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Linking Surface Water Content to Groundwater Levels in Tropical Peatlands: Insights from the van Genuchten Approach

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ABSTRACT

Tropical peatland in Indonesia have always been characterized by Peat Hydrology Units which have a function as a large amount of carbon storage and are able to regulate the hydrological cycle naturally. This study has two objectives, namely to analyze the variability of SWC, GWL, and rainfall parameters, to be able to understand the patterns of hydrological interactions in peatland ecosystems and to explain the quantitative relationship between SWC and GWL parameters using the van Genuchten Equation (VG) approach. The study also uses a VG based soil hydraulic curve modeling approach to describe groundwater retention and its impact on groundwater surface dynamics. The results showed that the SWC value was significantly influenced by the depth of the GWL and the intensity of rainfall, this underlined that the relationship between the two parameters is reciprocal. In addition, understanding the relationship between these parameters is very important, since the SWC value greatly determines the moisture status of the peat surface, in addition to directly the SWC value also affects the susceptibility of peat fires, while the GWL regulates the long-term hydrological balance and carbon emission potential. Therefore, conducting this study can improve understanding of hydrological feedback in peatlands. The results of the correlation analysis between parameters in this study showed that there was a strong relationship between SWC and GWL (R^2 = 0.6–0.8), while the correlation between GWL and Rainfall was weak (R^2 = 0.1–0.2). This suggests that SWC variation is primarily influenced by groundwater fluctuations rather than precipitation.

Introduction

Tropical peatland ecosystems in Indonesia are characterized by Peat Hydrology Units (PHU). Peatlands naturally have an important function as a hydrological cycle and carbon store globally [1]. The process of formation of peat soils through the process of anaerobic accumulation of organic matter, which produces different physical properties, is mainly characterized by low permeability and high water retention capacity. In addition, under natural conditions, if not degraded, peatlands will continue to be inundated, and will inhibit the decomposition of organic matter and consequently reduce the high amount of carbon emissions. However, these ecosystems are also highly vulnerable to various impacts of climate change and various anthropogenic activities, including land use change, deforestation, and drainage practices [2]. These interventions can lead to a decrease in soil moisture content (SWC) and groundwater level (GWL) value, as well as accelerate the decomposition process of peat and accelerate the rapid release of carbon into the atmosphere [3–6].

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In addition, in peatlands, oxygen depletion can reduce the GWL value and can stimulate the process of decaying bacterial activity quickly, this will accelerate the process of peat decomposition and carbon emissions, this process is also highly correlated with GWL variability [7–9]. However, a decrease in the value of the GWL will not necessarily result in a significant decrease in the value of the SWC, this is due to the uniqueness of the peat structure that has water retention in the upper layer [10]. In addition, peatland ecosystems that experience high degradation are often caused by intensive drainage, which causes faster loss of SWC value due to reduced pore structure, which can accelerate the drying process.

Drying of peatlands will trigger a decrease in the value of GWL, which will cause the formation of unsaturated zones in the top layer of peatland. However, even though the GWL has decreased, peatlands have porosity properties that can play a role in maintaining water content through capillary mechanisms. This ultimately makes moisture retention one of the important factors in understanding the dynamics of water movement in peatlands, this is because SWC wetness has a strong relationship with GWL. Therefore, the association between these parameters is specific to each PHU, and this is also highly dependent on the nature of the peat material and the hydrological characteristics of its constituent media [11]. Based on previous research, it is explained that peat soils are very different from the properties of mineral soils which generally have more uniform physical properties, it is very possible to model water retention more easily using mathematical models such as by using the van Genuchten equation. However, in the application of the peat model, it is very challenging because it has very porous, irregular, and compressible properties [12]. This complexity makes it very difficult to accurately capture water dynamics within peat soil layers, especially in partially saturated conditions.

Previous research has also tried to adapt VG parameters, such as residue saturation values and porosity indexes, to peatlands. However, this approach has not adequately addressed significant spatial and temporal variations in peatland SWC and GWL [13]. Although the VG model has proven to be effective for mineral soils, its application to peatlands remains a significant challenge and requires innovative solutions. This study aims to develop a VG model-based approach to improve our understanding of SWC-GWL relationships in tropical peatlands. One of the difficulties in applying the VG model is that tropical peat soils have highly variable hydrological properties [14–16]. This study has two objectives, the first objective is to be able to analyze the variability of hydrological parameters, such as SWC, GWL, and rainfall, to be able to understand the pattern of hydrological interactions in peatland ecosystems and the second objective is to be able to explain the quantitative relationship between SWC and GWL parameters using the VG Equation approach with the topic of discussion about dynamics measured through data from the field and utilizing data from derivatives through modeling.

Materials and Methods

Study Area

This research area is in a peat area in the PHU of South Sumatra Province which covers about 1.2 million hectares. This vast landscape is one of the largest tropical peatland areas in South Sumatra. The existence of this peat ecosystem is very necessary because it has an important function, namely being able to absorb carbon, regulate water management, and be able to preserve various biodiversity. It is wide range and ecological importance underscore its important role in promoting regional sustainability and regulating the global climate (Figure 1).

Hydrological In Situ Monitoring and Data Acquisition

The fire incident that occurred in 2015 on peatlands, coincided with the Super El Nino phenomenon, thus prompting the Indonesian government to make a policy by forming by establishing the Peatland and Mangrove Restoration Agency (*Badan Restorasi Gambut dan Mangrove*/BRGM) with the aim of being able to prevent future disasters. Therefore, to support peatland restoration, Midori Engineering Laboratory developed a Sensor Assisted Data Transmission System (SESAME) that continuously monitors important hydrological parameters, such as rainfall, GWL, and SWC. SESAME data is presented through the Peatland Monitoring Information System (*Sistem Informasi Pemantauan Lahan Gambut*/SIPALAGA), an online platform maintained by BRGM that provides public access to hydrological data from various PHU across Indonesia, with updates every 10 minutes. This study utilized data from three sample points collected between 2018 and 2020 to analyze the variability of these environmental parameters. To improve the accuracy of the hydrological estimates, the Kalman filter method was applied to minimize noise in the data. The analyses were performed using MATLAB R2025b.

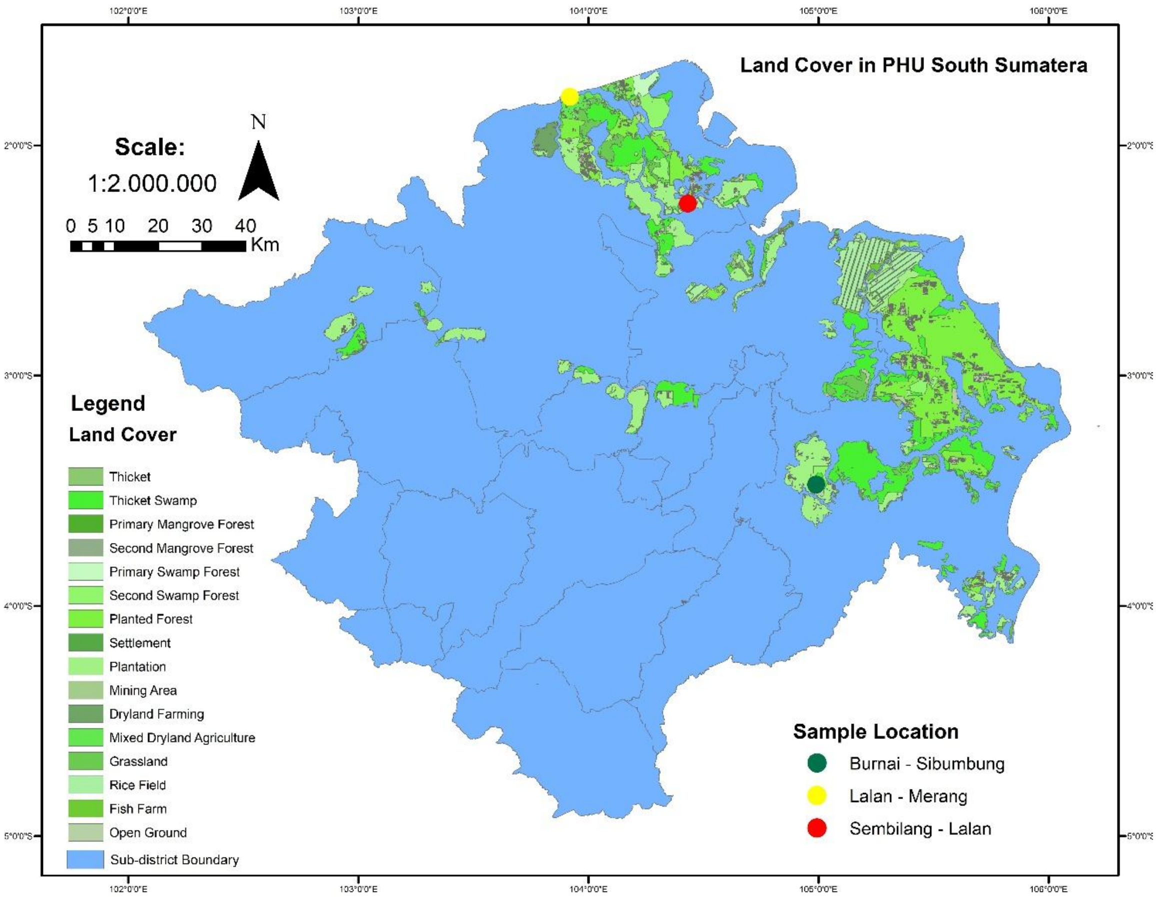

Figure 1. The research location is at PHU, South Sumatra Province. This map describes the research area, the scale of the map, and the legends. The legends used are various types of land cover and sampling points Burnai – Sibumbung PHU (green color), PHU Lalan – Merang (yellow color), and Sembilang – Lalan (red color), and at the location of this study using a map scale of 1:2,000,000 with a bar scale representing 0 – 100 km.

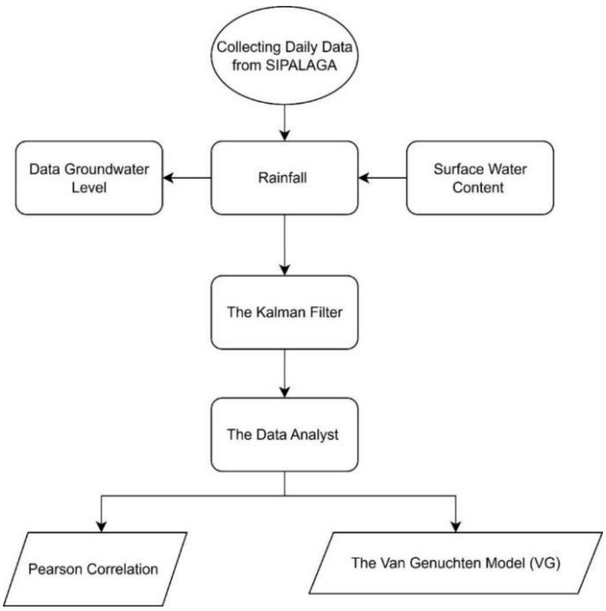

Figure 2. Research flowchart. The research data were obtained from SIPALAGA (GWL, SWC, and rainfall). The data obtained were controlled for data quality using a Kalman filter, after which Pearson correlation and VG model analysis were carried out.

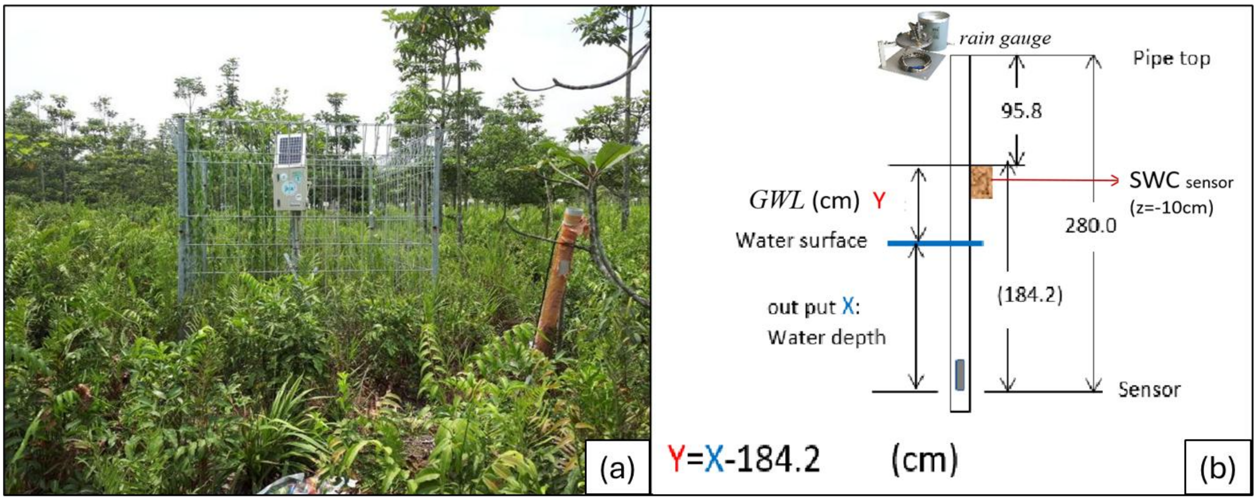

Figure 3. a) SESAME instrument, which is installed in the peatland area of South Sumatra, b) configuration of the hydrometeorology sensor.

Data Analysis

In statistical analysis, Pearson's correlation is often used to measure the strength and direction of a linear relationship between two numerical variables. This method is beneficial for understanding how closely two parameters are related, which in this study can be environmental variables such as soil moisture, rainfall, and GWL, among others. In this analysis, the data used were time series data collected over a specific period, from 2018 to 2020, with a resolution of daily observations. The raw data were initially processed into daily averages to remove short-term fluctuations and facilitate the analysis of the relationship between variables. Thus, Pearson's correlation was calculated based on the processed data. In general, mathematical models, to find the value of the Pearson correlation coefficient can be explained as follows (Equation 1) [17].

$$R_{xy} = \frac{N\sum_{i=1}^{N} x_i y_i}{\sqrt{\left(N\sum_{i=1}^{N} x_i^2 - \left(\sum_{i=1}^{N} x_i\right)^2\right)}\sqrt{\left(N\sum_{i=1}^{N} y_i^2 - \left(\sum_{i=1}^{N} y_i\right)^2\right)}} \quad (1)$$

The R_{xy} coefficient mdescribes the correlation coefficient, while the value of the x_i coefficient indicates the first data, and y_i describes the second data set, marked with the value of the correlation coefficient R with a range from –1 to 1. A positive R_{xy} value means that there is a linear relationship between parameters, and if R_{xy} is negative, it means that there is an inverse and non-linear relationship.

The SWC-GWL Model

The approach used to look at sustainable peatland management on wetlands is to use the relationship approach between SWC and GWL parameters. In addition to being used on mineral soils, models describing this relationship can also be used in peatlands, and this model is often known as the VG model [18]. The method often used in deriving the VG model is the integral method, which relies heavily on horizontal infiltration experiments. Furthermore, this approach is articulated through the groundwater retention curve (SWRC), which represents the hydraulic relationship of the soil. The quantitative aspect of this relationship is reflected in the hydraulic parameters of the soil. The van Genuchten model is described as follows in Equation 2 [19,20].

$$\theta(h) = \frac{\theta_s - \theta_r}{\left[1 + \left(\alpha|h|\right)^n\right]^m} + \theta_r \quad (2)$$

The VG model was used in this study to describe the relationship between volumetric SWC (θ) and head of pressure (h), which, in the context of tropical peatlands, corresponds to the water table height (GWL). In the VG equation, θ is the volumetric water content ($cm^3\ cm^{-3}$), θ_r is the residual water content, θ_s is the saturated water content, and $h = P/\rho g$ is the head of pressure, which is negative because it refers to subsurface peat conditions [21]. For modelling purposes, positive values are usually used; therefore, it is expressed as GWL × 100 cm. where α is the scaling factor (cm^{-1}), n is the curve shape parameter of the soil water retention function, and m is defined as 1-1/n. The main objective of the VG model in this study was to estimate the parameters α and n accurately.

In addition, the model allows parameter estimation through well-established mathematical techniques, such as least squares or sum of squares error (SSE) methods, especially when sufficient SWC and GWL observations are available through the optimisation as expressed in Equation 3 [22],

$$\min\ f = SSE(\alpha, n) = \sum_{i=1}^{N} \left[\theta_i - \theta(h_i; \alpha, n)\right]^2 \tag{3}$$

where θ_i is the observed SWC, θ (h_i) is the SWC calculated from the observed data hi, and *N* is the number of observed data points. We used unconstrained optimization of nonlinear functions. The function does not require derivatives of the objective function, making it suitable for cases in which the function cannot be differentiated analytically or is non-smooth. This method is suitable because the function VG is nonlinear.

Results and Discussion

Results

Variability of Hydrological Parameter

The initial stage of the investigation was to observe the variability of the SWC, GWL, and rainfall in the three PHUs, as depicted in Figure 4. Implementing the Kalman filter does not alter the variability pattern (Figure 4a to 4d) and closely resembles a low-pass filter. Furthermore, the general tendency exhibited by the SWC and GWL patterns demonstrates their interconnected nature, characterized by a reciprocal relationship in which the decline in one is in accordance with the decline in the other. Rainfall coincided with an increase in GWL.

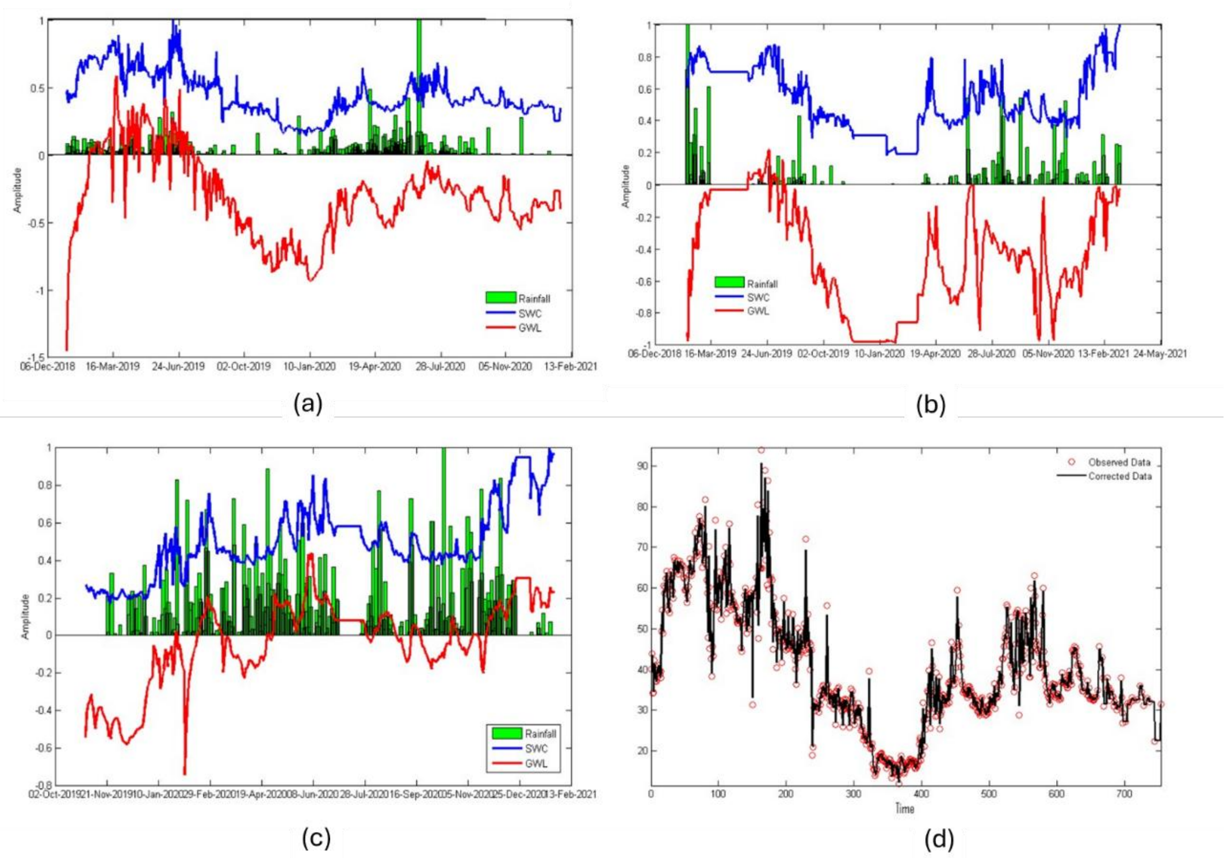

Figure 4. a) Time series of CH, SWC, and GWL with the amplitude normalized at the Sembilan – Lalan PHU; b) Time series of CH, SWC, and GWL at the Lalan – Merang PHU; c) Time series of CH, SWC, and GWL at the Burnai – Sibumbung PHU; d) Example of filtering out the noise in the GWL data using a Kalman filter.

The SWC-GWL Model

To analyze the hydrological characteristics of tropical peatlands, it is essential to elucidate the relationship between the SWC and GWL. In tropical peatlands, the GWL typically exhibits negative values during the dry season, whereas positive values (flooding conditions) are commonly observed during the rainy season. The depth of the peat water level can be represented by the pressure head parameter (cm) as follows: The SWC was expressed as a volumetric fraction (cm^3 cm^{-3}). This relationship can be quantitatively described in a closed form using the VG equation, as illustrated in Figure 5.

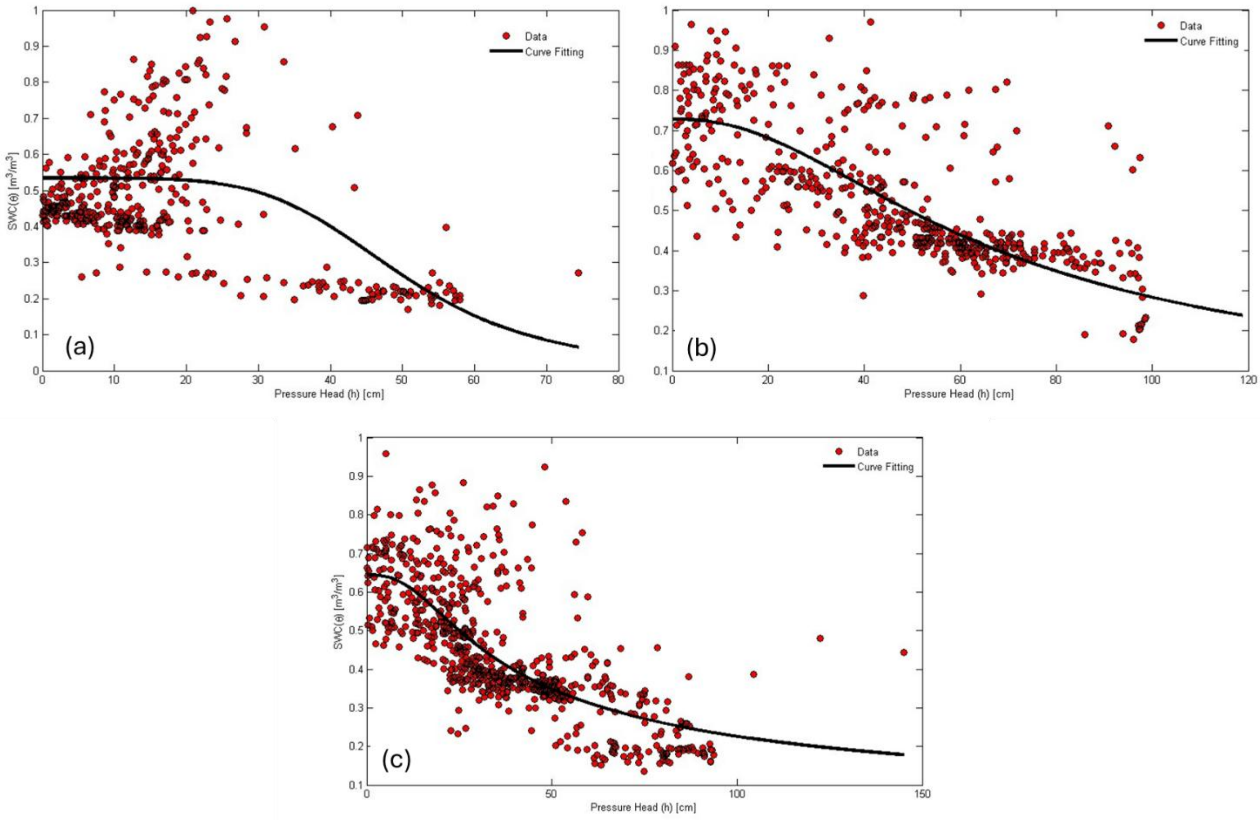

Figure 5. The results of the analysis of the installation of the curve between the pressure head and SWC were obtained using a nonlinear optimization method. a) VG curve in Sembilan – Lalan PHU; b) VG curve in Lalan – Merang PHU; and c) VG curve in Burnai – Sibumbung PHU.

Discussion

Area of Fire Incidents

Peatlands in South Sumatra province cover five districts: Ogan Komering Ilir (768,501 hectares), Musi Banyuasin (340,605 hectares), Banyuasin (252,707 hectares), Musi Rawas (34,126 hectares), and Muara Enim (24,104 hectares). In addition, several of these areas have undergone changes in land use, such as oil palm plantations and agriculture, including pineapple and rice. Furthermore, in 2014, according to statistical data from the National Disaster Management Agency (*Badan Nasional Penanggulangan Bencana*/BNPB), South Sumatra Province was one of the provinces in Indonesia with the largest area of peatland affected by fires (8,505 hectares). Meanwhile, in 2015, it experienced another fire with the second largest increase in burned area (144,410 hectares), even though the existence of this peatland can regulate the environment by storing relatively large amounts of carbon and managing water resources.

However, drainage systems on peatlands that experience a decrease in GWL values can cause peat oxidation and significant carbon emissions. This is because drained peatlands will be more susceptible to fire, especially during the Long dry season or extreme events, such as El Niño [23–25]. The 2015 Super El Nino caused widespread fires that burned about 144,410 hectares, the resulting impact of which was the destruction of peatland ecosystems and increased greenhouse gas emissions, especially carbon dioxide (CO_2) [26]. Understanding the hydrological conditions of these peatlands is critical for climate change conservation and mitigation. The steps that can be taken include blocking canals and managing the water level are needed with the aim of being able to reduce the risk of fire and be able to preserve the role of peatlands as carbon sinks.

Variability of Hydrological Parameter

The results showed that the GWL in PHU Sembilang-Lalan (Figure 4a) in 2019 decreased by –0.6. In addition, in 2020, PHU Sembilang-Lalan experienced the weakest El Niño conditions, with groundwater surface values tending to be high (approximately surface). As a result, the La Niña phenomenon is weakening until 2022. This phenomenon was also observed in the Burnai-Sibumbung PHU (Figure 4c), where the GWL decreased from June 2019 to January 2020, followed by increased variability near the surface throughout 2020. However, this phenomenon was not observed in the Lalan – Merang PHU (Figure 4b), where the GWL declined from July 2019 to January 2020, and throughout 2020, there was significant variability with an average depth of –0.5 m. This is in line with the Irfan et al. [27] that during the 2019 dry season, several areas experienced peat fires from June to November, as evidenced by the emergence of hotspots. These hotspots were observed in the Pandang Sugihan Wildlife Reserve, Sembilang National Park, and the protected forests of South Sumatra. In our study, we also recommend a minimum GWL depth of approximately 0.5 m for peatland fire prevention, as previously proposed [28].

The results of the correlation analysis between the parameters in this study are as follows: there is a strong relationship between Soil Moisture (SM) and GWL (R^2 = 0.6–0.8), while the correlation between GWL and Rainfall is weak (R^2 = 0.1–0.2). These results show that there is a highly variable relationship between SWC relationships that are strongly influenced by GWL fluctuations compared to rainfall. This makes the findings in this study very consistent with previous research, which explains that there is a high peat water storage capacity, which results in a delayed response to rainfall [29].

The SWC-GWL model

The results of the study from Syaufina et al. and Saharjo [30,31] explain that the value of the moisture content can be explained on the x-axis and on the pressure, head can be explained on the y-axis. From the relationship between the x and y axes, it can be made into a VG curve and this curve shows a profile in the form of an S-curve, and this curve is also known as a water retention curve. As the pressure head increases, according to the deeper water surface, the SWC will approach asymptomatic conditions. This trend highlights the nonlinear behavior of water retention in the soil at varying levels of humidity. Laboratory studies of soils ranging from very dry to fully saturated have confirmed the existence of an S-curve relationship between the pressure head and the SWC [32–34]. In this case, the VG curve presents soil moisture content with pore pressure, but for peatsoils the pore pressure is assumed to be the same as GWL [35]. However, with a nonlinear optimization approach, we obtained a VG coefficient numerically, where, in general, the VG coefficient was obtained by soil sampling [36]. A comparison of foundation consolidation with optimization will be carried out in future research.

Our results also show an S profile for the water retention curve. This shows that the surface moisture content decreases as the water level rises, and it suggests that the peat surface is becoming drier. It should be noted that each PHU has a different shape of the S-curve. For example, the shape of the S-curve shown by PHU, as depicted in Figure 5a, shows a constant SWC profile between the surface and a depth of 20 cm, a layer referred to as a homogeneous layer. However, this curve changes quite clearly at a depth of about 70 cm, where the SWC value undergoes a substantial shift, which indicates the emergence of a stratified layer, and conversely, for Lalan – Merang PHU, the thickness of the homogeneous layer is reduced to 10 cm (Figure 5b), with the stratified layer reaching 100 cm. Next, a homogeneous layer of about 10 cm was observed for the Burnai – Sibumbung PHU (Figure 5c), accompanied by a substantial stratification layer measuring 120 cm. This S-curve shows the hydrological characteristics of the three PHU in the tropical peatlands in PHU South Sumatra Province.

The relationship between the SWC and GWL is closely associated with the resilience of a peatland hydrological unit (PHU) to fire vulnerability. For instance, for the Katingan-Sebagau Kalimantan PHU, a 40-cm drop in GWL (equivalent to a hydrostatic balance of 4 kPa) results in a 0.5 SWC, thereby rendering peatlands susceptible to fire [34]. Most studies on the hydrological characteristics of peat have been conducted through experimental analyses of field samples. For instance, in peatlands at high latitudes, such as Finland and Sweden, the surface layer characteristically exhibits high bulk density, which is inversely proportional to porosity [37]. Additionally, the surface layer of degraded peat, resulting from anthropogenic activities such as agricultural practices and plantations, displays saturated hydrological conductivity compared to that of natural peat forests. Furthermore, it has been shown that the value of the VG constant differs according to the land use type. In general, a decrease in peat SWC of ≥ 10% reduces the unsaturated K value by a factor of two [38].

According to hydrophobic research, peatlands can be significantly affected by land cover [39]. A study of Polish peatlands found that intensive grasslands showed the highest Water Droplet Penetration Time (WDPT). Secondary birch and alder swamp forests show the lowest WDP, followed by semi-natural grasslands. As this study shows, differences in land cover and physical properties of peat layers in each PHU play an important role in hydrological conditions and fire susceptibility. In PHU Sembilang - Lalan, the ecosystem is almost natural with the dominance of mangrove forest land cover, peat swamp forests, shrubs, and wetland agriculture. In addition, the existence of conservation areas such as Sembilang National Park is very helpful in maintaining the stability of the peatland ecosystem. This is due to the existence of tides that can keep the peat surface layer saturated with water, in addition to the existence of conservation areas can also maintain the condition of the pore structure in peat soil so that it remains stable, and can maintain peat stratification so that it tends to be consistent with low decomposition rates and reduce the increase in carbon emissions [39]. In contrast to the land cover conditions at the Lalan – Merang PHU location which has been converted into oil palm plantations and industrial timber estates (HTI), this causes the degredation process of peatland to be fast and causes the peat soil layer at the PHU location to become dry, resulting in an increase in porosity, and an increase in saturation conditions. In addition, the value of different VG constants is influenced by the difference in land use in each PHU [33].

The value of the van Genuchten constant has to do with the ability of the soil to hold water and the characteristics of the flow of water in the soil. Burnai-Sibumbung PHU consists mostly of dry farmland, grassland, open bush, and oil palm plantations. The peat surface layer becomes hydrophobic due to the wide land clearance and degraded land conditions, especially in locations exposed to direct sunlight or fire scars. Peat soils in intensive grasslands show the highest WDPT and exhibit strong hydrophobicity. The dehydrated and compacted top layer of peat lowers the conductivity of unsaturated groundwater (K_{unsat}), which makes drought and forest fires more likely [37].

The physical and hydrological properties of peatlands differ based on depth and degree of decomposition. The results of the VG model curve show differences in the characteristics of peat groundwater retention based on three sets of parameters. In the initial subplot, shown by Figures 5a, 5b, and 5c, the soil moisture content (θ) remains relatively constant at 0.7282, although the matrix pressure (h) increases to 1. This suggests that soils with a very high-water retention capacity, with a highly porous fiber structure and many macropores, are most likely peat soils. This characteristic allows water retention even when the matrix pressure is high, ensuring stable moisture content. This type of soil is usually found in the surface layer of peat that is still fresh or undecomposed, which has high porosity and permeability. These results are in line with observations made by previous studies from [38], which showed that under moderate drainage conditions, the water level in the upper layers (0–30 cm) of peatlands in the Batanghari (Sumatra) and Kubu Raya (Kalimantan) regions increased. This study is in line with the results of Taufik et al. [38], which showed that peatlands with low decomposition rates have a flatter water retention curve due to the proportion of macropores that are able to hold larger amounts of water even though the matrix pressure increases.

The second subplot, shown by the Figures 5a, 5b, and 5c, shows a small variation in the trend. This shows the soil moisture content is about 0.644 and the only decrease is when the matrix pressure increases to 1. This pattern shows peatlands with moderate water retention capacity. It may be suitable for more degraded soils or deeper peat layers. These soils are characterized by a higher prevalence of micropores and a lower prevalence of macropores; Both of these conditions have been shown to help store water even when the volume is reduced. These results are in line with research conducted by Taufik et al. [38], which showed that soil samples from a depth of 40 to 70 centimeters had a lower water retention capacity than samples from the upper layers. It is very possible that there is a link between this phenomenon and an increase in the rate of decomposition in the lower layers, which results in smaller, denser pores. Not only that, the results of the study from Cooper et al. [24], explains that more decomposed and old colored peat soils will tend to have soil properties that have a lower water retention capacity compared to young soils, this is due to a decrease in macroporous volume.

The results of this study explain that there is a decrease in the water content value by 0.6, this is shown in subplot 3. The results of this study also show that peatlands that have a fairly low water retention capacity will experience higher density values, so that it will accelerate the decomposition process. In addition, a decrease in water retention capacity is generally formed due to narrower pore structures. Such soil forms are generally often found in peatlands that are very highly drained or in peatland conditions that have undergone land conversion, for example for plantation or agricultural purposes, where the fibers in the peat soil have been compacted. So that the condition of the soil loses a lot of water. The results of the study are related to previous research conducted on peatlands affected by severe drainage [39].

The results of this study also explain that faster water loss conditions will affect the level of drainage effectiveness and will experience a decrease in matrix pressure. The results of the study are strongly corroborated by another study conducted by Menberu et al. [22] which found that drainage in peatlands will significantly accelerate the loss of water availability in peatlands. The results of VG modeling in this study explain that water retention capacity varies in different peatland conditions. Peat soils with low retention capacity will be susceptible to drought, while with high retention will usually always be wet. Therefore, in order to maintain a sustainable management of soil on peatlands, it can be done by reducing the risk of fire events, this can be done by maintaining soil moisture stability, as well as managing carbon emissions efficiently. In addition to these findings, the study also explains that by combining more complex physical and chemical variables in peat soils, such as ash content, dry density, and decomposition rate, it can allow for more accurate and field-relevant soil moisture predictions by improving the VG model [34,37].

Conclusions

The results of the research study explain that by studying the types of land cover from different PHU and studying the hydrological characteristics and factors that affect them such as the parameters of GWL, SWC, and rainfall from various PHU in South Sumatra Province, it will be possible to find out how much there is a relationship between these parameters. Not only that, in this study, by utilizing the Kalman filter, it will be very easy to be able to reduce noise in the GWL data obtained from SIPALAGA without having to change the variability pattern. The results of the study show that there is a strong relationship between increased rainfall and GWL. Next, the relationship between the GWL parameter and the SWC shows the S-curve in the VG model, which shows that the S-curve is highly dependent on how much soil conditions are inherent and the degree of decomposition. The results of this study also show that there are peat conditions that have fairly homogeneous layers and stratification, when compared to the condition of peatland that has a fairly high degradation. These findings emphasize the importance of proper peat management to maintain hydrological stability and to be able to reduce the risk of fires, as well as the need to develop more accurate water retention models that take into account the physical and chemical variations of peatlands to support sustainable conservation. The method of determining the VG model in this study uses time series data, but there are limitations in the duration that must represent the dry and rainy seasons as well as the El Nino cycle. The next step in this study is to use long-term data in the next study.

Author Contributions

AIP: Data processing, Investigation, Writing, Review & Editing; **PD**: Writing, Review, & Supervision; **ABS**: Methodology, Review & Analysis; and **AS**: Conceptualization, and Writing.

AI Writing Statement

The authors did not use any artificial intelligence assisted technologies in the writing process.

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