RESEARCH PAPER

Groundwater Quality Analysis In Colliguay, Valparaíso Region: A Case Study In Rural Areas Of Central Chile

Cecilia Rivera[1], Isidora López[1], Nicole Roman[*], Antonio Ugalde[2], Miguel Rivera[2]

[1] Environmental Chemistry Laboratory (QA Lab), Department of Geography, Faculty of Natural and Exact Sciences, University of Playa Ancha. Avenida Carvallo 270, Playa Ancha, Valparaíso, Chile.

[2] Department of Applied Social Sciences, Feira de Santana State University, Feira de Santana, Brazil; Graduate Program in Administration - PPGA, Unifacs, Rua Dr. José Peroba 251,41770-235, Salvador, Brazil.

*Corresponding author: Cecilia Rivera, email: cecilia.rivera@upla.cl

ABSTRACT

In Chile rural regions, access to drinking water is impeded by drought, climate change, and the remoteness of localities. Some sectors continue to rely on the extraction of water through wells, waterwheels, and untreated springs. Colliguay Valley in the commune of Quilpué faces Water scarcity for over a decade and has been exacerbated by political water management and overuse for profit, as well as in the domains of livestock and agriculture. This study aims to evaluate the quality of the water available to users of the PRODESAL program in Quilpué, determining its safety for human consumption. In the autumn of 2018, 13 stations in the Marga Valley and Colliguay Valley, Quilpué, Valparaíso Region were subjected to comprehensive analysis including 20 physicochemical and microbiological parameters, in accordance with the regulations stipulated by NCh 409/Of.84 mod 2005, NCh1333/Of.78, and the World Health Organization (WHO) guidelines. As results, groundwater wells are predominantly freshwater and exhibit a high concentration of calcium carbonates. Most wells comply with the established Chilean regulations; however, it was observed that a number of these wells have exceeded the permitted limits for faecal and total coliforms, turbidity, and phosphates.

Keywords: Water quality, Rural areas, Water sustainability

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INTRODUCTION

Access to safe drinking water and adequate sanitation has been demonstrated to be directly related to human health and development [1]. Despite the increase from 79 percent in 1990 to 82 percent in 2000 in the percentage of people with access to treated water, it is estimated that more than one billion people worldwide lack a fixed supply of drinking water. Furthermore, it is estimated that 2.4 billion individuals, constituting more than one-third of the global population, currently lack access to adequate sanitation [2]. The sanitation problem is particularly acute, with 37 million urban dwellers and 66 million rural dwellers lacking these basic services [3].

In Chile, most rural areas are supplied with drinking water through a Rural Drinking Water (RPA) system. The system is comprised of committees or cooperatives that are responsible for maintenance and investments to improve and expand drinking water systems [4]. Institutions related to water in Chile, such as the Ministry of Public Works (MOP) and its dependencies, including the General Directorate of Waters and the Directorate of Hydraulic Works, among others, perform coordination and resolution functions [5]. Despite the initiation of novel initiatives aimed at enhancing the development of the APR, this system grapples with challenges in ensuring the quality and continuity of the service over an extended timeframe, thereby impeding access to water for a substantial segment of the population [6]. Consequently, a significant proportion of the rural population is reliant on groundwater or untreated springs as their primary source of drinking water.

The water problem in Chile is, to a large extent, a political problem [4]. Research has indicated that RPAs are characterised by deficiencies in the realm of water management, as evidenced by the presence of irregularities within public and administrative policies. These irregularities encompass a range of issues, including the administration of water rights, the utilisation of water resources, instances of water theft, and the sluggish implementation of the RPA Law. This phenomenon is indicative of an ineffective water resource management framework. Furthermore, a contentious issue persists regarding the utilisation of groundwater resources between local inhabitants and corporate entities [7].

Chile is among the countries worldwide that possess a high degree of surface water resources availability [5]. At present, the Metropolitan Region exhibits the highest demand for drinking water, accounting for 50.5% of total demand, while housing approximately 40% of the national population. The regions of Valparaíso and Maule have demonstrated a persistent consumption rate of 11.7% and 8.8%, respectively [8]. The Valparaíso region is confronted with water scarcity, a problem that has been exacerbated by the commodification of resources as stipulated by the Water Code [9, 10, 11].

This scenario is influenced by various forms of environmental governance and public policies that promote and encourage agricultural production [12]. The Chilean economy is predominantly reliant on the extraction of natural resources, particularly fisheries, forestry, and mining [13]. The implementation of these activities results in the imposition of substantial water stress on the respective regions, thereby effectively subordinating the notion of conservation. Livestock farming is one of the activities that has undergone the most transformations linked to the difficulty of accessing water resources [14, 15].

According to the World Health Organization [16], the definition of safe drinking water is as follows: water that, due to its condition and treatment, does not contain germs or toxic substances that can affect people's health. As stated by [17], the term can also be defined as "suitable for human consumption and for regular domestic use, including personal hygiene".

The Colliguay Valley, located 50 kilometers from the centre of Quilpué, in the Valparaíso region, is situated within a coastal mountain range and is surrounded by hills that make access to the commune difficult. This social isolation has enabled it to evolve as a sanctuary for various actors throughout its historical progression, culminating in its contemporary manifestation as the "plasterer of pleasure" [18, 12].

The primary objective of this study is to characterise and evaluate the quality of the water obtained from wells in the town of Colliguay through physical, chemical, and biological parameters. The secondary objective is to ascertain whether the water is suitable for human consumption.

MATERIAL AND METHODS

Study Area

The Colliguay Valley, a mountainous region of the Cordillera de la Costa, encompasses an area of 250 square kilometres, with altitudes ranging from 500 to 2,300 metres above sea level (Figure 1). The region's climate is classified as a dry temperate Mediterranean climate, characterised by summer drought and winter rainfall, with low temperatures. From October through April, the high-pressure system that is located in the eastern South Pacific moves toward more southern latitudes. This shift in the high-pressure system's position impedes the movement of frontal systems, thereby leading to an absence of rainfall in the region. As the high-pressure system withdraws to more northerly latitudes during the remaining months, the ingress of low-pressure systems becomes possible. As posited by [19], these systems are responsible for the production of precipitation, thereby replenishing the watercourses in the region.

Figure 1. Panoramic photo of Colliguay and some of the wells sampled.

With respect to its hydrography, the study area is situated within the drainage basin of the Puangue estuary, a sub-basin of the Maipo River. The hydrological regime of the estuary is defined by rainfall, which is sourced from the precipitation that accumulates within the local watershed, corresponding to the specific section of the Cordillera de la Costa within that particular extension. As [20] demonstrate, the flow is at its greatest during the winter months. According to the 2017 census, the sector contained 478 households and a total population of 330 individuals [21].

Colliguay maintains a certain degree of autonomy in economic terms, though it is in fact dependent on the commercial activities of Quilpué. The predominant economic activities in the region include agriculture, beekeeping, livestock farming, coal burning, and tourism, particularly during the summer months [22]. The Ministry of Agriculture has formally designated the area as a Protection Zone, in accordance with Decree Law 438 of 1974.

Selection of sampling stations and study period

A total of 13 sectors within the town of Quilpué were subjected to evaluation, with a particular focus on the Colliguay Valley. These sectors comprise populated areas distinguished by a permanent population. The sampling was conducted in May of 2018. A total of 13 groundwater wells were subjected to analysis, with 20 physicochemical and microbiological parameters being evaluated. The parameters in question were designated E1 through E13, thus representing the respective stations. Furthermore, a survey was conducted among the proprietors of the water wells, with the objective of collating pertinent data. This included details pertaining to the water usage patterns exhibited by these wells, any potential environmental concerns that may have been observed, and the health implications associated with water usage.

Table 1. Location of the analysed groundwater wells in the town of Colliguay.

	Ubicación	Coordenadas Geograficas Latitud (S°) / Longitud (W°)
E1	Los Molles, Fundo Santa Olga	33°04'41,0" / 71°24'55.84"
E2	Los Quillayes	33°10'58,34" / 71°19'57,31"
E3	Chacrillas	33°12'24,36" / 71°12'36.44"
E4	El Molino Sur	33°10'44,0" / 71°08'12,0"
E5	El Molino	33°10'9,84" / 71°08'12,0"
E6	Los Yuyos	33°11'20,64" / 71°05'58,59"
E7	Alto Totoral	33°11'22,69" / 71°14'35,73"
E8	Alto Totoral	33°12'04,0" / 71°09'11,0"
E9	Alto Totoral	33°11'20,21" / 71°14'37,87"
E10	Las Canales	33°10'45,41" / 71°10'01,54"
E11	Yuyos Altos	33°12'11,79" / 71°05'26,56"
E12	Las Canales	33°10'21,67" / 71°09'54,59"
E13	Cerro Viejo, Quebrada Seca	33°12'17,17" / 71°06'21,0"

Colliguay constitutes a rural sector of considerable extent, encompassing a variety of regions ranging from the Marga Marga estuary to the mountainous areas within the sector. The following figure illustrates the location of each of the sampled stations.

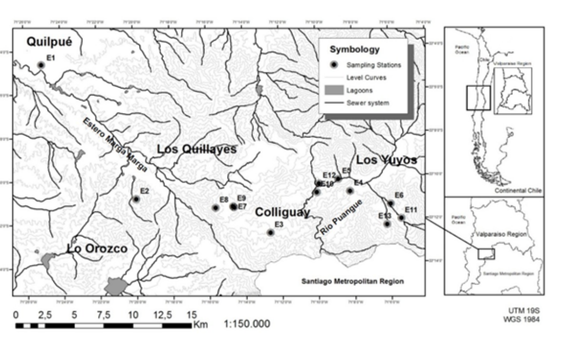

Figure 2. Geographical location and sampling stations located in the town of Colliguay.

Physicochemical and Microbiological parameters

An evaluation of water quality was conducted in accordance with the parameters established by the Chilean Drinking Water Quality Standard [23] and the Chilean Standard for Other Uses [24], with a particular focus on irrigation use. The findings were then compared with the recommendations provided by [16]. The analysis of twenty parameters was conducted in accordance with the provisions of the Standard Methods (ME) APHA-AWWA-WPCF [25]. For each station, parameters were evaluated in situ using a multiparameter equipment (Hanna Model HI-98194) corresponding to: The following parameters were measured: temperature (SM 2550-B), pH (SM 4500-HB), conductivity (SM 2510 A-B), dissolved solids (SM 2540-C), and dissolved oxygen (SM 4500 O-G). The water samples were collected in triplicate (n = 3) in accordance with the protocols stipulated in the Chilean Standard NCh 409/1 and NCh409/2. The samples were subsequently transferred for analysis to the Environmental Chemistry Research Laboratory (Lab QA) of the Faculty of Natural and Exact Sciences, University of Playa Ancha (UPLA). The remaining parameters that were evaluated included: The following parameters were analysed: turbidity (SM2130-B), colour (SM2120-C), odour (SM2150-B), taste (SM2160-B), free chlorine (SM4500-Cl G), total dissolved solids STD (SM2540-C), and total hardness (SM2340-C). The following parameters were analysed: total coliforms (SM 9221-B), faecal coliforms (SM 9221-A), iron (SM 3500-B), nitrate (SM 4500 NO3-B), nitrite (SM 4500 NO2-B), and phosphate (SM 4500-P).

Main Component Analysis

The present study employed Principal Component Analysis (PCA) as a means to transform a high-dimensional dataset into a lower-dimensional one, while ensuring that a substantial amount of the variability present in the original data was not lost. This objective was accomplished by elucidating the variance-covariance structure of a set of variables through the utilisation of a limited number of linear combinations of these variables. While principal components are generally required to replicate the complete variability of the system, a substantial portion of the original data can be elucidated by a limited number of principal components. From an algebraic perspective, the principal components are defined as linear combinations of the random variables pp, Y1, Y2, …, Yp.

Geometrically, these linear combinations represent the selection of a new coordinate system through rotation of the original system. The axes of the coordinates, denoted Y1, Y2, …, Yp, are thus defined. The new axes demonstrate directions with maximum variability and provide a simpler and more parsimonious covariance structure [26]. The principal component technique is contingent upon the covariance matrix (Σ) or the correlation matrix (ρ) of Y1,Y2,…,Yp. The development of PCA does not necessitate the assumption of multivariate normality. However, inferences can be made from the sample components when the population follows a multivariate normal distribution [26].

Conversely, a cluster analysis, illustrated schematically via a dendrogram, was employed to discern the associations and similarities between disparate data sets. The analysis was executed using Ward's method, also referred to as the minimum variance method. This approach quantifies the distance between two groups formed, with the objective of minimizing the sum of the squares of the differences within each group. This approach enabled the visualisation of the hierarchical groupings and relationships between the elements of the dataset, thereby facilitating the interpretation of the underlying structures [27, 26].

RESULTS AND DISCUSSION

The results indicate that the wells exhibit satisfactory water quality (Table 2). Specifically, 78.9% of the stations fall within the regulatory ranges established for human consumption and irrigation [23] [24] (NCh 409/1. 2005; NCh1333/78). The low turbidity (less than 1.73 ± 0.23 NTU), absence of colour, and low levels of total dissolved solids (averaging 189.62 ± 52.54 mg/L), iron (averaging 0.02 ± 0.03 mg/L), and chlorides (averaging 37.85 ± 23.13 mg/L) are noteworthy. The water is distinguished by its tasteless and odourless properties. The temperature measurements indicate an average of 20.76 ± 5.01 °C (ambient) and 15.93 ± 4.28 °C (water), respectively. Moreover, the pH level of the water was documented as 7.24 ± 0.25.

Table 2. Results obtained from the evaluated parameters of the town of Colliguay.

	Referencia Ubicación		Limite Máximo Permitido (LMP)	POZO 1	POZO 2	POZO 3	POZO 4	POZO 5	POZO 6	POZO 7	POZO 8	POZO 9	POZO 10	POZO 11	POZO 12	POZO 13
1	Temperatura Ambiente	°C		13.2	18.2	24.4	27.1	27	26.2	15.2	18.2	16.6	24.1	25.2	15.6	18.9
2	Temperatura Agua	°C		15.5	19.6	23.1	18.7	18.5	20.0	11.9	13.1	13.1	15.6	18.6	7.8	11.6
3	DT	°C		-2.3	-1.4	1.3	8.4	8.5	6.2	3.3	5.1	3.5	8.5	6.6	7.8	7.3
4	pH	--------	6,5-8,5	6.95	7.5	7.28	7.25	7.1	7.43	7.87	7.08	7.02	7.06	7.28	7.25	7.08
5	Profundidad	cm		500	NM	800	900	700	1100	500	NM	1400	3200	900	0.7	0.7
6	Turbiedad	NTU	5	0.29	0.56	0.16	1.64	0.63	0.27	4.57	5.28	1.85	0.68	6.51	0	0
7	Color	Pt-Co	20	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Olor	------------	Inodoro	Inodoro	Inodoro	Inodoro	herbaceo	Inodoro	Inodoro	Inodoro	Inodoro	Inodoro	Inodoro	Inodoro	Inodoro	Inodoro
9	Sabor	------------	Insipido	Insipido	Insipido	sabor a plástico	Ácido/ terroso	Insipido	Insipido	Insipido	Insipido	Insipido	Insipido	Insipido	Insipido	Insipido
10	Conductividad	uS/cm	< 750	627	387	450	361	329	385	134	234	394	375	360	369	360
11	Cloro Libre	mg/L	>0.1 - <2.0	0	0	0.37	0	0	0	0	0	0	0	0	0	0
12	Sólidos Disueltos Totales	ppm	1500	314	193	225	178	164	192	67	205	197	187	178	186	179
13	Dureza Total	mg/L $CaCO_3$	< 100	280	200	240	240	240	280	160	160	120	160	160	0.4	1.06
14	Coliformes Totales	NMP/100mL	0	23	110	330	23	9200	23	45	>16000	45	2	350	4.5	33
15	Coliformes Fecales	NMP/100mL	0	<1.8	<1.8	<1.8	<1.8	<1.8	<1.8	<1.8	<1.8	<1.8	<1.8	<1.8	<1.8	<1.8
16	Oxígeno Disuelto	mg/L	> 5.0	3.84	5.84	8.48	641	6.25	8.17	9.64	2.38	7.89	7.29	5.02	7.91	7.6
17	Hierro	mg/L	0.3	0.04	0.01	0.00	0.09	0.00	0.00	0.03	0.02	0.01	0.00	0.01	0.03	0.06
18	Cloruros	mg/L	250	70.90	70.9	42.54	56.72	42.54	56.72	14.18	14.18	28.36	56.72	14.18	9.45	14.6
19	Nitrato	mg/L	50	5.8	0.4	5	0.5	2.9	0.8	0.6	0.5	2.2	4.7	1.6	0	0
20	Nitrito	mg/L	3.0	0.16	0.15	0.28	0.12	0.22	0.20	0.02	0.03	0.02	0.03	0.06	0	0.00
21	Fosfato	mg/L	0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.36	3.0

The analysis revealed that all wells contained fresh water, with low average conductivity (< 366.54 ± 111.64 µS/cm). The wells E7 and E1 exhibited particularly low conductivity levels of 1.34 µS/cm and 627 µS/cm, respectively. The conductivity of water, influenced by dissolved ions of acids and salts, serves as an indirect indicator of the concentration of total dissolved solids. This parameter has the potential to adversely impact individuals with heart or kidney disease, contributing to the development of renal calculi [28, 29].

Water hardness, defined as the concentration of metal cations (e.g., calcium and magnesium) that precipitate out as calcium carbonate (CaCO3) [30, 31], is a critical indicator of water quality. According to the World Health Organization [16], the classification of water is as follows: soft if it contains less than 60 milligrams per litre of calcium carbonate (CaCO3), moderately hard if it contains between 61 and 120 milligrams per litre, and very hard if it contains more than 180 milligrams per litre. The findings suggest that two wells (E12 and E13) exhibit notably soft waters, while 76.9% of the remaining wells are classified as very hard, with an average content of 172.42 ± 91.25 mg/L CaCO3 [8, 32].

A total of four parameters were found to exceed the established limits: total and faecal coliforms at all stations, turbidity at E8 and E11, and phosphates at E12 with 1.36 mg/L. While the majority of parameters remain within regulatory limits, it is imperative to maintain continuous monitoring of water quality, particularly in cases where parameters such as total and faecal coliforms, turbidity, and phosphates exceed acceptable limits. These parameters are indicative of microbiological and organic contamination, potentially influenced by anthropogenic activities [14, 16].

Figure 3. Graphic representation of the physicochemical parameters of the water quality of the Locality of Colliguay, Valparaíso Region.

The presence of total and faecal coliforms poses a significant risk to public health, as it can facilitate the transmission of intestinal diseases [33]. This finding emphasises the pressing need to implement disinfection measures, such as chlorination of water, to ensure its safety for human consumption, in accordance with the recommendations of the World Health Organization [34, 35].

The Principal Component Analysis (PCA) depicted in Figure 4 offers supplementary insights into the interrelationships among the various parameters under consideration. The relationship between water temperature, total hardness, nitrite levels, and other parameters can provide insights into the dynamics of water quality in the wells studied, thus helping to identify key factors influencing the variability observed in the water quality data. [36] employed the principal component analysis (PCA) with Varimax rotation to determine the number of factors to be retained.

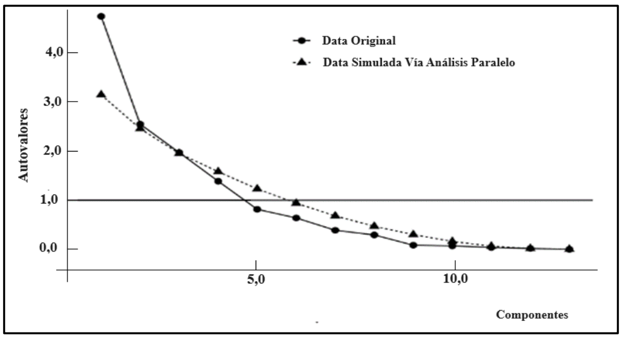

Figure 4. Graph of the eigenvalues resulting from the Principal Component Analysis (PCA), known as *the scree plot.*

The chi-square test of model goodness of fit ($\chi^2 = 103.61$; df = 32; $p < 0.01$) indicates that the model has a good interpretation of the correlation matrix between the items, suggesting that the model fit is adequate for the data. As demonstrated in Figure 3, the analysis of the eigenvalues identifies four primary factors that are the most significant, accounting for 81.98% of the total variance. As demonstrated in Table 3, Component 1 accounts for 28.98% of the variability, Component 2 for 24.10%, Component 3 for 14.72%, and Component 4 for 14.18%. This finding indicates that these four components are responsible for most of the observed variability in the data. Consequently, they provide a comprehensive perspective on the underlying factors that influence the variables under study.

Table 3. Explained variability of each of the Components

	Rotated Solution		
	Sum of the squared charges	**Proportional variability**	**Cumulative**
Component 1	3,7673	0,2898	0,2898
Component 2	3,1324	0,241	0,5308
Component 3	1,9135	0,1472	0,6779
Component 4	1,8437	0,1418	0,8198

As demonstrated in Table 4, the loads of the original variables on the principal components are illustrated, thus providing information regarding which variables have the greatest influence on each component. This analysis enables the identification of the variables that contribute most significantly to each principal component, thereby facilitating an interpretation of the components' representation of the original variables. For instance, in Main Component 1 (PC1), variables such as water temperature (0.9486), total hardness (0.8883), and nitrite levels (0.8662) have the highest loads, indicating their greatest influence on this component.

The results of the Principal Component Analysis (PCA) with Varimax rotation provide a detailed understanding of the relationships between different water quality parameters in the wells studied. The considerable number of variables, including water temperature, total hardness, and nitrite levels, on PC1 indicates a robust correlation among these factors and their potential contribution to water quality. Concurrently, the elevated levels of total dissolved solids, pH, and conductivity in PC2, along with dissolved oxygen and iron in PC3, underscore their significance in the observed variability in water quality data. This analysis is imperative in identifying the pivotal factors that influence water quality. Conducting this analysis will facilitate the development of effective management and conservation strategies.

Table 4. Results of Principal Component analysis, using the varimax rotation method applied.

	PC1	**PC2**	**PC3**	**PC4**	**Singularity**
Water Temperature	0,9486				0,0896
Total Hardness	0,8883				0,1864
Nitrite	0,8662				0,1543
Room Temperature	0,7253				0,3635
Chlorides	0,6538				0,2161
Total Dissolved Solids		0,9268			0,1039
pH		-0,8898			0,1117
Conductivity		0,8214			0,0658
Nitrate		0,6248			0,3165

Table 4. Results of Principal Component analysis, using the varimax rotation method applied.

	PC1	PC2	PC3	PC4	Singularity
Dissolved Oxygen			0,9303		0,0494
Iron			0,9025		0,0976
Total Coliforms				-0,8912	0,1812
Turbidity				-0,6446	0,4069

As illustrated in Figure 5, entitled "Path Analysis," the hypothetical causal relationships between the variables studied in the water quality of Colliguay are demonstrated. The diagram illustrates the interplay between direct and indirect relationships; whereby observed and latent variables are represented by arrows that denote the direction and magnitude of the effects. Direct relationships are observed when an arrow connects two variables directly, such as the relationship between ambient temperature and water turbidity. The phenomenon of indirect relationships emerges when one variable exerts an influence on another through intermediate variables. A notable illustration of this phenomenon is the observation that ambient temperature affects the concentration of total coliforms, with its effect on turbidity serving as an intermediary factor in this relationship. Regression coefficients are utilised to quantify the strength of these relationships, with higher coefficients denoting a greater effect.

The diagram under consideration elucidates several salient points regarding the quality of water. It has been demonstrated that the environmental temperature exerts a substantial influence on numerous parameters. This indicates that climatic conditions possess the capacity to influence biological activity and surface runoff, consequently affecting water quality. The presence of total coliforms has been demonstrated to be associated with turbidity and total dissolved solids, suggesting the possibility of faecal or agricultural contamination as a contributing factor. Furthermore, the interplay between pH, electrical conductivity (EC), and additional chemical constituents indicates intricate interactions that bear upon water quality, potentially associated with the geological characteristics of the region. This exhaustive analysis is imperative for the development of more efficacious management and conservation strategies. The analysis should focus on the most influential variables and the primary causal routes.

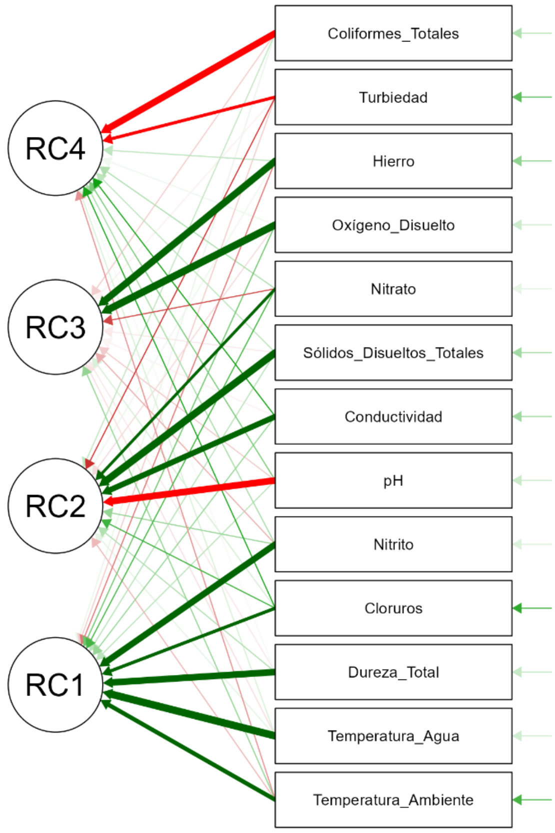

Figure 5. Path Diagram (Path Analysis).

Figure 6 presents the clustering analysis of the PCA, relating the stations to the variables. The graph indicates that stations E5 and E8 exhibit elevated levels of total coliforms, while other stations demonstrate predominance of parameters such as electrical conductivity (EC), total dissolved solids (TDS), and total hardness. This differentiation suggests the presence of specific factors influencing water quality variability across seasons, potentially associated with point sources of pollution or variations in geological and land-use characteristics. A positive correlation is observed between ambient temperature, turbidity, STDs, total hardness, total coliforms, and nitrite (NO2-). Conversely, negative correlations have been observed with parameters such as water temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), iron, chlorides (Cl-), nitrate (NO3-), and phosphates (PO4-3). The findings indicate a tendency for certain parameters to covary, thus suggesting the potential for interactions or shared processes that influence water quality.

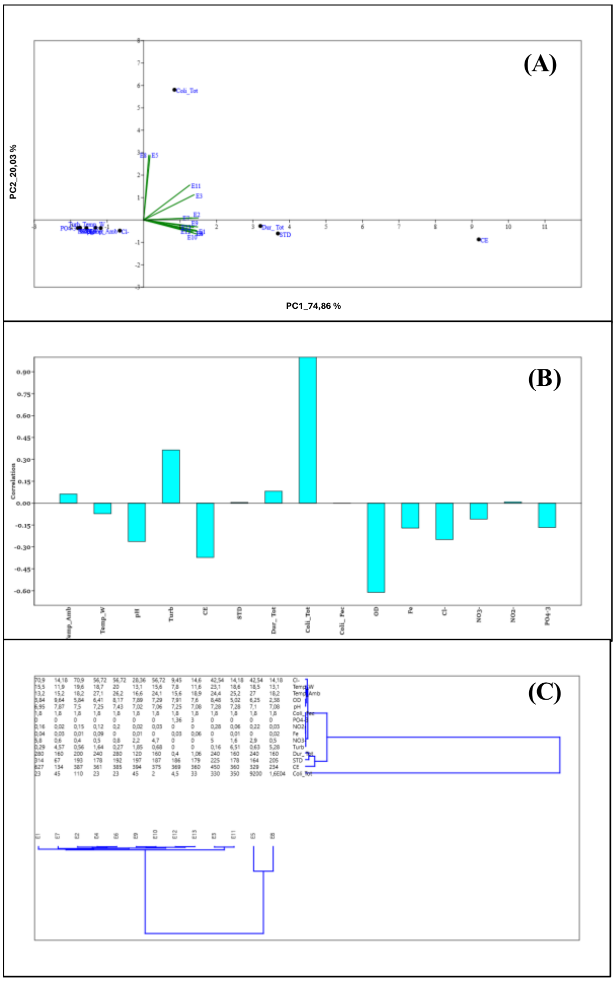

Figure 6. Results of the Principal Component Analysis (PCA) obtained through the clustering analysis of water quality variables of the town of Colliguay (A)

CONCLUSION

The study's findings indicate that while the water quality in the town of Colliguay is generally satisfactory, with 78.9% of the stations meeting regulatory standards for human consumption and irrigation, significant concerns persist. The results indicate low turbidity, absence of colour, and minimal levels of total dissolved solids, iron, and chlorides. However, the pervasive presence of total and faecal coliforms, accompanied by heightened turbidity in select stations and elevated phosphate levels in others, underscores the necessity for supplementary measures to guarantee potable water quality. The absence of chlorination in numerous wells designated for human consumption signifies a probable threat to public health. The implementation of suitable treatment methods, such as chlorination, oxidation, and adsorption, is strongly advised.

Principal Component Analysis (PCA) and cluster analysis have identified significant variations in water quality between stations, with some stations exhibiting high concentrations of total coliforms and others demonstrating greater sensitivity to parameters such as electrical conductivity (EC) and total hardness. Correlations between ambient temperature and other parameters suggest a climate impact on water quality, while clustering analysis highlights the need for differentiated management approaches to address variations in water quality between different seasons. The establishment of a continuous monitoring programme and the development of conservation strategies that consider both environmental factors and potential sources of pollution are of crucial importance for effective management.

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