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Geochemical Evaluation of Hot Springs in Southern Colombia and their possible Utilization for District Heating

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Abstract

This study assesses the geothermal potential of hot springs in southern Colombia for district heating. It was conducted as part of the GRÓ Geothermal Training Program (GRÓ-GTP) in Iceland which is operated under the auspices of UNESCO. The research promotes the direct use of geothermal energy, specifically Geothermal District Heating (GDH), to provide residential heating in high-altitude regions. Nine hot springs located in the southern Colombian departments of Cauca, Nariño, and Putumayo were selected. Geochemical analyses (Cl-SO_4-HCO_3, Piper, Na-K-Mg diagrams, and oxygen-18 and deuterium isotope delta plots) were used to classify the springs, trace their origins, and assess their characteristics. Reservoir temperatures were estimated using traditional geothermometers and mineral equilibrium modelling, revealing ranges from approximately 80°C to 240°C. Possible scaling problems generated by mixing hot springs in a future GDH were analysed, and mixing ratios were defined in which scaling would not be generated. Finally, municipalities around the hot springs which could benefit by GDH were defined, and the deliverable heat output (kW) per hot spring and the number of homes possibly benefitted by the GDH network was estimated.

1 Introduction

Since time immemorial, hot springs in Colombia have been used for recreational purposes, but today there is greater awareness of their relationship with a geothermal resource. There are currently twenty-one defined geothermal areas associated with volcanic systems in Colombia, located in the Central and Eastern Cordilleras, with a potential of 1,170 MWe (an important consideration for Colombia as geothermal energy could potentially account for approximately 9% of the country's energy demand) not including other geothermal systems than the volcanic ones, such as sedimentary basins, deep fractures, high pressure systems, blind systems, and hot dry rock systems according to the geothermal potential estimates for Colombia conducted by Alfaro et al. (2021).

Although Colombia has recognized its geothermal potential since 1980s, the country has not yet achieved significant development in this area. Recently, however, the government has begun to promote geothermal energy as part of its strategy to diversify the national energy matrix and meet international environmental commitments. Colombia is part of the Paris agreement and has committed to reducing its carbon footprint by 51% with an electricity emission factor lower than 1 g CO2/kWh by 2050 (Gobierno de Colombia, 2021). In line with these goals, the government has proposed the National Plan for Energy 2022- 2052 (UPME, 2024), which aims to identify technological alternatives in energy production and consumption that can diversify the country's energy mix while addressing the challenge of reducing CO_2 emissions by 2050. Aiming at promoting the direct use of Colombian geothermal resources in future Geothermal District Heating (GDH), as energy contribution to the mentioned national goals, this report briefly shows the geothermal areas defined in Colombia, geochemical analyses of hot springs located in the south of the country that have been selected as possible sources of GDH feeding. For these hot springs, reservoir temperatures were estimated, possible scaling problems identified, and a rough estimate made of the number of houses that could take advantage of this resource.

2 Geology of Colombia

Colombia has a tectonic framework influenced by the Caribbean and Nazca oceanic plates and the South American continental plate (Gómez & Montes, 2020). It is dominated by a transpressive regime resulting from the convergence among the Nazca and Caribbean Plates, Panamá, and the North Andean Block, which is part of the South American Plate (Monsalve-Bustamante, 2020). The volcanism in Colombia region is related to the oblique subduction of the Nazca Plate beneath the South American Plate. The bathymetric characteristics of the Eastern Panamá Basin and the Panamanian Isthmus have affected the process of the Nazca Plate subducting

under the South American Plate, thus determining the current configuration. The subduction of oceanic rifts might also play a role in controlling the locations and compositions of volcanoes and the division into segments along the Colombian and Ecuadorian front arc (Monsalve-Bustamante, 2020).

In Colombia, six natural regions are distinguished: Andean, Caribbean, Pacific, Orinoquia, Amazonian, and Insular. In the Colombian Andes, the volcanic activity has persisted since the Neogene, related to the orogenic paroxysm marked by the increase in volcanism in the late Miocene and the Pliocene. The resulting volcanic products formed the currently eroded volcanic structures on which most of the Pleistocene – Holocene volcanic edifices have developed (Monsalve-Bustamante, 2020). At least 121 hot springs have been identified throughout the territory, and most of them associated with volcanic systems located on the Central Cordillera in the Andean region.

2.1 Colombian Geothermal Areas

Twenty-one Geothermal Areas (GA) associated with convective volcano systems in the Andean Region have been identified and grouped in five Geothermal Blocks by Alfaro et al. (2021). These GA were preliminarily delimited based on surface evidence as heat sources (volcanic structure or igneous intrusions), discharge areas of possible geothermal reservoirs (hot springs and fumaroles) and geological structures such as faults and fractures, which control the main conduits of fluid circulation to and from the reservoirs (Alfaro et al., 2021). The Geothermal Blocks are: Paipa-Iza; San Diego; Cerro Bravo-Cerro Machín; Huila- Sucubún and Las Ánimas-Chiles (Figure 1 left).

2.2 Hot springs studied and their relationship with the Colombian Geothermal Areas

In order to analyse hot springs for a possible future Geothermal District Heating, and according to the methodology used for this study, nine hot springs were selected: La Mina and Pozo Azul in Cauca Department, Tajumbina I, Tajumbina II, Chimangual and Chiles 2 in Nariño Department, and Termales de Colón, La Josefina and Salado de Balsayaco in Putomayo Department. All are located at >2000 m a.s.l. (Figure 1 left).

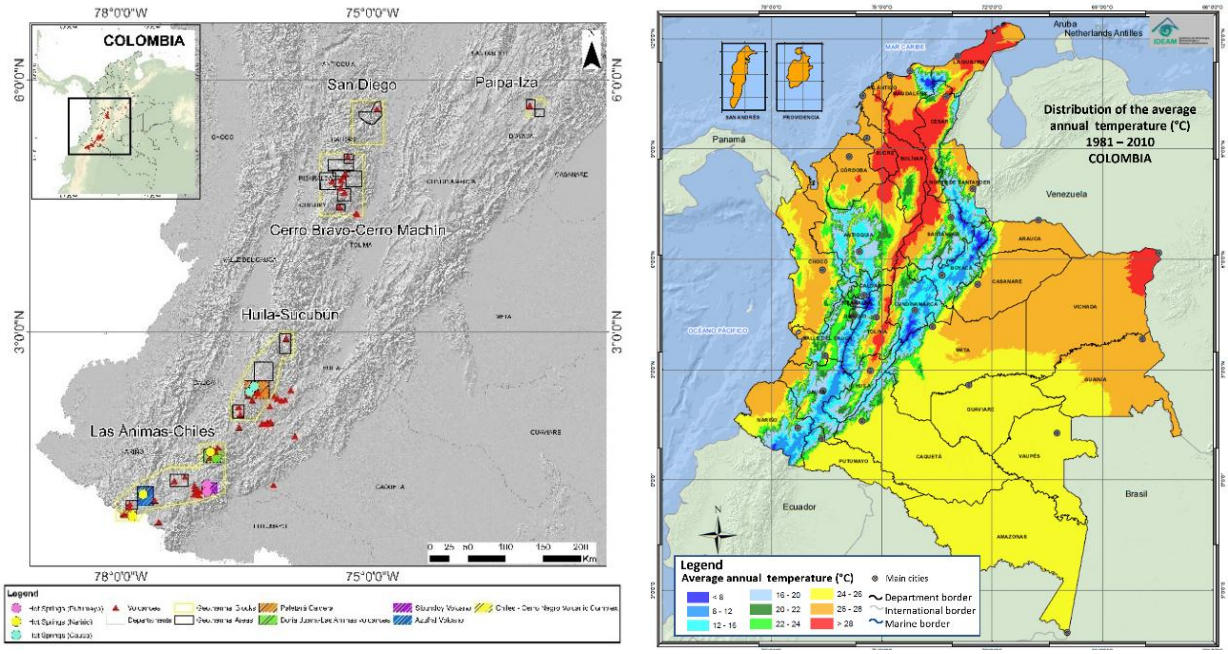


Figure 1. Left: Location of the Colombian geothermal areas, geothermal blocks and hot springs selected for analysis in this project. Right: Map of Colombia with the distribution of the average annual temperature (°C) for the years 1981-2010 (Scale for Colombia 1:9.000.000 – scale for San Andres and Providence islands 1:600.000) (taken and modified from IDEAM, 2014).

3 BACKGROUND OF GEOTHERMAL ENERGY UTILIZATION IN COLOMBIA

In Colombia, the concept of thermal districts is understood as District Heating or Cooling Systems, promoted through the government initiative Distritos Térmicos Colombianos. Currently, three District Cooling Systems are in operation (La Alpujarra, Lo Nuestro, and Serena del Mar) and one more, Potenza, is under development; however, none of these use geothermal fluids, and all focus exclusively on cooling.

In terms of direct geothermal applications, the first heat pump for cooling purposes was installed in Tocancipá, 40 km north of Bogotá, where it operates continuously to cool a 90 m^3 room to -10°C, marking the first geothermal project to benefit from incentives under Law 1715. Considering that Colombia's highest population density is concentrated along the Cordilleras, which coincide with geothermal areas linked to volcanic systems, and that many nearby municipalities experience annual average temperatures below 12°C (Figure 1 right) or close to 3°C in some periods during the year, the country has a clear need not only for district cooling but also for district heating, which could be developed by harnessing its abundant natural hot springs.

4 METHODOLOGY

4.1 Selection of hot springs

Nine hot springs out of the 121 hot springs reported in Colombia were chosen, located in the south of Colombia, considering which ones have temperatures greater than 40°C, with flow rates higher than 5 L/s, located in high topographical areas, and with average annual environmental temperatures less than 12°C. Location information, description, and chemical composition of hot springs was taken from the National Inventory of Hydrothermal Manifestations (SGC, 2022).

4.2 Geochemical classification

The samples chosen were plotted using Piper (1944), Cl-SO_4-HCO_3 (Giggenbach, 1991), Na-K-Mg (Giggenbach, 1988), and oxygen-18 and deuterium isotope delta diagrams, using the Liquid Analysis geochemical plotting spreadsheet created by Powell & Cumming (2010).

4.3 Speciation and mineral equilibria

The state of equilibrium of specific minerals in the hot springs was determined by the calculation of their aqueous speciation. Equilibrium mineral saturation diagrams, following the approach of Reed and Spycher (1984), were made using the geochemical modelling software PHREEQC version 3.7.3 (Parkhurst & Appelo, 2013) and its accompanying llnl database. The values of the equilibrium constant K, and the reaction quotient Q, along with the resulting saturation index were obtained for temperatures from 250°C to 30°C.

The relationship between the logarithm of the ratio of Q and K, gives the saturation index (SI) for each mineral:

$$\mathrm{SI} = \log \mathrm{Q} - \log \mathrm{K}$$

Then, when SI=0 means the fluid is in equilibrium, when SI is <0 means the fluid is undersaturated and no mineral will precipitate, and when SI>0 it means the fluid is supersaturated and minerals will precipitate. This thermodynamic condition allows us to know not only in which temperature you will have scaling problems, but also to stablish the equilibrium temperature for different minerals, and the temperature where two or more minerals are in equilibrium, therefore providing a range of reservoir temperatures, were plotted in the diagrams of temperature vs. SI for all the hot springs analysed, and so to define possible reservoir temperatures (Reed, 1982; Parkhurst & Appelo, 2013) .

The multiple mineral equilibrium temperatures (reservoir temperatures) obtained by the above procedures were compared with those calculated from conventional geothermometers; the Quartz (Fournier & Potter, 1982), Chalcedony (Fournier, 1977), Na/K (Arnorsson et al., 1983) and Na-K-Ca with and without Mg correction (Fournier & Truesdell, 1973), calculated either using the speciation program WATCH, version 2.4 (Arnórsson et al., 1982; Bjarnason, 2010), or the spreadsheet created by Powell & Cumming (2010).

Saturation index is also useful to determine possible scaling problems, which are very common in production or utilization. The most common deposits are due to silica, iron oxides, iron and aluminium silicates, sulphides, calcite, anhydrite, barite, apatite, borates, and sulphur (Ármannsson, 2009), in low-T utilization, calcite and amorphous silica are most common. To determine scaling problems in mixing hot springs studied in this project, for possible future use in district heating, a mixing routine was used in PHREEQC varying the ratios of the mixed hot springs, at their discharge temperature. Likewise, values of saturation indices for each possible mineral that would be formed were obtained and plotted as function of the mixture ratios.

Due to the fact that the La Mina and Pozo Azul hot springs, located in Cauca department, have a very low pH (3.7 and 1.7 respectively), which generates corrosion problems in the pipeline, PHREEQC was used to calculate, how much 10M NaOH (strong base) is necessary to raise the pH to 5.5 (recommended pH for skin care) and avoid corrosion problems.

4.4 Determination of possible impact

In order to recognize the size of the population that could possibly make use of the hot springs in a future district heating system, a buffer was created around each hot spring to know which municipalities or settlements could be influenced. Based on pipelines length of district heating systems in operation (Parlaktuna et al., 2021), a radius was defined around the hot spring. The radius of the impact zone around of the hot springs present in the department of Cauca (La Mina and Pozo Azul), was defined as 25 km; for the hot springs located in the department of Nariño (Tajumbina I, Tajumbina II, Chimangual and Chiles 2) and for those of the department of Putumayo (Termales de Colón, La Josefina and Salado de Balsayaco) the radius was 20 km.

To calculate the energy that each hot spring can deliver, the enthalpy difference (ΔH) of each hot spring was calculated and then multiplied by the flow rate (Q):

$$Heat = \Delta H * Q = (H_{in} - H_{out}) * Q$$

The enthalpy values for each temperature were calculated from steam table (IAPWS-IF97) using the Water97_v13.xla (Spang, 2002) MS Excel add-on.

In order to know in advance how many homes could benefit from the deliverable heat of each hot spring, the calculated deliverable heat in kW units, is converted to KWh-year, and then related to what the UPME (2009) has defined that each Colombian household consumes energy annually; 1884 kWh per year.

Based on this, two possible scenarios were constructed. A pessimistic one, in which the inlet temperature (T_{in}) was set 5°C lower than the discharge temperature of each hot spring, and the outlet temperature (T_{out}) was set at 25°C, to calculate the deliverable heat. The other scenario, the optimistic one, considers the use of the hot fluids with pumped extraction wells. It assumes the input temperature (T_{in}) to be 5°C below the lowest reservoir temperature estimate calculated with geothermometers or mineral balance, and that due to pumping of the wells, the flow rate is doubled. The outlet temperature (T_{out}) is set at 20°C.

5 RESULTS AND DISSCUSION

5.1 Characteristics of thermal fluids (hot springs)

The chemical analyses of the samples are presented in Table 1 (SGC, 2022). According to the Piper diagram, most of the thermal waters are dominated by sodium-potassium and sulphate-chloride components, although some variations exist between geothermal areas. The ternary diagrams of Na-K-Mg and Cl-SO_4-HCO_3 (Giggenbach, 1988; 1991), with the isotopic composition of oxygen and hydrogen, provide further insight into the origin and evolution of these fluids (Figure 2). The hot springs located in the Cauca department (La Mina and Pozo Azul) are classified as calcium-magnesium sulphate-chloride and sodium-potassium sulphate waters. Their very acidic pH values suggest a strong influence of volcanic gases and indicate these fluids correspond to immature waters associated with volcanic environments rather than equilibrated geothermal reservoir fluids. This interpretation is supported by their position in the Cl–SO_4–HCO_3 and Na–K–Mg diagrams. Isotopic data show that La Mina plots close to the meteoric water line, suggesting heating of meteoric water near the surface, whereas Pozo Azul displays a positive oxygen isotope shift that may reflect rock–water interaction or partial evaporation, consistent with its near-boiling temperature.

Most of the hot springs from the Nariño department (Tajumbina I and Tajumbina II and Chimangual) correspond to sodium-potassium sulphate-chloride waters and are also classified as immature waters according to the Na-K-Mg and Cl-SO_4-HCO_3 diagrams (Giggenbach, 1988; 1991). These hot springs show positive oxygen isotope shifts, suggesting occurrence of rock-water interaction processes. Tajumbina II plots closer to the partial equilibrium field than Tajumbina I, suggesting a slightly higher degree of water–rock equilibration. In contrast, Chiles 2 shows calcium-magnesium sulphate water and a negative oxygen isotope shift, which may be related by reaction of formation waters at low to intermediate temperatures (Nicholson, 1993), or could be taken place the hydration of primary silicates and the formation of clay minerals or isotopic exchange with a gas phase that is not initially in equilibrium with the environmental water (D'Amore & Panichi, 1985).

The hot springs from the Putumayo department are mainly classified as sodium potassium sulphate waters, with the exception of La Josefina, which corresponds to a sodium potassium bicarbonate type associated with peripheral waters. These springs are generally interpreted as immature waters; however, Salado de Balsayaco shows evidence of partial equilibrium with reservoir minerals. Their negative oxygen isotope shifts suggest possible interaction with formation waters or isotopic exchange processes in the subsurface.

Table 1. **Chemical results of thermal samples analyzed in this project.**

ID Hot Spring	La Mina	Pozo Azul	Tajum-bina I	Tajum-bina II	Chiman-gual	Chiles 2	Termales de Colón	La Josefina	Salado de Balsayaco
Flow rate (L/s)	30	12	5	6	50	6	12	13.09	7
pH in situ	1.71	3.76	6.11	6.7	7.11	6.22	9.14	7.5	7.33
Temp. (°C)	44.6	90.1	42	62.0	41	40.3	51.8	39.8	78.5
DIC as CO_2 (mg/L)	NR	NR	413.60	1416.8	290.4	NR	25.23	268.4	61.26
H_2S (mg/L)	14.68	NR	NR	NR	NR	NR	NR	NR	NR
SiO_2 (mg/L)	129	479	164	226	173	183	64	87	111
Na (mg/L)	249	867	415	1168	362	134	238	104	383
K (mg/L)	64	124	31	79	26	32	3	15	40
Mg (mg/L)	261	9	17	32	37	66	NR	10	0
Ca (mg/L)	190	24	64	158	56	98	9	15.5	80.6
Li (mg/L)	0	5	1	2	1	0	0	0.08	1
F (mg/L)	2.4	1.9	0.9	0.2	0.3	0.5	2.3	1.3	3.3
Cl (mg/L)	863	955	511	1332	604	88	293	60	564
SO_4 (mg/L)	3302	853	236	200	162	301	202	<0,2	291
Al (mg/L)	120	<5	<1	<1	<1	0.3	<1	<1	<1
Fe total (mg/L)	47	0.3	16	0.2	0.1	4.2	<0.2	0.2	<0.2
B (mg/L)	1.8	15.8	4.8	14.8	5.8	2.9	2.9	1.6	5.3
Mn (mg/L)	10.7	0.4	0.6	0.2	0.8	0.4	<0.2	<0.2	<0.2
TS (mg/L)	NR	NR	NR	NR	NR	NR	898	NR	NR
$\delta^{18}O$ (‰)	-11.29	-9.13	-9.96	-9.16	-10.15	-12.69	-11.34	-10.64	-10.98
δD (‰)	-80.4	-72.7	-70.3	-68.1	-74.5	-85.4	-75.0	-69.1	-69.7

BDL: Below detection limit. NR: Not reported

Overall, the geochemical analyses indicate that most of the studied hot springs correspond to immature waters influenced by volcanic activity, with limited equilibrium with reservoir minerals. Variations in chemical composition and isotopic signatures reflect different degrees of water–rock interaction, mixing with meteoric waters, and volcanic gas influence. The main geochemical characteristics and inferred fluid origins are summarized in Table 2.

Table 2. Geochemical classification of the hot springs analyzed in this project.

Hot spring	Department	Classification	Influence	Comments	O- isotope shift (‰)
La Mina	Cauca	Mg/Ca-SO_4	Volcanic water	Immature water	<0.1
Pozo Azul	Cauca	Na/K-SO_4	Volcanic water	Immature water	+1.2
Tajumbina I	Nariño	Na/K-Cl/SO_4	Peripheral water	Immature water	<0.1
Tajumbina II	Nariño	Na/K-Cl/SO_4	Peripheral water	Immature water	+0.6
Chimangual	Nariño	Na/K-Cl/SO_4	Peripheral water	Immature water	+0.4
Chiles 2	Nariño	Mg/Ca-Cl/SO_4	Volcanic water	Immature water	-0.8
Termales de Colón	Putumayo	Na/K-SO_4	Volcanic water	Immature water	-0.7
La Josefina	Putumayo	Na/K-HCO_3	Peripheral water	Immature water	-0.7
Salado de Balsayaco	Putumayo	Na/K-SO_4	Volcanic water	Partial equilibration	-1.0

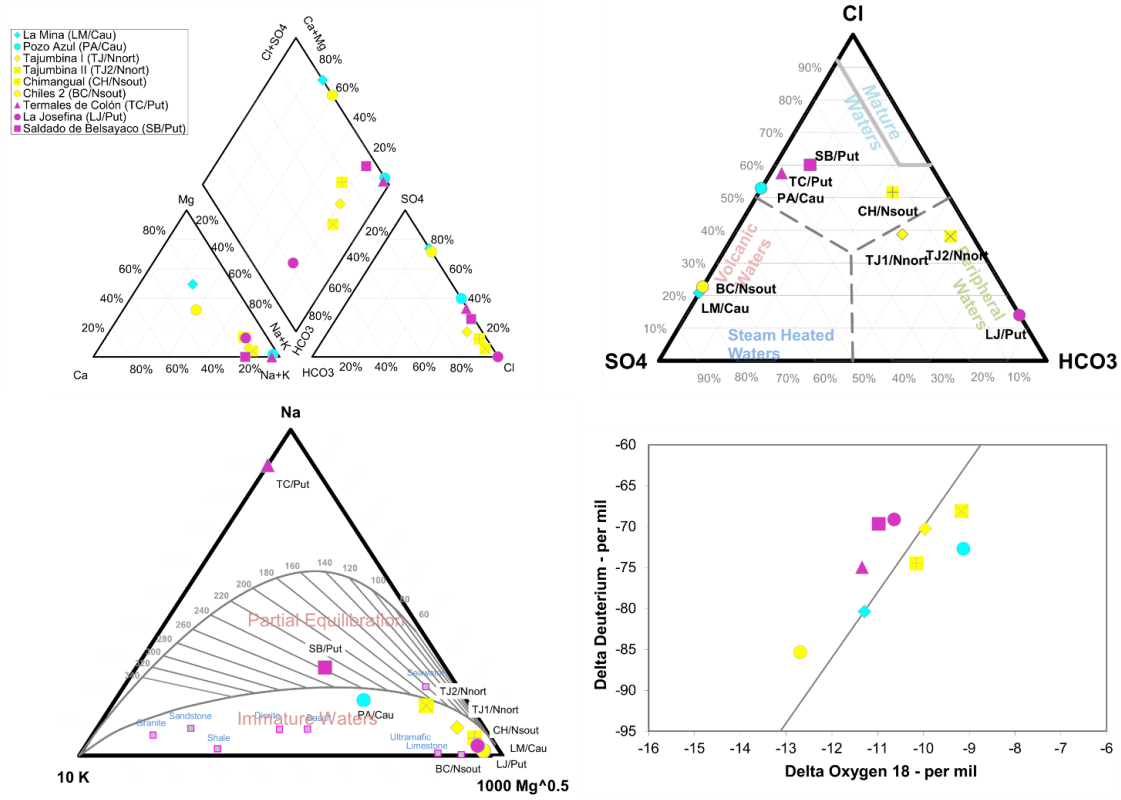


Figure 2. Overview of the aqueous geochemistry of hot springs analyzed. Top left: Piper diagram (Piper, 1944). Top right: ternary plot of Cl-SO_4-HCO_3 (Giggenbach, 1991). Bottom left: ternary plot of Na-K-Mg diagram (Giggenbach, 1988). Bottom right: Oxygen and hydrogen isotopes of geothermal fluids relative to Global Meteoric Water Line (Craig, 1961).

5.2 Speciation equilibrium and geothermometers

Reservoir temperatures were estimated using two approaches: (i) conventional geothermometers calculated with the WATCH speciation program and (ii) mineral equilibrium temperatures obtained from aqueous speciation modelling (multiple mineral equilibrium; MME). In the latter method, the saturation index (SI) of selected minerals was calculated as a function of temperature using the PHREEQC software, and reservoir temperatures were inferred from the intersection of mineral equilibrium curves near SI = 0. These temperatures are summarized in Table 3. Although the temperatures estimated by the different techniques are not identical for each hot spring, several results show comparable values between methods, suggesting a moderate degree of agreement, marked with *(*)* in Table 3. For example, Tajumbina I presents reservoir temperatures close to 144°C using the chalcedony geothermometer and approximately 123°C from the mineral assemblage of quartz and K-feldspar. Similar consistency between silica geothermometers and mineral equilibrium calculations is observed for several of the studied hot springs, supporting the reliability of the estimated temperature ranges.

In contrast, the hot springs La Mina and Pozo Azul have large differences in calculated reservoir temperatures. La Mina has 152°C using the quartz geothermometer but 135°C from mineral equilibria calculations, while Pozo Azul has temperature values of 240°C using chalcedony geothermometer and 178°C with the mineral equilibrium between chalcedony and anorthite. These discrepancies likely reflect the immature nature of these waters and their strong volcanic influence, as also suggested by their low pH values. Such conditions indicate that the fluids may represent steam heated surface waters rather than equilibrated reservoir fluids and therefore provide limited information about the reservoir conditions.

Bearing in mind the accepted temperature values for the hot springs Tajumbina I, Tajumbina II, Chimangual, Chiles 2, Termales de Colon, La Josefina and, Salado de Balsayaco; and taking precautions with La Mina and Pozo Azul, a reservoir temperature range is proposed per each hot spring (Table 4). These ranges suggest the presence of moderate- to high-temperature geothermal systems in the studied areas.

Table 3. Reservoir temperatures obtained with geothermometers using WATCH software, and mineral equilibrium using PHREEQC software. A moderate degree of acceptance is highlighted in blue. All the temperatures in Celsius degrees.

Hot spring	pH in situ	T in situ	Quartz[1]	Chalcedony[2]	Na/K[3]	T of mineral equilibria[4]	Mineral equilibria components[5]
La Mina 1	1.71	44.6	152	127	300	82 135	Chalcedony, Alunite Albite, Anhydrite, Quartz
Pozo Azul	3.76	90.1	253	240	236	178	Chalcedony, Anorthite
Tajumbina I	6.11	42	167	*144 (*)*	171	*123 (*)*	Quartz, K-felds
Tajumbina II	6.70	62	*189 (*)*	168	161	135	Chalcedony, Anorthite
						185 (*)	Albite, K-felds, Quartz
Chimangual	7.11	41	170	*147 (*)*	167	*145 (*)*	Quartz, Albite
Chiles 2	6.22	40.3	174	*152 (*)*	296	104	Chalcedony, Albite
						140 (*)	K-felds, Quartz
Termales de Colón	9.14	51.8	*92 (*)*	61	50	*96 (*)*	K-felds, Albite, Quartz, Gibbsite
La Josefina	7.50	39.8	129	*102 (*)*	243	*100 (*)*	Quartz, Albite
Salado de Balsayaco	7.33	78.5	*143 (*)*	*117 (*)*	205	*100 (*)*	Quartz, Talc
						140 (*)	K-felds, Anhydrite

1. Fournier & Potter, 1982. 2.Fournier, 1977. 3. Arnorsson et al., 1983. 4.PHREEQC. 5.Mineral assemblage

Table 4. Reservoir temperature range selected per hot spring.

Hot spring	Tempe rature	Reservoir temperature range estimated (°C)	Technique used for estimating
La Mina	44.6	82-152	MME, Quartz, Chalcedony
Pozo Azul	90.1	132-240	Na-K-Ca, MME, Chalcedony
Tajumbina I	42.0	123-144	MME, Chalcedony
Tajumbina II	62.0	135-189	Quartz, MME
Chimangual	41.0	145-170	MME, Quartz
Chiles 2	40.3	104-152	MME, Chalcedony
Termales de Colón	51.8	92-96	Quartz, MME
La Josefina	39.8	100-129	MME, Quartz
Salado de Balsayaco	78.5	100-143	MME, Quartz

5.3 Prediction of scaling or corrosion problems (Characteristics of fluid mixtures)

Mixing simulations were carried out to evaluate potential scaling problems when combining hot springs from the same geothermal areas for possible future direct uses. The calculations were performed using PHREEQC, varying the proportions of the mixed waters at their discharge temperatures and evaluating the resulting saturation indices of relevant mineral phases. The mixing ratios that predict no mineral precipitation are illustrated in Figure 3.

The results indicate that several combinations of hot springs can be mixed without generating scaling problems. In the Cauca department, La Mina and Pozo Azul show complementary mixing behaviour, with acceptable ratios ranging from approximately 45–100% for La Mina and 55–0% for Pozo Azul. In the Putumayo area, mixtures are dominated by La Josefina (70–100%), with smaller contributions from Termales de Colón (20–5%) and Salado de Balsayaco (10–0%). In Nariño Norte, Tajumbina I and Tajumbina II display inverse mixing proportions, with Tajumbina I ranging from 65–100% and Tajumbina II from 35–0%. In Nariño Sur, Chimangual contributes between 0–45%, while Chiles 2 shows the opposite trend, ranging from 100–55%.

These optimal mixing ranges correspond to conditions where the saturation index of the relevant minerals remains below the precipitation threshold, as shown by the dashed red areas in Figure 3. For example, a mixture containing less than 55% Pozo Azul water and at least 45% La Mina water is predicted to avoid scaling problems.

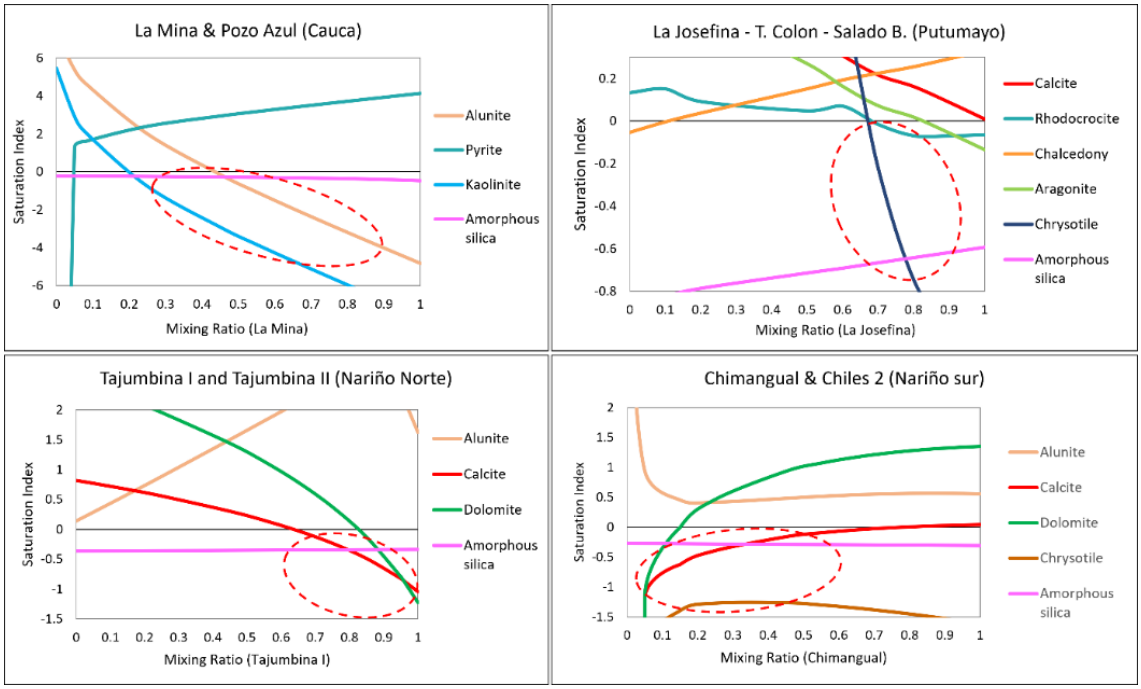


Figure 3. Plots of saturation index of the mineral facies as function of natural mixing ratios of the hot springs per area. The dashed red lines show the mixing ratios without scaling problems.

On the other hand, the required injection rate of NaOH (10 M) to raise the pH of the La Mina hot spring to 5.5 is 4.6 mL/s, while for the Pozo Azul hot spring it is 0.1 mL/s. This pH adjustment helps prevent oxidation of potential facilities without increasing the risk of silica precipitation.

5.4 Possible Impact: Deliverable heat

In this project, the loss factor of a utilization system, for example a heating district, is not considered, this means that the deliverable heat values presented are overestimated. To estimate the number of houses that could be heated by each hot spring, two scenarios were proposed. The pessimistic scenario assumes natural flow conditions, with the inlet temperature set 5°C below the hot spring discharge temperature and the outlet at 25°C. The optimistic scenario considers pumped extraction wells that double the flow rate, with the inlet temperature 5°C below the lowest reservoir estimate and the outlet at 20°C. The results of deliverable heat, and number of households that might benefit from the district heating system for both the pessimistic and optimistic scenarios, in rounded figures, are presented in Table 5.

Table 5. Estimated heat and potential benefits per housing unit per hot spring

Hot spring	Pessimistic Scenario		Optimistic Scenario	
	Hot spring heat output (kW)	Possible number of houses heated*	Hot spring heat output (kW)	Possible number of houses heated*
La Mina	1,831	8,000	14,306	66,000
Pozo Azul	3,018	14,000	15,562	71,000
Tajumbina I	251	1,000	4,114	19,000
Tajumbina II	803	4,000	5,549	25,000
Chimangual	2,299	10,000	59,163	271,000
Chiles 2	258	1,000	8,951	41,000
Termales de Colón	1,093	5,000	3,632	17,000
La Josefina	536	2,000	8,333	38,000
Salado de Balsayaco	1,420	7,000	4,397	20,000

* Rounded figures

6 CONCLUSIONS

The use of ternary diagrams (Cl-SO_4-HCO_3 and Na-K-Mg), Piper plots, and hydrogen–oxygen isotope data revealed that La Mina and Pozo Azul (Cauca) are likely of volcanic origin, while Salado de Balsayaco (Putumayo) shows the strongest evidence of water–mineral equilibrium. Most of the remaining hot springs, however, are immature waters, as they are not in equilibrium with the minerals that control cation concentrations. Their geochemical classification varies from Na/K-Cl to Ca/Mg-SO_4 types. Isotopic compositions show that most of the samples plot very close to the local meteoric water line (within 1‰). The Pozo Azul, Tajumbina I, Tajumbina II, and Chimangual hot springs have a positive oxygen isotope shift, possibly due to the rock-water reaction or boiling/evaporating, while small negative shifts in Chiles 2, Termales de Colon, La Josefina, and Salado de Balsayaco may be caused by reaction of formation waters at low to intermediate temperatures, or clay minerals, or isotopic exchange with a gas phase.

Although the immaturity of most waters limits the reliability of geothermometric calculations, estimated reservoir temperatures were relatively consistent across different methods. These values suggest a geothermal potential across the region, with proposed ranges of La Mina (82–152 °C), Pozo Azul (131–240 °C), Tajumbina I (123–144 °C), Tajumbina II (135–189 °C), Chimangual (145–170 °C), Chiles 2 (104–152 °C), Termales de Colón (92–96 °C), La Josefina (100–129 °C), and Salado de Balsayaco (100–143 °C). Springs with higher temperatures, such as Pozo Azul, Salado de Belsayaco, and Tajumbina II, stand out as promising candidates for geothermal development. Mixing studies demonstrate that combining nearby springs is feasible without creating scaling problems, a critical condition for direct use. Proposed ratios include 45% La Mina with Pozo Azul in Cauca; 70% La Josefina, 20% Termales de Colón, and 10% Salado de Balsayaco in Putumayo; 65% Tajumbina I with Tajumbina II in northern Nariño; and up to 45% Chimangual with Chiles 2 in southern Nariño. Acidic springs, particularly in Cauca, would require pH adjustment using NaOH before utilization. The quantity of NaOH at 10 M to raise the pH to 5.5 in the Cauca hot springs is 4.6 mL/s for La Mina, and 0.1 mL/s for Pozo Azul.

Temperature values of the fluid, and its flow rate, are key parameters to calculate the heat (kW), and the number of possible benefitted houses. In a conservative scenario without drilling, between 1,000 and 14,000 households could benefit, while in an optimistic scenario, in which the flow is assumed to be doubled due to drilling and pumping, and the temperature of the fluid is increased by extracting fluid from the reservoir at the calculated reservoir temperature, between 17,000 and 271,000 households could be supplied. Given that Colombia's most densely populated areas are in the Cordilleras, regions that overlap with geothermal areas, the sustainable use of these resources could provide significant social and economic benefits, contributing to cleaner energy access and regional development.

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