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 provinces, Indonesia. Danau Ranau geothermal field was classified as high terrain volcanic hydrothermal system and controlled by Sumatran fault as the permeability zone. The study aims to characterized Danau Ranau reservoir, updated conceptual model, and assessed the geothermal power capacity couple with Monte Carlo simulation. Therefore, the numerical reservoir simulation was perform using TOUGH2 software to achieve natural state model based on geoscience interpretation data. The output of numerical reservoir model concise with the geology, geochemist, and geophysics interpretation, thus became the important information (3D pressure and temperature, heat and mass flow, location of heat source, boundary condition, reservoir geometry) to updated conceptual model. The probabilistic heat stored method result based on output natural state model shown that Danau Ranau geothermal field can be generated to 30 MW.

1. INTRODUCTION

Danau Ranau geothermal working area 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 9462000 mN - 9449200 mN, with a land area about 127 km². This geothermal field located at Lampung and South Sumatra Provinces, Sumatra, Indonesia. About 70% of the area of investigation is in the District Sukau, West Lampung, Lampung Province and 30% included in Banding Agung Sub-District, South Oka, South Sumatra Province. The nearest airport is the Agung Banding Airport, with approximately 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 is only up to geoscience studies (geology, geochemistry, and geophysics). The results of the integrated geoscience study are used to estimate the conceptual model of the Danau Ranau geothermal field. In this field, no exploration wells or gradient temperature wells that have been drilled in this area. However, we think 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 from 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 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 follows the topographic contour so the water table in shallow zone including lake Ranau geometry was defined as water to approach reliable model. The model described all major physical process such as mass transport, heat transfer, saturated gas, and other that take place in the system. The physical parameter 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. CONCEPTUAL MODEL REVIEW

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 studies, geological studies, geochemical studies, 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 conducted are detailed in the following discussion.
2.1.1 Geological Studies

The 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 which shows explosive eruptions with high energy. Based on the position of the appearance of the manifestation, it is estimated that the remaining magma erupts as a heat source of the manifestations that emerge originating 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 dextral moving direction that is directed relative 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 in 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 (Tija, 1977). The faults that developed in this region were the Talang Kedu Fault, Kota Batu Fault, Wai Uluhan Fault, Talang Biak Fault, and Kukusan Fault which was in northwest-southeast directions. The East-West fault is the Seminung Fault.

The morphology of the investigation area consists of plains to mountains with different rock characteristics. The slopes formed 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 structure that develops influences the formation of steep cliffs. Wilayah gunung Seminung merupakan wilayah yang subur dengan curah hujan tinggi. In the southern part of Mt. Seminung, there is Sulung Hill and Kukusan Mountain which predicted as rain catchment and geothermal system recharge area. 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, namely in the Lumbok and Kota Batu areas (Figure 1).

Based on Figure 1, the oldest rock type is the old volcanic lava flow (Tit) 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 were found which were estimated to be formed at temperatures <340˚C and included in the argillic type hydrothermal zone. When 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.

Figure 1: Danau Ranau geothermal field geological map. Two cross sections are displayed to estimate the type of rock that forms the overlapping arrangement of the Mt. Seminung (PT. PLN, 2017).
2.1.2 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 indications in the surface. A detailed study of this report was carried out through 10 data of surface manifestations (thermal spring) consisting of: 4 hot spring (55-63°C), and 6 warm spring (<50°C) that spread on the slopes of Mount Seminung following NW-SE fault direction (Kota Batu fault) and NE-SW (Lombok Fault). The thermal 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 argillitic alteration on the surface which also associated with NW-SE directed faults. Travertine deposits are also found to be associated with the presence of several thermal spring, followed by high HCO₃ value. The quality of manifestation data based on ion balance analysis is very good (excellent) with an Ion Balance value of <5%.

![Image: Danau Ranau geothermal features and surface manifestations](image.png)

**Figure 2:** Danau Ranau geothermal features and surface manifestations (PT. PLN, 2017).

The results of geochemical analysis based from water sampling shows that all spring manifestations on Danau Ranau have Bicarbonate water types (HCO₃), except for Lumbok springs - 4 types of dilute springs HCO₃-SO₄ and dilute springs, both dilute HCO₃-Cl. Based on the similarity of the location of the plotting results based on the Cl-Li-B content all springs characterize being in the same environment, characterizing all the hot springs in the Danau Ranau area and surrounding areas in volcanic rocks (Powell, 2010). The low Na/Ca geoindicator ratio in all manifestation water samples shows that Danau Ranau manifestations are in the outflow zone of the geothermal system.

Based on the abundance of 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 geochemical 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.

2.1.3 Geophysical Studies

Residual Bouguer Anomaly data shows permeable zone due to complex structure, where the contour patterns have positive values and negative values 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. Other structures that appear in the middle point west-east, and in the south with the northwest-southeast directions (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 Lombok region with a range of values <400nT. This low anomaly value can be caused by hydrothermal activity which weakens magnetic remanence in rocks. Very low anomaly magnetic values on the Seminung mountain body are estimated to be due to subsurface magma activity that can be estimated as a heat source of Danau Ranau's geothermal system.
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 to role as caprock in the Danau Ranau geothermal system. Based from Figure 3, the geometry of the caprock is dome shaped around the Mt. Seminung, with a discontinuity of high resistivity between low resistivity value on the Talang Biak fault, so the fault is assumed to be permeable. 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, indicates 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 Danau Ranau geothermal area.

2.2 Geoscience Conceptual Model

Danau Ranau geothermal system is classified as high-terrain geothermal systems as post-caldera eruption that construct mount Seminung stratovolcano and controlled by Sumatran fault. Based from geothermometer calculations results that indicates the reservoir temperature between 200-220°C, and classified as medium enthalpy geothermal system (Hochstein, 2000). Post-eruptions magma that remains below Mount Seminung probably act as geothermal heat source due to gravity survey interpretation result shown high density value. The presence of caprock in the Danau Ranau geothermal system located at depth of 1000-1500 meters with layer thickness from 1000 meters to 2000 meters. The cap rock layer in this area mainly by argillic alteration rock in the Hulu Simpang formation composed of lava and tuff rocks with apparent resistivity value of less than 20 ohm.m.

Up flow zone of Danau Ranau geothermal prospect area is estimated to be found around Mount Seminung, also become to be 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 is spread over an area of 54.25 km² mainly in steep hills around Mount 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 Ranau lake) 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 shown in the Figure 4.
3. METHODOLOGY

The method in developing natural state reservoir model consists of several steps. It starts with collecting geoscience data (geological, geophysical, geochemical data) and conceptual model from the latest study. A computer numerical model based on the conceptual model is made using 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 8.

![Diagram](image)

**Figure 5:** Flow Chart of the Study

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 conceptual model. It is covering 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 10. 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 follow the real topographical condition. The total number of grid blocks is 11.552 by using rectangular grid type. This model used EOS1 for water non isothermal because of data limitation and to simplify the modeling process (Pruess et al., 1999).

![Image](image)

**Figure 6:** Rotation Simulation Model Area (National Geological Agency, 2017)

4.2 Initial and 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 atmosphere (surface) are homogenously at 1 bar and 25°C, respectively (Akbar et al., 2018). Lake water in the Lake 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 calculate 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 side boundaries are in impermeable condition (permeability values are 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 (Assign Material)

During the numerical modelling, determining permeability structure is the most essential step to be iteratively adjusted until the natural state condition was achieved. The iterative process is done by several trial 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 also shown in Table 1.
Table 1: Rock Properties

<table>
<thead>
<tr>
<th>Layer</th>
<th>Sub Layer</th>
<th>ρ (kg/m³)</th>
<th>Φ (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>1.00</td>
<td>0.99</td>
<td>10</td>
<td>10</td>
<td>2.5</td>
<td>2.5</td>
<td>9.0E05</td>
</tr>
<tr>
<td>Water</td>
<td>WTR</td>
<td>1000.0</td>
<td>1.00</td>
<td>1000</td>
<td>1000</td>
<td>2.5</td>
<td>2.5</td>
<td>4.0E05</td>
</tr>
<tr>
<td>Ground Water</td>
<td>GWT</td>
<td>2600.0</td>
<td>0.02</td>
<td>0.1</td>
<td>0.1</td>
<td>2.0</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>2.0</td>
<td>2.0</td>
<td>1000</td>
</tr>
<tr>
<td>Reservoir</td>
<td>RES 1</td>
<td>2500.0</td>
<td>0.10</td>
<td>200</td>
<td>200</td>
<td>2.0</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>2.0</td>
<td>2.0</td>
<td>1000</td>
</tr>
<tr>
<td>Basement</td>
<td>BMT 1</td>
<td>2500.0</td>
<td>0.01</td>
<td>0.1</td>
<td>0.1</td>
<td>2.0</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>2.0</td>
<td>2.0</td>
<td>1000</td>
</tr>
<tr>
<td>Boundary</td>
<td>BO1</td>
<td>2600.0</td>
<td>0.10</td>
<td>0.01</td>
<td>0.01</td>
<td>2.0</td>
<td>2.0</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>BO2</td>
<td>2600.0</td>
<td>0.10</td>
<td>0.04</td>
<td>0.04</td>
<td>2.0</td>
<td>2.0</td>
<td>1000</td>
</tr>
<tr>
<td>Heat Source</td>
<td>HSC</td>
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<td>0.01</td>
<td>1000</td>
<td>1000</td>
<td>2.0</td>
<td>2.0</td>
<td>1000</td>
</tr>
</tbody>
</table>

Figure 7: Material assignment to the gridding model

5. RESOURCE ASSESSMENT

5.1 Natural State Condition

The main purpose of numerical model is to achieve the natural state condition. Natural state condition simulation is conducted by using TOUGH2 software with EOS1 module (water, non-isothermal). The computer model simulation was run until geological time and achieve natural steady state condition, shown by the converge value of DT (time increment) and simulation time (1.8E15 in simulation time). The result then compared against the result of geoscience survey (geological, geophysics and geochemical survey) that conclude 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 conclusions of the results of the geoscience survey that has been carried out. We should have to consider direction of fluid flow and heat transfer through the model. In reservoir, we must ensure that heat transfer process through convection and conduction and fluid can flow due to reservoir consist of permeable rock. In the cap rock and boundary, heat transfer process through conduction and fluid flow could be negligible due to in cap rock and boundary consist of impermeable rock.
Figure 8: The cross section from NE-SW of natural state result. The color gradient refers to the temperature value based from temperature profile simulations. The vector refers to heat flow beneath the subsurface.

In figure 12, the result of temperature distribution between conceptual model and simulation model is suitable matching. Based on geothermometer analysis, indicate that reservoir temperature range between 200-269°C. The heat flow from heat source to upward through permeable zone and halted in impermeable zone (caprock). Then the heat flow to north east and south west, it’s clearly match with field data of hot spring manifestation in north east (Kota Batu) and hot spring manifestation in south west (Lumbok).

Figure 9: Vertical cross section from direction NE-SW, the color scalebar refers to temperature gradient. The vector direction shows the mass flow beneath the subsurface.

5.3 Permeability Distribution

Based on the simulation process, distribution of permeability gives impact to the ability 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 in permeable zone (reservoir) and impermeable zone (caprock and boundary). Detail of the adjustment in permeability value summarized in Table 2 below.

Table 2: Rock Properties

<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 (x) mD</td>
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<tr>
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<td>ATM</td>
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<td>0.4</td>
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<td>WTR</td>
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<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>
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<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>
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</tr>
<tr>
<td>Heat Source</td>
<td>HSC</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
5.4 Reservoir Characteristic

Based on result of numerical modelling of natural state, the model could determine reservoir characterization. Two dummy wells were made to represent the hot spring manifestations on 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 the 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 show that the reservoir is in a compressed liquid state. This also can be confirmed from the SG (saturated gas) value in the simulation results. Figure 16 show temperature and pressure profile of dummy well 1 and dummy well 2 that located at outflow zone and dummy well 3 that located at upflow zone.

![ 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). ]

5.5 Updated Conceptual Model

![ Figure 11: Updated Conceptual Model of Danau Ranau Geothermal Field.](image)
The updated conceptual model shown in figure 18 was designed based on preliminary geoscience study without any well data and simulated to create numerical model approach. It appears that hot geothermal fluid is flow upwelling from the deep part of the Mount 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 fluids that ascends through the vertical permeability with some fluids flow in lateral direction. In contrary to the initial model, there is a change in determining the depth of top reservoir as the updated model has followed the interpretation of Magnetotelluric. It stated that in general top of reservoir of Lumbok geothermal area is situated around the depth of -500 masl, the only exception applied for Kota Batu area in which the reservoir reached the depth of -700 masl.

5.6 Resources Assessment

The estimation of resource in Danau Ranau geothermal field used heat stored principal. There are two methods including deterministic and probabilistic approach. Deterministic approach used volumetric method and probabilistic approach used 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 model, reservoir characterization, and general assumptions. Monte Carlo simulation is calculation of iterations from probabilistic model that simulate properties physic in distribution value for estimating geothermal resource by heat stored principal. The estimate of minimal, maximal, and most likely value in each parameter of geothermal resource need to define before.

The proven area in Danau Ranau geothermal field was bounded by surface manifestation and thermal distribution (200 - 220°C) based on 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 reservoir is obtained from high temperature profile. From 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 about 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 Danau Ranau geothermal field is assumed about 30 years. The detail about parameters that inputted to Monte Carlo simulation as seen in Table 3.

The numerical model based on Monte Carlo simulation, using 60,000 random numbers, define 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, presented also in figure 17. Based on Monte Carlo simulation calculation, the geothermal potential of Danau Ranau geothermal field is lower than 25 MW for highest degree confidence.

Table 3: Input parameters for Monte Carlo simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
<th>Most</th>
<th>Remarks</th>
</tr>
</thead>
<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>
<td>0.08</td>
<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>-</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>Tl (°C)</td>
<td>200</td>
<td>220</td>
<td>-</td>
<td>Temperature distribution based from 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>

Figure 12: Distribution of Monte Carlo Simulation Result

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. Range of productive zone (reservoir) area between 14-17 km². The reservoir temperature in range of 200-220°C were numerically simulated. The reservoir predicted to be compressed liquid based form 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 Lake Ranau act as infiltration and recharge zones for this geothermal system. The existence of magma in 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 details geoscience survey for investigation of Danau Ranau upflow zone that indicated at Seminung mountain.

2. Need further advanced exploration survey including geological, geochemical, geophysical and exploration drilling investigations (based on SNI 1998) to improve the conceptual model.

3. The numerical simulation model should be updated by addition the result of advance exploration survey.

4. The Resource Assessment should be improved by experiment design (ED) principal which use measurement from model.

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9. REFERENCES


