Groundwater model using finite difference method on open- pit coal mine in West Aceh Regency, Nanggroe Aceh Darussalam, Indonesia

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AIP Conference Proceedings

RESEARCH ARTICLE | NOVEMBER 23 2021

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AIP Conference Proceedings 2363, 030003 (2021)
https://doi.org/10.1063/5.0061082

Groundwater Model Using *Finite Difference Method* on *Open-pit Coal Mine* in West Aceh Regency, Nanggroe Aceh Darussalam, Indonesia

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Abstract. The change of land use caused by mining operation indeed affect the availability of groundwater that exist in the surrounding region. Especially mining operation that used open-pit methods for its operation. Open-pit mine is a surface mining technique that extracts coal by removing the overburden that conceals the coal itself. By removing the materials located above the coal, it will indeed affect the hydrology condition of the region whether it is the groundwater elevation or groundwater availability of the surrounding area because some aquifer were cut in the process that leads to groundwater disturbance.. This condition indeed reflects the condition of the research model area in Meureubo, West Aceh Regency. Geologically, the formation that exists in the research area is tutut formation which has dip $< 10^o$ in the direction of the southwest. The hydrogeological boundary of the model is two big rivers located in the west of the model (Nagan river) and the river in the northeast of the model. The model consists of 5 layers in total that include 2 layers as aquifer (sandstone) and 3 layers as an aquitard. Those aquifer is separated by a clay layer which functions as an aquitard in this model. The goal of this research is to create a model that resembles the impact on the groundwater condition in the research model caused by the coal mining activity that will be held years from now on. To achieve that goal, knowing the hydrology and hydrogeology condition of the area is critical in order to create an accurate model that show the groundwater condition before and after the mining activity. The model will be created using the finite difference method, which is a numerical simulation in MODFLOW. The results of the research will show the groundwater fluctuation around the location of the mining activity and also in the mine location itself. From the analysis that had been done, the results show that there is a decrease in groundwater level elevation in the pit area for about 8 meters in 10 years based on the mine plan design and 3-5 meters in the settlement around the mining area. The change in groundwater elevation was caused by the removal of an aquifer that happened during the mining progress.

Keywords: Groundwater, Groundwater Model, Hydrogeology, Open-pit, Aquifer.

INTRODUCTION

Surface mining is considered one of the most destructive activities to the environment that had been done by humans to extract natural resources from nature itself. That been said, surface mining also one of the cheapest and most efficient ways to extract mineral and non-mineral resources on a large scale. It affects many aspect of the surrounding environment due to its scale and its method. One of the most affected aspects is groundwater flow and availability [1].

3rd International Conference on Earth Science, Mineral, and Energy
AIP Conf. Proc. 2363, 030003-1–030003-9; https://doi.org/10.1063/5.0061082
Published by AIP Publishing. 978-0-7354-4154-5/$30.00

In the research area, which is located in West Aceh Regency, the mining activity that has been held is using open-pit surface mining. Those activities affect the groundwater condition in the mining area itself and the area surrounding the mine. Those the needs to study the impact on the groundwater condition by the mining activity, especially in open-pit coal mine, is proven to be needed in the purpose of handling unwanted problems such as potential landslide disaster on the pit slopes and also water drought in the nearby settlement [2]. The study results will show the change in groundwater conditions during the period of mining activity.

LITERATURE REVIEW

A groundwater model is an effective instrument to represent groundwater flow and its component that affect the groundwater itself. Creating a groundwater model is a crucial element in every groundwater plan, design, development, utilization, management, and conservation in a specific area. A model is an approach to the field condition that is complex and not the reality itself. A Groundwater model is a tool that is designed to represent a groundwater condition in a simple matter [3]. A Groundwater model is used to predict a variable that has an unknown value in a limited time and space. The level of accuracy of a model is determined by the level of simplification and assumption that is used during the model creation. More simplification and assumption that is used means lower the level of accuracy of a model.

Darcy Law in Groundwater Modeling

Differential equations are used as base of groundwater flow modeling. Such differential equations are typically supported by Darcy Law in the form of a linear macroscopical fluid momentum balance equation **[4]**. Depending on the model condition, specific condition may have to be taken into account. A confined aquifer model is different from unconfined aquifer. The dimension of the model, be it 1 Dimension, 2 Dimension, or 3 Dimension rely upon the actual condition and the goal of the model. Based on the same sense of condition, choosing between steady-state models versus transient models must be taken. Simply to call the fundamental properties of the model. The aim of this model is to portray the groundwater condition in the research area due to mining activity. Therefore for a complete description of the situation in the field, a 3 D model is the most suitable to the goal of the research.

$$\frac{\partial}{\partial t}(\phi\rho_f) = -\nabla.(\rho_f V) + Q \quad (1)$$

$$S\frac{\partial h}{\partial t}(\phi\rho_f) = -\nabla.T\nabla h + P - Q \quad (2)$$

These are a different formula for the differential equations. The mass balance which stated in equation (1) was stated in 3D, where porosity were indicated by ϕ , ρ_f is fluid density, V is the 3D vector on Darcy Velocity, and mass sources were represented by Q. Simplified equation (1) is well suited for most model that is justifiable towards constant density ρ_f. Darcy's Law help the equations so its frequently reconstructed as far as hydraulic head h. Equation (1) are the simplified 2D renditions from a diversed confined and unconfined aquifers. In equation (2) which explained confined aquifers, Q and P represent the recharge and pumping rate of the model. T is the transmissivity and S is storativity of the model input.

Finite Difference Method

Groundwater models commonly need the appropriate response of partial differential equations. The equations portraying the groundwater streams are the second request to partial differential conditions, which might be arranged on the possibility of their numerical properties **[4]**. The two fundamental kinds of mathematical models that are acknowledged for explaining the groundwater conditions are the Finite Element Method and the Finite Difference Method introduced in mathematical equation (3). Both of these mathematical methodologies necessitate that the aquifer to be sub-separated into a grid and examining the flow-related inside a solitary zone of the aquifer or nodal grid. A partial equation could be portraying the groundwater stream. It is regularly settled numerically by a systematic or mathematical solution. However, expository solutions are hard to apply in light of the fact that it necessitates that boundary and limits to be exceptionally idealized.

$$S_s\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left[T_{xx}\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[T_{yy}\frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial z}\left[T_{zz}\frac{\partial h}{\partial z}\right] - G \quad (3)$$

The groundwater stream condition is the numerical relationship that is utilized to depict the progression of groundwater through an aquifer (3). In the investigation of the groundwater stream equation, an examination of a steady-state flow and transient flow is recommended in the process. The transient flow is depicted by a type of dispersion condition which speaks to the adjustment in condition because of time in the model. A flow that is affected by the change of time during the modeling is called transient flow **[5]**. Meanwhile, The steady-state flow is depicted by a style of Laplace equation. In steady-state flow, all of the conditions remain constant throughout the time model. The groundwater flow equation is a form of derivative of total volume where its properties are assumed to be constant. To achieve a transient flow equation, A mass balance is acquired on the water flowing in and out according to Darcy's law. A 3-dimensional flow with the harmonic capacity and has numerous analogs in other fields (4) is another form of Equation (3).

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=0 \qquad (4)$$

In modelling, whether using finite element or finite difference a nodal point system is used over the domain of the model. In finite difference method, nodes may be located inside cells (**FIGURE 1.b)** or at the intersection of grid lines. The finite-difference grid shown in **FIGURE 1.b** is a block centered node. Meanwhile the grid shown in **FIGURE 1.c** is a mesh centered node. Aquifer properties and head are assumed to be constant within each cell in **FIGURE 1.b**. In **FIGURE 1.c**, the area of influence of each node is defined following one of several different conventions. Regardless of the presentation, the equation that is used in finite difference, it doesn't directly involve in the type of nodal point used in the model.

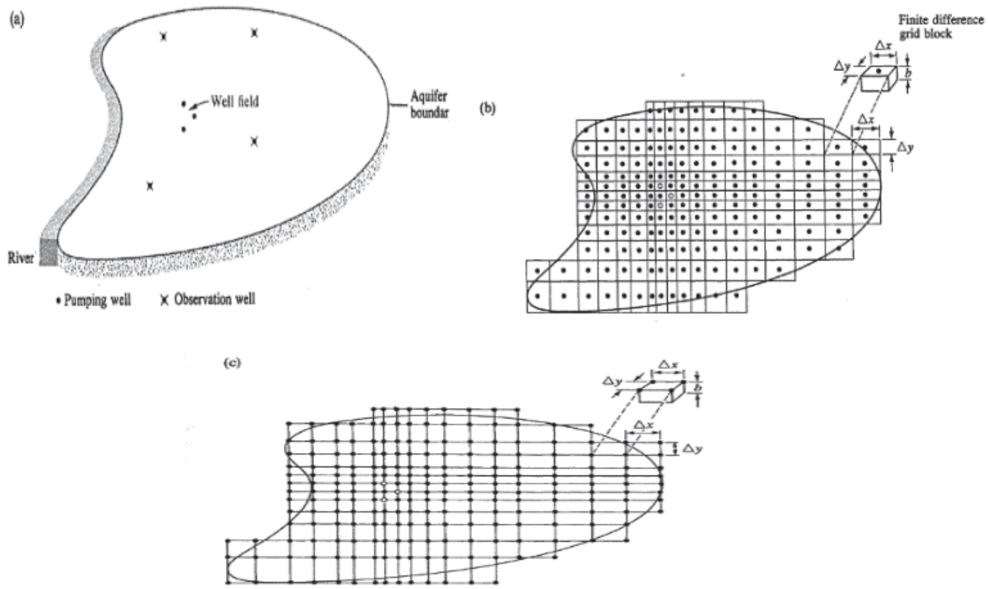


FIGURE 1. a,b,c Nodal Point in Finite Difference Method [4]

Conceptual Model

Conceptual model is described as an accurate and brief compound of all structural and component features of the SUI (System Under Investigation) presented in a spesific format. It gives a fundamental component for the construction of the simulation program [6,7]. Groundwater model development needs its conceptualization as an essential first step before progressing into a more detailed step [8]. It will overcome any issues between hydrogeological conception and groundwater modeling by providing a systematic overview of system boundaries, properties, and processes relevant to the research question. In order to achieve a precise numerical model, a conceptual model is prominent to be constructed first. There are various aspects of the conceptual model that are not possible to be modeled in the numerical model because the hydrological system is very complex. The conceptual model here is defined as a simplified and generalized schematic presentation of a more complex real-world process

[9]. Geological and hydrological information such as borehole information, observed water level, and meteorological data are used as the fundamental component for developing a conceptual model.

An overview qualitative explanation of groundwater system that includes its hydrogeological aspect, system boundaries, transport properties, and have a time-varying input can be called a conceptual model in hydrogeological modeling [8,11]. A hypothesis or a combination of hypotheses for the hydrological condition in the research area can also be seen as a conceptual model. A good conceptual model can be achieved by inputting various hydrology and hydrological variables into the model, making it more complex and represent the condition as it is in the field. Having less assumption and generalization in the conceptual model means having a more detailed and complex model as its final output.

METHODOLOGY

This research was conducted in March-April 2020 in an open-pit coal mine located in West Aceh Regency, Nanggroe Aceh Darussalam Province. Several data were obtained during the time of the research, such as water levels, borehole location, river properties, and geological component (borehole data, geological map, topography map, and meteorology data). That information was analyzed and processed to be the foundation of the groundwater model that will be created. Although that information was eligible to create a representative model at the present time, creating an accurate transient model on groundwater condition need more comprehensive and complete information during a period of time. That information was unable to achieve due to the lack of observation points in the research area that keep track of several important data in a specific period of time that will be used as the base prediction for a model moving forward. This problem is solved by finding information manually and create a worst-case scenario from it. Information such as water level conditions in a period of time can be overcome by estimating the lowest point of water level by equalizing it with the topography elevation and also during the calibration part of the research. The research scheme can be viewed in a simplified way in **FIGURE 2** below.

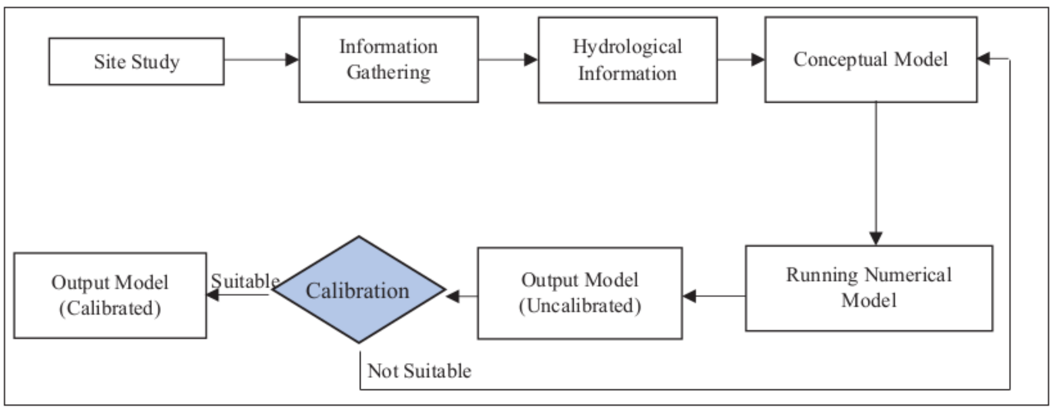


FIGURE 2. Research Flow Diagram

RESULT AND DISCUSSION

Groundwater System

The existence of groundwater was indicated by water wells located around the mining area [12]; it shows the status quo elevation of groundwater in time the research was conducted. As it is shown in **FIGURE 3**, the number of measurement of the groundwater elevation data were so limited due to the fact that most of the well located around the mining area cant be measured because the well openings are already sealed and can't be opened. For overcoming such problems, Interpolation was used between two rivers located in the west and east part of the model and also from known groundwater elevation in the wells that can be measured to create a reference in groundwater elevation that serves purposes to help the numerical model to run smoothly. The groundwater assumption that was used in the model will be overcome during the calibration process by matching the groundwater elevation in the model that created and actual groundwater elevation that existed in the field.

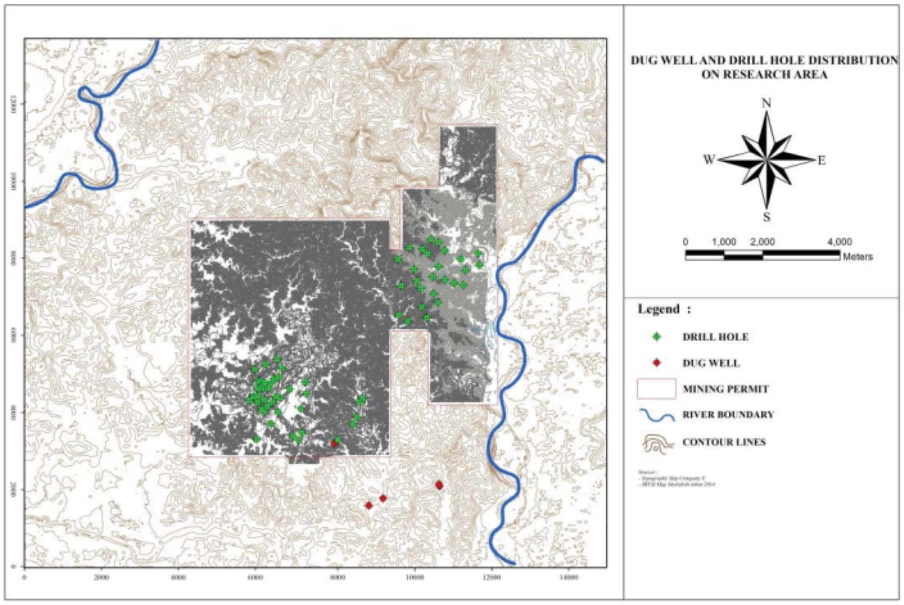


FIGURE 3. Dug Well and Drill Hole Distribution

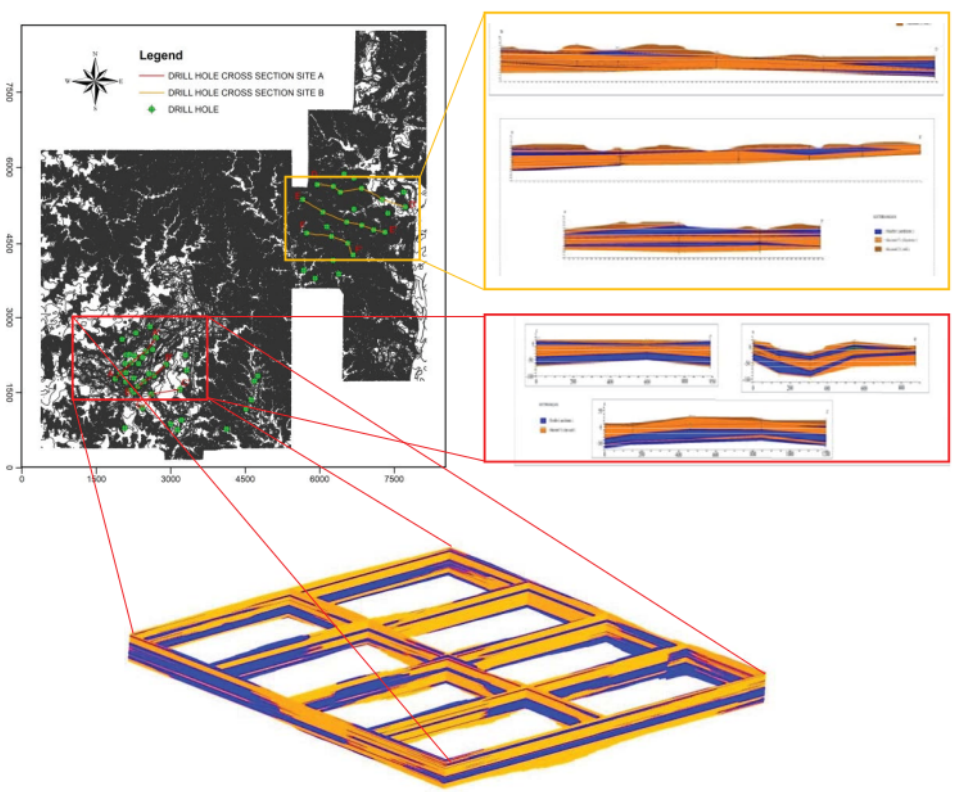
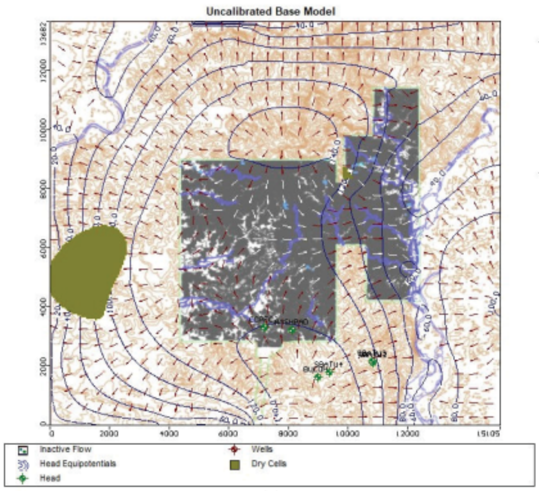


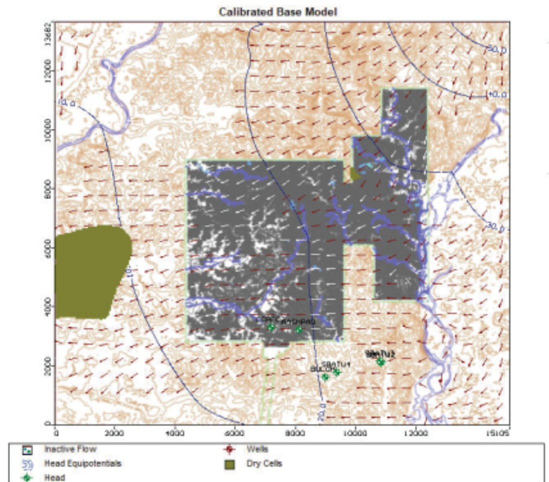
FIGURE 4. Hydrological Model Interpretation

Model Calibration

Based on the log bore data that were acquired during the research (**FIGURE 4**), an interpretation of hydrostratigraphy can be created across the model. A combination of that data and geological map, a more comprehensive and accurate interpretation of hydrostratigraphy can be created that limits the use of assumption in the model which can be seen in the fence diagram in **FIGURE 4**. The interpretation is then used as the base of the numerical model that will be run after other parameters were inputted. In general, the research area was constructed by layers of sandstone, clayey sand, clay, and also coal in between those layers. The depth of the log bore is up to 90 m, with general layer interpretation as clayey sand (±10-33 masl) with a thickness of 1-13 m, sandstone (± -20-10 masl and ± -70 - -85 masl) with a thickness of 0,5-15 m, clay (± -70 - -20 masl and ±-85 - -105 masl) with a thickness of 1-20 m. All the sandstone (> 0,5 m) were defined as aquifer and other than sandstone were defined as aquitard to simplified hydrostratigraphy interpretation in the model.



(a)



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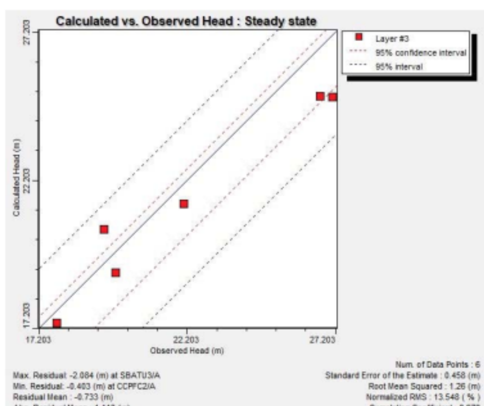


(c)

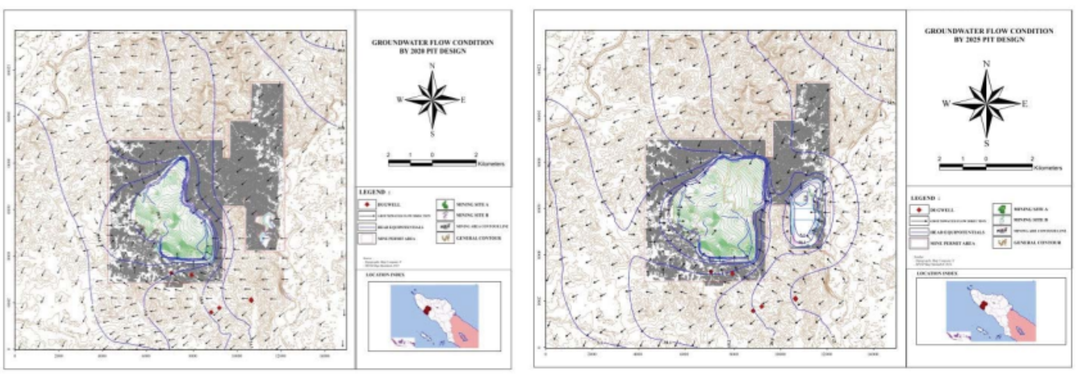
FIGURE 5. (a) Uncalibrated Steady-State Model, (b) Calibrated Steady-State Model, (c) Calibration Result

FIGURE 5 shown the groundwater model that was created using the data input that was obtained during the research and the groundwater model that has been calibrated to match the actual condition in the field. The calibration process used a trial and error method to adjust the hydraulic conductivity and recharge value in the model to create a groundwater condition similar to the actual groundwater condition **TABLE 1**. The hydraulic conductivity in the uncalibrated model was acquired by the slug test which is relatively cheap compared to other tests **[10]**. By changing the parameter value in the model can change the output model of the groundwater condition itself. By matching it to the groundwater elevation acquired in the dug well during the research in the field, it can create a groundwater model similar to the current condition **FIGURE 5.c**. From the calibration result, it shows an RMS value of 13,548 %. It has a standard error of estimate for 0,458 m which means the model that has been created has a high accuracy level to resembles and match the groundwater condition that has been acquired during the research. It is a steady-state model that was calibrated and used as the base model of the transient model later in the prediction of groundwater changes. To predict the groundwater fluctuation during the mining process, a transient model that includes a change in a surface condition caused by mining activity need to be created.

TABLE 1. Parameter Value Calibration

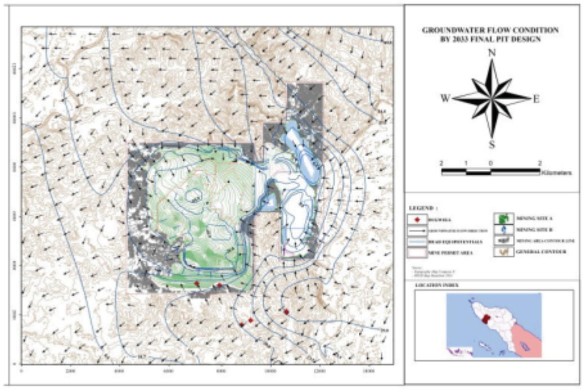
Parameter Input	Uncalibrated Model Value	Calibrated Model Value
K_1 (Aquitard)	$1.71E^{-6}$ m/s	$2.72E^{-5}$ m/s
K_2 (Aquifer)	$1.38E^{-4}$ m/s	$2.76E^{-3}$ m/s
K_3 (Aquitard)	$1.71E^{-6}$ m/s	$1.71E^{-5}$ m/s
K_4 (Aquifer)	$1.38E^{-4}$ m/s	$2.76E^{-3}$ m/s
K_5 (Bottom Layer)	$1.71E^{-6}$ m/s	$1.71E^{-5}$ m/s
Recharge Value	1700 mm/yr	500 mm/yr

Groundwater Prediction Model



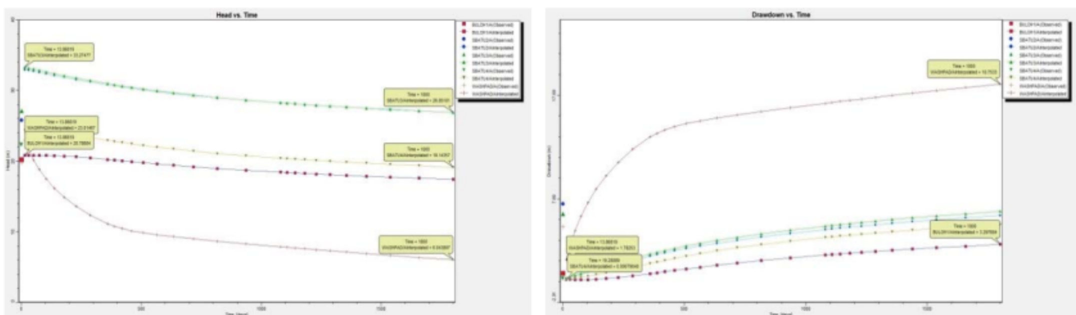
(a) (b)

The transient model in **FIGURE** 6 is a model to predict groundwater changes due to the mining activity that has been done in a specific time and place. Those model were created by inputting the mine plan design into a base model that will create a disturbance in topography condition which can cut existing aquifer and causes changes to groundwater flow in and around the mining area. From the prediction model, we can conclude there is a change in groundwater flow affected by the mining. There are 2 mining sites inside the model, which each of them plays a significant role in groundwater obstruction that happened. In mining site A which is the biggest among the two of them, have a deeper and wider scope of the area that undertake a mining activity. This can be seen disrupt the groundwater flow that comes from the northeast of the model that flows towards the southwest part of the model. The groundwater tends to flow towards the mining pit because there were two major aquifer that has been cut due to the mining activity. This will cause a groundwater fluctuation in the surrounding area especially in the southwest part of the mining area.



(c)

FIGURE 6. (a) Transient Model using 2020 Pit Design, (b) Transient Model using 2025 Pit Design (c) Transient Model using 2033 Final Pit Design



(a) (b)

FIGURE 7. (a) Comparison of groundwater level against time, (b) Drawdown of groundwater elevation against time

Observation wells were used to calibrate the base model, there is a fluctuation in groundwater elevation (**FIGURE 7**). It shows a decline of groundwater elevation in observed wells, the most impacted area is in the southwest of the mining area and also inside the mining area itself (Washpad Wargi, CCPFC 2) because the groundwater flows from direction of the northeast to the south-southwest of the model and the mining activity disturb that flow by cutting the aquifer that has been transported it.

TABLE 2. Groundwater elevations in all observed wells

Location	Year 2020	Year 2025	Year 2033 (Final Pit Design)
Washpad Wargi	24.4 m	18.8 m	6 m
CCPFC 2	20.1 m	15.9 m	Cut due to pit design
Buloh I	20.7 m	20.6 m	17.4 m
Sumberbatu I	32.9 m	29 m	26.5 m
Sumberbatu II	24.4 m	22.6 m	19.1 m

As shown in **TABLE 2**. all of the groundwater elevations in all observed wells are having a decrease. In this simulation, the assumption was the recharge value of the model remains the same across the mining progress. So those groundwater degradations occurred because of the aquifer stripping during the mining activity. This simulation also provides information on the area that has little impact on them, such as in Buloh village which only having a 3 m decrease in 13 years of simulation. Those areas are nearly affected because the location is far away from the mining location and also the origin flow of the area has not been cut off in the mining process.

CONCLUSIONS

A decrease in groundwater elevation in the research area is mostly caused by mining activity that been held in that area. A cut-off in aquifer can cause a significant decrease in groundwater elevation, which in this research the area located in the southwest of the mining area will be affected the most. This can cause another problem especially in a rural area that relies much on groundwater availability that serves purposes in the agricultural section to water their crops. The location which did not significantly affected is located in north-northeast of the mining area and places that located far away from mining activity.

ACKNOWLEDGEMENT

The authors express deep gratitude to Lembaga Penelitian Pengabdian Masyarakat (LPPM) UPN "Veteran" Yogyakarta, PT. Studio Mineral Batubara, and also those who participate in this research for the support both financially, academically and data to finish this research.

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