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Hydrogeochemical Characterization Of Water Resources In Volcano-Sedimentary Basin Of Antsirabe, Vakinankaratra Region-Central Highland Of Madagascar

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Abstract: This paper deals with the survey of the water resources vulnerability in the volcano-sedimentary deposit of Antsirabe, Central Highland of Madagascar. The purpose of this study is to determine the hydrogeochemical characteristics of water, in order to understand their chemistry and assess their quality. Additionally, we aim to identify the origin of their mineralization and the mechanisms behind different types of pollution.

The water sampling method consists of collecting water samples from specific wells, springs, boreholes and surface water. These samples were then subjected to in-situ physico-chemical measurements and laboratory chemical analyses.

The collected waters from four types of aquifers exhibit heterogeneity, ranging from low to moderate and excessive mineralization. We can distinguish five chemical facies based on the dominant chemical elements: calcium bicarbonate, calcium-magnesium bicarbonate, sodium-potassium bicarbonate, and sodium-potassium chloride.

In some samples, the nitrate concentration exceeds both the Malagasy potability standard and the WHO guideline. The values vary between 50,88mg/L (AB18) and 232,65mg/L (AB29). Additionally, water samples collected from the industrial zone of Ambohimena and Antsampanimahazo, show high chloride content varying between 37,66mg/L (AB18) and 132,92mg/L (AB29). Two possible explanations for this excess are proposed: first, non-compliance with construction standards for the water source, specifically the distance from latrines; second, the lithology of aquifer, groundwater flow, and geographical location relative to the industrial zone.

Overall, the groundwater in this basin is weakly mineralized, reflecting the lithological nature of the aquifer. Excessive mineralization in some water samples indicates contamination, either from anthropogenic sources (animal or human feces) or industrial activities.

Key words: Aquiferous, Facies, Minéralisation, Water Quality, Pollution, Antsirabe.

I. INTRODUCTION

The protection and the preservation of groundwater become an important topic that preoccupies scientists and engineers who work in water resource management these last 30 years [1]. These precious vital resources are influenced by environmental and human constrained. Most urban contamination originates from dispersed sources, such as in situ sanitation and sewer, which leads to increases in salinity, nutrient and pathogen groundwater concentrations [2]. Like in the Dhaka city, where the discharge of untreated wastewater rich in dyes, heavy metals, and other chemicals into the surrounding rivers has led to severe pollution, affecting the quality of drinking water and public health [3]. Urban aquifers are therefore vitally important, but very fragile, easily contaminated and could take a long time to be repaired and restored.

The Antsirabe city has considerable economic potential, evident through the presence of numerous industries, mainly concentrated in the southern area, particularly in Ambohimena [4]. The industrial sector in Antsirabe is includes various types of industries, such as agro-food industries, textile industries, manufacturing industries, artisanal industries and processing industries, as well as mechanical industries. The city experienced significant demographic growth till 2004, with its population increasing from 126 062 habitants in 1993 to 180 665 in early 2004, representing a 43% growth over a decade. This expansion is primarily attributed to urbanization and positive migration flows [5]. The city of Antsirabe and its surroundings are suffering from the negative impacts linked to the population growth, industrial development and environmental degradation on the quantity and especially the quality of groundwater.

Previous works showed that the Antsirabe basins are negatively impacted by human activities [6]. Their survey of pollutant parameters, physical and chemical quality of water showed an excess of some chemical parameter concentration in water samples such as nitrate (50mg/L to 167, 96 mg/L) and potassium (51,47mg/L). These high concentrations of potassium and nitrate originate from the decomposition of organic matter of animal origin, due to the storage of manure and other organic waste near the wells, as well as from industrial and urban discharges [7] [6] . They deserve an extreme protection in order to maintain groundwater quality and ensure its perpetuation [8]. That why this study will take place, with the aim of determining the overall quality of these waters and assessing the risk of pollution in the basin. To attend its objective, the determination of the hydrogeochemical characteristics of the water, identification of water mineralization is the first way to detect the presence of pollutants in the water resources using standard methods for analyzing chemical parameters.

II. METHODOLOGIES

1. Presentation of the study area

1.1. Climate context

The basin of Antsirabe is part of the high earth of Madagascar, situated on the central part of the island from 163 km of the capital. Antsirabe city is overing an area of 180 km², located at an altitude approximately 1500 m. With 1330, 6 mm of rainfall average. Characterized by a tropical climate and considered as the coolest zone of the island, marked by two very distinct seasons, dry season from May to September of which cold with a minimum temperature until 0°C and a maximum of 25 °C. A hot and rainy season of the month is in October to April. The temperatures during this period are generally range from 10°C to 30°C (Service of hydrology and meteorology).

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SURVEY ZONE LOCALIZATION

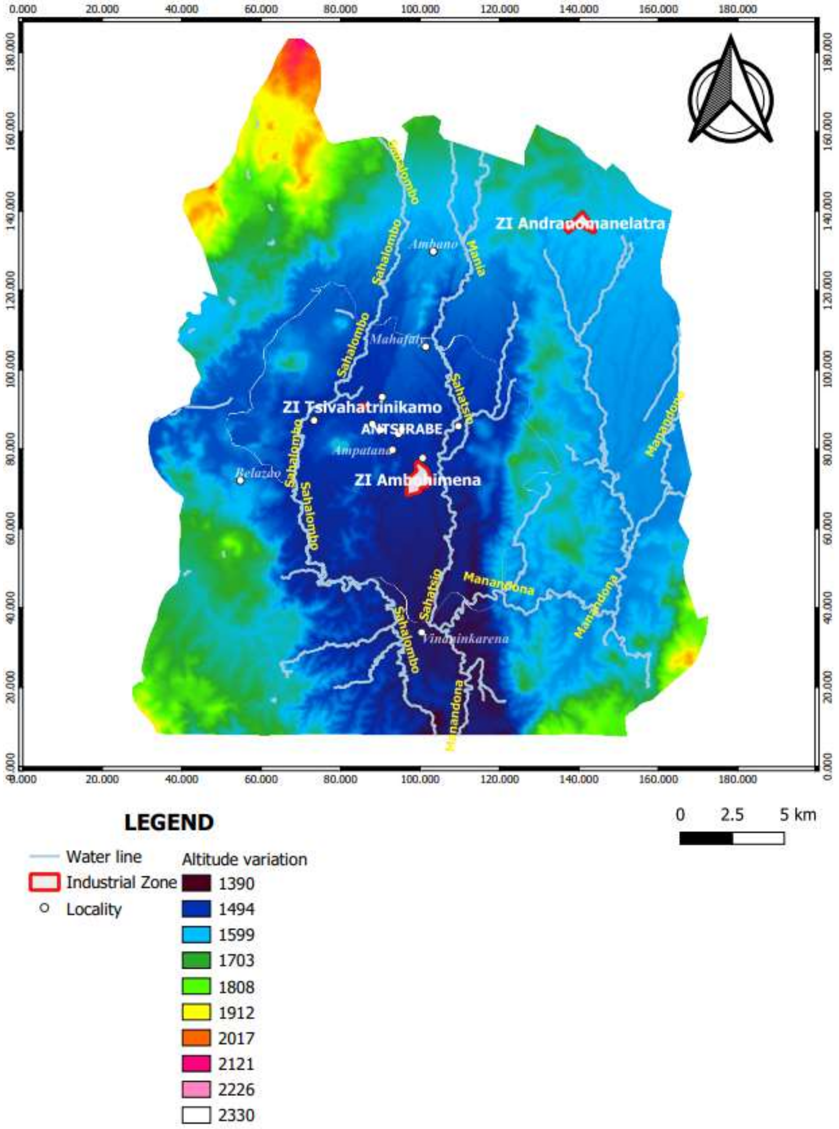

Fig-1: Survey zone localization map (Source: BD500 FTM: Foibe Tao-tsarintany Malagasy)

1.2. Geological context

The Antsirabe basin, located in a zone of lithospheric thinning [9], presents a complex geology with various geological formations, including a Precambrian basement overlain by sedimentary and volcanic formations. This complexity is due to the East-West extension of the central region of Madagascar [10] leading to strong volcanic activity that disrupts the hydrographic network and promotes sedimentary deposits [11].

The study area is part of the Precambrian basement of Madagascar, belonging to the Antananarivo domain [12]. It is composed of migmatites, invaded by granitic intrusions [13]. The Vavavato granite, rich in minerals, constitutes the northern and western boundary of the basin [14].

The Ankaratra volcanic massif covers the ancient basement with Pliocene trachytic and rhyolitic domes and more recent basaltic flows. The Plio-Quaternary extension tectonics favored volcanic activity and the formation of faults, with four phases of volcanic eruptions recorded, ranging from the Pliocene to the Oligocene [15]. The formation of the Ankaratra massif during the Miocene constitutes a natural barrier to the hydrographic network of the region. This facilitates sediment deposition, with the earliest deposits dating from the Pliocene, consisting of conglomerates with trachyte pebbles or metamorphic basement [11]. These are overlain by intercalated lacustrine deposits consisting of the volcanic flows and projections from the Pliocene and Pleistocene [16] [11] [17] 18].

SURVEY ZONE GEOLOGICAL MAP

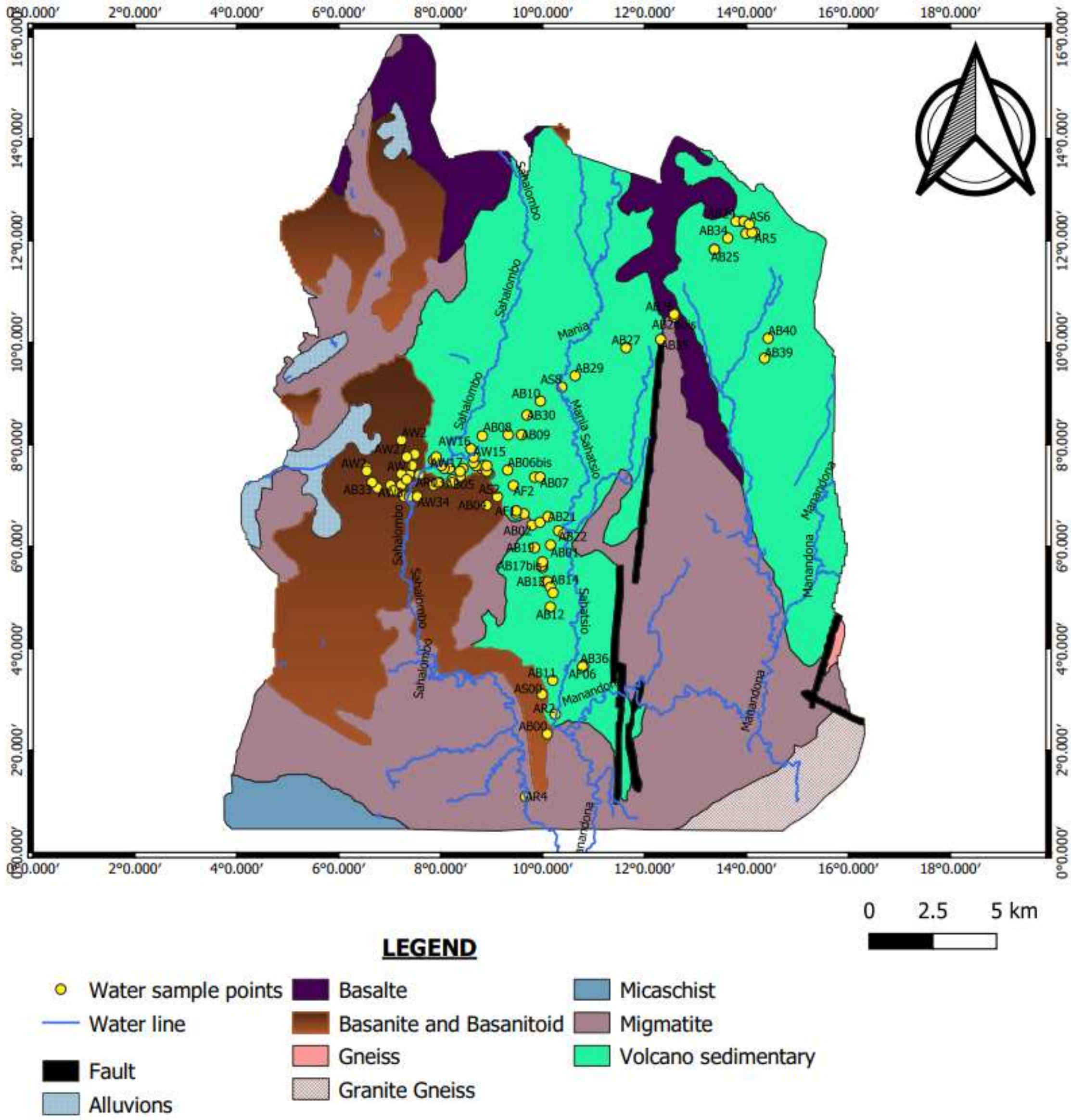

Fig-2: Geological map of survey zone (modified by PGRM, 2012, O. Sracek and al, 2019)

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2.3. Hydrological and hydrogeological settings

The hydrographic network of the zone is constituted by three permanent rivers that constitute the three under-basins respectively of which in the East Manandona, Sahatsio in the center and Sahalombo to the west [19]. Also, the three lakes: Andraikiba, Andranobe (source of provision in drinking water of the city) and Andranomafana (discharge of the city waste waters).

Groundwater in this area originates from volcanosedimentary and alluvial aquifers located beneath the city of Antsirabe, as well as from fractured bedrock and volcanic massif aquifers ([11] [7] [20]. Recharge of the aquifers mainly occurs through precipitation and river drainage. These waters have low mineralization but are exposed to pollution.

Being part of the hydrogeological area of the high earth the aquiferous are constituted by alluviums, the heterogeneous volcano-sedimentary sediments and the aquiferous of fractured rock [21]. During the dry season, the watertable shows on a surface coast of 1m. It retires progressively during the dry season, active until 8 and 12 m of depth according to the place.

2.4. Water sampling and laboratory analysis methods

Water samples were collected during three sampling campaigns between 2017 and 2019. The first campaign took place during the low water period in May 2017, during which 16 samples were collected, including 11 wells, 2 thermal water boreholes, one spring, and 2 rivers. The second campaign was conducted during the interseason in October 2018, allowing the collection of 40 samples, including 32 wells (5 from the first period and 27 new), 6 springs, borehole and river. These samples were distributed across industrial zones, urban concentrations, and different types of aquifers in the region. The last campaign was carried out during the high water period in December 2019, with the collection of 28 samples. These included 21 wells (13 previously visited during previous campaigns and 8 new wells located in the industrial zones of Andranomanelatra, Tsivatranikamo, Antsampanimahazo, and Ambohimena), 4 springs, one borehole, one river, and a sample from Andraikiba lake. In total, 84 samples were collected across all three campaigns.

During field work, 50 mL plastic bottle was used for *water* sampling intended for major ions analysis. Samples intended for cation analysis preserved with one drop of nitric acid. The bromocresol and phenolphthalein were used for in situ alkalinity measurement. The collected samples were preserved in a cooler after filtration with 0.40 µm microfilter. Field measurements include certain physico-chemical parameters such as pH, redox potential, temperature, electrical conductivity, and dissolved oxygen, measured with the HACH HQd/IntelliCAL Multimeter. Alkalinity is measured by titration with 0.16N or 1.6N sulfuric acid in the presence of green bromocresol and phenolphthalein.

In the laboratory, major ions such as Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}, Cl^{-}, $SO4^{2-}$, NO^{3-} are analyzed by ion chromatography (Dionex ICS 1100) at the isotopic hydrology laboratory of INSTN Madagascar (Institut National des Sciences et Techniques Nucléaires). Heavy metal such as Fe is analyzed by flame chromatography at the X-ray Fluorescence Technique laboratory of INSTN Madagascar. The samples in 2019 only undergoes the Fe analyses. For data processing, we used software such as Excel-Stat, QGIS, and Diagram.

III. RESULTS

Physical parameters

The table 1 regroups the statistical summary and the physical dataset of each water sample collected during the three campaigns. The calculation is based on 16 samples for the year 2017, 40 samples for 2018, and 28 samples for 2019.

Table-1: Statistical results of the physical parameters

Year	Type		EC (µS/cm)	pH	Eh (mV)	T°C	OD (mg/L)	TDS (mg/L)
2017	groundwater	Minimum	71.3	5.11	-45.6	20	0.59	118
		Maximum	559	7.79	100	21.7	7.62	577
		Average	411.83	6.62	37.11	20.63	4.14	276.58
		Standard deviation	134.98	0.78	35.21	1.00	2.16	120.68
	Surface water	Minimum	162	7.14	-18.8	23.5	6.12	124
		Maximum	171.5	7.29	-10,7	26.3	7,23	223
		Average	166.75	7.215	-16.5	24.9	6.68	173.5
		Standard deviation	6.72	0.11	5.73	1.98	0.78	70.00
	thermal water	Minimum	2550	7.66	-65.2	37.5	3.73	2873
		Maximum	6180	8.08	-41,7	40.9	4.82	4753
		Average	4365	7.87	-53.45	39.2	4.275	3813
		Standard deviation	98.99	0.30	5.73	2.40	0,77	324.56
2018	groundwater	Minimum	22.00	5.61	-69	20.10	0.12	28.00
		Maximum	927.00	7.96	19.8	30.90	11.85	836.00
		Average	290.51	6.91	-14.22	24.18	3.88	194.15
		Standard deviation	243.89	0.50	23.74	2.37	2.90	150.14
	surface water		59	7.27	15.12	21.40	7.87	61
2019	groundwater	Minimum	22	5.22	-59	19.8	0.97	17
		Maximum	854	6.9	75.3	23.7	19.7	510
		Average	266.50	6.36	-1.5	21.42	5.70	144.08
		Standard deviation	236	0.38	1.02	34.8	5.83	113.28
	surface water	Minimum	53	6.45	-18.7	19.9	3.42	111
		Maximum	106	7.8	15.8	24.3	7.47	366
		Average	79.5	7.12	-1.45	22.1	5.45	238.50
		Standard deviation	37.48	0.95	3.11	24.4	2.86	180.31

3.2 Chemical parameters

The chemical characterization of the different types of water in the zone is based on the analysis of the major ions, the table 2 regroups the statistical results of chemical parameters analyses in waters samples. The result of Fe analyses show that this element is not detectable in the majority of water point. Except the well AB19 and stream AR5.

Table -2: Statistical results of chemical parameters

Year	Type	Etat	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO3 (mg/L)	Cl (mg/L)	SO4 (mg/L)	NO3 (mg/L)
2017	groundwater	Minimum	15.44	3.51	8.12	2.45	1.5	3.25	1.35	1.43
		Maximum	42.19	29.19	92.61	28.90	395.00	106.99	3.30	48.56
		Average	24.92	11.08	29.59	9.54	166.03	17.98	2.03	15.38
		Standard deviation	1.09	9.92	23.89	0.75	106.81	5.64	0,67	15.01
	surface water	Minimum	11.38	4.84	13.21	6,15	71.74	4.07	2.19	2.75
		Maximum	12.92	5.39	35.13	7.21	142.00	12.04	12.05	3.99
		Average	12.15	5.12	24.17	6.68	106.87	8.06	7.12	3.37
		Standard deviation	1.09	0.38	15.50	0.75	49.68	5.64	6.97	0.88
	thermal water	Minimum	116.85	62.21	84.51	746.97	1500	273.47	17.07	72.13
		Maximum	138.86	71.90	160.59	1430.69	2230.56	510.79	25.26	184.44
		Average	127.86	67.06	122.55	1088.83	1865.28	392.13	21.17	128.29
		Standard deviation	15.56	6.85	53.80	483.46	516.58	167.81	5.79	79.42
2018	groundwater	Minimum	2.581	0.58	1.89	0.42	1.56	2.72	0.74	2.75
		Maximum	126.92	49.44	84.92	25.44	360	132.93	20.6	232.65
		Average	18.59	7.98	18.79	6.42	66.63	23.94	3.70	40.36
		Standard deviation	20.64	10.31	20.00	5.23	75.71	29.64	3.65	48.57
	surface water		2.58	1.40	12.06	1.86	32.00	5.12	1.48	4.58
2019	groundwater	Minimum	0.42	0.46	1.58	1.43	2.05	2.71	0.38	2.24
		Maximum	104.55	8.92	49.09	23.12	342.74	89.17	5.88	74.83
		Average	16.64	3.58	14.64	5.72	52.19	19.94	1.38	29.97
		Standard deviation	22.90	2.36	11.48	5.45	74.51	20.17	1.10	24.87
	surface water	Minimum	13.86	3.11	4.51	1.39	73.81	6.6	0.97	2.22
		Maximum	84,7	6,89	5,47	2,56	259,29	7,65	1,38	3,36
		Average	49,28	5	4,99	1,975	166,55	7,125	1,175	2,79
		Standard deviation	50,09	2,67	0,68	0,83	131,15	0,74	0,29	0,81

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2.3. Chemical facies

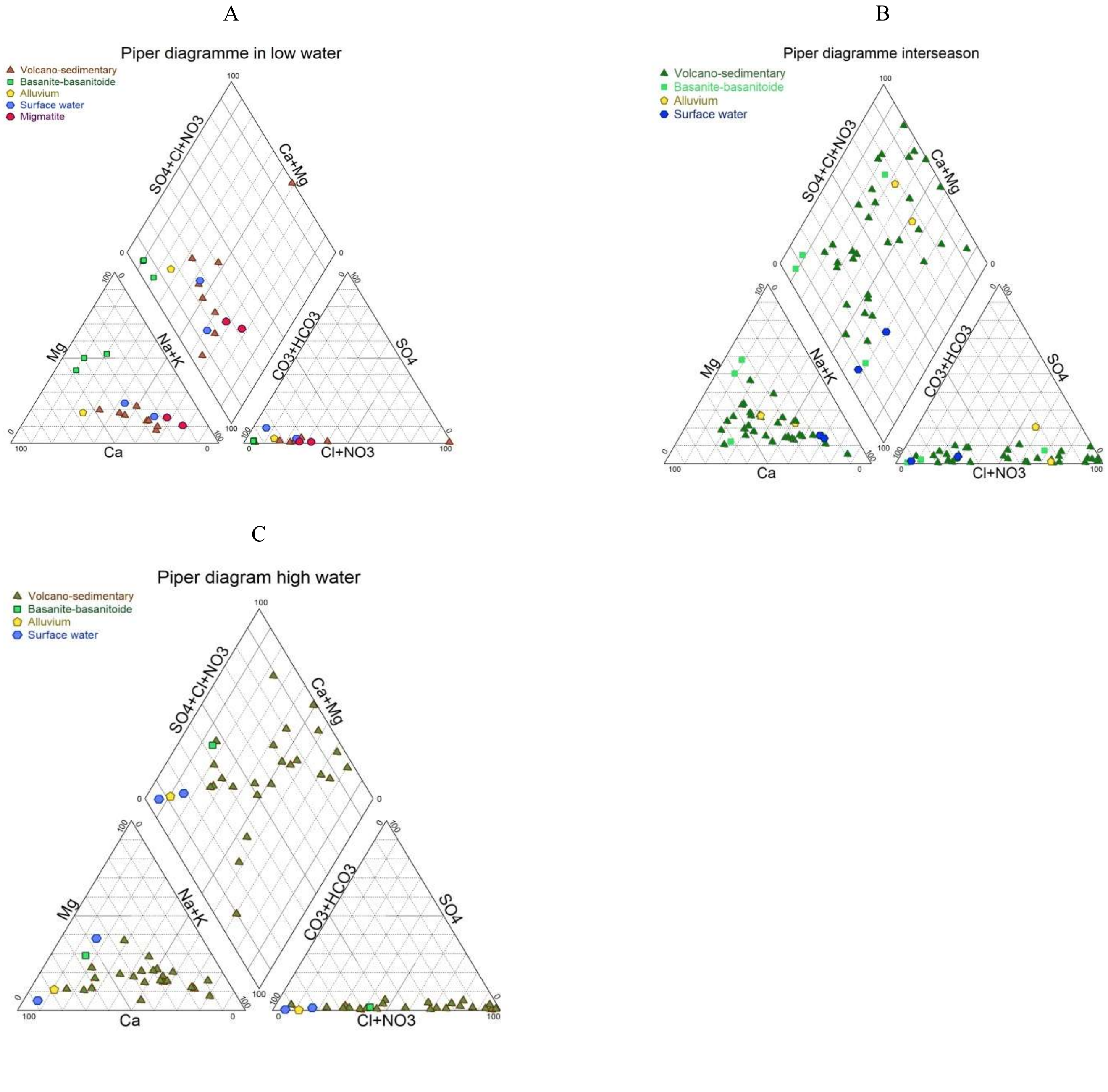

Fig-3: Piper diagram in low water (A), inter season (B), high water (C)

IV. DISCUSSION

3.1. Physical parameters

The sampled waters have a Total Dissolved Solids (TDS) generally low for fresh water (TDS < 600 mg/L): with little variation between the low, interseason and high-water periods, but a significant difference between soft and thermal water. In general, the fresh waters are weakly mineralized, having an average that varies between 144.08 mg/L and 276.58 mg/L for underground water, and between 61 mg/L and 238.50 mg/L for surface water. For thermal water, TDS can reach up to 3813 mg/L.

This already demonstrates that these two types of water originate from different aquifers. The schematic explanation of thermomineral water circulation by Ref [11] shows that thermomineral water comes from a deep fractured bedrock aquifer. Alternatively, it could come from a volcanic aquifer fractured due to the systematic presence of cooling joints and fracture patterns [22]. Deep fractures or faults often act as conduits and discharge points for the thermomineral groundwater [23]. This facilitates water interaction with various mineral in geological formations. High temperatures also promote chemical reactions that accelerate the dissolution of minerals from surrounding rocks and contribute to the water's mineral enrichment. Meanwhile, the freshwater aquifer in the area consists of volcano-sedimentary deposits, primarily composed of either sandy clay or cinerite [11]. It is also evident that groundwater shows higher mineralization than surface water due to water-rock interaction [24].

The average concentration of Dissolved Oxygen (DO) in the collected samples varies between 2.83 mg/L and 4.30 mg/L for underground water during the low water period, and between 4.06 mg/L and 6.03 mg/L for surface water. A few elevated values, up to 10 mg/L, have been noticed at some points such as AB27 and AS6 in Andranomanelatra area and AB31 and AS7 in Tsivatranikamo area. The average for thermal water is 3.11 mg/L. During the high water period, the average concentration increases slightly, varying between 5.70 mg/L and 12.74 mg/L for underground water, and between 5.45 mg/L and 7.87 mg/L for surface water.

During the low water period, the DO concentrations in fresh water are relatively low, indicating that the water may not be well-oxygenated during this period. The surface waters are more oxygenated, it's normal because they are in direct contact with the atmosphere. The general increase value during the high waters period, indicating that the water may be more oxygenated during this time. This probably due to a better oxygenation by the precipitations and a faster renewal of waters [25]. Interestingly, an elevated value higher than the average concentrations showed in the Andranomanelatra and Tsivatranikamo areas are suggesting that there may be localized factors influencing the oxygen levels in these areas. First the aquifer porosity, especially in aquifer with high permeability and low water tables. Next, the interaction between groundwater and oxygen in minerals of the aquifer rock can release oxygen into the water, increasing the DO concentration. Weatherage of volcanic and sedimentary layers will creating preferential paths for water, and consuming the oxygen especialy for Andranomanelatra and Tsivatranikamo.

The average DO concentration in thermal water is lower than the average concentrations in both underground and surface water during the low water period. This will be due to the circulation of hot fluids with low oxygen concentration or a mixture with deoxygenating deep waters.

The groundwaters have a pH, ranging from neutral to basic (7.03 to 7.93) in Mandaniresaka and Antsampanimahazo. But slightly acidic (4.73 to 6.70), in the industrial zone of Ambohimena and Tsivatranikamo. Surface waters have a neutral pH, varying between 6.45 and 7.80. Thermo-mineral water has a slightly basic pH, with an average of 7.79 and a maximum of 8.08. The pH of water increases with the depth of the water table.

Waters have a weakly acidic to weakly basic pH, depending on groundwater depth and the surrounding environment [22]. The waters of the volcano-sedimentary aquifer in the industrial zone of Ambohimena are generally weakly acidic, while water extracted from the migmatitic aquifer at depths greater than 30 m has a weakly basic character.

The Electrical Conductivity (EC) and TDS of water show a large variation in mineralization, from weak to excessive. The weak mineralization of waters is characteristic of water located in volcanic and volcano-sedimentary zones [26]. For the few points of water monitored over these three years, slight increases in EC and pH values have been noticed. The chemical evolution in the aquifer has caused variations in the concentration of some ionic species.

3.2. Chemical parameters

The thermal water, show an excessive mineralization compared to groundwaters and surface waters, and groundwater contains higher concentrations of chemical elements more than surface water. Among the wells, springs, and surface waters visited during these three periods, the mineralization is dominated by bicarbonate and chloride ions for anions, and sodium and calcium for cations. According to Malagasy and WHO standards, 25% of the visited wells are not potable due to the high nitrate (NO3) concentrations.

In this study area, hydrochemical facies are used to describe the main components of the water and assess its potability [27]. Chemical data are represented on a Piper diagram to facilitate this determination. Groundwater is classified into five groups based on the lithology of the aquifer: volcano-sedimentary sediment, basanite and basanitoid, alluvium, fractured migmatite and surface water (lake and river). The Piper diagram during the low water period shows four types of chemical facies:

- The majority of samples in the volcano-sedimentary aquifer and alluvial aquifer have the calcium and magnesium bicarbonate (Ca-Mg-HCO_3) facies.
- Some well water in the volcano-sedimentary aquifer with surface water and thermal water have the sodium and potassium bicarbonate (Na-K-HCO_3) facies.
- All basanit and basanitoid have a calcium bicarbonate (Ca-HCO_3) facies
- Only one well sample coded AB01in volcano-sedimentary aquifer of Ambohimena (industrial site) has the sodium chloride and potassium type (Na-Cl-K)

The Piper diagram during the interseason and high water level period shows five types of chemical facies:

- The same types of water are identified, but the water of well coded AB01 in volcano-sedimentary aquifer of Ambohimena, becomes a type of facies calcium chloride and sulphated (Ca-Cl-SO4), along with AB32 of the basanite-basanitoid aquifer and half of the wells sampled in the volcano-sedimentary aquifer.
- The other wells from this last group are sodium and potassium chloride (Na-K-Cl) facies.
- For the surface water and the spring AS6, water type are calcium bicarbonate (Ca-HCO3) facies.

The Piper diagram highlights the impact of geology on water quality, with the chemical facies of waters being due to the lithology of the aquifer [28]. During the low water period, the sampled waters show a clear dominance of sodium ions in both surface and groundwater. This confirms the interaction between these two types of water due to low flow. The sodium enrichment comes from water percolation through weathered silicate minerals like albite, as justified by the Na/Cl ionic ratio exceeding 1 [29] [30]. presumably by dissolution of Na-silicates [31]. The majority of water water facies in volcano-sedimentary aquifer have bicarbonated-magnesium type, indicating carbonate dissolution and cation exchange (Mg, Ca)/Na in the clays (Fig-4) [32].

The binary graphs in Figure 3 showing the relationship between calcium and sodium ion concentrations, illustrate the dissolution of calcium plagioclase and sodium feldspar. An increase in calcium ion concentration is often accompanied by an increase in sodium concentration, indicating a positive correlation between these two ions. Sometimes, this correlation is dominated by the process of ion exchange with clay in the aquifer [33]. In summary, the groundwater in this region shows signs of chemical reactions with the surrounding rocks, leading to the release of magnesium and sulfate, as well as a cation exchange between magnesium, calcium, and sodium.

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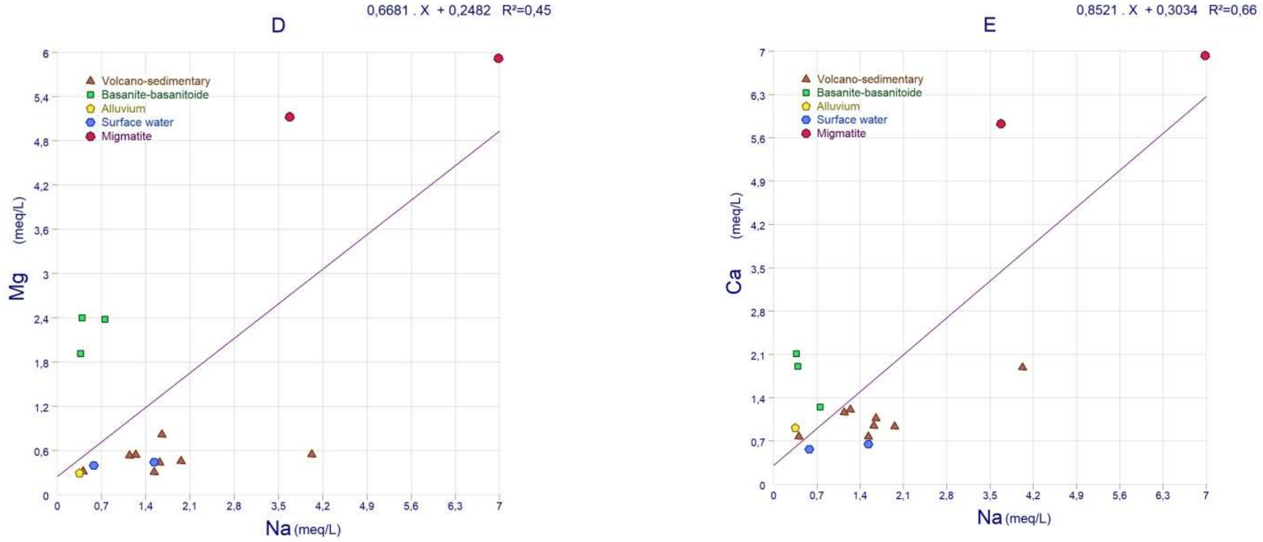

Fig-4 : Relationship between Mg vs Na (D) and Ca vs Na (E)

The water in the study area is slightly enriched in calcium especially in the high level water period. This is a characteristic of aquifers in volcanic areas [28] [26]. This enrichment is obvious view that Ca is the main constituent of igneous rocks minerals [34]. This is likely due to ion exchange between the aquifer and the underlying layer, confirmed by an average base exchange index (IEB) below 0. However, groundwater in the Tsivahatrinikamo zone is characterized by a clear dominance of Mg ions [35] as cations. The ionic report enters (Mg^{2+}) / (Ca^{2+}) in the aquifer dominated by volcanic deposit is increase until 1.8, it shows the enrichment in Mg^{2+} due to ionic exchange and by the change of the mafic minerals as the biotite [30]. A good interrelationship, between the Ca+Mg and bicarbonate (Fig-5) permits to deduct and confirm that the origin of these ions is the water-rock interaction [26].

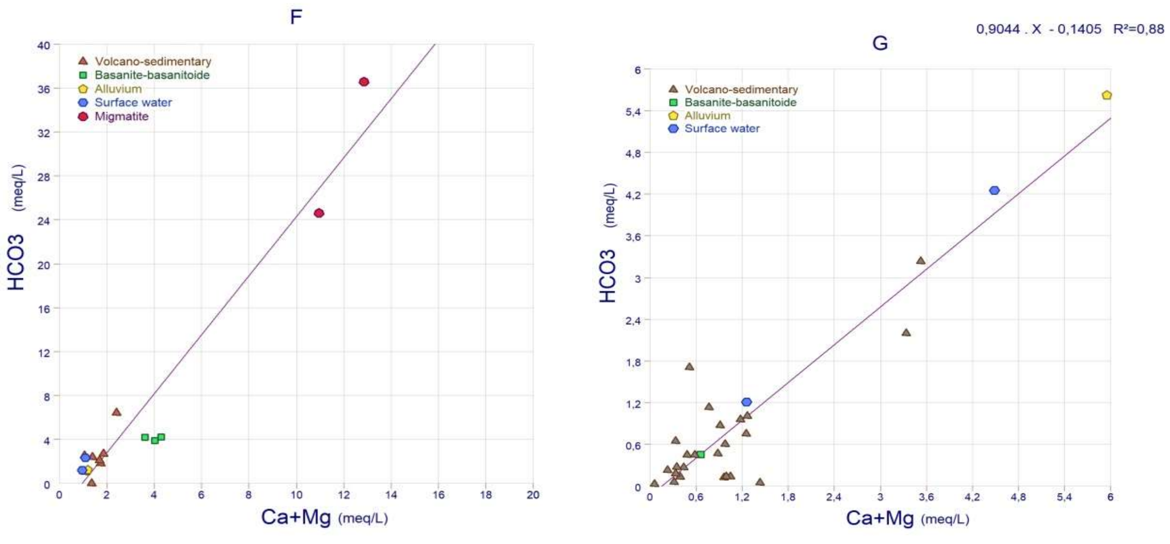

Fig-5: Relationship between HCO3 and Ca+Mg in low water (F) and high water (G)

For anions, HCO3 dominates in all, followed either by Cl or NO3 depending on the location, aquifer type, well depth and environment. Interestingly, the HCO3 concentration decreases, especially in surface water, while NO3 and Cl concentrations increases in some groundwater samples in the industrial area of Ambohimena and the wells AB28, AB29 in Antsampanimahazo.

Where, high nitrate and potassium concentrations exceeding the WHO standard were accompanied by significative chloride concentrations vary between 28.02mg/L to 132.92mg/L. Several factors can contribute to elevate these ions concentrations such as poor sanitary conditions, chemical fertilizers and industrial effluents effectively by human activity [7] [36]. The potassium concentrations in some wells exceed the WHO standard. It varies between 14.10mg/L to 25.44 mg/L. The concentration of potassium in water decrease compared with the result of the Ref [6] and [7]. These potassium concentrations were presumably supplied by industrial reject [37].

The mineralization and ionic concentration of water in the well AB28 and AB29 confirm the heterogeneity of the aquifer in the basin. These two wells are located in the same area, same geological context, same static level but the AB29 well has a depth of 1m besides. The mineralization of the water of the AB29 well is 4 times superior the one of the AB28 well. Characterized by a facies chlorinated sodium and potassium, accompanied by an excessive content in NO3. This situation already shows that the two wells capture different aquiferous.

The Cl, SO4, and K+ content are generally lower in the majority of samples, and their presence is linked to atmospheric origin and organic matter decomposition [38]. Iron is a minor element, traceable only in the water from well AB19 and stream water AR05 downstream of an industrial site. The enrichment and depletion of elements in groundwater are closely related to the aquifer's lithology. This phenomenon is governed by major reactions, including: interaction between water and carbonate rock, involving Ca and Mg exchange and base exchange between the aquifer clay and the Na-Ca or Na-Mg layer.

According to Ref [39] hypothesis on the chemical evolution of water, between the three main layers of the aquifer, most of the sampled waters come from phreatic aquifers, characterized by active groundwater flow through relatively weathered rocks. Hence, the dominance of bicarbonate ions accompanied by low TDS [34], bicarbonate ion is from infiltration of actual recharge [22]. The ionic concentration of some water points monitored over the three-year study reflects hydrochemical evolution in the aquifer. As the geology of the survey zone is characterized by sedimentary deposits in the middle of a Precambrian pedestal, it is very likely that the bicarbonate comes from the silicate weathered by the reaction of feldspar hydrolysis [31] [40].

V. CONCLUSIONS

The objective of the study is to examine the groundwater quality and understand the source of pollution. The analysis of the physical and chemical parameters of the sampled waters reveals significant variations in mineralization and pH levels across to different water types and periods. Fresh waters generally exhibit low TDS and weak mineralization, while thermal waters show much higher TDS values. The pH levels range from slightly acidic to slightly basic, influenced by the depth of the water table and the surrounding environment.

Dissolved Oxygen concentrations also vary, with notable increases during the high water period. The Electrical Conductivity and TDS measurements indicate a wide range of mineralization, reflecting the diverse geological and environmental conditions of the study area.

Chemical analysis highlights the dominance of bicarbonate and chloride ions among anions, and sodium and calcium among cations. The presence of high nitrate concentrations in some wells raises concerns about water quality, with 25% of the sampled wells exceeding safe drinking water standards. Among the five groups of water sampled in the zone, five types of chemical facies have been identified, of which the majority of waters have calcium and magnesium bicarbonate (Ca-HCO3 and Mg-HCO3) facies. Follows by the facies chlorinated calcium and sulphated, as well as the facies chlorinated sodium and potassium. Finally, the sodium and potassium bicarbonate (Na-K-HCO3) facies and the calcic bicarbonate facies. In the industrial area of Ambohimena and the urbanized zone of Antsampanimahazo some wells are contaminated by nitrate and have an alarmed concentration of chloride. It is important to supervise these levels and to take some measure to protect the quality of the drinking water.

Overall, the study underscores the heterogeneous nature of the aquifer system in the Antsirabe basin, influenced by both geological formations and human activities. Continuous monitoring and management are essential to ensure the sustainability and safety of water resources in the region.

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