Application of groundwater modeling to predict the effectiveness of various peat dome restoration methods in Pulang Pisau District, Central Kalimantan Province

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Abstract. A number of Indonesian Peat Hydrological Units (Kesatuan Hidrologis Gambut/KHG) have undergone severe degradation and require an effective restoration measure to increase their ecological, social, and economic function. A peat dome located in Garung village, Pulang Pisau District, Central Kalimantan Province, was selected in this research. It aimed to apply the mathematical modeling to predict the effect of various restoration methods on the sustainability of ecological functions of peak dome in this area and reveal the advantage and disadvantages of each specified method. The groundwater model was performed in this research to simulate the influence of four different restoration methods on the groundwater level of the peak dome. The water budget and the hydraulic conductivity of groundwater assigned in the modeling were derived from the previous research done in the other village within the same Peat Hydrological Units. Meanwhile, the soil property data and the other data related to groundwater and canal properties were obtained from the field measurement at the location during the rainy season. The result of modeling indicates that the restoration method employing a combination of canal backfilling and revegetation affects the most effectively the rising groundwater level of peat dome in the model domain, followed by the individual canal backfilling and canal blocking methods, respectively. The modeling approach enables us to prove the outcome of each applied restoration method toward the area of peak dome having groundwater level lower than 40 cm. In order to be able to apply this model in the other peatland area, a model validation utilizing the field measurement of hydraulic conductivity, groundwater level, and the canal water level is necessary to be carried out throughout the year, particularly during the dry season.
1. Introduction

Restoration of peatland ecosystems are activities carried out to restore degraded peat ecosystems so that the hydrological conditions, structure, and functions of peat ecosystems are in accordance with or close to their original properties and functions through natural succession, hydrological restoration, revegetation, and/or other methods in accordance with scientific developments and technology [1].

The Indonesian government has made efforts to restore damaged peat ecosystems through the 3R program, namely Rewetting, Revegetation, and Revitalization of the Local Livelihood [1]. He suggested that rewetting or wetting peatlands aim to restore the hydrological function of peat as a water reservoir. This effort is carried out by constructing canal blocks that block water flow in the canals so that water continues to wet the peatlands. Water regulation can be made, among others, by making sluice gates or canal blocking that can regulate the water level in the channel and on peat soil. In addition to adjusting the water level, revegetation or replanting cover crops can also help to maintain soil moisture. This aims to maintain the condition of the peat water content at always above the critical point to prevent further damage to peat properties, such as irreversible drying, land fires, and sufficient water for plants to be cultivated (plant rehabilitation).

Study of [2] revealed that the lower groundwater level causes oxidation of the peat layer above the groundwater level during dry periods, resulting in subsidence. During the dry season in Central Kalimantan, the water table can fall to more than one meter below the peatland surface, even in undisturbed natural forests. Meanwhile, in drained peatlands, subsidence increases markedly with declining groundwater levels. The subsidence rate is linearly related to the depth of the groundwater level, i.e. subsidence rate (cm per year) = 0.1 x depth of the water table (cm). In addition, it was reported that fire risk increases if the groundwater level falls below 0.40 m.

Indonesian government [3] stipulates that a Peat Ecosystems with cultivation functions are damaged if they meet the following criteria:

a. the groundwater level on peatland is more than 0.4 meters below the peat surface at the point of compliance; and/or
b. exposure of pyrite and/or quartz sediments under peat layers.

The purpose of this study is to apply ground water numerical modeling to predict the effect of the application of open canals (business as usual), the application of restoration using canal blocking water construction technology, canal backfilling and the effect of the application of a combination of canal backfilling technology with revegetation on the water level of the peat dome. The application of those restoration methods are designed to maintain or increase the groundwater level on peat land in order to be less than 0.4 meters below the peat surface at the point of compliance.

To analyze the water balance in tropical peat swamps, a method based on a groundwater-balance approach was developed. Two groundwater modelling packages, MODFLOW and SIMGRO, were used to quantify the groundwater recharge by assessing the water balance in three peat swamps in Indonesia and Malaysia [4]. In addition, the research aimed to develop the management operation of water management in tertiary block of oil palm plantation was conducted in peatlands with the maturity of hemic until sapric levels in South Sumatra. A Drainmod model was applied in the research designed to predict the dynamics of ground water daily for a year [5].

2. Materials and methods

2.1. Research location

The peat dome point chosen in this research is located in Garung Village, Jabiren Raya District, Pulang Pisau Regency, Central Kalimantan Province. It is located at 114°6'6.99" - 114°20’01.08” East Longitude and 2°34’51.82” - 2°40’42.84’ South Latitude. The research location is presented in figure 1.
Figure 1. The research location in Garung Village.

2.2. Materials
The tools and materials used in this research include measuring groundwater level and canal water level, Excel software, ArcGIS software, and QGIS-FREEWAT software.

2.3. Data collection
This study used several data and information, such as 1) The latest detailed data of Peat Hydrological Unit (Kesatuan Hidrologis Gambut/KHG) S. Kahayan – S. Sebangau Block C, 2) Latest hydrometeorological and climatological data at KHG S. Kahayan – S. Sebangau Block C (rainfall, evapotranspiration, temperature, and humidity), 3) Latest data and information related to water infrastructure and water management, such as canals, canal blocking, embankment canals, and other types of restoration in KHG S. Kahayan – S. Sebangau Block C, 4) Data and information on the type and number of businesses/activities and settlements around KHG S. Kahayan – S. Sebangau, 5) Data on water demand per type of
business/activity and settlement around KHG S. Kahayan – S. Sebangau  6) The latest map (shp file) at KHG S. Kahayan – S. Sebangau Block C, 7) Related Research reports include
   a. Calculation of water balance in KHG S. Kahayan – S. Sebangau Block C [6];
   b. Modeling the water balance and groundwater level in the Pulang Pisau Peat Hydrological Unit Peat Hydrological Units, Sub KHG 3 and 4 Central Kalimantan [6];
   c. Measuring the effectiveness of canal blocking using modeling [7];
   d. Final Report (unpublished). Study on the Effectiveness of Canal Blocking and Filling in Peat Hydrology Recovery [8].

2.4. Method

The methods and scope of work in this study can be described as follows: 1) Conduct field verification and collect data and field information, 2) Perform water balance calculations and analysis, 3) Perform groundwater flow modeling applying QGIS-Freewat software, 4) Conduct validation process using measured and secondary data, 5) Perform simulation the effect of various restoration methods and water and land management on the groundwater level of peat, 7) analysis the result of four simulation scenarios.

In this study, the groundwater flow modeling of freewat (free and open-source tools for water resource management) is applied. Freewat is a horizon 2020 project financed by the EU Commission under the call water innovation [9]. Freewat main result is an open-source, and public domain GIS integrated modeling environment that is capable of simulating water quantity and quality in surface water and groundwater with an integrated water management and planning module. Freewat is designed as a composite plugin for the well-known GIS (http://qgis.org) open-source desktop software QGIS.

The main component of Freewat includes a reliable and robust modeling tools for performing groundwater flow and related processes. The hydrological model implemented in Freewat allows simulating the entire hydrological cycle provided that climate data are available. However, it is also able to concentrates only on selected parts of the model. According to [10], the simulated processes that can be conducted by Freewat plugin are as follows:
   a. groundwater flow in the saturated zone, including interaction with surface water bodies (e.g., rivers, lakes, drains);
   b. vertical flow through the unsaturated zone and beneath surface water streams;
   c. 3D vertically integrated variable-density groundwater flow and seawater intrusion

The stages of modeling the peat groundwater level in Garung Village include 1) conceptual model, 2) model design, 3) simulation, 4) validation, 5) analysis. The modeled location is peatland with an area of 320 x 650 m, bordered by canals on the west and north, while on the east and south, it is bordered by peatlands. The modeled aquifer layer is only one layer with a soil surface texture dominated by loamy sand. The average water level in the modeled location is 2.3 m above mean sea level. Meanwhile, the length of the modeled canal is 620 m, with an average canal water level of 1 m above mean sea level. The conceptual model used in the modeling of the peat groundwater level in Garung Village is shown in figure 2, while the model design can be seen in table 1.
Figure 2. Conceptual model of peat groundwater level in Garung Village.

Table 1. Model design of peat groundwater level in Garung Village.

| No. | Model Parameters                              | Score            | Description          |
|-----|-----------------------------------------------|------------------|----------------------|
| 1   | Evapotranspiration                            | 0.003341 m/hr    | Pangau, 2019         |
| 2   | Recharge                                      | 0.055 m/hr       | Pangau, 2019         |
| 3   | Hydraulic conductivity (Kx=Ky)                | 25 m/hr          | Pangau, 2019         |
| 4   | Aquifer Thickness                             | 3 m              | Field measurement    |
| 5   | Groundwater level of peatland                 | 2.3 m            | Field measurement    |
| 6   | Peatland surface elevation                    | 3 m              | DEM                  |
| 7   | Constant Boundary Head                        | 1.8 m            | Field measurement    |
| 8   | Canal water level                             | 1 m              | Field measurement    |
| 9   | Hydraulic conductivity of canal base layer    | 0.08 m/hr        | Field measurement    |
| 10  | Thickness of canal base layer                 | 0.1 m/hr         | Field measurement    |
| 11  | Canal average width                           | 20 m             | Field measurement    |

The groundwater flow modeling in this study was validated by data on groundwater level and canal water level measurements in November 2020, which was the rainy season. Based on the water balance analysis in the Peat Hydrological Unit Block C, Pulang Pisau Regency, there are five months that experienced a water deficit, namely June, July, August, September, and October [6]. Therefore, it is necessary to watch out for a decrease in the groundwater level, triggering peatland fires during these five months. However, since the study field measurement was done only in November 2020, this model has not been validated using groundwater level and canal level data in five months during the dry season.

Perform simulation of the effect of various restoration methods and water and land management on the groundwater level of peat by applying the following four scenarios:

a. Simulation of the first scenario was carried out to show the effect of open canals on the groundwater level of the surrounding peat.
b. The second scenario was carried out to predict the effect of canal blocking on the groundwater level of the surrounding peat. In addition, it can be simulated how far the impact of canal blocking on peatlands is.

c. The third scenario was carried out to simulate the effect of canal backfilling on the groundwater level of the surrounding peat.

d. The fourth scenario was carried out to predict the combined effect of canal backfilling with certain tree planting ( revegetation) on groundwater level and peatland water balance so that it can be used to estimate the effectiveness of planting certain trees in maintaining and increasing water availability in peatlands.

3. Results and discussion

Peatland restoration that aims to restore the function of peatlands can be carried out in an integrated manner using a combination of various approaches and technologies and taking into account technical, social, and economic aspects. In this case, the groundwater flow modeling helps measure the effectiveness and efficiency of applying various types of restoration techniques, primarily when used at the planning and evaluation stages.

The use of groundwater flow modeling at the planning stage can be done by simulating and predicting the effects of various restoration techniques that are planned to be applied to increase the groundwater level of peatlands, making it easier to choose the most effective restoration technique.

The first scenario simulation was carried out to show the effect of unblocking canal method (open canal) on the groundwater level of the surrounding peat. This scenario represents water management that is generally carried out on cultivated peatlands. The simulation result of scenario 1 shows that the depth of the groundwater table in the peatlands in the modeled locations has completely passed the standard criteria for peatland damage, which is 40 cm. At the model located in the center, the maximum groundwater level or closest to the ground surface is found, which is 43 cm deep, and the closer to the edge, the groundwater table gets deeper until it reaches 193 cm, while the average groundwater level is 109 cm.

The second scenario was carried out to predict the effect of the canal blocking method on the surrounding peatland groundwater level. The simulation result of scenario 2 shows that the application of canal blocking technology with a spillway height of 50 cm affects increasing the average height of the peat groundwater level. The groundwater level closest to the ground level is 28 cm, located in the center of the modeled area, and the deepest is 143 cm at the edge of the modeled area, while the average depth is 83 cm. Thus, the average is still higher than the standard criteria for peatland damage of 40 cm. The modeling result also shows that the peatland area with a groundwater table depth of less than 40 cm is 0.77 ha or 3.73% of the modeled area.

The third scenario was carried out to simulate the effect of canal backfilling on the surrounding peat ground water level. The simulation result of scenario 3 shows that the canal backfilling with 250 m has a very significant effect on increasing the average height of the peat groundwater level. The canal backfilling causes the groundwater level closest to the ground level to be 41 cm, which is located in the area closest to the canal backfilling, while the deepest is about 194 cm at the furthest part from the canal filling location, while the average depth is 92 cm. Since the backfilled canal only covers a length of 250 cm, the affected area is only close to the backfilled canal.

The fourth scenario of groundwater level modeling was carried out to predict the combined effect of the application of restoration with canal backfilling methods and certain tree planting ( revegetation) on the groundwater level and peatland water balance. This scenario is also designed to estimate the effectiveness of the combination of water management and land management. This model assumes that planting Shorea
belangeran and rubber trees can increase percolation by 15% and reduce evapotranspiration by 10% compared to before tree planting.

The simulation result of scenario four indicates that the combination of backfilling a 250 m long canal and planting trees has a significant effect on increasing the average water level of the peat soil. The canal backfilling causes the maximum groundwater level to be 32 cm which is located in the area closest to the canal backfilling, while the deepest is about 193 cm at the furthest part of the canal backfilling location, while the average depth is 85 cm. Since the backfilled canal only covers 250 cm, the affected area is only close to the backfilled canal. However, land that meets the standard criteria for damage (groundwater depth is less than 40 cm) is relatively wider than canal blocking and canal backfilling methods, which is 1.83 ha or 8.88% of the modeled area.

The comparison of the restoration effect on the peatland groundwater level in the modeled location and the comparison of the effectiveness of the restoration method applied can be predicted by comparing the modeling results of the four simulation scenarios.

Comparison of groundwater level and the effectiveness of peatland restoration methods include:

a. Comparison of the groundwater level of the canal with blocking and the groundwater level of the unblocking canal (open canal);

b. Comparison of groundwater level of canal backfilling and groundwater level of unblocking canal (open canal) technique;

c. Comparison of groundwater level with restoration methods that combine canal backfilling and revegetation techniques with groundwater level as a result of unblocking canal (open canal);

d. Comparison of the effectiveness of restoration that combines canal backfilling and revegetation techniques with the effectiveness of canal blocking techniques;

e. Comparison of the effectiveness of restorations that combine canal backfilling and revegetation techniques with the effectiveness of canal backfilling only.

![Figure 3](image_url)

Figure 3. The difference between the groundwater level of the blocked channel method and the groundwater level of the unblocked channel method.
Figure 3 shows the difference between the simulated groundwater level of the blocked canal and the unblocked canal, which means that the canal blocking restoration method affects the increase in groundwater level in the entire modeled area. A maximum groundwater level difference of 50 cm was found in the center of the modeled region. This also shows that the canal blocking technique using a 50 cm high spillway is technically effective for increasing groundwater levels in all modeled areas.

Figure 4. The difference between the groundwater level of the canal filling method and the groundwater level of the unblocked canal method.

Meanwhile, the comparison of the groundwater level of the canal backfilling method and the groundwater level of the unblocked canal method shown in figure 4 indicates that the maximum height difference between groundwater level after canal backfilling and groundwater level before filling (open canal) is very significant, namely 112 cm. This can be seen in peatlands which are located very close to the canal backfilling. However, the further away from the filled canal, the smaller the effect, therefore enhancing its impact on the groundwater level in the entire modeled area. It is necessary to extend the length of the filled canal.
Figure 5. The difference between groundwater level caused by a combined method of canal backfilling and revegetation with groundwater level method of the unblocked canal (open canal).

The comparison of the effectiveness of using the method of combined canal backfilling and revegetation with the method of the unblocking canal can be shown from the difference in groundwater level from the simulation results of the two conditions. Based on figure 5, it can be predicted that the maximum groundwater level that can be increased through the combined method of restoration of canal backfilling and revegetation is 121 cm, a number that is quite significant and the highest compared to the canal blocking method and the canal backfilling method only.

Figure 6. The difference between the groundwater level of the canal backfilling method and the groundwater level of the canal blocking method.
The comparison of the effectiveness of the canal backfilling with the canal blocking method is shown in figure 6, which is the difference in groundwater level from scenario three simulation results with scenario two simulation results. The positive groundwater level difference means that the canal backfilling method has a higher effect than the canal blocking method. If the value is negative, it means the opposite, the canal blocking restoration method has a higher effect than the canal backfilling restoration method.

The groundwater level difference is relatively high, and a positive value is found in the area near the location of the backfilled canal with a maximum groundwater level difference of 69.5 cm. However, the negative difference is also found in areas far from the canal backfilling location, which means that the canal blocking method has a higher effect on groundwater levels in that area. This shows that the canal backfilling method is very effective and significantly affects increasing groundwater level around the canal backfilling location, but the further away from the canal backfilling location, the smaller the effect. Meanwhile, the canal blocking method has an even impact throughout the modeled area, although the effect is relatively not too high.

![Groundwater level difference](image)

*Figure 7. The difference between the groundwater level of the combined canal backfilling and revegetation method and the groundwater level of the canal blocking method.*

Furthermore, the comparison of the effectiveness of the combined canal backfilling and revegetation method and the canal blocking method can be seen in figure 7, which is the difference in groundwater level from scenario four simulation results with scenario two simulation results. The difference with a positive value means that the combination method of canal backfilling and revegetation has a higher effect than the canal blocking method. If the value is negative, it means the opposite, the canal blocking method has a higher effect than the combined canal backfilling and revegetation method.

The difference in groundwater level is relatively high, and a positive value is found in the area near the location of the filled canal with a maximum difference of 77.7 cm. In addition, the positive groundwater level difference extends to almost all modeled areas. Although, it is found that a small number of areas have a negative groundwater level difference, which means that in this area, the canal blocking method has a
higher effect on groundwater level. This shows that the combined method of canal backfilling and revegetation is very effective and significantly affects increasing groundwater levels in almost all modeled areas, especially around the embankment canal.

Figure 8. The difference between groundwater level applying combination method of canal backfilling and revegetation with groundwater level of canal backfilling method.

The results of the last modeling are the comparison of the effectiveness of the combined method of backfilling canals and revegetation and the effectiveness of the method of backfilling canals only, which is shown in figure 8, which is obtained from the difference in groundwater level from scenario four simulation results with scenario three simulation results. The maximum groundwater level difference of 11.3 cm is found in the affected areas close to the canal backfilling location. The average difference is 8 cm, and there is no negative value in the entire modeled area showing that the combined canal backfilling and revegetation method is more effective than applying the solely canal backfilling method as well as when it is compared to the canal blocking method.

The comparison of the effects of the four restoration methods on the groundwater level of peatlands in the modeled locations and the comparison of the effectiveness of the applied restoration methods can be considered well predicted by groundwater flow modeling using four scenarios. A clearer comparison of effectiveness is seen by identifying groundwater levels at transect points, as shown in figure 9. Based on figure 9, it can be indicated that the combination of canal backfilling and revegetation method is the most effective, followed by the canal backfilling method and canal blocking method. While the canal unblocking (open canal) method is proven as the least effective one. However, each of these methods has advantages and disadvantages.

It can be noted that the linear relation between the subsidence rate and the groundwater level depth cannot be made since the groundwater level data throughout the year is not yet collected.
4. Conclusion

The analysis of the water balance in KHG Sebungan-Kahayan Block C, Pulang Pisau Regency, revealed that there are five months that experienced a water deficit, namely June, July, August, September, and October. Thus, it is necessary to watch out for a decrease in the groundwater level in these five months, which can trigger peatland fires, subsidence, and irreversible drying. The groundwater flow modeling in this study was validated by data on groundwater level and canal water level measurements in November 2020, which was the rainy season. Note that this model has not been validated using groundwater level and canal level data at five months during the dry season. However, the model used in this study is expected to provide benefits for predicting and evaluating the effects of applying various restoration methods and techniques on the groundwater level in peatlands.

It can be indicated that the combination of canal backfilling and revegetation method is the most effective in increasing the groundwater level in the modeled area, followed by the canal backfilling method and canal blocking method. While the canal unblocking (open canal) method is proven as the least effective one. However, each of these methods has advantages and disadvantages.

The use of groundwater flow models such as that used in this study at the planning stage is designed to select the most effective restoration methods and techniques. Meanwhile, at the evaluation stage, groundwater flow models are intended to measure the effectiveness of restoration methods and techniques and optimize restoration techniques.
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