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**Title:** Hydro-chemical characterization and spatial distribution of groundwater quality in a watershed in Antananarivo Madagascar

**Titre :** Caractérisation hydrochimique et distribution spatiale de la qualité des eaux souterraines d'un bassin versant localisé à Antananarivo Madagascar

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#### **ABSTRACT:**

Groundwater exploitation contributes to achieving sustainable development goal 6: access to safe and affordable drinking water for all. This study aims to determine hydro-chemical facies, groundwater quality, and its spatial distribution in the Antananarivo watershed. Various parameters including pH, Electrical Conductivity (EC), Turbidity, major cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{K}^+$ ), and major anions ( $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ , and  $\text{HCO}_3^-$ ) were measured to estimate the Water Quality Index (WQI). Spatial analysis was conducted using the Inverse Distance Weighted (IDW) method in QGIS. Principal Component Analysis (PCA) of Pearson correlation was used to analyse the relationships between variables. Approximately 75% of groundwater samples, mainly from lithosol areas, were found to be suitable for drinking purposes based on the established WQI. However, less than 25% of wells located in ferralitic and hydro-morphic mineral soils, primarily in lower altitude areas, were deemed unsuitable for human consumption. The aquifers in the watershed were characterized by three hydro-chemical facies: Calcium – Chloride (44 wells), Calcium – Magnesium – Chloride (6 wells), and Calcium – Magnesium – Bicarbonate (2 wells), with Chloride and Calcium dominating.

**Keywords:** *Groundwater, hydrochemistry, Water Quality Index (WQI), spatial interpolation, Watershed*

#### **RESUME**

L'exploitation des eaux souterraines contribue à la réalisation de l'objectif de développement durable n°6 : accès à l'eau potable et abordable pour tous. L'étude vise à déterminer le faciès hydrochimique, la qualité des eaux souterraines et leur répartition spatiale dans le bassin versant d'Antananarivo. Divers paramètres, notamment

le pH, la conductivité électrique (CE), la turbidité, les cations majeurs ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  et  $\text{K}^+$ ) et les anions majeurs ( $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$  et  $\text{HCO}_3^-$ ) ont été mesurés pour estimer l'indice de qualité de l'eau (WQI). L'analyse spatiale a été réalisée à l'aide de la méthode Inverse Distance Weighted (IDW) dans QGIS. L'analyse en composantes principales (ACP) de la corrélation de Pearson a été utilisée pour analyser les relations entre les variables. Selon l'IQE établi, environ 75 % des échantillons d'eaux souterraines, principalement provenant de zones de lithosol, se sont révélés propres à la consommation. Cependant, moins de 25 % des puits situés dans des sols ferrallitiques et hydro-morphes minéraux, principalement dans les zones de basse altitude, ont été jugés impropres à la consommation humaine. Les aquifères du bassin versant sont caractérisés par trois faciès hydrochimiques : Calcium – Chlorure (44 puits), Calcium – Magnésium – Chlorure (6 puits) et Calcium – Magnésium – Bicarbonate (2 puits), à dominante Chlorure et Calcium.

**Mots clés :** Eaux souterraines, hydrochimie, Indice de la Qualité des Eaux, Interpolation spatiale, Bassin versant

## 1. INTRODUCTION

Sustainable Development Goal 6 (SDG 6) focuses on ensuring availability and sustainable management of water and sanitation for all. It aims to achieve universal and equitable access to safe and affordable drinking water for everyone, as well as adequate and equitable sanitation and hygiene for all, by 2030 (The United Nations World Water Development Report 2022). It is an unevenly distributed renewable natural resource and accounts for almost half of the drinking water in the world.

In 2016, only 23% of the population had access to safe drinking water in Madagascar; Within the agglomeration of Antananarivo, capital city, 71.88% of the population had access to drinking water which was calculated based on various infrastructures such as private connections, public standpipes of JIRAMA (the National Company of Electricity and Water in Madagascar), boreholes, and wells with human-powered pumps (MAHTP & JICA, 2019). Despite the efforts of JIRAMA to provide water connections, the coverage is still not complete, there are areas within the agglomeration where access to drinking water is lacking. The low coverage of urban water infrastructure and the limited service provided by JIRAMA significantly impact the quantity, quality and reliability of water provision. Only 33 % of population in the Urban Commune of Antananarivo have access to private water connection (Ognard, Taglioni 2019).

Aquifers are porous and permeable geological formations that act as natural reservoirs of water. They are supplied by natural recharge processes, such as rainfall, and are used by the urban dwellers for various activities.

19 Aquifers are pumped for human activities, including domestic use and small-scale private or community irriga-  
20 tion. Some residents of Antananarivo rely on groundwater from aquifers for drinking water. City residents prefer  
21 this source over the water provided by JIRAMA because the latter is thought to be contaminated, non-potable  
22 and potentially pose health harm. Groundwater from aquifers is believed to be protected from microorganisms.  
23 During the infiltration of water into the aquifer, the soil and rocks act as natural filters, removing or reducing the  
24 presence of harmful microorganisms.

25 Protecting and conserving this resource entails managing both its quantity and quality. Natural phenomena and  
26 anthropogenic activities can impact groundwater quality. The nature of the chemical facies is influenced by fac-  
27 tors such as evaporation rates, precipitation, weathering of primary or secondary minerals through water-rock  
28 interaction, and soil quality above the aquifer (Salim et al. 2020). The acid hydrolysis of rocks is significant in  
29 mineralizing water, enriching it with nutritive salts, affecting the solubility of  $Mn^{2+}$  and  $Fe^{2+}$ , and making Al species  
30 available, primarily through kaolinite and/or gibbsite dissolution (Ahoussi et al. 2013, Aka et al. 2013). Weathering  
31 of feldspars increases the concentration of  $Na^+$ ,  $Ca^{2+}$ , and  $K^+$  in groundwater; Groundwater interacts with vegeta-  
32 tion, atmospheric  $CO_2$ , and soil microorganisms, enriching it with  $HCO_3^-$  and increasing water alkalinity (Saravanan  
33 et al. 2015). Environmental conditions such as high temperature, low rainfall, and high evaporation can lead to  
34 increased dissolved salt content in groundwater and decreased recharge rates (Ahmad et al. 2020).

35 Groundwater deterioration is a significant environmental concern influenced by various human activities such as  
36 urbanization, agricultural development, use of fertilizers, overexploitation, and strong demographic pressure  
37 which produce high quantities of solid and liquid wastes. These activities lead to both pollution and depletion of  
38 groundwater resources (Ahmad et al. 2020). Nitrate, sulphate, and chloride pollution through sewers, organic  
39 waste spreaded on the ground, and use of nitrogenous fertilizers can originate from agricultural practices, indus-  
40 trial processes, and domestic activities (Aka et al. 2013, Zheng et al. 2017); rain water and irrigation carry pollu-  
41 tants through the soil layers by infiltration, so that they can leach into groundwater (Chen et al. 2023).

42 The current study focuses on analyzing the physicochemical properties of groundwater to understand the influ-  
43 ences of natural and human activities. By conducting geochemical analyses using the Piper diagram, the study  
44 aims to determine hydrochemical facies and elucidate the presence of various ions and salts. The spatial distri-  
45 bution of the Water Quality Index (WQI) within these hydro chemical facies is examined to provide valuable in-  
46 sights for aquifer management (Ahoussi et al. 2013).

## 47 2. MATERIAL AND METHODS

### 48 2.1. Description of study area

49  
50 The watershed covers 21 fokontany (smallest political subdivision in Madagascar) in Antananarivo, with a total  
51 area of 4,16 km<sup>2</sup>. It was delineated from ASF ALOS PALSAR – Digital Elevation Map (Figure 1) using hydrological  
52 processing tool in GRASS-GIS. It lies between latitudes -18,9472306°S; -18,9193111°S and longitudes  
53 47,5225889°E; 47,5438889°E. The highest elevation, approximately 1 433 m, is observed in the fokontany of  
54 Manjakamiadana where the queen’s palace is located. Sewerage and storm water are collected in the lowland of  
55 the watershed, reach the outlet (47, 52900844°E, -18, 94124730°S) and discharging into Ikopa River in An-  
56 drondrakely Saropody. The majority of the city’s inhabitants get their water supply from standpipes rarely from  
57 wells. Groundwater are mainly used for domestic and permaculture watering activities.

58 Antananarivo has a tropical climate characterised by a dry and cold winter from May to September, a rainy and  
59 warm summer from October to April. The mean annual temperature is 18°C, with a maximum of 26°C in Novem-  
60 ber and a minimum 10°C in July. The annual rainfall ranges from 1,000 mm to 1,600 mm per year.

61 Figure 3 depicts three soil types in the study area: ferralitic (FS), mineral hydromorphic (HM) and lithosoil (LS)  
62 (Bourgeat 1968). FS are characterised by their iron and aluminium content, low exchange capacity, low base con-  
63 tent, low pH and red colour. HM or low humus and gley soils, form in poorly drained areas, with permanent deep  
64 waterlogging and fairly significant fine alluvium. The organic horizon is more compact than in the previous types  
65 and is generally no more than 20 to 30 cm thick. Organic matter levels are frequently in the order of 4 to 5% and  
66 less than 10%. HM with pseudo gley are acid with variable granulometry, low saturation rate with few mineral  
67 reserves. Unprocessed mineral soils named lithosols (LS) may not occupy large areas in the valleys of ancient  
68 massifs. These soils are normally micaceous, with an acid reaction, rather poor in mineral elements.

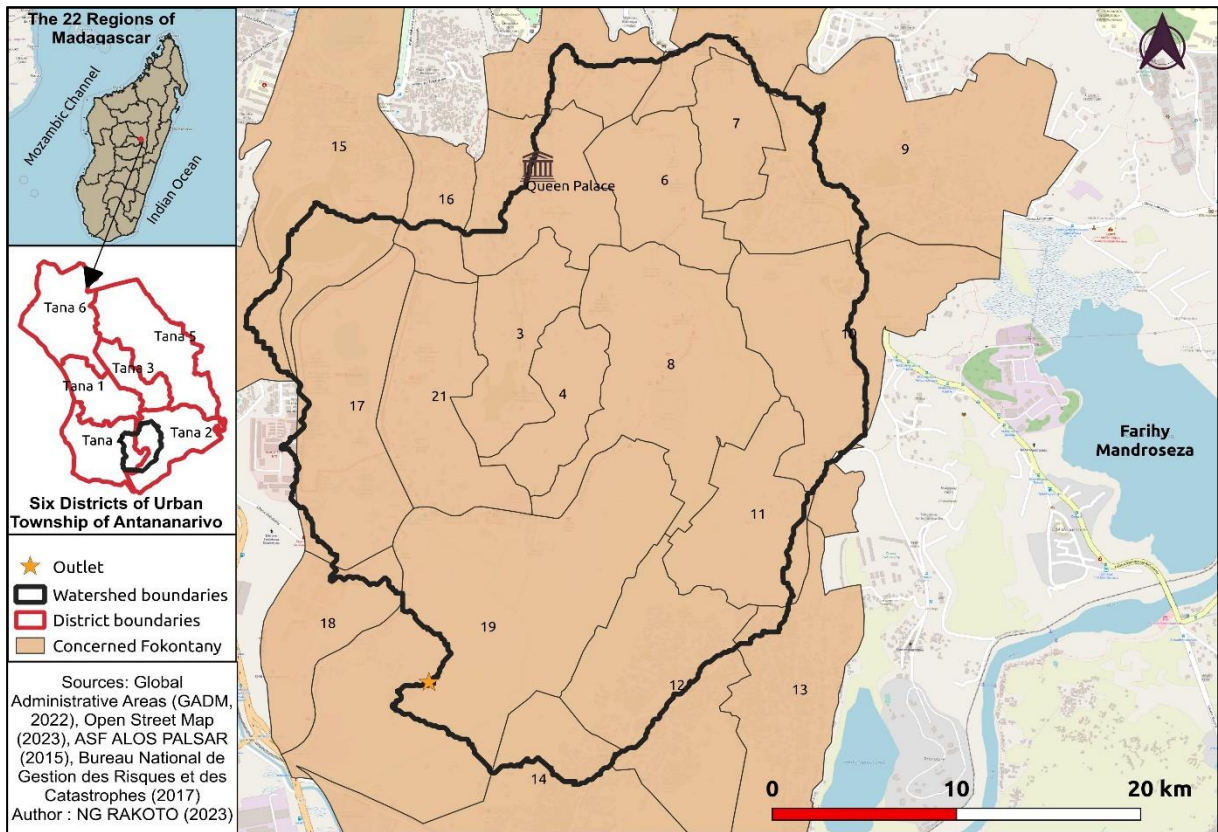


Figure 1: Watershed localization in Antananarivo Madagascar  
Antananarivo Madagascar

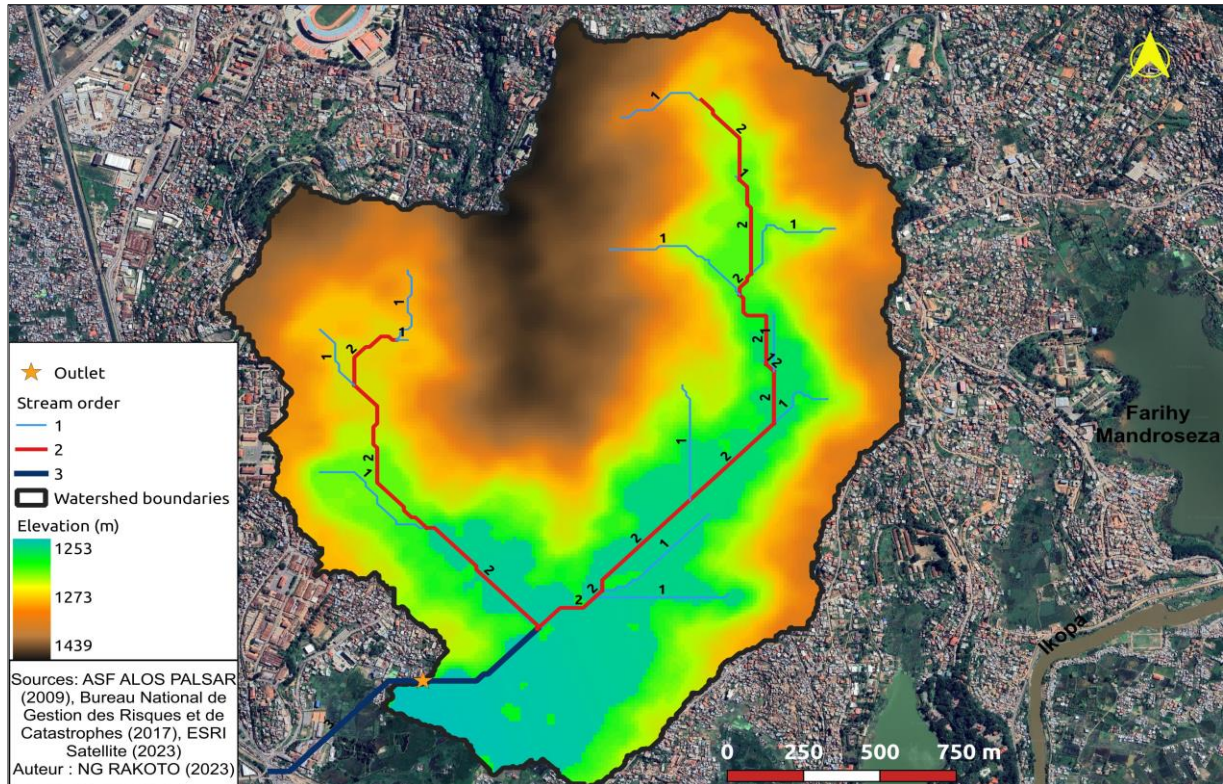
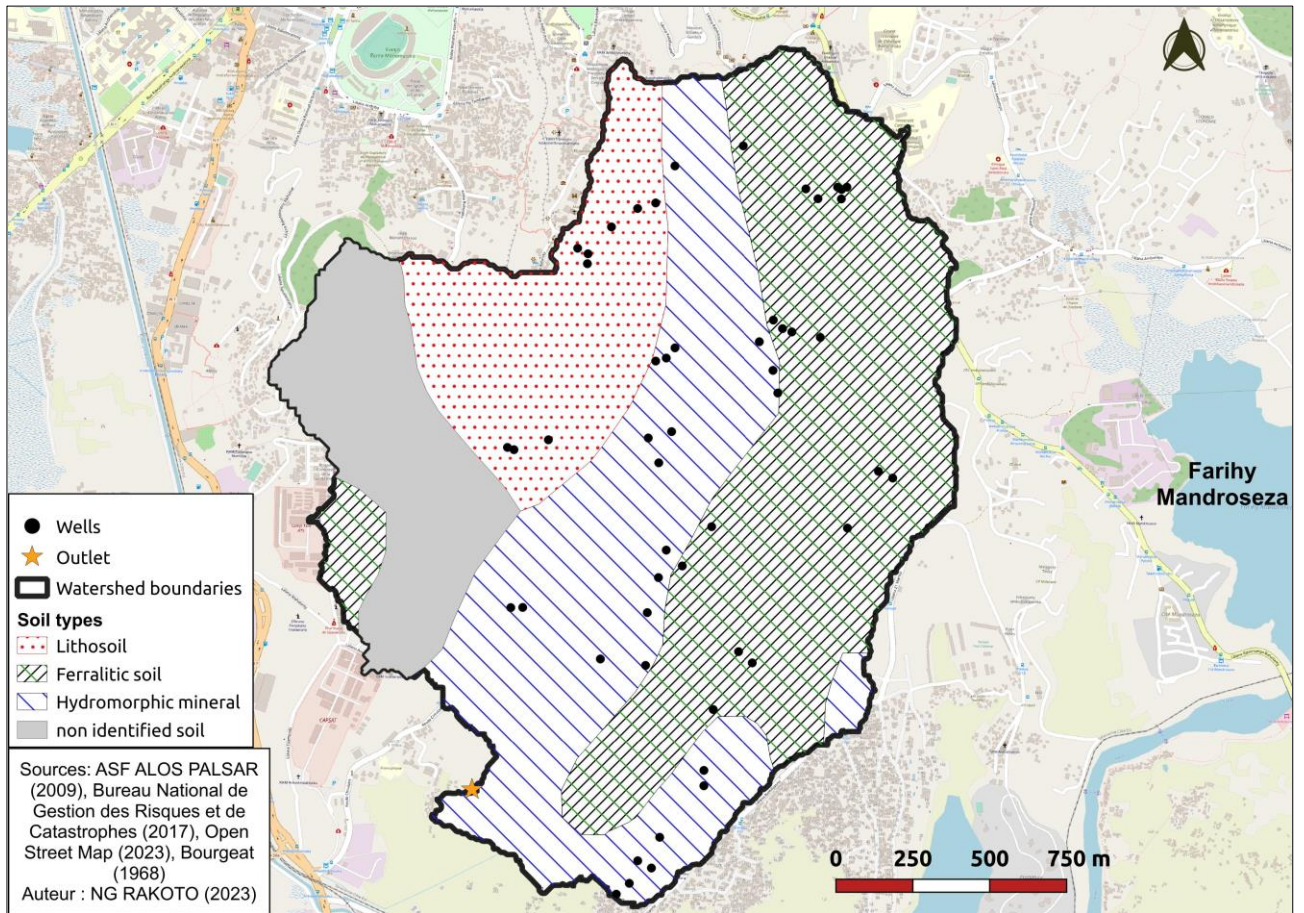


Figure 2: Elevation and stream order characteristics of the watershed

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**Figure 3: Soil types characteristic of the watershed**

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## 2.2. Water quality analysis

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Water samples were collected from 52 wells of Antananarivo watershed during June 2023, beginning of dry and cold season (Figure 3, table 1). They were georeferenced using kinematic GPS. The water from these wells is used for various purposes including domestic activities, drinking, and agricultural activities. Rinsed PolyEthylene Terphthalate bottles of one litre were used for collecting samples. The samples were kept at a temperature below 4°C during transportation and conservation to maintain their integrity before analysis.

Soil type	Number of wells for sampling
Ferralitic soil (FS)	19
Lithosol (LS)	9
Mineral Hydromorphe (HM)	24

81

**Table 1: Number of wells per soil types**

82

83

The pH and Electrical Conductivity (EC) were measured in-situ, at the same time as geographical data collection, using portable analyzers pH-meter Greisinger instruments and Conductimeter HANNA. Turbidity was measured

84 using a turbidimeter HANNA. The bicarbonate ( $\text{HCO}_3^-$ ) was analysed by Gran titration method using  $\text{HCl}$  ( $0,1 \text{ mol.l}^{-1}$ ).  
85  $^1$ ). The Hardness or TH (an indication of concentration of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  dissolved in water), calcium ( $\text{Ca}^{2+}$ ) and  
86 magnesium ( $\text{Mg}^{2+}$ ) were measured by EDTA – Complexation and the potassium ( $\text{K}^+$ ) by HANNA photometer. The  
87 procedure of determination of sulphate ( $\text{SO}_4^{2-}$ ) amount in water involve its precipitation by barium chloride, fol-  
88 lowed by stabilization with TWEEN 20 solution. The homogeneous suspensions were measured with a spectro-  
89 photometer at 650 nm. The chloride was measured by volumetric method based on Mohr method using silver  
90 nitrate ( $\text{Ag NO}_3$ ) and potassium chromate ( $\text{K}_2\text{CrO}_4$ ).

91 Descriptive statistic using excel tool such as boxplot was employed for data statistical analysis. Major cations ( $\text{K}^+$ ,  
92  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ) and major anions ( $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ ) were plotted on Piper diagram used to visualize and describe the  
93 groundwater quality.

94 Water Quality Index (WQI) is a numerical single value used to evaluate the overall quality of water based on  
95 various parameters. The WQI is particularly useful in assessing groundwater quality for different purposes such  
96 as drinking, irrigation, or industrial use (Chidiac et al. 2023). WQI is used to assess groundwater quality status,  
97 taking into account water quality parameters. Determining WQI consists of three main steps:

98 **Step 1: Weighting:** Ten parameters such as pH, EC, Turbidity, hardness (TH),  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$  and  $\text{HCO}_3^-$   
99 were considered, and relative weights are assigned to each parameter which can be calculated as:

100 
$$Wi = \frac{wi}{\sum_{i=1}^n wi}$$

101  $Wi$ : Relative weight for each parameter

102  $wi$ : weight assigned for each parameter

103  $n$ : number of parameters selected

104 **Step 2: calculating rating scale**

105 In general, water quality parameters have different units. This step aims to transform all parameters into common  
106 scale. The rating scale values  $Qi$  depend on the permissible limits from Malagasy drinking water standard and can  
107 be calculated by the following equation:

108 
$$Qi = \frac{Ci - Co}{Si - Co} \times 100$$

109  $Qi$ : Rating scale value

110  $Ci$ : parameter value

111  $Co$ : Ideal value of the parameter ( $Co = 0$ ) except for pH ( $Co = 7$ )



112 Si: Standard value

### 113 Step 3: Aggregation and Producing WQI

114 The final step is calculating sub-index Sli by multiplying the rating scale values with weights. Then, the WQI  
115 value can be determined by aggregating Sli values.

$$116 \quad Sli = Wi * Qi$$

$$117 \quad WQI = \sum_{i=1}^n Sli$$

118 Si: sub-index parameters

119 Qi: Rating scale value based on amount of  $i^{th}$  parameter

120 n: number of the parameter

121 The water quality status depends on WQI values and provided on table 2

122 **Table 2: water quality status (Siriwardhana et al. 2023)**

WQI	Water Quality Status	Possible use		
		Drinking	Agricultural	Industrial
0 - 25	Excellent	Suitable	Suitable	Suitable
25 - 50	Good	Suitable	Suitable	Suitable
50 - 75	Poor	Not suitable	Suitable	Suitable
75 - 100	Very poor	Not suitable	Suitable	Not suitable
Above 100	Not suitable for drinking or fish culture	Proper treatment required		

123

124 Principal Component Analysis (PCA) was performed by using Pearson Correlation Method providing insight into  
125 the relationship between pairs of water quality parameters. Pearson correlation coefficient ranges between -1  
126 and +1. Coefficient equal to zero means no linear correlation between the two variables, negative value next to -  
127 1 and positive value next to 1 means respectively negative and positive correlation between the two variables.

### 128 2.3. Hydrochemical properties analysis

129

130 Hydrochemical properties of groundwater are related to groundwater resident time, lithology and human activ-  
131 ities can indeed reflect the composition of the rocks through which the water has flowed. The Piper diagram is a  
132 graphical method used in hydrogeochemistry to analyze and classify the chemical composition of water based on  
133 the concentrations of major cations (such as calcium, magnesium, sodium, and potassium) and major anions  
134 (such as bicarbonate, sulphate, and chloride). Piper diagram is useful in understanding groundwater quality, iden-  
135 tifying sources of contamination, and studying water-rock interactions. It presents the variation type of facies in  
136 groundwater chemistry. This ternary diagram is composed by two triangles corresponding with dominant cations  
137 and anions and one diamond which illustrate the facies types.

#### 138 2.4. Spatial analysis

139 Spatial distribution maps of the water quality index were created using the Inverse Distance Weighted (IDW)  
140 method. It is an effective tools for spatial interpolation of groundwater quality and predicts the value of a variable  
141 at an unsampled point by an average weight of the observed variables (Ram et al. 2021). The weighting is a  
142 function of the distance between the observation point and the forecast point so that the closer points have more  
143 influence.  
144

### 145 3. RESULTS AND DISCUSSION

#### 146 3.1. Physico-chemical characteristics of groundwater

147  
148 The pH of all studied water samples were slightly acidic. More than 75 % of water from lithosoil have circumneu-  
149 tral pH. The remaining 25 % of samples under mineral hydromorphic soil and under ferralitic soil are more acidic.  
150 The lower pH values are attributed to CO<sub>2</sub> carried by precipitation which recharges groundwater through infiltra-  
151 tion. The dissolution of this entity produce carbonic acid and decrease pH value (Huang, Ma 2019, Miller 1987).  
152 High acidity might be associated to organic acid issued from decomposition of vegetation (Zakaria et al. 2015);  
153 when vegetation decomposes through biologic and microbiologic activity, organic acids such as humic acid, fulvic  
154 acid, and tannic acid can be released into the surrounding environment.

155 The EC indicates mineralization degree of water. A significant variation of these parameter is observed for samples  
156 under the same soil type: between 330  $\mu\text{S.cm}^{-1}$  and 1670  $\mu\text{S.cm}^{-1}$  for samples under mineral hydromorphic soil,  
157 between 250  $\mu\text{S.cm}^{-1}$  and 960  $\mu\text{S.cm}^{-1}$  for samples under ferralitic soil and between 470  $\mu\text{S.cm}^{-1}$  to 1050  $\mu\text{S.cm}^{-1}$   
158 for samples under lithosoil. EC values respect the standard (3000  $\mu\text{S.cm}^{-1}$ ) for drinking water recommended by

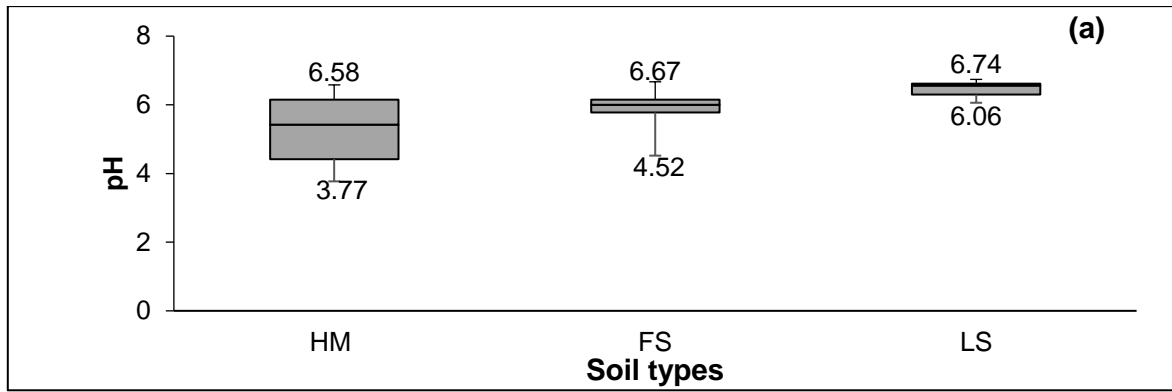
159 Environmental Ministry in Madagascar. Highly mineralized water contains high amount of  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  as for sam-  
160 ples under hydromorphic soil ( $1670 \mu\text{S}\cdot\text{cm}^{-1}$ ) (**Figure 4**). This could origin from anthropogenic activities such as  
161 agricultural, commercial and domestic which make water unsuitable for human consumption. Atmospheric dep-  
162 osition contribute also in increasing the amount of  $\text{Cl}^-$  in groundwater and a weakly acid water could increase  
163  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  concentrations by dissolving mainly carbonate minerals; These two processes rise groundwater EC  
164 (Huang, Ma 2019).

165 Turbidity measures the clarity of water, the majority of groundwater samples are characterized by low turbidity,  
166 less than 5 NTU (Nephelometric Turbidity Unit), limit value required for drinking water by Environmental Ministry  
167 Malagasy (*NORME DE POTABILITE MALAGASY 2004*). Thus, turbid water was found on some wells under ferralitic  
168 soil, it might be caused by silt, inorganic matter such as clay, organic matter like decaying plant material, dissolved  
169 organic compounds, and microscopic organisms such as algae or bacteria.

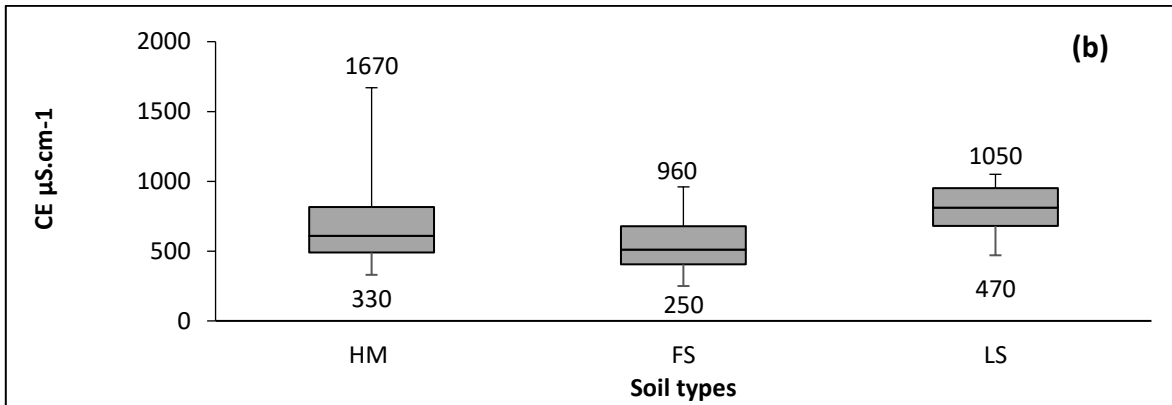
170 Only one sample from well under hydromorphic soil contain an excess of  $\text{Mg}^{2+}$ . All the amount of the other ions  
171 in each sample respect standard values of drinking water ( $\text{Ca}^{2+} = 200 \text{ mg/l}$ ,  $\text{Mg}^{2+} = 50 \text{ mg/l}$ ,  $\text{Cl}^- = 250 \text{ mg/l}$  and  
172  $\text{SO}_4^{2-} = 250 \text{ mg/l}$ ) (**Figure 5**). A correlation coefficient greater than 0.5 implies a significant degree of positive  
173 correlation. EC presents a good correlation with  $\text{Cl}^-$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ , which suggests that mineralization is mainly  
174 coming from these elements. A correlation coefficient of 0.5 between the prevalence of  $\text{SO}_4^{2-}$  and  $\text{Ca}^{2+}$ , of 0,53  
175 between potassium ( $\text{K}^+$ ) and chloride ( $\text{Cl}^-$ ), of 0,63 between  $\text{Ca}^{2+}$  and  $\text{Cl}^-$ , of 0,48 between  $\text{Mg}^{2+}$  and  $\text{Cl}^-$  suggest a  
176 moderate positive correlation (**Table 3**). This could indeed indicate that some of the sulphate ions in solution may  
177 have originated from the dissolution of minerals such as  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  (gypsum), where  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  ions are  
178 released into solution during weathering processes (**Gura, Aguro 2007**); and the presence of  $\text{Ca}^{2+}$  and  $\text{Cl}^-$  ions in  
179 solution could be coming from weathering of minerals containing calcium sulfate ( $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$ ) and calcium  
180 chloride ( $\text{CaCl}_2$ ). Anthropogenic activities such as agricultural practices, industrial processes, and urbanization can  
181 introduce magnesium and chloride ions into the environment. These ions can be transported through various  
182 pathways, including streams, where they may infiltrate into groundwater or be carried further downstream. No  
183 relationship was found between  $\text{HCO}_3^-$  and all other ions, it indicates that carbonates did not influence the pres-  
184 ence of these ions in groundwater.

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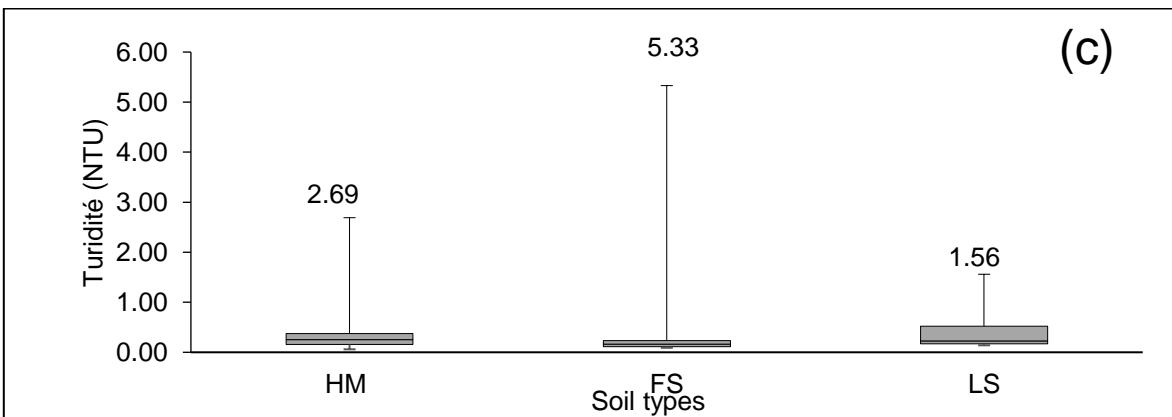
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**Figure 4: Box plot of indicators of: (a) acidity (pH), (b) conductivity (EC) and (c) turbidity (HM: Hydromorphic mineral, FS Ferralitic Soil, LS: Lithosoil)**

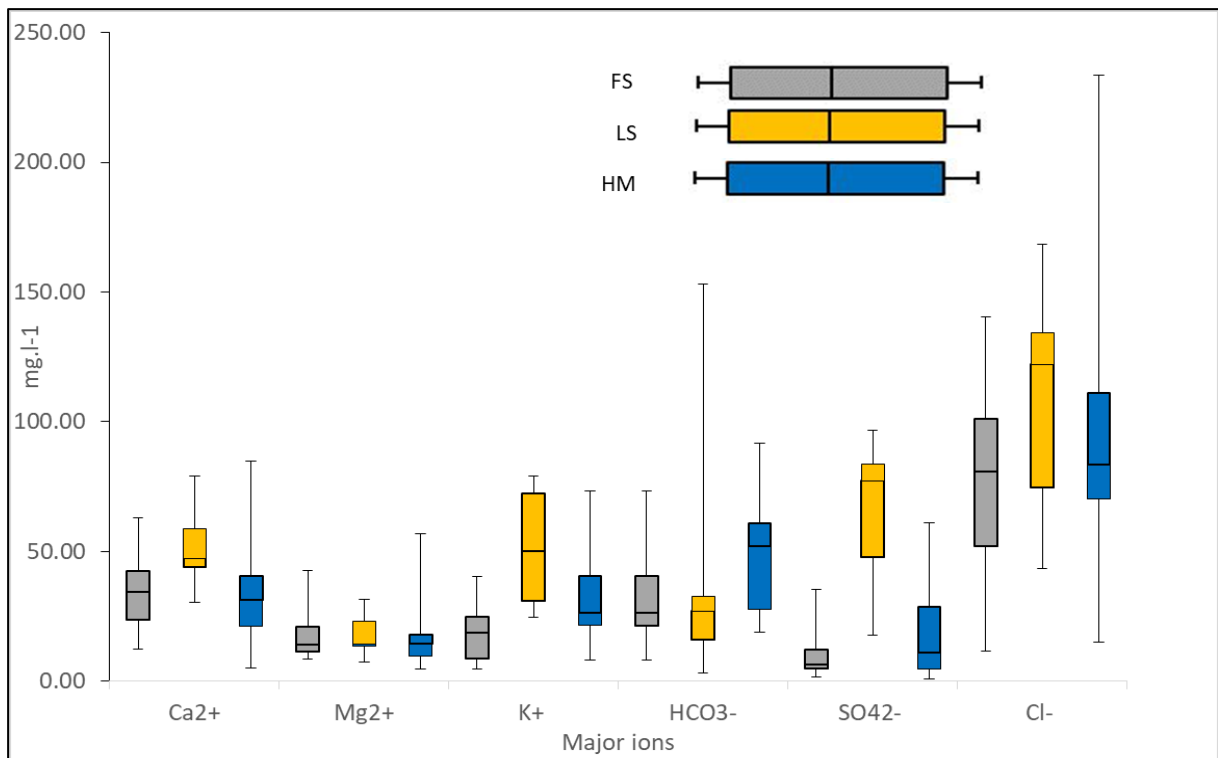


Figure 5: Box plot for the major ions (HM: Hydromorphic mineral, FS Ferralitic Soil, LS: Lithosoil)

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	<i>pH</i>	<i>CE</i>	<i>Turbidity</i>	<i>HCO<sub>3</sub><sup>-</sup></i>	<i>TH</i>	<i>Ca<sup>2+</sup></i>	<i>Mg<sup>2+</sup></i>	<i>SO<sub>4</sub><sup>2-</sup></i>	<i>Cl<sup>-</sup></i>	<i>K<sup>+</sup></i>
<i>pH</i>	1									
<i>CE</i>	-0.09	1.00								
<i>Turbidity</i>	0.11	-0.12	1.00							
<i>HCO<sub>3</sub><sup>-</sup></i>	0.52	0.27	0.48	1.00						
<i>TH</i>	0.11	0.72	-0.02	0.11	1.00					
<i>Ca<sup>2+</sup></i>	0.29	0.68	0.06	0.23	0.93	1.00				
<i>Mg<sup>2+</sup></i>	-0.12	0.65	-0.11	-0.04	0.90	0.67	1.00			
<i>SO<sub>4</sub><sup>2-</sup></i>	0.35	0.48	-0.04	0.24	0.44	0.54	0.24	1.00		
<i>Cl<sup>-</sup></i>	0.08	0.83	0.07	0.39	0.61	0.63	0.48	0.47	1.00	
<i>K<sup>+</sup></i>	0.10	0.69	-0.06	0.35	0.39	0.47	0.23	0.69	0.53	1.00

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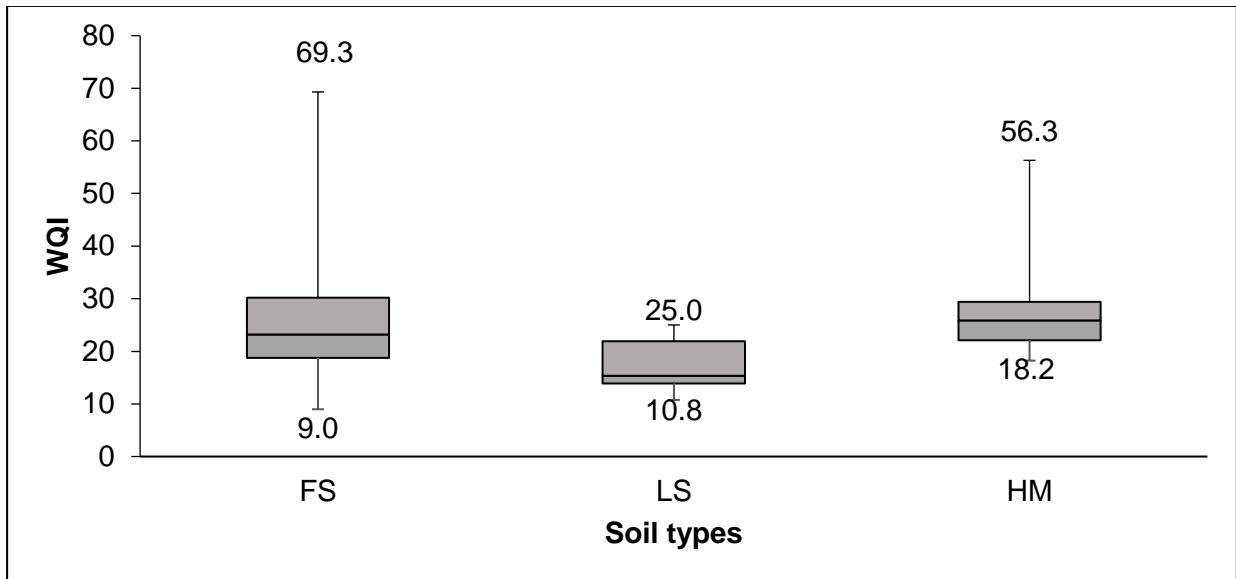
Table 3: Pearson Correlation between physico-chemical parameters

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### 3.2. Spatial distribution of water quality

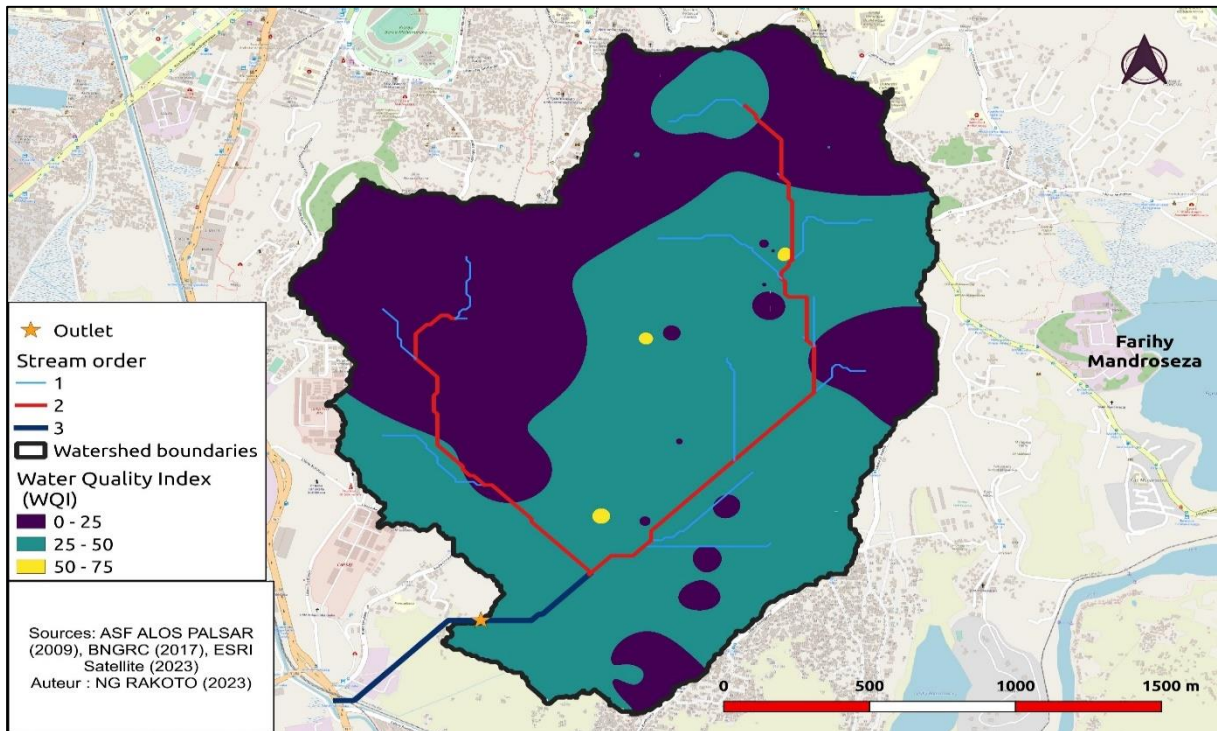
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199 The WQI was used to aggregate diverse parameters and their dimension into a single spatial map (figure 7). More  
 200 than 75% of groundwater samples analyzed have a WQI ranging between 9.0 and 50. These samples were pre-  
 201 dominantly found under lithosoil (Figure 6). They are classified as exhibiting good to excellent quality and are  
 202 suitable for drinking, irrigation and industrial uses. Less than 25% from wells under ferralitic and hydromorphic  
 203 soils have WQI range between 50 and 75, they are not suitable for drinking use. They are mainly located in low  
 204 altitude.



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**Figure 6: Box plot of WQI** (HM: Hydromorphic mineral, FS Ferralitic Soil, LS: Lithosoil)



208  
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**Figure 7: Spatial distribution of the water quality**

### 210 3.3. Hydro chemical facies

211

212 Piper diagram shows three facies hydro-chemical types (**Figure 8**) with domination of Chloride for the anions and

213 Calcium or no domination for the cations:

214 • Calcium – Chloride facies (type 1) for 44 samples of groundwater: Calcium-Chloride in groundwater oc-  
215 curs rarely, in continental groundwater systems. Chloride ions in groundwater of this type may originate  
216 from atmospheric deposition. These ions reach the groundwater through precipitation infiltration re-  
217 charge. This ion is commonly used as tracers in water cycle and are helpful in estimating water recharge  
218 processes. (Huang, Ma 2019).

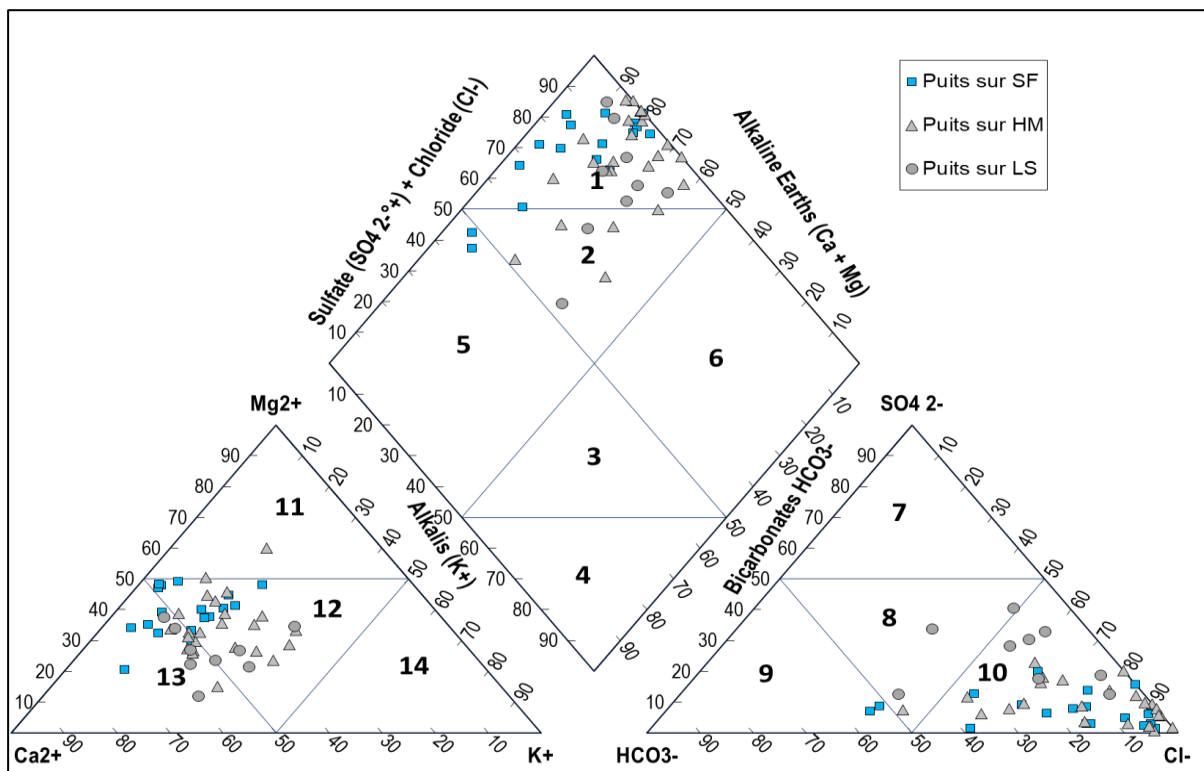
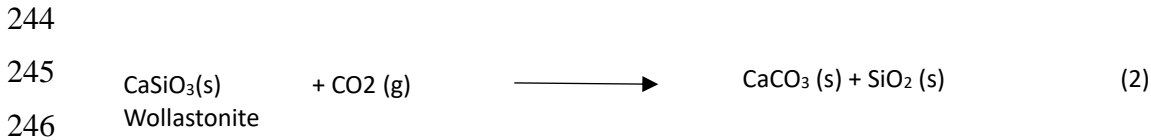
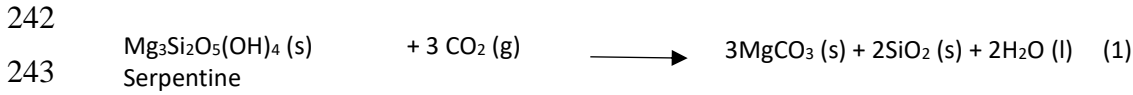
219 • Calcium-Magnesium-Chloride facies (type 2) for six samples of groundwater: it is characterized by water  
220 with high amount of Calcium and Magnesium ( $Mg^{2+} > Ca^{2+}$ ). These ions originate from complex rocks rich  
221 in calco-magnesian minerals such as scapolites, pyrites, and mica that are also rich in chlorides (Zakaria  
222 et al. 2015).

223 • Calcium – Magnesium – Bicarbonate facies (type 5) for two samples of groundwater under ferralitic soil:  
224 Infiltrating atmospheric precipitation and the dissolution of silicate minerals within the ferralitic soil con-  
225 tribute to the recharge of the aquifers. This process involves water percolating through the soil and rock  
226 layers, increasing dissolved ions along the way. As the groundwater interacts with the surrounding soil  
227 and rock formations, ions exchange occurs. This process involves the replacement of certain ions in the  
228 water with others present in the soil or rock minerals. In this case, the transition from a Ca-Mg-Cl facies  
229 to a Ca-Mg- $HCO_3^-$  facies suggests that chloride ions ( $Cl^-$ ) are being replaced by bicarbonate ions ( $HCO_3^-$ )  
230 through ion exchange reactions. (Nur, Ishaku, Yusuf 2012)

231 For Ca-Cl, Ca-Mg-Cl and Ca – Mg –  $HCO_3^-$  facies, major cations  $Ca^{2+}$  and  $Mg^{2+}$  into the water from various geological  
232 sources, particularly carbonates and clay minerals such as kaolinite, smectites, and illites. When water interacts  
233 with these minerals, either through weathering or dissolution processes, the cations present in the minerals,  
234 including  $Ca^{2+}$  and  $Mg^{2+}$ , can be released into solution, affecting the composition of the water (Huang, Ma 2019).

235 Silicate minerals, which are abundant in the Earth's crust, can weather and dissolve when exposed to weak car-  
236 bonic acid, a product of the dissolution of carbon dioxide ( $CO_2$ ) in rainwater. This process is known as carbonation  
237 or carbonic acid weathering. As silicate minerals weather, they release various ions, including silica  $SiO_3^{2-}$  calcium  
238 ( $Ca^{2+}$ ), magnesium ( $Mg^{2+}$ ), and other elements into the water. Serpentine and wollastonite, two silicate minerals,

239 release these ions by mineral carbonation which can be describe by reactions 1 and 2. These ions can then be  
 240 transported by groundwater, increasing the concentration of dissolved silica and other elements in the ground-  
 241 water (Nur, Ishaku, Yusuf 2012).



247  
 248 **Figure 8: Groundwater facies**

249 **Diamond:** 1: Ca-Cl type; 2 : Ca-Mg-Cl (Mixed) type; 3: Ca-K-HCO<sub>3</sub><sup>-</sup>(Mixed) type; 4 : K – HCO<sub>3</sub><sup>-</sup> type ; 5: Ca – Mg –  
 250 HCO<sub>3</sub><sup>-</sup> type; 6: K– Cl type;

251 **Two triangles:** Cations and anions dominant: 7: Sulphate; 8 and 12: no dominant type; 9: Bicarbonate; 10: Chlo-  
 252 chloride; 11: Magnesium; 13: Calcium; 14: Potassium

## 253 4. CONCLUSION

254 This study highlights the groundwater quality within a specific watershed, focusing on various parameters includ-  
 255 ing pH, electrical conductivity (EC), turbidity, major anions (SO<sub>4</sub><sup>2-</sup>, Cl<sup>-</sup>, HCO<sub>3</sub><sup>-</sup>), major cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup>), pH,  
 256 and the Water Quality Index (WQI).  
 257



258 The findings indicate that most of the groundwater from wells under lithosoil meets good quality standards suit-  
259 able for drinking purposes, constituting 75% of the sampled wells. However, a portion of wells (less than 25%)  
260 under ferralitic and mineral hydromorphic soils are deemed suitable only for agricultural use but not potable.  
261 Additionally, wells located at lower altitudes are more susceptible to pollution, rendering them unsuitable for  
262 drinking.

263 The study identifies three facies types within the watershed: Calcium-Chloride (Ca-Cl) facies, Calcium-Magne-  
264 sium-Chloride (Ca-Mg-Cl) facies, and Calcium-Magnesium-Bicarbonate (Ca-Mg-HCO<sub>3</sub><sup>-</sup>) facies, with chloride and  
265 calcium predominating.

266 Future research will focus on understanding the impact of climatic parameters on groundwater quality in the  
267 studied area, indicating a commitment to further investigation and potential mitigation strategies to address any  
268 identified issues.

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