Updated Conceptual Model and Resource Assessment using Numerical Reservoir Simulation of Danau Ranau Geothermal Field Indonesia

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Abstract. Danau Ranau geothermal field is located in Lampung and South Sumatra province, Indonesia. It is classified as a high terrain volcanic hydrothermal system controlled by the Sumatran fault as the permeability zone. The study aims to characterize the Danau Ranau reservoir, update the conceptual model, and assess the geothermal power capacity coupled with Monte Carlo simulation. Therefore, the numerical reservoir simulation is performed using TOUGH2 software to achieve a natural state model based on geoscience interpretation data. The numerical reservoir models’ output matches the geological, geochemical, and geophysical interpretation, thus becoming important information (3D pressure and temperature, heat and mass flow, location of heat source, boundary condition, reservoir geometry) in the updated conceptual model. The probabilistic heat stored method results based on the natural state model’s output show that Danau Ranau geothermal field can generate up to 30 MW.

1. Introduction
The Danau Ranau geothermal working area was established through a decree of the Minister of Energy and Mineral Resources of Indonesia (No. 1151K/30/MEM/2011, April 21st, 2011). Preliminary geological exploration has been carried out on an area coverage at UTM 380000 mE - 392000 mE and 9462000 mN - 9449200 mN, with an area of 127 km². The geothermal field is located within the Lampung and South Sumatra provinces, Indonesia. About 70% of the investigation area is in the Sukau District, West Lampung, Lampung Province, while 30% is in the Bandung Agung Sub-District, South Oku, South Sumatra. The nearest airport is the Agung Banding Airport, with an approximate distance of about 15 km from the geothermal field. The nearest port is Bintuhan, approximately 60 km from the location of the geothermal field.

Danau Ranau is a geothermal field that has not been previously explored and assigned to PT PLN to develop an installation of a geothermal power plant. Only the initial geoscience exploration stage has been carried out (geology, geochemistry, and geophysics) by the National Geological Agency [1]. This limited integrated study has resulted in a provisional geoscience conceptual model that cannot accurately describe the subsurface conditions due to the lack of subsurface information provided by...
drilling wells, both exploration and thermal gradient wells. However, we believe that the results from geoscience surveys are enough to support the physical parameters needed by the numerical model to be developed, including reservoir geometry from geophysical interpretations, reservoir temperature based on geothermometers, and estimations of subsurface rock physics by interpreting geological features. The numerical model simulation is expected to overcome geological conceptual models’ shortcomings and provide a more precise and accurate estimation of subsurface features.

The natural state of a geothermal system refers to the system’s condition before geothermal exploitation begins [2]. The natural state model is used to simulate thermodynamic processes occurring in the subsurface. Thus, it can infer the circulation of the thermal fluid, in terms of heat and mass, within the reservoir and through the outflows, eventually up to the surface. The numerical model simulation can update the conceptual model built so that the subsurface conditions can be better estimated [3, 4, 5].

The natural state model of Danau Ranau field was developed using the TOUGH2 numerical reservoir simulator with the EOS1 equation of state for pure water. The ground surface represents the top model boundary so that shallow aquifers are represented within the model. The model describes the physical processes that take place in the system and are controlling its thermodynamic state. The natural state obtained is used to update the conceptual model regarding temperature distribution, fluid flow paths, and reservoir geometry. The new conceptual model is used for the resource assessments using the heat stored method complemented with the Monte Carlo approach.

2. Initial Exploration Data
The preliminary geoscience survey was carried out by the Ministry of Energy and Mineral Resources (specifically implemented by the PSDG). The preliminary exploration phase consists of remote sensing, geological, geochemical, and geophysical studies. However, there are no exploration wells, temperature gradients, or exploitation wells in this geothermal field. Based on available data, an initial conceptual model can be generated from geoscience studies. Interpretation of the integrated geoscience studies and the conceptual model is considered useful to build numerical models for reservoir simulation. The conducted studies are explained in detail in the following discussion.

2.1. Geological Studies
Danau Ranau geothermal field is a Pleistocene caldera from Mount Ranau formed on the Sumatran fault system, which forms a basin due to the formation of a pull-apart fault system. The southeastern part of Danau Ranau formed Mount Seminung, a stratovolcano type post-caldera mountain [6]. The products of Mount Seminung are lava and pyroclastics, suggesting explosive eruptions with high energy. Based on manifestations’ appearance on the surface, we suspect that the magma at Mount Seminung is still active and a heat source for the Lake Ranau geothermal system.

The Sumatran fault system controls permeable zones in the Danau Ranau geothermal field, a strike-slip fault with a dextral moving direction relatively directed to the northwest-southeast. The separation of the fault section by step-over with an en-echelon pattern results in the formation of extension movement that forms volcanic-tectonic depression at Danau Ranau. Fault patterns form a trend of northwest-southeast, north-northwest-south-southeast, and northeast-southwest direction, associated with the main, synthetic, and antithetic faults of the Sumatra fault, better known as the Semangko Fault [1]. The faults developed in this region are Talang Kedu Fault, Kota Batu Fault, Wai Uluhan Fault, Talang Biak Fault, and Kukusan Fault, which is in northwest-southeast directions. The East-West fault is the Seminung Fault.
The morphology of the investigated area consists of plains to mountains with different rock characteristics. The formed slopes are the result of endogenous and exogenous processes since the tertiary period. Volcanic rocks dominate the area and form rough and steep reliefs. The developed structure influences the formation of steep cliffs. Mount Seminung area is a fertile region with a high rainfall rate, which suggests that it acts as a water catchment and recharge area in the geothermal system. In the southern part of Mt. Seminung, Sulung Hill and Kukusan Mountain are considered rain catchments and geothermal system recharge areas. The discharge zone’s appearance on the surface is characterized by surface manifestations that come out of the lithological contact and faults that form around Mount Seminung, located in Lumbok and Kota Batu areas (Figure 1).

The oldest rock type is the old volcanic lava flow (Tlt) formed in the Early Miocene, while the youngest rock is the formation of Seminung 3 (Qls-3) lava rock, which is an aphanitic andesite rock being the last product of Mt. Seminung in the quaternary period (Figure 1). Travertine deposits have also been found in the Kota Batu area caused by high carbonaceous values due to mixing with surface water and lake Ranau water (Figure 2). At Danau Ranau geothermal field, alteration minerals such as halloysite, illite, montmorillonite, and jarosite are found and estimated to be formed at temperatures <340°C and included in the argillic type hydrothermal zone. When it is viewed from the current surface manifestation state, the mineral alteration found is a type of paleo-alteration mineral, so that the Danau Ranau geothermal system has entered the cooling phase of magma.
2.2. Geochemistry Studies
Danau Ranau geothermal field is indicated by surface manifestations in the forms of hot springs and warm springs, without any steam or gas manifestation at the surface. A detailed study was carried out on 10 surface manifestations (thermal spring) consisting of 4 hot springs (55-63°C) and 6 warm springs (<50°C) that spread on the slopes of Mt. Seminung following NW-SE fault direction (Kota Batu Fault) and NE-SW (Lumbok Fault). The geothermal hot spring and warm spring distribution are limited to only these two areas, whereas in the SE section, there are traces of the hydrothermal process in the form of argillic alteration on the surface, which is also associated with NW-SE faults. Travertine deposits are also found to be associated with several thermal springs, followed by high HCO₃ values. The quality of manifestation data based on ion balance analysis is excellent [7] with an Ion Balance value of <5%.

The geochemical analysis results based on water sampling show that all spring manifestations at Danau Ranau have bicarbonate water types (HCO₃), except for Lumbok springs. The Lumbok springs have four types of dilute springs, which contain HCO₃-SO₄ and HCO₃-Cl fluid. According to the similarity of the location of manifestation point in the plotting results based on the Cl-Li-B content, all springs are characterized to be in the same environment, representing that all hot springs are formed because of the rocks convection activities on Mt. Seminung [9]. The low Na/Ca geo-indicator ratio in all manifestation water samples shows that Danau Ranau manifestations are in the geothermal system’s outflow zone. Based on isotope analysis, the ratio value of ¹⁸O with deuterium in Talang Kedu and Kota Batu-1 springs is plotted away from the meteoric water line, indicating that the water in this manifestation originates from a magmatic process in the subsurface. In contrast, the manifestation of the Lumbok-1 spring has the opposite value, which indicates a mixture with surface water [7].

Based on the abundant elements in the sample of water manifestations, a geothermometer is calculated based on the value of each manifestation’s dominant element’s characteristic. Na-K geothermometer with Mg correction is used because almost all manifestations are related to mixing with surface water [7], so the Mg element concentration is relatively high. The results of this geothermal calculation show estimated reservoir temperature at 200-220°C. In addition to the geothermometer method, an enthalpy value approach is based on analysis using a mixing diagram with
an enthalpy-silica ratio, showing an enthalpy value of 980 kJ/kg. However, mixing surface water and lake water can cause the calculation results to be overestimated. Thus, it is necessary to update the data along with the process of the exploration phase, which is still ongoing.

2.3. Geophysical Studies
Residual Bouguer anomaly shows contrasting rock density values that can confirm the identification of local geological structures based on field observations. The western part has a structure in the northeast-southwest direction and northwest-southeast. In the northeast and east region, there is a structure that has a northwest-southeast direction. The other structure that overlays the upper area consists of WE fault direction and the lower area consists of NW-SE fault direction [1].

Geomagnetic studies show a high magnetic intensity value in the southern part of Mount Seminung, including Sulung Hill and Kukusan Mountain. This high magnetic value is associated with the presence of high-density rocks in the form of cooled volcanic products and magma intrusion. Anomaly of low magnetic remanence intensity was detected in the northwest area of the Lumbok region with a range of values <400 nT. This low anomaly value can be caused by hydrothermal activity, which weakens magnetic remanence in rocks. Very low anomaly magnetic value on the Seminung Mountain body is estimated to be due to subsurface magma activity that can be estimated as a heat source of Danau Ranau’s geothermal system.

Figure 3. Cross-sections of apparent resistivity data from magnetotelluric survey data processing in Danau Ranau geothermal prospect area [8].

Low resistivity values in cross-sections are suspected to be metamorphic rock types with mineral alteration due to subsurface hydrothermal activity. The low resistivity anomaly is interpreted as the caprock zone of the Danau Ranau geothermal system. Based on Figure 3, the caprock’s geometry is dome-shaped around Mt. Seminung hillside, with a discontinuity of high resistivity between low resistivity values on the Talang Biak fault, so the fault is assumed to be impermeable. The low resistivity layer is found at a depth of 200-500 m with a thickness between 500-1000 m. Whereas the results of the magnetotelluric survey indicating the low resistivity layer are in the north towards the west and northeast of the study area, with thicknesses varying between 500-1500 m. The low resistivity zone is thought to be an altered rock acting as the Danau Ranau geothermal area’s caprock.
2.4. Initial Conceptual Model
Danau Ranau geothermal system is classified as a high-terrain geothermal system linked to a post-caldera eruption that constructed Mt. Seminung stratovolcano and is controlled by Sumatra fault. Based on geothermometer calculation, results indicate reservoir temperature between 200-220°C and a geothermal system classified as a medium enthalpy system. Post-eruptions magma that remains below Mt. Seminung probably ‘act’ as a geothermal heat source suggested by gravity survey interpretation results that show high-density value. The Danau Ranau geothermal system’s caprock is located at a depth of 1 – 1.5 km with layer thickness from 1 – 2 km. The caprock is mainly related to argillic alteration rock in the Hulu Simpang formation composed of lava and tuff rocks with an apparent resistivity value of less than 20 ohm.m.

Figure 4. Danau Ranau geothermal system conceptual model based on integrated study modified from [8].

The upflow zone of Danau Ranau geothermal prospect area is estimated to be found around Mt. Seminung, also the heat source for this geothermal area. The outflow area is in the northeastern region, where the manifestations of Cukuh, Way Wangi, Kota Baru, and Kerincing are found. The recharge area spreads over 54.25 km² mainly in steep hills around Mt. Seminung, around the Sulung Hills in the south, and Kukusan Mountain in the northeastern part of the investigation area. Discharge zones are located in plain areas (on the banks of Danau Ranau) with 55% coverage of the investigation area at an <500 masl elevation. Based on the preliminary geoscience survey, geothermal conceptual models can be obtained, describing the obtained subsurface results. Integration of geoscience studies results in the conceptual model, as shown in (Figure 4).

3. Methodology
The method of developing the natural state reservoir model consists of several steps. It starts by collecting geoscience data (geological, geophysical, geochemical data) and conceptual models from the latest study. A computer numerical model based on the conceptual model is built using the TOUGH2 simulator to model fluid and heat flow processes in the reservoir [10]. The numerical model uses a space discretization grid to assign the inferred spatial distribution of rock petro-physical properties. Initial and boundary thermodynamic conditions of the system are assigned based on the conceptual model. The numerical model is run to large times until steady-state conditions are reached, considered a good proxy for the natural state system. The material properties are calibrated iteratively to obtain the best match between the model and the conceptual model, which indicates that the model successfully represents the reservoir’s natural state condition. The workflow of this simulation is shown in (Figure 5).
4. Numerical Model

4.1. Model Building

The spatial discretization grid is rotated 30° counterclockwise to be aligned with the main features of the conceptual model. It covers a total area of 10 km x 4.6 km equal to 46 km² and a total thickness of 2.50 - 3.37 km as shown in (Figure 6). The horizontal dimension of grid blocks varies from the smallest 200 x 200 m to the biggest 474 x 474 m. The smallest grid size is set to accommodate more detailed calculations on the reservoir part. The model is divided into 8 layers and 11 sub-layers formed by 11552 grid models with some of the top layers following the real topographical condition. The total number of grid blocks is 11,552 by using a rectangular grid type. This model uses EOS1 for pure water [11] because of data limitation and simplifying the modeling process.

4.2. Initial and Boundary Condition

The initial conditions need to be assigned to each grid-block on the model. As initial conditions, the normal gradient is used for both temperature and pressure. Atmospheric conditions are applied to the top boundary layer over Mt. Seminung by assigning pressure and temperature at 1 bar and 25°C, respectively. The Danau Ranau Lake is modeled by assigning constant initial conditions to the top grid layer in correspondence of lake surface. It allows for the simulation of the possible relationships between the lake and the geothermal system. Through the lateral boundaries, it is assumed that there is no flow of fluids and heat.
4.3. Material Properties

During the numerical modeling, determining the spatial permeability structure is the most essential step to be iteratively adjusted until the natural state’s inferred system is reproduced. The iterative process is done by several trials and errors. Physical parameters assumptions such as density and permeability are determined based on gravity studies’ interpretation of geophysical exploration. The existence of anomaly in the gravity survey indicates differences in the layers’ structure and the types of rocks and minerals. Low-density rocks have high porosity values. Porosity is also directly proportional to the permeability. Vertical layer arrangement is determined based on the interpretation of the cross-section of the magneto-telluric and geoelectric methods. The permeability structure used in the final modeling is shown in Table 1, and its distribution to the grid model is also shown in (Figure 7).

| Domain | Density (kg/m³) | Porosity | Permeability (mD) | Thermal Cond. (W/m°C) | Specific Heat (J/kg °C) |
|--------|----------------|----------|-------------------|-----------------------|------------------------|
| ATM    | 1.0            | 0.99     | 10 10 10          | 2.5                   | 9.0E05                 |
| WTR    | 1000.0         | 1.00     | 1000 1000 1000    | 2.5                   | 4.0E05                 |
| GWT    | 2600.0         | 0.02     | 0.1 0.1 0.1       | 2.0                   | 1000                   |
| CAR    | 2400.0         | 0.05     | 0.022 0.011 0.011 | 2.0                   | 1000                   |
| RES 1  | 2500.0         | 0.10     | 200 200 100       | 2.0                   | 1000                   |
| RES 2  | 2600.0         | 0.08     | 80 80 40          | 2.0                   | 1000                   |
| BMT 1  | 2500.0         | 0.01     | 0.1 0.1 0.1       | 2.0                   | 1000                   |
| BMT 2  | 2500.0         | 0.01     | 0.1 0.1 0.01      | 2.0                   | 1000                   |
| BO1    | 2600.0         | 0.10     | 0.01 0.01 0.005   | 2.0                   | 1000                   |
| BO2    | 2600.0         | 0.10     | 0.04 0.04 0.002   | 2.0                   | 1000                   |
| HSC    | 3000.0         | 0.01     | 1000 1000 100     | 2.0                   | 1000                   |

**Figure 7.** Spatial distribution of rock properties in the reservoir simulation model. Fault structures (grey vertical surfaces) are used as a reference for permeable grid placement and are not accounted for in reservoir simulations.
5. Resource Assessment

5.1. Natural State Condition
One of the primary purposes of numerical modeling is to reproduce the natural state of the field. The simulations were run until steady-state conditions were reached, shown by a large number of time steps and achieved simulation time about 1.8E15 s and confirmed by the constant values of mass and volume balances. The results are then compared against geoscience surveys (geological, geophysics, and geochemical surveys) integrated into the prospect area’s conceptual model. Temperature validation is based on a thermal gradient approach calculated using temperature distribution of surface manifestations (springs) based on geochemical study data. Reproduction of target system features is obtained by trial-and-error adjusting TOUGH2 input parameter iteratively. Main adjusted parameters are:

1. Temperature and pressure of heat source
2. Location of heat source at the model bottom
3. Permeability structure in x, y, and z-direction
4. Material properties such as porosity, rock density, thermal conductivity, and specific heat
5. The geometry of caprock and reservoir

5.2. Heat Transfer and Fluid Flow
The simulation results must reproduce on each grid layer the temperature and pressure distribution inferred from geoscience surveys carried out. Fluid flow path and heat transfer through the model are also considered, with convective and conductive heat transfer dominating in reservoir and cap-rock domains.

In Figure 8, the result of computed temperature distribution along a vertical section crossing Mt Seminung shows a suitable matching to the distribution inferred by the conceptual model indicating reservoir temperature in the range 200-269°C. The heat flows from the heat source upward through the permeable reservoir and is partially diverted by the caprock through which only the conduction component is active. Figure 9 shows the pressure and fluid flow distribution along the same model section. Fluids are outflowing to the northeast and southwest, where the hot spring manifestation of Kota Batu (NE) and hot spring manifestation of Lumbok (SW) are located.
5.3. Permeability Distribution
The permeability distribution exerts a primary control on fluid flow patterns and hence on the convective contribution to heat flows within the up-flow and reservoir domains. The detail of the calibrated permeability value is summarized in Table 2 below.

| Layer       | Sub-layer | Initial Permeability (mD) | Final Permeability (mD) |
|-------------|-----------|---------------------------|-------------------------|
|             |           | $k(x)$ | $k(y)$ | $k(z)$ | $k(x)$ | $k(y)$ | $k(z)$ |
| ATM         | ATM       | 0.400 | 0.400 | 0.200 | 10.000 | 10.000 | 10.000 |
| Water       | WTR       | 1.000 | 1.000 | 0.001 | 1000.00 | 1000.00 | 1000.00 |
| Ground Water| GWT       | 1.000 | 1.000 | 0.001 | 1000.00 | 1000.00 | 1000.00 |
| Caprock     | CAR       | 0.025 | 0.020 | 0.022 | 0.022  | 0.011 | 0.011 |
| Reservoir   | RES 1     | 150.000 | 150.000 | 75.000 | 200.00 | 200.00 | 100.00 |
|             | RES 2     | 150.000 | 150.000 | 75.000 | 80.00  | 80.00  | 40.00  |
| Basement    | BMT 1     | 1.000 | 0.100 | 0.010 | 0.100  | 0.100  | 0.010  |
|             | BMT 2     | 0.010 | 0.010 | 0.010 | 10.000 | 10.000 | 1.000  |
| Boundary    | BO1       | 0.010 | 0.010 | 0.010 | 0.010  | 0.010  | 0.005  |
|             | BO2       | 0.010 | 0.010 | 0.010 | 0.040  | 0.040  | 0.002  |
| Heat Source | HSC       | 100.000 | 100.000 | 100.000 | 1000.00 | 1000.00 | 1000.00 |

5.4. Reservoir Characterization
Based on the natural state’s numerical modeling, the distribution of reservoir thermodynamic conditions can be determined. Two dummy wells on-deliverability were used to represent the hot spring manifestations at Danau Ranau geothermal field. Dummy wells were simulated by setting wellbore pressure at atmospheric value and productivity index calibrated to fit surface manifestations mass flow based on field conditions. Because there are no temperature gradient well’s data that can be used, the subsurface temperature evaluation is carried out using an isothermal temperature gradient approach, which is obtained from the estimated reservoir temperature (obtained from geothermometer analysis) and the temperature of the existing manifestations. Boiling point versus depth (BPD) curves are plotted to highlight the thermodynamic state of the reservoir. Based on the BPD curve, the interpretation shows that the reservoir is in a compressed liquid state. Of course, it is directly given from the simulated SG (gas phase saturation) values. Figure 10 shows the temperature and pressure profile of Dummy Well 1 and Well 2, located in the outflow zone and Dummy Well 3, located close to the up-flow zone.
Figure 10. Temperature, pressure, and saturation temperature profiles of (a) Well 1 representing the Lumbok manifestation, (b) Well 2 representing the Kota Batu manifestation, and (c) Well 3 located close to the up-flow area. Wells location is shown in the model grid map (d).

5.5. Updated Conceptual Model
The updated conceptual model shown in Figure 11 was designed based on the preliminary geoscience study without any well data and the simulated natural state of the system. It appears that hot geothermal fluid flows upwelling from the deep part of Mt. Seminung magma intrusion to the surface following the rock permeability spatial structure. Talang Biak Fault and Kota Batu Fault control the flows of hot fluid ascending vertically to the surface. In contrast to the initial model, there is a change in determining the reservoir top’s depth as the updated model has followed the interpretation of Magnetotelluric. It stated that the top reservoir of Lumbok geothermal area is situated around the depth of -500 masl, the only exception applied for the Kota Batu area in which the reservoir reaches the depth of -700 m asl.
5.6. Resource Assessment

The estimation of resources at Danau Ranau geothermal field is made using the heat stored method, complemented with a Monte Carlo approach, which allows estimating the amount of heat initially stored in the reservoir and the amount of heat that can be converted into electric energy into a given time frame. The volumetric method needs parameters including resource area and depth, density, rock’s specific heat capacity, initial and final water saturation, initial and final temperature, recovery factor, conversion factor, project time. The parameters are estimated from the conceptual model, reservoir characterization, and general assumptions. Monte Carlo simulation consists of calculating stored heat and resource power potential for many different input parameters that are varied within probabilistic distributions accounting for the uncertainty on reservoir properties and thermodynamic conditions.

Table 3. Input variables for the heat stored method and parameters of their probabilistic distribution for the Monte Carlo simulation.

| Parameter                                | Min  | Max  | Most | Remarks                                                                 |
|------------------------------------------|------|------|------|-------------------------------------------------------------------------|
| Area (km²)                               | 14   | 17   | 15   | Area with temperatures of 200-220°C                                     |
| Thickness (m)                            | 700  | 900  | -    | Layers with temperatures of 200-220°C                                   |
| Rock density (kg/m³)                     | 2500 | 2600 | -    | Layers with temperatures of 200-220°C                                   |
| Porosity (fraction)                      | 0.08 | 0.1  | -    | Layers with temperatures of 200-220°C                                   |
| Rock specific heat (kJ/kg °C)            | 1    | 0.1  | -    | Layers with temperatures of 200-220°C                                   |
| Lifetime (years)                         | 30   | -    |      | Common assumption                                                       |
| Recovery Factor (fraction)               | 0.2  | 0.25 | -    | Theoretical geothermal recovery factor as function of porosity by [10, 12] |
| Electricity conversion factor            | 0.09 | 0.1  | -    | [12]                                                                    |
| Ti (°C)                                  | 200  | 220  | -    | Temperature distribution based on numerical model.                      |
| Tf (°C)                                  | 120  | 180  | -    | [12]                                                                    |
| Initial Water Saturation (fraction)      | 1    | -    | [13] |                                                                         |
| Final Water Saturation (fraction)        | 0.8  | 0.9  | -    | [10]                                                                    |

The proven area in Danau Ranau geothermal field was bounded by surface manifestation and thermal distribution. The probable area is obtained from reservoir characterization based on surface manifestation distribution and minimum temperature distribution (200°C) based on simulation. The
thickness of the reservoir is obtained from vertical temperature distribution, from approx. -500 masl down to -1400 masl, for a total of about 900 m. The rock porosity is assumed from 0.08 to 0.10. Recovery factor is estimated from a correlation as a function of porosity varies between 0.2 to 0.25. The project lifetime of the Danau Ranau geothermal field is assumed to be about 30 years. The details about the input parameters of Monte Carlo simulation are listed in Table 3.

The results of Monte Carlo simulation, consisting of 60,000 realizations, are given in terms of confidence ranks corresponding to a probability of 10%, 50%, and 90% (P_{10}, P_{50}, and P_{90}), respectively. Obtained values are: P_{10} = 25 MW, P_{50} = 43 MW, and P_{90} = 62 MW, as presented in (Figure 12). Based on the Monte Carlo simulation, Danau Ranau geothermal field’s geothermal potential is lower than 25 MW for the highest degree of confidence.

6. Conclusions
1. The first 3D numerical model of the Danau Ranau geothermal field has been successfully developed and validated against interpreted geoscience data. This numerical model is considered a starting model to be updated based on continuous exploration data from new field development stages.
2. The range of the productive zone (reservoir) area is estimated to be between 14-17 km². The reservoir temperature was numerically simulated in the range of 200-220°C. The reservoir is predicted to be liquid dominated based on surface manifestation type and silica-enthalpy mixing diagram result.
3. Based on the updated conceptual model, it can be estimated that heat flow and mass circulate in the reservoir at a depth that moves up to the surface through the Talang Biak Fault and the Kota Batu Fault. Bukit Suluh and Danau Ranau act as infiltration and recharge zones for this geothermal system. Magma in a cooling stage acts as a heat source for the Danau Ranau geothermal field. Numerical model simulations estimated a heat source temperature in the order of 250°C.
4. The Danau Ranau field can generate up to 25 MW within a P_{90} confidence interval or 43 MW with a P_{50} confidence interval. This evaluation has been obtained using the heat stored method complemented with a Monte Carlo approach based on the updated conceptual model and the field’s modeled natural state.

7. Recommendation
1. Need further detailed geoscience survey for investigation of Danau Ranau up-flow zone that is inferred beneath Mt. Seminung.
2. Need further advanced exploration surveys, including geological, geochemical, geophysical exploration, and drilling investigations based on [14] to improve the conceptual model.
3. The numerical simulation model should be updated with the result of future detailed exploration surveys.
4. The Resource Assessment should be improved by Experimental Design (ED), which uses measurement from the model.

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