to agricultural and domestic sources

Table 11. Total variance explained by principal component analysis (PCA).

Component	Initial Eigenvalues	Extracted Sums of Squared Loadings	
	Total	% of variance	Cumulative %
F1	8.11	54.06	54.06
F2	2.41	16.08	70.14
F3	1.37	9.15	79.29

Extraction method: Principal Component Analysis (PCA). Rotation not applied.

Table 12. Principal component matrix of hydrochemical parameters (PCA).

Variables	Components		
	F1 (54.06%)	F2 (16.08%)	F3 (9.15%)
Cl^-	0.99	0.05	-0.09
HCO_3^-	0.98	-0.05	0.03
SO_4^{2-}	0.98	0.02	-0.11
K^+	0.97	-0.07	0.00
Na^+	0.98	-0.09	-0.07
Ca^{2+}	0.61	0.48	-0.28
Mg^{2+}	0.94	-0.10	-0.19
NO_3^-	-0.53	0.19	-0.61
NO_2^-	0.59	-0.02	0.26
NH_4^+	0.49	0.18	0.60
CE	0.98	0.02	-0.09
Cd^{2+}	-0.32	-0.47	0.49
Mn^{2+}	-0.14	0.82	-0.03
Al^{3+}	0.16	0.74	0.43
Fe^{2+}	-0.27	0.80	0.08

Extraction method: Principal Component Analysis (PCA). Rotation not applied.

4. Discussion

The hydrochemical analysis of well water from the Continental Terminal aquifer of Bonoua reveals a contrasting quality, characterized by low mineralization (mean: 165.85 $\mu\text{S}/\text{cm}$) and pronounced acidity (mean pH: 5.16), typical features of shallow sedimentary aquifers in humid tropical climates. The acidic environment, coupled with low bicarbonate concentrations, enhances the solubilization of metals such as aluminium, iron, manganese, and cadmium, which frequently exceed World Health Organization (WHO) guideline limits. Similar findings have been reported in comparable tropical systems (Tapsoba, 1995; Matini et al., 2009; Takem et al., 2015), where the decomposition of surface organic matter generates carbon dioxide (CO_2), thereby acidifying groundwater. Concurrently, reducing redox conditions favours metal mobility (Appelo & Postma, 2005). Although nutrient concentrations (NO_3^- , NO_2^- , NH_4^+) generally comply with WHO standards, sporadic occurrences of ammonium and phosphate indicate domestic and agricultural inputs. This pattern aligns with the findings of Douagui et al. (2019) for groundwater in Abidjan (Treichville and Koumassi). The spatial variability of turbidity and suspended solids further suggests inadequate sanitary protection of some wells (Kouassi et al., 2020). Elevated concentrations of manganese (up to 998 $\mu\text{g}/\text{L}$), iron (>1000 $\mu\text{g}/\text{L}$), and aluminium (>200 $\mu\text{g}/\text{L}$) were observed, levels comparable to those reported in other West African aquifers (Naminata et al., 2018; Aka et al., 2019; Agbo et al., 2021). Such concentrations raise both health and aesthetic concerns. Aluminium enrichment can result from multiple factors, including acidic pH, weathering of aluminosilicate minerals (Filipek et al., 1987), and potential anthropogenic contributions (Lantzy & Mackenzie, 1979; RNCAN, 2018). Krewski et al. (2007) highlighted the neurological risks of chronic aluminium exposure, advocating for strengthened monitoring programs, a recommendation echoed by Savadogo et al. (2023) in the Abidjan district.

Practical implications of these findings are particularly relevant for low-cost household water treatment. Simple methods such as sand filtration and aeration can be effective in reducing iron and aluminium concentrations. Sand filtration removes suspended solids and associated iron and aluminium compounds, while aeration promotes the oxidation and precipitation of iron, facilitating its removal. These low-cost approaches provide feasible options for improving water quality at the household level, especially in areas where access to centralized water treatment systems is limited.

The Water Quality Index (WQI) confirms this heterogeneity, ranging from 7.08 (excellent) to 758.40 (very poor). Such variability reflects both geochemical diversity and the uneven influence of anthropogenic pressures (Singh & Kamal, 2014; Kumar et al., 2018). While 23.33% of wells exhibited good to excellent quality, 76.67% exceeded the threshold of 50, and 40% recorded $\text{WQI} > 100$, rendering them unsuitable for consumption without treatment. The most affected wells are located near latrines, croplands, or waste dumps, where surface runoff facilitates contaminant infiltration. Comparable conditions have been reported in other

peri-urban regions (Adejuwon & Adhlakun, 2012; Tyagi et al., 2013; Hyarat et al., 2022; Ardjane et al., 2025), where groundwater degradation stems from combined geogenic and anthropogenic effects.

The health risk assessment further underscores the gravity of the situation, particularly for children, whose mean hazard index (HI = 19.50) significantly exceeds that of adults (HI = 8.49). This disparity reflects greater physiological susceptibility, lower body mass, and higher per capita water intake among children (Calderon, 2000; USEPA, 2002; Järup, 2003). HI values exceeded 1 in 97% of wells for children and 73% for adults, indicating potential chronic health risks, consistent with previous findings in West Africa (Tanouayi et al., 2015; Tohouiri et al., 2017). Aluminium was the dominant contributor to overall risk, followed by cadmium, iron, and manganese, originating from both geogenic and anthropogenic sources (Shrestha & Kazama, 2007). In some wells (P3, P4, P5, P11, P23, and P27), HI values exceeded 40, indicating an urgent need for intervention to mitigate exposure risks (Ouattara et al., 2016; Hounsounou et al., 2018; Traoré et al., 2006).

Principal Component Analysis (PCA) clarified the underlying processes governing water quality. Three principal components explained 79.29% of the total variance: 1) natural mineralization through dissolution of sedimentary minerals, locally influenced by anthropogenic inputs; 2) mobilization of Mn^{2+} , Fe^{2+} , and Al^{3+} under acidic-reducing conditions; and 3) localized contamination by NH_4^+ and Cd^{2+} , likely from domestic and agricultural sources. These findings reveal the interplay between geogenic and anthropogenic processes shaping groundwater quality in Bonoua and underscore the necessity for integrated management strategies combining systematic monitoring, wellhead protection, and community awareness programs.

5. Conclusion

This study revealed that during the rainy season, well water from the Continental Terminal aquifer of Bonoua is characterised by low mineralisation, acidic pH, and elevated concentrations of heavy metals (aluminium, manganese, iron, and cadmium), exceeding the guideline values established by the World Health Organization (WHO). The Water Quality Index (WQI) and Health Risk Index (HI) indicate overall poor water quality and significant health risks, particularly among children (97% of HI > 1) and, to a lesser extent, adults (73% of HI > 1). Principal Component Analysis (PCA) identified three major sources of pollution: natural mineralisation, acid-driven mobilisation of metals, and anthropogenic contamination from domestic and agricultural activities.

These findings highlight the urgent need for regular water quality monitoring during both rainy and dry seasons, improved sanitary protection of wells, and the promotion of low-cost household treatment methods such as sand filtration, activated carbon, or coagulation-flocculation systems. Additionally, raising community awareness on water safety and integrating hydrochemical data into local groundwater management plans are crucial to mitigate health risks and ensure the

sustainable use of the Continental Terminal aquifer.

Acknowledgements

The authors express their gratitude to the Ivorian Anti-Pollution Centre (Centre Ivoirien Anti-Pollution, CIAPOL) for providing the necessary data for this research. Special thanks are extended to Mr. Sangaré Madou for his logistical support and in-depth field knowledge, which contributed greatly to the success of the sampling campaign.

Author Contributions

TOHOURI Privat: Conceptualization, data collection, analysis, interpretation, visualization, and original draft writing. ANONGBA Braphond Benjamin Vincent Rodrigue: Conceptualization, data collection, review, and editing. OROU Kotchi Rodrigue: Conceptualization, analysis, review, and editing. ADJA Miessan Germain: Data collection, interpretation, and review of the manuscript.

All authors read and approved the final manuscript and agreed to be accountable for all aspects of the work.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- Abbasi, T., & Abbasi, S. A. (2012). *Water Quality Indices* (353 p.). Elsevier.
- Abbasnia, A., Alimohammadi, M., Mahvi, A. H., Nabizadeh, R., Yousefi, M., Mohammadi, A. A. et al. (2018). Assessment of Groundwater Quality and Evaluation of Scaling and Corrosiveness Potential of Drinking Water Samples in Villages of Chabahr City, Sistan and Baluchistan Province in Iran. *Data in Brief*, 16, 182-192. <https://doi.org/10.1016/j.dib.2017.11.003>
- Adejuwon, J. O., & Adelakun, M. A. (2012) Physicochemical and Bacteriological Analysis of Surface Water in Ewekoro Local Government Area of Ogun State, Nigeria: Case Study of Lala, Yobo and Agodo Rivers. *International Journal of Water Resources and Environmental Engineering*, 4, 66-72.
- AFNOR (1997). *Water Quality. Volume 1: Terminology, Sampling and Evaluation of Methods* (3rd ed., 34 p.). AFNOR.
- Agbo, A. D. D., Djagouri, K., Brigui, J. O., & Kakou, K. P. (2021). Determination of Element Levels of Lagoon from Townships near Cocody City, Abidjan, Côte d'Ivoire, Using Energy Dispersive X-Ray Fluorescence. *World Journal of Nuclear Science and Technology*, 11, 109-118. <https://doi.org/10.4236/wjnst.2021.112008>
- Aka, N., Gboko, Y. D. A., Bamba, S. B., & Soro, N. (2019). Impact of Anthropogenic Activities on Water Resources in the Western Periphery of Abidjan (South-East Côte d'Ivoire). *Journal of International Science and Technology of Water and Environment*, 4, 1-78.
- Appelo, C., & Postma, D. (2005). *Geochemistry, Groundwater and Pollution* (2nd ed., 67 p.). CRC Press. <https://doi.org/10.1201/9781439833544>
- Ardjane, T. A., Meddah, B., Bekkoussa, B. S., Zemour, K., & Mairif, M. (2025). Groundwater Quality Assessment Using Water Quality Index Coupled with Multivariate Statistical

- Analysis in the Alluvial Plains of El-Abd and El-That, Tiaret Region, Northwestern Algeria. *Acque Sotterranee-Italian Journal of Groundwater*, *14*, 73-88.
<https://doi.org/10.7343/as-2025-852>
- Brown, R. M., McClelland, N. I., Deininger, R. A., & O'connor, M. F. (1972). A Water Quality Index—Crashing the Psychological Barrier. In S. H. Jenkins (Ed.), *Proceedings of the International Conference on Water Pollution Research* (Vol. 6, pp. 787-797). Elsevier. <https://doi.org/10.1016/b978-0-08-017005-3.50067-0>
- Calderon, R. L. (2000). The Epidemiology of Chemical Contaminants of Drinking Water. *Food and Chemical Toxicology*, *38*, S13-S20.
[https://doi.org/10.1016/s0278-6915\(99\)00133-7](https://doi.org/10.1016/s0278-6915(99)00133-7)
- Douagui, A. G., Kouamé, I. K., Mangoua, J. M. O., Kouassi, A. K., & Savané, I. (2019). Using Water Quality Index for Assessing of Physicochemical Quality of Quaternary Groundwater in the Southern Part of Abidjan District (Côte d'Ivoire). *Journal of Water Resource and Protection*, *11*, 1278-1291. <https://doi.org/10.4236/jwarp.2019.1110074>
- Filipek, L. H., Nordstrom, D. K., & Ficklin, W. H. (1987). Interaction of Acid Mine Drainage with Waters and Sediments of West Squaw Creek in the West Shasta Mining District, California. *Environmental Science & Technology*, *21*, 388-396.
<https://doi.org/10.1021/es00158a009>
- Halle, B., & Bruzon, V. (2006). *Environmental Profile of Côte d'Ivoire* (128 p.). Final Report.
- Hounsounou, E. O., Ayi-Fanou, L., Ayena, A. C., Agassounon, D. T. M., & Mama, D. (2018). Well Water Contamination by Salmonella and Non-O1/Non-O139 Vibrios in Slums of the Sixth District of Cotonou (Southern Benin). *European Scientific Journal*, *14*, 252-268. <https://doi.org/10.19044/esj.2018.v14n6p252>
- Hyarat, T., Al Kuisi, M., & Saffarini, G. (2022). Assessment of Groundwater Quality Using Water Quality Index (WQI) and Multivariate Statistical Analysis in Amman-Zarqa Area/Jordan. *Water Practice and Technology*, *17*, 1582-1602.
<https://doi.org/10.2166/wpt.2022.076>
- Järup, L. (2003). Hazards of Heavy Metal Contamination. *British Medical Bulletin*, *68*, 167-182. <https://doi.org/10.1093/bmb/ldg032>
- Kaiser, H. F. (1960). The Application of Electronic Computers to Factor Analysis. *Educational and Psychological Measurement*, *20*, 141-151.
<https://doi.org/10.1177/001316446002000116>
- Kouassi, D. K., Kouame, I. K., Koffi, K., Douagui, A. G., Sandu, A. V., & Sandu, I. (2020). Assessment of the Quality of Quaternary Groundwater under the Influence of Anthropogenic Activities in the Low-Income Neighbourhoods of the Treichville Municipality (Abidjan, Côte D'ivoire). *SN Applied Sciences*, *2*, Article No. 1716.
<https://doi.org/10.1007/s42452-020-03478-4>
- Krewski, D., Yokel, R. A., Nieboer, E., Borchelt, D., Cohen, J., Harry, J. et al. (2007). Human Health Risk Assessment for Aluminium, Aluminium Oxide, and Aluminium Hydroxide. *Journal of Toxicology and Environmental Health, Part B*, *10*, 1-269.
<https://doi.org/10.1080/10937400701597766>
- Kumar, B., Singh, U. K., & Ojha, S. N. (2018). Evaluation of Geochemical Data of Yamuna River Using WQI and Multivariate Statistical Analyses: A Case Study. *International Journal of River Basin Management*, *17*, 143-155.
- Lantzy, R. J., & Mackenzie, F. T. (1979). Atmospheric Trace Metals: Global Cycles and Assessment of Man's Impact. *Geochimica et Cosmochimica Acta*, *43*, 511-525.
[https://doi.org/10.1016/0016-7037\(79\)90162-5](https://doi.org/10.1016/0016-7037(79)90162-5)
- Liu, R. H. (2003). Health Benefits of Fruit and Vegetables Are from Additive and Synergis-

- tic Combinations of Phytochemicals. *The American Journal of Clinical Nutrition*, 78, 517S-520S. <https://doi.org/10.1093/ajcn/78.3.517s>
- Loroux, B. F. E. (1978). *Contribution to the Hydrogeological Study of the Coastal Sedimentary Basin of Côte d'Ivoire* (93 p.). PhD Thesis, University of Bordeaux I.
- Matini, L., Moutou, J. M., & Kongo-Mantono, M. S. (2009). Hydrochemical Evaluation of Groundwater in an Urban Area in South-West Brazzaville, Congo. *African Science*, 5, 82-98. <https://doi.org/10.4314/afsci.v5i1.61709>
- Naminata, S., Kwa-Koffi, K. E., Marcel, K. A., & Marcellin, Y. K. (2018). Assessment and Impact of Leachate Generated by the Landfill City in Abidjan on the Quality of Ground Water and Surface Water (M'Badon Bay, Côte d'Ivoire). *Journal of Water Resource and Protection*, 10, 145-165. <https://doi.org/10.4236/jwarp.2018.101009>
- Ouattara, A., Meite, A., Dally, T., Ouattara, H., & Kati, C. S. (2016). Study of Drinking Water Quality in the Locality of N'Zianouan (Sub-Prefecture of Tiassalé) and in Slum Areas of Three Municipalities in the District of Abidjan (Koumassi, Treichville, Attécoubé). *Journal of Applied Biosciences*, 102, 9708-9715.
- Ramakrishnaiah, C. R., Sadashivaiah, C., & Ranganna, G. (2009). Assessment of Water Quality Index for the Groundwater in Tumkur Taluk, Karnataka State, India. *Journal of Chemistry*, 6, 523-530. <https://doi.org/10.1155/2009/757424>
- Reghunath, R., Murthy, T. R., & Raghavan, B. R. (2002). The Utility of Multivariate Statistical Techniques in Hydrogeochemical Studies: An Example from Karnataka, India. *Water Research*, 36, 2437-2442. [https://doi.org/10.1016/s0043-1354\(01\)00490-0](https://doi.org/10.1016/s0043-1354(01)00490-0)
- RNCan (2018). *Facts about Aluminium*. Natural Resources Canada, Government of Canada, Ottawa.
- Rodier, J., Legube, B., & Merlet, N. (2009). *Water Analysis* (9th ed., pp. 141-159). Dunod.
- Roose, E., & Cheroux, M. (1965). *Soils of the Sedimentary Basin of Côte d'Ivoire* (92 p.). ORSTOM.
- Sahu, P., & Sikdar, P. K. (2008). Hydrochemical Framework of the Aquifer in and around East Kolkata Wetlands, West Bengal, India. *Environmental Geology*, 55, 823-835. <https://doi.org/10.1007/s00254-007-1034-x>
- Savadogo, I., Aw, S., & Oga, Y. M. S. (2023). Impacts of Aluminium and Nitrogen Compounds (Nitrate and Ammonium) on the Physico-Chemical Quality of Groundwater in the District of Abidjan. *American Journal of Environmental Protection*, 12, 150-159. <https://doi.org/10.11648/j.ajep.20231206.11>
- Shrestha, S., & Kazama, F. (2007). Assessment of Surface Water Quality Using Multivariate Statistical Techniques: A Case Study of the Fuji River Basin, Japan. *Environmental Modelling & Software*, 22, 464-475. <https://doi.org/10.1016/j.envsoft.2006.02.001>
- Singh, G., & Kamal, R. (2014). Application of Water Quality Index for Assessment of Surface Water Quality Status in Goa. *Current World Environment*, 9, 994-1000. <https://doi.org/10.12944/cwe.9.3.54>
- Takem, G. E., Kuitcha, D., Ako, A. A., Mafany, G. T., Takounjou-Fouepe, A., Ndjama, J. et al. (2015). Acidification of Shallow Groundwater in the Unconfined Sandy Aquifer of the City of Douala, Cameroon, Western Africa: Implications for Groundwater Quality and Use. *Environmental Earth Sciences*, 74, 6831-6846. <https://doi.org/10.1007/s12665-015-4681-3>
- Tanouayi, G., Gnandi, K., Ahoudi, H., & Ouro, S.K. (2015). Metallic Contamination of Surface and Groundwater in the Phosphate Mining Area of Hahotoe-Kpogame (Southern Togo): Case of Cadmium, Lead, Copper, and Nickel. *Larhyss Journal*, 21, 25-40.
- Tapsoba, S. (1995). *Contribution to the Geological and Hydrogeological Study of the*

- Dabou Region (Southern Côte d'Ivoire): Hydrochemistry, Isotopy and Cationic Ageing Index of Groundwater* (201 p.). PhD Thesis, University of Cocody.
- Tohouri, P., Soro, G., Ahoussi, K. E., Adja, M. G., Ake, G. E., & Biemi, J. (2017). Pollution by Trace Metals in Surface Waters during High-Water Period in the Bonoua Region (South-East Côte d'Ivoire). *Larhyss Journal*, 29, 23-43.
- Traoré, S.K., Mamadou, K., Dembele, A., Lafrance, P., Mazellier, P., & Houenou, P. (2006). Groundwater Contamination by Pesticides in Agricultural Regions of Côte d'Ivoire (Central-South and South-West). *African Journal of Environmental Science*, 1, 1-9.
- Tyagi, S., Sharma, B., Singh, P., & Dobhal, R. (2013). Water Quality Assessment in Terms of Water Quality Index. *American Journal of Water Resources*, 1, 34-38.
<https://doi.org/10.12691/ajwr-1-3-3>
- USEPA (1989). *Risk Assessment Guidance for Superfund, Vol. I: Human Health Evaluation Manual (Part A)* (291 p.). U.S. Environmental Protection Agency.
- USEPA (2002). *A Review of the Reference Dose and Reference Concentration Processes*. U.S. Environmental Protection Agency.
- USEPA (2004). *Risk Assessment Guidance for Superfund, Vol. I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment)* (156 p.). U.S. Environmental Protection Agency.
- USEPA (2011). *Integrated Risk Information System (IRIS)*. U.S. Environmental Protection Agency. <https://www.epa.gov/iris>
- World Health Organization (2004). *Guidelines for Drinking-Water Quality* (3rd ed., 516 p.). WHO.
- World Health Organization (2017). *Guidelines for Drinking-Water Quality* (4th ed., 631 p.). WHO.
- Wu, B., Zhao, D. Y., Jia, H. Y., Zhang, Y., Zhang, X. X., & Cheng, S. P. (2009). Preliminary Risk Assessment of Trace Metal Pollution in Surface Water from Yangtze River in Nanjing Section, China. *Bulletin of Environmental Contamination and Toxicology*, 82, 405-409. <https://doi.org/10.1007/s00128-008-9497-3>

Appendix A. Detailed Hazard Quotient (HQ) and Hazard Index (HI) Values

Table A1. Hazard Quotient (HQ) values by parameter and corresponding Hazard Index (HI) for children.

Well Code	Non-carcinogenic Risk Index (HQ) for Each Parameter								Hazard Index
	NO ₃ ⁻	NO ₂ ⁻	NH ₄ ⁺	Zn	Cd	Mn	Al	Fe	HI = \sum HQ
P1	0.59	0.01	0.07	0.00	ND	0.01	2.83	0.00	3.51
P2	0.57	0.01	0.03	ND	ND	0.48	27.00	0.01	28.10
P3	0.07	0.05	0.28	0.06	ND	0.22	84.00	0.00	84.68
P4	0.82	0.05	0.07	0.02	ND	0.00	52.50	0.02	53.49
P5	0.45	0.05	0.02	ND	0.13	0.01	42.83	0.00	43.49
P6	0.47	0.05	0.23	ND	ND	0.46	35.83	0.02	37.08
P7	0.56	0.00	0.02	ND	1.93	0.01	2.33	0.00	4.85
P8	0.72	0.00	0.03	ND	ND	0.06	0.33	ND	1.15
P9	0.65	0.02	0.05	0.00	ND	0.15	0.17	ND	1.05
P10	0.61	0.04	0.03	0.00	5.20	0.03	13.67	0.00	19.57
P11	0.84	0.01	0.03	0.00	ND	0.31	41.83	0.03	43.05
P12	0.44	0.00	0.04	ND	0.47	0.01	0.83	0.00	1.80
P13	0.46	0.01	0.03	0.01	ND	0.15	15.67	0.00	16.32
P14	0.66	0.03	0.01	ND	ND	0.12	7.00	0.00	7.82
P15	0.72	0.04	0.19	0.08	ND	0.21	11.67	0.00	12.90
P16	0.39	0.05	0.18	0.02	ND	0.06	0.17	ND	0.87
P17	0.44	0.00	0.04	ND	0.47	0.01	0.83	0.00	1.80
P18	0.44	0.04	0.20	0.01	ND	0.15	17.50	0.01	18.35
P19	0.56	0.00	0.06	0.05	ND	0.17	8.33	0.00	9.17
P20	0.67	0.01	0.03	0.03	ND	0.20	0.83	0.00	1.76
P21	0.73	0.01	0.01	ND	ND	0.29	3.33	0.00	4.37
P22	0.64	0.01	0.07	ND	ND	0.15	24.33	0.01	15.22
P23	0.65	0.01	0.01	0.01	ND	0.42	61.67	0.04	62.80
P24	0.61	0.01	0.02	0.17	0.33	0.27	32.33	0.04	33.78
P25	0.55	0.01	0.01	0.00	ND	0.17	0.50	D	1.23
P26	0.84	0.00	0.00	0.05	ND	0.18	1.00	0.00	2.08
P27	0.91	0.00	0.01	ND	0.40	0.34	51.17	0.02	52.85
P28	0.55	0.01	0.06	ND	1.60	0.00	1.50	0.00	3.73
P29	0.54	0.16	0.03	0.07	0.07	0.04	10.33	0.01	11.25
P30	0.78	0.00	0.01	ND	0.07	0.20	5.83	0.01	6.89

HQ and HI values greater than 1 are highlighted in **bold**; ND = Not Detected.

Table A2. Hazard Quotient (HQ) values by parameter and corresponding Hazard Index (HI) for adults.

Well Code	Non-carcinogenic Risk Index (HQ) for Each Parameter								Hazard Index
	NO ₃ ⁻	NO ₂ ⁻	NH ₄ ⁺	Zn	Cd	Mn	Al	Fe	HI = \sum HQ
P1	0.25	0.00	0.03	0.00	ND	0.00	1.21	0.00	1.5
P2	0.24	0.01	0.01	ND	ND	0.20	11.57	0.01	12.04
P3	0.03	0.02	0.12	0.03	ND	0.09	36.00	0.00	36.29
P4	0.35	0.02	0.03	0.01	ND	0.00	22.50	0.01	22.92
P5	0.19	0.02	0.01	ND	0.06	0.00	18.36	0.00	18.64
P6	0.20	0.02	0.10	ND	ND	0.20	15.36	0.01	15.89
P7	0.24	0.00	0.01	ND	0.83	0.00	1.00	0.00	2.08
P8	0.31	0.00	0.01	ND	ND	0.03	0.14	ND	0.49
P9	0.28	0.01	0.02	0.00	ND	0.07	0.07	ND	0.45
P10	0.26	0.02	0.01	0.00	2.23	0.01	5.86	0.00	8.39
P11	0.36	0.00	0.01	0.00	ND	0.13	17.93	0.01	18.45
P12	0.19	0.00	0.02	ND	0.20	0.00	0.36	0.00	0.77
P13	0.20	0.01	0.01	0.00	ND	0.07	6.71	0.00	7.00
P14	0.28	0.01	0.00	ND	ND	0.05	3.00	0.00	3.35
P15	0.31	0.02	0.08	0.03	ND	0.09	5.00	0.00	5.53
P16	0.17	0.02	0.08	0.01	ND	0.03	0.07	ND	0.37
P17	0.19	0.00	0.00	0.01	ND	0.06	0.14	ND	0.41
P18	0.19	0.02	0.09	0.00	ND	0.07	7.50	0.00	7.86
P19	0.24	0.00	0.02	0.02	ND	0.07	3.57	0.00	3.93
P20	0.29	0.00	0.01	0.01	ND	0.08	0.36	0.00	0.75
P21	0.31	0.00	0.01	ND	ND	0.12	1.43	0.00	1.87
P22	0.27	0.00	0.03	ND	ND	0.07	10.43	0.01	10.81
P23	0.28	0.00	0.00	0.00	ND	0.18	26.43	0.02	26.92
P24	0.26	0.00	0.01	0.07	0.14	0.11	13.86	0.02	14.48
P25	0.24	0.00	0.00	0.00	ND	0.07	0.21	ND	0.53
P26	0.36	0.00	0.00	0.02	ND	0.08	0.43	0.00	0.89
P27	0.39	0.00	0.00	ND	0.17	0.15	21.93	0.01	22.65
P28	0.24	0.01	0.02	ND	0.69	0.00	0.64	0.00	1.69
P29	0.23	0.07	0.01	0.03	0.03	0.02	4.43	0.00	4.82
P30	0.33	0.00	0.00	ND	0.03	0.08	2.50	0.01	2.95

HQ and HI values greater than 1 are highlighted in bold; ND = not detected.