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Geochemical Processes In Groundwater In Mountainous And Coastal Areas Of The Dominican Republic

Yenny Rodríguez[1], Napoleón Bergés[1], María Guadalupe Silva[1],
Australia Ramírez[2], Adriana Cabrera[3] Y Mónica Blarasin[3]
[1] *Pedro Henríquez Ureña National University (Unphu)- Dominican.*
[2] *National Geological Service Of The Dominican Republic (Sgn).*
[3] *Departament Of Geology. National University Of Río Cuarto (Unrc), Argentina*

Abstract:
Background*: Water geochemistry is essential for understanding the natural and anthropogenic processes that influence water composition, which is crucial for sustainable management. In the Caribbean, groundwater is increasingly modified by climatic factors and human activities. In the Dominican Republic, groundwater in mountainous regions like San Juan Valley typically has low salinity and elevated levels of bicarbonate due to the weathering of silicate minerals. In contrast, groundwater in coastal plains such as Azua tends to be more saline because of mineral dissolution and the potential intrusion of seawater. This study examines the chemical composition of groundwater in San Juan and Azua, interprets the geological and anthropogenic processes that affect it, and evaluates its suitability for human consumption*

Materials and Methods*: The study utilized a combination of satellite images, maps, and SGN reports, along with fieldwork, to analyze the geology and geomorphology of the region. Groundwater samples were collected from wells in Azua and San Juan, where field parameters such as pH, electrical conductivity (EC), and temperature were measured. Additionally, major ions, arsenic, and fluoride were analyzed. Hydrogeological data, including water levels, were also gathered. The geochemical processes were interpreted using molar ratio diagrams, Piper-Hill diagrams, and principal component analysis (PCA), after standardizing the data.*

Results*: In San Juan, the groundwater is predominantly fresh and classified mainly as calcium bicarbonate type, with some sodium bicarbonate waters associated with higher fluoride levels. Elevated concentrations of nitrates and chlorides in a few wells indicate possible contamination from human waste. Factor analysis has identified three main influences on the water chemistry: natural salinity from mineral weathering, potential contamination (including nitrate, chloride, sulfate, magnesium, and arsenic), and minor cation exchange processes. In Azua, the water is also fresh and primarily of the bicarbonate type, but it is more geochemically diverse. About 42% of the samples showed nitrate levels exceeding the natural background, likely due to contributions from livestock or sanitation sources. Factor analysis revealed both contamination (measured by nitrate, electrical conductivity, sulfate, and magnesium) and natural processes such as silicate weathering, halite/gypsum dissolution, calcite presence in some wells, and the mobilization of arsenic and fluoride under specific geochemical conditions.*

Conclusion: *Groundwater in San Juan is primarily fresh and classified as calcium bicarbonate type, although there is some local sodium enrichment and minor contamination from nitrates and chlorides. Additionally, arsenic may be released due to acid mine drainage associated with mining activities. In Azua, the water is more geochemically diverse, exhibiting higher and more widespread nitrate contamination stemming from human and livestock waste. While mineral dissolution adds salt to the water, there is no evidence of seawater intrusion. Understanding these local processes is crucial for protecting the quality of drinking water in both regions.*

Key Word*: Geochemistry, Sedimentary aquifer, Human water supply, Mountain ranges, Plains.*

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I. Introduction

Water geochemistry is a fundamental tool for understanding the natural processes that govern the chemical composition of water resources, with critical implications for their sustainable management and conservation [1]. Recent studies highlight the growing importance of hydrogeochemical analyses in differentiating aquifer systems based on their geological and climatic contexts, particularly in tropical regions where weathering processes and rock-water interactions strongly influence water quality [2] [3].

In Latin America and the Caribbean, groundwater resources face increasing pressure due to climate variability, anthropogenic activities, and natural geogenic processes [4], making the study of hydrogeochemical dynamics essential for ensuring water security.

In mountainous regions of the Dominican Republic, such as the Cordillera Central, groundwater interacting with igneous and metamorphic rocks (e.g., basalts, amphibolites) tends to exhibit low salinity and elevated concentrations of silica and bicarbonate due to weathering of silicate minerals [5] [6]. Similar hydrogeochemical patterns have been documented in other Caribbean island aquifers with comparable lithologies (e.g., Puerto Rico [7]). Conversely, in sedimentary basins and coastal plains, groundwater often exhibits higher salinity due to mineral dissolution (e.g., evaporites) and potential seawater intrusion [8]. Coastal aquifers in the Caribbean are particularly vulnerable to salinization, both from natural processes (e.g., paleo-seawater intrusion) and anthropogenic overexploitation [9]. However, distinguishing natural geochemical evolution from contamination remains a key challenge in these systems [1].

The primary goal of this study is to describe the characteristics of groundwater in two representative areas of the Dominican Republic: the mountainous region of San Juan and the coastal plain of Azua. This groundwater is intended for human consumption. The study aims to interpret the geochemical processes that influence the chemical composition of the water and assess its suitability for human use.

General characterization of the study area

The Dominican Republic has aquifer systems of great importance, among which the mountain area of San Juan and the Plain of Azua stand out. These systems have geochemical and hydrogeological characteristics, influenced by their geology, climate, and natural processes of water-rock interaction.

The San Juan Valley consists of terraces and alluvial cones, interspersed with ancient basaltic lava flows. Due to its dry climate, which features scarce and almost nonexistent rainfall in winter, the region experiences a shortage of surface water and very high rates of evapotranspiration. The primary sources of groundwater are found in the alluvial deposits composed of sands, gravels, and conglomerates from the Arroyo Seco and Arroyo Blanco formations. Beneath these layers, marls from the Trinchera and Sombrerito formations, which have low permeability, serve as aquicludes. In the center of the valley, highly permeable materials dominate, promoting the presence of extensive aquifers with significant potential [10]. Azua is located north of Ocoa Bay, at the confluence between the Central Cordillera and the Azua Basin. In the mountain range, the oldest materials outcrop, from the Peralta Belt, composed of very coarse Paleogene sediments with turbidites (Peralta and Ocoa River Groups). The basin features an important Neogene sedimentary sequence, transitioning from marine environments-represented by the Sombrerito, Trinchera, and Quita Coraza formations- to continental environments, which include the Arroyo Blanco and Vía formations. However, these layers are not consistently exposed, as they are often covered by alluvial fans that extend to the coast. The region is characterized by a dense hydrographic network, with several intermittent rivers and streams flowing into the bay. Notable rivers in the area include the Jura, Vía, Grande, Banilejo, and Ocoa. From a stratigraphic and hydrogeological perspective, three groups of materials are identified: Eocene, Neogene, and Quaternary [11].

II. Material And Methods

The research was conducted through the analysis and compilation of satellite images, maps, and reports provided by the National Geological Survey (SGN).

The regional geological and hydrogeological characteristics were identified through fieldwork. A geological and geomorphological study was performed by describing the terrain and the exposed lithological profiles.

Water samples were collected in the provinces of Azua and San Juan, focusing on wells operated by the National Institute of Drinking Water and Sewerage (INAPA), the National Institute of Hydraulic Resources (INDRHI), as well as individual wells. Hydrogeological data were obtained from INAPA and INDRHI. Additionally, piezometric levels were measured in wells and boreholes using a SEBA Kll-T-100 water level meter.

Field parameters, including pH, electrical conductivity (EC), and temperature (T), were measured in situ using a multiparameter probe (Hanna HI9829).

A total of 15 wells in San Juan and 20 wells in Azua were sampled (Fig. 1). However, one sample from Azua corresponds to an artesian well that draws water from a shallow layer, which is covered by an impermeable layer that confines it. Water samples were collected in 1 L high-density plastic bottles, and the following parameters were analyzed: Na^+, K^+, HCO_3^-, Cl^-, Mg^{2+}, Ca^{2+}, SO_4^{2-}, NO_3^-, As, and F^-. The average ion balance error was 2.1% (max. 7.7%). Molar ratio diagrams were created and analyzed to estimate the potential geochemical processes at work. The samples were classified according to the geochemical type (Piper–Hill), and univariate and multivariate statistical analyses (principal component factorial- PC) were performed. To this end, the chemical data were standardized so as to be able to correlate variables of different magnitudes. The Varimax rotation method was used and the number of factors was determined using the Kaiser-Guttmann criterion (eigenvalue > 1) or Parsimony principle depending on the area. CO_3^{2-} and TDS were excluded from the multivariate analysis due to their known binding to pH and EC, respectively.

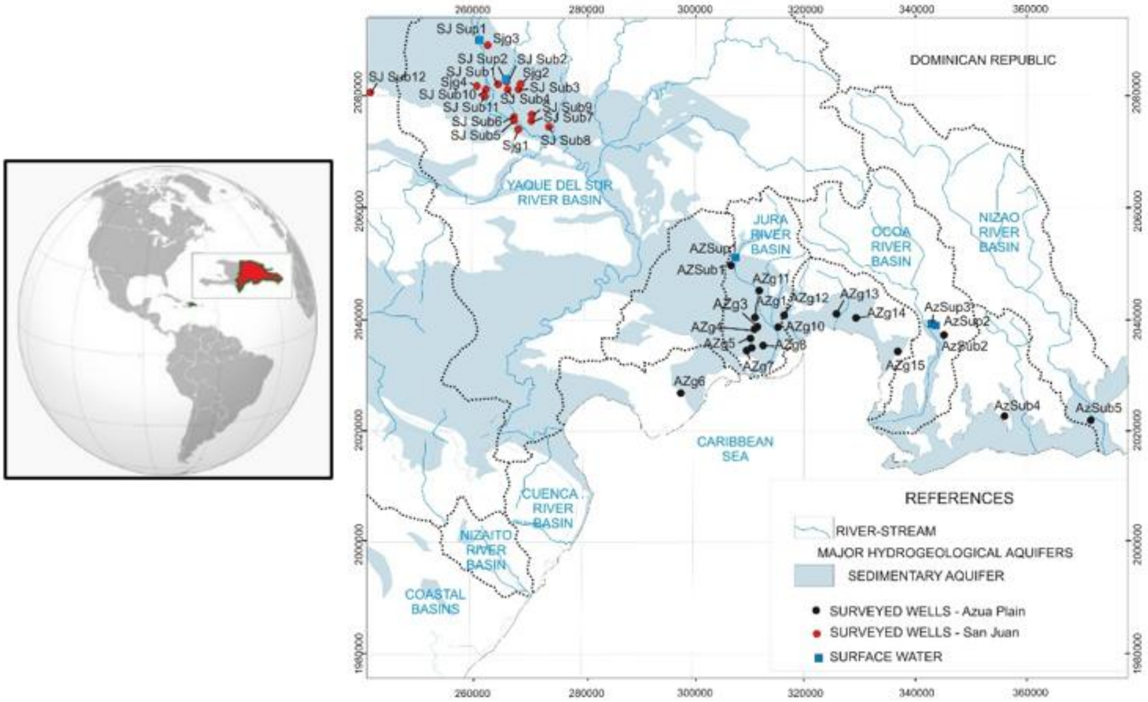
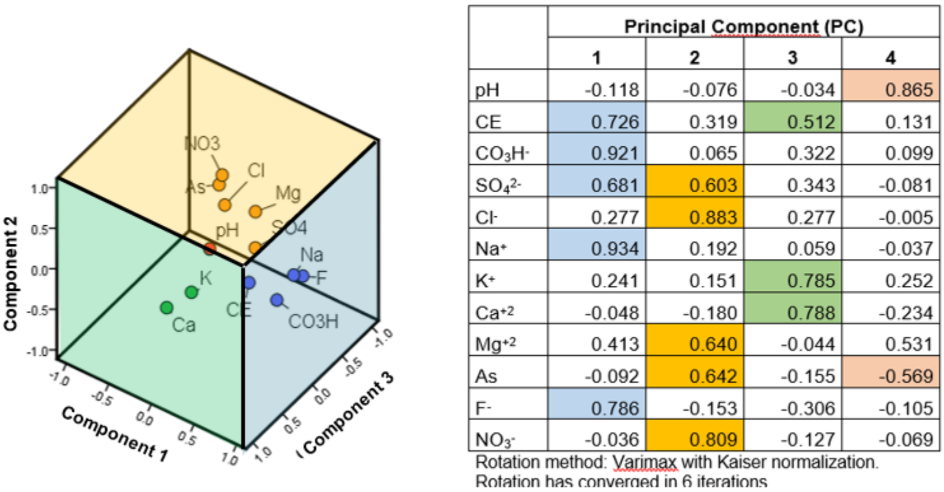


Figure 1. Location of sampled points

III. Result And Discussion

Chemical composition of groundwater in the San Juan area: The wells surveyed supply fresh water, with an average EC of 549 µS/cm (min. 298 mg/L (SJSub 10), max. 938 mg/L (SJSub 6)). Regarding the geochemical type, the samples are mainly calcium bicarbonates, except SJSub6 and SJSub9, which were sodium bicarbonates. It should be noted that the SJg2 and SJSub6 samples have a higher chloride (Cl^-) content compared to the other samples analyzed. Nitrate (NO_3^-) levels are generally below the natural background values (NBV) for water quality, defined by various authors worldwide as between 10 and 12 mg/L [1], derived from the decomposition of organic matter in the aquifer, except SJg2 (34 mg/L), SJSub1 (25 mg/L) and SJSub5 (24 mg/L). The moderate and positive correlation between $Cl^–$ and $NO_3^–$, especially in these three samples, suggests possible contamination by infiltration of human waste from latrines near the water wells, as recorded in the field. Fluorides are in most cases below the LD, except in SJSub1 and SJSub9 where they have been determined in the order of 0.3 and 0.4 mg/L, respectively. Arsenic levels are very low, ranging from 0.5 to 5 µg/L. The factor analysis of chemical variables identified four principal components (PCs) that explain 83.1% of the total variance (Fig. 2), offering an initial understanding of the dominant hydrogeochemical processes in the area. PC1 (30.5%) explains the natural salinity of water by linking electrical conductivity (EC) to the main ions: HCO_3-, SO_4^{2-}, and Na^+, as reflected in the composition and geochemical type of these sodium-rich waters. Furthermore, fluoride is also associated with this principal component, since the two samples in which it was detected are those with high sodium and bicarbonate concentrations. This relationship is confirmed by the geochemical type of sodium bicarbonate waters, which also has a higher fluorine content. PC2 (23.8%) associates NO_3- with Cl^-, SO_4^{2-}, as well as Mg^{2+} and As. This association can be interpreted in two ways: first, it may indicate contamination from anthropogenic sources involving NO_3^- and Cl^-, and second, it could relate to natural processes such as the dissolution and weathering of minerals containing SO_4^{2-}, Mg^{2+}, and As. This is particularly relevant considering the mining activities in the area associated with a gold deposit, which may lead to acid mine drainage (AMD). The PC3 component (16.5%) collects Ca^{2+} and K^+ weakly linked to EC, so they can be interpreted as part of the major ions that explain the salinization of water from the contribution of precipitation and weathering of minerals. Finally, the PC4 component (12.7%) shows an inverse relationship between pH and As, indicating that low pH leads to high Arsenic values (e.g., derived from arsenopyrite), which may be explained by acid mine drainage (AMD).



	Principal Component (PC)			
	1	2	3	4
pH	-0.118	-0.076	-0.034	0.865
CE	0.726	0.319	0.512	0.131
CO3H-	0.921	0.065	0.322	0.099
SO42-	0.681	0.603	0.343	-0.081
Cl-	0.277	0.883	0.277	-0.005
Na+	0.934	0.192	0.059	-0.037
K+	0.241	0.151	0.785	0.252
Ca+2	-0.048	-0.180	0.788	-0.234
Mg+2	0.413	0.640	-0.044	0.531
As	-0.092	0.642	-0.155	-0.569
F-	0.786	-0.153	-0.306	-0.105
NO3-	-0.036	0.809	-0.127	-0.069

Rotation method: Varimax with Kaiser normalization.
Rotation has converged in 6 iterations

Figure 2. Principal Component Analysis (PCA). San Juan

The atmospheric contribution is believed to be the main reason for the presence of SO_4^{2-} and Cl^- ions, primarily due to the influence of marine precipitation. It is important to note that there is insufficient evidence to suggest the presence of gypsum or halite in the materials comprising the aquifer. This conclusion is supported by the calculated molar ratios, which do not indicate that these ions originate from the mentioned minerals (Fig. 3). In addition to this contribution, the processes of mineral dissolution and/or weathering (as shown in Figures 3 and 4) occur as water circulates through the sedimentary aquifer. Although the cation exchange process is secondary (CAI-1 ranges from -10.7 to -0.7, and CAI-2 from -0.03 to -0.2), it indicates that Ca^{2+} and Mg^{2+} are retained in fine sediments while Na+ are released into the solution.

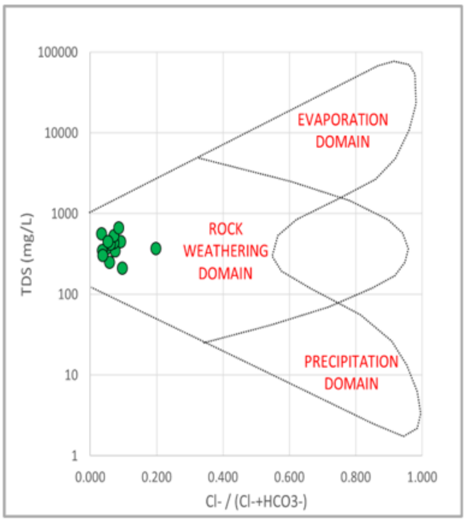


Figure 3. Molar relationships in groundwater, San Juan.

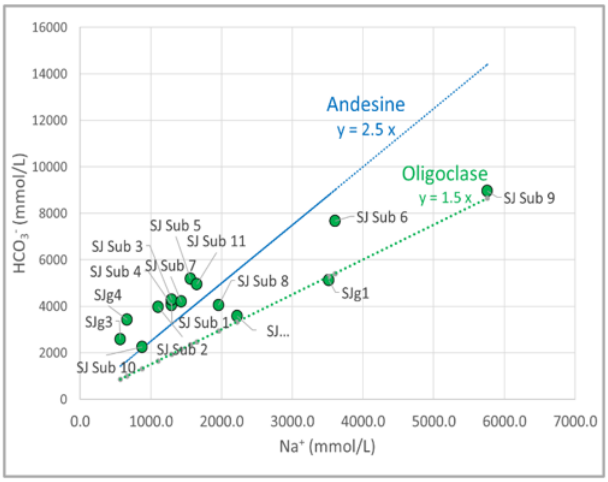


Figure 4. Molar relationships in groundwater, San Juan.

Chemical composition of groundwater in the Azua plain: Groundwater is fresh, with an average EC of 629 µS/cm (min.: 409 mg/L (Azg5) and max.: 877 mg/L (AzSub4)). According to their ionic composition, they are bicarbonate waters, except Azg13 and Azg11, which were mixed (bicarbonate-chloride and chloride, respectively), and mainly of sodium type. Additional types were also identified: AzSub5 (calcium), Azg3, Azg13, and AzSub1-4 (sodium-calcium), along with Azg1, Azg2, Azg7 (artesian well), Azg14, and Azg15 (sodium-magnesium). Nitrate levels exceed the natural background in 42% of cases, with maximum concentrations recorded at 75 mg/L for sample AZSub4 and 72 mg/L for sample AzSub5. There is a moderate positive correlation between NO_3^- and EC, with a correlation coefficient of $r = 0.570^*$ ($p = 0.05$) across all samples. This suggests potential contamination from livestock waste in nearby pens and/or human waste infiltrating from sanitation systems near the wells. Azg11 has notably higher Cl^- levels compared to the surrounding area, where a significant number of animals were observed near the well. This could indicate contamination (NO_3^-: 23 mg/L) from livestock effluents.

The factor analysis, where the Azg7 sample (well-spring) was excluded, defines 4 PCs that explain 77.8% of the variance. The PC1 component (25.9%) indicates contamination processes, in scenarios where the pollutant source provides nutrients such as NO_3^-, but also produces an increase in EC, SO_4^{2-}, and Mg^{2+}. The remaining components (19.1%, 18.8%, and 14.1%) represent natural processes that affect the ion input in water, shaping its overall chemical composition (Fig. 5). PC2 and PC4 indicate that As and F^- are controlled by different geochemical processes linked to the mineralogy and alteration of the aquifer matrix. Arsenic, grouped in PC2 and positively correlated with Na^+ and inversely with Ca^{2+}, suggests greater mobility in sodium-rich waters, possibly due to ion exchange or desorption under high pH and low Ca^{2+} conditions. , PC3explains the processes of atmospheric CO_2 dissolution that increase HCO_3^- and decrease pH. Finally, Fluoride, associated with K^+ in CP4, likely reflects its release through dissolution or weathering of potassium-bearing minerals (such as micas or feldspars).

	Principal Component (PC)			
	1	2	3	4
pH	-0.302	0.157	-0.712	0.228
CE	0.805	-0.172	0.506	-0.027
CO_3H^-	-0.053	-0.069	0.921	0.066
SO_4^{2-}	0.636	-0.221	0.362	0.262
Cl^-	0.680	0.548	-0.014	0.153
Na^+	0.293	0.762	0.517	0.091
K^+	0.084	0.280	-0.091	0.771
Ca^{2+}	0.474	-0.685	0.303	-0.147
Mg^{2+}	0.700	0.258	0.129	0.175
As	-0.029	0.814	-0.305	0.031
F^-	-0.004	-0.078	0.009	0.898
NO_3^-	0.832	-0.118	-0.195	-0.278

Rotation method: Varimax with Kaiser normalization
Rotation has converged in 10 iterations.

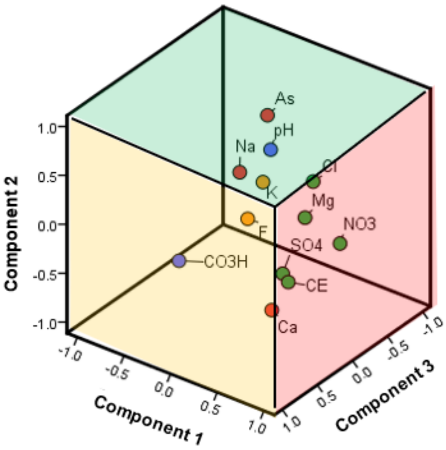


Figure 5. Principal Component Analysis (PCA). Azua.

Similar to the San Juan area, it is believed that atmospheric contributions are a major source of solutes in water. However, the molar relationships between major ions and their connection to geochemical processes suggest that the hydrolysis of silicates is one of the most common processes in many cases. Furthermore, in addition to the dissolution of halite observed in the artesian well (AZg7) and in sites Azg13 and Azg11, the dissolution of gypsum occurs in Azg15, Azg9, and to a lesser extent in Azg14, Azg10, and Azg6. Additionally, calcite dissolution is noted specifically in Azg11 (see Fig. 6).

Finally, cation exchange is added in the Azg5 and AzSub1 samples, since the calculated CAI-1 and CAI-2 indices (-3.8 and -2.0, respectively) indicate that Ca^{2+} is retained in fine sediments and Na+ is released into the water.While the Cl^-/HCO_3^- index values (>1.3) could initially indicate the possibility of marine intrusion in the surveyed wells, the high Na^+/Cl^- ratio (Glover index, ranging from 1 to 7.2; >0.86) and the low Mg^{2+}/Ca^{2+} ratio (ranging from 0.7 to 2.2; <5) contradict this hypothesis.

Figure 6. Molar relationships and associations with geochemical processes in groundwater of Azua

IV. Conclusion

The comparative hydrogeochemical study conducted in the regions of San Juan and Azua reveals distinct characteristics in the composition and processes that influence the quality of groundwater intended for human consumption. In San Juan, the water is generally fresh and primarily composed of calcium bicarbonate. However, some exceptions were noted, showing elevated levels of sodium (Na^+) and chloride (Cl^-). The salinity of natural water is mainly affected by the weathering of silicate minerals and by the deposition of sulfates and chlorides from the atmosphere. Some wells showed localized contamination from nitrates and chlorides, indicating potential infiltration of human and animal waste from the surrounding area. The presence of a possible acid mine drainage (AMD), although still in the early stages, is suggested by the correlation between low pH levels and high concentrations of arsenic, likely linked to gold mining activities in the region. Additionally, cation exchange plays a secondary role in this context.

In Azua, the water is primarily fresh and sodium bicarbonate type, but there is greater variability in the geochemical types. This includes mixed waters as well as sodium and magnesium chloride types. The contamination by nitrates (NO_3^-) is more widespread and significant than in San Juan, indicating a stronger influence from anthropogenic sources, such as livestock waste and human waste. Additionally, processes of mineral dissolution, including halite, gypsum, and calcite, have been identified in some wells. Cation exchange is also present, exhibiting behavior like that observed in San Juan. Despite being close to the coast and considering the hydrochemical results, particularly regarding cation exchange, it is estimated that there is no marine intrusion. Instead, the increase in chloride (Cl^-) levels is associated with nitrate (NO_3^-) pollution. This is evidenced by the proximity of various pollution sources to the wells.

These findings are crucial for generating strategies to manage and protect groundwater resources in the Dominican Republic. It is essential to consider the unique hydrogeochemical characteristics of each region and to address the identified sources of contamination to ensure that the water is safe for human consumption.

V. Acknowledgements

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