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Hydrogeochemical Characterization and Geothermometric Assessment of the Gunung Kapur Geothermal System and Surrounding Thermal Waters, Jambi, Indonesia

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Abstract

The Gunung Kapur area in Jambi is part of a geothermal region characterized by volcanic, plutonic, and hydrothermal alteration features. This study evaluates the hydrogeochemical characteristics, fluid types, equilibrium conditions, and inferred reservoir temperatures of the Gunung Kapur geothermal system and surrounding thermal waters using pH, major-ion chemistry, Cl–SO_4–HCO_3 classification, silica and cation geothermometers, and the Na–K–Mg geoindicator. The dataset includes thermal waters from Idung Mancung, Sapan Melolong, Semurup 1, and Semurup 2, together with Kerinci cold water as a reference. The hydrochemical data indicate contrasting fluid characteristics. Idung Mancung is strongly acidic and sulfate-rich, consistent with shallow steam-heated water, whereas Sapan Melolong and Semurup 1 exhibit chloride-bearing characteristics and lower Mg concentrations, suggesting greater interaction with deeper geothermal fluids. Semurup 2 shows a more mixed and immature signature, while Kerinci cold water is dominated by bicarbonate and represents a shallow meteoric or peripheral component. Geothermometric estimates vary according to fluid maturity and water type. Semurup 1 yields the most consistent high-temperature indications, with estimated reservoir temperatures generally ranging from approximately 194 to 243 °C, whereas Sapan Melolong indicates moderate-temperature conditions of approximately 169–188 °C. In contrast, cation geothermometer estimates for strongly acidic or immature waters should be interpreted cautiously because of shallow alteration, mixing, and disequilibrium effects. The results indicate that the regional geothermal system contains chemically heterogeneous waters representing steam-heated, deeper chloride-bearing, mixed, and meteoric components. These findings provide a hydrogeochemical basis for understanding subsurface fluid circulation and geothermal potential in the Gunung Kapur region, although direct confirmation of reservoir conditions requires additional site-specific geochemical, geophysical, and subsurface data.

Keywords: hydrogeochemistry; geothermal hydrology; geothermal fluids; geothermometry; Cl–SO_4–HCO_3; Na–K–Mg; Gunung Kapur; Jambi

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INTRODUCTION

Geothermal energy is an important renewable energy resource that can contribute to low-carbon and sustainable energy development. The occurrence and behavior of geothermal resources are controlled by interactions among geological structure, heat sources, hydrothermal alteration, groundwater circulation, and water–rock interaction. Hydrogeochemical investigation is therefore an important component of geothermal exploration because the chemical composition of thermal fluids can provide information on fluid origin, subsurface processes, reservoir conditions, and possible fluid–rock equilibrium (Simmons, 1998; Suharno, 2012; Karyanto et al., 2021). In particular, major-ion chemistry and fluid pH are useful for distinguishing different geothermal water types and for evaluating whether surface manifestations represent deep reservoir fluids, steam-heated waters, mixed waters, or shallow meteoric components.

The chemical composition of geothermal fluids varies considerably depending on the source of recharge, contributions from magmatic or metamorphic volatiles, water–rock interaction, boiling, condensation, and mixing with shallow groundwater. These processes can strongly modify the original reservoir-fluid composition during ascent to the surface (Giggenbach et al., 1983; Simmons, 1998). Consequently, interpretation of geothermal-fluid chemistry requires consideration not only of individual ion concentrations but also of the hydrological processes that control fluid evolution. Classification using the $Cl–SO_4–HCO_3$ ternary diagram is widely applied to distinguish chloride, sulfate, bicarbonate, and mixed geothermal waters and to infer their relationship with upflow, steam-heated, and peripheral zones within a geothermal system (Nicholson, 1993).

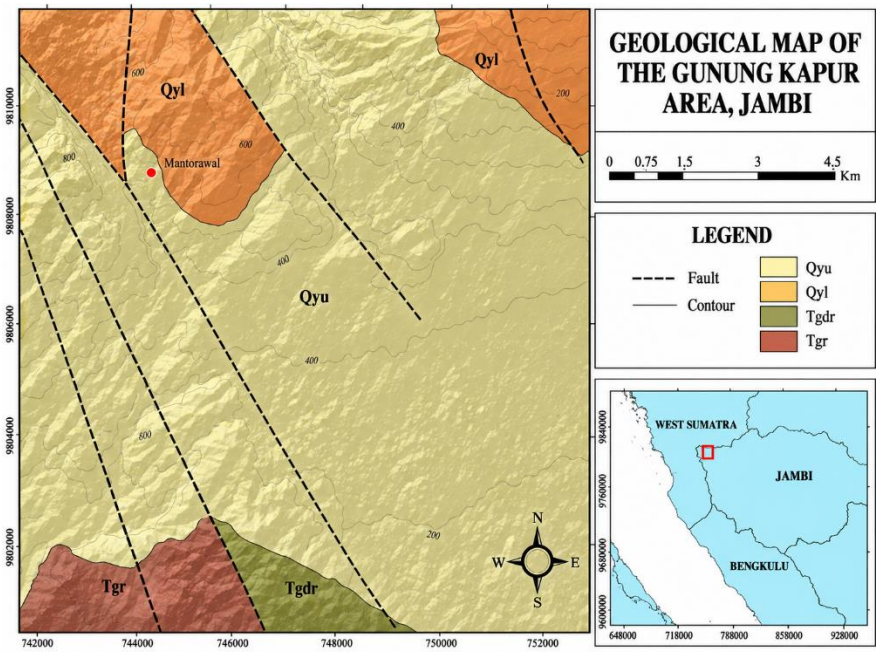


Figure 1. Geological map of the Gunung Kapur geothermal area, Jambi, showing the distribution of the principal lithological units, major fault structures, topographic contours, and the location of Mantorawal. The inset map shows the regional location of the study area in relation to West Sumatra, Jambi, and Bengkulu Provinces.

Geothermometry provides an additional approach for estimating subsurface thermal conditions from dissolved chemical constituents. Silica geothermometers are commonly applied where silica concentrations reflect equilibrium with quartz or chalcedony, whereas Na–K and K–Mg geothermometers are used to estimate reservoir temperatures based on temperature-dependent cation exchange reactions (Fournier, 1977, 1979; Fournier & Truesdell, 1973; Giggenbach, 1988). However, the applicability of each geothermometer depends strongly on fluid maturity and the degree of water–rock equilibrium. Waters affected by boiling, dilution, steam heating, or strong mixing may yield unreliable cation-based temperatures. The Na–K–Mg geoindicator is therefore particularly useful for evaluating whether a fluid is immature, partially equilibrated, or approaching full equilibrium before reservoir-temperature estimates are interpreted (Giggenbach, 1988, 1991).

The Gunung Kapur geothermal area is located within the Bukit Barisan volcanic and tectonic belt of Sumatra. Regionally, the area is composed of volcanic, plutonic, metavolcanic, and younger Quaternary volcanic units, including rocks associated with Gunung Kapur, Gunung Kerinci, and surrounding volcanic centers. The structural framework includes northwest–southeast-trending strike-slip and normal faults related to the broader Sumatran Fault system, as well as local volcanic structures. Hydrothermal alteration has been reported around Welirang Mati, where illite, pyrophyllite, nontronite, opal, montmorillonite, and kaolinite indicate acidic hydrothermal conditions, while additional alteration near Sungai Lintang reflects more neutral fluid interaction at lower temperatures. The regional geological setting of the study area is presented in **Figure 1**.

Although hydrothermal alteration occurs in the Gunung Kapur area, direct hot-spring manifestations were not identified at the main site. Therefore, thermal-water data from surrounding geothermal manifestations, including Idung Mancung, Sapan Melolong, and Semurup, were used together with Kerinci cold water to evaluate the broader hydrogeochemical characteristics of the regional geothermal system. The available dataset includes pH and major dissolved constituents such as Na, K, Ca, Mg, Cl, SO_4, HCO_3, and SiO_2. This configuration makes it important to distinguish between direct manifestations, regional thermal waters, and shallow meteoric components when interpreting possible reservoir conditions.

Despite the availability of regional geological and geochemical information, the hydrological relationships among these fluids, their equilibrium states, and the reliability of reservoir-temperature estimates remain insufficiently integrated. Previous studies have demonstrated the usefulness of geothermal-fluid classification, ion-balance analysis, and geothermometry in Indonesian geothermal systems (Hidayatika et al., 2015; Suharno et al., 2015a, 2015b; Karyanto et al., 2021), but a systematic interpretation of the Gunung Kapur system and its surrounding thermal waters is still needed. Accordingly, this study aims to characterize the hydrogeochemical properties of the Gunung Kapur geothermal system and surrounding thermal waters by integrating pH, Cl–SO_4–HCO_3 classification, silica and cation geothermometers, and the Na–K–Mg geoindicator. The study specifically evaluates fluid type, degree of water–rock equilibrium, and plausible reservoir-temperature ranges, while distinguishing between steam-heated, deeper chloride-bearing, mixed, and meteoric-water components.

METHOD

Data Sources and Hydrogeochemical Dataset

This study uses hydrochemical data from thermal and cold-water manifestations associated with the Gunung Kapur geothermal region and surrounding geothermal areas in Jambi. The dataset comprises five water samples: Idung Mancung hot spring, Sapan Melolong hot spring, Semurup 1 hot spring, Semurup 2 hot spring, and Kerinci cold water. The available parameters include pH, Na, K, Ca, Mg, Cl, SO_4, HCO_3, and SiO_2 concentrations. The hydrochemical dataset **Table 1** was compiled from the geothermal investigation data reported by the Ministry of Energy and Mineral Resources of Indonesia (2017). Because direct hot-spring manifestations were not identified within the principal Gunung Kapur area, thermal-water samples from nearby geothermal systems were evaluated as regional analogs to assess the broader hydrogeochemical characteristics and possible subsurface thermal conditions of the Gunung Kapur region. Kerinci cold water was included as a shallow meteoric or peripheral-water reference. This distinction was considered when interpreting the representativeness of each sample for deeper geothermal conditions.

Hydrochemical Classification Based on pH

The first stage of the analysis involved classification of geothermal waters according to their measured pH. The pH values were used as an initial indicator of fluid characteristics and near-surface hydrothermal processes. Strongly acidic waters were interpreted as potentially associated with steam-heated or acid-sulfate conditions, whereas neutral to slightly alkaline waters were evaluated as possible chloride, bicarbonate, mixed, or peripheral geothermal fluids depending on their major-ion composition. The interpretation followed the hydrochemical framework described by Simmons

(1998) and Karyanto et al. (2021), in which geothermal waters may range from strongly acidic sulfate-rich fluids to neutral or alkaline chloride- and bicarbonate-bearing waters.

Table 1. Hydrochemical data of geothermal manifestations in the Gunung Kapur region, Jambi

No	Sample	pH	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Cl (ppm)	SO_4 (ppm)	HCO_3 (ppm)	SiO_2 (ppm)
1	Idung Mancung Hot Spring	2.0	60.0	7.5	202.0	126.0	226.0	1904.0	0.0	81.0
2	Sapan Melolong Hot Spring	8.1	880.0	47.5	40.5	0.1	1532.0	65.1	59.0	81.0
3	Semurup Hot Spring 1	7.6	470.0	35.5	1.9	0.19	488.0	160.0	267.0	450.0
4	Semurup Hot Spring 2	7.8	401.0	6.09	9.66	0.96	220.0	44.0	706.0	162.0
5	Kerinci Cold Water	7.8	5.3	1.92	5.93	5.99	10.0	10.0	92.9	77.3

Source: Modified from the Ministry of Energy and Mineral Resources of Indonesia (2017).

Cl–SO_4–HCO_3 Ternary Classification

The relative proportions of chloride, sulfate, and bicarbonate were evaluated using the Cl–SO_4–HCO_3 ternary diagram following the geothermal-fluid classification approach of Nicholson (1993). Prior to normalization, ion concentrations should be converted from mg/L to milliequivalent per liter (meq/L) to account for differences in ionic charge and equivalent weight. The conversion is expressed as Equation (1);

$$C_{meq/L} = \frac{C_{mg/L}}{EW} \qquad \dots (1)$$

where $C_{mg/L}$ is the concentration of each ion and EW is its equivalent weight. The normalized percentage of each anion is then calculated as Equation (2);

$$X_i = \frac{C_i}{C_{Cl}+C_{SO4}+C_{HCO3}} \times 100 \qquad \dots (2)$$

where (X_i) represents the normalized proportion of Cl, SO_4, or HCO_3. The resulting values Table 2) were plotted on the ternary diagram to distinguish chloride-dominated, sulfate-dominated, bicarbonate-dominated, and mixed waters. These hydrochemical facies were subsequently interpreted in terms of deep geothermal contribution, steam-heated conditions, peripheral flow, and mixing with shallow meteoric water.

Table 2. Calculated proportions of Cl–SO_4–HCO_3 anions

No	Sample	S	Cl	SO_4	HCO_3
1	Idung Mancung Hot Spring	2357.4	0.10	0.81	0.10
2	Sapan Melolong Hot Spring	3128.5	0.49	0.02	0.49
3	Semurup Hot Spring 1	1137.5	0.43	0.14	0.43
4	Semurup Hot Spring 2	483.5	0.45	0.09	0.45
5	Kerinci Cold Water	30.0	0.33	0.33	0.33

Reservoir Temperature Estimation Using Water Geothermometers

Reservoir temperatures were evaluated using silica and cation geothermometers. The original analysis includes quartz no-steam-loss, quartz maximum-steam-loss, chalcedony, Na–K Fournier, Na–K Giggenbach, and K–Mg geothermometers. The calculated temperature estimates for each sample are summarized in **Table 3** of the manuscript. Silica geothermometers were used to estimate subsurface temperature based on dissolved SiO_2 concentrations. The interpretation considered quartz under no-steam-loss and maximum-steam-loss conditions, as well as the chalcedony geothermometer.

Silica geothermometry is particularly useful where dissolved silica reflects temperature-dependent mineral solubility. However, the resulting estimates may be modified by dilution, boiling, steam loss, rapid cooling, or silica precipitation during fluid ascent. Therefore, silica-derived temperatures were interpreted in conjunction with fluid type and maturity rather than as stand-alone reservoir temperatures. The use of quartz and chalcedony geothermometers follows the general framework described in the manuscript and the cited geothermal geochemistry literature.

Table 3. Estimated reservoir temperatures using water geothermometers

No	Sample	Na (ppm)	K (ppm)	Mg (ppm)	SiO_2 (ppm)	Quartz, No Steam Loss (°C)	Quartz, Maximum Steam Loss (°C)	Chalcedony (°C)	Na/K Fournier (°C)	Na/K Giggenbach (°C)	K/Mg (°C)
1	Idung Mancung Hot Spring	60.0	7.5	126.0	81.0	126	123	98	237	251	34
2	Sapan Melolong Hot Spring	880.0	47.5	0.1	81.0	126	123	98	169	188	184
3	Semurup Hot Spring 1	470.0	35.5	0.19	450.0	243	218	234	194	211	160
4	Semurup Hot Spring 2	401.0	6.09	0.96	162.0	166	157	143	96	117	82
5	Kerinci Cold Water	5.3	1.92	5.99	77.3	123	121	95	360	361	37

Na–K geothermometers were applied to estimate reservoir temperature from the temperature-dependent exchange relationship between sodium and potassium. The study uses both Fournier and Giggenbach formulations. These geothermometers are generally more appropriate for waters that have experienced sufficient water–rock interaction and approach chemical equilibrium. For chemically immature, strongly acidic, or heavily mixed waters, Na–K temperatures were treated cautiously because the cation ratios may not represent equilibrium conditions in the deep reservoir. The calculations are based on the approaches of Fournier (1977, 1979) and Giggenbach (1988).

The K–Mg geothermometer was used as an additional indicator of subsurface equilibration and lower-temperature re-equilibration. Because Mg concentrations can respond relatively rapidly to shallow water–rock interaction, K–Mg temperatures were interpreted together with the Na–K–Mg equilibrium state. The method follows the geochemical framework cited in the original manuscript. Fluid maturity and water–rock equilibrium were evaluated using the Na–K–Mg ternary geoindicator proposed by Giggenbach (1988, 1991). The diagram was used to distinguish among: immature waters, partially equilibrated waters, fully equilibrated or mature waters.

The relative positions of the samples on the Na–K–Mg diagram were used to determine whether cation geothermometer temperatures could reasonably be interpreted as reservoir temperatures. Waters plotting in the immature-water field were treated with caution because their chemistry may have been modified by shallow mixing, dilution, steam heating, or incomplete water–rock equilibration. The original manuscript presents the Na–K–Mg calculations in **Table 4** and the ternary plot in **Figure 3**.

The final interpretation integrated four complementary lines of evidence: 1. pH-based fluid characteristics, 2. Cl–SO_4–HCO_3 hydrochemical facies, 3. silica and cation geothermometer estimates, and 4. Na–K–Mg equilibrium state. Rather than selecting a single geothermometer value for all samples, the preferred temperature range was evaluated according to the hydrochemical character

and maturity of each water. Steam-heated or chemically immature waters were not considered reliable indicators of deep-reservoir temperature using cation geothermometers, whereas more equilibrated chloride-bearing waters were considered more representative of deeper geothermal conditions. This integrated approach was used to distinguish between shallow steam-heated waters, deeper chloride-bearing thermal waters, mixed or peripheral waters, and cold meteoric components, and to develop a hydrogeochemical interpretation of the Gunung Kapur geothermal region.

Table 4. Calculated Na–K–Mg proportions for geothermal fluid equilibrium assessment

No	Sample	Na (ppm)	K (ppm)	Mg (ppm)	S	%Na	%Mg
1	Idung Mancung Hot Spring	60.0	7.5	126.0	112.65	3.6	89.79
2	Sapan Melolong Hot Spring	880.0	47.5	0.1	126.42	46.4	16.02
3	Semurup Hot Spring 1	470.0	35.5	0.19	67.79	46.3	1.4
4	Semurup Hot Spring 2	401.0	6.09	0.96	37.65	71.0	12.83
5	Kerinci Cold Water	5.3	1.92	5.99	5.24	6.7	56.6

RESULTS AND DISCUSSION

Hydrochemical Characteristics of the Thermal and Cold Waters

The hydrochemical dataset consists of four thermal-water samples Idung Mancung, Sapan Melolong, Semurup 1, and Semurup 2 and one cold-water sample from Kerinci. The measured parameters include pH, Na, K, Ca, Mg, Cl, SO_4, HCO_3, and SiO_2 concentrations, as summarized in **Table 1**. The waters display substantial chemical variability, indicating that they do not represent a single homogeneous fluid type but instead reflect different stages of geothermal-fluid evolution, shallow steam-heating, water–rock interaction, and mixing with meteoric water (Hidayatika et al., 2024).

Idung Mancung is the most acidic sample, with a pH of 2.0, SO_4 concentration of 1904 ppm, and relatively high Mg of 126 ppm. In contrast, Sapan Melolong, Semurup 1, and Semurup 2 are neutral to slightly alkaline, with pH values of 8.1, 7.6, and 7.8, respectively. Kerinci cold water also has a pH of 7.8 but is characterized by substantially lower concentrations of dissolved ions, consistent with a shallow meteoric or peripheral-water component. These differences indicate contrasting hydrogeochemical environments within the broader geothermal region (Nicholson, 1993; Suharno., 2003).

The strong acidity and high sulfate content of Idung Mancung are consistent with acid-sulfate or steam-heated water, which commonly develops when H_2S-rich geothermal vapor rises toward the surface, dissolves in shallow groundwater, and becomes oxidized to sulfuric acid (Simmons, 1998; Nicholson, 1993). By contrast, the higher Cl concentrations of Sapan Melolong and Semurup 1 suggest a stronger contribution from deeper geothermal fluids, while the elevated HCO_3 concentration in Semurup 2 and particularly Kerinci cold water suggests stronger interaction with shallow groundwater or peripheral flow.

Fluid Classification Based on the Cl–SO_4–HCO_3 Diagram

The relative proportions of Cl, SO_4, and HCO_3 were evaluated using the ternary classification presented in **Table 2** and **Figure 2**. This approach is commonly used to distinguish deep chloride waters, shallow steam-heated sulfate waters, bicarbonate-rich peripheral waters, and mixed geothermal fluids (Nicholson, 1993). Idung Mancung plots toward the sulfate-rich field in **Figure 2**, consistent with its very low pH and high SO_4 concentration. This position supports interpretation of the sample as shallow steam-heated water rather than direct deep-reservoir discharge. Therefore, its chemistry is likely to reflect near-surface oxidation and condensation processes more strongly than deep reservoir equilibrium. Sapan Melolong plots toward the chloride-bearing side of the diagram and is characterized by high Cl (1532 ppm), relatively low Mg (0.1 ppm), and alkaline pH. These characteristics suggest a stronger deep-geothermal component than in Idung Mancung. Semurup 1 also shows a chloride-bearing composition, with Cl = 488 ppm and relatively low Mg = 0.19 ppm, indicating more extensive water–rock interaction and a potentially more mature fluid.

Semurup 2 contains substantial HCO_3 (706 ppm), suggesting a greater contribution from peripheral or mixed water. Kerinci cold water is even more strongly influenced by bicarbonate, with

HCO_3 = 92.9 ppm compared with only 10 ppm Cl and 10 ppm SO_4, supporting interpretation as shallow meteoric or peripheral water rather than a direct geothermal reservoir fluid. Overall, the ternary classification suggests that the analyzed waters represent several hydrogeochemical components within the regional system: steam-heated sulfate water, chloride-bearing thermal water, mixed or peripheral water, and meteoric cold water (Suharno et al., 2012; Suharno., 2013a; Suharno., 2013b).

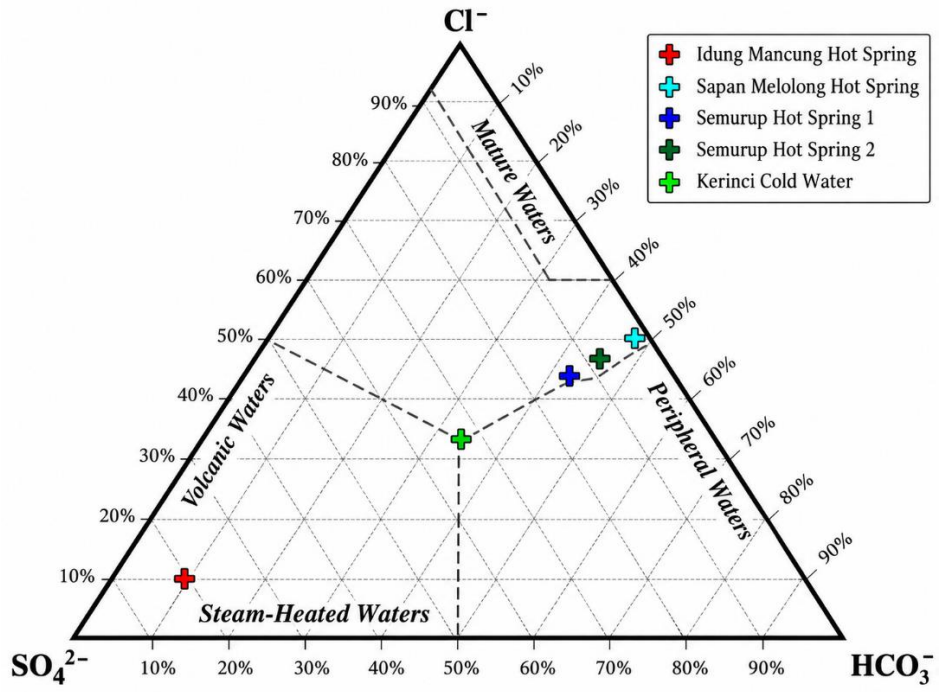


Figure 2. Cl–SO_4–HCO_3 ternary diagram showing the hydrochemical classification of thermal and cold-water samples from the Gunung Kapur geothermal region and surrounding areas.

Reservoir Temperature Estimates from Water Geothermometers

Reservoir-temperature estimates calculated using silica, Na–K, and K–Mg geothermometers are summarized in **Table 3**. The results show substantial differences among geothermometers and among samples, reflecting variations in fluid maturity and the degree of equilibrium between water and reservoir minerals. For Idung Mancung, quartz geothermometers yield temperatures of approximately 123–126 °C, while chalcedony indicates about 98 °C. In contrast, Na–K geothermometers produce much higher values of 237–251 °C, whereas K–Mg gives only 34 °C. The large disagreement among these estimates reflects the strongly acidic, Mg-rich, steam-heated character of the water. Consequently, Na–K-derived temperatures should not be considered reliable deep-reservoir estimates for this sample. The lower silica temperatures are more consistent with strong shallow alteration, cooling, or mixing.

Sapan Melolong shows a more internally consistent relationship among the cation geothermometers. Na–K estimates range from approximately 169 to 188 °C, while K–Mg gives approximately 184 °C. The similarity between these values supports interpretation of this sample as partially equilibrated thermal water. The silica geothermometers yield lower temperatures of about 98–126 °C, which may indicate cooling, dilution, or silica re-equilibration during fluid ascent. Semurup 1 provides the highest and most coherent high-temperature estimates among the samples. Quartz geothermometers yield approximately 218–243 °C, chalcedony gives about 234 °C, Na–K Fournier gives approximately 194 °C, and Na–K Giggenbach gives approximately 211 °C. These values, together with the very low Mg concentration and relatively high SiO_2 content, suggest stronger water–rock equilibration and a more representative deep thermal-fluid signature (Suharno et al., 2013a; Suharno., et al 2013b).

Semurup 2 yields quartz temperatures of approximately 157–166 °C and a chalcedony estimate of about 143 °C, while Na–K gives substantially lower values of approximately 96–117 °C and K–Mg about 82 °C. The broader spread among geothermometers indicates that this water is less

equilibrated and more strongly affected by shallow mixing or dilution. Kerinci cold water produces highly inconsistent results, including unrealistic Na–K estimates of approximately 360–361 °C despite its low dissolved-ion concentrations and cold-water character. These values should not be interpreted as reservoir temperatures. Instead, Kerinci cold water functions primarily as a shallow meteoric or peripheral-water reference.

Fluid Equilibrium Based on the Na–K–Mg Geoindicator

The degree of fluid equilibrium was further evaluated using the Na–K–Mg ternary diagram. The calculated proportions are presented in **Table 4**, while the resulting fluid-maturity classification is shown in **Figure 3**. The samples occupy different positions in the Na–K–Mg diagram, indicating different degrees of water–rock equilibrium. Semurup 1 plots closest to the more equilibrated portion of the diagram, consistent with its low Mg concentration and relatively coherent high-temperature geothermometer estimates. This supports interpretation of Semurup 1 as the most mature thermal water among the analyzed samples.

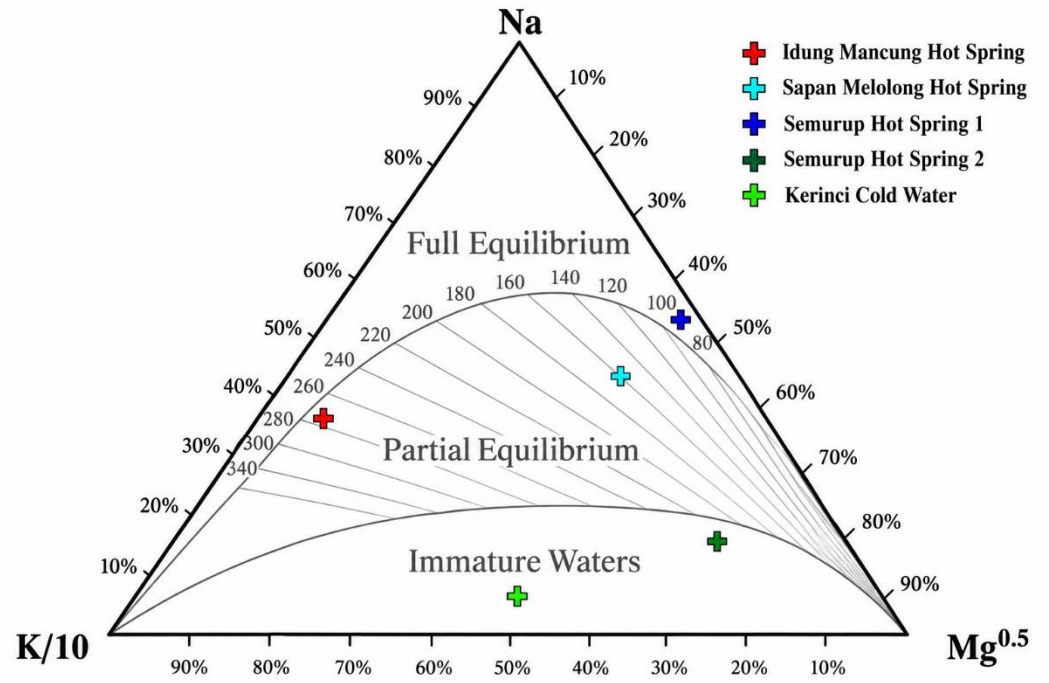


Figure 3. Na–K–Mg ternary geoindicator showing the relative equilibrium conditions of thermal and cold-water samples from the Gunung Kapur geothermal region and surrounding areas, following Giggenbach (1988, 1991).

Sapan Melolong occupies the partial-equilibrium field, in agreement with its low Mg concentration and the relatively similar temperatures derived from Na–K and K–Mg geothermometers. The sample therefore appears to preserve a stronger deep-reservoir signature than the more immature waters. Semurup 2 plots within the immature-water field, supporting interpretation of shallow mixing or dilution. This is consistent with the discrepancy among its silica and cation geothermometer estimates.

Kerinci cold water also plots within the immature-water field, as expected for a shallow meteoric or peripheral water. Its relatively high Mg content further confirms limited equilibration with high-temperature reservoir minerals. Idung Mancung occupies a position that should be interpreted cautiously because its high Mg and strongly acidic sulfate chemistry indicate strong near-surface modification. Although the plotted position may appear near the partial-equilibrium field, the hydrochemical characteristics do not support using it as a reliable indicator of deep reservoir equilibrium (Suharno et al., 2013a; Suharno., et al 2013b).

Hydrogeochemical Interpretation of Individual Waters

Idung Mancung is characterized by pH 2.0, SO_4 = 1904 ppm, Mg = 126 ppm, and Cl = 226 ppm. These characteristics indicate strongly acidic sulfate water formed predominantly by steam-heating processes. The high sulfate concentration and low pH are consistent with oxidation of H_2S in the shallow subsurface, while the high Mg concentration suggests strong interaction with shallow groundwater and surrounding rocks. Although Na–K geothermometers yield temperatures above 230 °C, these values are not considered reliable because the fluid is chemically immature and strongly modified by shallow processes. Silica-based estimates of approximately 98–126 °C are more consistent with shallow re-equilibration, cooling, or mixing. Therefore, Idung Mancung should primarily be interpreted as a surface expression of vapor-dominated or steam-heated processes rather than as direct evidence of the deep reservoir temperature.

Sapan Melolong has pH 8.1, Cl = 1532 ppm, Na = 880 ppm, and very low Mg = 0.1 ppm. The chloride-rich chemistry and low Mg concentration indicate greater interaction with deeper geothermal fluids. Its position in the Na–K–Mg diagram suggests partial equilibrium, while Na–K and K–Mg geothermometers yield similar temperatures of approximately 169–188 °C and 184 °C, respectively. These results indicate a medium-temperature thermal-water component that has undergone substantial water–rock interaction but may still have experienced some cooling or mixing during ascent.

Semurup 1 has pH 7.6, Na = 470 ppm, Cl = 488 ppm, Mg = 0.19 ppm, and SiO_2 = 450 ppm. Among all samples, it shows the strongest geochemical evidence for a deeper and more mature thermal fluid. Quartz geothermometers indicate approximately 218–243 °C, while Na–K methods yield approximately 194–211 °C. The consistency of these estimates and the very low Mg concentration suggest relatively advanced water–rock equilibration. Therefore, Semurup 1 provides the strongest indication of high-temperature conditions within the broader regional geothermal system. However, because Semurup is not a direct Gunung Kapur manifestation, these temperatures should be interpreted as regional analog evidence rather than direct confirmation of the Gunung Kapur reservoir.

Semurup 2 is characterized by pH 7.8, HCO_3 = 706 ppm, Cl = 220 ppm, Mg = 0.96 ppm, and SiO_2 = 162 ppm. The elevated bicarbonate content and its position in the immature-water field indicate stronger interaction with shallow groundwater. Silica geothermometers yield temperatures of approximately 143–166 °C, whereas cation-based estimates are considerably lower. This suggests that mixing or dilution has altered the cation chemistry. Accordingly, the silica estimates provide a more plausible indication of thermal conditions than the Na–K values for this sample.

Kerinci cold water is characterized by low concentrations of Na, K, Cl, and SO_4, together with a relatively higher HCO_3 concentration of 92.9 ppm. Its chemistry is consistent with shallow meteoric or peripheral groundwater. The high Mg concentration relative to the thermal waters and its immature position in Figure 3 indicate limited interaction with high-temperature reservoir rocks. Therefore, the very high Na–K geothermometer values obtained for this sample are not physically meaningful and should not be used for reservoir-temperature estimation.

Conceptual Hydrogeochemical Model and Geothermal Implications

The combined hydrochemical and geothermometric evidence suggests that the regional geothermal system contains multiple fluid components rather than a single homogeneous reservoir discharge. Idung Mancung represents a shallow steam-heated acid-sulfate component, Sapan Melolong represents partially equilibrated chloride-bearing thermal water, Semurup 1 represents the most mature and high-temperature thermal-fluid analog, Semurup 2 reflects mixed or peripheral conditions, and Kerinci cold water represents shallow meteoric groundwater.

This interpretation is consistent with the conceptual behavior of geothermal systems, in which meteoric recharge penetrates along permeable fractures, is heated at depth, and subsequently rises through structural pathways. During ascent, the fluids may undergo boiling, steam separation, condensation, dilution, or mixing with shallow groundwater (Giggenbach et al., 1983; Simmons, 1998; Suharno, 2012). The geothermometric results suggest that the broader regional system may include medium- to high-temperature thermal conditions, with the most reliable indications coming from Sapan Melolong and Semurup 1. However, the available data do not directly prove that these temperatures characterize the Gunung Kapur reservoir itself because the thermal waters were

collected from surrounding geothermal manifestations rather than from direct Gunung Kapur hot springs. Therefore, the results should be interpreted as a regional hydrogeochemical framework rather than a definitive reservoir model.

From a hydrological and environmental perspective, the coexistence of acidic sulfate water, chloride-bearing thermal water, mixed bicarbonate water, and meteoric groundwater indicates active interaction among deep geothermal fluids, shallow groundwater, and near-surface hydrothermal processes. These interactions are important for understanding subsurface fluid pathways, potential water-quality changes, and the environmental behavior of geothermal fluids in the Gunung Kapur region.

CONCLUSION

This study demonstrates that the thermal and cold waters associated with the Gunung Kapur region and surrounding geothermal areas exhibit distinct hydrogeochemical characteristics that reflect different stages of fluid evolution and water–rock interaction. Integration of pH, $Cl–SO_4–HCO_3$ classification, silica and cation geothermometers, and the Na–K–Mg geoindicator shows that the analyzed waters cannot be interpreted as a single homogeneous geothermal fluid system. Idung Mancung is characterized by strongly acidic, sulfate-rich water and is best interpreted as a shallow steam-heated manifestation rather than direct deep-reservoir discharge. Sapan Melolong shows a stronger chloride-bearing signature and partial-equilibrium characteristics, with cation geothermometers indicating temperatures of approximately 169–188 °C. Semurup 1 provides the strongest indication of a more mature and higher-temperature thermal fluid, with geothermometric estimates generally ranging from approximately 194 to 243 °C. Semurup 2 reflects a more mixed and immature fluid condition, whereas Kerinci cold water represents a shallow meteoric or peripheral component. The differences among silica, Na–K, and K–Mg temperature estimates emphasize that geothermometer results must be interpreted according to fluid type and equilibrium state. Cation geothermometers are not considered reliable for strongly acidic or chemically immature waters because shallow mixing, steam heating, and disequilibrium can significantly modify the original reservoir-fluid composition. Therefore, the most reliable temperature constraints are obtained from the more equilibrated chloride-bearing thermal waters, particularly Sapan Melolong and Semurup 1. Overall, the hydrogeochemical evidence suggests that the broader regional geothermal system includes steam-heated, deeper chloride-bearing, mixed peripheral, and meteoric-water components. These results provide a useful framework for understanding subsurface fluid circulation and geothermal conditions around Gunung Kapur. However, because the analyzed thermal waters are derived from surrounding geothermal manifestations rather than direct hot-spring discharge at Gunung Kapur, the inferred reservoir temperatures should be regarded as regional hydrogeochemical constraints rather than definitive temperatures of the Gunung Kapur reservoir itself. Further site-specific geochemical sampling, geophysical investigations, and subsurface data are required to confirm the reservoir structure, temperature, and geothermal potential of the Gunung Kapur system.

AUTHOR CONTRIBUTIONS

Conceptualization, AkH, AgH, and S; methodology, AkH, AgH, S, and MKP; software, FF and NH; validation, AgH, S, and MKP; formal analysis, AkH, FF, MKP, and NH; investigation, AkH, S, MKP, and NH; resources, AkH, S, and MKP; data curation, AkH, FF, and NH; writing—original draft preparation, AkH; writing—review and editing, AkH, AgH, S, FF, MKP, and NH; visualization, AkH, FF, and NH; supervision, AgH and S; project administration, AkH. All authors have read and agreed to the published version of the manuscript.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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