Relation of groundwater level and rainfalls in the peat swamp forest, burned peatland and mixed plantation areas of Kampar Peninsula, Riau Province

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Abstract. Peatland forest in the Kampar peninsula have converted into various land uses, mainly converted to palm oil plantation. The massive conversion has decreased biodiversity, changed the hydrological cycle, and increased the peatland fire that dramatically decreased the quality of the peatland ecosystem. It is essential to understand the peatland characteristics and its hydrological cycle to develop sustainable peatland management. This study aimed to determine the characteristics of peat soil and the response of groundwater level to rainfall on burned peatland, mixed plantation and primary peat swamp forests in Siak district. The study was conducted from July to December 2018 by using a hydrometeorological station equipped with rainfall and groundwater level sensors. Disturbed and undisturbed soil samples were analyzed to identify the soil characteristics. The response of groundwater level to rainfall was analyzed using simple regression. The results showed that the burned peatland and mixed plantation have increased bulk density, decreased soil porosity, and caused a decrease of water infiltration. Simple regression analysis between the rainfall and the increase of GWL on the primary peat swamp forest resulted in $0.941(P)^{0.5106}$ and an $R^2$ value 0.6189, meanwhile on the burned peatland resulted in $1.2127(P)^{0.7818}$ and an $R^2$ value 0.8616, and on the mixed resulted 0.7455 in $(P)^{0.7831}$ and an $R^2 = 0.7557$.

1. Introduction
Indonesia has the largest peatland in the Southeast Asia region [1], which is 14.9 million hectares, distributed over 6.4 million ha (43%) in Sumatra, 4.8 million ha (32%) in Kalimantan and 3.7 million ha in Papua [2]. Riau Province has the largest peatland in Sumatra, which is 3.89 million ha [3], and Siak Regency contributes 461,527 ha [4]. Nearly 50% of peatland in Indonesia belongs to a deep peat category that has a peat thickness of >200 cm [5].

Peatlands are ecosystems that have high conservation value and play essential roles in environmental function and biodiversity conservation. Peatlands have various kinds of potential such as the ability to store water and carbon [6], have high biodiversity [7, 8], and can be utilized as areas of oil palm and acacia plantations [9, 10]. Therefore, peatlands have important values both in terms of ecological and economic functions that cause multi-interests on the land. However, tropical peatlands currently remain a relatively neglected ecosystem with low conservation priority in terms of their intrinsic biodiversity value [11].
Peatlands utilized for large-scale economic interests in the last two decades [12], whether at national, regional, and global levels. The use of peatland is in line with the conversion of natural forest land to non-forest. Forests in peat areas in Southeast Asia are reported to have decreased by 31,000 km² of the total forest cover in two decades and predicted to be depleted by 2030 [13]. Within these two decades, there has been an increase in oil palm plantation production in Sumatra and Kalimantan, which occupies 3 million ha of peatland [9]. As a detail, the use of peatland in Siak has reached 147,511 ha, consisting of plantations (158,190 ha) and plantation forest (89,321 ha) [14].

Natural factors and human factors can cause damage that occurs in peatland ecosystems. Natural factors are more influenced by climate, while human factors are more influenced by human activities. Some human activities referred to for example land conversion, peat extraction, infrastructure developments, forest fire, vegetation clearance, utilization of natural resources, peatland canaling, and control of uninhabited land [15, 16]. Land use changes to oil palm and community mixed plantations and the treatment of peatland such as canaling, have damaged peatlands such as changes in land and hydrological characteristics and decreased ecological functions [17]. In some development locations, drainage was dug too deep (> 1.5 meters) regardless peat thickness and depth of the pyrite layer. Drainage will accelerate the subsidence of soil and increased soil and water acidity [10, 18], which may contribute to peatland fires in the dry season and cause various kinds of losses [19, 20]. The most burned land from 2007 to 2014 occurred in Riau Province [21].

If peatlands used as agricultural or plantations, improved water management could contribute to a significantly reduced risk of fire [22]. This approach can be achieved using scientific peat information, which ultimately serves as the implementation of policies and guidelines for peatlands uses in Kampar Peninsula. Thus, the design of conservation-based peatland management will benefit the community and the environment. Based on the above explanation, research is needed to determine the characteristics of peatland in various land conditions, namely primary peat swamp forest, burned peatlands, and community mixed plantation, as well as to learn the dynamics of peat groundwater level in Kampar Peninsula, Riau, Indonesia.

2. Methodology
2.1. Study sites
The research was conducted in three locations, namely the primary peat swamp forest of Zamrud National Park (0° 42'54" S; 102° 13'35" E), burned peatland area (0° 52'16" S; 102° 20'22" E), and community mixed plantation (0° 52'35" S; 102° 20'41" E) in Sungai Rawa Village, Sungai Apit Sub-District, Siak Regency, Riau (Figure 1). The research was conducted from July to December 2018 for the installation and data downloads of instruments such as rain gauge sensors and mini data loggers, as well as vegetation and soil characteristics data collection at the research sites. The vegetation and soil characteristics data brought over to laboratory for analysis. There are canals with different distances, sizes and depth at each research location. In the primary peat swamp forest, the distance of the nearest canal was 250 m with a width of 6 meters and a depth of 2 meters. In contrast, in the burned peatland, the distance of the closest canal was 50 meters with a width less than 1 meter and a depth less than 1 meter. In mixed plantation, the distance of the closest canal was 45 meters with a width of 1 meter and depth of 1.5 meters.
2.2. Data collection
The soil sample was collected using the disturbed and undisturbed method. The disturbed soil sample was collected to obtain data in the form of soil color and soil maturity level, then was analyzed using the van post squeeze method [23] with as many as three repetitions for each sample. Items collected from each repetition ranging from the topsoil and a depth of 20 cm, 40 cm, and 60 cm. The undisturbed soil sample data was collected using ring and square sample tools.

The soil samples obtained then were analyzed to acquire the values of water content, porosity, and bulk density. The undisturbed soil sample also consisted of 3 repetitions, with the depth starting from the topsoil, 20 cm, 40 cm, and 60 cm. Soil samples analyzed in the laboratory. During the field investigation, peat thickness measured by peat drill, pyrite content by a fast reaction in the form of froth by using 30% hydrogen solution (H\textsubscript{2}S\textsubscript{2}), and also analyzing the soil pH by pH stick. In testing soil samples using the quick probe, three repetitions were also performed with the depth starting from the topsoil and a depth of 20 cm, 40 cm, and 60 cm.

Vegetation profile of poles and trees measured in the plot of 25 m x 80 m. In each corner and center of the profile placed a nested sample plot to observe seedling density, with a plot size of 2 m x 2 m and 5 m x 5 m for sapling observation. Each profile diagram consists of 5 plots. Data collected were tree height, branch-free stem height, canopy width for each of the four cardinal directions, stem diameter, species, and the number of individuals. Vegetation data from all growth rates was used to calculate vegetation density. Meanwhile, canopy width and treewidth data were used to estimate the canopy cover area.
Figure 2. Design of vegetation and soil data plots.

The data of peat groundwater level (GWL) dynamics and rainfall obtained from automatic water level recorder and automatic rainfall recorder installed for six months. Downloaded data then subsequently processed to separate in each rainfall event, so the dynamics of the groundwater level can be observed. The calibration of the peat groundwater level was also carried out manually to match the data between the recorded data with the actual field measurement to increase the accuracy in the analysis. The selected rainfall data then was analyzed using statistical regression approach to find out the relationship between rainfall and groundwater level dynamics. The regression equation results presented in the graph showing the relationship between rainfall and groundwater level for each location.

2.3. Data analysis
The vegetation density data processed using Sexl FS software. The results were presented in vertical and horizontal structures of the plots.

Data of GWL obtained separately in each rainfall event. The increased GWL was calculated by the maximum GWL minus the initial GWL. The maximum GWL was influenced by rainfall, while the initial GWL measured before the rainfall. The series data on increasing GWL paired with rainfall to describe the impact of rainfall event on the increase of peat groundwater level in each location. Other factors affecting GWL are canals, soil characteristics, and vegetation cover.

3. Result and Discussion
3.1. Characteristic of peat soil
Tropical peat soils have unique and specific characteristics compared to mineral soils, both physically and chemically. Specific characteristics of peat soil that are different from the general mineral soil, among others: easily experiencing irreversible drying, subsidence, low land bearing capacity, low nutrient content and a limited number of microorganisms [24].

The research sites of primary peat swamp forest and burned peatland both have peat soil thickness up to > 3 meters (m), whereas, in the mixed plantation location, the depth was only up to 8 meters, based on the peat drill. The peat soil maturity level at the burned peatland and mixed plantation site was hemic maturity level starting from the topsoil layer up to the depth of 20 cm. At the same time, at the location of the natural peat swamp forest, the topsoil layer up to the depth of 20 cm and 40 cm had a fibric maturity level, while at a depth of 60 cm had a sapric maturity level. It can be due to the fibric layer in the upper layer that has been lost as form crushed soil particles or fine ash. The crushed soil particles or fine ash might be carried away by wind and water to fill soil pores [25, 26] at the burning process and the land management process for agricultural and plantation activities. According to [27],
if peat swamp forest burned, then not only the plant biomass burned, but a few centimeters of the upper layer dry peat will also be burned and will be released into carbon into the air and will damage the topsoil layer. Besides, when the groundwater level deeper than 1 m, underground fires may reach up to 0.5-1.0 m below the peat surface [17].

In the primary peat swamp forest, the color of topsoil layer was dominated by the 10R ¾ (Dusky Red) soil color, at a depth of 20 cm the color is 10R 2.5/2 (Very Dusky Red) and at a depth of 40 cm the color is 2.5R 3/2 (Dusky Red). At the burned peatland location, the topsoil layer was dominated by the 5 YR 2.5/1 (Black) color, and at a depth of 20 cm, the color was 5 YR 3/2 (Dark Reddish Brown). These results indicated that the upper layer was darker from burned land. The soil color analysis showed the same results both in mixed plantation and burned peatland sites. The topsoil layer was 5 YR 2.5/1 (Black) color, and at the 20 cm layer was 5 YR 2.5/2 (Dark Reddish Brown) color. This result was the same as the color of the burned land because mixed plantation also has burned. According to [28], the upper layer is darker than the bottom layer because of the impact of land burning.

The next peat soil characteristic is pyrite content. In the burned peatland and mixed plantation locations, the pyrite content was not found at the topsoil layer up to 20 cm deep. In the primary peat swamp forest location, pyrite content was not found from the topsoil layer up to 60 cm deep. In the burned peatland and mixed plantation locations, pyrite measured up to a depth of 20 cm because of low GWL in the rainy season. Soil with high pyrite content and potential sulfate soil is potentially more acidic if exacerbated with the deep drainage and extreme dry season conditions, and vice versa [29]. The increase of soil acidity will be stopped with an increase in groundwater level [29]. For this reason, it is crucial to keep the peat wet, so that plants can develop well on peatlands.

Another characteristic of peatlands is a very high acidity level. According to [30], the level of peat acidity has a close relationship with the content of organic acids. Based on the research finding in the burned peatland and mixed plantation locations, a pH of 4 starting from the topsoil layer up to the depth of 60 cm. This is the opposite to the primary peat swamp forest location that shows higher acidity result: pH of 2.7 at peat depth of 20 cm, pH of 3.3 at peat depth of 40 cm and 60 cm. Fire and land management in plantations may increase pH value to be more alkaline, while the acidity of peat soil in primary peat-swamp forests tends to decrease along with the depth of peat. It is similar to [31] because the upper layer of shallow peat tends to have a higher pH than thick peat.

One of the distinctive peatland characteristics is its different abilities to absorb and store water at different peat depth. In the primary peat swamp forest location, at a depth of 20 cm, it has an average water content of around 627.85 to 766.92%. At a depth of 40 cm, it is around 823.15 to 845.86 %. This result is different from the 20 cm deep at burned peatland fire, where the average water content is lower, which is around 312.89 % to 461.11%. In mixed plantation location at a depth of 20 cm, it has an average water content value of approximately 183.14% to 471.55%. According to [28], the maximum water-binding capacity for fibric peat is 580-3,000%, for hemic peat is 450-850%, and for capric peat is <450%. According to [32], the ability to absorb and retain water from peat depends on the level of maturity. However, according to [33] statement, the availability of groundwater is not only based on its maturity. However, it is also influenced by rainfall, the ability of the soil to retain water, evapotranspiration, and groundwater level. Water content is also influenced by bulk density because the soil will hold less water [34]. The bulk density (BD) in burned peatland and the mixed plantation are higher than in the primary peat swamp forests. The distance of canals in the forest is farther than in the burned peatland, and mixed plantation affects the water content value of each study location. According to [34], the farther the distance from the canal, the lower BD value is directly related to the increasing peat maturity due to the decomposition of organic matter. It becomes a reason why the ability of peat soils to absorb and bind water to fibric peat is higher than the hemic and capric peat, whereas hemic peat is higher than capric [35].

[36] stated that porosity positively correlated with the depth or the maturity level of peat. The thicker the peat, the less mature the peat is. The less mature the peat, the higher the porosity value, and therefore the higher the ability to hold the water. In the primary peat swamp forest, the porosity value
at a depth of 20 cm and 40 cm has an average value of 89.43% - 91.53% and 91.06% - 91.13%, respectively. The burned peatland fire location at a depth of 20 cm has a lower porosity value, which is around 84.51% - 85.22%. In a mixed plantation location, the porosity value was higher than the burned peatland fire locations, which is the average value of around 85.31% - 86.55% at the same depth of 20 cm. According to [3], the porosity value of the degraded peatland is 72.21% - 84.39%, while the porosity value of non-degraded peatland is 87.19% - 96.38%. By referring to those criteria, our result in two locations of burned peatland and mixed plantations were classified as degraded land, while primary peat swamp forests were not degraded. It has occurred due to the process of land burning and land processing for agroforestry that resulted in the percentage decrease of soil pore-space and increase the bulk density [25, 26], which ultimately decreased the soil porosity.

Another characteristic related to water content and porosity is the bulk density (BD). [37] stated that the weight content of peat in Indonesia, which is between 0.07 to 0.27 g cm$^{-3}$, is shallow compared to mineral soils, ranging from 1.2 to 1.8 g cm$^{-3}$. In primary peat swamp forest, BD values at a depth of 20 cm and 40 cm were ranging between 0.10-0.13 g cm$^{-3}$ and 0.10-0.11 g cm$^{-3}$, respectively. The average BD in burned peatland fire was ranging between 0.17-0.19 g cm$^{-3}$, and in the mixed plantation was ranging between 0.17-0.20 g/cm$^3$. BDs of burned peatland and mixed plantation were higher than that of primary peat swamp forests at a depth of 20 cm. It is because soil compaction or soil enhancement can occur as a result of land burning processes and as a result of human activities in converting peatland into plantation areas. This is in line with [37] statement, that the activities of drying and fire events can increase the weight of peat soil contents. Besides, the distance of the canal also causes an increase in BD. The finding is following [38] statement that peat soil near-to-canals increased the bulk density of peat in the upper layer. It is caused by groundwater level drawdown exacerbating drainage-related processes such as peat shrinkage, compaction, and biological oxidation, as well as vegetation change and fire occurrence.

### 3.2. Vegetation in the research location

The permanent sample plot (PSP) of the primary peat swamp forest is composed of natural vegetation because the location is situated in a national park area. The vegetation structure of the primary peat swamp forest was analyzed using SexiFS software (Figure 3).

![Figure 3](image_url)

**Figure 3.** Profile diagram of primary peat swamp forest, vertical (a) and horizontal (b).

In terms of species number in the PSP, there were about two species of woody plants with the largest stem diameter of about 58 cm - 80 cm. These plants species were *Shorea uliginosa* dan *Goniothalamus* sp. However, most plants in the PSP were dominated by *Shorea uliginosa* and *Ganua motleyana*. The density values for each growth level are presented in Table 1.
Table 1. Vegetation density based on growth level in the primary peat swamp forest.

| Growth Level | Density (Individu 2,000 m\(^2\)-1) | Density (Individu ha\(^{-1}\)) |
|--------------|----------------------------------|-------------------------------|
| Seedling     | 4,300                            | 21,500                        |
| Sapling      | 1,296                            | 6,480                         |
| Pole         | 53                               | 265                           |
| Tree         | 39                               | 195                           |

The results indicated that the density of the seedling growth level reached 21,500 individual/ha. This indicates that plant regeneration was excellent, and the environmental condition allowed the seeds to germinate and grow well into seedlings. The sapling growth level was around 6,480 individual/ha, then the pole growth level was about 265 individual ha\(^{-1}\). Meanwhile, the tree growth level was about 195 individual ha\(^{-1}\). In the PSP of burned peatland, most vegetation was lost due to wildfire, so there was only a small amount of vegetation that survived in the research location. The profile diagram in the PSP is presented in Figure 4. Only three individual trees and one individual pole were found in the burned peatland.

Figure 4. Profile diagram of burned peatland, vertical (a) and horizontal (b).

Consequently, in hectares, the number of trees is only 15 individual ha\(^{-1}\) while the number of the pole is only 5 individual ha\(^{-1}\). The species occurred in the location was *Acacia crassicarpa* and *Elaeis guineensis*. The density values for each growth level are presented in Table 2.

Table 2. Vegetation density based on growth level in the burned peatland fire.

| Growth Level | Density (Individu 2000 m\(^2\)-1) | Density (Individu ha\(^{-1}\)) |
|--------------|----------------------------------|-------------------------------|
| Seedlings    | 0                                | 0                             |
| Saplings     | 0                                | 0                             |
| Poles        | 1                                | 5                             |
| Trees        | 3                                | 15                            |

In the PSP of the mixed plantation, the vegetation composition is designed by the community based on their purposes need. The vegetation consisted of *Hevea brasiliensis* (18 trees), *Syzygium* sp. (5 trees) and *Elaeis guineensis* (78 trees). The profile diagram in the PSP is presented below (Figure 5).
Figure 5. Profile diagram of the mixed plantation, vertical (a) and horizontal (b).

The measurement result in the field shows the density value at each growth level and the type. These values are presented in Table 3.

| Growth Level | Density (Individu $2000 \text{ m}^{-2}$) | Density (Individu ha$^{-1}$) |
|--------------|--------------------------------------|-----------------------------|
| Seedlings    | 800                                  | 4,000                       |
| Saplings     | 16                                   | 80                          |
| Poles        | 5                                    | 25                          |
| Trees        | 18                                   | 90                          |

3.3. The dynamics of peat groundwater level

In this research, rainfall data was used as the independent variable, which was analyzed concerning the response of peat groundwater level (GWL) and the increase as the dependent variable. Rainfall events were selected manually with Power Regression analysis. This was intended to ensure that the increase in GWL was only affected by the presence of rain. Based on the selected data during the observation, the primary peat swamp forest as the research location (see Table A1 in Appendix A) has a total of 52 rainfall events with manual selection.

The primary peat swamp forest showed that the highest rainfall data was only 96 mm, which had raised the groundwater level by 22.9 cm while the lowest rainfall was 1 mm that occurred mostly in primary peat swamp forests. The lowest rainfall, which was 1 mm, had caused the GWL to increase by 0.7 cm to 2 cm. The increase in GWL could be influenced by several factors, including the distance of the canal and vegetation cover. According to [34], the farther the canal and the vegetation cover, the greater the porosity and the smaller the BD. However, the shallower the groundwater level, the slower the decomposition and the higher the soil moisture. Even a small amount of rainfall can increase the GWL in the primary peat swamp forest.

The primary peat swamp forest location is included in the light to heavy daily rainfall intensity category. Table 4 showed that high rainfall did not always raise the GWL to reach the ground surface. For example, the rainfall of 28.9 mm was categorized as medium rainfall intensity. It could increase the peat GWL up to 5.6 cm, but the peat GWL was still on 5.7 cm below the ground surface, which means that it has not been able to raise the GWL high enough to cause flooding. The result might be influenced by evapotranspiration, rainfall and BD [33]. The groundwater can be reduced, and the presence of heavy rain does not always increase GWL.

In contrast, in the rainfall event to 37 with 1 mm, it was only able to raise the peat groundwater level by 0.7 cm. However, the peat GWL could reach the height of 26.1 cm above the ground surface, which means that there was an abundance of water over the surface, or it can be interpreted that the primary peat swamp forest experienced 26.1 cm of water flooding. These results showed that peat soils far from the canal have high soil moisture, and wetting occurs in all soil layers [34] so that it might affect the increase in GWL with light rainfall.
The research location in the primer peat swamp forest with original vegetation cover at a particular time (Table 4) was experiencing flooded. This is supported by [39] stated in peat swamp forest areas that are still intact and has its original vegetation cover (so-called pristine forest), surface inundation or flood in center of peat dome and the edge of the dome is common.

Figure 6. Graphic of the peat GWL response to rainfall in the primary peat swamp forest.

Simple regression analysis between the rain thickness and the increase of water table level in the primary peat swamp forest location resulted in $0.941(P^{0.5106})$ and an $R^2$ value of 0.6189 (Figure 6). This means that rainfall has a powerful impact on the increase of GWL. The rainfall impact on the peat GWL response was 61.89 %, while other variables or factors influenced the rest.

Based on the available data, the research location in the burned peatland has a total of 21 rainfall events with selected manually (see Table B1 in Appendix B). Table B1 showed the highest rainfall reached 82.3 mm, and it was able to increase the GWL by 29.7 cm. However, the lowest rainfall data in the burned peatland fire location was 2 mm that was able to increase the peat GWL by 2 cm to 2.1 cm. The burned peatland fire location is included in the light to heavy daily rainfall intensity category. Looking at the response of the GWL by the rainfall events, there were two rainfall events of 21 rainfall events over six months that can raise the peat GWL to exceed the ground surface, which is interpreted as stagnant or flooded water. The rainfall value that caused flooding occurred in the rainfall of 62 mm with an increase GWL of 51.9 cm and in the rainfall 48.7 with an increase GWL of 42.8 cm reaching 7.8 cm and 1.5 cm above the ground surface, respectively.

Table B1 showed that high rainfall did not always raise the GWL to exceed the ground surface. For example, on the rainfall of 82.3 mm that categorized as high rainfall intensity, it should increase the peat GWL up to 29.7 cm, but the peat GWL was still on 62.1 cm below the ground surface. It means that the rainfall was not able to raise the GWL high enough to cause flooding. These results indicated canalization, reduced canopy cover, and evaporation in burned peatland potentially cause dry peat [40], so high rainfall intensity (82.3 mm) was not able to raise the GWL high enough to cause flooding. However, a lower rainfall intensity of 62 mm was able to increase the peat GWL by 51.9 cm. It has caused flooding as high as 7.8 cm above the ground. These results indicated that land drainage, canalization, and reduced canopy cover in this location have caused peat surface heating, causing organic peat fiber to shrink and BD to increase which resulted in soil compaction [40]. The high rainfall intensity (62.1 mm) has been able to raise the GWL high enough to cause flooding. This is supported by [41] that increased BD may decrease the infiltration capacity and soil porosity as well as increasing surface runoff in peatlands.
Simple regression analysis between the rainfall and the increase of GWL on the burned peatland location resulted in $1.2127(P)^{0.7818}$ and an $R^2$ 0.8616 (Figure 7), which means that the rainfall significantly correlated with GWL. The rainfall impact on the peat GWL response was 86.16%, while other variables or factors influenced the rest.

In the mixed plantation location, there were 45 selected rainfall events (Table C1 in Appendix C) with the highest rainfall of 82.3 mm. It was able to increase the peat GWL by 38.1 cm, while the peat GWL was 79.3 cm below the ground surface. Canalization and the impact of fires in the mixed plantation, as well as gaps in canopy cover, have the potential to cause peat to dry [39], so the high rainfall intensity (82.3 mm) was not able to raise the GWL high enough to cause flooding. In contrast, the lowest rainfall of 1.5 mm was able to increase the peat GWL by 1.4 cm, but the peat GWL could exceed the ground surface of about 33.8 cm. Perhaps, this condition could be caused by soil compaction and high rainfall.

Simple regression analysis between the rainfall and the increase of GWL on the mixed plantation location resulted in $0.7455(P)^{0.7831}$ and an $R^2$ value of 0.7557 (Figure 8), which means that the rainfall has a powerful impact on the GWL increase. The rainfall impact on the peat GWL response was 75.57%, while other variables or factors influenced the rest.

**Figure 7.** Graphic of the peat GWL response to rainfall in the burned peatland.

**Figure 8.** Graphic of the peat GWL response to rainfall in the mixed plantation.
4. Conclusion
Land-use changes and fire on peatland with canalization and reduction of vegetation cover have caused changes in peat soil characteristics. This includes the increase of BD, the decrease of the soil porosity, the ability to store water, and the increase in pH values and decrease in the peat soil layer, which ultimately have degraded the function of peatland. The final impact is excessive land drought and water flooding that might occur due to canal development and reduced cover vegetation, as well as changes in soil characteristics on the peatlands. The rainfall has a powerful impact on the GWL increase in peat groundwater level in the primary peat swamp forest locations, the burned peatland, and mixed plantation. Controlling the peatland cover by vegetation, peat soil disturbance, canal development, and peat groundwater level could help to maintain the hydrological process in the peat soil.

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Appendix A

Table A1. Selected manually in the primary forest location.

| Rain Event | Date/Month   | Rainfall (mm) | Increase GWL (cm) | GWL (cm) |
|------------|--------------|---------------|------------------|----------|
| 1          | 03/07/2018   | 1.5           | 2.1              | 3.6      |
| 2          | 14/07/2018   | 4.8           | 1.4              | 6.4      |
| 3          | 18/07/2018   | 3             | 2.7              | 10.6     |
| 4          | 20/07/2018   | 1             | 1.3              | 11.3     |
| 5          | 20/07/2018   | 26.1          | 12.4             | 0.2      |
| 6          | 29/07/2018   | 2             | 1.4              | -0.5     |
| 7          | 06/08/2018   | 1.4           | 1.4              | 4.3      |
| 8          | 21/08/2018   | 11.6          | 3.4              | 16.8     |
| 9          | 22/08/2018   | 3.9           | 0.7              | 18.9     |
| 10         | 24/08/2018   | 2             | 2.7              | 18.9     |
| 11         | 28/08/2018   | 1.5           | 0.7              | 23.7     |
| 12         | 31/08/2018   | 8.5           | 1.3              | 27.9     |
| 13         | 09/09/2018   | 23.5          | 3.5              | 32       |
| 14         | 13/09/2018   | 1             | 1.3              | 18.9     |
| 15         | 17/09/2018   | 4.3           | 2.8              | 38.2     |
| 16         | 22/09/2018   | 1             | 0.7              | 34.8     |
| 17         | 26/09/2018   | 10.6          | 2.1              | 43.1     |
| 18         | 28/09/2018   | 1             | 0.7              | 47.2     |
| 19         | 01/10/2018   | 7.7           | 2.1              | 40.3     |
| 20         | 02/10/2018   | 5.8           | 2.8              | 37.5     |
| 21         | 05/10/2018   | 5.4           | 5.6              | 38.2     |
| 22         | 07/10/2018   | 6.9           | 3.4              | 42.4     |
| 23         | 08/10/2018   | 15.9          | 3.5              | 38.2     |
| 24         | 09/10/2018   | 15.5          | 3.5              | 14       |
| 25         | 11/10/2018   | 28.9          | 5.6              | 5.7      |
| 26         | 12/10/2018   | 21.4          | 2.7              | 2.3      |
| 27         | 13/10/2018   | 1.8           | 0.7              | 5        |
| 28         | 14/10/2018   | 2             | 1.4              | 5.7      |
| 29         | 16/10/2018   | 8.4           | 3.4              | 8.5      |
| 30         | 17/10/2018   | 20            | 6.3              | 4.3      |
| 31         | 21/10/2018   | 4.8           | 2.1              | -1.9     |
| 32         | 23/10/2018   | 28.1          | 3.5              | -19.9    |
| 33         | 27/10/2018   | 1             | 1.4              | -21.3    |
| 34         | 28/10/2018   | 7.2           | 1.4              | -17.8    |
| 35         | 31/10/2018   | 2             | 1.4              | -17.1    |
| 36         | 05/11/2018   | 21.8          | 7.6              | -35.1    |
| 37         | 15/11/2018   | 1             | 0.7              | -26.1    |
|   | Date     | 1   | 1.3 | -22.6 |
|---|----------|-----|-----|-------|
| 38| 22/11/2018| 1   | 1.3 | -22.6 |
| 39| 26/11/2018| 50.3| 9.7 | -27.5 |
| 40| 30/11/2018| 1.5 | 1.4 | -25.4 |
| 41| 02/12/2018| 1.4 | 1.3 | -23.3 |
| 42| 05/12/2018| 2.9 | 4.1 | -49.6 |
| 43| 06/12/2018| 36.9| 4.2 | -54.5 |
| 44| 07/12/2018| 4.9 | 1.4 | -49.6 |
| 45| 10/12/2018| 1.9 | 0.7 | -44.1 |
| 46| 12/12/2018| 6.9 | 1.3 | -39.9 |
| 47| 13/12/2018| 96  | 22.9| -71.8 |
| 48| 14/12/2018| 2.5 | 2   | -64.8 |
| 49| 15/12/2018| 9.3 | 1.4 | -67.6 |
| 50| 18/12/2018| 13.9| 2.1 | -51   |
| 51| 25/12/2018| 12.6| 2.8 | -43.4 |
| 52| 28/12/2018| 2.4 | 0.7 | -35.1 |
### Appendix B

**Table B1.** Selected manually in the ex-peatland fire.

| Rain Event | Date/Month | Rainfall (mm) | Increase GWL (cm) | GWL (cm) |
|------------|------------|---------------|-------------------|----------|
| 1          | 03/07/2018 | 62            | 51.9              | -7.8     |
| 2          | 09/07/2018 | 48.7          | 42.8              | -1.5     |
| 3          | 25/07/2018 | 19.2          | 10.3              | 40       |
| 4          | 27/07/2018 | 2             | 2                 | 24.1     |
| 5          | 03/08/2018 | 2             | 2.1               | 60       |
| 6          | 21/08/2018 | 28.9          | 16.6              | 72.5     |
| 7          | 27/08/2018 | 36.1          | 27                | 52.4     |
| 8          | 28/08/2018 | 7.7           | 8.3               | 36.5     |
| 9          | 01/10/2018 | 2.9           | 2.1               | 96       |
| 10         | 09/10/2018 | 8.7           | 9                 | 91.2     |
| 11         | 11/10/2018 | 82.3          | 29.7              | 62.1     |
| 12         | 16/10/2018 | 3.5           | 4.8               | 73.9     |
| 13         | 18/10/2018 | 17.2          | 15.2              | 62.8     |
| 14         | 18/10/2018 | 24.8          | 15.2              | 63.5     |
| 15         | 23/10/2018 | 47.5          | 12.4              | 48.3     |
| 16         | 28/10/2018 | 11.5          | 4.9               | 61.4     |
| 17         | 30/10/2018 | 3.9           | 2.7               | 40.7     |
| 18         | 31/10/2018 | 6.3           | 6.3               | 51.7     |
| 19         | 15/11/2018 | 12            | 6.2               | 52.4     |
| 20         | 25/11/2018 | 11            | 9                 | 69       |
| 21         | 26/11/2018 | 27.7          | 9.7               | 60       |
**Appendix C**

**Table C1.** Selected rainfall manually in the mix plantation

| Rain Event | Date/Month | Rainfall (mm) | Increase GWL (cm) | GWL (cm) |
|------------|------------|---------------|-------------------|----------|
| 1          | 03/07/2018 | 62            | 12.4              | -13.4    |
| 2          | 09/07/2018 | 51.7          | 12.4              | 57.2     |
| 3          | 11/07/2018 | 0.5           | 0.7               | 68.9     |
| 4          | 19/07/2018 | 6.8           | 5.5               | 82.8     |
| 5          | 25/07/2018 | 19.2          | 4.2               | 86.2     |
| 6          | 27/07/2018 | 2             | 0.7               | 86.9     |
| 7          | 03/08/2018 | 2             | 0.7               | 78.6     |
| 8          | 17/08/2018 | 13            | 5.6               | 86.8     |
| 9          | 21/08/2018 | 28.9          | 13.2              | 76.5     |
| 10         | 22/08/2018 | 12.1          | 5.5               | 89.7     |
| 11         | 27/08/2018 | 36.1          | 11                | 71.1     |
| 12         | 28/08/2018 | 7.7           | 7.6               | 92.5     |
| 13         | 31/08/2018 | 12.4          | 5.6               | 74.4     |
| 14         | 08/09/2018 | 48            | 20.1              | 64       |
| 15         | 15/09/2018 | 8.3           | 1.4               | 84.1     |
| 16         | 21/09/2018 | 17.3          | 11.8              | 82.7     |
| 17         | 25/09/2018 | 7.7           | 5.5               | 94.5     |
| 18         | 05/10/2018 | 1.5           | 0.7               | 111.8    |
| 19         | 07/10/2018 | 11.5          | 3.5               | 113.2    |
| 20         | 09/10/2018 | 1             | 1.4               | 115.3    |
| 21         | 11/10/2018 | 82.3          | 38.1              | 79.3     |
| 22         | 12/10/2018 | 4.5           | 4.8               | 79.3     |
| 23         | 13/10/2018 | 3             | 1.3               | 116      |
| 24         | 16/10/2018 | 14.5          | 1.4               | 73.8     |
| 25         | 18/10/2018 | 24.3          | 17.3              | 64.1     |
| 26         | 21/10/2018 | 13            | 4.1               | 72.4     |
| 27         | 23/10/2018 | 47.5          | 22.8              | 41.3     |
| 28         | 26/10/2018 | 2.5           | 2.8               | 70.3     |
| 29         | 27/10/2018 | 8.6           | 7.6               | 73       |
| 30         | 28/10/2018 | 11.5          | 4.1               | 48.9     |
| 31         | 30/10/2018 | 4.8           | 1.4               | 62.7     |
| 32         | 04/11/2018 | 3.9           | 1.4               | 56.5     |
| 33         | 05/11/2018 | 40            | 19.4              | 39.9     |
| 34         | 09/11/2018 | 2             | 0.7               | 68.2     |
| 35         | 15/11/2018 | 6.4           | 1.4               | -57.3    |
| 36         | 17/11/2018 | 1.5           | 1.4               | -33.8    |
|   | Date       |   |   |     |
|---|------------|---|---|-----|
| 37| 18/11/2018 | 1.5| 1.3| -28.9 |
| 38| 22/11/2018 | 5.8| 2.1| -38.6 |
| 39| 23/11/2018 | 3.4| 1.3| -37.2 |
| 40| 23/11/2018 | 3.4| 3.5| -35.2 |
| 41| 24/11/2018 | 2.5| 2.8| -32.4 |
| 42| 25/11/2018 | 11 | 2.8| -31   |
| 43| 27/11/2018 | 21.6| 11.1| -40.7 |
| 44| 04/12/2018 | 8.2| 8.3| -46.9 |
| 45| 19/12/2018 | 2.4| 1.4| -39.9 |