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Analysis of Reservoir Temperature Estimation using Major Elements in Sulili Geothermal Field, South Sulawesi, Indonesia: Implications for Geothermal Energy Forecasts

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Abstract

Geothermal is a natural resource energy in the form of hot water or steam that forms in reservoirs within the earth through the heating of subsurface water by hot igneous rocks. Based on field surveys, the Sulili area shows characteristics of geothermal energy in the form of hot springs. The research aims to use the Na-K geothermometer to find out the temperature of the geothermal reservoir below the ground and the Na-K-Mg geothermometer to look into the type of fluid that is in the geothermal reservoir. The research employs the geochemical analysis method in conjunction with the Na-K geothermometer method. Reservoir subsurface temperature is estimated at EPU station 1 at 326.504°C, EPU station 2 at 473.369°C, and station EPU 3 at 456.508°C. According to the results, the hot springs at the three sites are chlorides with temperatures below ground that are part of the high-temperature geothermal system and are >225°C. The hot spring is in the immature water group. Based on the calculation, the Sulili Geothermal Field with an average reservoir temperature of 418°C is approximately 68.33 MWh. This is a simplified calculation, and actual energy output can vary based on several factors, including the specific characteristics of the geothermal reservoir and the efficiency of the power plant.

Keywords: geothermal energy; geothermometer; manifestation; major elements; reservoir temperature

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INTRODUCTION

Geothermal energy is a renewable and sustainable source of power that harnesses the Earth's internal heat. The term "geothermal" comes from the Greek words "geo" (earth) and "therme" (heat), referring to the natural heat stored within the Earth (Giggenbach, 1992). This energy is produced primarily by the radioactive decay of elements such as potassium, thorium, and uranium in the

Earth's crust and mantle (Hochstein & Sudarman, 1993; Millot et al., 2012; Rybach et al., 2003; Schäffer et al., 2018).

The Earth's internal heat manifests in various forms, including volcanoes, geysers, hot springs, and fumaroles. Geothermal energy can be captured and utilized for various applications, such as heating buildings, generating electricity, and even for industrial processes (Nukman & Hochstein, 2019). Geothermal energy is considered environmentally friendly because it produces significantly lower greenhouse gas emissions compared to fossil fuels. Additionally, it provides a stable and reliable energy source, as it is available, unlike solar and wind energy (Gede Boy Darmawan et al., 2015; Iqbal & Kusumasari, 2024).

The development of geothermal energy involves drilling wells into geothermal reservoirs to access hot water or steam, which can then be used directly for heating or converted into electricity using different technologies. There are three main types of geothermal power plants: dry steam plants, flash steam plants, and binary cycle power plants. Geothermal energy is one of the alternative energies that has many advantages for development (Rybach et al., 2003). In addition to its vast reserves, geothermal energy is an environmentally friendly energy source and relatively competitive for use as a power plant. Geothermal energy is a natural resource in the form of hot water or steam that is formed in reservoirs within the earth through the heating of water beneath the surface by hot igneous rocks (Masuda et al., 1985). Surface water originating from rivers, rain, lakes, seas, and so on seeps into groundwater, flows, and comes into contact with magma bodies or hot igneous rocks, causing it to boil and subsequently form hot water and steam (Millot et al., 2012; Schäffer et al., 2018). This geothermal energy can be directly utilized for drying agricultural products, tourism, and household needs, or indirectly as a turbine driver for power generation.

Based on field surveys, the Sulili area shows geothermal characteristics in the form of manifestations, namely hot springs (Umar, et al., 2020a). The presence of geothermal manifestations in the research area has been previously studied regarding geological exploration, specifically the influence of geological structures on the emergence of hot springs in the Sulili area, and the physical fluid analysis in the utilization of hot springs (Umar et al., 2022). Additionally, the exploration of resistivity geoelectrics in subsurface mapping and hydrochemical analysis in determining the type and classification of Sulili geothermal fluids indicates the need for further research to be conducted continuously by analyzing hot spring fluids geochemically or hydrochemically for the further utilization of geothermal energy potential in the research area (Umar, et al., 2020b).

The Sulili Geothermal Field, located in South Sulawesi, Indonesia, presents a significant opportunity for geothermal energy development. Understanding the reservoir temperature is crucial for assessing the potential and sustainability of geothermal resources. This study focuses on estimating the reservoir temperature using major elements found in geothermal fluids. By analyzing the concentrations of these elements, we can gain insights into the subsurface conditions and predict the geothermal energy potential of the Sulili field (Umar et al., 2022).

Geothermal energy is a renewable and environmentally friendly source of power that harnesses the Earth's internal heat. Accurate estimation of reservoir temperatures is essential for optimizing the exploration and exploitation of geothermal resources (Arienzo et al., 2020; Vuataz, 1983). This research employs geochemical techniques to analyze the major elements in geothermal fluids, providing a reliable method for temperature estimation (Tsay et al., 2017; Zheng & Hermann, 2014).

The findings of this study have significant implications for geothermal energy forecasts in the region. By improving our understanding of the Sulili Geothermal Field's reservoir temperatures, we can enhance the efficiency and effectiveness of geothermal energy extraction, contributing to Indonesia's renewable energy goals.

Geological setting

The Sulili Geothermal Field, located in South Sulawesi, Indonesia, is characterized by a complex geological setting that plays a crucial role in its geothermal potential (**Figure 1**). The Sulili Geothermal Field is situated in a tectonically active region influenced by the subduction of the Indo-Australian Plate beneath the Eurasian Plate. This tectonic activity results in high geothermal gradients and the presence of magmatic intrusions, which are essential for geothermal energy generation (Fauziyyah et al., 2016; Triani et al., 2021).

The area is characterized by numerous faults and fractures that act as pathways for geothermal fluids. These geological structures facilitate the circulation of hot water and steam from deep within the Earth to the surface. The presence of volcanic rocks and recent volcanic activity in the region indicates a significant heat source at depth. The volcanic activity contributes to the high temperatures observed in the geothermal reservoirs. The lithology of the Sulili Geothermal Field includes a variety of rock types such as volcanic rocks, sedimentary rocks, and intrusive igneous rocks. The volcanic rocks, in particular, are associated with the geothermal reservoirs (Jihad et al., 2021; Umar et al., 2020a; Umar et al., 2020b).

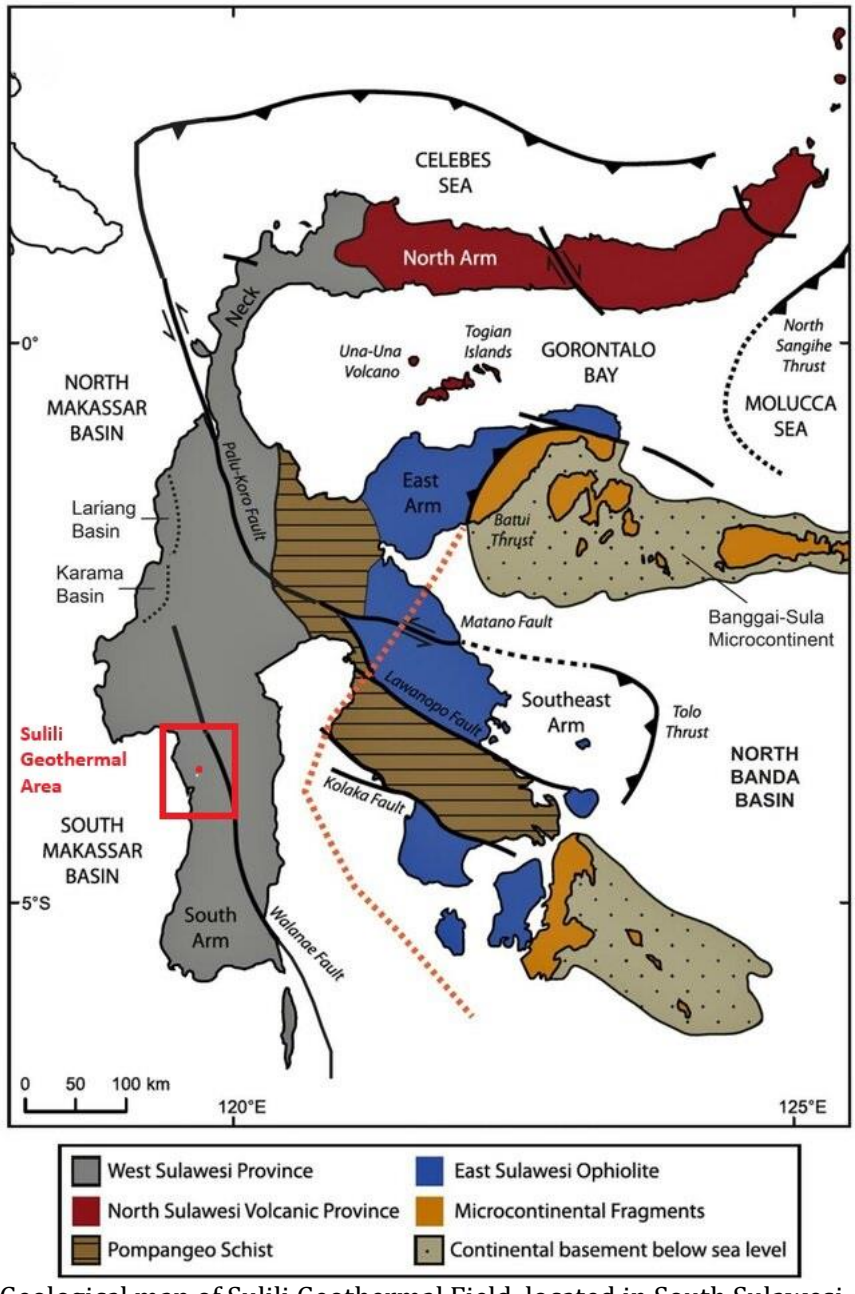

Figure 1. Geological map of Sulili Geothermal Field, located in South Sulawesi, Indonesia

The rocks in the geothermal field exhibit hydrothermal alteration, which is a result of the interaction between hot geothermal fluids and the surrounding rocks. This alteration can affect the permeability and porosity of the rocks, influencing the movement of geothermal fluids. The geothermal reservoirs in the Sulili Geothermal Field are typically located at depths where temperatures are sufficiently high for geothermal energy extraction (Fauziyyah et al., 2016; Riogilang et al., 2012). These reservoirs are characterized by high permeability and porosity, allowing for the efficient flow of geothermal fluids. The temperatures in the geothermal reservoirs can vary, but they

are generally high enough to support the generation of geothermal energy. The pressure conditions within the reservoirs also play a crucial role in the movement of geothermal fluids (Harlaux et al., 2017).

Geophysical surveys, including gravity and magnetic surveys, are conducted to map the subsurface geological structures and identify potential geothermal reservoirs (Triani et al., 2021). These surveys provide valuable information about the distribution of heat sources and the pathways for geothermal fluids. The geological setting of the Sulili Geothermal Field, with its tectonic activity, volcanic influence, and complex geological structures, makes it a promising site for geothermal energy development. Understanding the geological characteristics of the field is essential for optimizing the exploration and exploitation of its geothermal resources (Umar, et al., 2020b).

METHOD

This study collects data directly at the research location by following a series of well-defined steps. Initially, coordinates are taken at each station to ensure accurate data collection. The physical and chemical characteristics of the hot springs, such as temperature, color, and pH, are then recorded. Hot water samples are collected using the Kemmerer water sampler, filtered with filter paper, and stored in bottles rinsed with the filtered water sample. Each water sample, with a minimum volume of 500 ml, is immediately packaged and labeled with a location code for anion analysis. The chemical analysis employs the Atomic Absorption Spectrophotometer (AAS) method and the gravimetric method, as outlined by Batsala et al., (2012). This comprehensive approach ensures the accuracy and reliability of the data, providing a solid foundation for estimating reservoir temperatures in the Sulili Geothermal Field.

Figure 2 and 3 is the activity of taking samples using the Kemmerer water sampler tool, after which the water sample is first filtered using filter paper, after which it is put into a sample bottle. The last stage is packing the sample bottle then given a location code and then put into a cooler box to keep the sample safe and not contaminated with bacteria around the research area.

Figure 2. Hot water sampling process using tools kemmerer water sampler photographed in the direction of Northeast N 45°E

Figure 3. Hot water sampling process using the kemmerer tool water sampler photographed in the direction of Northwest N 337°E

Laboratory analysis phases

Samples of hot springs collected from the research site were analyzed in the laboratory to determine their chemical content. The hardness of elements such as Ca^{2+}, Mg^{2+}, Cl^{-}, and HCO_3^{-} was assessed using the titrimetric (or volumetric) method, which involves quantitative analysis by reacting the substance being analyzed with a standard solution of known concentration. The reaction between the analyzed substance and the standard solution proceeds quantitatively (Blanchette et al., 2010).

For determining the hardness of Ca^{2+}, the procedure outlined by Batsala et al., (2012) was followed:

1. Pipette 100 ml of the sample into an Erlenmeyer flask.
2. Add 4.0 ml of 1 N NaOH and mix.

3. Add 0.1-0.2 grams (approximately the tip of a stirrer) of murexide indicator, then stir and immediately titrate with Na-EDTA cautiously until a color change from red (pink) to purple (orchid purple) occurs. The titration endpoint is marked by the addition of one drop of titrant, which no longer changes the intensity of the purple-blue color.

Determination of Sulfate (SO_4), K, Na, NH_3

In determining the sulfate content in the sample, the procedure carried out for its analysis is the Atomic Absorption Spectrophotometer (AAS) method. Spectrophotometer: a tool consisting of a spectrometer and photometer. The spectrometer produces light from a spectrum with a certain wavelength, and the photometer is a measuring device for the intensity of transmitted or absorbed light. Atomic Absorption Spectrophotometer (AAS) is a tool used in analytical methods for the determination of metal elements and metalloids based on the absorption of radiation by free atoms (Batsala et al., 2012; Harlaux et al., 2017; Thomas, 2001; Toki et al., 2016).

A spectrophotometer is an instrument to measure the transmittance or absorbance of a sample as a function of wavelength, measuring a series of samples at a single wavelength. In determining the sulfate content in the sample, the procedures carried out for its analysis are:

1. Pipette 50 mL of sample water and put it into an Erlenmeyer flask.
2. Add exactly 2.5 mL of conditioning reagent (a mixture of 75 g NaCl, 30 mL concentrated HCl, 100 mL 95% ethanol, 50 mL glycerol, and distilled water), stirring continuously with a glass stirrer or magnetic stirrer.
3. Add $BaCl_2$ crystals as much as 1 small spoon (0.2-0.3 ml capacity), run a stopwatch, and let it stir continuously until exactly 1 minute.
4. Immediately take measurements on the device every 30 seconds for 4 minutes. If there are a number of samples to be examined, check the calibration with one of the standard solutions for every 3 or 4 samples measured.
5. Make a blank solution of 50 ml of distilled water. Record the constant reading value as a correction factor.
6. Prepare calibration standard solutions containing 5, 10, 15, 20, 30, 40, and 50 mg/L sulfate by careful dilution of a 100 mg/L standard solution. Record the constant measurement values, and use these values in the calibration curve or regression equation that will later be used in the calculation of sulfate content in the sample.

The results of the laboratory analysis can be seen in **Figures 4**. Starting from the analysis of hardness, HCO_3, Cl, NH_3 and SO_4. In this laboratory analysis stage, all elements can be studied in the Chemical Oceanography Laboratory of the Marine Department, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia.

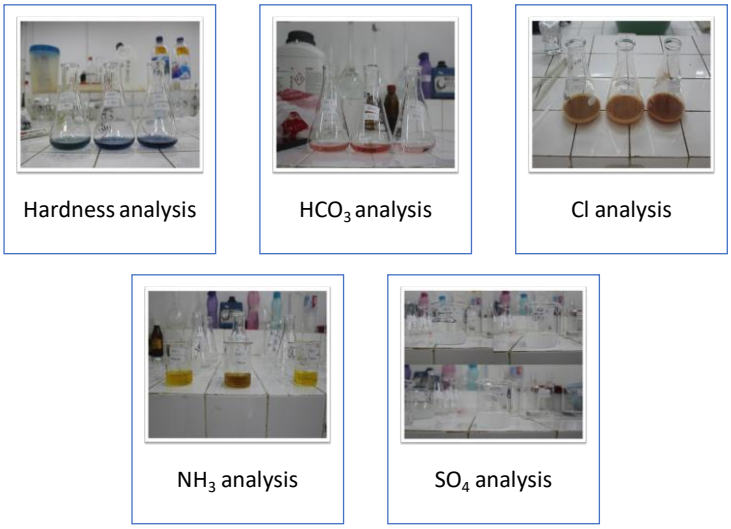

Figure 4. The process of hot spring water analysis from the analysis of hardness, HCO_3, Cl, NH_3 and SO_4.

Data analysis and evaluation phase

Processing of hot water samples was carried out at the Chemical Oceanography Laboratory, Department of Marine Sciences, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia. The results obtained are the values of the content of chemical elements. From these chemical elements we can determine the origin of the hot spring fluid, the type of geothermal fluid, and the subsurface temperature using a geothermometer (Anuar et al., 2021a; Idroes et al., 2019).

Geothermal fluids are distinguished by the main anions, namely chloride (Cl), sulfate (SO_4), and bicarbonate (HCO_3). The determination of hot spring type is to select representative hot springs to determine reservoir temperature using the geothermometer method (Iqbal et al., 2023). The determination of hot spring type is based on the classification of the trilinear diagram (Anuar et al., 2021a, 2021b).

The results of the chemical analysis then serve as parameters in determining the type of hot spring based on the classification of the trilinear diagram, modified from (Giggenbach, 1992) in (Idroes et al., 2019; Sadashivaiah et al., 2008; Singh et al., 2020). In this study, reservoir temperature was determined using the Na-K and Na-K-Mg geothermometer methods. The equation that can be used in calculating the temperature of the Na-K ratio (Iqbal et al., 2019; Iqbal & Kusumasari, 2024).

RESULTS AND DISCUSSION

Based on field observations and sampling, physical data collected from the research area included the pH, color, and temperature of each hot spring. Hot spring stations EPU 1, EPU 2, and EPU 3 exhibited a pH of 7 and clear color, with varying temperatures: EPU 1 at 45°C, EPU 2 at 57°C, and EPU 3 at 49°C. Hot spring water samples were collected using the Kemmer Water Sampler and subsequently analyzed in the laboratory to determine their chemical composition. The chemical analysis was conducted at the Chemical Oceanography Laboratory, Department of Marine Science, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, Indonesia, employing a geochemical approach. The chemical elements identified in the hot water samples are presented in **Table 1**.

Table 1. Results of analysis of the chemical element content of hot springs in the research area.

No	Parameters	Units	Analysis Result		
			EPU 1	EPU 2	EPU 3
1	pH (laboratory)	-	7,83	7,99	7,9
2	pH	-	7	7	7
3	Temperature	°C	45	57	49
4	Calsium (Ca)	mg/L	120,12	200,2	1033,032
5	Magnesium (Mg)	mg/L	20,897	-	-
6	Clhoride (Cl)	mg/L	1772,55	1725,75	1526,85
7	Natrium (Na)	mg/L	178,924	120,184	74,056
8	Kalium (K)	mg/L	48,351	92,646	51,739
9	Ammoniac (NH_3)	mg/L	0,010	0,125	0,015
10	Sulfate (SO_4)	mg/L	39	29	39
11	Bicarbonate (HCO_3)	mg/L	56	80	52

Subsurface temperature

The calculation of the subsurface temperature of the study area was carried out using the Na-K and the Na-K-Mg geothermometer equation. The geothermometer with an Na/K ratio gives an indication of high subsurface temperature by looking at sodium and potassium elements. The equation that can be used in calculating the temperature of the Na-K ratio (Giggenbach, 1992). For Na/K values obtained from laboratory analysis can be seen in **Table 2**.

Table 2. Calculation Results of Geothermal Reservoir Temperature in the Study Area

No	Manifestation Station	Temperature (°C)
1	EPU 1	326,504

2	EPU 2	473,369
3	EPU 3	456,508
	Temperature Avarage	**418,793**

Based on the results of calculations using the Na-K geothermometer, it can be seen that the subsurface temperature of the research area is around 326.504 °C, 473.369 °C, and 456.508 °C, as well as the average temperature of 418.793 °C, so that it can be classified into a high-temperature system that has a reservoir temperature > 225 °C (Arrofi et al., 2024; Rybach et al., 2003; Vuataz, 1983). This indicates that the hot water comes directly from a depth with a high temperature and then gets the influence of surface water recharge. This is characterized by a fairly high Mg element content. In addition, the presence of Na and K elements in the chemical content of hot water usually comes from the surface (Schäffer et al., 2018).

A ternary plot is a triangular diagram used to represent the proportions of three variables that sum to a constant. In the context of hot spring water, a ternary plot for Cl (chloride), SO_4 (sulfate), and HCO_3 (bicarbonate) is used to classify the water based on its chemical composition. If chloride (Cl) is dominant in the Cl-SO_4-HCO_3 ternary plot, this usually indicates the characteristics and source of geothermal water. Based on the results of the Sulili geothermal analysis, the water is rich in chloride ions compared to sulfate (SO_4) and bicarbonate (HCO_3) ions (**Figure 5**). Chloride-dominated water often has a neutral to slightly alkaline pH, which affects the solubility of minerals and the behaviour of other dissolved ions. Based on its source and origin, chloride-dominated water usually indicates deeper circulation of geothermal fluids. The fluid may have interacted with the underlying rock and magmatic gas. In some cases, high chloride content can also indicate the contribution of seawater, especially in coastal geothermal systems (Arrofi et al., 2024; Fauziyyah et al., 2016; Iqbal & Kusumasari, 2024; Schäffer et al., 2018).

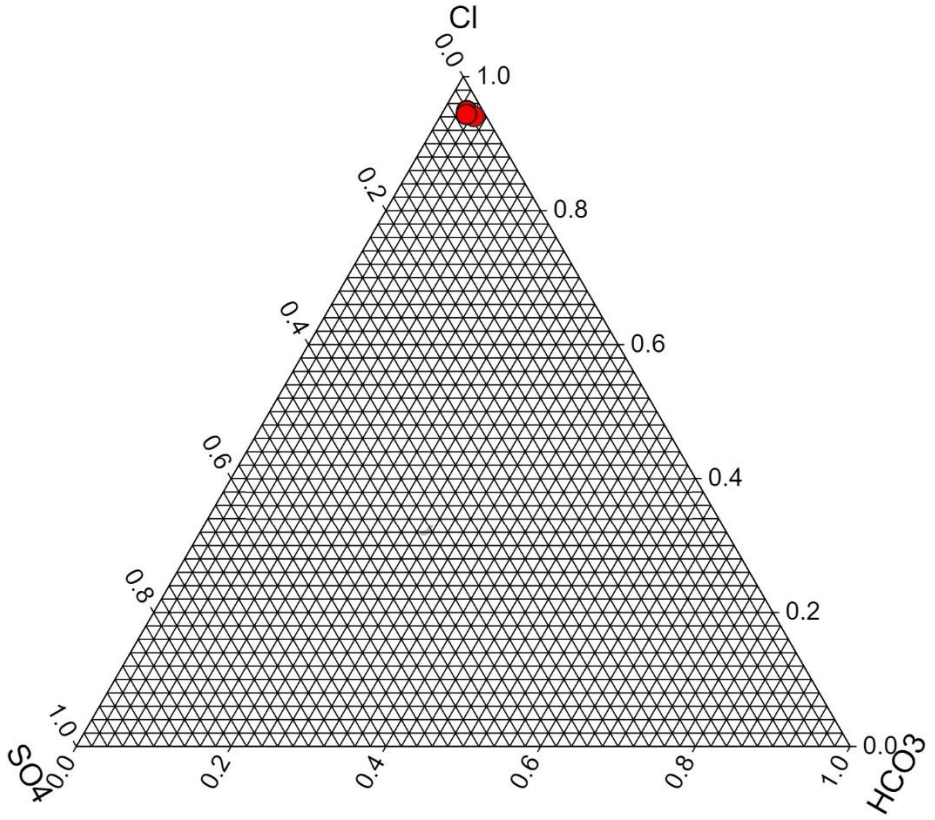

Figure 5. Ternary plot of Cl-SO4-HCO3 of water samples in Sulili geothermal system.

Chloride-rich waters are often associated with high-temperature geothermal reservoirs. High chloride content can help stabilise dissolved silica, preventing it from settling. The presence of chloride ions may indicate a magmatic contribution to the geothermal system. Magmatic gases such as HCl can dissolve in geothermal fluids, increasing the chloride content.

High chloride concentrations can cause scaling and corrosion problems in geothermal power plants. Proper management and treatment of geothermal fluids is essential to mitigate these effects. The presence of predominantly chloride-bearing water in the high-temperature Sulili geothermal reservoir indicates significant potential for energy extraction, making it a valuable target for geothermal exploration and development.

Thermal energy estimation

To estimate the electrical energy potential of the Sulili Geothermal Field with an average reservoir temperature of 418°C (**Table 2**). The thermal energy available in the geothermal reservoir can be calculated using the formula (Hristov et al., 2019):

$$Q = m.c.\Delta T$$

where Q is the thermal energy (in joules), m is the mass of the geothermal fluid (in kilograms), c is the specific heat capacity of the fluid (in joules per kilogram per degree Celsius), and ΔT is the temperature difference between the reservoir and the surface (in degrees Celsius). The thermal energy is then converted into electrical energy using a conversion efficiency factor. Geothermal power plants typically have an efficiency of around 10-20%. For the electrical energy (in megawatt-hours, MWh) can be calculated using the formula (Idroes et al., 2019; Rybach et al., 2003):

$$E = Q.\eta$$

where E is the electrical energy (in MWh), and η is the conversion efficiency (as a decimal). Based on the Sulili Geothermal Field with an average reservoir temperature of 418°C is approximately 68.33 MWh. This is a simplified calculation, and actual energy output can vary based on several factors, including the specific characteristics of the geothermal reservoir and the efficiency of the power plant. For more detailed and accurate estimates, advanced modeling and field data would be required.

CONCLUSION

The subsurface temperature of the study area of each station based on the Na-K geothermometer is station EPU 1 326.504°C, station EPU 2 473.369°C and station EPU 3 456.508°C. Based on the *ternary* diagram, one of the hot springs in the study area, namely EPU 1 station, is included in the *immature waters* group, while the two hot spring stations cannot be plotted on the *ternary* diagram due to too high Mg levels in the two stations. To estimate the electrical energy potential of the Sulili Geothermal Field with an average reservoir temperature. The Sulili Geothermal Field with an average reservoir temperature of 418°C is approximately 68.33 MWh. This is a simplified calculation, and actual energy output can vary based on several factors, including the specific characteristics of the geothermal reservoir and the efficiency of the power plant.

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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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