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 and controlled by Sumatran fault as the permeability zone. The study aims to characterize Danau Ranau reservoir, updated 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 output of numerical reservoir models concise with the geological, geochemical, and geophysical interpretation, thus becomes an important information (3D pressure and temperature, heat and mass flow, location of heat source, boundary condition, reservoir geometry) to the updated conceptual model. The probabilistic heat stored method result based on output natural state model is shown that Danau Ranau geothermal field can be generated to 30 MW.

1. INTRODUCTION

The Danau Ranau geothermal working area was established through a decree of the Minister of Energy and Mineral Resources (No. 1151K/30/MEM/2011 dated April 21st, 2011). Preliminary geological exploration located at UTM 380000 mE - 392000 mE and 946200 mN - 9449200 mN, with a land area about 127 km². This geothermal field is located in Lampung and South Sumatra, Sumatra, Indonesia. About 70% of the investigation area is at the Sukau District, West Lampung, Lampung Province and 30% at Banding Agung Sub-District, South Oku, South Sumatra. The nearest airport is the Agung Banding Airport, with an approximate distance about 15 km from the geothermal field. The nearest port is Bintuhan Port with a distance of 59.96 km from the location of the WKP.

Danau Ranau geothermal field is a “virgin” geothermal field assigned to PT PLN to be developed. Until now, the exploration stage that has been carried out by the National Geological Agency (PSDG, 2004) only has limited data, which depends only on geoscience studies (geology, geochemistry, and geophysics). The results of the integrated geoscience studies are used to estimate the conceptual model of the Danau Ranau geothermal field. At this field, there are no exploration wells or gradient temperature wells that have been drilled in this area. However, we assume that the results from geoscience are enough to support the physical parameters needed by the numerical model to be developed, including reservoir geometry, reservoir temperature based on geothermometers, and estimations of subsurface rock physics. Numerical model simulation is expected to be able to overcome the shortcomings of geological conceptual models and provide more precise and accurate estimation of subsurface features.

The natural state of a geothermal system refers to the condition of the system before any form of geothermal exploitation. This model is used to simulate thermodynamic processes that occur below the subsurface. Thus, it can be estimated on how the thermal fluid circulates from the reservoir to the surface, both in terms of heat and mass. The results of numerical model simulation calculations can be used to update the conceptual model that has been built, so that the subsurface model can be estimated better.

The natural state model of Danau Ranau geothermal field was developed using TOUGH2 software and was built using non-isothermal-pure water equation of state (EOS 1). The surface of the model followed the topographic contour so the water table in shallow zones including Danau Ranau geometry was defined as water to approach a reliable model. The model described all major physical processes such as mass transport, heat transfer, saturated gas, and others that took place in the system. The physical parameter is then used to remake updated conceptual model with isothermal and fluid pathway approach, reservoir geometry, and other geothermal features. The new conceptual model is then used to calculate resource assessments using Monte Carlo simulation calculations.

2. INITIAL EXPLORATION DATA

2.1 Geoscience Review

The geoscience preliminary 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 derived from the study of geoscience. The results of the interpretation of the integration of studies and the conceptual model of geoscience are considered capable of being used to estimate the shape of numerical models and can be used for reservoir simulation approaches. The studies that were conducted are detailed in the following discussion.
2.1.1 Geological Studies

Danau Ranau geothermal field is a Pleistocene caldera from Mount Ranau formed on the Sumatra 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, which is a stratovolcano type post-caldera mountain (Muraoka et al., 2010). The products of Mount Seminung are lava and pyroclastic that show explosive eruptions with high energy. According to the appearance position of the manifestation, it is estimated that the remaining magma erupts as a heat source of the emerging manifestations that originate from Mount Seminung.

Permeable zones in the Danau Ranau geothermal field are controlled by the Sumatran fault system which is a strike-slip fault with a dextral moving direction that is 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 forming trend of northwest-southeast, north-northwest-south-southeast and northeast-southwest direction, associated with the main, synthetic, and antithetic faults of the Sumatra fault, or better known as the Semangko Fault (Tjia, 1977). The faults that were 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.

Figure 1: Danau Ranau geothermal field geological map. Two cross sections are displayed to estimate the type of rock that forms an overlapping arrangement of Mt. Seminung (modified from PT. PLN, 2017).

The morphology of the investigation 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 investigation 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 shows that the region acts as a water catchment and recharge area in the geothermal system. In the southern part of Mt. Seminung, there are Sulung Hill and Kukusan Mountain which are predicted as rain catchment and geothermal system recharge areas. While the discharge area is in the lowlands and the appearance of surface manifestations in the deformation of the structure of the valley zone and river flow from Mt. Seminung which is located in Lumbok and Kota Batu areas (Figure 1).

Referring to 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 aphanitic andesite rock as the last product of Mt. Seminung in the quarter period. Travertine deposits have also been found in the Kota Batu area which can be 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.

2.2.2 Geochemistry Studies

Danau Ranau geothermal field is indicated by the presence of surface manifestations in the form of hot springs and warm springs, without any steam or gas manifestation indication in the surface. A detailed study of this report was carried out through 10 data of 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 is limited to only those 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 the presence of several thermal springs, followed by high HCO3 value. The quality of manifestation data based on ion balance analysis is excellent (Nicholson, 1993) with an Ion Balance value of <5%.

![Figure 2: Danau Ranau geothermal features and surface manifestations (modified from PT. PLN, 2017).](image)

The results of geochemical analysis 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-CI 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 (Powell, 2010). The low Na/Ca geoindicator ratio in all manifestation water samples show that Danau Ranau manifestations are in the outflow zone of the geothermal system. 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. While the manifestation of the Lumbok-1 spring has the opposite value, which indicates that there is a mixture with surface water (Nicholson, 1993).

Based on the abundant elements in the sample of water manifestations, a geothermometer is calculated based on the value of the dominant elements possessed by each manifestation. Na-K geothermometer with Mg correction is considered to be used because almost all manifestations are related to mixing with surface water (Nicholson, 1993), so the concentration of the Mg element is quite high. The results of this geothermal calculation show the 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.

2.2.3 Geophysical Studies

Residual Bouguer Anomaly data shows permeable zones due to complex structure, where the contour patterns have both positive and negative value and form separate groups, indicating to be predominantly caused by the local structure. The western part has a structure in 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 (PSDG, 2004).

Geomagnetic studies show that there is 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 region 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 (PT. PLN, 2017)

Low resistivity values in cross sections are suspected as metamorphic rock types which have mineral alteration due to subsurface hydrothermal activity. The low resistivity value is interpreted as the caprock zone of the Danau Ranau geothermal system. Based on Figure 3, the geometry of the caprock 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 between 200-500 meters with a thickness between 500-1000 meters. Whereas the results of 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 meters. The low resistivity value is thought to be an altered rock as a cap rock of the Danau Ranau geothermal area.

2.2 Initial Conceptual Model

Figure 4: Danau Ranau geothermal system conceptual model based on integrated study (modified from PT. PLN, 2017)

Danau Ranau geothermal system is classified as high-terrain geothermal systems as a post-caldera eruption that constructed Mt. Seminung stratovolcano and is controlled by Sumatra fault. Based on geothermometer calculation results that indicate the reservoir temperature between 200-220°C and classified as a medium enthalpy geothermal system (Hochstein, 2000). Post-eruptions magma that remains below Mt. Seminung probably acts as a geothermal heat source due to gravity survey interpretation results that show high density value. The presence of caprock in the Danau Ranau geothermal system is located at depth of 1000-1500 meters with layer thickness from 1000 meters to 2000 meters. The caprock layer in this area is mainly by argillic alteration rock in the Hulu Simpang formation composed of lava and tuffrocks with apparent resistivity value of less than 20 ohm.m.
The upflow zone of Danau Ranau geothermal prospect area is estimated to be found around Mt. Seminung, also becoming a 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 featured. The recharge area spreads over an area of 54.25 km² mainly in steep hills around Mt. Seminung, and around the Sulung Hills in the south and Kukusan Mountain in the northeastern part of the investigation area. Discharge zones are dominated in plain areas (on the banks of Danau Ranau) with 55% coverage of the investigation area at an elevation of <500 masl. Based from geoscience preliminary survey, geothermal conceptual models can be obtained which can describe the subsurface approach. Integration of geoscience studies results in the conceptual model as shown in Figure 4.

3. METHODOLOGY

The method in developing the natural state reservoir model consists of several steps. It starts with collecting geoscience data (geological, geophysical, geochemical data) and conceptual models from the latest study. A computer numerical model based on the conceptual model is made using a TOUGH2 simulator to simulate fluid and heat flow process of the reservoir. This numerical model consists of grid blocks in which each block is assigned with material properties. Top, bottom, and boundary conditions of the model are set based on the conceptual model. The model is run to get the result of the model. The material properties, top, bottom, and boundary conditions are calibrated iteratively to obtain the best match between the model and the conceptual model which indicates that the model successfully represents the natural state condition of the reservoir. The workflow of this simulation is shown in Figure 5.

![Flow chart of this study.](image)

4. NUMERICAL MODEL

4.1 Model Building

The grid of the model is rotated at 30° to the north to accommodate the material assignment to be necessary in arrangement with the alignment of the conceptual model. It covers a total area of 10 km x 4.6 km or equal to 46 km² and a total thickness of 2.50 - 3.37 km which is demonstrated in Figure 6. The horizontal dimension of grid blocks varies from the smallest 200 m x 200 m to the biggest 474 m 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 with some of the top layers following the real topographical condition. The total number of grid blocks is 11,552 by using rectangular grid type. This model uses EOS1 for water non-isothermal because of data limitation and to simplify the modeling process (Pruess et al., 1999).

![The simulation model is rotated based on the perpendicular direction of the fault structure as the permeability zone and the area of interest to be studied.](image)
4.2 Initial Boundary Condition

The initial condition is needed to input the initial temperature and pressure for each grid-block on the model to fasten the process in running the model. At the initial condition, the normal gradient is used for both temperature and pressure. Atmosphere is applied to the top boundary condition by assigning pressure and temperature in the atmosphere (surface) are homogeneously at 1 bar and 25°C, respectively (Akbar et al., 2018). Lake water in the Danau Ranau area is modeled as a material composed of water, so it is defined as a separate material layer. This is done to accommodate the calculation of the existence of lake water intrusion in the geothermal system. Inside the boundary, it is assumed that there are no flows of fluid. All of the side boundaries are in impermeable condition (permeability value is about 0.001 mD) which is there are no flows of both heat and mass coming into or going out the system during natural state condition.

4.3 Material Properties

During the numerical modelling, determining permeability structure is the most essential step to be iteratively adjusted until the natural state condition is achieved. The iterative process is done by several trials and errors. Physical parameters such as density and permeability are determined based on the interpretation of gravity studies on geophysical exploration. Interbedding material is determined based on the interpretation of the cross-section of the magnetotelluric and geoelectric method. The permeability structure used in the final modelling is shown in Table 1 and its distribution to the grid model is also shown in Table 1.

Table 1: Rock properties in Lake Ranau geothermal reservoir simulation model.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Sub Layer</th>
<th>ρ (kg/m³)</th>
<th>( \Phi ) (Fraction)</th>
<th>k(x) mD</th>
<th>k(y) mD</th>
<th>k(z) mD</th>
<th>Thermal Conductivity (W/m°C)</th>
<th>Specific Heat Capacity (J/kg °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATM</td>
<td>ATM</td>
<td>1</td>
<td>0.99</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>2.5</td>
<td>9.0E05</td>
</tr>
<tr>
<td>Water</td>
<td>WTR</td>
<td>1000.0</td>
<td>1</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>2.5</td>
<td>4.0E05</td>
</tr>
<tr>
<td>Ground</td>
<td>GWT</td>
<td>2600.0</td>
<td>0.02</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>2.0</td>
<td>1000</td>
</tr>
<tr>
<td>Caprock</td>
<td>CAR</td>
<td>2400.0</td>
<td>0.05</td>
<td>0.022</td>
<td>0.011</td>
<td>0.011</td>
<td>2.0</td>
<td>1000</td>
</tr>
<tr>
<td>Reservoir</td>
<td>RES 1</td>
<td>2500.0</td>
<td>0.1</td>
<td>200</td>
<td>200</td>
<td>100</td>
<td>2.0</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>RES 2</td>
<td>2600.0</td>
<td>0.08</td>
<td>80</td>
<td>80</td>
<td>40</td>
<td>2.0</td>
<td>1000</td>
</tr>
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<td>Basement</td>
<td>BMT 1</td>
<td>2500.0</td>
<td>0.01</td>
<td>0.1</td>
<td>0.1</td>
<td>0.01</td>
<td>2.0</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>BMT 2</td>
<td>2500.0</td>
<td>0.01</td>
<td>10</td>
<td>10</td>
<td>1</td>
<td>2.0</td>
<td>1000</td>
</tr>
<tr>
<td>Boundary</td>
<td>BO1</td>
<td>2600.0</td>
<td>0.1</td>
<td>0.01</td>
<td>0.01</td>
<td>0.005</td>
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<tr>
<td></td>
<td>BO2</td>
<td>2600.0</td>
<td>0.1</td>
<td>0.04</td>
<td>0.04</td>
<td>0.002</td>
<td>2.0</td>
<td>1000</td>
</tr>
<tr>
<td>Heat Source</td>
<td>HSC</td>
<td>3000.0</td>
<td>0.01</td>
<td>1000</td>
<td>1000</td>
<td>100</td>
<td>2.0</td>
<td>1000</td>
</tr>
</tbody>
</table>

Figure 7: Material placement and determination of rock properties in the reservoir simulation model. Fault structures are used as a reference for permeable grid placement and are not counted in reservoir simulations.
5. RESOURCE ASSESSMENT

5.1 Natural State Condition

The main purpose of numerical models is to achieve the natural state condition. Natural state condition simulation is conducted by using TOUGH2 software with EOS 1 module (water, non-isothermal). The computer model simulation was run until geological time and achieved a natural steady state condition, shown by the converge value of DT (time increment) and simulation time (1.8E15 in simulation time). The result is then compared against the result of a geoscience survey (geological, geophysics, and geochemical survey) that concludes in early conceptual model and prospect area. Temperature validation is based on manual isothermal calculations based on the temperature distribution of surface manifestations of springs based on geochemical study data. If the results of the comparison show an incompatibility, it will be adjusted to the TOUGH2 parameter iteratively. Some parameters that are made by adjustments are:

1. Temperature and pressure of heat source
2. Adjusting location of heat source in bottom boundary
3. Permeability structure in x, y, and z direction
4. Adjusting material properties such as porosity, rock density, thermal conductivity and specific heat
5. The size grid blocks of caprock, reservoir and heat sources

5.2 Heat Transfer and Fluid Flow

The results of the simulation must consider the temperature and pressure distribution at each layer in the correct conditions according to the conclusion of the results of the geoscience survey that has been carried out. We have to consider the direction of fluid flow and heat transfer through the model. In a reservoir, we must ensure that the heat transfer process through convection and conduction and fluid can flow due to the reservoir consisting of permeable rock. In the caprock and boundary, heat transfer processes through conduction and fluid flow can be negligible due to impermeable rock.

Figure 8: The cross section from NE-SW of natural state result. The color gradient refers to the temperature value based on temperature profile simulations. The vector refers to heat flow beneath the subsurface.

Figure 9: Vertical cross section from direction NE-SW, the color scale bar refers to temperature gradient. The vector direction shows the mass flow beneath the subsurface.
In Figure 8, the result of temperature distribution between conceptual model and simulation model is suitable matching. Based on geothermometer analysis, it indicates that reservoir temperature ranges between 200-269°C. The heat flows from heat source to upward through permeable zone and halted in impermeable zone (caprock). Then the heat flows to northeast and southwest, it clearly matches with field data of hot spring manifestation in northeast (Kota Batu) and hot spring manifestation in southwest (Lumbok).

5.3 Permeability Distribution

Based on the simulation process, the distribution of permeability gives impact to the ability of rock to flow the fluid and flow distribution of temperature (conductive and convective heat transfer). Convective heat transfer may occur in permeable zone (reservoir) and conductive heat transfer may occur both in permeable zone (reservoir) and impermeable zone (caprock and boundary). The detail of the adjustment in permeability value is summarized in Table 2 below.

Table 2: Rock properties assignment in the geothermal system model.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Sub-Layer</th>
<th>Initial Permeability [mD]</th>
<th>Final Permeability [mD]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>k (x) mD</td>
<td>k (y) mD</td>
</tr>
<tr>
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<td>ATM</td>
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<td>0.4</td>
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<td>Water</td>
<td>WTR</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ground Water</td>
<td>GWT</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Caprock</td>
<td>CAR</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Reservoir</td>
<td>RES 1</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>RES 2</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Basement</td>
<td>BMT 1</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>BMT 2</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Boundary</td>
<td>BO1</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>BO2</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Heat Source</td>
<td>HSC</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

5.4 Reservoir Characterization

Figure 10: Graph with temperature, pressure, and saturation temperature curves of Well 1 which is in the manifestation of Lumbok (a), Well 2 that is in the manifestation of Kota Batu (b), and Well 3 as a dummy well to determine the physical response at that point (c). The location of the well is shown in the lateral section (d).
Based on the result of numerical modelling of natural state, the model could determine reservoir characterization. Two dummy wells were made to represent the hot spring manifestations at Danau Ranau geothermal field. Dummy wells are simulated by setting the well deliverability value at atmospheric pressure and certain productivity index to fit mass flow based on field conditions. In the process of examining the model, subsurface temperature validation was carried out based on the 3D isothermal estimation method based on the idea of calculating subsurface temperature gradients. The calculation is done by determining the reservoir temperature based on the geothermometer and temperature of the surface manifestations, then the subsurface temperatures for each depth can be obtained. Boiling point versus depth (BPD) curves are plotted to determine the characteristics of the reservoir. Based on the BPD curve, the interpretation shows that the reservoir is in a compressed liquid state. This can also be confirmed from the SG (saturated gas) value in the simulation results. Figure 10 shows the temperature and pressure profile of Dummy Well 1 and Dummy Well 2 that are located at the outflow zone and Dummy Well 3 that is located at the upflow zone.

5.5 Updated Conceptual Model

The updated conceptual model shown in Figure 11 was designed based on preliminary geoscience study without any well data and simulated to create a numerical model approach. It appears that hot geothermal fluid flows upwelling from the deep part of Mt. Seminung magma intrusion to the surface by rock permeability and porosity. The deep leakage of fracture permeability from Talang Biak Fault and Kota Batu Fault control the flows of hot fluid that ascends through the vertical permeability with some fluids flow in lateral direction. In contrast to the initial model, there is a change in determining the depth of the top reservoir 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 reached the depth of -700 masl.

![Figure 11: Updated Conceptual Model of Danau Ranau Geothermal Field](image)

5.6 Resource Assessment

The estimation of resources at Danau Ranau geothermal field uses heat stored principal. There are two methods including deterministic and probabilistic approach. Deterministic approach uses a volumetric method, while a probabilistic approach uses Monte Carlo simulation. The volumetric method needs some parameters including area, depth, porosity, rock density, heat rock capacity, initial and final water saturation, initial and final temperature, recovery factor, conversion factor, and project time. The parameters are obtained from conceptual models, reservoir characterization, and general assumptions. Monte Carlo simulation is calculation of iterations from a probabilistic model that simulates properties of physics in distribution value for estimating geothermal resources by heat stored principle. The estimate of minimal, maximal, and most likely value in each parameter of geothermal resource need to be defined previously.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
<th>Most</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
<td>Area (km²)</td>
<td>14</td>
<td>17</td>
<td>15</td>
<td>Area with temperatures of 200-220°C</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>700</td>
<td>900</td>
<td>-</td>
<td>Layers with temperatures of 200-220°C</td>
</tr>
<tr>
<td>Rock Density (kg/cu-m)</td>
<td>2500</td>
<td>2600</td>
<td>-</td>
<td>Layers with temperatures of 200-220°C</td>
</tr>
<tr>
<td>Porosity (fraction)</td>
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<td>0.1</td>
<td>-</td>
<td>Layers with temperatures of 200-220°C</td>
</tr>
<tr>
<td>Rock Heat Capacity (kJ/(kg.°C))</td>
<td>1</td>
<td>0.1</td>
<td>-</td>
<td>Layers with temperatures of 200-220°C</td>
</tr>
<tr>
<td>Lifetime (years)</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>Common assumption</td>
</tr>
<tr>
<td>Recovery Factor (fraction)</td>
<td>0.2</td>
<td>0.25</td>
<td>-</td>
<td>Sarmiento (2013)</td>
</tr>
<tr>
<td>Electricity Efficiency (fraction)</td>
<td>0.09</td>
<td>0.1</td>
<td>-</td>
<td>Sarmiento (2013)</td>
</tr>
<tr>
<td>Ti (°C)</td>
<td>200</td>
<td>220</td>
<td>-</td>
<td>Temperature distribution based on numerical model.</td>
</tr>
<tr>
<td>Tf (°C)</td>
<td>120</td>
<td>180</td>
<td>-</td>
<td>Sarmiento (2013)</td>
</tr>
<tr>
<td>Water Saturation Initial (fraction)</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>SNI 13-6482-2000</td>
</tr>
<tr>
<td>Water Saturation Final (fraction)</td>
<td>0.8</td>
<td>0.9</td>
<td>-</td>
<td>Acuna (2008), Reyes (2003)</td>
</tr>
</tbody>
</table>
The proven area in Danau Ranau geothermal field was bounded by surface manifestation and thermal distribution (200 - 220°C) based on the simulation result. 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 a high temperature profile. From a high temperature profile, the thickness is from -500 masl down to -1400 masl. The thickness of the reservoir is approximately about 900 m. The rock porosity is obtained around 0.08 to 0.1. Recovery factor is obtained from correlation between recovery factor and porosity, the value is about 0.2 to 0.25. The project time of the Danau Ranau geothermal field is assumed to be about 30 years. The details about parameters that are input to Monte Carlo simulation as seen in Table 3.

The numerical model based on Monte Carlo simulation, using 60,000 random numbers, is defined by the type of degree confidence rank (P10, P50, and P90). The highest degree confidence respectively from P10, P50, and P90. Input parameters value for Monte Carlo simulation is shown in Table 3. The value of P10 is 25 MW, P50 is 43 MW, and P90 is 62 MW, which is also presented in Figure 12. Based on the Monte Carlo simulation calculation, the geothermal potential of Danau Ranau geothermal field is lower than 25 MW for highest degree confidence.

![Figure 12: Distribution of Monte Carlo simulation result.](image)

### 6. CONCLUSION
1. The first 3D numerical model of Danau Ranau geothermal field has been successfully developed and validated with only geoscience interpretation data. This numerical model is used as a basic model to be updated based on the addition of continuous exploration data from each stage of development.
2. The range of the productive zone (reservoir) area is between 14-17 km². The reservoir temperature in the range of 200-220°C was numerically simulated. The reservoir is predicted to be compressed liquid 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. The existence of magma in the cooling process acts as a heat source for the Danau Ranau geothermal field. Numerical model simulations can estimate isothermal values with heat source temperature values at 250°C.
4. The numerical reservoir simulation of Danau Ranau, based on Monte Carlo simulation, could generate electricity of 30 MW.

### 7. RECOMMENDATION
1. Need further detailed geoscience survey for investigation of Danau Ranau upflow zone that is indicated at Mt. Seminung.
2. Need further advanced exploration surveys including geological, geochemical, geophysical exploration and drilling investigations (based on SNI 1998) to improve the conceptual model.
3. The numerical simulation model should be updated by addition of result of advance exploration survey.
4. The Resource Assessment should be improved by experiment design (ED) principle which uses measurement from model.

### 8. ACKNOWLEDGEMENT
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### REFERENCES


