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Hydrogeochemical Studies in Drought Scenarios: Canelones, Uruguay Case Study

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Abstract

The water scarcity in quality and quantity is becoming more noticeable and an urgent concern around the world. In Uruguay, these issues become exacerbated by the need to obtain drinking water in coastal areas, influenced by the climate change. Basic and structural geologies are strong conditioners in heterogeneous coastal aquifers. The objective of this study is to characterize the hydrochemistry of the fractured aquifers after having identified the main bearing fractures and the causes of aleatoreous water scarcity and quality problems, for hydric resources sustainable management. Identification of water bearing fracture, hydrogeochemical analysis and water quality evaluation are specific objectives. Some strategies were performed: 1) a base map in *QGIS Software*; 2) fracture photointerpretation; 3) geological correlation; 4) statistical analysis of the background geochemistry data; 5) ions analysis of strategically located wells. There were found water bearing fractures corresponding to 28 m^3/h maximum flow rate for the NW-SE and 12 m^3/h maximum flow rate for the NE-SW fracture direction, respectively. Besides, there could be a problem related to the high Sodium (Na) and Chloride (Cl) levels. In this respect, having previous data from 25 well samples, ions geochemical analysis has been carried out for 14 wells from Costa Azul and surrounding to have a first approach about the possible cause for the high values of Na (max. 385 mg/L) and Cl (max. 381 mg/L). The selected area for this study has a particular characteristic, because it corresponds to a heterogeneous fractured aquifer, which makes it difficult to catch water with enough flow rates and water quality to meet the population demand.

Keywords

Water Bearing Fractures, Hydrogeochemistry, Water Quality, Sustainable

Management

1. Introduction

Coastal aquifers over the world are facing the impact of urbanization, industrialization, agriculture and natural process such as groundwater discharge and saltwater intrusion (Liu et al., 2017). The importance of hydrogeochemical studies is remarked in the literature (Wang & Jiao, 2012; Raja et al., 2021). Salinity water composition of groundwater can be due to a geogenic origin, evaporation or saltwater intrusion. These are the three hypothesis taken into account and hydrogeochemical analysis is the key to understand which process is taking place in the case study. In this context, the heterogeneties of the fractured aquifers on the extent and distribution of saltwater intrusion is well documented in the literature (Allen et al., 2005; Mehdizadeh et al., 2014; Pool et al., 2015; Shi et al., 2018).

The study area is located at the southeast of Canelones Department in Uruguay (**Figure 1** and **Figure 2**), where hydric resources are often scarce. At Costa Azul, Bello Horizonte, La Floresta and Guazubirá in Canelones Department, there is much water demand in the summer season (December to March), mainly because of the tourism activity in the coastal area. In the northern area, there is an increase of water demand associated with agriculture and livestock farming activities. The southern area has a high impact in Uruguayan tourism, since it has a large influx of foreign tourists. In this region, the population density is one of the highest of the country. During 2023, it was reported that Canelones was the most visited department for tourism in Uruguay, with a total of 4.303.473 domestic tourists per year (El País, 2023a), having Uruguay 3.444.263 (INE Census, 2023). This denotes the human impact that the area receives, giving rise to thinking about sustainable planning for water management and sanitation.

Since 2020, the La Plata River basin has been going through an extraordinary period of drought (Naumann et al., 2023). And, between 2022 and 2023, southern Uruguay has gone through the greatest drought on record (Barreiro, 2023). As a consequence of this, both the quantity and quality of groundwater and surface water in the region have been affected (El País, 2023b).

As an example of this situation, since April to August 2023, tap water in Montevideo (the capital of Uruguay) and the metropolitan area (1.7 million inhabitants) has changed its composition and taste. The State drinking water and sanitary works institution (O.S.E.: *Obras Sanitarias del Estado*) is treating water for human consumption from the Rio de la Plata, whose salinity levels are about 32o/oo (Burone et al., 2013), because the surface freshwater reservoirs have dried up. So, there is an urgent need to water prospection, know what other sources of fresh or less saline water can be considered for drinking water.

The main objective of the research is the hydrogeological and hydrogeochemical

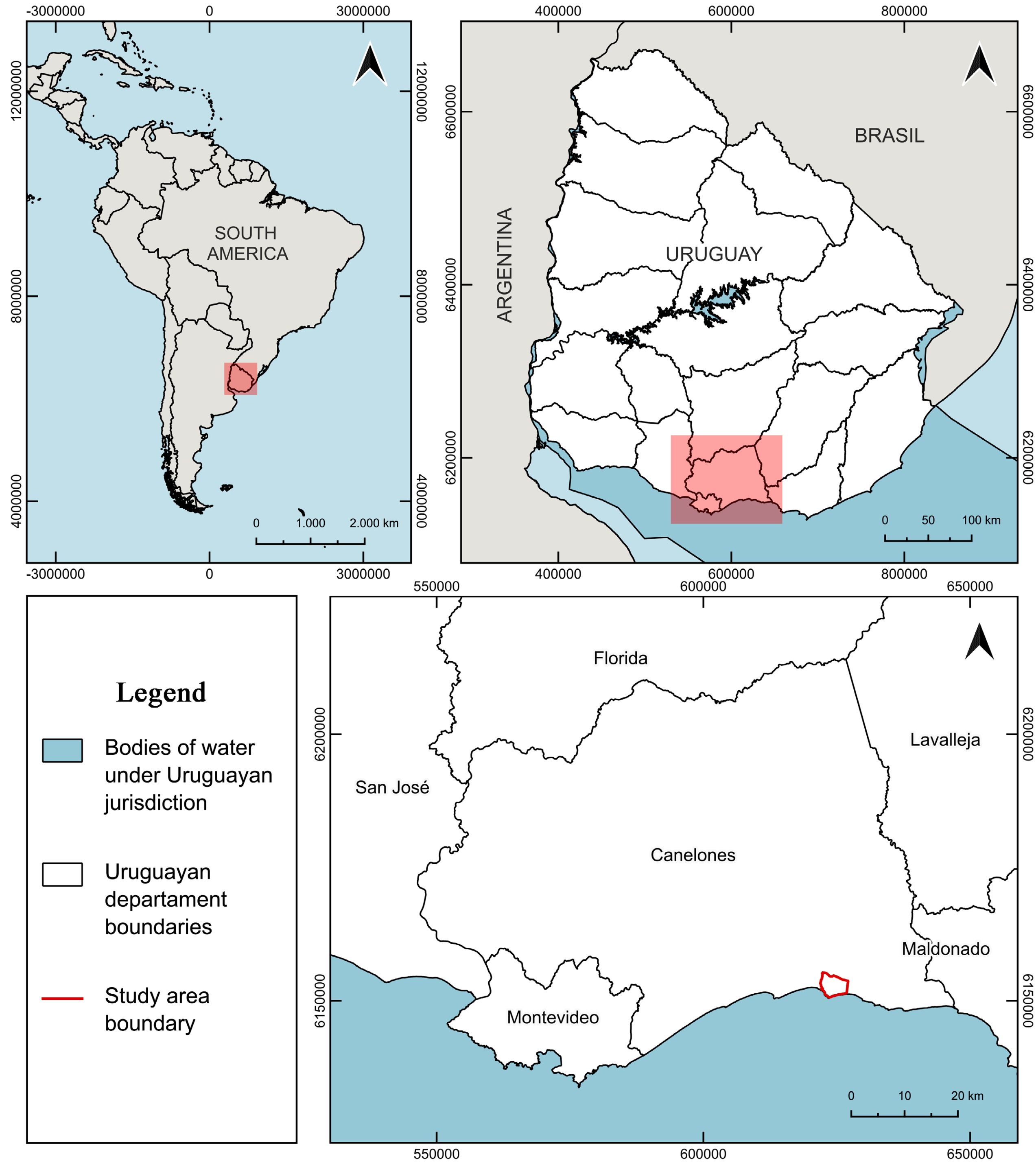

Figure 1. General location of the study area in Uruguay.

characterization of the fractured aquifer in Costa Azul and its surroundings (48 km to Montevideo) for groundwater sustainable management. Specific objectives are: (a) to identify the main structural alignment and their correlation with the flow rate and other hydrogeological properties, to find the main water bearing fractures; (b) to study the possible relationship of the electrical conductivity, temperature, dissolved oxygen, Eh (redox potential), pH, majority ions and

Figure 2. Detailed localization of the study area in Costa Azul, Canelones Department, Uruguay. Green points correspond to O.S.E. wells with pervious information, CA1 to CA14 correspond to the analyzed well samples.

bromide to characterize hydrogeochemicaly groundwater; (c) evaluation of water quality.

2. Geological Framework

There is a detailed and complete update about Uruguayan Precambrian rocks in Bossi & Gaucher (2014). The study area is part of the Piedra Alta Terrane, named Tandilia Terrane below the Colonia Shear Zone (Bossi et al., 2005; Ribot et al., 2005; Bossi & Cingolani, 2009; Abre et al., 2014; Pamoukaghlián et al., 2017). Other authors (Oyhantçabal et al., 2006) consider all this part as Rio de la Plata Craton and do not recognize Colonia Shear Zone as a tectonostratigraphic terrane division. This part of the Piedra Alta Terrane or the Tandilia Terrane (Bossi, Piñeyro, & Cingolani, 2005) is represented by the Pando Belt (Bossi et al., 1998), with a regional development to the E-NE direction, forming part of the base of the Santa Lucia tectonic basin. The Pando Belt is composed of the Montevideo Formation (volcano-sedimentary sequence of Paleoproterozoic age) and abundant intrusions of granites, pegmatites, aplites and lamproites. The Montevideo Formation is bounded to the north by the Mosquitos Formation and is cut by the Soca Granite. The Montevideo Formation is developed in the Departments of Montevideo and Canelones with a general direction E-W. Originally defined by Bossi et al. (1975), it includes an association of oligoclastic gneisses to two micas, ortho- and para-amphiboles, graphite paragneiss and orthogneiss. The Pando Belt is trimmed by granite bodies of Paleoproterozoic age: 1) The Soca Granite, coarse-grained heterogranular and occasionally with wiborgitic texture (Oyhantçabal et al., 1998, 2006) with an age of 2054 ± 11 determined by ICP LA MS method (Hartmann et al., 2001). 2) The Sosa Díaz granite (Coronel & Oyhantçabal, 1988). 3) The La Tuna granite, of Paleoproterozoic age according to Pamoukaghlián et al. (2017) and 4) The La Paz Granite, of Neoproterozoic age (Spoturno et al., 2004). To the east of the study area, the geological units are arranged stratigraphically from base to top as follows (Pamoukaghlián et al., 2021a): a) Paleoproterozoic basement formed by the Montevideo Formation, the Soca Granite and the Coronilla Granite. b) Neoproterozoic sedimentary rocks of the Piedras de Afilar Formation, which rest in discordance on the basement, observing contact with the Soca Granite in a ballast quarry ("González Quarry"). The Piedras de Afilar Formation is also in contact with tectonic fault (La Tuna fault) with quartzites from Montevideo Formation and with La Tuna Granite, in the coastal outcrops of Araminda (Pamoukaghlián et al., 2017) c) Phanerozoic dolerites (382 ± 11 Ma., Cingolani et al., 1990) which intrude the Piedras de Afilar Formation, appreciating this in outcrops and wells, which are close to the "fault of the train track" (Jones, 1956; Coronel & Oyhantçabal, 1990; Spoturno et al., 2004; Pamoukaghlián, 2012; Pamoukaghlián, Poiré, & Gaucher, 2014). This succession of geological units theoretically makes up the fractured aquifer system, regionally. Cenozoic sediments overlie in discordance with the Precambrian rocks.

Geology of the Study Area

In the study area, according to research advances, Precambrian rocks of the Montevideo Formation such as amphibolites and granites and gneisses that intrude this unit (Pando Belt) are found in depth. The granites are possibly associated with the Soca granite and the La Coronilla granite, last mentioned, with intercalations of graphitic schists. The basement is found with a variable depth between 30 and 70 meters. Cenozoic sediments are placed in direct discordance on these granites but generally with thin thickness. The Cenozoic formations are: Fray Bentos Formation, Raigón Formation and Libertad Formation (see geologic map and references from Spoturno et al., 2004; **Figure 3**). Pérez et al. (2022) based on well lithological information, have encountered that the Paleoproterozoic rocks are less thick and the Cenozoic sediments are thicker from west to east (**Figure 4**).

3. Hydrogeological Background

According to the hydrological characterization of the Piedra Alta Terrain presented by Montaño et al. (2014), the lithotypes are distinguished within it in

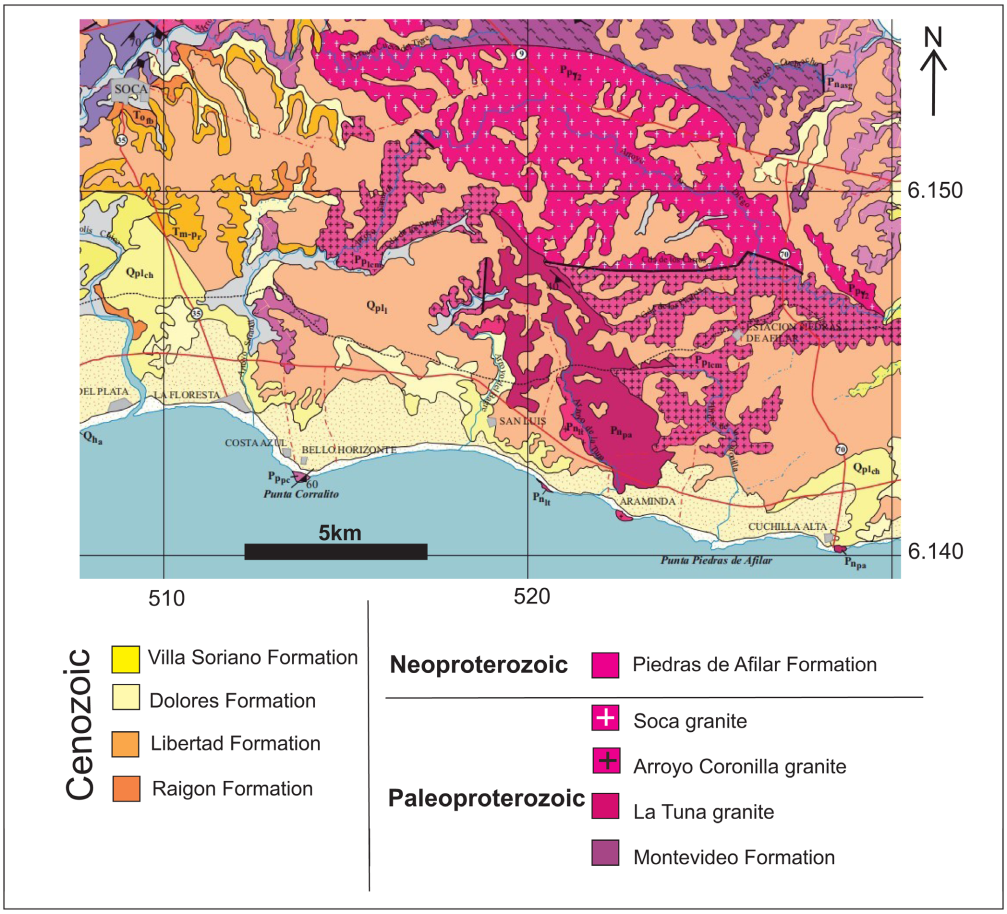

Figure 3. Geological map of Costa Azul study area and surroundings, modified from Spoturno et al. (2004). Coordinate are in Universal Transversal Mercator (UTM) system.

relation to its hydraulic conductivity. Coarse-grained granites tend to generate open fractured systems, which favor the accumulation and circulation of water. The gneisses have open and interconnected fractures, which favor the accumulation and circulation of water as well. Gneisses have fractures with a little filling or with sandy filling, also generating good productivity (Montaño et al., 2000a, 2000b, 2003). Amphibolites (Yorio, Facultad de Ciencias, unpublished data, 2019) and mica schists have good fracturing, but generally with clay filling that hinders the circulation of groundwater. Montaño et al. (2014) present a regional statistical analysis of wells for the entire Piedra Alta Terrain, where 12% of the drillings have maximum depths of 30 and 60 meters and 20% correspond to depths greater than 60 meters. 14% of the wells are not productive, 60% show flow rates of 0.1 to 5 m^3/h ("Movement for the Eradication of Rural Unhealthy Housing", MEVIR data source, in 2014) and between 5 and 20 m^3/h in wells used for irrigation. In the selected area and according to the Geological Mining Visualizer of DINAMIGE (Mining and Geology National Direction of the Industry and Energy Ministry) (DINAMIGE, 2022), there is a good density of wells considered to be enough to carry out the proposed study. Likewise, the Groundwater Division of the Drinking Water Management of O.S.E. has a database of

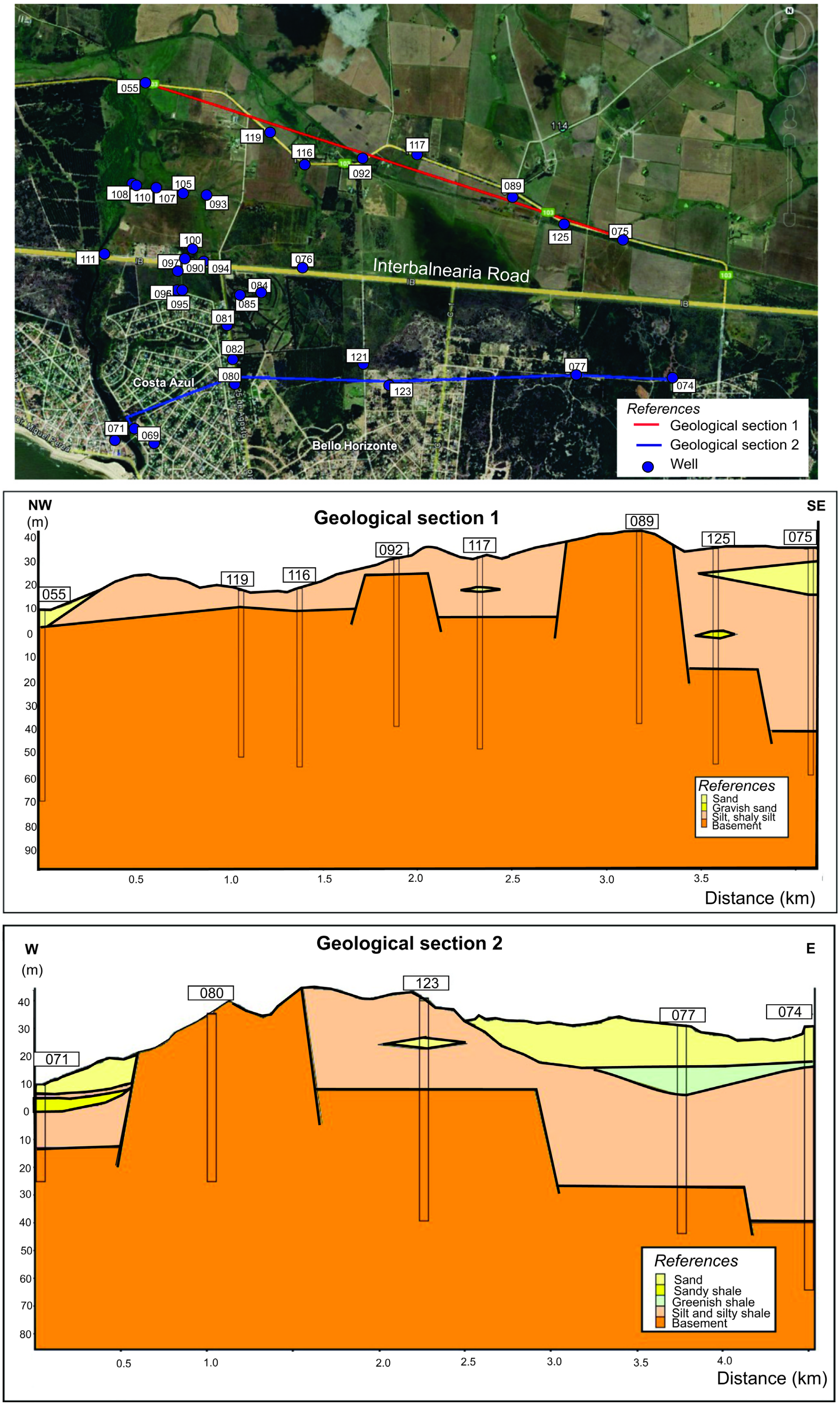

Figure 4. Geological sections in the study area, modified from Pérez et al. (2022). Note the vertical exaggeration scale. In the first image the wells are indicated with green points.

descriptions with reference samples and a good well density (1.6 wells/km^2) in the study area. Blanco (2003) analyzed the variability of hydraulic parameters in the near eastern area according to a classical methodology (point graphs and histograms: frequency of wells). More recently, O.S.E. researchers published about geological and hydrogeological main characteristics of the immediately surrounding area and of similar characteristics (coastal and fractured aquifer composed of Precambrian rocks), San Luis, with expanded abstracts and posters presented at the corresponding Uruguayan Geological Congresses (Pérez et al., 2010; Mlynarski et al., 2016). From another point of view, Goso, Mesa, & Del Carmen Alvez (2011) and Goso et al. (2014) studied the coast dynamics in this part of Canelones and the coastal aquifer vulnerability.

Hydrogeochemical Background

There are hydrogeochemical studies carried out by Montaño et al. (2004), Guerequiz et al. (2005) for a fractured coastal area in Punta Espinillo, Montevideo. Pérez et al. (2010) published some results about a possible saltwater intrusion in San Luis, 5 km to the east of the study area. Regarding data on the chemical parameters of wells in the study area, the information has not been found in available publications, the closest to the area is shown in Heinzen et al. (2003). According to unpublished data reported in student bachelor monographs of the Hydrogeology course of the Geology career of the Faculty of Science, UDELAR (Virginia Strambini, Facultad de Ciencias, unpublished data, 2019 and Facundo Plenc, Facultad de Ciencias, unpublished data, 2019), groundwater information from San Luis, Los Titanes, Araminda and Santa Lucia del Este (Canelones) implies the following hydrochemical characteristics: water pH in the wells varies between 6.9 and 7.7 and electrical conductivity varies between 732 and 2204 uS/cm. The hardness of water varies from 103 to 460 mg/L. The alkalinity presents a maximum of 540 mg/L. The concentration of Chloride (Cl^-) varies from 46 to 491 mg/L. The concentration of Sulfate (SO_4^{2-}) from the water in the wells varies from 11 to 114 mg/L. The concentration of Nitrate (NO_3^-) varies from 1.6 to 19.0 mg/L. The Fluoride (F^-) ranges from 0.5 to 0.75 mg/L. That is why it is essential to expand hydrochemical studies, obtaining new information that allows a greater understanding of the processes that make saline high levels.

There is a lack of information and very few published data about the hydrochemistry of groundwater in Canelones coastal area, specifically our research would yield valuable data for the country.

4. Materials and Methods

The following activities are carried out in order to achieve the main objective: *Phase* 1: Bibliographic revision of geological and hydrogeological data from the baseline, with the elaboration of a complete well inventory database and base maps using QGIS free software and high resolution images (i.e. *Google*, *Bing*). *Phase* 2: Photointerpretation and identification of main photo lineaments. *Phase*

3: First field trip work to explore the zone and select the sample points and identification of the water bearing fractures. *Phase* 4: Second fieldwork to carry out sampling of 14 previously selected wells for hydrogeochemical analysis in situ (using Hanna® multiparametric probe) and in the laboratory. *Phase* 5: Well water sample analysis in *Water and Soil Laboratory* (Water Department, CENUR Litoral Norte), to obtain water majority ions, including alkalinity and hardness analysis. *Phase* 6: Geochemistry data modeling and evaluation.

Groundwater sampling was coordinated with O.S.E. considering that wells were preferably located in the water bearing fractures, trying to select wells in the two main fracture directions after photointerpretation and covering all the area the most homogeneously as possible. However the O.S.E. authorities conditioned sampling selection because some wells were disabled due to quality or quantity problems. Soca well, which is rather far from the coast, was selected because the known quality problems and high Na values.

4.1. Procedure and Chemical Analysis

The testing of well water was carried out through an internal protocol of the Water and Soil Laboratory (CENUR LN, UDELAR), based on the standard methods of water and effluent analysis (APHA, 2017) and the analytical methods used pass the quality control suggested in APHA for each one (internal protocols of Laboratory). Well purge of at least 3 well volumes was performed before the sample was taken. Physicochemical parameters (electrical conductivity, temperature, dissolved oxygen, Eh (potential redox) and pH) of the water from the wells which were selected near the coastal zone in the field, were analyzed with a Hanna® multiparameter probe existing in the Hydrogeology chair of the Science Faculty, UDELAR. The collected samples were conditioned in 500 mL PET or similar and were stored at 4˚C to be transported to the Laboratory for subsequent analysis. In the Water and Soil Laboratory, the ions Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2-}, NO_3^- and Br– were filtered (Whatman®, Uniflo Nylon, 25 mm, 0.45 μm) and analyzed by ion chromatography according to APHA_4110-B in the Thermo Dionex AquoION® Chromatography, alkalinity and bicarbonate (HCO_3^-) by APHA_2320-B hardness by APHA_2340-B respectively (APHA, 2017). Chemical analysis was performed by duplicates. The processing of results was carried out using EasyChem® hydrochemical modeling software to be defined and statistics such as InfoStat® and CoDaPack® for compositional statistics (Azurica Chéchile, 2017).

Error assessment for water quality data analysis, was performed as ionic balance as follows:

$E (\%) = [(\Sigma_{cations} - \Sigma_{anions})/(\Sigma_{cations} - \Sigma_{anion}s) * 100$ (APHA, 2017; Custodio & Llamas, 2001).

Concentrations are computed as mili equivalents per litre. Accordingly Custodio & Llamas (2001) an admissible error of 10% correspond to EC: 200 uS/cm levels.

A statistical analysis of the well chemistry parameters database provided by O.S.E. was carried out. This database was homogenized and analyzed, according to specific criteria: (a) all values (n) preceded by a "minor" sign were considered like $n_1 = 1/(n)^{1/2}$; (b) all values (n) preceded by a "major" sign were considered like the same value: $n_1 = n$; only table completed values for the different chemistry elements were considered. In this respect and taking into account, the analysis methodology (*O.S.E.* Central Laboratory) the majority elements Na and Cl, minority elements Fe, F and one trace element (As) were considered. Statistical analysis carried out is: 1) a general distribution of the Na, Cl, F, Fe and As for the period of time 2002-2022; 2) sample time evolution for each well (Na, Cl, Fe, F, As). Afterwards, correlation coefficients between these variables have been studied. Furthermore, the majority ions analysis gave a more accurate local geochemical characterization of one specific and representative part of the study area. First of all the ionic balance was made. After this, we used the Piper diagram, Schöeller diagram and Salinity diagram (SAR) (Custodio & Llamas, 2001) to classify the water and see its behavior. In this preliminary analysis, we have analyzed three representative samples from Costa Azul coastal area and compared them with three samples from Cuchilla Alta, Santa Ana and Soca respectively. Besides Na/Cl ratio and Simpson ratio were used in order to evaluate the contamination with saltwater, as a possible cause of the high Na and Cl levels.

4.2. Statistical Studies

Multivariate statistical analyses are used in hydrogeochemical studies to determine the correlation between chemical parameters and water samples (Cloutier et al., 2008; Chai et al., 2020). The statistical methods were performed using Python libraries such as MatplotLib and Pandas in Anaconda platform. Correlation of O.S.E. database seeks the association between variables, not their dependency, relationship between them or a third variable. This strength of correlation is measured through the correlation index "r", and depending on the characteristics of the variables, the index type will be chosen (Pearson, Spearman).

In order to select the most appropriate correlation coefficient, the normality of the variables was studied by various graphical and statistical methods. Skewness and kurtosis are two calculations used to see the deviation from normality. Values between −1 and 1 are considered a slight deviation from normality, between −2 and 2 are considered an evident deviation from normal but not extreme (Bulmer, 1979; Amat, 2021). Other statistical methods are the Shapiro-Wilk test (Hanusz, Tarasinska, & Zielinski, 2016) and D'Agostino's K-squared test (Macian-Sorribes et al., 2022). In these, the null hypothesis considers that the data follow a normal distribution, so if the p-value is higher than the selected alpha value, there is no evidence to rule out the normality of the data. In this case it was considered the value of alpha = 0.05.

Pearson's correlation works well for quantitative variables with a normal or near-normal distribution but is sensitive to extreme values. Spearman's correlation is used with quantitative variables (continuous or discrete). It does not use the value directly, but a rank order and is a non-parametric method used when the normality condition is not satisfied (Amat, 2021).

In order to observe the historical variation of some hydrogeochemical parameters, it was necessary to use the resampling carried out by O.S.E. in 7 wells supplied by them. The values of each parameter were plotted as a function of time, from the first sampling to the last, and broken down by well.

5. Results

5.1. Hydrogeological Studies

Firstly, there are interesting results about the fractures lineation, observing that the main orientation of fractures is NW-SE and NE-SW (**Figure 5**). Although the aquifer is extremely heterogeneous, N30W to N45W fracture directions are associated with maximum flow rate of 28 m^3/h. N20E to N45E fracture directions are associated with maximum well flow rate of 12 m^3/h. However, there are unproductive wells in both directions (less than 0.1 m^3/h). NE-SW fracture directions have a maximum length of 800 m while NW-SE fracture directions have a maximum length of 500 m. Secondly, piezometry has not still been addressed because in the study case the aquifer is so heterogeneous that this should be hardly interpreted and there would be needed more studies for a future work. Finally, hydrogeological parameters were studied according to O.S.E. supplied data (**Table 1**) and these were graphically analyzed with frequency wells diagrams and comparison parameters diagrams. For example, the diagram which correlates pumping flow and specific flow (pumping flow divided by drawdown

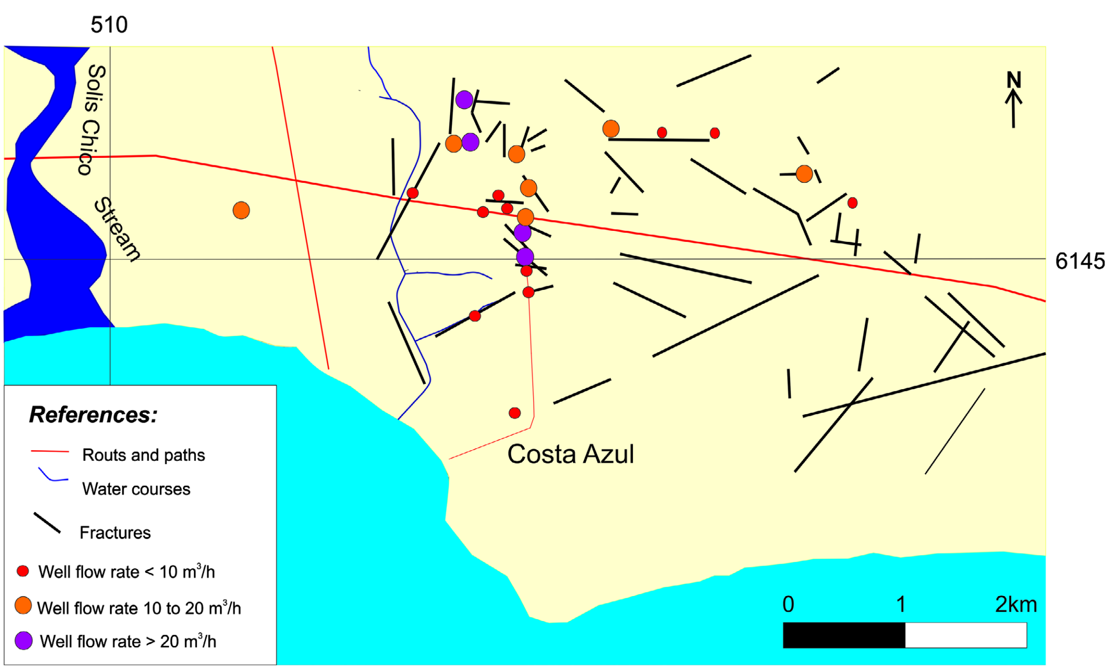

Figure 5. Geographic map with fracture representation and well flow rate data. Coordinates are in Universal Transversal Mercator (UTM) system.

Table 1. Well information as data summery from available hydraulic information provided by O.S.E.

Hydraulic parameters	Well number and parameters							
	Wells	Depth	Usefull depth (m)	Flow rate	Water level	Dynamic level (m)	Level drop	Pump depth
count	125	109	109	23	23	22	22	22
unique	25							
mean		50.555	49.942	12.796	9.672	28.19	18.746	42.482
std		15.03	16.225	14.123	8.199	15.817	16.09	15.948
1min		15	14	0.3	0	2.64	2.1	12
25%		47	47	4.25	1.735	16.14	8.005	34.15
50%		49.5	49.5	8	9.37	26.79	13.675	45
75%		60	60	12	13.26	39.21	27.033	54.5
max		99	99	53	27.1	69.15	67.65	72

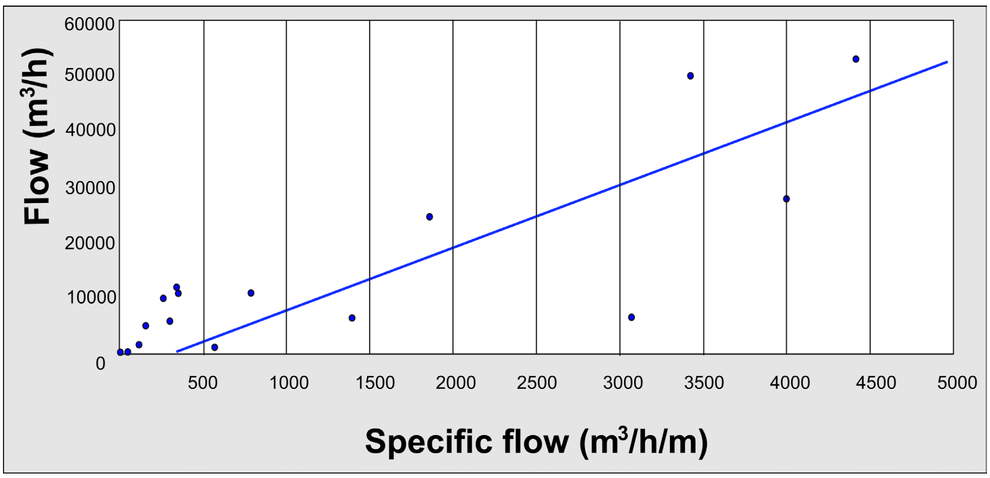

Figure 6. Groundwater flow behavior in the fractured aquifer: pumping flow vs. specific flow (pumping flow divided by drawdown in the well), corresponding to O.S.E. wells (Table 1).

in the well) (Figure 6) could give useful information about the fracture aquifer behavior. According to Montaño et al. (2014) there is a tendency to the alignment of the resulting curve which can be used to predict the new well flow. However, in the studied wells for the coastal area of Costa Azul, these parameters seem to be rather disordered and do not show a good correlation (Figure 6). More studies as pumping test analysis are needed to have a better comprehension, to know possible drawdowns in the water level, possible high groundwater extraction and water quantity problems. This will be carried out in future researches.

5.2. Background and Base Line Hydrogeochemistry Data Analysis

A baseline was elaborated, according to the information provided by O.S.E, regarding the State Law Number 18.381, in respect of the available public information, including data from 25 wells monitored since 2012 to 2022 in an area of 16 km^2 (**Figure 7**).

A number of 2A number of 20 chemical parameters were analyzed during the above mentioned period and a database containing N = 125 was built (**Table 2**). Respect salinity results, Electrical conductivity presents high values in most of the wells, with a minimum of 571 µs/cm, maximum of 2.460 µs/cm and an average of 1.340 + 533.5 µs/cm. This suggests that salt content is rather high in the selected coast region. In fact, chloride maximum values arise 381 mg/L and sodium maximum values arise 385 mg/L, both are above the maximum allowed value by the national regulations for drinking water (UNIT 833, 2008). These results are relevant because the hydrochemical background studies around the study area are almost non-existing.

In the 7 wells with resampling used for the study of the temporal variation of some hydrogeochemical parameters, it is worth highlighting the behavior of some measured parameters. The pH remains neutral and stable in all wells over the 10 years measured. Alkalinity remains without significant variations and shows an increase in baseline values towards the north. Arsenic also shows no major variations and remains around the limit (10 µg/L) suggested by the World Health Organization (WHO). Manganese shows strong variations, exceeding the

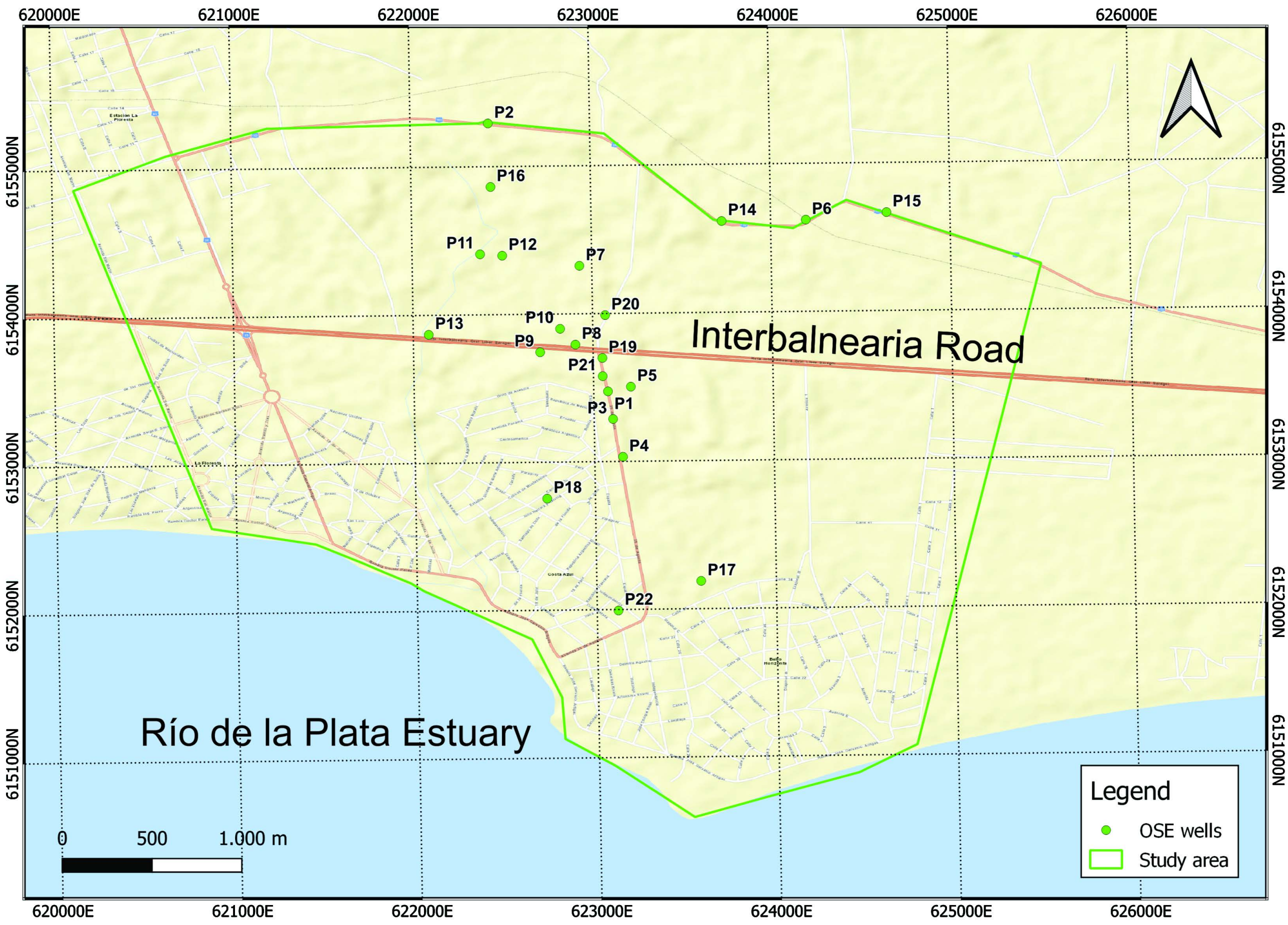

Figure 7. Detailed localization of O.S.E. background wells with previous information in the study area.

Table 2. Well information as data summery from available chemical results provided by O.S.E.

Chemical information	Chemical elements												
	Cl (mg/L)	Na (mg/L)	As (mg/L)	Fe (mg/L)	F (mg/L)	Cond (μs/cm)	Hardness (mg/L)	Alkalinity (mg/L)	NO_3 (mg/L)	NO_2 (mg/L)	NH_4 (mg/L)	SO_4 (mg/L)	pH
count	75	104	79	109	77	82	76	76	76	76	76	12	82
mean	148.73	209.221	0.01	0.072	0.46	1340.134	224.039	408.816	8.103	0.0126	0.28	56.667	7.301
std	92.51	91.814	0.004	0.174	0.156	533.548	69.858	118.131	3.34	0.0198	5.6×10^{-17}	33.641	0.167
min	44	58	0.002	0.04	0.35	571	110	187	2.3	0.01	0.28	18	6.9
25%	52.5	126	0.007	0.04	0.35	856.5	154.75	335.25	5.8	0.01	0.28	30.75	7.2
50%	177	244.5	0.011	0.04	0.35	1593.5	238.5	451	8	0.01	0.28	51.5	7.3
75%	214.5	274.8	0.012	0.04	0.57	1737.3	264	485.75	11	0.01	0.28	80.5	7.4
max	381	385	0.017	1.7	0.86	2460	424	626	17	0.18	0.28	128	7.7

maximum allowed value in Uruguay in one of the southernmost wells. Chlorides remain stable over time, except for the northernmost wells which show small variations in recent years, as well as higher values compared to the southern wells, revealing 2 well-differentiated groups. The behavior of sodium also shows 2 well-differentiated groups, similar to chlorides, with the lower values found further south. Additionally, two of these southern wells show a sharp increase in 2015, surpassing the maximum allowed value and reaching the values of the northernmost wells.

For the O.S.E. data base wells, the variables considered are ion chloride (Cl), ion sodium (Na), total As (As), total Fe (Fe) and ion fluoride (F^-). The normality study shows that the variables considered do not have a normal distribution. The presence of outliers occurs only in the Fe variable. In the study case, due to the lack of normality of the variables and the presence of outliers in one, the Spearman coefficient was chosen to show the correlation between the different variables with each other (**Figure 8**). At the very beginning, it was procured the distribution of the variables using scatter plots and density plots, as well as histograms for each variable. The correlation coefficient of the variables was calculated and visualized using Python's libraries such as Pandas and Matplotlib.

The correlation coefficients show a high correlation in one case, medium in one case, small in three cases and very small in five cases. The p-values are less than 0.05 for the high and medium correlations and in 1 case of the very small ones, stated as follows: 1) 0: null association, 2) 0.1: small association, 3) 0.3: medium association, 4) 0.5: moderate association, 5) 0.7: high association, 6) 0.9: very high association. Na and Cl show a high correlation, with r value of 0.87 and a p-value of 4.39×10^{-19}. Na and As show a medium correlation, with a r value of 0.42 and a p-value of 1.35×10^{-4}. A correlation between the studied variables Na, Cl, As, F, Fe can be observed in a matrix of variables and a matrix of correlation (**Figure 10**). Na-Cl shows a high correlation, As shows a medium

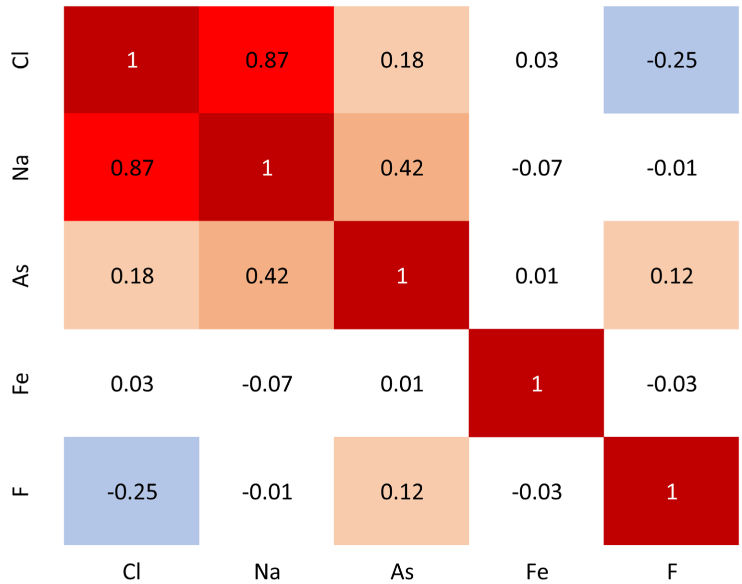

Figure 8. Matrix of Spearman's coefficient correlation of the variables.

correlation with Na, while F shows a very poor correlation with all other variables. As shown in Figure 9, the Na with respect to Fe shows a high mobility of Na and low mobility of Fe, and it does not show a trend line but a random distribution and correlation index is very low (correlation index = −0.072). The As with respect to the Na also shows a random distribution confirming its low correlation's coefficient. The Na-Cl relationship presents a high correlation index (0.86) favoring the hypothesis of a saltwater intrusion to explain the rather high values of Na and Cl. However as it can be seen below there are other arguments that contradict this interpretation.

5.3. Update of the Hydrogeochemistry Data

In 2023 fourteen O.S.E. wells were resampled, according to previous criteria and O.S.E. suggestions. Sampling includes wells reaching the locality of Soca 8 km to the north and Cuchilla Alta 10 km to the east (Figure 2 and Figure 10).

Hydrogeochemical majority ions results were carried out for the study area in Costa Azul, La Floresta, Cuchilla Alta and Soca (Figure 2). Chemical results are presented in Table 3 and Table 4.

The quality of the chemical analyses was checked by calculating ionic balance and it was verified.

Hardness values show soft and moderate hard waters and their levels were between 63.5 to 334.4 mg $CaCO_3$/L. Alkalinity values were between 122.6 to 570.5 mg $CaCO_3$/L (Table 4).

Major ion characterization of all groundwater samples was performed according to Piper diagram (Figure 11).

Three samples from Costa Azul (CA1, CA2, CA3) can be classified as sodium chloride type, while other samples from Costa Azul are Sodium bicarbonate type or mixed type (CA7, CA8, CA10, CA11, CA12 and CA13). The CA5 sample

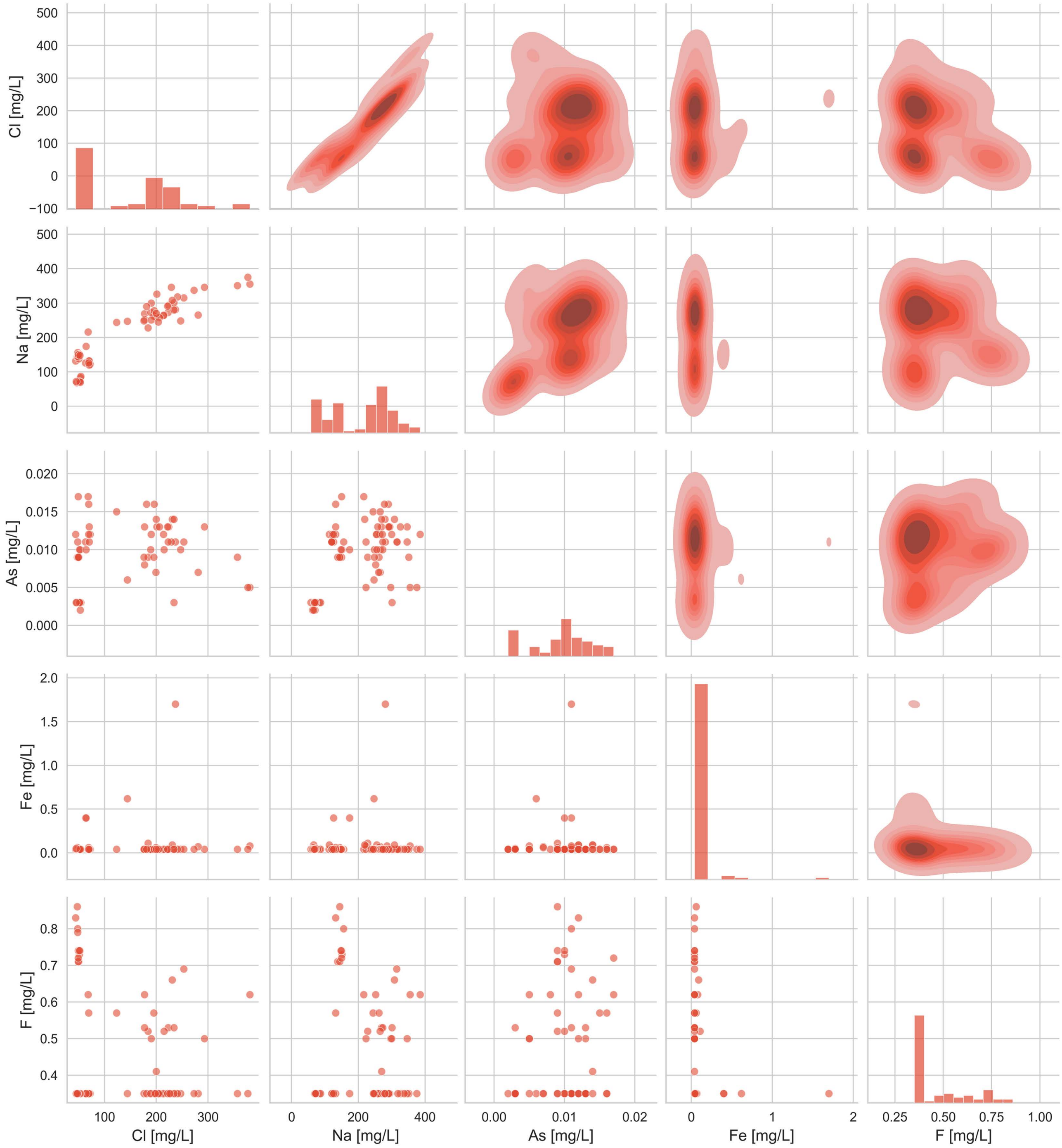

Figure 9. Matrix of the variables showing their relationship by means of scatterplots and density plots. All charges from ions were delete and total arsenic is represented by As, for practical reasons.

from Santa Ana is classified as well as sodium chloride water and CA4 sample from Cuchilla Alta is sodium bicarbonate type. The sample from Soca (CA6) can be classified as sodium bicarbonate type.

Curiously in Costa Azul samples that are rather far to the coast (CA1, CA2, CA3) are sodium chloride type, and in other samples that are near to the coast (CA8, CA9) there were observed sodium bicarbonate water. Mixed type was

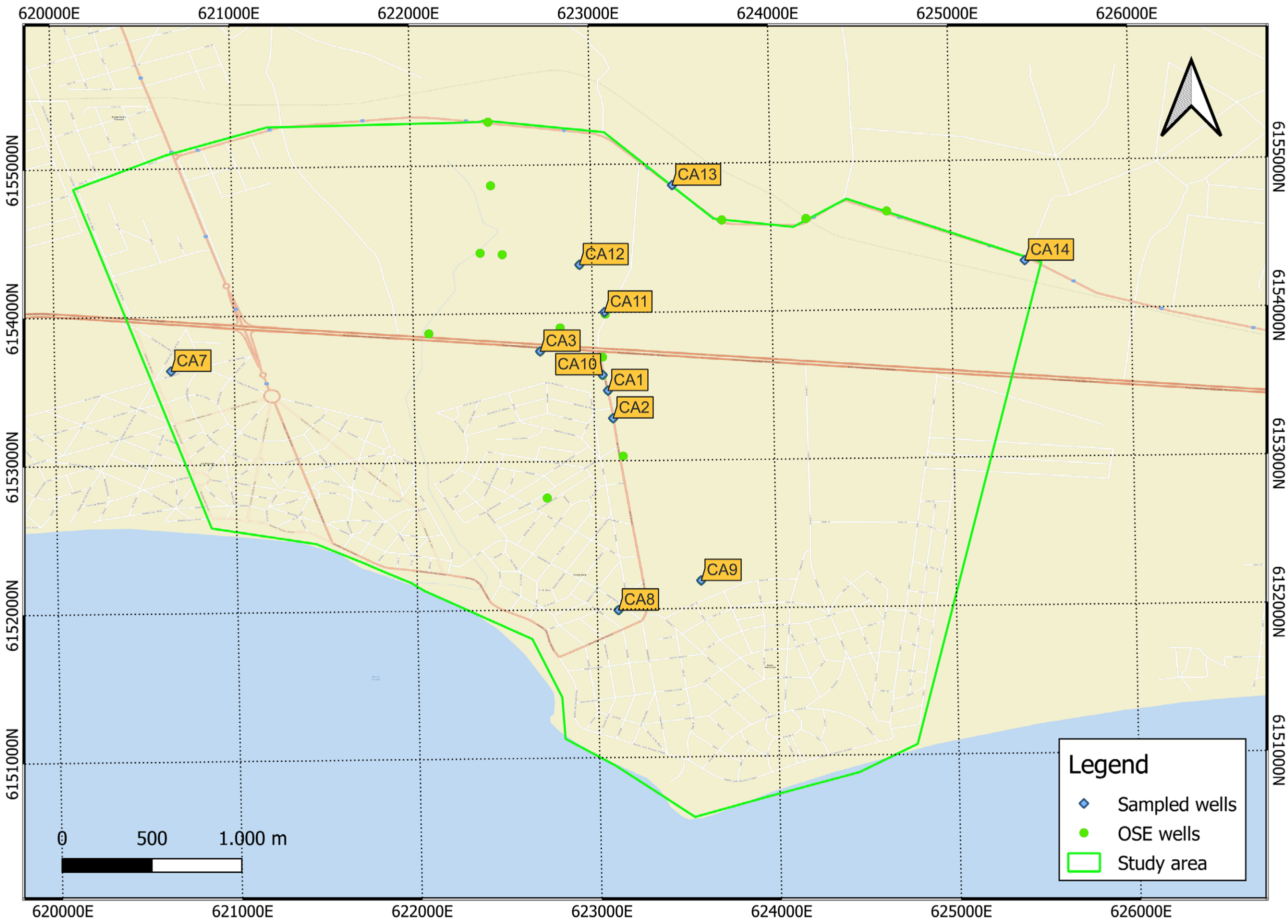

Figure 10. New sample wells analyzed in the study area.

Table 3. Field collected data for well samples CA1 to CA14. Physicochemical parameters measured in situ by duplicate and results indicate (mean + standard deviation). and some well information. Geographic location (X. Y) corresponds to Universal Transversor Marcator (UTM) coordinates system.

Field data Well	Coordinates		Sample ID Sample	Chemical parameters							Hydraulic parameters		
	X	Y		pH	Eh (mV)	DO (mg/L)	Conductivity (μs/cm)	TDS (mg/L)	Turbidity (FNV)	Temperature (˚c)	Water level (m)	Depth (m)	Flow rate (m^3/h)
1	623,079	6,153,474	CA1	7.34 ± 0.31	161.4 ± 3.75	1.96 ± 0.11	2002 ± 69	1002 ± 69	1.3 ± 0.2	19.4 ± 1.0	23	60	8
2	623,105	6,153,287	CA2	7.40 ± 0.35	144.7 ± 2.33	1.12 ± 0.31	1323 ± 97	661 ± 77	0.5 ± 0.1	19.6 ± 1.1	25.11	60	4
3	622,705	6,153,743	CA3	7.18 ± 0.12	331.0 ± 1.98	4.74 ± 0.33	2489 ± 78	1244 ± 74	0.4 ± 0.1	18.6 ± 1.0	14.52	42	4
4	637,971	6,149,227	CA4	7.62 ± 0.43	265.1 ± 1.34	5.74 ± 0.38	812 ± 62	405 ± 67	0.3 ± 0.1	19.8 ± 1.0	13	73	7
5	640,634	6,150,378	CA5	7.49 ± 0.34	242.2 ± 0.99	4.20 ± 0.25	916 ± 121	458 ± 60	0.4 ± 0.1	18.5 ± 0.6	11	31.5	6.5
6	618,379	6,161,494	CA6	7.30 ± 0.21	232.2 ± 6.51	3.70 ± 0.57	1522 ± 8	761 ± 4	0.3 ± 0.0	19.3 ± 0.4	3.88	49	20

Continued

7	620,648	6,153,635	CA7	7.16 ± 0.05	240.1 ± 0.95	0.56 ± 0.12	1090 ± 51	547 ± 20	1.5 ± 0.1	18.0 ± 0.5	5.8	32	20
8	623,622	6,151,246	CA8	6.95 ± 0.08	241.2 ± 1.00	0.26 ± 0.13	532 ± 25	266 ± 19	0.5 ± 0.1	18.8 ± 0.5	11.4	47	4
9	623,581	6,152,754	CA9	6.95 ± 0.22	235.6 ± 1.20	0.23 ± 0.11	815 ± 24	407 ± 46	0.2 ± 0.0	18.4 ± 0.8	2.2	34.6	7
10	623,050	6,153,580	CA10	6.99 ± 0.16	235.3 ± 1.95	0.60 ± 0.13	1554 ± 11	777 ± 39	0.3 ± 0.1	19.5 ± 0.8	20	49.5	53
11	623,066	6,154,003	CA11	6.96 ± 0.17	232.1 ± 2.15	0.47 ± 0.05	1524 ± 21	762 ± 32	0.2 ± 0.1	18.8 ± 1.0	10	60	12
12	622,931	6,154,324	CA12	6.97 ± 0.22	231.6 ± 0.95	0.75 ± 0.05	1590 ± 68	795 ± 51	0.4 ± 0.1	18.5 ± 1.3	0.5	31	12
13	623,454	6,154,854	CA13	6.98 ± 0.21	233.9 ± 0.55	1.81 ± 0.06	1553 ± 17	776 ± 63	1.0 ± 0.1	18.6 ± 0.5	7.35	70	25
14	625,411	6,154,322	CA14	6.9 ± 0.18	227 ± 2.50	0.66 ± 0.09	1803 ± 61	902 ± 76	0.2 ± 0.0	19.3 ± 1.0	10.8	80	11

Table 4. Hydrogeochemistry analysis of majority and trace ions. On top the major ions ionic balance error (E%) and the detected levels. At the bottom Alkalinity and Hardness laboratory, duplicate results. ND: no detected.

Hydrogeochemistry	Samples													
	CA1	CA2	CA3	CA4	CA5	CA6	CA7	CA8	CA9	CA10	CA11	CA12	CA13	CA14
Total anions	16.8	16	20.3	10.7	7	20.4	4.4	5.4	8.9	16.1	16.6	16.9	16.7	19.1
Total cations	14	13.2	16.5	8.7	5.7	17	5.1	6	9.2	17.2	17.4	18.5	18.4	20.2
Error (%)	−9	−10	−10	−10	−11	−9	−10	−9.6	−3.5	−6.2	−4.8	−8.8	−9.5	−5.6
Cl (mg/L)	264.3	276.6	396.8	89.5	137.8	268.1	28	38.5	47.6	205.1	225.6	259.6	249.2	341.4
Br− (mg/L)	2.5053	1.5464	1.806	0.9421	1.0839	1.4125	ND	ND	ND	0.452	0.452	0.452	0.452	0.452
F− (mg/L)	0.6542	0.8655	0.7542	0.2141	0.222	0.7228	0.2042	0.1703	0.411	ND	ND	ND	ND	ND
NO_3 (mg/L)	15.2	61	14.9	26.4	1	30	2.5	9.7	11.9	9.5	11	13.2	15.1	5.7
SO_4 (mg/L)	110.1	145.6	127.7	26.1	31.9	67.1	8.4	15.6	27.5	89.7	72.6	63	64.9	73
Na (mg/L)	288.3	274.8	335.5	168.7	93.7	344.2	63.5	68.9	155.7	284.9	279.5	278	289.9	284.4
K (mg/L)	0.4	0.3	0.5	1	0.7	1.1	1.8	0.9	0.1	1.9	0.4	0.3	0	1.6
Mg (mg/L)	7.6	6	9.2	5.8	5.5	12.2	6.5	7.8	7.8	20.2	24.3	26.4	21.7	32.5
Ca (mg/L)	16.5	15.5	21.6	17	22.1	18.8	21.4	34.9	29.2	40.6	48.8	53.4	46.6	80.4
HCO_3 (mg/L)	430.4	317.4	393.8	464	149.6	696	249.5	267.7	432	571.9	571.9	590.2	596.3	547.6
*Alkalinity	352.8 ± 3.5	260.2 ± 21.2	322.8 ± 3.5	380.3 ± 7.1	122.6 ± 3.5	570.5 ± 7.1	204.5 ± 3.5	219.4 ± 7.1	354.1 ± 7.1	468.8 ± 3.5	468.8 ± 3.5	483.8 ± 7.1	488.8 ± 7.1	448.9 ± 3.5
*Hardness	72.3 ± 3.9	63.5 ± 2.4	91.8 ± 1.1	66.2 ± 0.4	77.5 ± 0.6	97.2 ± 1.0	80.2 ± 4.6	119.2 ± 1.4	104.9 ± 4.4	184.7 ± 6.8	221.9 ± 3.4	242.2 ± 4.4	205.5 ± 3.2	334.4 ± 2.1

*Data correspond to mean of duplicate values.

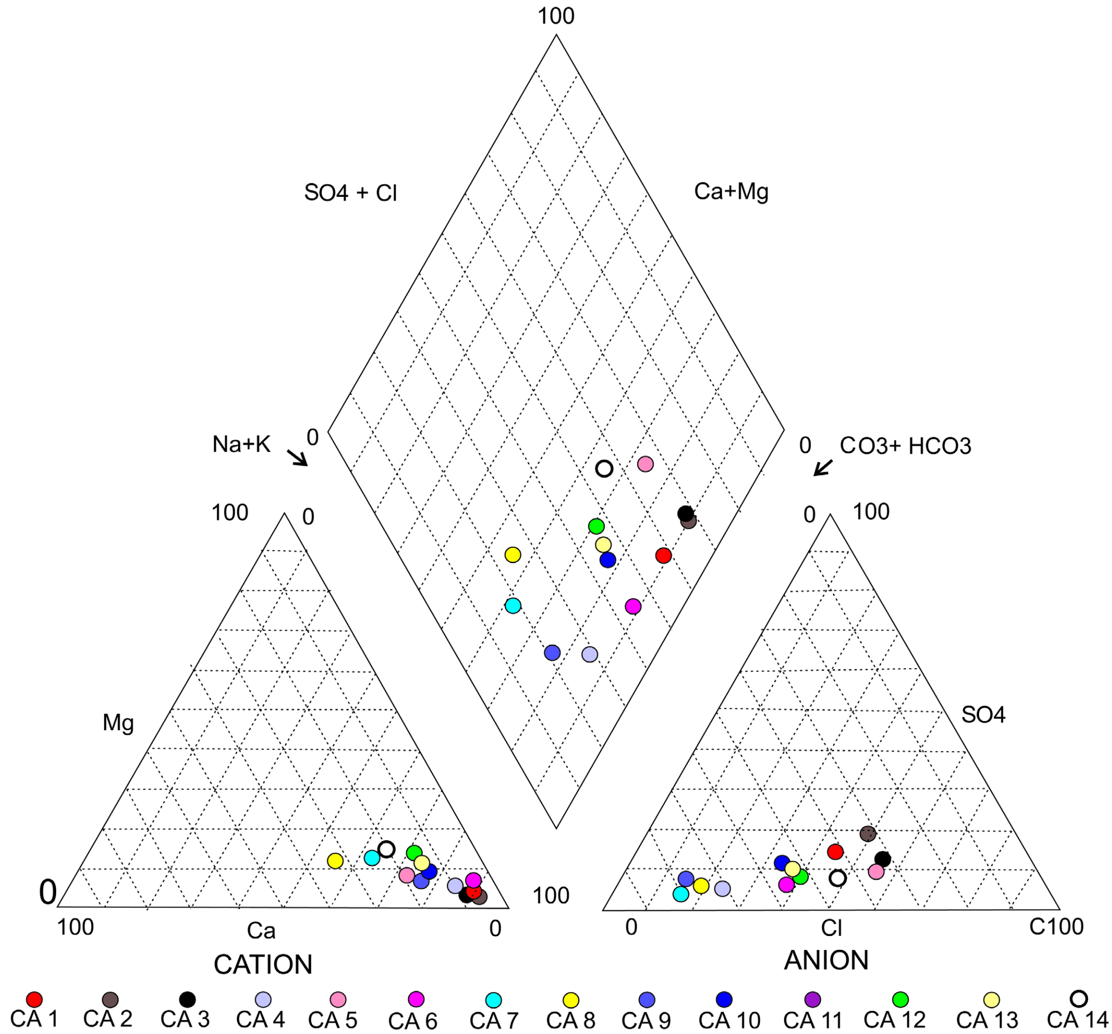

Figure 11. Piper diagram for Costa Azul wells samples of Costa Azul, La Floresta, Cuchilla Alta, Santa Ana and Soca.

observed in the northern area (CA10, CA11, CA12, CA13).

In general, samples which are in the northern part of the study area in Costa Azul show a sodic bicarbonate composition, where $CO_3 + HCO_3$ concentration is greater than SO_4 + Cl and Na + K is greater than Ca + Mg as in the last mentioned case.

12 km to the east, in Cuchilla Alta (CA4) sodium bicarbonate type was detected. Although very near in Santa Ana (CA5) sodium chloride water was observed. It is important to mention that CA4 sample is corresponding to Neoproterozoic basement water supply and CA5 is corresponding to Cenozoic sediments. La Floresta well (CA7) raised sodium bicarbonate waters although it is rather near to the coast. As well as the Santa Ana well (CA5) the water supply corresponds to Cenozoic sediments and not to the fractured aquifer.

Shoeller-Berkaloff diagram (**Figure 12**) show relative proportion of major ions, relatively high values for Na, Cl and HCO_3 from the Costa Azul northern area (CA10, CA11, CA12, CA13, CA14) and in the middle southern area (CA1,

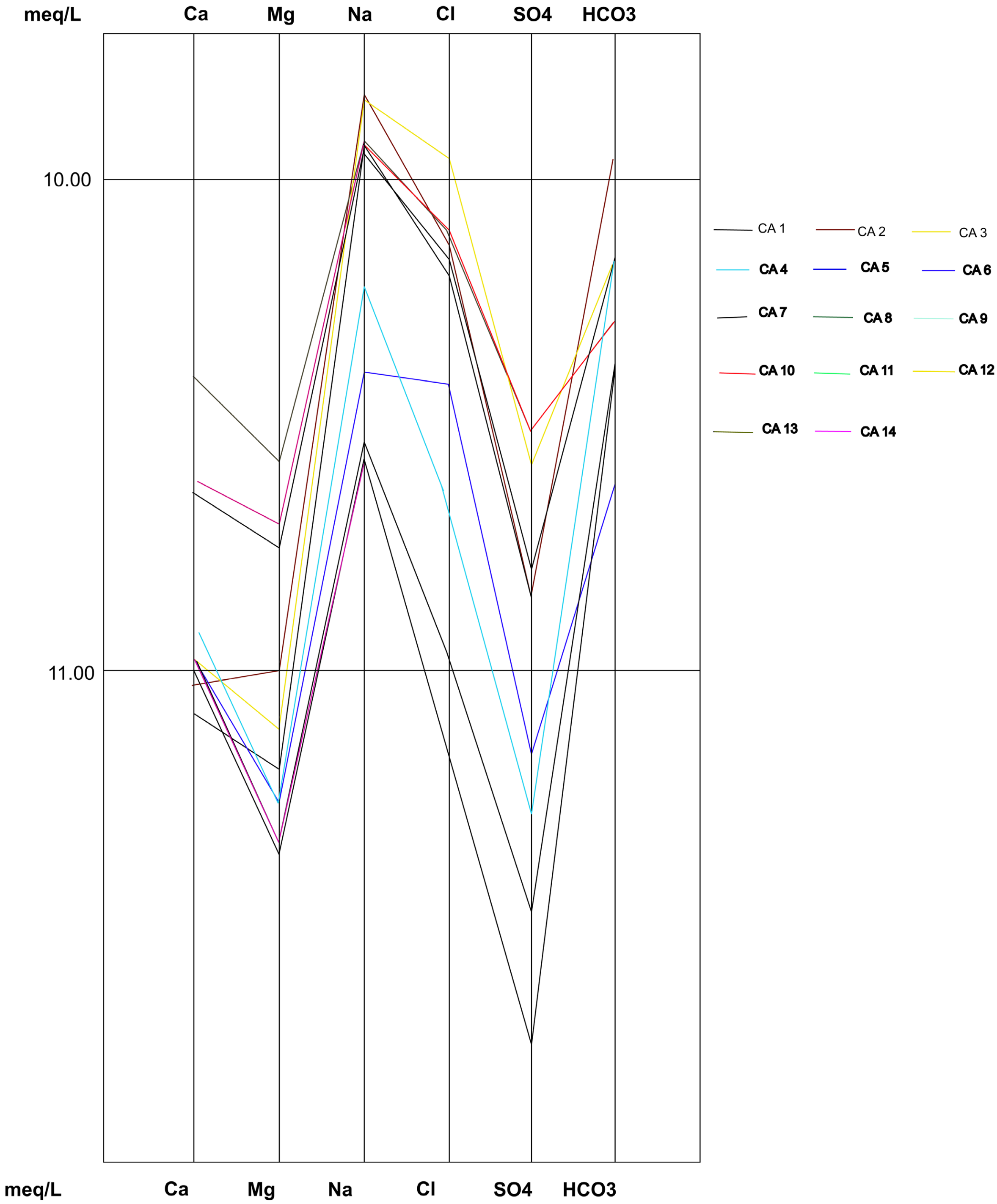

Figure 12. Schöeller-Berkaloff diagram.

CA2, CA3) and from Soca well (CA6) (**Figure 11**). Cuchilla Alta (CA4) well and Santa Ana (CA5) well have slightly lower concentrations of Na, Cl and HCO_3.

Salinity specific analysis were carried out, considering that Uruguay has its own law regulating water quality that is defined according to the uses of water as drinking water, irrigation, recreation and environmental preservation (Decrete 253/79, 2023). According to the salinity diagram for classification, which could be taking into account to evaluate water for irrigation purpose (**Figure 13**) (EasyChem®), most of the Costa Azul samples (CA1, CA2 CA3, CA10, CA11, CA12, CA13, CA14) could have high saline risk, with the highest electrical conductivity values for sample CA3. However samples CA7, CA8 and CA9 from Costa Azul show low salinity risk with the lowest electrical conductivity for CA8 sample.

Santa Ana samples, show low salinity risk, taking into account that these samples correspond to a different aquifer (sedimentary Cenozoic aquifer), this is perfectly understandable. Cuchilla Alta sample corresponds to the fractured aquifer conformed by the Neoproterozoic sandstones of the Piedras de Afilar Formation and different from the Paleoproterozoic granite-gneissic Costa Azul aquifer, so the salinity risk for the first mentioned is different and classified as low risk. Soca sample could present high saline risk despite the corresponding

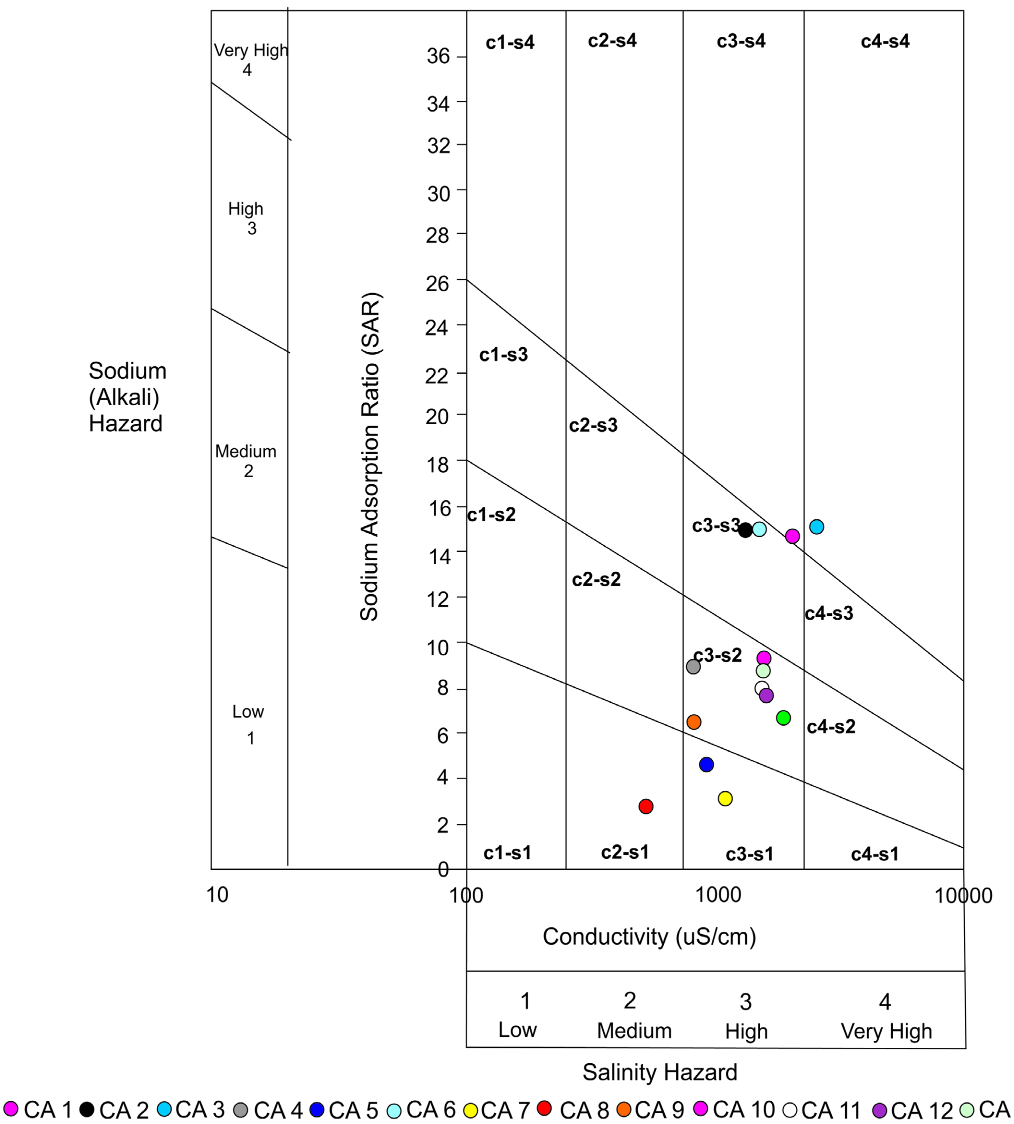

Figure 13. Salinity diagram for classification of irrigation waters for Costa Azul well samples (CA1, CA2, CA3, CA5, CA6, CA7, CA8, CA9, CA10, CA11, CA12, CA13, CA14), La Floresta sample (CA4), Cuchilla Alta sample (CA4), Santa Ana sample (CA5) and Soca sample (CA6).

well being further away from the sea than the other samples of the study area (see Figure 2). All these results should be strengthened by increasing the number of wells to analyze.

To investigate the existence of a possible saltwater intrusion, five different indicators (ionic ratios) were determined with the data obtained from the samples of the study area, Soca and Cuchilla Alta. The Santa Ana and La Floresta samples was not considered because it comes from another aquifer (sedimentary, Cenozoic).

Two of these indicators to assess whether an aquifer is contaminated by seawater are electrical conductivity (EC) and Cl^- concentration. Besides the Bromide provides valuable information and the analyzed water samples are between 0.4520 and 2.5053 mg/L. In the case of EC, the values obtained for all the samples are in the range for natural groundwater (<2000 µS/cm) (EPA, 2012). On the other hand, Cl^- content can be used to classify the type, where the samples can be classified as fresh-brackish (Ghezelsofloo et al., 2021). The correlation between EC and Cl^- concentration is strong ($r^2 = 0.84$) indicating that the EC is controlled by the concentration of chloride ions in the groundwater of the area. Saline water contaminated with seawater is characterized by a low Na/Cl ratio (<0.86, molar ratio) (Vengosh & Rosenthal, 1994). This ratio varies between 1.0 and 2.9, which indicates that there is not a seawater intrusion in the study area. Another proper indicator to identify a seawater intrusion is the Simpson Ratio ($Cl/(HCO_3+ CO_3)$) (Todd, 1959). According to this, from CA1 to CA14, wells CA4 and CA6 to CA13 show good quality, while the rest are slightly contaminated with seawater (Figure 14). Seawater has relatively uniform Cl and Br

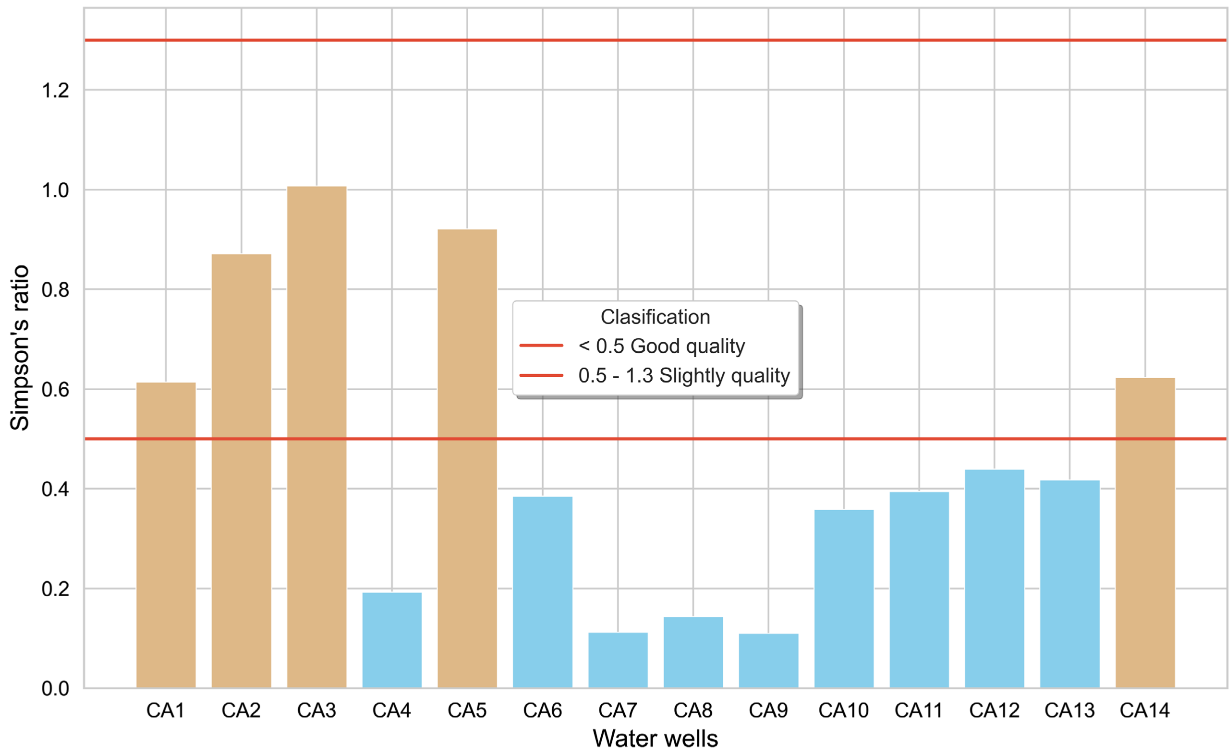

Figure 14. Simpson Ratio for the analyzed well samples, from CA1 to CA14.

concentrations and their Cl/Br molar ratio is around 655. For the study area, the samples indicate a ratio between 213 and 470, showing a different origin than saline intrusion (Alcalá & Custodio, 2008).

6. Discussion

A hydrochemistry characterization of the fractured aquifers from Costa Azul and surroundings Canelones, Uruguay, was performed and which shed light on whether or not there could be a saltwater intrusion after having identified the main bearing fractures and using well information.

Regarding photointerpretation and field work, main fractures were identified in NE direction and the complementary fracture in NW direction. This is very similar to the Punta Espinillo zone (Montaño et al., 2000a; Montaño et al., 2003), to the Arroyo Carrasco zone (Montaño Xavier, 1999) and also similar to the analysis of the southeast part of Montevideo Department (Pamoukaghlián et al., 2021b).

According to hydrogeochemical groundwater characterization by Piper diagram, over the study area samples from the north side of Costa Azul can be classified as sodium chloride water, those from the south side of Costa Azul are bicarbonate sodium and mixed type. Cuchilla Alta sample shown slight shift to bicarbonate sodium type and Soca sample is a mixed type of both. Schöeller-Berkaloff diagram (**Figure 10**) illustrates that Costa Azul samples and Soca sample have a high ionic content and Cuchilla Alta and Santa Ana samples have a rather lower ionic content. This suggests that the saltwater problem is in Costa Azul and spreading to the northern area reaching Soca. Most well samples (8) in the study area arise Na (max. 385 mg/L) and Cl (381 mg/L) values and EC values (2489 uS/cm) that are above the recommended limit for Na (200 mg/L) and for Cl (250 mg/L) and EC (2000 uS/cm) also exceed the standard recommended limits in most cases (UNIT, 2008, WHO, 2023).

However according to Tomaszkiewicz et al. (2014) groundwater classification from the study area are just moderately saline, taking into account a relative classification pondering chloride more than the total dissolved solids and electric conductivity. Sodium slightly high concentrations could be explained because of sodium mineral dissolution process, probably originated from sodium plagioclase in granites detected in most wells of the pilot area or even input from arcilles of the overlapping Libertad Formation.

Hydrogeological and hydrogeochemistry information obtained from this research suggest that Libertad Formation presents more thick overlapping the crystalline basement when Na concentration in groundwater is higher, suggesting a possible origin of the Na from arcilles of this sedimentary unit.

Another explanation could be the incorporation of sodium and chloride from rainfall which is product of the evaporation of saline water. Besides variations in Na could also be explained because the Río de la Plata estuary is affected by saline variability and at the same time, this can in fact attenuate a possible saltwater intrusion. Not only in the coastal aquifer there is rather high concentration of sodium but also in Soca locality, which is 8.9 km from the coast. Soca groundwater sample was classified as moderately to slightly saline water, similar to some coastal aquifer samples (CA1, CA2 and CA3). These results should be expanded by increasing the geological exploration and the numbers of monitored wells. However, this was a first approach to the saline intrusion studies by a hydrochemical studies. The next stage of this research should be incorporating isotope studies, to investigate the possible presence of some permeability fault that exerts a strong control on the local groundwater chemistry could be known.

According to the water quality analysis, hydrochemical results of CA2 indicates nitrate levels (61 mg/L) above the national maximum allowed value (50 mg/L) for water for human consumption and irrigation (UNIT 833:833, 2008; Decrete 253/79, 2023). The well CA6 also showed high levels of nitrates, although it is still under regulation limit. The possible reason of these results could be related to the organic matter contamination from septic tank leaks, near the wells, located to a distance less than the protection perimeter (20 m) (Article R.1718.18, Resolution 4809/19 Montevideo Municipality, 2019). Fluoride results showed a range of 0.1703 to 0.8655 mg/L, complying with Uruguayan regulations.

Sustainable management would imply to control pumping in order to avoid the increase of ionic concentration, specially sodium, chloride, nitrate, fluoride and arsenic. In wells related to NE-SE fractures where Na concentration is higher pumping should be reduce up to the necessary requirements. Afterwards hydrogeological prospection might take into account this feature and select other associated fracture directions although flow rates could be lower.

7. Conclusion

The fractured aquifer of Costa Azul shows a very heterogeneous behavior, according to the analyzed fracture directions and flow parameters and hydrogeochemistry. Main bearing fracture directions are NW-SE and NE-SW. Sampled wells in Costa Azul corresponding to NW-SE fracture direction have moderately saline groundwater. NE-SW and E-W direction related wells have lightly saline groundwater. Considering that higher flow rates correspond to NW-SE fractures, there is required a specific quality/quantity evaluation in order to select the best prospection context and this should be complemented with an evaluation of the thick of Libertad Formation which could be inputting Na.

The Costa Azul aquifer was studied from a statistical point of view and the only ionic ratio that showed a correlation index next to 1 was Na/Cl. According to O.S.E. data, arsenic was studied, but there are no high values and the ratio Na/As was medium. F and Fe showed a low correlation index with Na. The Rio de la Plata estuary is near the study area, its water is brackish-salty and it is possible that Cl and Na from the analyzed wells came from the estuary. The salinity variations over this area must be approached taking into account climate change and possible changes in the direction of ocean currents.

Hydrogeochemical characterization, Simpson ratio and other indicators suggest no evidence of saltwater intrusion in the study area. Instead high Na levels might be a product of mineral disolusion from granitic rocks of the crystalline basement or from the alteration of arcilles of the quaternary overlapping sediments.

According to drinking water quality evaluation, high Na and Cl values might impact in human health. Although the encountered values might affect only sensorial aspects for most of the population, this could be harmful for children and adult hypertensive people groups. The high nitrate levels detected could be related to organic matter contamination from septic tank leaks.

8. Recommendations

Some recommendations that should be taken into account to improve these studies near Costa Azul and Soca study areas are: 1) Frequent hydrochemical parameters monitoring and drinking water quality evaluation should be addressed. 2) Increasing the number of well samples analysis in Costa Azul and comparing the nearest to the coast as well as the bearing fractures direction, salinity classification and evaluating again the causes for the presence of the rather high values of Na and Cl. 3) Isotope analysis should be promoted in this area to enhance the understanding of the saline origin.

Finally, a comprehensive and interdisciplinary study to expand knowledge of coastal aquifers is essential forward to good practices in groundwater management.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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