
Impacts of Aluminium and Nitrogen Compounds (Nitrate and Ammonium) on the Physico-Chemical Quality of Groundwater in the District of Abidjan

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Abstract: The boreholes used to supply drinking water in the District of Abidjan are located in heavily urbanised areas. This high level of urbanisation is increasingly contributing to the deterioration of groundwater quality. The objective of this study is to assess the impact of aluminium and nitrogen compounds on the physico-chemical quality of groundwater in the District of Abidjan. To achieve this objective, the physico-chemical parameters of fifty (50) groundwater samples were determined over a four-year period (2019-2022) during the dry and rainy seasons. A total of 400 groundwater samples were analysed. With the exception of aluminium, nitrate and ammonium, all the chemical elements analysed namely Ca^{2+} , Mg^{2+} , K^+ , O_2 , SO_4^{2-} , SiO_2 , PO_4^{3-} , NO_2^- , Cl^- , Mn^{2+} , Cu^{2+} , Zn^{2+} , Fe^{2+} , Fe , H_2S and F^- were below the values recommended by the World Health Organisation for water intended for human consumption. High levels of aluminium, nitrate and ammonium were observed in 49.5%, 10.75% and 18, 25% of the water samples analysed respectively. The study of spatial and temporal variation shows that groundwater pollution depends on the geographical location of the groundwater and not on the seasons. Principal Component Analysis (ACP) reveals the natural and anthropogenic mineralisation of groundwater.

Keywords: Abidjan, Groundwater, Aluminium, Nitrate, Ammonium, Principal Component Analysis

1. Introduction

The availability and relatively low cost of treatment have led the Ivorian authorities to take an interest in groundwater. This water is generally of good quality compared with surface water because of the depth of the water table. For the drinking water supply in the District of Abidjan, the decision was made to use groundwater from the Continental Terminal. This groundwater is tapped at a depth of between 60-130 m and connected to drinking water treatment plant [1]. Despite their depth, the quality of groundwater can be degraded by a lack of environmental protection [2]. The District of Abidjan is the main urban and economic power of Ivory Coast, is facing an

environmental problem. It is the most populated area of Ivory Coast, with an estimated population of 6,300,000 according to the General Population and Housing Census [3]. This high population has had consequences such as an increase in the need for drinking water, the uncontrolled installation of precarious neighbourhoods with independent sanitation systems and the installation of numerous industries. These consequences have led to a high production of solid and liquid waste, threatening the quality of groundwater and surface water. Several previous studies have reported local groundwater pollution in the Abidjan district, with high levels of aluminium, nitrate and ammonium [4-9]. It is important to note that the high levels of aluminium in the human body can have adverse effects on our bones [10, 11], kidneys [11],

reproduction and development [12-14]. Nitrogen compounds can cause diseases such as methaemoglobinaemia when they are present in large quantities in the human body [15]. It is therefore necessary to monitor the levels of aluminium, nitrate and ammonium in drinking water in order to control health risks. The objective of this study is to assess the impact of aluminium and nitrogen compounds on the physico-chemical quality of groundwater in the District of Abidjan.

2. Material and Methods

2.1. Presentation of the Study Area

The District of Abidjan is located in the south of Ivory Coast. It is located between latitudes 5°10 and 5°38 North and longitudes 3°45 and 4°21 West (Figure 1). It comprises

thirteen (13) municipality: Abobo, Adjamé, Attécoubé, Cocody, Koumassi, Marcory, Plateau, Port-Bouët, Treichville, Yopougon, Bingerville, Songon and Anyama. The District covers an area of 1,160 km², or 0.6% of the national territory. It is bordered by Agboville to the north of the Atlantic Ocean, to the south-east by the Grand-Bassam, to the south-west by Jacquville, to the East by Alépé and to the West by Dabou. The climate is equatorial, with four alternating seasons [1]. A long rainy season (May - July), a short dry season (August - September), a short rainy season (October-November) and a long dry season (December-April). The District has a very extensive hydrographic network, consisting of the Ebrié, Aghien and Potou lagoons, as well as the Ebrié, Aghien, Potou and the Anguédédou, Gbangbo and Banco rivers.

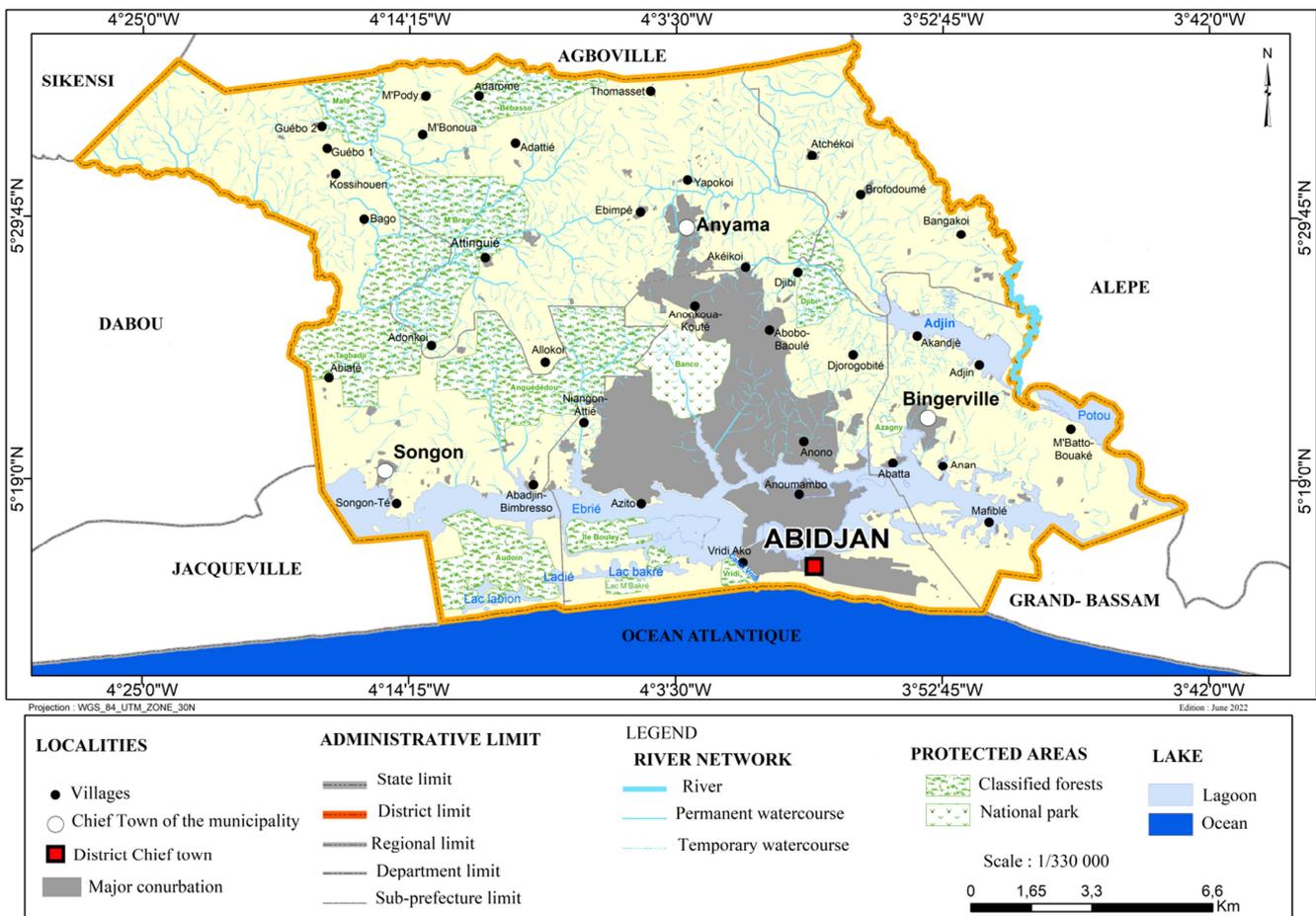


Figure 1. Map of District d'Abidjan.

Figure 2 shows the geological map of the various aquifers encountered in the Abidjan District [16]. The study area is located in the Ivorian sedimentary basin of Cretaceous-Quaternary age. The geological formations are sand, clay and marl. Geological formations and favourable climatic conditions mean that the District of Abidjan has groundwater resources at its disposal. This groundwater is

present in three types of aquifer. The Quaternary aquifer is highly threatened by anthropogenic pollution because of its depth near the surface [8; 17]. The Continental Terminal aquifer (Mio-pliocene age) is the water table used to supply drinking water in the District of Abidjan. The Maestrichtian aquifer (upper Cretaceous) is the deepest aquifer in the Ivorian sedimentary basin, and can reach a depth of 200 m.

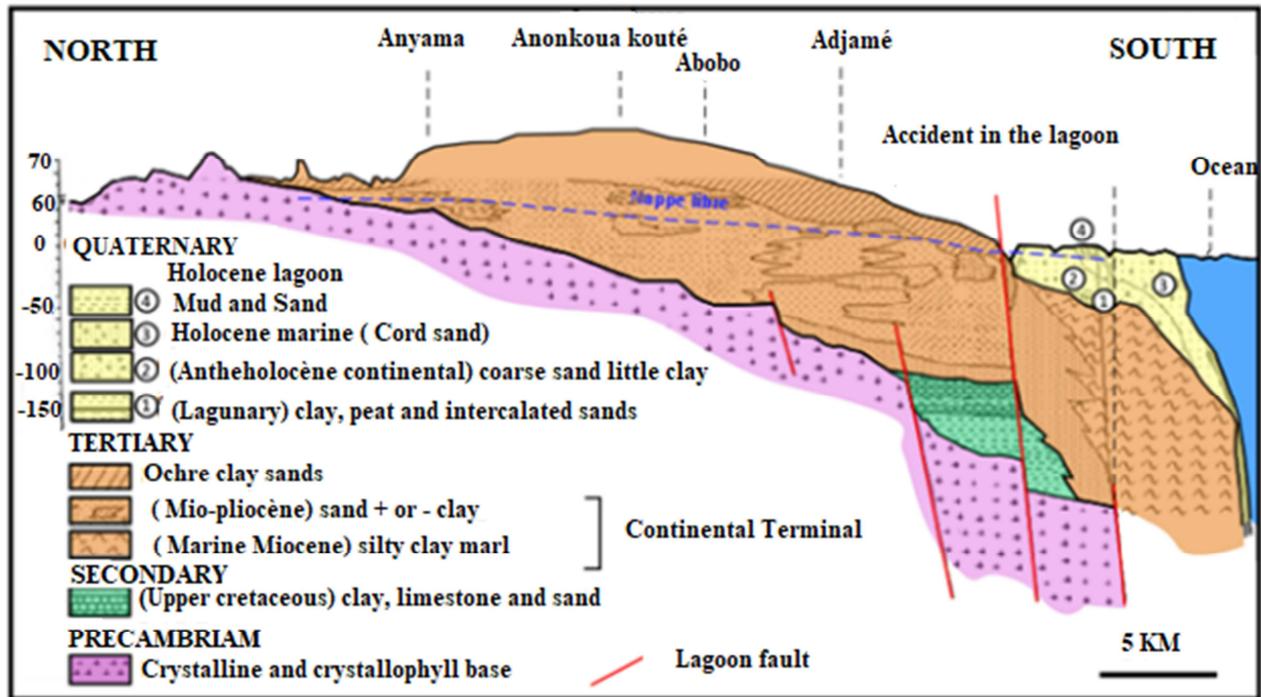


Figure 2. Geological map of the different aquifers in the Abidjan District [16].

2.2. Physico-Chemical Analysis Methods

The points chosen were boreholes used to supply drinking water in the District of Abidjan. The wellfields selected were those impacted by the presence of aluminium and/or nitrogen compounds. Table 1 shows the wellfields affected by the pollution. Two groundwater sampling campaigns were carried out each year between 2019 and 2022 on fifty (50) boreholes in the dry and rainy seasons. A total of four hundred (400) groundwater samples were analysed. Before the water samples were taken the geographical coordinates of the boreholes were taken, using a Garmin-type GPS. The groundwater sampling protocol consists of rinsing the bottles with the water to be reduced or completely eliminated any contamination that may have been introduced. The water samples are then taken at the wellhead in polyethylene bottles with a capacity of 1 litre, tightly closed without leaving any air bubbles in the bottle. Lastly, the samples were kept at 4°C in a cool box for chemical analysis in the laboratory. Figure 3 shows a map of the sampling points. The pH of the

groundwater was measured in situ using a WTW-type pH meter. Before to pH measurements, the pH meter was calibrated in the laboratory using the following buffer solutions pH 4, pH 7 and pH 10. Turbidity was measured using a turbidimeter of the type HACH 2100Q. Conductivity and temperature were measured using a WTW multiparameter. In the laboratory, concentrations of chemical elements such as nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), sulphate (SO_4^{2-}), phosphate (PO_4^{3-}), chloride (Cl^-), silica (SiO_2), potassium (K^+), aluminium, (Al^{3+}), manganese (Mn^{2+}), ferrous iron (Fe), total iron (Fe), copper (Cu^{2+}), zinc (Zn^{2+}), fluorine (F^-), hydrogen sulphide (H_2S), dissolved oxygen (O_2), Total hardness or hydrometric titre (THT), calcium hardness (Ca^{2+}) were measured. With the exception of total hardness and calcium hardness, all the chemical elements were measured spectrophotometrically using a spectrophotometer HACH DR 6000. Total hardness and calcium hardness were determined by titrimetry. The concentration of magnesium was obtained by calculating the difference between the total hardness and calcium hardness [18].

Table 1. Designation and number of Boreholes per wellfield.

Wellfield	Designation	Number of boreholes	Number of samples
Adiopodoumé	W1	1	8
Adjamé Nord	W2	2	16
Anonkoua Kouté	W3	13	104
Avocatier	W4	2	16
Filtisac	W5	2	16
Riviera Centre	W6	6	48
East zone	W7	6	48
North zone	W8	8	64
West zone	W9	10	80

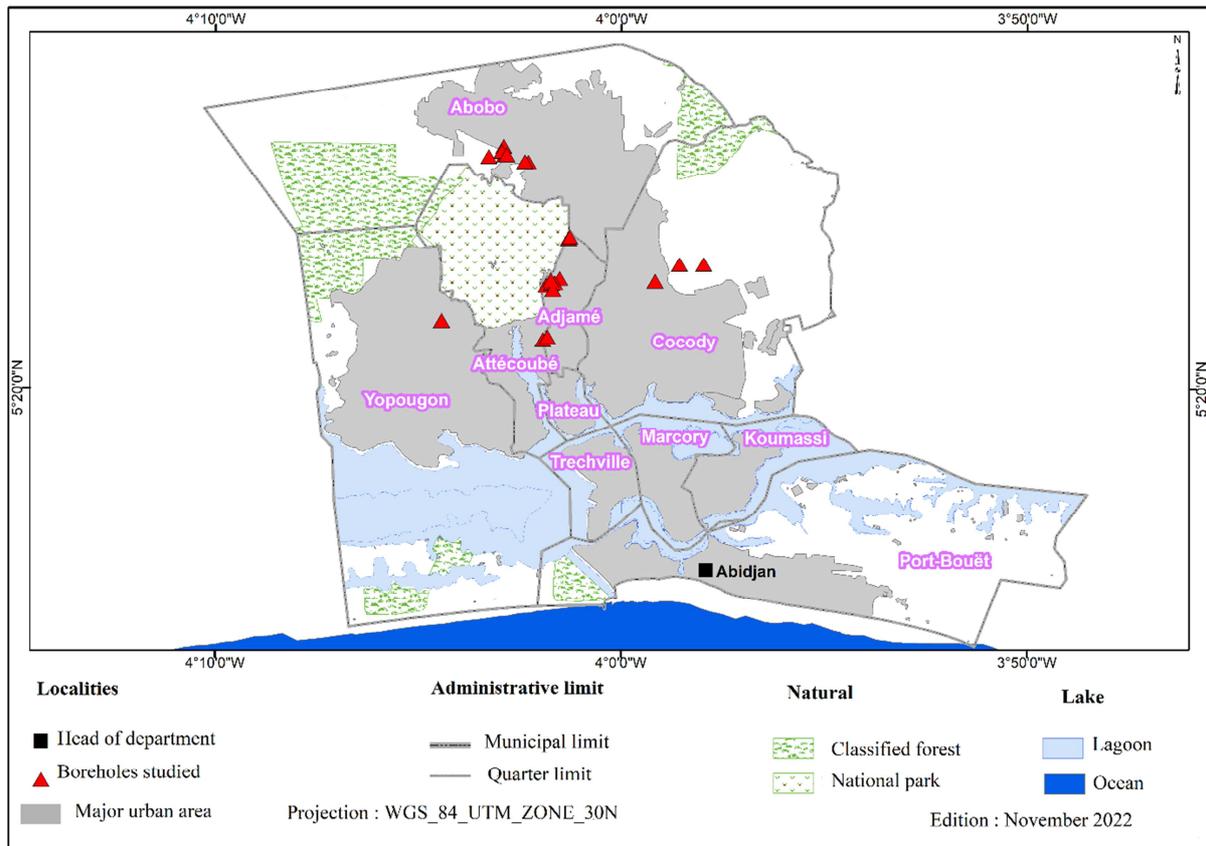


Figure 3. Mapp of boreholes studied.

The results of the groundwater physico-chemical parameters obtained were compared with the drinking water potability criteria according to the World Health Organisation [19] in order to assess the level of water contamination. The Kruskal-Wallis ANOVA test was used to compare the means of the physico-chemical parameters between the wellfields and between seasons. There are significant differences between the averages of the physico-chemical parameters if p value is less than 0.05. Otherwise, the difference is said to be insignificant. Multivariate statistical methods, in this case Principal Component Analysis (PCA), were applied to the physico-chemical parameters. Several authors have used this method to explain the relationships or associations between physico-chemical parameters and their origins in water [20 - 24]. Before carrying out the PCA, we performed statistical tests to prove its application. Indeed, we performed the Bartlett sphericity test and the measure of sampling adequacy with the feasibility of PCA by the Kaiser-Meyer-Olkin method (KMO Index). Multivariate statistical analysis was carried out on all physico-chemical parameters with the exception of Cu^{2+} , Zn^{2+} , Fe^{2+} , F^- , O_2 and H_2S . These chemical elements are very low in groundwater and correlate poorly with the other variables. SPSS software was used to carry out the PCA.

3. Results Physico-Chemical Characterisation of Groundwater

The minimum, maximum and average values of the

physico-chemical parameters of all the water samples analysed and the drinking water potability criteria according to the WHO (2017) are recorded in Table 2. The analysis shows that the hydrogen potential varies from 3.38 to 5.94, with an average of 4.53 ± 0.41 . All the water analysed has a pH below the WHO guide values (6.5-8.5). This shows the acidic nature of the groundwater. The average temperature of the borehole water was $27.17 \pm 0.82^\circ\text{C}$, ranging from 25 to 30°C . The majority of groundwater has a temperature above 25°C , the WHO standard. Turbidity values ranged from 0.1 to 2.83 NTU, with an average of 0.47 ± 0.3 NTU. All these waters have low turbidity. Dissolved oxygen levels ranged from 0 to 3.20 mg/l, with an average of 0.42 ± 0.42 mg/l. Groundwater conductivity values ranged from 35.2 to 479 $\mu\text{S}/\text{cm}$, with an average of 178.53 ± 75.45 $\mu\text{S}/\text{cm}$. Some boreholes (16.5%) have a conductivity greater than 250 $\mu\text{S}/\text{cm}$ (the threshold value). The average hardness of the groundwater is $1.28 \pm 0.83^\circ\text{F}$, with a range of variation from 0.09 to 4.7°F . The hardness values show that this groundwater is soft. Calcium varies between 0.08 and 32.90 mg/l with an average of 8.18 ± 6.03 mg/l. Magnesium concentrations range from 0.0 to 21 mg/l with an average of 4.41 ± 3.42 mg/l. Potassium levels varied between 0.02 and 23.2 mg/l, with an average of 2.47 ± 2.22 mg/l. Silica content varied between 0.8 and 30 mg/l, with an average of 10.73 ± 2.51 mg/l. Nitrate levels in the water varied between 1 and 198 mg/l, with an average of 30.19 ± 21.94 mg/l. The maximum nitrate content is three times higher than the standard recommended by the

WHO (50mg/l). High nitrate levels were observed in 10.75% of the samples analysed. Nitrite concentrations ranged from 0.01 to 0.1 mg/l, with an average of 0.02 ± 0.01 mg/l. Ammonium levels ranged from 0.01 to 9.5 mg/l, with an average of 0.98 ± 1.26 mg/l. The maximum ammonium concentration exceeded the WHO standard (1.5 mg/l) by a factor of 6. High ammonium levels were observed in 18.25% of the samples studied. Chloride ions are low in groundwater with an average of 11.27 ± 6.55 mg/l. The low chloride content is 0.1 mg/l and the high content is 41 mg/l. Sulphate ions are present in the groundwater but at low concentrations. The lowest concentration is 0.0 mg/l and the highest concentration is 19.5 mg/l, with an average of 2.87 ± 3.25 mg/l. Phosphate ion levels ranged from 0.0 to 0.85 mg/l, with an average of 0.15 ± 0.11 mg/l. All the groundwater has a phosphate content below 5 mg/l, the WHO guide value. Hydrogen sulphide

concentrations ranged from 0 to 21 μ g/l, with an average of 4.29 ± 3.57 μ g/l. Aluminium levels ranged from 0.02 to 1.37 mg/l, with an average of 0.28 ± 0.41 mg/l. The maximum aluminium content was 6 times higher than the WHO standard (0.2 mg/l). High aluminium concentrations were observed in 49.5% of the samples analysed. Ferrous ion concentrations ranged from 0.0 to 0.1mg/l, with an average of 0.02 ± 0.01 mg/l. Iron concentrations varied between 0.00 and 0.44 mg/l with an average of 0.04 ± 0.05 mg/l. Manganese levels ranged from 0.01 to 0.14 mg/l with an average of 0.04 ± 0.02 mg/l. The average copper content is 0.05 ± 0.03 mg/l. The lowest copper content is 0.00 mg/l and the highest is 0.20 mg/l. Zinc levels varied between 0.00 and 0.78 mg/l, with an average of 0.04 ± 0.07 mg/l. Fluoride concentrations ranged from 0.00 to 1.05 mg/l, with an average of 0.06 ± 0.11 mg/l.

Table 2. Minimum, maximum and average values for physico-chemical parameters and drinking water potability criteria.

Parameters	Unit	WHO	Minimum	Maximum	Average
pH	-----	6.5 – 8.5	3.38	5.98	4.53 ± 0.41
Temperature	°C	25	25	30	27.17 ± 0.82
Turbidity	NTU	5	0.10	2.83	0.47 ± 0.30
O ₂	mg/l	5	0.00	3.20	0.42 ± 0.42
Conductivity	μ S/Cm	250	35.2	479	178 ± 75.45
THT	°F	-----	0.09	4.94	1.28 ± 0.83
Ca ²⁺	mg/l	100	0.08	32.90	8.18 ± 6.03
Mg ²⁺	mg/l	50	0.0	21	4.41 ± 3.42
K ⁺	mg/l	12	0.02	23.20	2.47 ± 2.22
SiO ₂	mg/l	-----	0.8	30	10.73 ± 2.51
NO ₃ ⁻	mg/l	50	1	198	30.19 ± 21.94
NO ₂ ⁻	mg/l	0.1	0.01	0.1	0.02 ± 0.01
NH ₄ ⁺	mg/l	1.5	0.01	9.5	0.98 ± 1.26
Cl ⁻	mg/l	200	0.1	41.00	11.27 ± 6.55
SO ₄ ²⁻	mg/l	250	0.0	19.5	2.87 ± 3.25
PO ₄ ³⁻	mg/l	5	0.0	0.85	0.15 ± 0.11
H ₂ S	μ g/l	50	0.0	21	4.29 ± 3.57
Al ³⁺	mg/l	0.2	0.02	1.37	0.28 ± 0.41
Fe ²⁺	mg/l	3	0.0	1	0.02 ± 0.01
Fe	mg/l	3	0.0	0.44	0.04 ± 0.05
Mn ²⁺	mg/l	0.5	0.01	0.14	0.04 ± 0.02
Cu ²⁺	mg/l	0.2	0.00	0.20	0.05 ± 0.03
Zn ²⁺	mg/l	3	0.00	0.78	0.04 ± 0.07
F ⁻	mg/l	1.5	0.00	1.05	0.06 ± 0.11

Spatial variation in physico-chemical parameters

In order to study the spatial variation of physico-chemical parameters, we calculated the average value of physico-chemical parameters according to the wellfields (table 3). Analysis of the results shows that for most physico-chemical parameters, the difference is significant from one wellfield to another. However, there was no significant difference between the averages of one wellfield to another for certain elements such as phosphate, copper, zinc and fluoride. Wellfield 6 recorded the lowest values for conductivity, hardness, calcium, magnesium, potassium, nitrate, chloride, aluminium and manganese. The highest values for parameters such as dissolved oxygen, conductivity, hardness, calcium, magnesium, potassium, nitrate, ammonium,

chloride, hydrogen sulphide, iron, total iron and fluoride were observed in wellfield 2. Maximum levels of nitrite and aluminium were observed in wellfield 1.

Seasonal variation in physico-chemical parameters

To study the impact of seasonal variation on groundwater quality, we also calculated the average of physico-chemical parameters according to season (table 4). This reveals a non-significant difference between the averages of physico-chemical parameters in the dry and rainy seasons. However, there was a significant difference between the means of dissolved oxygen in the dry and rainy seasons ($p=0.00$). The rainy season recorded the highest mean dissolved oxygen (0.48 ± 0.52 mg/l) and the lowest mean was observed in the dry season (0.36 ± 0.28 mg/l).

Table 3. Variation in physico-chemical parameters according to wellfields.

Parameters	W1	W2	W3	W4	W5	W6	W7	W8	W9	P value	Sign
pH	4.28±0.17	4.43±0.24	4.40±0.30	4.18±0.15	4.25±0.45	4.75±0.49	4.79±0.49	4.75±0.49	4.47±0.49	0.00	S
T (°C)	27.3±0.74	26.5 ±1.4	27.4 ±0.50	27.0±0.79	26.9 ±0.6	27.2±0.5	27.4±0.8	27.1±0.9	26.8±0.8	0.00	S
Turb (NTU)	0.43±0.2	0.47±0.25	0.50±0.23	0.37±0.21	0.68±0.84	0.74±1.31	0.45±0.24	0.40±0.15	0.40±0.21	0.00	S
O ₂ (mg/l)	0.23±0.16	0.80±0.85	0.30±0.28	0.44±0.34	0.46±0.18	0.34±0.33	0.44±0.35	0.53±0.64	0.44±0.31	0.00	S
CE(µs/Cm)	248.0±24	313.9±104	166.1±72	193.6±50	240.7±63	102.6±44	166.3±49	170.7±52	199.2±65	0.00	S
THT (°F)	1.82±1.05	2.56±1.10	1.01±0.44	1.05±0.29	1.71±0.98	0.73±0.39	1.05±0.42	1.64±0.92	1.31±0.82	0.00	S
Ca ²⁺ (mg/l)	13.47±8.3	14.77±8.84	6.21±2.92	6.17±2.13	11.05±7.24	3.79±3.45	6.76±4.39	10.39±6.3	9.01±6.74	0.00	S
Mg ²⁺ (mg/l)	5.01±3.21	7.51±3.97	4.87±2.86	3.96±2.44	6.83±2.69	2.56±1.93	2.88±2.07	5.65±5.12	3.67±2.71	0.00	S
K ⁺ (mg/l)	4.37±3.54	9.51±4.69	1.67±1.23	2.38±0.74	1.89±0.85	1.38±1.19	2.30±0.89	2.21±1.40	3.05±1.42	0.00	S
SiO ₂ (mg/l)	10.35±0.9	11.48±1.69	10.76±2.83	10.58±2.04	11.91±1.45	10.27±3.08	10.54±2.64	9.88±1.39	11.77±2.48	0.00	S
NO ₃ ⁻ (mg/l)	35.65±12	91.06±52	27.7±16.4	28.69±4.2	42.53±7.6	13.34±6.1	21.1±6.8	29.88±12.3	33.7±17	0.00	S
NO ₂ ⁻ (mg/l)	0.04±0.04	0.02±0.01	0.02±0.01	0.03±0.02	0.01±0.00	0.02±0.00	0.02±0.00	0.02±0.01	0.02±0.01	0.00	S
NH ₄ ⁺ (mg/l)	0.33±0.18	2.99±0.90	0.31±0.41	1.45±0.22	1.36±0.55	1.50 ±2.25	2.21±1.49	0.42±0.36	0.76±0.54	0.01	S
Cl ⁻ (mg/l)	12.63±7.6	26.85±8.27	9.05 ± 4.68	13.55 ± 8.1	14.24 ± 5.2	8.19 ± 4.93	11.52 ± 4.5	12.08 ± 5.7	10.50±5.78	0.00	S
SO ₄ ²⁻ (mg/l)	2.875±1.5	6.07 ±3.51	1.61 ±1.71	2.88 ±1.22	1.81 ±1.33	2.50 ±2.89	6.79 ±5.51	2.34 ±2.56	2.19± 1.79	0.00	S
PO ₄ ³⁻ (mg/l)	0.09±0.04	0.14 ±0.06	0.17 ±0.14	0.18 ±0.19	0.14 ±0.03	0.13 ±0.12	0.11 ±0.04	0.13±0.08	0.17 ±0.13	0.75	NS
H ₂ S (mg/l)	2.5 ± 2.67	5.31 ±4.01	5.05 ±3.78	3.44 ±2.83	4.49 ±5.03	3.75 ±2.91	4.48 ±4.19	4.44 ±1.93	3.03 ±3.68	0.00	S
Al ³⁺ (mg/l)	0.91±0.21	0.73±0.49	0.23±0.17	0.38±0.05	0.48±0.19	0.08±0.04	0.11±0.04	0.24±0.09	0.38±0.19	0.00	S
Fe ²⁺ (mg/l)	0.02± 0.01	0.04±0.03	0.02±0.01	0.02±0.00	0.01±0.00	0.02± 0.00	0.02±0.01	0.02±0.02	0.02±0.01	0.00	S
Fer (mg/l)	0.04± 0.04	0.12± 0.14	0.03±0.03	0.04±0.03	0.04±0.03	0.04±0.04	0.04±0.03	0.04±0.03	0.05±0.03	0.00	S
Mn ²⁺ (mg/l)	0.04± 0.02	0.05±0.02	0.04±0.03	0.04±0.03	0.07±0.02	0.03±0.02	0.04±0.02	0.04±0.02	0.04±0.02	0.00	S
Cu ²⁺ (mg/l)	0.05±0.00	0.06±0.06	0.05±0.02	0.07±0.03	0.03±0.01	0.06±0.04	0.06±0.04	0.05±0.03	0.06±0.03	0.05	NS
Zn ²⁺ (mg/l)	0.03± 0.03	0.02± 0.02	0.03± 0.02	0.03±0.02	0.03±0.03	0.03±0.04	0.04±0.03	0.07±0.17	0.05±0.04	0.10	NS
F ⁻ (mg/l)	0.03±0.02	0.11±0.12	0.06±0.14	0.03±0.02	0.08±0.26	0.05±0.05	0.08±0.11	0.04±0.05	0.03±0.03	0.14	NS

Table 4. Seasonal variation in the physico-chemical parameters.

Parameters	Dry season	Rainy season	p value	Sign
pH	4.55 ± 0.44	4.51 ± 0.38	0.35	NS
CE (µS/Cm)	180.84 ± 78.03	176.2 ± 72.91	0.54	NS
T°C	27.25 ± 0.93	27.10 ± 0.69	0.31	NS
Turb (NTU)	0.47 ± 0.28	0.47 ± 0.32	0.96	NS
O ₂ (mg/l)	0.48 ± 0.52	0.36 ± 0.28	0.00	S
NO ₃ ⁻ (mg/l)	29.44 ± 21.65	30.93 ± 22.26	0.49	NS
NO ₂ ⁻ (mg/l)	0.02 ± 0.01	0.02 ± 0.01	0.22	NS
NH ₄ ⁺ (mg/l)	0.94 ± 1.21	1.01 ± 1.32	0.61	NS
THT (°F)	1.29 ± 1.08	1.30 ± 0.82	0.92	NS
Ca ²⁺ (mg/l)	8.09 ± 6.09	8.27 ± 5.98	0.16	NS
Mg ²⁺ (mg/l)	4.18 ± 3.07	4.66 ± 3.74	0.05	NS
K ⁺ (mg/l)	2.47 ± 2.37	2.46 ± 2.08	0.96	NS
SiO ₂ (mg/l)	10.41 ± 2.72	11.06 ± 2.24	0.01	NS
Cl ⁻ (mg/l)	10.78 ± 6.72	11.76 ± 6.36	0.13	NS
SO ₄ ²⁻ (mg/l)	2.73 ± 3.12	3.01 ± 3.39	0.39	NS
PO ₄ ³⁻ (mg/l)	0.14 ± 0.09	0.16 ± 0.13	0.11	NS
H ₂ S(µg/l)	4.08 ± 3.42	4.51 ± 3.72	0.24	NS
Al ³⁺ (mg/l)	0.27± 0.24	0.29 ± 0.24	0.52	NS
Fe ²⁺ (mg/l)	0.02 ± 0.01	0.02± 0.01	0.05	NS
Total iron (mg/l)	0.04 ± 0.05	0.04 ± 0.04	0.85	NS
Mn ²⁺ (mg/l)	0.04 ±0.02	0.04 ± 0.02	0.22	NS
Cu ²⁺ (mg/l)	0.05± 0.03	0.06 ±0.04	0.52	NS
Zn ²⁺ (mg/l)	0.05 ± 0.10	0.03 ± 0.03	0.10	NS
F (mg/l)	0.06 ± 0.13	0.05 ±0.10	0.20	NS

Correlation between physico-chemical parameters

The correlation coefficients between the physico-chemical parameters taken in pairs are shown in Table 5. These coefficients provide information on the strength of the associations between them [22]. In the correlation matrix, the significant Pearson correlation coefficients (P < 0.00) are greater than 0.5 and are shown in bold. Conductivity was significantly and positively correlated with aluminium (0.65), nitrate (0.64) and potassium (0.57). Nitrate correlated significantly with aluminium (0.74), potassium (0.69) and chloride (0.58). Ammonium was significantly correlated with

sulphate (0.65).

Measurement of sampling adequacy and Bartlett's sphericity test

The Kaiser-Meyer-Olkin (KMO) index of 0.78 can be described as commendable. This value indicates that the correlations between the physico-chemical parameters are of good quality. The result of Bartlett's sphericity test is significant (p < 0.00) and the Chi-square value obtained is 2197.973 for a degree of freedom of 190. We can therefore carry out the PCA.

Principal Component Analysis

The choice of the number of components to be extracted is important in a PCA. It is determined by the variance accumulation test known as the "scree test". The extraction of components is completed at the point where the change in

slope appears in the eigenvalue graph [25] (Figure 4). The number of components to be extracted must take into account the interpretation capacity of the extracted dimensions. In this study, the first six (6) components are retained.

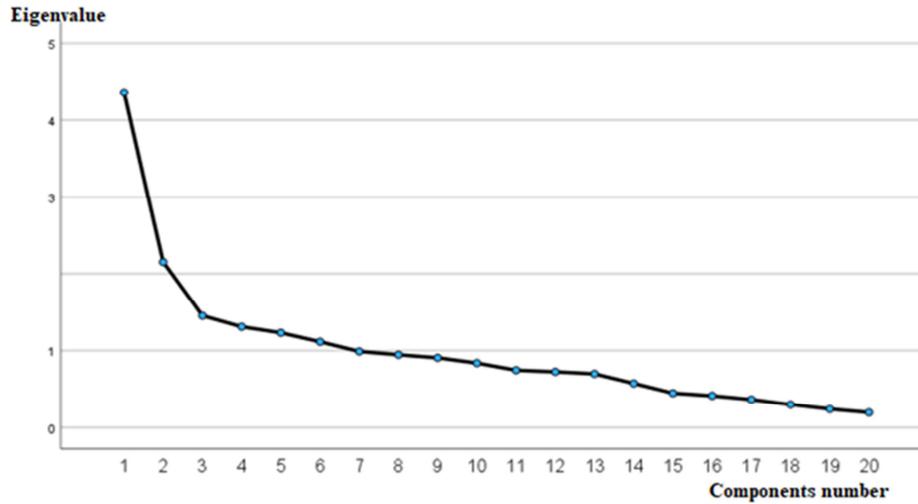


Figure 4. Eigenvalue plot for principal component analysis.

Table 5. Correlation matrix for groundwater physical-chemical parameters.

	Tur	pH	CE	T	Ca ²⁺	Mg ²⁺	SiO ₂	K ⁺	SO ₄ ²⁻	Cl ⁻	PO ₄ ³⁻	NH ₄ ⁺	NO ₃ ⁻	NO ₂ ⁻	Al ³⁺	Fe	Mn ²⁺
Tur	1.00																
pH	0.02	1.00															
CE	-0.10	-0.18	1.00														
T	0.02	0.24	-0.07	1.00													
Ca ²⁺	0.10	-0.02	0.41	0.04	1.00												
Mg ²⁺	0.05	-0.20	0.19	0.06	0.32	1.00											
SiO ₂	0.03	-0.26	0.12	-0.13	0.08	-0.04	1.00										
K ⁺	-0.04	-0.11	0.57	-0.06	0.49	0.15	0.15	1.00									
SO ₄ ²⁻	-0.05	0.27	0.23	0.04	0.24	-0.05	-0.03	0.35	1.00								
Cl ⁻	-0.09	0.04	0.46	0.12	0.47	0.22	0.02	0.58	0.38	1.00							
PO ₄ ³⁻	0.13	-0.14	-0.03	-0.02	-0.01	-0.05	0.22	-0.01	-0.13	-0.11	1.00						
NH ₄ ⁺	0.03	0.22	0.31	-0.01	0.19	-0.04	0.00	0.43	0.65	0.41	-0.07	1.00					
NO ₃ ⁻	-0.05	-0.32	0.64	-0.08	0.41	0.26	0.17	0.69	0.12	0.52	0.00	0.22	1.00				
NO ₂ ⁻	0.00	-0.07	0.12	-0.01	0.05	-0.03	0.02	-0.02	0.05	0.02	0.02	0.02	0.10	1.00			
Al ³⁺	-0.08	-0.35	0.65	-0.10	0.44	0.23	0.19	0.66	0.04	0.47	0.02	0.14	0.73	0.08	1.00		
Fe	-0.01	0.24	0.05	-0.09	0.00	-0.07	0.01	0.08	0.04	0.05	-0.03	-0.00	-0.02	-0.06	-0.03	1.00	
Mn ²⁺	-0.03	-0.14	0.33	0.06	0.19	0.15	0.09	0.18	0.03	0.16	-0.04	0.03	0.33	-0.06	0.29	0.09	1.00

Table 6 shows the matrix of total variance explained. Its observation shows that the first six (6) components extracted explain 58.05% of the total variance. Component 1 is the most important, accounting for 21.78% of the total variance, followed by component 2, which explains 10.75%, and component 3, which accounts for 7.25%. The correlation coefficients linking the physico-chemical parameters to the six components are shown in Table 7. Significant coefficients are greater than 0.5 and are shown in bold. Component 1 represents 21.78% of the total variance and is made up of conductivity, calcium, potassium, nitrate, aluminium and chloride. The second component accounts for 10.75% of the total variance. It is made up of hydrogen potential, sulphate and ammonium.

Table 6. Total variance of the eigenvalues.

Component	Total variance explained		
	Total	% of variance	% Cumulative
1	4,35	21,78	21,78
2	2,15	10,75	32,54
3	1,45	7,25	39,80
4	1,13	6,54	46,34
5	1,23	6,14	52,49
6	1,11	5,56	58,05

Table 7. Correlation coefficients between variables.

Variables	Component					
	1	2	3	4	5	6
Tur	-0,07	-0,03	-0,03	0,37	0,39	0,53

Variables	Component					
	1	2	3	4	5	6
pH	-0,21	0,76	-0,07	0,14	-0,05	0,03
CE	0,79	-0,07	0,04	-0,04	-0,10	-0,11
T	-0,05	0,29	-0,50	0,17	0,34	-0,09
Ca ²⁺	0,64	0,05	-0,15	0,08	0,25	0,12
Mg ²⁺	0,33	-0,22	-0,46	-0,05	0,31	0,00
SiO ₂	0,19	-0,36	0,41	0,27	-0,11	0,25
K ⁺	0,84	0,07	0,17	0,03	-0,01	0,04
SO ₄ ²⁻	0,38	0,68	0,29	-0,11	0,08	0,10
Cl ⁻	0,73	0,29	-0,09	0,03	0,10	-0,09
PO ₄ ³⁻	-0,05	-0,30	0,26	0,53	0,20	0,24
NH ₄ ⁺	0,46	0,59	0,34	-0,10	0,12	0,19
NO ₃ ⁻	0,84	-0,24	-0,01	-0,02	-0,04	-0,05
NO ₂ ⁻	0,08	-0,06	0,25	0,10	0,26	-0,59
Al ³⁺	0,81	-0,31	-0,03	0,02	-0,07	-0,09
Fe	0,03	0,24	-0,04	0,41	-0,61	0,00
Mn ²⁺	0,39	-0,16	-0,34	0,05	-0,35	0,16

4. Discussion

The physico-chemical analyses carried out on the groundwater in Abidjan District show that the water is acidic. This acidity was observed in all the wellfields and during both seasons. Several authors have already pointed out the acidity of groundwater in the Abidjan District [6, 7, 8]. The acidity of groundwater in Greater Abidjan is linked to the partial pressure of carbon dioxide [4, 7, 26]. Rainwater becomes acidic as it carries carbon dioxide dissolved in the soil to the groundwater table. The temperature of the groundwater varies between 25 and 30°C, which is line with the annual temperature of the ambient air during the decades of between 25 and 30°C [1]. The high conductivity values in some boreholes can be explained by the high presence of aluminium, nitrate and ammonium. The high levels of aluminium were observed in all the wellfields and during the dry and rainy seasons. Ingestion of high levels of aluminium can have negative effects on our bones [10, 11], kidneys [11], reproduction and development [12, 13, 14]. Aluminium levels in water therefore need to be reduced before consumption. Several studies have detected high levels of aluminium in groundwater [5, 7, 10]. Aluminium content in groundwater can be linked to the geological nature of the aquifer [27]. X-ray diffractometry analyses carried out on a rock sample from the Continental Terminal in the Abidjan District indicate the presence of alumino-silicate minerals such as: quartz (SiO₂), kaolinite (Al₂Si₂O₅(OH)₄), anorthite (CaAl₂Si₂O₈), microcline (KAlSi₃O₈) and illite (K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O₁₀(OH)₂) [4]. The existence of alumino-silicate minerals in the Continental Terminal aquifer could be a source of aluminium contamination of groundwater. The acidic nature of groundwater facilitates the dissolution of aluminium [28]. The presence of aluminium in groundwater can also be linked to anthropogenic inputs. Industrial, electronic, pharmaceutical and food waste contribute to the increase in its content in the environment [29, 30]. Typical scrap metal or iron trade activities carried out in the District of Abidjan could be a source of aluminium contamination of groundwater. These scrap metal activities are carried out around the wellfields, with the exception of wellfields 6 and 7. The high nitrate and ammonium levels have a major impact on the physico-chemical quality of the groundwater. Consumption of such water can cause illnesses

such as methaemoglobinaemia in infants [15]. As a result, such water must be treated before consumption. Several authors have detected high concentrations of nitrate and ammonium in groundwater [6-9]. The high presence of nitrate and ammonium in the water indicates anthropogenic pollution. As the boreholes are located in the highly urbanised districts of Abidjan, where agriculture is rarely practised, the main source of nitrate and ammonium contamination of groundwater is the infiltration of domestic wastewater. Studies using nitrogen-15 as a tracer, indicate that nitrate in groundwater in the city of Abidjan comes mainly from urban wastewater [7]. High concentrations of nitrate and ammonium may indicate contamination of groundwater by bacteria [31]. Studies by Jourda [6] detected 909 cfu/100 ml of *Escherichia coli* in borehole 6 of the Zone Ouest wellfield in 2004. The presence of these micro-organisms in groundwater is due to human faecal contamination. In addition, excessive pumping of boreholes at production stations can cause polluted water (septic tanks and sub-surface water) to flow into the groundwater [4, 7]. Excessive pumping from boreholes has already led to salt water entering freshwater (Q=250 m³; Conductivity 4200 µS /cm) [32]. The study of spatio-temporal variation showed that there is a significant variation in aluminium, nitrate and ammonium content from one wellfield to another. Wellfield 2 (Adjamé Nord) recorded the highest average concentration of nitrate (91.06 ± 52 mg/l) and ammonium (2.99 ± 0.90 mg/l). The highest average aluminium concentration was observed in wellfield 1, with a value of 0.91±0.21 mg/l. The spatial variation in nitrate and ammonium levels in the groundwater of the Abidjan District shows the multiple sources of production of these nitrogen compounds. These levels are linked to population density and the quantities of waste [9]. In the commune of Adjamé, population density is very high, with many precarious dwellings. Some dwellings are not connected to the collective sanitation system to evacuate their liquid waste. These residents use septic tanks that do not comply with installation standards or construction technology. These sanitation practices can lead to the infiltration of liquid waste into the groundwater. In addition, the work of Oga and Kouadio points to the existence of an old dump in the vicinity of the Adjamé Nord wellfield [4, 33]. This trend in nitrate pollution is no longer confined to the old districts. It is now spreading to the new residential centres in the industrial zones of Yopougon (West Zone). The significant correlation between electrical conductivity and aluminium (0.65), nitrate (0.64) and potassium (0.57) shows that the mineralisation of groundwater is mainly due to human activity. The high correlation between nitrate and aluminium (0.74) shows a common origin for both chemical elements. Nitrate is an indicator of anthropogenic pollution. The significant correlation between these two elements shows that anthropogenic inputs contribute to the increase in aluminium content. The significant correlations between potassium and nitrate (0.69) and with aluminium (0.66) show that anthropogenic inputs contribute to the increase in potassium levels. The presence of potassium minerals in the aquifer could be a source of potassium in groundwater. Principal component analysis reveals that component 1, which accounts for 21.78% of the total variance, is made up of conductivity, calcium, potassium, chloride, nitrate

and aluminium. This component shows two chemical elements (Ca^{2+} , Al^{3+}) originating from the geological nature of the aquifers [8, 22, 34]. However, all the other parameters depend mainly on human activities [8, 9, 34]. Component 1 therefore represents both natural mineralisation and anthropogenic water pollution. Component 2 accounts for 10.75% of the variance and is made up of pH, sulphate and ammonium. The presence of ammonium and sulphate indicates organic pollution [8, 34]. Component 2 therefore explains the organic pollution of groundwater.

5. Conclusion

The objective of this study was to assess the impact of aluminium and nitrogen compounds on the physico-chemical quality of groundwater in the District of Abidjan. The physico-chemical analyses carried out on the 50 boreholes during the dry and rainy seasons from 2019 to 2022 show that the water is acidic, soft, not very turbid and not very mineralised overall. High levels of aluminium, nitrate and ammonium were detected in 49.5%, 10.75% and 18.25% of the water samples analysed respectively. A study of the spatio-temporal variation in physico-chemical parameters shows that pollution depends on the geographical location of the boreholes and not on the seasons. Principal Component Analysis (PCA) shows natural mineralisation and anthropogenic pollution of groundwater. Given the high levels of aluminium, nitrate and ammonium contamination in some boreholes, we recommend blending the water before distribution in order to reduce the abundance of chemical elements. Against a backdrop of rapid population growth, increasing drinking water requirements and growing contamination of boreholes by nitrates, ammonium and aluminium, it is important to find a way of removing these pollutants from groundwater.

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