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Including the Topographic Profile of the Geothermal Field on Geothermal Reservoir Modelling: How Important is it?

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ABSTRACT

Geothermal reservoir models are already used extensively to support the planning and development of geothermal fields. Current technology's growth is also affecting the geothermal reservoir modeling. It makes the simulation process more accurate and reliable for assessing the geothermal system. However, the common practice in reservoir models only focus on the deep geothermal and do not usually include the near-surface system. Some modelers tend to simplified the model by using constant P,T water table at the top. This simplification makes the model unable to unable to predict the effect of reservoir production on the near surface. In real geothermal system, production can result in changes to surface features, such as the disappearance of hot springs, the appearance of new steaming areas, and subsidence. Therefore, geothermal reservoir modelling must be improved by integrating the deep reservoir and near-surface system. The integration will be beneficial to support environmental monitoring and impact mitigation.

This paper is aimed to discuss the importance of including topographic profiles in geothermal reservoir models. We will also cover the brief procedure to develop an integrated numerical model based on the latest best practice by Nugraha et al. (2022). The result of this study is expected to raise awareness for geothermal reservoir engineers to build reservoir models by integrating the deep reservoir and near-surface system.

1. INTRODUCTION

Indonesia has huge potential energy either conventional or renewable energy, one of the renewable energies that currently developed is geothermal energy. Fortunately, Indonesia has a strategic location at the Pacific Ocean ring of fire. It makes Indonesia the second-largest resource in the world with 23,356 MW of potential electricity generated by geothermal energy (Bahan Pengembangan Panas Bumi, 2022). The Government of Indonesia (GOI) has utilized geothermal energy for electricity in 2022 around 2,687 MW or 11.5% of the resource, which means there are still many geothermal resources that have not been utilized. One of the obstacles in the geothermal utilization is the high uncertainty in the early project development (ESMAP, 2021).

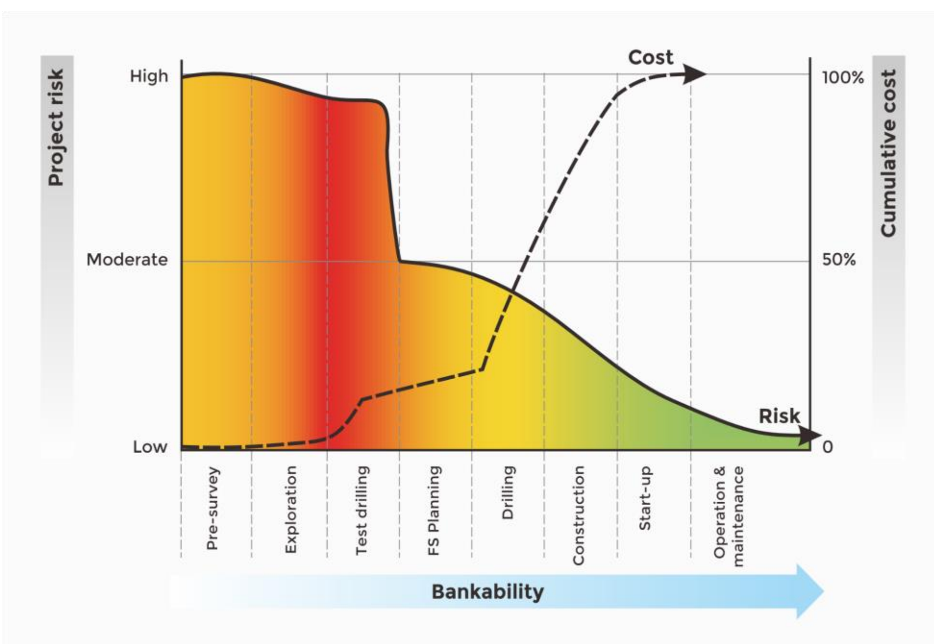

Figure 1. Geothermal Project Business Risk (modified from ESMAP, 2012)

The first phase of geothermal development is pre-survey and exploration that considered as the riskiest activity of geothermal project development. Significant investment is required to recover the project cost, yet the geothermal resource has not known at this stage (ESMAP, 2012). Thus, geothermal resources analysis is needed to minimize the uncertainty. This could be done by carry out geothermal reservoir modeling activities. According to Nugraha et al. (2020) and Purba et al. (2021), geothermal modelling could be utilized since the early stage of geothermal development, and it's considered as the most reliable tools to assess geothermal resource.

With the current growth in computer technology, the reservoir simulation process becomes more accurate and reliable for assessing the geothermal system resource. However, because of the limited technology in the past, modelers used to simplify the boundary conditions and exclude the topographic profile. It makes the model may fail to represent the complexity and the heterogeneity of the geothermal system. In reservoir modelling, to represent the entire geothermal system, it required to models and integrate both deep reservoir and near-surface system.

This paper will discuss the importance of including topographic profiles in geothermal reservoir models. We will also explain the procedure to develop an integrated numerical model based on the latest best practice by Nugraha et al. (2022). The result of this study is expected to raise awareness for geothermal reservoir engineers to build reservoir models that integrated the deep reservoir and near-surface system.

2. THE DEVELOPMENT OF GEOTHERMAL RESERVOIR MODELING

Geothermal reservoir modeling is the process of building a representative model of a geothermal field to study the behavior of the geothermal system. It is primarily aimed to evaluate the performance of the reservoir and developing strategies for future development. It would be beneficial to apply and update the numerical model throughout the life of the geothermal project, including the exploration phase. However, the geothermal numerical model has different purposes in each project phase as described below:

1. **Early exploration phase**. During the exploration phase, the amount of data for quantitative calibration is limited. Thus, only a natural state model can be carried out. Usually, this model is built according to conceptual models, which are based on data obtained from geological and geophysical surveys and the chosen input parameters (Grant, 2011). The result from this simulation can provide a useful check on the conceptual model and may help to develop well targets for the exploration drilling.
2. **Post-exploration drilling phase**. After exploration drilling, the numerical model will be updated by calibrating it with pre-production data, including exploration well data, surface features (geysers, hot pools, springs, etc.), and completion test data from the first production wells. This updated model can be used to identify potential reservoir zones, estimate resource capacity, and predict future well performance following the initial test.
3. **Development phase**. In this phase, the natural state model will be calibrated with production history data to create a production model. This production model can be used to evaluate reservoir performance and forecast the future scenario, the scenario that defines expected future production, reinjection strategies, make-up well strategies, environmental change due to production, etc.

As the key tools in the planning and management of geothermal developments, the study of geothermal reservoir models has been done since the early 1970s. It began to be used and accepted in the geothermal industry in the 1980s (Stanford Geothermal Program, 1980). However, computer power available in the 1980s limited the size of the computational meshes used. Thus, most of the early three-dimensional models were simplified by omitting low-permeability zones or by using a relatively small number of blocks. For example, the Wairakei model developed by Pritchett et al. (1976, 1980) consisted of only 174 blocks with a vertical slice running through the main Borefields (O'Sullivan et al, 2009). This simplification of the model causes a limited representation of the actual details of the geothermal system.

In the early 2000s, reservoir models have developed with more complex 3D structures and consist of thousands of blocks or elements. Typical minimum horizontal and vertical dimensions are 200 m and 100 m, respectively. In this era, some modelers have tried to model the shallow zone in a geothermal field. However, to get high accuracy of surface feature representation, very thin layers at the top of the model are needed. The computer technology at this period were not supporting the practices. The smallest block size is still quite large, and the matching time is still quite long.

According to O'Sullivan (2000), two important matters in setting up a geothermal system are its size and the boundary conditions to be applied on the sides of the model. With the rapid change in computer technology, model and block size is not a problem anymore. Geothermal models already consist of millions blocks and has faster running time. However, the common practice to date is only focus on the deep geothermal resource and do not usually resolve the near-surface system. The boundary conditions are simplified by using a constant pressure and temperature water table at the top of the model, constant pressure and temperature at the bottom boundary, and the inclusion of only a small part of the reservoir within the area covered by the model grid (Nugraha et al., 2022). Whereas, in a real geothermal system, the water table level may drop as the fall of shallow pressure. The shallow temperature will also change during the production period. There is no way of representing the change of water table level and shallow temperature by only assuming constant P,T water table at the top. This simplified boundary condition affects geothermal production, particularly from shallow steam caps or if shallow cold groundwater incursion occurs. It can also make the model unable to simulate the near-surface physical behaviour, including the change of geothermal surface features during production. Some examples of surface feature changes that may occur during production are the disappearance of hot springs, the appearance of new steaming areas, and subsidence.

The latest study explained that one of the best practices is to extend the geothermal model up to the ground surface following the topography of the area. The top ground surface parameter must be included in the numerical model. This practice is also supported by current developments in computer technology. Currently, reservoir simulators can simulate geothermal reservoir models with multi-millions of blocks. Due to this upturn, it is now possible to create a model that represents a wider zone, including the surface area parameters, such as topography and surface hydrological systems. Thus, we can integrate shallow and deep reservoir systems that are able to predict the effect of reservoir production on the near-surface environment.

3. RELATION OF TOPOGRAPHY AND NUMERICAL MODEL

Fluid mechanics in a convective geothermal system consists of the dynamic between reservoir fluid, local hydrological system, surface manifestation, and recharge. Thus, in order to accurately simulate geothermal fluid in production and reinjection phase, it is necessary to understand the effect of topography on these features.

Hydrogeology

Hydrogeology considers the interrelationship between water processes (mainly groundwater) and geologic controls of physiography, surface geology, and topography of a drainage basin. Groundwater is an aspect of hydrogeology that stands as a main consideration in geothermal drilling and production process. It is known to provide hydraulic pressure to the reservoir, affect heat flow patterns, form shallow geothermal resources, etc. Groundwater can be defined as water stored bellow the zone of saturation inside a permeable layer of rock (aquifer). The top of the zone of saturation is referred to as a water table, while the unsaturated zone above it is known as the vadose zone (Fetter, 2014). Figure **2** displays a typical model of a groundwater profile.

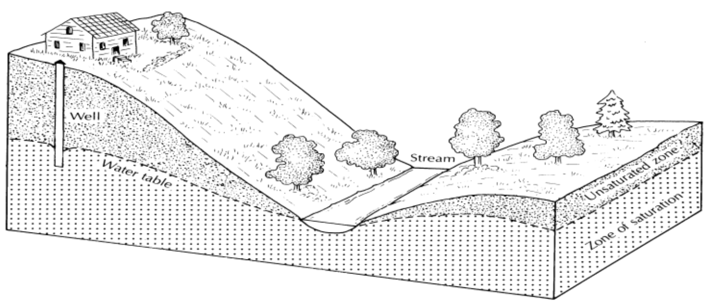

Figure 2. Groundwater profile (Fetter, 2014)

Previously, water table in numerical models are often simplified as a flat surface with constant pressure and temperature values. However, this approach is not representative to simulate the natural water table, pressure, and temperature conditions (Nugraha et al., 2022). The following assumptions can usually be made in regards to the water table:

1. The shape of a water table will share the general shape of surface topography with a more subdued relief. As a result, the depth of the water table is typically greater beneath hills than beneath valleys. The elevation of the water table is a dynamic component that may fluctuate due to climatic conditions, e.g. wet season, recent rainfall (Fetter, 2014).
2. Following the second law of thermodynamics, groundwater flow from higher topography towards lower topography (Song, 1992). Low spots where the water table coincides with the topographical depression contour will form groundwater discharge (depression spring).
3. Mountainous terrain of high topographic relief will reinforce the influence of surface topography to patterns of groundwater flow, which also affects advective thermal disturbance and isotherm. In contrast, heat flow tends to be laterally constant in low relief terrain (Forster & Smith, 1989).

By large, topographic controls, flow directions, and isothermal lines are obtained from the 3G survey phase and should already be incorporated in the 3G conceptual model. The specific elevation of the water table, however, can be hard to measure directly. Measure of groundwater level in the field survey phase involve using piezometer or mapping of depression springs in an extensive area. Mapping of springs may not be very reliable in a geothermal setting, since springs can form in various conditions that doesn't always reflect the water table. Most accurately, water table are noted from well data.

For green fields with no well data available, the relationship between groundwater, surface water, and seawater can be an alternative to predict the water table elevation. Surface water bodies, such as rivers and lakes, if situated bellow the groundwater contour will receive input from the groundwater. This is called a gaining stream (Figure **3**). It should be noted that the use of surface water is best in humid regions taken at the wetter season to make sure that the stream or lake is gaining. Otherwise, the surface water bodies may actually be losing streams. Instead of receiving groundwater input, the streams act as groundwater recharge. Larger scale rivers and lakes are preferable. The same principles can be applied to geothermal systems located in coastal areas. Groundwater will discharge towards the sea, following the bathymetry profile. If the aquifer has been depleted, salt water intrusion will function as recharge to the system.

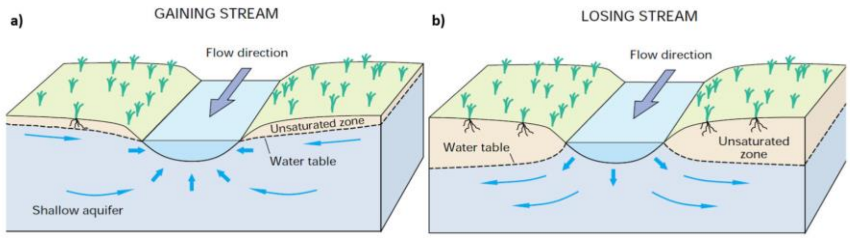

Figure 3. Right: gaining stream profile, left: losing stream profile (adapted from Winter et al., 1998)

Surface Manifestation

Surface manifestations are key elements in a convective geothermal systems and are the only representation of reservoir fluid condition that can be measured from the surface. The presence of a convective system forms new patterns to water movement. The delineation of upflow and outflow zones describes these patterns best. The upflow zone is defined as zones of higher temperature with mainly upward flow patterns. Fluid flow is mainly facilitated by structural or lithology generated permeability (Moeck, 2014). This is due to thermally generated buoyancy affecting fluid movement enabling flow from low to high topography (Freeze and Cherry, 1979). In two-phase systems or vapor dominated systems, vapor will rise easier than liquid phase, sometimes through diffusion to form thermal manifestations, forming manifestations such as fumarole, solfatara, boiling spring, etc. As reservoir fluid rise to the near surface, energy dissipation lessens the effect of buoyancy, flowing towards the outflow zone. The outflow zone is a zone with lower temperature, dominated by lateral fluid flow influenced by faulting and topography. Due flow in lower topography, fluid will normally occur at shallower depth (<1 km). Hot and warm spring are the typical type of manifestations found in the outflow zone. Hydrochemical characteristics can vary according to the geological controls of the system. The upflow and outflow zone can also form in different locations in relation to topography. Jolie et al. (2021) characterized caldera and rhyolitic dome hosted geothermal resources, associated with silicic volcanic setting, to form lower topographic relief systems with higher primary permeability compared to andesitic volcanic systems. This will result in different formations of upflow and outflow type thermal manifestations. In systems with higher topographic relief, Forster and Smith (1988) states that permeable fracture zones will play larger parts in controlling fluid flow and thermal regimes.

Meteoric Recharge

Geothermal systems are self-replenishing systems in its free convection condition. Extracting fluids from a geothermal well will generate a cone of depression around the produced well. The resulting lowered pressure gradient surrounding the depression cone will cause surrounding fluids to surge and refill the depleted area if sufficient input is available to match the rate of production. Natural recharge can be facilitated by fluid from various sources, both deep sourced and/or surficial. Deep recharge is often sourced from magmatic or juvenile fluid, best accommodated using a hot plate boundary as the base of the numeric model. Meanwhile, surficial recharge mechanism can come from surface water bodies (with the mechanism explained in the hydrogeology section) as well as meteoric input.

In an area bounded by topographical highs (watershed), precipitation will either infiltrate unsaturated ground or flow downslope as streams. Infiltration of unsaturated ground is followed by percolation, where meteoric input flows towards the aquifer layer beneath it and recharges the system. The infiltration and percolation rate is a function of soil/rock permeability (can be increased by structure). In mountainous areas, the upslope part are usually marked by a deeper saturated zone. Water infiltrates better here, as the soil is largely unsaturated (Mhiret et al., 2022). Water inside the aquifer can then penetrate deeper to the subsurface or move considerable distances laterally through gravity-driven mechanism (Pirajno, 2009). To replicate this in a numerical model, input of annual precipitation can be gained from rain gauge measurements or even satellite data. Using an assumption of ~10% infiltration rate, meteoric recharge can be simulated using Python script. To accommodate lateral recharge and the pressure gradient drop inside the cone of depression, it is also best to set the side boundaries of the model to approximately 4-5 km to all sides of the resistivity boundary of the system (Nugraha et al., 2022).

Furthermore, water tend to migrate inside of watershed boundaries, thus precipitation that falls on one area may not add towards the recharge of the neighboring watershed. This is important if a geothermal system spans a wide area, possibly covering multiple watersheds. Recharge may also be hindered by compressive geological structure that acts as fluid barriers, low permeability lithology, intrusions, etc.

4. HOW TO DEVELOP AN INTEGRATED NUMERICAL MODEL

Based on the current best practice, a geothermal model must be extended up to the ground surface. It is also suggested to make a numerical model to be in conjunction with the conceptual model of the geothermal system. It is aimed to simulating the actual state of the system. Thus, the topography profiles must be included since the early development of the static model.

Developing 3D conceptual model

A 3D conceptual model must begin after the completion of 3G exploration survey. It must accurately represent as much of the actual system as possible by incorporating all the geological information, including:

- Topography.
- Stratigraphy.
- Lithology.

- Temperature distribution (isotherms).
- Geological structure.
- Hydrothermal alteration.
- Heat source.
- Fluid phases (liquid, two-phase, steam).
- Chemistry, thermal manifestations.
- Hydrological system.
- Recharge area.
- Fluid flows within the system (upflows, outflows, inflow/recharge).

The topography is created by importing the topography point from DTM/DEM data. Having the data imported, topography profile was created from point. The creation of conceptual model, including the topography profiles, is best to use Leapfrog Geothermal. It has the capacity to store all 3G survey data, along with GIS and well data, then further compile them into an integrated and very useful 3D geological model. Additionally, once a 3D geological model has been developed, Leapfrog can generate a TOUGH2 numerical model (Nugraha and O'Sullivan (2018) and Nugraha et al. (2022)).

Numerical model set up

To accurately represent the surface features of a geothermal system, the shallow, unsaturated zone must be included in the model domain. High vertical resolution is also needed to capture the high temperature gradients. To accommodate this condition, the most suitable equation of state must be selected. The numerical models are then developed by incorporating as much information about the real system as possible. This information includes:

- The topography of the area from the static model.
- The geology.
- Fault structures.
- Rainfall infiltration.
- The deep upflow.

Setting top boundary conditions

Top boundaries play a critical role in representing the geothermal surface features. Thus, to represent the near-surface system, topography profiles must be used as the top boundary of the model. The following descriptions of the best practice in setting up top boundary conditions are summarised from Ratouis et al. (2015), O'Sullivan et al. (2016), O'Sullivan & O'Sullivan (2016), Nugraha et al. (2018), Nugraha and O'Sullivan (2020), and Nugraha et al. (2022).

- **Submerged geothermal system:** For submerged geothermal system, the bathymetry data of that particular area must be included in the model.
- **Top of the model**: dry atmospheric conditions are assigned to the dry-land surface, with a pressure of 1 bar and a mean temperature equal to the field's ambient temperature. The environment beneath the water body vary according to the hydrostatic pressure, and the temperature fluctuates based on the temperature data collected.
- **Equation of State (EOS)**: The model uses the air-water equation of state to simulate mixtures of water and air and incorporate the vadose zone, effectively describing the system up to the surface. The CO_2-water equation of state should be used in fields where CO_2 is the principal gas.
- **Hydrological system**: To simulate the surface hydrological system, a Python script is used to apply the yearly rainfall rate and an appropriate infiltration rate (say ~10%).
- **Rock properties**: The rock properties of the top layers in the model are then modified using a Python script with attributes corresponding to unconsolidated soil conditions with a large permeability at the ground surface. These model configurations will simulate precipitation infiltrating at the ground surface and migrating to lower elevations following the terrain included in the model.

Once the top boundaries are set, the later stages of model development can follow current best practices described by Nugraha et al. (2022).

4. MAIN BENEFIT OF GENERATING MODEL FOLLOWING TOPOGRAPHY OF THE FIELD

As described in the previous section, there is possibility of changes in geothermal surface features during production. One of the well-known related phenomena is Karapiti or Craters of the Moon in Taupo, a part of Wairakei geothermal. This new surface manifestation appeared in the 1950s in the north of Taupo. It was suddenly began to get hot and emit steam. The event was triggered by the lowering of underground water pressure by a nearby geothermal power station. Superheated water rose to the surface, and the Craters of the Moon was born. Figure **4** shows the model of Karapiti geothermal. This model has integrated the deep reservoir and near-surface system. It has succeeded in predicting the production effect to the environment. It is explained that many environmental effects are controlled by the pressure and temperature in the geothermal system. Thus, surface features can be affected by production.

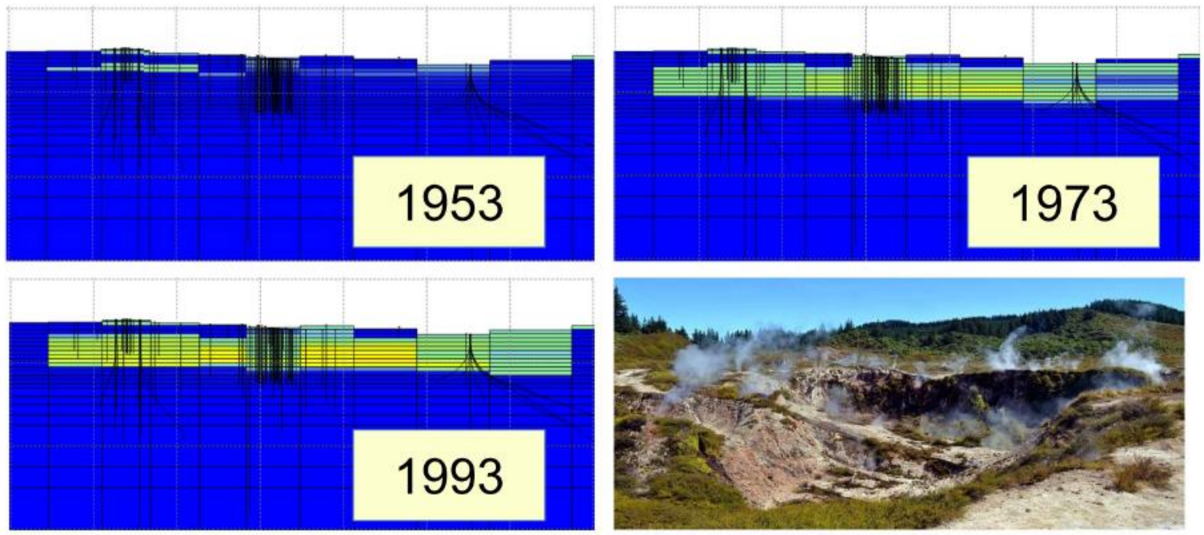

Figure 4. Geothermal Model of Karapiti or Craters of the Moon in Taupo (O'Sullivan et al., 2019)

From the case discussed, we can conclude that it is best to have integrated geothermal reservoir model that covers both deep reservoir and near-surface system. The model provides a valuable tool for predicting the environmental effect of production, such as decreased deep pressure in nearby production system, increase in the level of surface manifestation, or land subsidence. By combining the model with an extensive monitoring program, any negative impacts on its unique surface features should be able to be anticipated and mitigated.

5. CONCLUSION

With the advancement of reservoir simulation technology, modeling practices must be improved by following the latest best practices in the industry. The use of the water table as the top of the model should not be applied since it may fail to fully represent the complexity and heterogeneity of the geothermal system. Thus, topography profile must be used as top boundary of the model.

By including the topography profiles on geothermal model, we can have an integrated geothermal model. The model covers both deep reservoir and near-surface system. This practice will help in predicting the production effect to the environment. Furthermore, it can also help to define policies around the expansion of geothermal resource utilization.

REFERENCES

Alcaraz, S., Chambefort, I., Pearson, R., & Cantwell, A. (2015). An Integrated Approach to 3-D Modelling to Better Understand Geothermal Reservoirs. *World Geothermal Congress.* Australia.

Bodvarsson, G., Pruess, K., Haukwa, C., & Ojiambo, S. (1990). Evaluation of Reservoir Model Predictions for the Olkaria East Geothermal Field, Kenya. *Geothermics*, 399-414.

Burnell, J., Clearwater, E., Kissling, W., O'Sullivan, J., O'Sullivan, M., & Yeh, A. (2012). Future Directions in Geothermal Modelling. *New Zealand Geothermal Workshop.* New Zealand.

ESDM. (2022). Pengembangan Panas Bumi di Indonesia. Indonesia.

ESMAP. (2012). Geothermal Handbook: Planning and Financing Power Generation. Washington DC: The World Bank Group.

Fetter, C. (2014). *Applied Hydrogeology Fourth Edition.* United States of America: Pearson.

Forster, C., & Smith, L. (1988). Groundwater Flow Systems in Mountainous Terrain. *Water Resources Research*, (pp. 999-1010).

Forster, C., & Smith, L. (1989). The Influence of Groundwater Flow on Thermal Regimes in Mountainous Terrain: A Model Study. *Journal of Geophysical Research, Vol. 49*, 9439-9451.

Freeze, R., & Cherry, J. (1979). *Groundwater.* New Jersey USA: Prentice-Hall, Inc. .

Grant, M., & Bixley, P. (2011). Geothermal Reservoir Engineering, 2nd Ed. Academic Press: Oxford.

Jolie, E., Scott, S., Faulds, J., Chamberfort, I., Axelsson, G., Gutiérrez-Negrín, L., . . . Zemedkun, M. (2021). Geological Controls on Geothermal Resources for Power Generation. *Nature Reviews: Earth & Environment.*

Mhiret, D., Dersseh, M., Guzman, C., Dagnew, D., Abebe, W., Zimale, F., . . . Steenhuis, T. (2022). Topography Impacts Hydrology in The Sub-Humid Ethiopian Highlands. *MDPI*, 196.

Nugraha, R. P., O'Sullivan, J. P., O'Sullivan, J. M., & Abdurrachman, F. H. (2022). Geothermal Modelling: Industry Standard Practices. *47th Workshop on Geothermal Reservoir Engineering.* California.

Nugraha, R., & O'Sullivan, J. (2020). Modelling Application to Estimate the Thermal Output of Weh Island, Nangro Aceh Darussalam, Indonesia. *World Geothermal Congress 2020+1.* Reykjavik.

Nugraha, R., O'Sullivan, J., & O'Sullivan, M. (2018). A 3D Geological Model and Natural State Simulation of Jaboi Geothermal Field, Nangro Aceh Darussalam, Indonesia. *New Zealand Geothermal Conference.* Taupo.

O'Sullivan, J. P., Ratouis, T. M., & O'Sullivan, J. M. (2015). Using Reservoir Models for Monitoring Geothermal. *International Scholarly and Scientific Research & Innovation 9(3).*

O'Sullivan, J. P., Renaud, T., Croucher, A., Yeh, A., Gravatt, M. J., Riffault, J., . . . O'Sullivan, M. J. (2020). Comparisons of AUTOUGH2 and Waiwera on Geothermal Fields. *42nd New Zealand Geothermal Workshop.* New Zealand.

O'Sullivan, J., Arthur, S., & O'Sullivan, M. (2016). A new reservoir model to support environmental monitoring of the Orakeikorako geothermal system. *Geothermics*, 90-106.

O'Sullivan, J., Croucher, A., Popineau, J., Yeh, A., & O'Sullivan, M. (2019). Working with Multi-million Block Geothermal Reservoir Models. *44th Workshop on Geothermal Reservoir Engineering.* California.

O'Sullivan, M. J., Press, K., & Lippmann, M. J. (2000). Geothermal Reservoir Simulation: The State-of-Practice and Emerging Trends. *World Geothermal Congress.* Japan.

O'Sullivan, M. J., Yeh, A., & Mannington, W. I. (2009). A history of numerical modelling of theWairakei geothermal field. *Geothermics*, 155-168.

O'Sullivan, M., & O'Sullivan, J. (2016). Reservoir Modeling and Simulation for Geothermal Resource Characterization and Evaluation. In *Geothermal power generation: developments and innovation.* Woodhead Publishing.

Ponggohong, C. R., Suryantini, & Pratama, A. B. (2021). An Integrated 3D Geological and Isothermal Modelling to Better Understand. *World Geothermal Congress 2020+1.* Iceland.

Pritchett, J., Rice, L., & Garg, S. (1978). Reservoir Engineering Data: Wairakei. *ReportNo. SSS-R-78-3597. Systems, Science and Software.* California.

Pritchett, J., Rice, L., & Garg, S. (1980). eservoir Simulation Studies: Wairakei. *Final Report, Geothermal Reservoir Engineering Management Program Lawrence Berkeley Laboratory report LBL-11497.* California.

Pruess, K. (2002). Numerical Modeling of Geothermal Systems. In *Mathematical Modeling of Fluid Flow and Heat Transfer* (pp. 27-46).

Purba, D., Adityatama, D., Ayuningtyas, R., Chandra, V., Al Hassan, M., Ramadhan, R., & Rizqy, M. (2021). Resource Assessment Methods Selection for Geothermal Exploration Project in Indonesia: What are the Considerations? *46th Workshop on Geothermal Reservoir Engineering.* California.

Ratouis, T. M., O'Sullivan, J. M., & O'Sullivan, P. J. (2016). Modelling Geothermal Surface Features in the Rotorua Geothermal Fluid. *Proceedings 38th New Zealand Geothermal Workshop.* New Zealand.

Song, C. C. (1992). The Role of Energy Dissipation in Fluid Flows. University of Minnesota.

Stanford Geothermal Program. (1980). *Special Panel on Geothermal Model Incomparison Study.* California: Stanford Geothermal Program report SGP-TR-42.