



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

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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 (Ca^{2+} , Mg^{2+} , and K^{+}), and major anions (SO_4^{2-} , Cl^{-} , and 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 ferrallitic 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 (Ca^{2+} , Mg^{2+} et K^+) et les anions majeurs (SO_4^{2-} , Cl^- et 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 ferralitiques 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.

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

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

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

The current study focuses on analyzing the physicochemical properties of groundwater to understand the influences of natural and human activities. By conducting geochemical analyses using the Piper diagram, the study aims to determine hydrochemical facies and elucidate the presence of various ions and salts. The spatial distribution of the Water Quality Index (WQI) within these hydro chemical facies is examined to provide valuable insights for aquifer management (Ahoussi et al. 2013).

2. MATERIAL AND METHODS

2.1. Description of study area

The watershed covers 21 fokontany (smallest political subdivision in Madagascar) in Antananarivo, with a total area of 4,16 km². It was delineated from ASF ALOS PALSAR – Digital Elevation Map (Figure 1) using hydrological processing tool in GRASS-GIS. It lies between latitudes -18,9472306°S; -18,9193111°S and longitudes 47,5225889°E; 47,5438889°E. The highest elevation, approximately 1 433 m, is observed in the fokontany of Manjakamiadana where the queen's palace is located. Sewerage and storm water are collected in the lowland of the watershed, reach the outlet (47, 52900844°E, -18, 94124730°S) and discharging into Ikopa River in Andronrakely Saropody. The majority of the city's inhabitants get their water supply from standpipes rarely from wells. Groundwater are mainly used for domestic and permaculture watering activities.

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

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

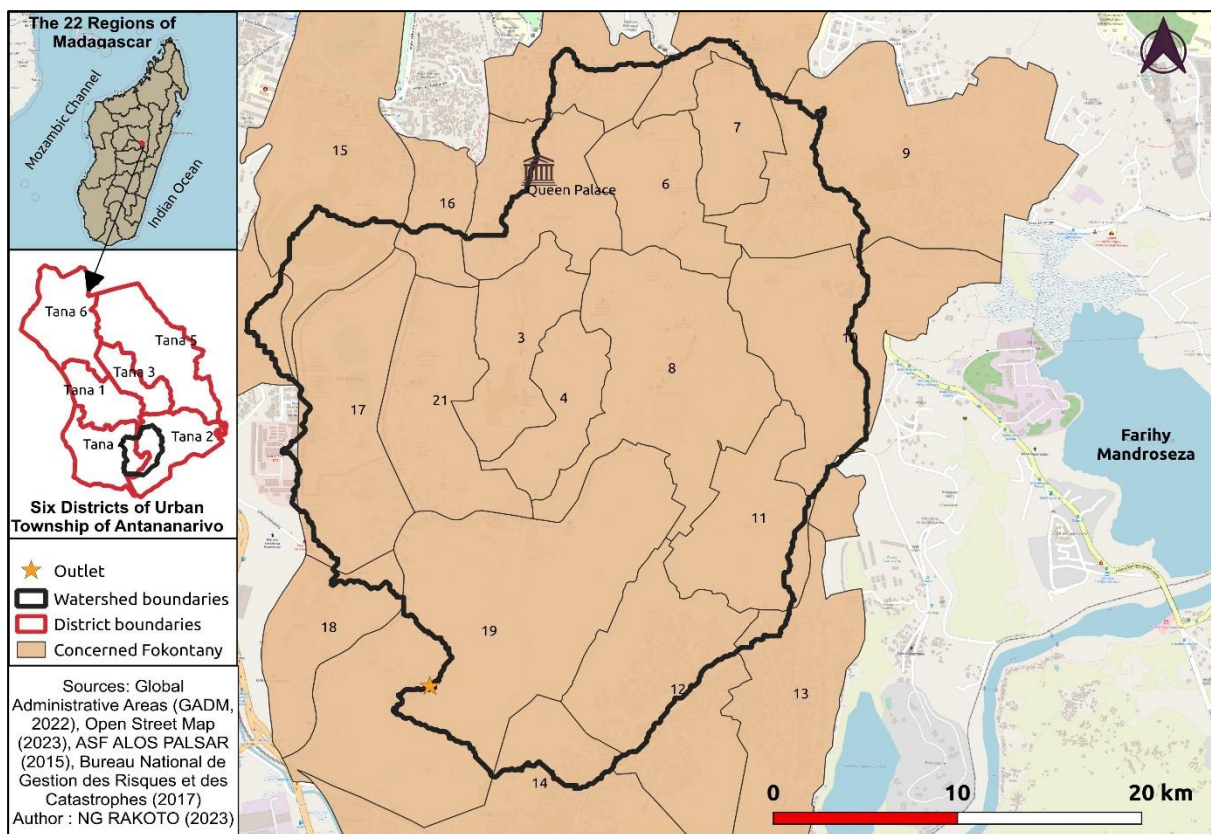


Figure 1: Watershed localization in Antananarivo Madagascar

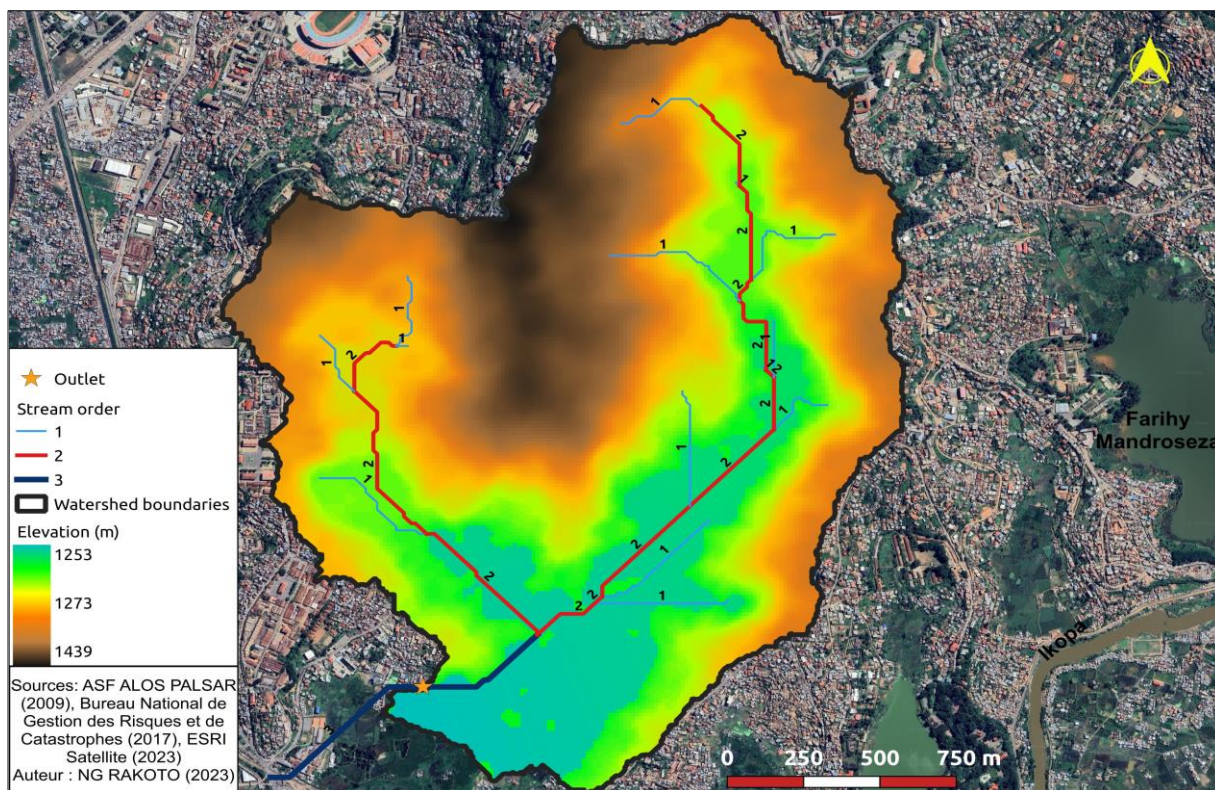


Figure 2: Elevation and stream order characteristics of the watershed

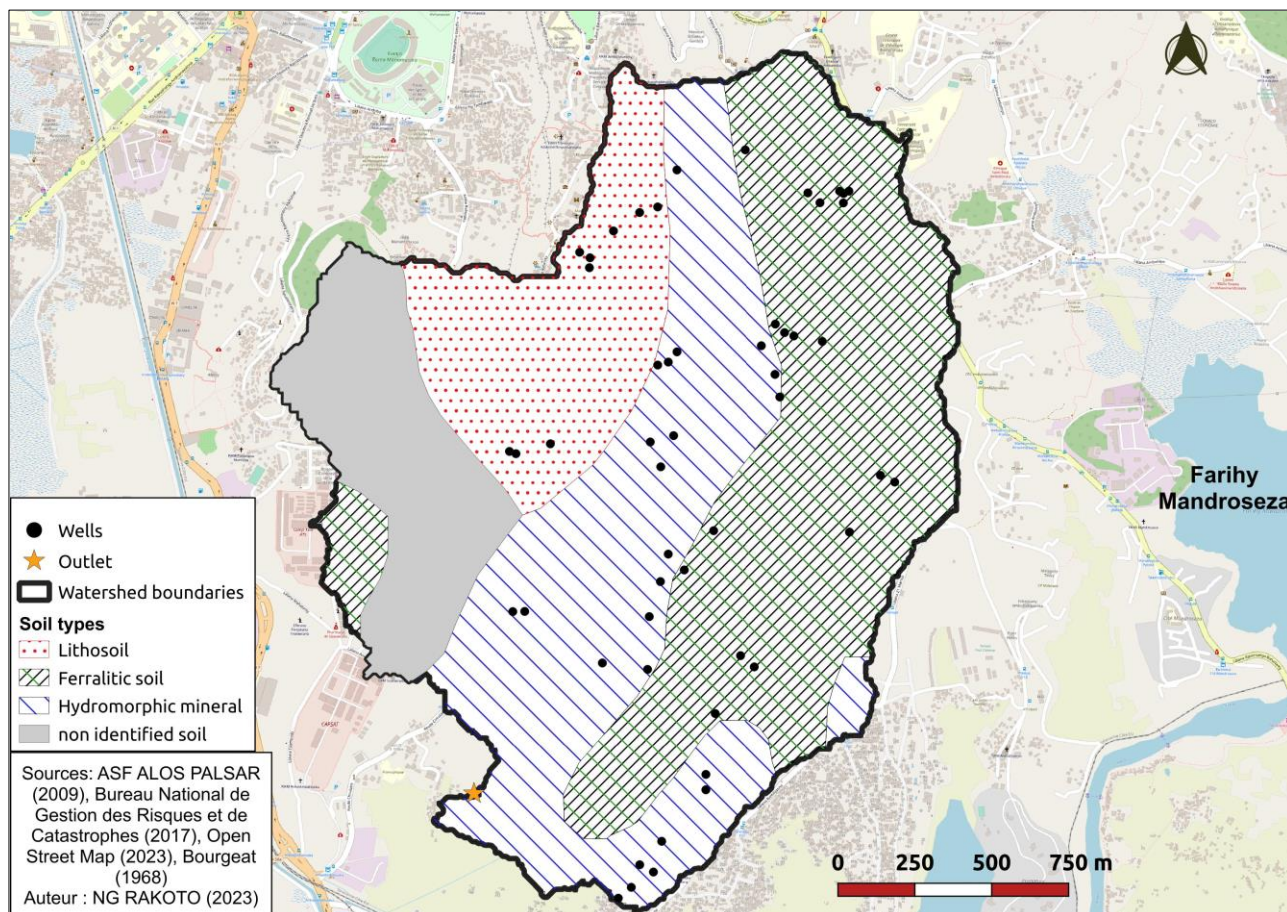


Figure 3: Soil types characteristic of the watershed

2.2. Water quality analysis

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 PolyEthylen 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

Table 1: Number of wells per soil types

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

using a turbidimeter HANNA. The bicarbonate (HCO_3^-) was analysed by Gran titration method using HCl ($0,1 \text{ mol.l}^{-1}$). The Hardness or TH (an indication of concentration of Ca^{2+} and Mg^{2+} dissolved in water), calcium (Ca^{2+}) and magnesium (Mg^{2+}) were measured by EDTA – Complexation and the potassium (K^+) by HANNA photometer. The procedure of determination of sulphate (SO_4^{2-}) amount in water involve its precipitation by barium chloride, followed by stabilization with TWEEN 20 solution. The homogeneous suspensions were measured with a spectrophotometer at 650 nm. The chloride was measured by volumetric method based on Mohr method using silver nitrate (Ag NO_3) and potassium chromate (K_2CrO_4).

Descriptive statistic using excel tool such as boxplot was employed for data statistical analysis. Major cations (K^+ , Mg^{2+} , Ca^{2+}) and major anions (HCO_3^- , SO_4^{2-} , Cl^-) were plotted on Piper diagram used to visualize and describe the groundwater quality.

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

Step 1: Weighting: Ten parameters such as pH, EC, Turbidity, hardness (TH), Ca^{2+} , Mg^{2+} , K^+ , SO_4^{2-} , Cl^- and HCO_3^- were considered, and relative weights are assigned to each parameter which can be calculated as:

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

Wi: Relative weight for each parameter

wi: weight assigned for each parameter

n: number of parameters selected

Step 2: calculating rating scale

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

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

Q_i : Rating scale value

C_i : parameter value

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

Si: Standard value

Step 3: Aggregation and Producing WQI

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

$$Sli = Wi * Qi$$

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

Si: sub-index parameters

Qi: Rating scale value based on amount of ith parameter

n: number of the parameter

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

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		

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

2.3. Hydrochemical properties analysis

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

2.4. Spatial analysis

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

3. RESULTS AND DISCUSSION

3.1. Physico-chemical characteristics of groundwater

The pH of all studied water samples were slightly acidic. More than 75 % of water from lithosoil have circumneutral pH. The remaining 25 % of samples under mineral hydromorphic soil and under ferralitic soil are more acidic. The lower pH values are attributed to CO₂ carried by precipitation which recharges groundwater through infiltration. The dissolution of this entity produce carbonic acid and decrease pH value (Huang, Ma 2019, Miller 1987). High acidity might be associated to organic acid issued from decomposition of vegetation (Zakaria et al. 2015); when vegetation decomposes through biologic and microbiologic activity, organic acids such as humic acid, fulvic acid, and tannic acid can be released into the surrounding environment.

The EC indicates mineralization degree of water. A significant variation of these parameter is observed for samples 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, 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 $\mu\text{S.cm}^{-1}$ for samples under lithosoil. EC values respect the standard (3000 $\mu\text{S.cm}^{-1}$) for drinking water recommended by

Environmental Ministry in Madagascar. Highly mineralized water contains high amount of Cl^- and SO_4^{2-} as for samples under hydromorphic soil ($1670 \mu\text{S}\cdot\text{cm}^{-1}$) (**Figure 4**). This could origin from anthropogenic activities such as agricultural, commercial and domestic which make water unsuitable for human consumption. Atmospheric deposition contribute also in increasing the amount of Cl^- in groundwater and a weakly acid water could increase Ca^{2+} and Mg^{2+} concentrations by dissolving mainly carbonate minerals; These two processes rise groundwater EC (Huang, Ma 2019).

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

Only one sample from well under hydromorphic soil contain an excess of Mg^{2+} . All the amount of the other ions 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 $\text{SO}_4^{2-} = 250 \text{ mg/l}$) (**Figure 5**). A correlation coefficient greater than 0.5 implies a significant degree of positive correlation. EC presents a good correlation with Cl^- , K^+ , Mg^{2+} , Ca^{2+} , which suggests that mineralization is mainly coming from these elements. A correlation coefficient of 0.5 between the prevalence of SO_4^{2-} and Ca^{2+} , of 0,53 between potassium (K^+) and chloride (Cl^-), of 0,63 between Ca^{2+} and Cl^- , of 0,48 between Mg^{2+} and Cl^- suggest a moderate positive correlation (**Table 3**). This could indeed indicate that some of the sulphate ions in solution may have originated from the dissolution of minerals such as $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (gypsum), where Ca^{2+} and SO_4^{2-} ions are released into solution during weathering processes (**Gura, Aguro 2007**); and the presence of Ca^{2+} and Cl^- ions in solution could be coming from weathering of minerals containing calcium sulfate ($\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$) and calcium chloride (CaCl_2). Anthropogenic activities such as agricultural practices, industrial processes, and urbanization can introduce magnesium and chloride ions into the environment. These ions can be transported through various pathways, including streams, where they may infiltrate into groundwater or be carried further downstream. No relationship was found between HCO_3^- and all other ions, it indicates that carbonates did not influence the presence of these ions in groundwater.

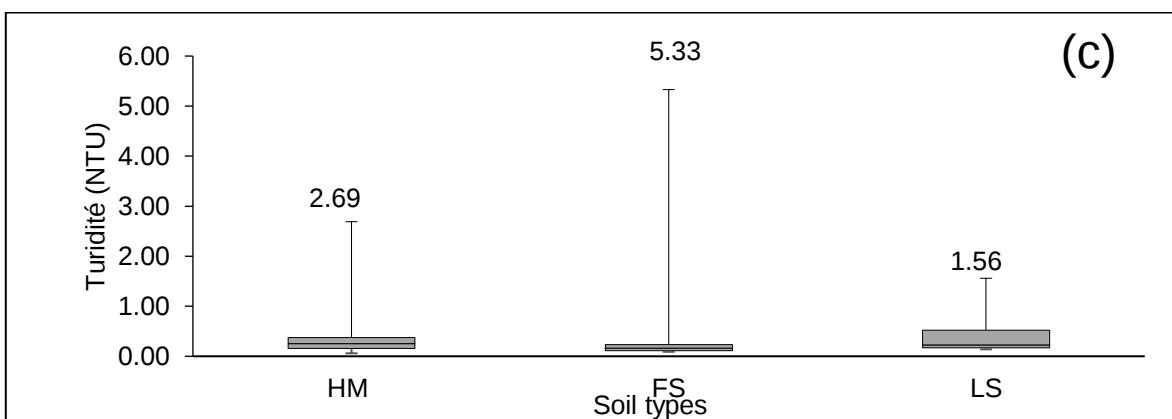
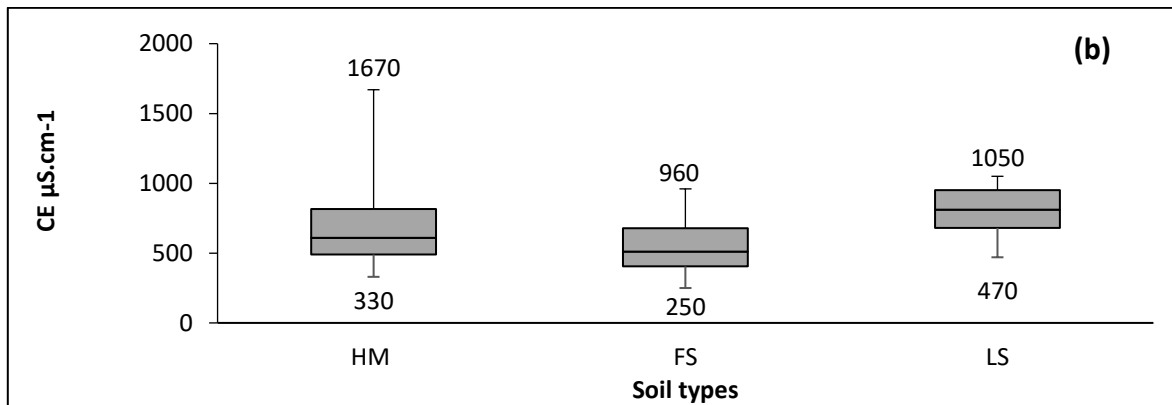
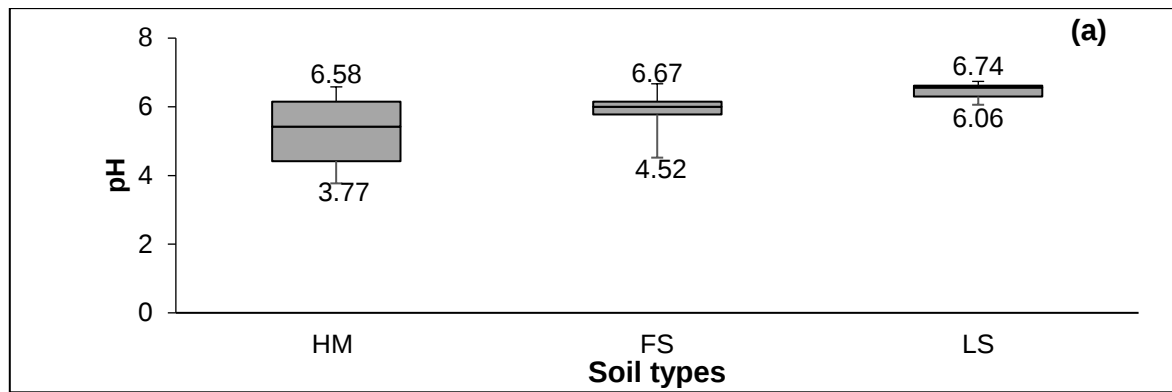


Figure 4: Box plot of indicators of: (a) acidity (pH), (b) conductivity (EC) and (c) turbidity (HM: Hydromorphic mineral, FS Ferralitic Soil, LS: Lithosoil)

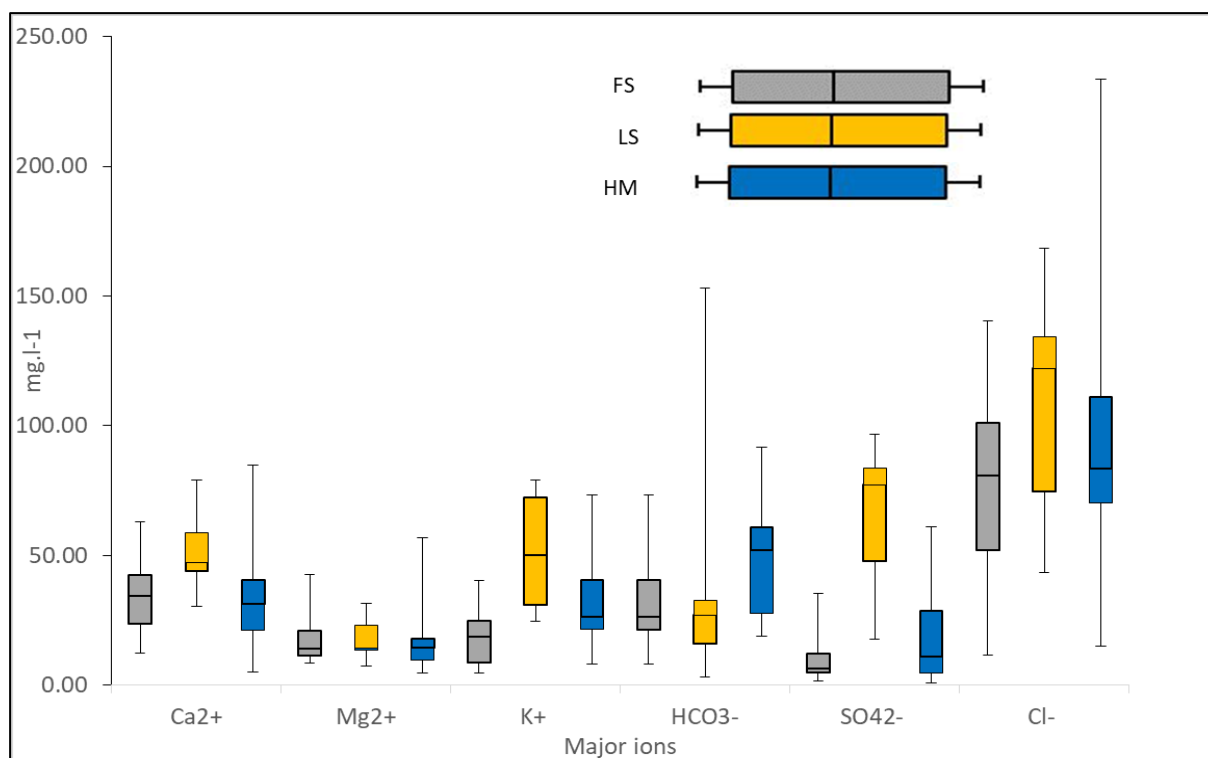


Figure 5: Box plot for the major ions (HM: Hydromorphic mineral, FS Ferrallitic Soil, LS: Lithosoil)

	<i>pH</i>	<i>CE</i>	<i>Turbidity</i>	<i>HCO₃⁻</i>	<i>TH</i>	<i>Ca²⁺</i>	<i>Mg²⁺</i>	<i>SO₄²⁻</i>	<i>Cl⁻</i>	<i>K⁺</i>
<i>pH</i>	1									
<i>CE</i>	-0.09	1.00								
<i>Turbidity</i>	0.11	-0.12	1.00							
<i>HCO₃⁻</i>	0.52	0.27	0.48	1.00						
<i>TH</i>	0.11	0.72	-0.02	0.11	1.00					
<i>Ca²⁺</i>	0.29	0.68	0.06	0.23	0.93	1.00				
<i>Mg²⁺</i>	-0.12	0.65	-0.11	-0.04	0.90	0.67	1.00			
<i>SO₄²⁻</i>	0.35	0.48	-0.04	0.24	0.44	0.54	0.24	1.00		
<i>Cl⁻</i>	0.08	0.83	0.07	0.39	0.61	0.63	0.48	0.47	1.00	
<i>K⁺</i>	0.10	0.69	-0.06	0.35	0.39	0.47	0.23	0.69	0.53	1.00

Table 3: Pearson Correlation between physico-chemical parameters

3.2. Spatial distribution of water quality

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

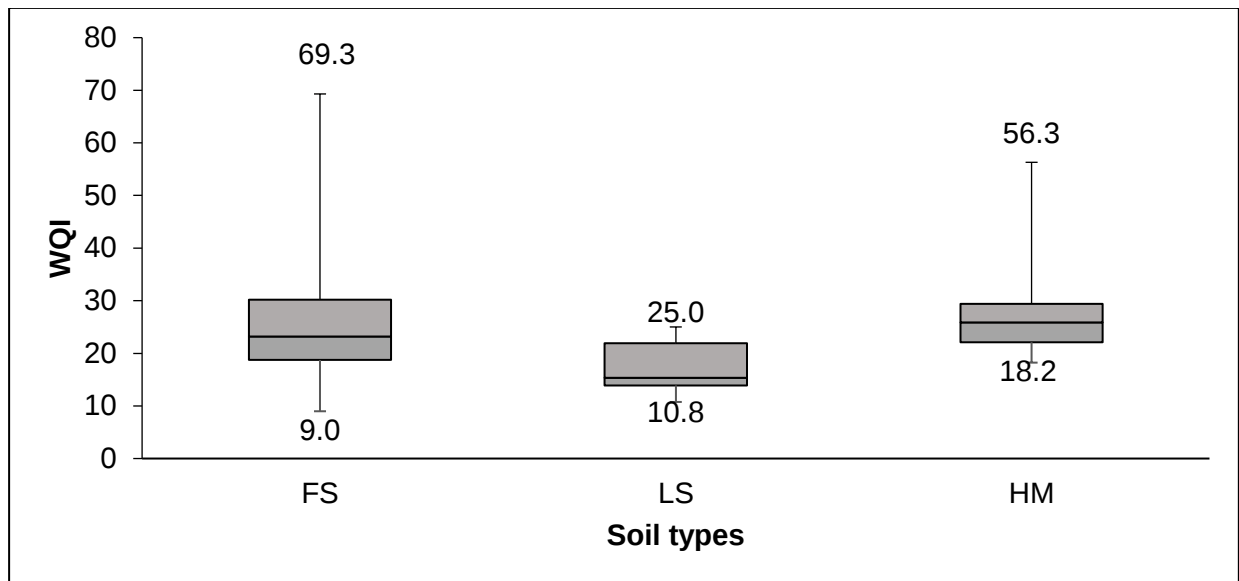


Figure 6: Box plot of WQI (HM: Hydromorphic mineral, FS Ferralitic Soil, LS: Lithosoil)

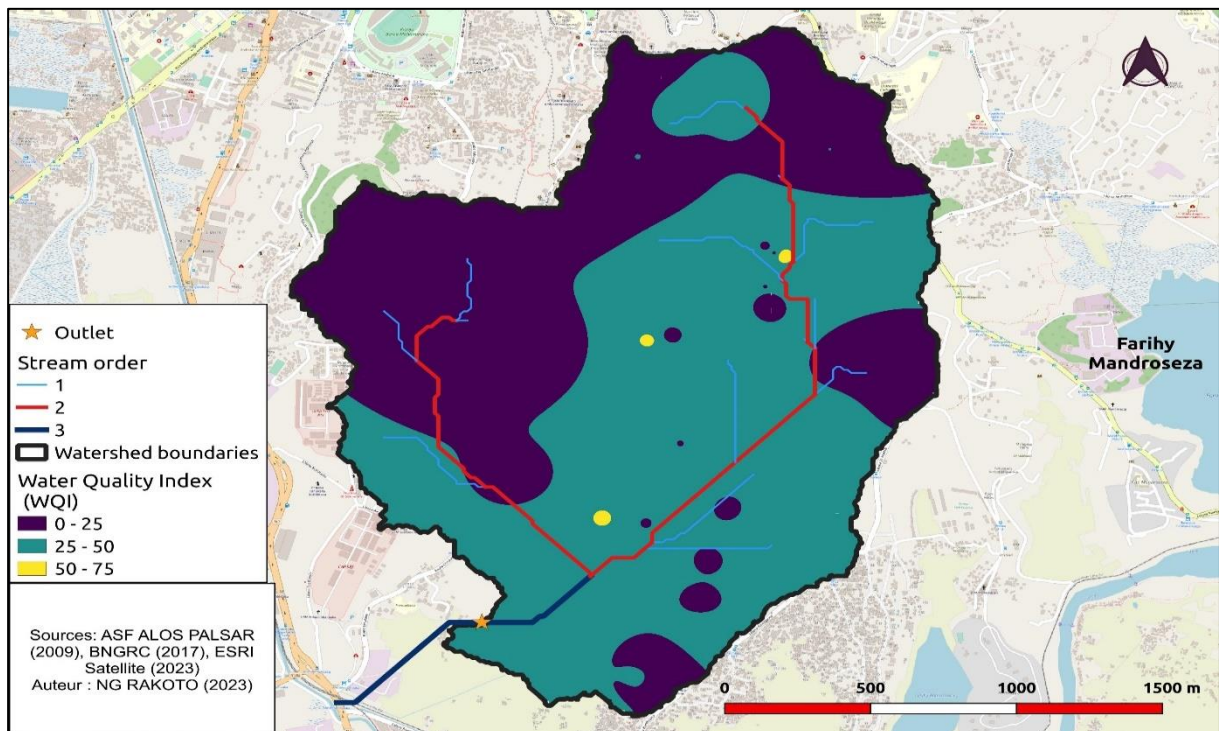


Figure 7: Spatial distribution of the water quality

3.3. Hydro chemical facies

Piper diagram shows three facies hydro-chemical types (**Figure 8**) with domination of Chloride for the anions and Calcium or no domination for the cations:

- Calcium – Chloride facies (type 1) for 44 samples of groundwater: Calcium-Chloride in groundwater occurs rarely, in continental groundwater systems. Chloride ions in groundwater of this type may originate from atmospheric deposition. These ions reach the groundwater through precipitation infiltration recharge. This ion is commonly used as tracers in water cycle and are helpful in estimating water recharge processes. (Huang, Ma 2019).
- Calcium-Magnesium-Chloride facies (type 2) for six samples of groundwater: it is characterized by water with high amount of Calcium and Magnesium ($Mg^{2+} > Ca^{2+}$). These ions originate from complex rocks rich in calco-magnesian minerals such as scapolites, pyrites, and mica that are also rich in chlorides (Zakaria et al. 2015).
- Calcium – Magnesium – Bicarbonate facies (type 5) for two samples of groundwater under ferralitic soil: Infiltrating atmospheric precipitation and the dissolution of silicate minerals within the ferralitic soil contribute to the recharge of the aquifers. This process involves water percolating through the soil and rock layers, increasing dissolved ions along the way. As the groundwater interacts with the surrounding soil and rock formations, ions exchange occurs. This process involves the replacement of certain ions in the water with others present in the soil or rock minerals. In this case, the transition from a Ca-Mg-Cl facies to a Ca-Mg- HCO_3^- facies suggests that chloride ions (Cl^-) are being replaced by bicarbonate ions (HCO_3^-) through ion exchange reactions. (Nur, Ishaku, Yusuf 2012)

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 sources, particularly carbonates and clay minerals such as kaolinite, smectites, and illites. When water interacts with these minerals, either through weathering or dissolution processes, the cations present in the minerals, including Ca^{2+} and Mg^{2+} , can be released into solution, affecting the composition of the water (Huang, Ma 2019). Silicate minerals, which are abundant in the Earth's crust, can weather and dissolve when exposed to weak carbonic acid, a product of the dissolution of carbon dioxide (CO_2) in rainwater. This process is known as carbonation or carbonic acid weathering. As silicate minerals weather, they release various ions, including silica SiO_3^{2-} calcium (Ca^{2+}), magnesium (Mg^{2+}), and other elements into the water. Serpentine and wollastonite, two silicate minerals,

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

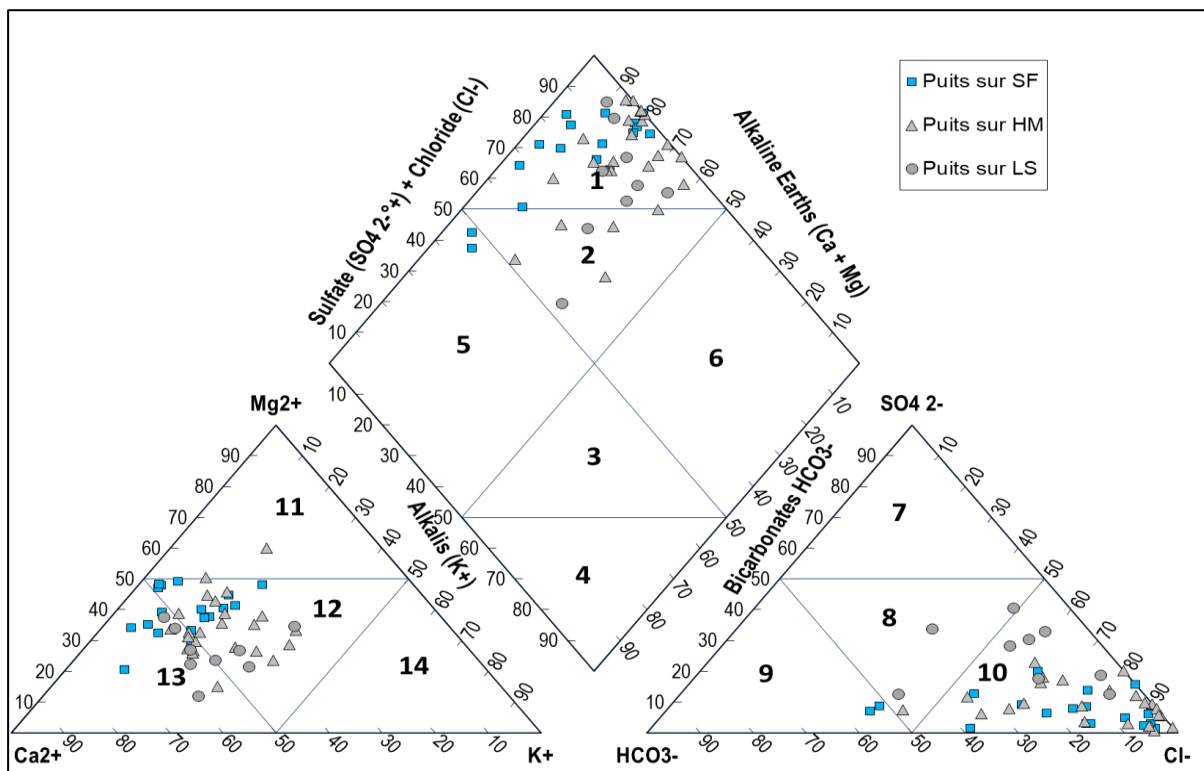
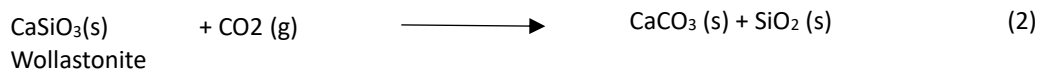


Figure 8: Groundwater facies

Diamond: 1: Ca-Cl type; 2 : Ca-Mg-Cl (Mixed) type; 3: Ca-K-HCO₃⁻(Mixed) type; 4 : K – HCO₃⁻ type ; 5: Ca – Mg – HCO₃⁻ type; 6: K– Cl type;

Two triangles: Cations and anions dominant: 7: Sulphate; 8 and 12: no dominant type; 9: Bicarbonate; 10: Chloride; 11: Magnesium; 13: Calcium; 14: Potassium

4. CONCLUSION

This study highlights the groundwater quality within a specific watershed, focusing on various parameters including pH, electrical conductivity (EC), turbidity, major anions (SO₄²⁻, Cl⁻, HCO₃⁻), major cations (Ca²⁺, Mg²⁺, K⁺), pH, and the Water Quality Index (WQI).

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-HCO₃⁻) 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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