Mapping Geological and Geochemical Suitability to Determine Geothermal Favorability Using Spatial Analysis in the Ungaran Geothermal Field, Central Java, Indonesia

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Abstract. The Ungaran Geothermal Field in Central Java, Indonesia, holds significant potential for geothermal energy exploration due to its volcanic origin and active geothermal manifestations, such as fumaroles, hot springs, and hydrothermal alteration zones. Additionally, its strategic location in one of Indonesia's dynamic and rapidly growing provinces, with a population exceeding 36 million in 2023 and thriving industrial development, underscores strong market potential for geothermal power plant (PLTP) development to meet the region's high energy demand. This study utilizes Geographic Information System (GIS)-based spatial analysis to integrate six thematic layers—faults, volcanic domes, eruption sources, fumarole manifestations, hot springs, and hydrothermal alteration zones—collected through geological and geochemical surveys conducted by PT PLN (Persero) in 2019. Using the Index Overlay method, these layers were analyzed to assess geological and geochemical suitability for geothermal resource development. The results indicate that Gedongsongo and Kendalisodo exhibit the highest suitability values, making them priority targets for further exploration. This approach demonstrates the effectiveness of GIS in integrating diverse datasets to enhance predictive accuracy, support strategic exploration decision-making, and promote sustainable geothermal resource utilization in dynamic regions such as Central Java.

Keywords: *Ungaran Geothermal Field, Central Java, Geothermal exploration, Geographic Information System (GIS), Index Overlay, geothermal power plant (PLTP), geothermal potential, sustainable energy, spatial analysis, geological and geochemical suitability.*

1 Introduction

Modern exploration of geothermal resources has demanded a variety of concepts that require a lot of time and significant costs. Exploratory targeting does not only rely on one concept, but rather on the integration of these various concepts. It is a complex and important discipline in the conceptual phase for semi-quantitative prediction and probability of resources that ultimately leads to the decision to

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select potential areas (Hronsky and Groves., 2008). Another challenge in geoscience is efforts to reduce geoscience risks and provide more cost-effective exploration projects, although it often relies on probabilities input based on subjective assessments that are generally not very optimistic, inconsistent and biased because they have to rely on the experience of geoscientists (Kreuzer et al., 2008). In addition, the exploration program is also considered complex because it has to combine data sets to be more meaningful. The complexity ofexploratory data is also illustrated by the many methods used to produce individual data that are increasingly evolving over time, thus adding to the complexity of each source of information. This has consequences on the branching decision paths. Under such conditions, traditional decision-making based on heuristics may lose relevance with the ability of modern data to produce more accurate decisions on potential areas (Aitken et al., 2018).

According to Longley et al. (2011), one of the modern concepts that has been used as a tool to formulate scientific discoveries or decision-making in potential areas that is more effective is Spatial Analysis or Geographic Information System (GIS). GIS can connect non-spatial data with spatial data and create large geodatabases. Data that is connected to a location can produce a more in-depth analysis (Grekousis., 2020). In geothermal exploration, spatial analysis methods have been used as a decision-making tool in determining potential areas of geothermal resources on a regional and local scale (Noorollahi et al., 2007). Geoscience data can be integrated to determine geothermal potential models using Boolean, Fuzzy Logic or Index Overlay methods. The Index Overlay method is considered to be able to map a more concentrated area (Prol-Ledesma, 2000).

In this study, the model was constructed by integrating spatial data to evaluate p otential geothermal resource areas based on geological and geochemical explora tion data. The results of this model integration are then used to determine geolo gical and geochemical suitability areas in the Ungaran Geothermal Field.

2 Conceptual model on the field

The Ministry of Energy and Mineral Resources of the Republic of Indonesia (2017) reported that the Ungaran Geothermal Field, one of the Geothermal Working Areas (WKP) assigned to PT PLN (Persero) for development, has an estimated reserve potential of 100 MWe. A geoscience study conducted by PLN (2024) indicates the potential of geothermal resources concentrated in the Mount Ungaran area (Figure 1). The Ungaran geothermal system is a volcanic-hydrothermal system with an upflow zone located around the Gedongsongo fumarola manifestation with a magmatic heatsource, covering the top of Mount Ungaran and its surroundings up to a radius of 500 meters. The outflow zone covers most of the foot of Mount Ungaran, except for the west and northeast sides. The reservoir is dominated by high-temperature vapor fluids that are likely to be under a layer of clay cap at an elevation of 0 to -2200 meters below sea level with a thickness of 1000 to 1500 meters (Jatmiko et al., 2022).

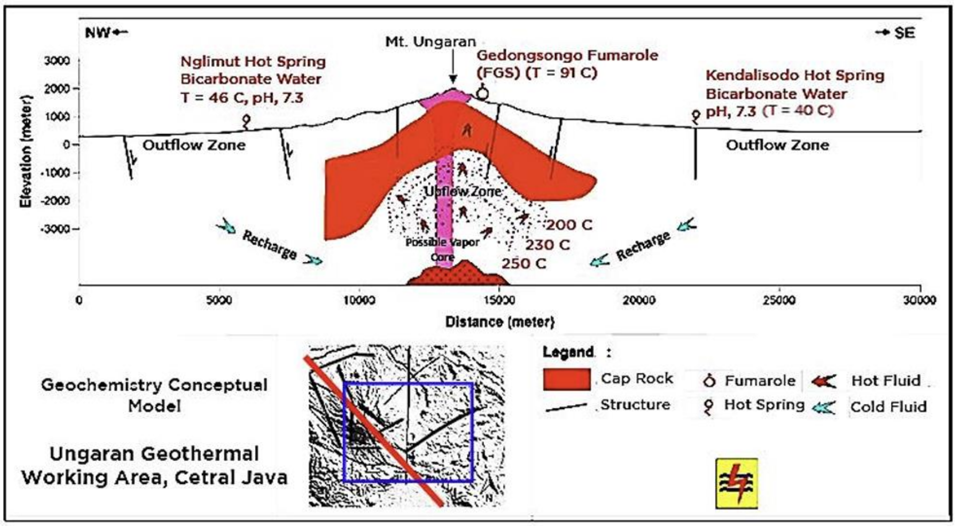

Figure 1 Conceptual model of the Ungaran Geothermal System (Jatmiko et al, 2022)

3 Input Data

Six data sets were used to develop a GIS-based model to predict areas with the highest geothermal potential in the Ungaran Geothermal Field. These data layers included faults and fractures, volcanic domes, eruption sources, fumarole manifestations, hot springs, and alteration zones, each providing unique insights into the geothermal characteristics of the region. The data were collected from geological and geochemical surveys conducted by the Exploration Team of PT PLN (Persero) in 2019, as outlined in PLN's Limited Report (2024). The GIS model processed these data layers using QGIS software, where the data were integrated and analyzed through the Index Overlay method to assess the geological and geochemical suitability for geothermal resource development. The presence of fumaroles and hot springs indicates active geothermal systems, while alteration zones reflect hydrothermal activity, all of which are key indicators of geothermal potential. By integrating these diverse data sets, the model facilitates targeted exploration and optimizes resource management, directly supporting the goal of identifying the most promising areas for geothermal energy development in Central Java.

3.1 Faults and Fractures

Faults and fractures are generally considered important in geothermal systems because they have higher permeability (Hanano, 2000). Surface indicators of the presence of major faults and solid fracture zones have proven useful in finding areas with secondary permeability (Prol-Ledesma, 2000). Thus, faults and associated fractures zones can be used as evidence when looking for more permeable zones.

Geological studies on Mount Ungaran have identified the structure well. The structure was obtained based on analysis and ranking (score 1-7) to indicate the presence of high permeability which is most likely a path for the rise of geothermal fluids to shallower depths.

3.2 Volcanic Dome

The spatial distribution of the volcanic dome was digitized from geological maps and used as a layer of evidence. It is assumed that the dome will be related to an intrusive object that serves as a heat source for the hydrothermal system. The youngest dome is located in Kemalon (measured age: <0.6 Ma), Mergi and kemalon (measured age 0.62±0.5 Ma) and Munding (measured age 0.68±0.5).

3.3 Eruption Source

In this study, the source of the eruption identified and used as *evidence* is the source of the eruption that comes from the eruption source that comes from the last eruption activity of Mount Ungaran. In identifying the source of the eruption, several datasets in the form of DEMnas and available geological maps were used. Based on the observation of the data, 3 (three) eruption sources can be identified that identify the morphological features that characterize the eruption sources such as circular, conical and lava rocks that are assumed to be formed close to the eruption sources around Mount Ungaran.

3.4 Fumarole Manifestation

In the context of GIS modeling, fumarole manifestations are used as a layer of evidence to predict areas of geothermal potential. Its spatial distribution helps in delimiting zones with high-temperature fluids, which is important for geothermal exploration. In this study, fumarole data was concentrated in the Gedongsongo area identified as the upflow zone of the Ungaran system.

3.5 Hot Spring Manifestation

Geothermal manifestations are crucial indicators in understanding the geothermal potential of an area. The 2019 Geochemical Survey by the Mount Ungaran

Exploration Team revealed hot spring manifestations with temperatures exceeding 28°C. These manifestations indicate the presence of subsurface heat sources that could be potential areas for geothermal resources. By incorporating this data into GIS modeling, geothermal potential areas can be predicted more accurately, identifying zones with high heat flow that are critical for geological exploration and development.

3.6 Alteration Zone

The alteration zone is an area where rocks and minerals have undergone chemical and mineralogical changes due to hydrothermal activity. In the geological context, this zone indicates the presence of a flow of hot fluids that affect the mineralogy of the surrounding rocks. Data from alteration zones are used as a layer of evidence in GIS modeling to predict geothermal potential. The presence of alteration zones indicates areas with intensive hydrothermal activity that may have high temperatures and significant fluid flows. Based on the 2019 Exploration Team's field survey, a delineation map of the altered rock area has been produced, which strengthens the analysis and interpretation of this alteration zone. By integrating alteration zone data with other thematic maps, geothermal potential areas can be identified more accurately.

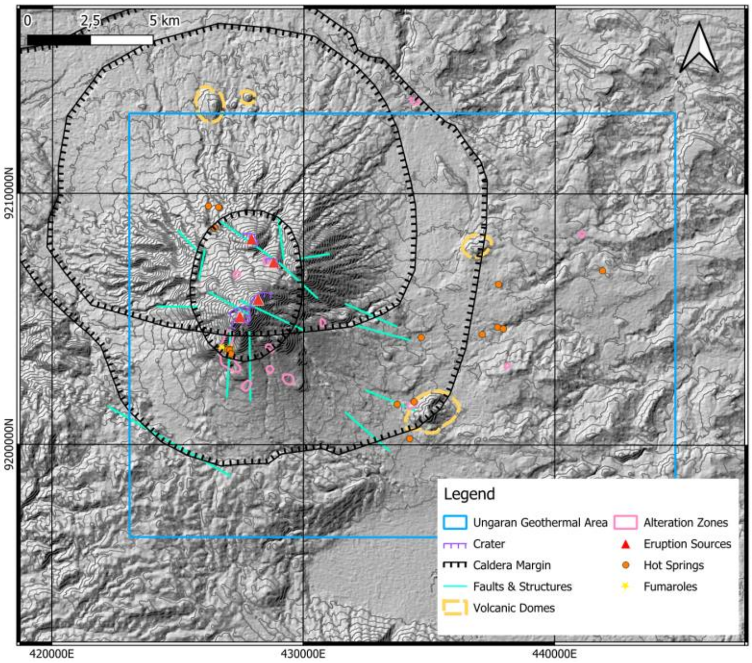

Figure 2 Distribution Map of Geological and Geochemical Data in Mt. Ungaran, Indonesia

4 GIS and data integration modelling (Index Overlay)

In the application of data integration models for geothermal exploration, expertise is essential when gathering information and selecting maps that will provide key predictors for geothermal resources, as this will reduce the amount of data overload and, thus, reduce costs (Prol-Ledesma, 2000). The determination of the weight factor for use in the Index Overlay model (Bonham-Carter, 1994) and the determination of the appropriate relative distance in the Boolean model will also follow the empirical relationships that depend on the conceptual model developed for the system. The initial evaluation of the geothermal prospects is mainly based on the results of geoscience investigations conducted during the early stages of exploration. Geoscience data is examined to infer the properties, characteristics, and possible sizes of geothermal resources as well as to build a conceptual model of the system. Based on the data collected during the exploration stage, the GIS integration model for the exploration data should provide evidence that the GIS model is capable of defining the areas most likely to produce commercial amounts of geothermal fluids (Noorollahi et al., 2007 and 2008). A data integration model using GIS is proposed, namely the Overlay Index model.

Favorable areas for geothermal exploitation are assumed to be located:

- Near volcanic domes and the location of eruption sources, which are suspected to be related to one or more near-surface heat sources;
- close to a more permeable area of the system as defined by faults and fractures;
- around surface manifestations (e.g. fumaroles, hot springs and hydrothermal alteration zones), which may indicate the main fluid flow in the system.

Index overlay is a GIS operation in which layers with the same area are combined based on their placement in space (Bonham-Carter, 1994; Clarke, 1999). This overlay function creates a composite map by combining various data sets. Each map class is scored differently, which allows for a more flexible weighting system. The score table and map weights can be customized to reflect the judgment of experts in the area of application under consideration. At a given location, the output score, S, is defined as follows:

$$S = \frac{\sum W_i A_i}{\sum W_i} \tag{1}$$

where Wi is the weight of the map, and Ai is the score on the ith map (Bonham-Carter, 1994). Subjective-based analysis is carried out using the index overlay model. Data layers in the same category or subject are first combined and analyzed to define promising areas. The resulting map layers from the various categories are then weighted, overlayed, combined, and analyzed until promising areas have been defined and classified. This cascading layer merging continues until all layers of data are used in the analysis. All available information regarding the study area is grouped into geological and geochemical datasets. Figure 3 shows the flowchart for the index overlay method used in the geothermal potential analysis. The class factors and weights used in the exploration of local geothermal resources are presented in Tables 1 and 2.

The geological dataset consists of three layers of evidence: faults and fractures, volcanic domes and eruption sources. To achieve geological conformity, the faults and fractures layer is combined with the geological contact of the volcanic dome and the eruption center to be subsequently buffered and weighted according to the data quality of each evidence layer in QGIS. The study area is divided into several classes of 200 and 100 meters distance based on the distance from the geological dataset features. In the distance analysis based on the layers of geological evidence, the study area was divided into 10 classes, each corresponding to a distance interval of 200 and 100 m. Specific weights, which decrease with distance, are assigned to each class (Table 1).

Table 1 Geology Class factors and weights used in geothermal resource potential (local scale)

Fault & Fracture (A)		**Eruption Source (B)**		**Volcanic Dome (C)**	
Score	**Factor Class**	**Score**	**Factor Class**	**Score**	**Factor Class**
9	0-200	9	0-200	9	0-100
8	201-400	8	201-400	8	101-200
7	401-600	7	401-600	7	201-300
6	601-800	6	601-800	6	301-400
5	801-1000	5	801-1000	5	401-500
4	1001-1200	4	1001-1200	4	501-600
3	1201-1400	3	1201-1400	3	601-700
2	1401-1600	2	1401-1600	2	701-800
1	>1600	1	>1600	1	>800
Weight 7		**Weight 5**		**Weight 5**	

The geochemical and geological evidence layers have similar characteristics, with buffer intervals used for the geochemical layer being 200 and 100 meters (Table 2). The geochemical dataset consists of evidence layers for fumarole manifestations, hot springs, and hydrothermal alteration zones. Fumarole manifestation data is given the highest weight compared to hot springs and alteration zones. This is done to highlight more favorable areas specifically near fumaroles, which usually indicate the presence of upflow zones in the system.

Table 2 Geochemical Class factors and weights used in geothermal resource potential (local scale)

Fumarole (D)		Hot Spring (E)		Alteration Zone (F)	
Score	**Factor Class**	**Score**	**Factor Class**	**Score**	**Factor Class**
9	0-200	9	0-200	9	0-100
8	201-400	8	201-400	8	101-200
7	401-600	7	401-600	7	201-300
6	601-800	6	601-800	6	301-400
5	801-1000	5	801-1000	5	401-500
4	1001-1200	4	1001-1200	4	501-600
3	1201-1400	3	1201-1400	3	601-700
2	1401-1600	2	1401-1600	2	701-800
1	>1600	1	>1600	1	>800
Weight 7		**Weight 5**		**Weight 5**	

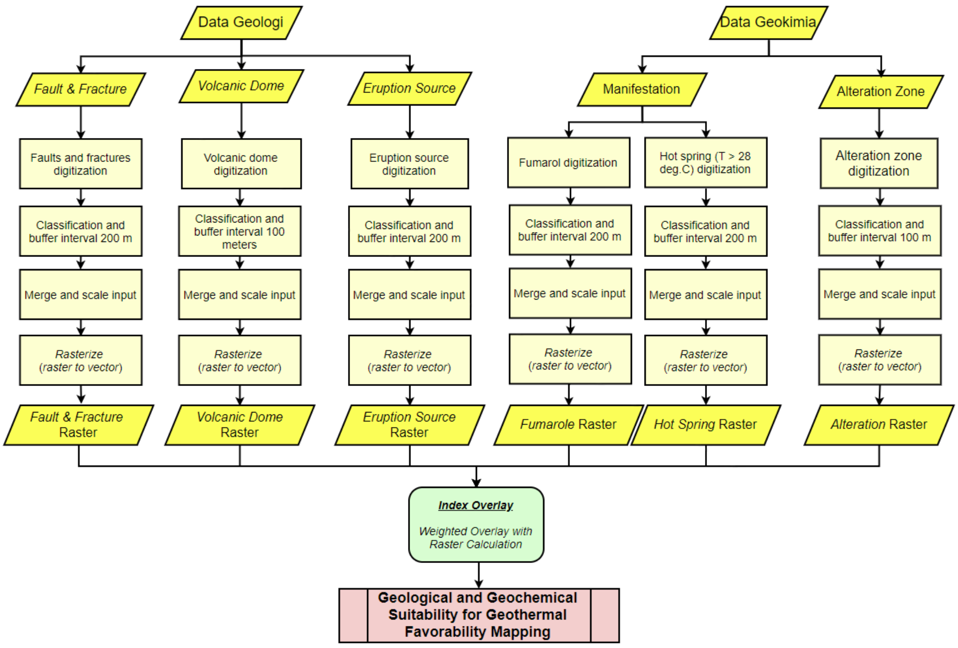

Figure 3 Flow diagram for Index Overlay model to identify geological and geochemical suitability for geothermal favorability mapping

To delineate geothermal suitability based on geological and geochemical data, the geological and geochemical suitability maps were overlaid using weight factors derived from the data accuracy levels indicated in Tables 1 and 2. Faults and fractures data, along with fumarole data, were assigned a weight of 7 because they represent high permeability zones and higher temperature areas with relatively better quality compared to other data. On the other hand, volcanic dome data, eruption sources, hot springs (with temperatures above 28°C), and alteration zones were assigned a weight of 5. Consequently, the area was divided into several ranking classes (from high to low), as shown in Figure 4.

Based on the index overlay formulation, the value of each layer must be multiplied by the assigned weight to enhance the main layer's value. Finally, the sum will be multiplied by 24 (total coefficients) with the following formulation:

$$S = \frac{(Ax\,7)+(Bx5)+(Cx5)+(Dx7)+(Ex5)+(Fx5)}{(7+5+5+7+5+5)} \quad (2)$$

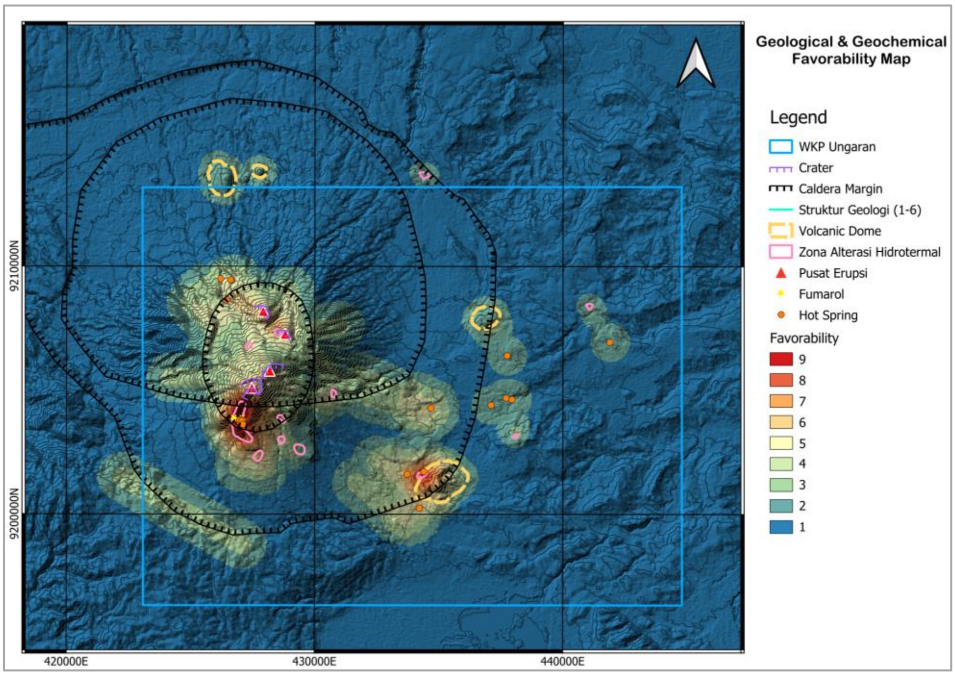

Figure 4 Overlain geological and geochemical favorability maps for the study area

Figure 4 shows that geological and geochemical suitability (Figure 4: red-colored areas) is concentrated in two favorable areas: around the summit and slopes of Mount Ungaran (Gedongsongo) with the presence of fumarole manifestations, and the southern side of the study area near volcanic dome features, geological structures (such as faults and caldera margins), with the presence of hot spring manifestations.

5 Conclusion

Digital data layers and maps are utilized in the GIS model to identify the most suitable areas based on geological and geochemical thematic data in the Mount Ungaran geothermal field. The GIS model includes six thematic layers: faults and fractures, volcanic domes, eruption sources, fumarole manifestations, hot springs, and hydrothermal alteration zones. These layers are classified and overlaid using a weighted overlay index, defining and prioritizing areas with conformity values to produce thematic maps of geological and geochemical suitability. The faults and fractures layer identifies high permeability zones, volcanic domes indicate the presence of heat sources, eruption sources highlight recent volcanic activity, and fumarole manifestations, hot springs, and hydrothermal alteration zones mark significant heat flow and fluid movement. The resulting maps show that the highest geology and geochemical suitability values are concentrated in the Gedongsongo and Kendalisodo areas, indicating these areas could become focal points for determining geothermal favorability in this study location, characterized by their geological and geochemical features, suggesting favorable conditions for geothermal exploration and development.

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