Geological Risks Assessment and Quantification in Ulumbu Geothermal Field, East Nusa Tenggara, Indonesia

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Abstract. The Ulumbu geothermal power plant is currently operating with a total capacity of 10 MWe. However, the Ulumbu geothermal field still holds the potential for further resource utilization, with at least 40 MW available for the next development phase. This further development carries risks of failure, making geological risk assessment and quantification crucial for calculating the success of development drilling in terms of resource risks. The method of geological risk assessment and quantification in geothermal exploration has been previously developed and applied to two fields, Galunggung and Patuha. The more frequently this method is applied to other geothermal fields, the more valid it becomes, considering that each geothermal field has its unique characteristics in terms of geothermal play type and resource conditions. This paper applies the geological risk assessment and quantification method to the Ulumbu geothermal field under two conditions: pre-drilling (3G data before 1992) and post-drilling (1996 drilling data and the latest 3G data). The results show that the pre-drilling condition exhibits a higher geological risk compared to the post-drilling condition.

Keywords: *geothermal, geologic risk, risk quantification, Ulumbu Geothermal Field, hydrothermal system, risk assessment.*

1 Introduction

The Ulumbu geothermal field is located in Manggarai Regency, Flores Island, East Nusa Tenggara Province, Indonesia, approximately 20 km south of Ruteng City. This field has been the focus of exploration surveys for geothermal power plant development since the early 1970s. Advanced 3G studies continued from 1984 and were summarized in the research by Mahon, T., et al. (1992). Between 1994 and 1996, three wells were drilled: one vertical well (ULB-01) and two directional wells (ULB-02 and ULB-03). Only ULB-02 was used as a production well, generating a total of 10 MWe. Research findings indicate that the Ulumbu geothermal field is dominated by Quaternary andesitic lava and pyroclastic rocks altered by neutral pH fluids, with numerous thermal features identified within the crater and on the western flank of the Poco Leok complex (Kasbani, et al., 1997)

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(see Figure 1). Subsurface data and further studies show that the Ulumbu geothermal field is a hydrothermal geothermal system with a reservoir predominantly in the liquid phase. The field still holds the potential to be developed further, with an estimated capacity of at least 40 MW (PLN, 2017). However, the extended development of the Ulumbu geothermal power plant carries risks of failure, making geological risk assessment and quantification essential to evaluate the success of development drilling, particularly regarding resource risks.

Additionally, the availability of two sets of data for the Ulumbu geothermal field are pre-drilling and post-drilling conditions provides valuable input for the geological risk assessment and quantification method developed by Suryantini and Wibowo (2015). This method has so far been applied to only two geothermal fields, Galunggung and Patuha. Given that each geothermal field has unique characteristics in terms of geothermal play type and resource conditions, applying and studying this method in other fields is crucial to enhance its validity.

2 Risk Assessment and Quantification

The primary uncertainty in geothermal project development is always associated with the quantity and quality of geothermal fluids that can be extracted from the subsurface. This uncertainty significantly impacts the determination of downstream power plant design parameters, such as sizing, technology selection, and other engineering aspects (Matek, 2014). Subsurface resource uncertainty is one of the exploration risks closely linked to the geological conditions of the geothermal field, often referred to as geological risk. Geological risk represents the most challenging exploration risk to assess and quantify due to the numerous factors involved, each with varying levels of uncertainty (Suryantini and Wibowo, 2015).

Quantitative risk assessment can assist decision-makers and engineers in better understanding geoscience information, which is typically qualitative in nature. By quantifying risks, it is expected to obtain a more objective and standardized risk analysis (Hikmi et al., 2019). The concept of geological risk assessment and quantification in geothermal projects is adopted from oil and gas projects, as conducted in the study by Otis & Schneidermann (1997), and has been previously applied in the study by Suryantini and Wibowo (2015). Before conducting quantitative risk assessment, a qualitative assessment is necessary by examining the geological variables that contribute to the success of geothermal project development.

In the method developed by Suryantini and Wibowo (2015), geological risk is assessed with consideration for the fact that geothermal development for power generation in Indonesia requires significant resources, which are usually found in convective geothermal play types. In these systems, heat transfers from depth to shallow reservoirs or the surface through upward fluid movement along permeable pathways (Moeck, 2014), particularly in hydrothermal systems. This method considers three independent components for evaluating a geothermal field's potential: an adequate heat source, typically derived from volcanic activity dating between 50,000 to 250,000 years ago (Wohletz and Heiken, 1992); a large reservoir potential (influenced by rock and fluid properties); and the sustainability of the geothermal system, which is assessed through recharge and discharge areas.

The list of critical aspects from the geological risk assessment developed by Suryantini and Wibowo (2015) includes:

1) Heat Source: The thermal potential of the heat source (preferably magmatic or volcanic), which consists of geometry, age, and proximity to the reservoir.

2) Reservoir: This is divided into: a) Thermal potential related to rock properties, including area, thickness, temperature, porosity-permeability, density, and thermal conductivity. b) Thermal potential related to fluid properties, including fluid phase, volume (porosity or permeability), and density. c) Presence of cap rock. d) Steam quality, including NCG (Non-Condensable Gas) content, scaling potential, corrosion potential, pH, flow rate, and enthalpy.

3) Recharge – Discharge: This includes heat loss, area extent, upflow-outflow zones, and hydrological conditions

The Probability of Geologic Success (Pg) is obtained by multiplying the probability of the presence of each of the three components:

$$(Pg) = (Pheat\ source)\ x\ (Preservoir)\ x\ (Pdischarge\ recharge) \qquad (1)$$

where the probability of each component is derived from the assessment of risk factor elements. These elements are categorized as unfavourable, questionable, neutral, encouraging, and favourable (Table 1). The final assessment result is the Probability of Geologic Success, which is determined with values ranging from 0.01 (high risk) to 0.99 (low risk).

Table 1 The risk assessment worksheet provides a method for transferring qualitative judgments on geologic risk to quantitative probability of geologic success (Suryantini and Wibowo, 2015)

Probability Factor					
	Unfavourable	Questionable	Neutral	Encouraging	Favourable
1. Heat Source					
1.1. Geometry					
1.2. Age					
1.3. Proximity to reservoir					
etc					
	Unfavourable	Questionable	Neutral	Encouraging	Favourable
2. Reservoir					
2.1. Rock properties					
2.2. Fluid properties					
2.3. Steam quality					
etc					
	Unfavourable	Questionable	Neutral	Encouraging	Favourable
3. Recharge - Discharge					
3.1. Heat loss					
3.2. Area extent					
3.3. Upflow - outflow					
etc					

Table 2 The risk description for every risk score range (modified from Otis and Schneidermann, 1997)

For any risk factor, the "weakest" element determines the risk

Range	**Risk Description**
< 0.3	Risk factor contains unfavorable elements
0.3 - 0.5	One or more elements are questionable
0.5	Elements unknown or no definition data
0.5 - 0.7	All elements at least encouraging to favorable
> 0.7	All elements well documented and encouraging to favorable

Unfavorable | Neutral | Favorable

0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

Model based

| Model supported by data |

| Model fully documented by data from prospect area |

Table 3 Risk Category based probability of geologic success (modified from Otis and Schneidermann, 1997)

Risk Category	Pg	
	min	max
very low risk	0.50	1.00
low risk	0.25	0.50
moderate risk	0.13	0.25
high risk	0.06	0.13
very high risk	0.03	0.06

3 Case Study in Ulumbu Field – Pre-Drilling Data

The pre-drilling conditions of the field are represented by secondary data from Mahon, T., et al. (1992), which integrated 3G data for the Ulumbu field before 1992, when no exploration drilling had been conducted. The Ulumbu field was the first geothermal field in Flores Island to be studied for its geothermal potential in the early 1970s. This was followed by a collaboration between the New Zealand and Indonesian governments in 1987, and further 3G studies, which included geology (Setiawan and Suparto, 1984 in Mahon, T., et al., 1992), geophysics (Simanjuntak and Akhmad, 1985 in Mahon, T., et al., 1992), and geochemistry (Kartokusumo and Somad, 1987 in Mahon, T., et al., 1992).

Most of the thermal activity in the Ulumbu field is concentrated in the Poco Rii-Leok volcanic caldera and its slopes (covering approximately 28 km^2). Manifestations observed include hot springs, fumaroles, sinter deposits, and altered ground. The Ulumbu geothermal field is situated on the slopes of the Poco Leok volcanic complex (see Figure 1). Quaternary rocks in this area reach elevations of about 1,600 meters above sea level, overlying Tertiary basement rocks primarily composed of lava, breccia, and tuff, with possible limestone sediments. Volcanic products formed as a result of early Quaternary volcanism (approximately 258,000 years ago) are centered at north of Ulumbu, around the Mandasawu Volcanic Mountains (Mahon, T., et al, V., 1992). The heat source is believed to originate from the Mandasawu Volcanic Mountains. The proximity of the reservoir to the heat source is indicated by geophysical data, such as low resistivity findings and isotopic geochemical data from manifestation samples, but further confirmation of deep geological structures using subsurface data is needed. Based on geometry (volume) and the age of the volcano, the heat source factor indicates an encouraging probability, supported by field findings.

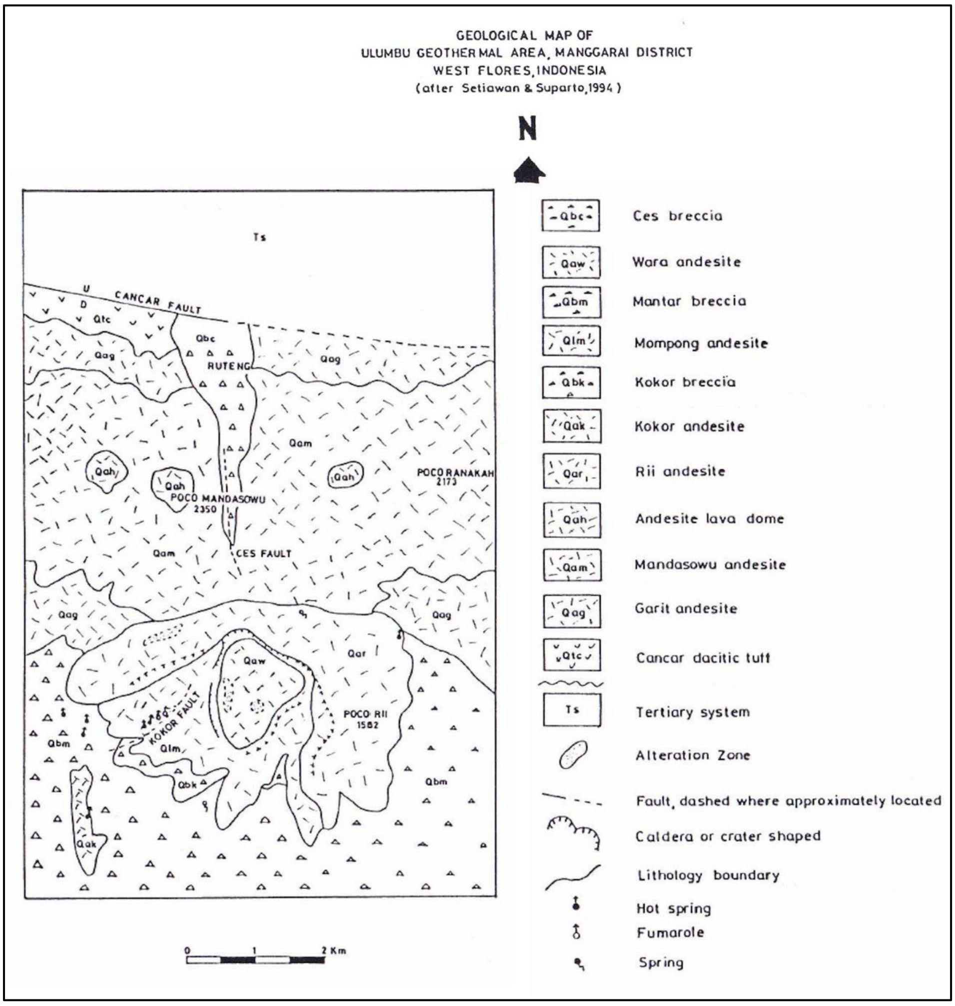

Figure 1 Geological Map Ulumbu (Utami dan Brown (1996) after Setiawan dan Suparto (1984)

The distribution of surface manifestations and resistivity anomaly data estimate the geothermal prospect area of the Ulumbu field to be around 50 km², with a low-resistivity layer indicating a reservoir thickness of about 600–800 meters. Sub-factors such as area, thickness, and cap rock indicate an encouraging probability. The fluid phase in the Ulumbu field remains uncertain, and there is no chemical evidence suggesting the presence of a large reservoir containing hot sodium chloride water. The fluid phase sub-factor indicates a neutral to encouraging probability. Gas geothermometry from fumaroles suggests that the fluid resource temperature exceeds 250°C, with the temperature sub-factor indicating an encouraging probability. Sub-factors such as rock properties like porosity, permeability, rock density, and thermal conductivity indicate neutral values due to limited data and reliance on analogue models from similar fields.

Estimates of heat loss from local thermal manifestations range from 20 MWt to 100 MWt, resulting in an encouraging probability for the heat loss sub-factor. The primary upflow zone is identified beneath Kokor or towards Lungar, but the outflow zone has yet to be defined, making it difficult to delineate the area extent. The upflow-outflow zone sub-factor indicates a neutral to encouraging probability, while the area extent sub-factor shows a neutral probability.

4 Case Study in the Ulumbu Field – Post-Drilling Data

The post-drilling conditions of the field are represented by secondary data, including recent 3G results from the Additional Geoscience Survey Report of WKP Ulumbu (PLN, 2020, unpublished) and well data from the Feasibility Study Report: Ulumbu Prospect (PLN, 2017, unpublished). Between 1994 and 1996, three wells were drilled: one vertical well, ULB-01, and two directional wells, ULB-02 and ULB-03. Only ULB-02 was used as a production well, generating a total of 10 MWe. At this stage, the Ulumbu field has been extensively studied, with new data collection such as remote sensing analysis using updated imagery (ASTER ASTGTM (2009), DEMNAS (April 2019), Landsat 7 ETM+ & 8 OLI (September 2019), Global Marine Gravity Model (September 2019), and LiDAR (2018), detailed geological mapping, and recent geochemical sampling (2019), reprocessing magnetotelluric data, new gravity data collection, and updating the conceptual model.

The Ulumbu geothermal field is located within the Quaternary Rii Caldera, identifying it as a volcano-hydrothermal system. Geophysical data suggest that the heat source is likely beneath Lungar Crater and Ulumbu Crater, at a depth of about +4 km. The age of the volcanostratigraphic units in the study area corresponds to the Older Pleistocene Volcanic Deposits Unit (QTv) (approximately 258,000 - 180,000 years ago). Reservoir identification within the geothermal system is interpreted based on the location of upflow zones. The existence of two distinct upflow zones (Lungar Crater and Ulumbu Crater) suggests the possibility of two separate reservoirs beneath each crater at shallower depths (see Figure 2). The heat source factor indicates a favourable probability according to the latest conceptual model, supported by new field data.

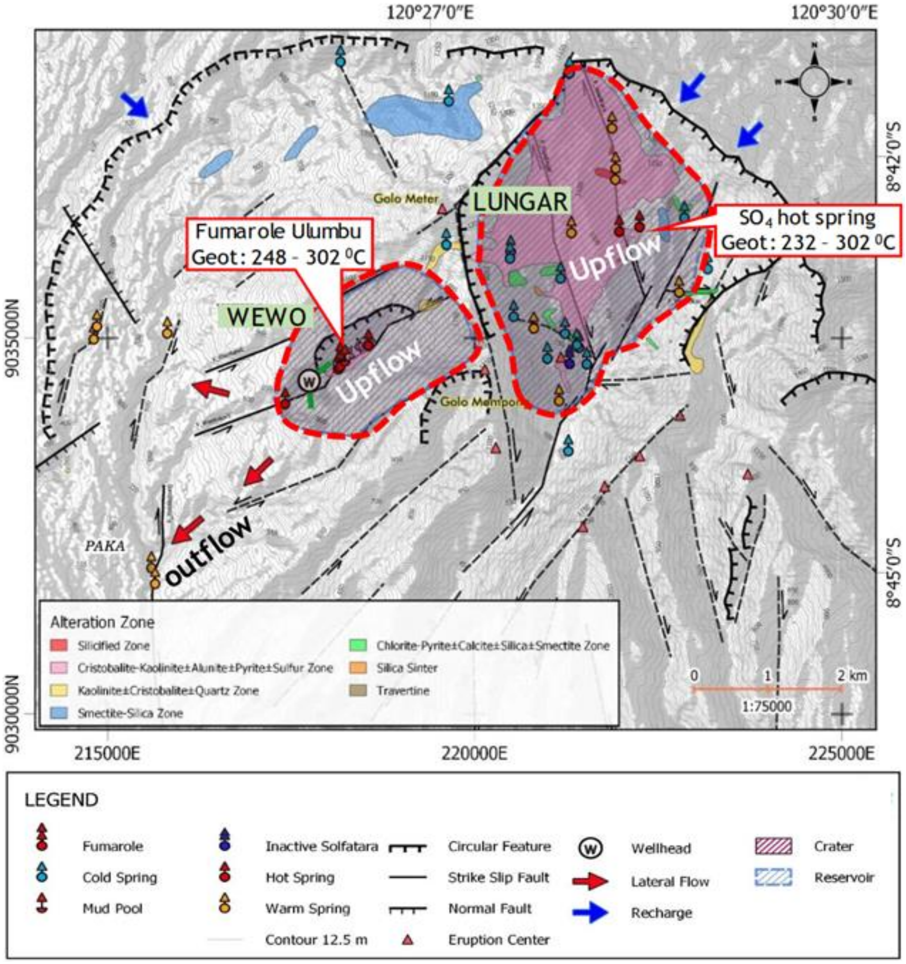

Figure 2 Map view konseptual model lapangan Ulumbu (PLN, 2020)

The exploitable resource area in the Wewo prospect is estimated at 1.5 km² to 4.0 km², while the Lungar prospect resource area ranges from 1.6 km² to 10.2 km². Reservoir thickness is determined using existing well data and controlled by gravity data. The top of the reservoir is mapped based on the presence of continuous epidote minerals identified from well data. Bedrock distribution is controlled by forward gravity modelling, determining reservoir thickness to be around 1000–1500 meters. The cap rock of the Ulumbu geothermal system has a thickness of 500-800 meters. This thickness is derived from MT geophysical data, showing a conductive zone (7-10 Ωm) at an elevation of -300 meters above sea level. Additionally, well drilling indicates the presence of alteration minerals in the cap rock, such as smectite, smectite-chlorite, and chlorite-smectite layers at a depth of approximately ±800 meters. Sub-factors like area, thickness, and cap rock for rock properties indicate a favourable probability, supported by surface and subsurface data. The predominance of volcanic rocks at depth suggests good porosity based on what is known from similar lithologies in other geothermal fields, with porosity most likely assumed to be around 10%. A minimum porosity of 8% and a maximum of 15% are considered, reflecting the dominance of andesitic volcanic rocks. The porosity-permeability sub-factor indicates a neutral to encouraging probability. Rock density relates to the density of minerals, not the overall bulk density of the rock, which includes pore space. These values are analogized for andesite and basaltic andesite rocks. This is also true for thermal conductivity due to the limitations of direct measurements, resulting in neutral probabilities for the density and thermal conductivity sub-factors.

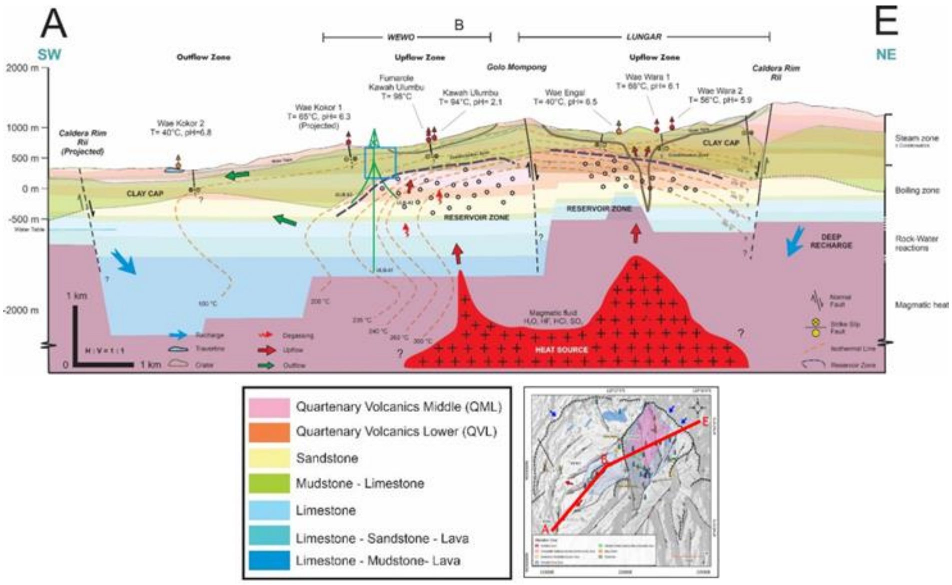

Figure 3 Conceptual model geothermal of Ulumbu (PLN, 2020)

Temperature estimates are based on well temperature data and fumarole geothermometry. Gas and liquid geothermometry from manifestations in the Ulumbu crater indicate temperatures between 248-302°C in the Wewo prospect, while manifestations in the Lungar area suggest reservoir temperatures ranging from 232–302°C. Previous well drilling showed temperatures of around 240°C in wells ULB-1, ULB-2, and ULB-3 at a depth of 700-800 mD. Well data indicate that this field is steam-dominated in the upper section and water-dominated in the lower section, with temperatures around 230-240°C. The temperature and fluid phase sub-factors indicate favourable probabilities. Differences in pH between hot springs and groundwater in Ulumbu suggest an acidification process (steam heated) occurring in hot springs, but neutral pH fluids were found in wells. Silica and calcite mineral precipitation is expected to be minimal in both wells, with sulfide minerals considered insignificant. The pH and scaling sub-factors for fluid properties indicate favourable probabilities.

The updated conceptual model provides a more comprehensive view of the Ulumbu geothermal system, indicating upflow zones at Ulumbu Crater and Lungar Crater, with an outflow zone in the Paka area (flowing westward) (see Figure 3). The extent of the area can be delineated with the support of new data. The recharge-discharge factor indicates a favourable probability.

5 Risk Calculation and Assessment

The results of the geological risk assessment and quantification for the Ulumbu field under pre-drilling and post-drilling conditions are summarized in Table 4. In the pre-drilling condition, the probabilities of occurrence for the heat source, reservoir, and recharge-discharge are 0.6, 0.5, and 0.5, respectively. The calculated geological success probability (Pg) is 0.15, which, according to the risk category in Table 3 is classified as moderate risk.

In contrast, the assessment results for the post-drilling condition show probabilities of occurrence for the heat source, reservoir, and recharge-discharge of 0.8, 0.5, and 0.8, respectively. The calculated geological success probability (Pg) is 0.32, categorized as low risk.

6 Discussion and Concluding Remark

The geological success probability value (Pg) for each condition of the Ulumbu field is determined by examining the same geological risk factors. This allows us to observe the differences in geothermal development risks faced in the Ulumbu field under pre-drilling and post-drilling conditions. It is evident that the geological success probability (Pg) value for the pre-drilling condition is lower than that for the post-drilling condition, indicating that the Ulumbu field experiences higher risks during the pre-drilling phase compared to the post-drilling phase.

The unavailability of data will score the risk assessment of a particular aspect in geological risk to be neutral (0.5). This is because the aspect under evaluation forces us to rely on model-based approaches or to draw analogies from other similar fields. In the sub-factor related to rock properties, particularly in the elements of density and thermal conductivity, a neutral probability is indicated due to the difficulty in obtaining data for these aspects. This will affect the reservoir probability value because the probability values of each geological risk

Table 4 Assessment of Probability of Geologic Factor of Ulumbu Field (pre-drilling and post-drilling conditions)

		Pre-Drilling					Post-Drilling				
No	Geologic Factor / Elements	Unfavorable	Questionable	Neutral	Encouraging	Favorable	Unfavorable	Questionable	Neutral	Encouraging	Favorable
I	**Heat Source**			**0.6**					**0.8**		
	Volume (Geometry)				0.7						0.8
	Age				0.6						0.9
	Proximity to reservoir				0.6						0.9
II	**Reservoir**			**0.5**					**0.5**		
	Rock Properties										
	Area				0.7						0.8
	Thickness				0.7						0.9
	Cap Rock				0.7						0.9
	Porosity - Permeability			0.5						0.6	
	Density			0.5					0.5		
	Thermal conductivity			0.5					0.5		
	Fluid Properties										
	Temperature				0.7						0.9
	Fluid phase			0.5							0.8
	pH			0.5							0.8
	Scaling			0.5							0.8
III	**Recharge - Discharge**			**0.5**					**0.8**		
	Heat loss				0.7						0.8
	upflow-outflow zone				0.6						0.9
	Area extent			0.5							0.9
	Geology Succes (Pg)			**0.15**					**0.32**		
	Risk Category			**Moderate Risk**					**Low Risk**		

factor refer to the lowest value in the sub-factors/elements (Table 1). The unavailability of data will lower the geological success probability value, which means it will increase the risks faced in the development of geothermal fields.

This study applies the geological risk assessment and quantification method developed by Suryantini and Wibowo (2015) to a geothermal field is Ulumbu, but under two different conditions: pre-drilling and post-drilling. The results reveal differences in the probability of geological success (Pg), where the pre-drilling condition, which lacks drilling (subsurface) data shows higher risk compared to the post-drilling condition, which includes updated data and additional drilling data. For example, elements in the heat source sub-factor (volume, age, and proximity to the reservoir) show a change in Pg values from encouraging (0.6–0.7) to favourable (0.8–0.9). This change is due to the reliance on surface data during the pre-drilling phase, while the post-drilling phase incorporates subsurface data and additional follow-up surveys that strengthen evidence of the heat source, thereby reducing geological risk (see Table 4). Similarly, for elements in the reservoir and recharge-discharge sub-factors, such as temperature, the pre-drilling condition Pg value is 0.7 (encouraging). This is because, despite strong evidence of high temperatures in surface manifestations, there was no direct subsurface data confirming high reservoir temperatures. In the post-drilling condition, the Pg value rises to 0.9 (favourable) due to direct subsurface temperature measurements. This trend applies to other elements as well.

These results suggest that the method is valid, considering that during the early stages of geothermal field development, high uncertainties are faced, resulting in the highest project risks. Over time, with the availability of additional data and drilling, uncertainties related to geothermal resources decrease, leading to reduced project risks compared to earlier stages.

Nomenclature

°C	=	Celsius Degree
3G	=	Geology, Geochemistry, and Geophysics
mD	=	Meter Depth
NCG	=	Non-Condensable Gas
MW	=	Megawatt
MWe		Megawatt electric
MWt		Megawatt thermal
Ωm	=	Ohm meter
PLN	=	*Perusahaan Listrik Nasional* (State Electricity Company in Indonesia)
pH	=	Potential of Hydrogen
WKP	=	*Wilayah Kerja Panas Bumi* (Geothermal Working Area)

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