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Ground Penetrating Radar Method for Estimating Peat Thickness and Volume: Case Study in Kubu Raya, Indonesia

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Abstract: Tropical peatlands in Indonesia are very large, covering an area of about 13.4-14.9 million hectares. Kubu Raya Regency, West Kalimantan Province, is known to have significant natural resources and large regions of peatland. Therefore, this study aimed to estimate the thickness and volume of peat soil in the Rasau Jaya and Sungai Raya Subdistricts of Kubu Raya Regency. The method adopted was the Ground Penetrating Radar (GPR), where the Plug-In Cobra GPR SE70 tool with a frequency of 80 MHz was used. In the process, a total of 23 tracks was applied with validation by three drill points. This consisted of nine tracks in Sungai Raya Subdistrict and 14 in Rasau Jaya Subdistrict. GPR data was processed through several processes, including static correction, dewow, Butterworth bandpass, background removal, gain, subtracting the average, and horizon picking. The results showed that the subsurface electromagnetic wave propagation velocity at the study location was 0.026 m/ns, with a peat thickness of 0.8-4.2m. The deepest peat layer was in the east, with a thickness of 3.8-4.2m, while the shallowest was in the west, at a thickness of 0.8-1.1m. Based on observation, the volume of peat in the study location was 4.8×107 m^3.

Keywords: *Electromagnetic wave, ground penetrating radar, peat thickness, volume.*

1. Introduction

Peat soils are formed from organic plant fragments subjected to chemical processes. These soils are compressible, with a high water content and a distinctive color ranging from dark brown to black (Wahab et al., 2022). They are generally discovered around tropical forests in lowland areas with moist conditions, abundant water, and relatively low temperatures. Tropical peatlands in Indonesia are very large, covering an area of approximately 13.4-14.9 million hectares. The lands are spread over several islands, including Sumatra, Kalimantan, Papua, and Sulawesi, with areas of 5.85 million hectares (43.5%), 4.54 million hectares (33.8%), 3.01 million hectares (22.4%), and 0.03 million hectares (0.3%), respectively (Yuwati et al., 2021). Based on records, West Kalimantan Province has an area of approximately 1.73 million hectares (Putri, 2017). Rasau Jaya Subdistrict, located in Kubu Raya Regency, West Kalimantan, is known to possess significant natural resources, specifically extensive peatlands. In the Rasau Jaya Subdistrict, the land reaches approximately 14,371.392 hectares, making it an essential area for peat ecosystem management in Indonesia (Tampubolon et al., 2020).

Peatland restoration has become a global concern, specifically in tropical regions such as Indonesia and Malaysia. This is because more than 20 million hectares are thought to have been disturbed by human activities. Restoration efforts through maintenance of soil moisture levels at optimal levels not only help prevent fires but also allow peat ecosystems to recover and resume functioning as effective carbon sinks. This process includes restoring natural hydrology, increasing water content, and reducing greenhouse gas emissions such as carbon dioxide and methane released when peat becomes dry (Damanik et al., 2024). The restoration is also essential for maintaining biodiversity, as these ecosystems support a variety of endemic species that depend on a moisture-rich environment. Furthermore, other benefits include reducing the risk of peatland fires. Restoring soil moisture levels can significantly reduce fires while preserving carbon stocks in deep peat layers and preventing the loss of large amounts of carbon to the atmosphere (Vernimmen et al., 2020). These efforts are crucial to achieving global carbon emission reduction targets and climate change mitigation. Peatlands have a deficient soil-bearing capacity in infrastructure development, making building foundations vulnerable to subsidence. The thicker the peat layer, the greater the potential for subsidence in building foundations (Tanjung et al., 2017).

A method that is often used to estimate peat thickness and volume is the drilling method. It is considered inefficient because the equipment is challenging to move and requires a lot of personnel. Therefore, peatland analysis needs to be conducted using geophysical surveys. Ground Penetrating Radar (GPR) is a geophysical method suitable for peatland studies (Sinyutkina, 2021). The method has the advantages of effectiveness, practicality, and non-destructiveness (Rais et al., 2024). It works by using electromagnetic waves propagating to the subsurface and detecting signals reflected by sediment interfaces with

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different electromagnetic properties (Ryazantsev & Ignashov, 2022; Knödel et al., 2007). The high water content of the peat layer causes electromagnetic waves to propagate at a low velocity. Significant differences in water content at the peat-sediment interface lead to high-amplitude reflections, which contribute to the signal response (Pezdir et al., 2021). Good signal reflections are generally produced when there is a significant difference in the dielectric constant between the peat layer and other layers below. However, when the layer is clay, the electromagnetic wave may have significant attenuation, reducing the reflectance clarity at the interface.

This study aims to apply the GPR method to estimate the thickness and volume of peat soil in Rasau Jaya and Sungai Raya Subdistricts, Kubu Raya Regency. The result is expected to produce more accurate information on peat thickness and volume to support more optimal restoration, by estimating carbon reserves, reducing the risk of peatland fires, and building infrastructure foundations. However, limited data on the thickness and volume in the region remains a significant obstacle to restoration planning and environmental impact mitigation. The inefficient use of conventional methods often takes a long time. Therefore, the application of the GPR enables the mapping of peat thickness over a larger area in a relatively short time, increasing the effectiveness of data collection in the field. The results of this study are also expected to help local governments, analysts, activists, and the general public in planning more targeted and sustainable restoration strategies.

2. Material and Method

The Study Location

This study was conducted in Kubu Raya Regency, West Kalimantan Province. Data were collected through 23 tracks, consisting of nine in the Sungai Raya Subdistrict and 14 in the Rasau Raya. A track in the Rasau Raya Subdistrict (L22) with a length from 192 m to 887 m was used as a reference to measure the velocity wave propagation in the peat layer. Furthermore, this study applied four drill points, with three being adopted for interpolation in areas not covered by the GPR survey track. The remaining drill point was located on L22 to validate the thickness of the peat layer on that track. The measurement track and drill point locations are shown in Figure 1. Equipment used in this study was a Plug-In Cobra GPR SE70 with a frequency of 80 MHz, as presented in Figure 2.

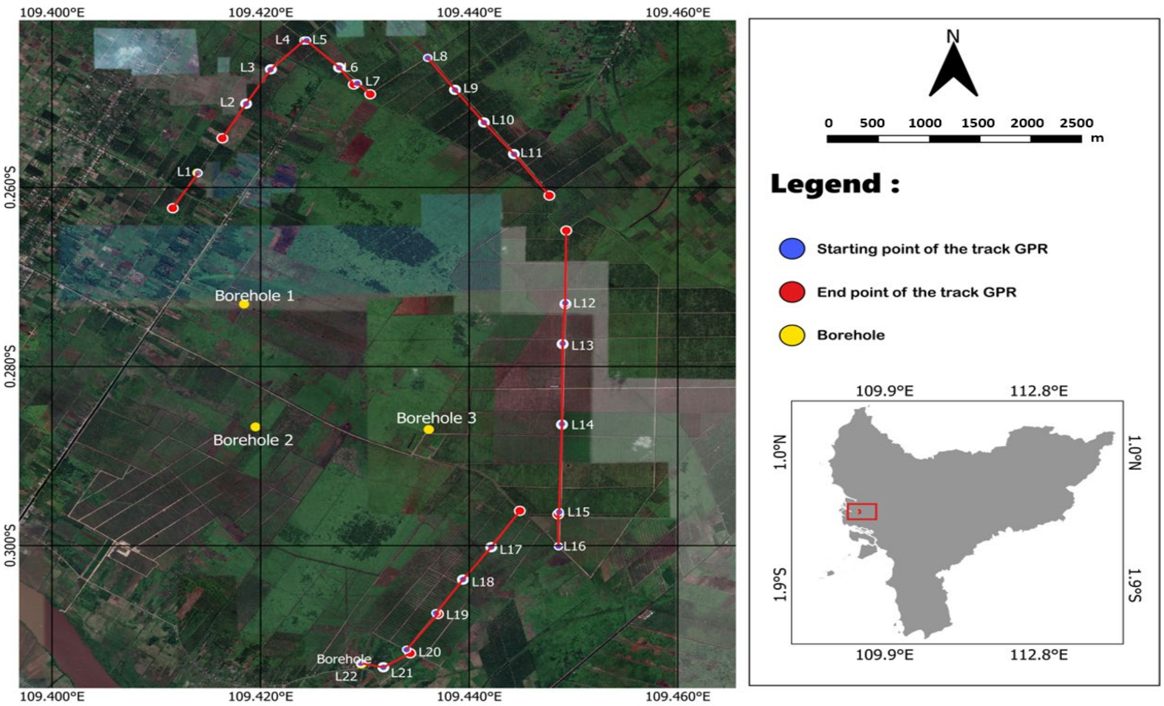

Figure 1. Study design; measurement track and drill point locations

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Figure 2. The GPR survey equipment, i.e., Plug-In Cobra GPR SE70

Data Processing

The propagation velocity of electromagnetic waves in peat layers was determined based on drill depth data by using the concept of Two-Way Time (TWT). The time measured is the wave's travel duration from the surface to the boundary of the subsurface layer and back to the surface. Therefore, the total time measured was twice the layer distance. By identifying the peat layer thickness d (m) and wave travel time t (ns), the electromagnetic wave velocity v was determined using Equation (1).

$$v = 2\frac{d}{t} \quad (1)$$

Peat thickness was identified by showing the peat layer boundary on the radargram. The thickness boundary was visible from the amplitude contrast marked by the color difference in the radargram profile. Processing of radargram data includes a series of processes aimed at improving the quality of the details obtained from the measurements. It began with raw data processing through static correction to account for positional and topographical variations, including time-zero correction based on the initial wave arrival. A dewow procedure was subsequently applied to eliminate low-frequency noise (Koyan et al., 2023). A Butterworth bandpass filter was applied to filter frequencies outside the desired range, while the background removal process eliminated signals unrelated to the subsurface structure (Wu et al., 2022). The energy decay effect of the radar signal generated during penetration into the subsurface was removed. This was followed by subtracting the average method to remove the horizontal coherent energy appearing with low frequencies (L. Zhang et al., 2021). The final step was manual gain, which ensured reflections at various depths could be seen.

Peat thickness profiles were generally classified into four classes based on the depth/thickness of the layer. This includes shallow (0.5-1 m), medium (1-2 m), deep (2-3 m), and very deep (3-5 m) (Suryani et al., 2022). The kriging interpolation method in 3D modeling facilitates more accurate mapping of the peat layer's volume in the study location. The method has been used effectively in several studies to accurately determine soil layer thickness. It can be adopted to map peat thickness and carbon stock in degraded peatlands (Fiantis et al., 2024; Beucher et al., 2020). The kriging method was also applied to estimate soil layer thickness by incorporating topographic and vegetation variables with significant results (S. Zhang et al., 2021). Therefore, the 3D peat layer profiles were obtained using this method. This provides more accurate results in mapping peat thickness and estimating the total volume, specifically in areas with topography.

3. Results and Discussion

Electromagnetic Wave Propagation Velocity

A clear reflector was identified at a depth of about 2.1 m, signified by the dashed white line, as shown in Figure 3. This suggests a significant change in the characteristics of the subsurface material, which could be due to differences in density or moisture content. Therefore, the difference in physical properties was interpreted as a boundary between peat and clay layers. High-amplitude subsurface layers signified the stronger reflections of these layers (blue and purple), while the underlying layers had weaker reflections (yellow). This showed a decrease in material contrast with increasing depth. Electromagnetic waves propagate at velocities that depend on the dielectric properties of the material. In general, the propagation velocity of electromagnetic waves in peat layers was 0.026 m/ns. The thickness of the peat layer was accurately determined through a boring test conducted on track L22 at a trace distance of 102 out of 196 traces. Meanwhile, the travel time t of 161.8 ns was obtained from the radargram recording. The wave velocity was relatively low, hence, the material in the area was suspected to possess a high water content or be organic (Sumargana et al., 2019; Zhou et al., 2019).

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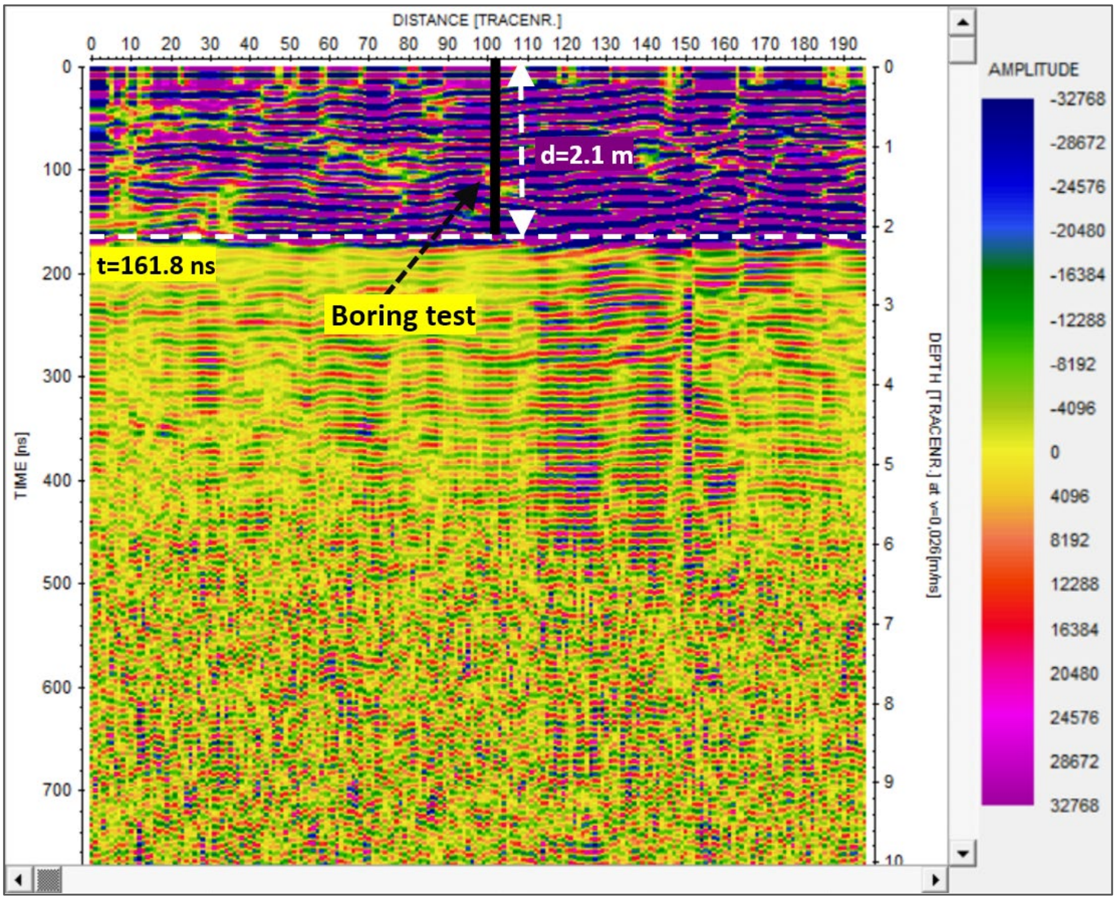

Figure 3. Parameters on the radargram L22 to obtain the wave propagation velocity

Data Processing to Identify Peat Layer Boundaries

The radargram data (raw data) processing consists of several steps, namely static correction, dewow, Butterworth bandpass, background removal, energy decay, subtracting average, and manual gain, as shown in Figure 4. The whole process was essential in estimating peat thickness, as it can improve the accuracy of detecting different subsurface layers, including peat layers. Removing noise and clarifying the reflection signal helped identify the boundary between the peat layer and the layers below.

Peat Thickness

The peat thickness was identified by marking the horizontal layer boundaries (horizons) on the radargram data from the manual gain process through horizon picking. An example of the results of the horizon-picking process used to identify the thickness in each layer is shown in Figure 5. The boundary between the peat and clay layers was obtained from the dominant contrast between the high and low amplitudes. The peat layer at the study location was classified as very deep because most of it had a thickness of more than 1 m. The deepest peat had a thickness of 4.2m on track L12, and the shallowest was 0.8m on track L1.

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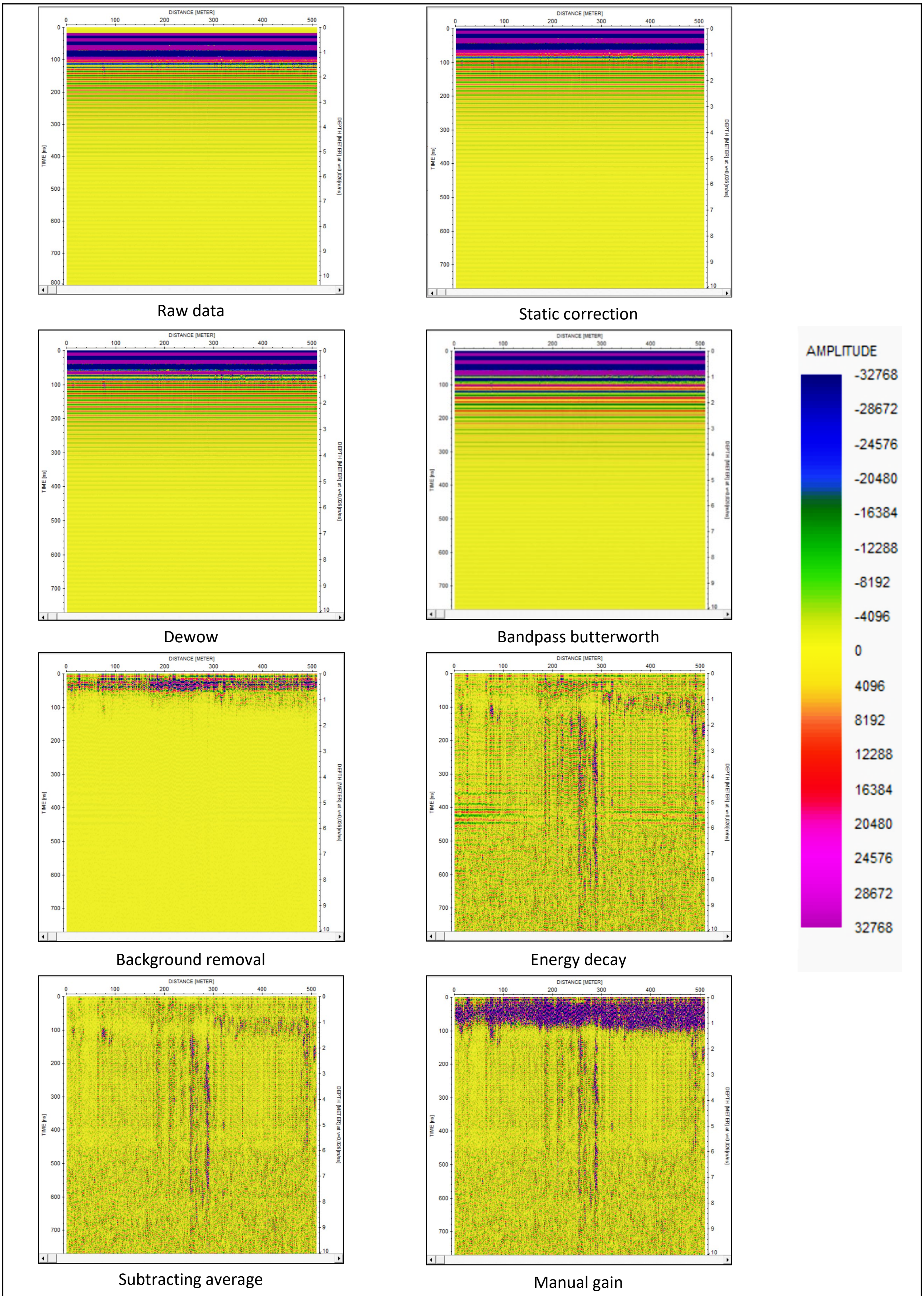

Figure 4. Examples of radargram processing results at each stage

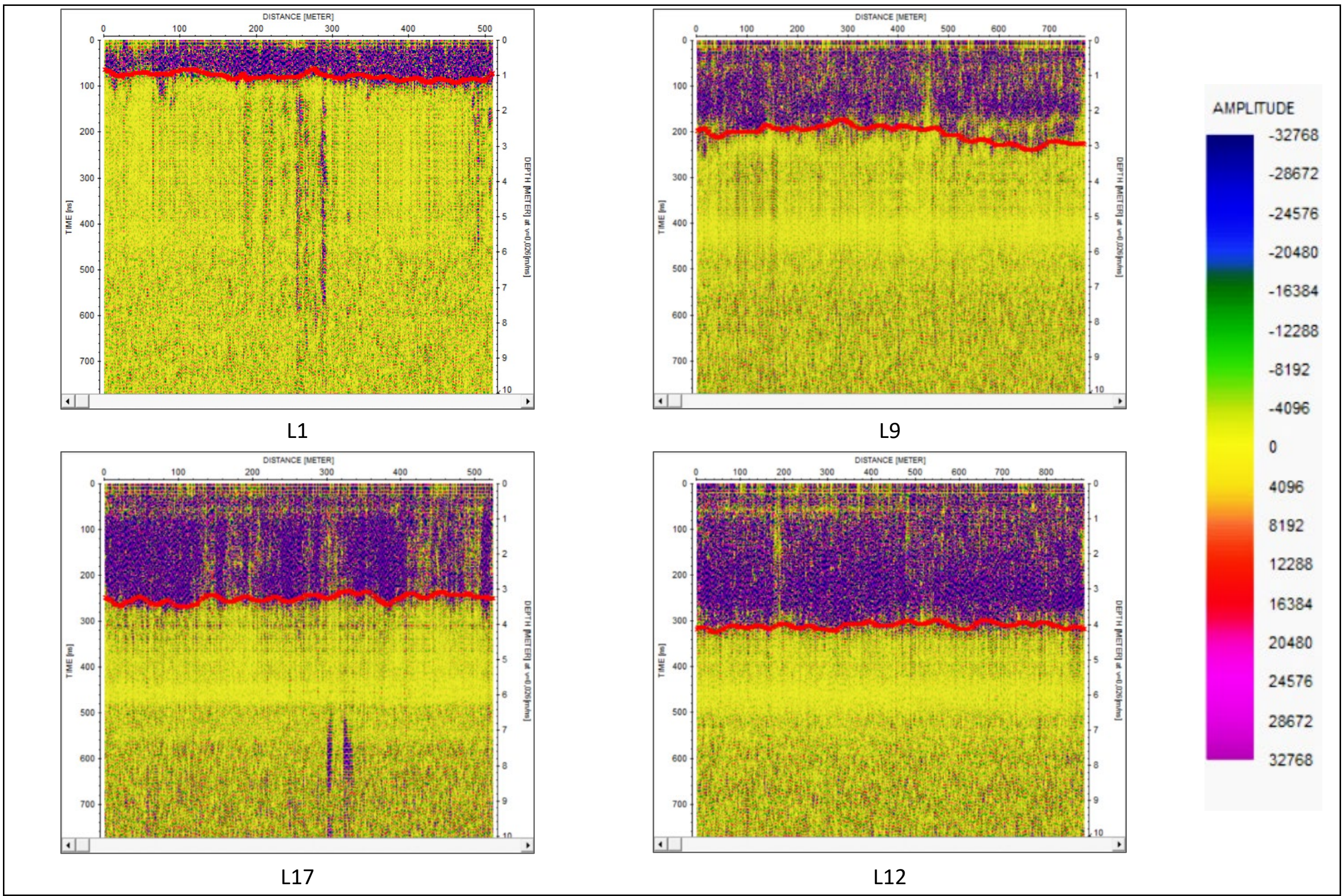

Figure 5. Example of peat thickness through the horizon picking process at shallow (L1), medium (L9), deep (L17), and very deep (L12)

This study obtained the wave propagation velocity by calculating the drill depth and trace data at the drill point. The radargram was adjusted to the depth of the trace point to obtain the travel time, leading to a wave propagation velocity of 0.026 m/ns. Wave propagation velocity possessed different values for each medium it passed through. The velocity in a medium was influenced by the permittivity of the materials composing the medium. The higher the ability of a material to store electrical energy in an electrical field (permittivity of the material), the smaller the wave propagation velocity (Mbango et al., 2022). Peat thickness in each track at the study location is shown in Table 1. At the location, the pear had different thicknesses and was classified as very deep because it is dominated by thicknesses of >3-5m.

The distribution of peat thickness in 2D contours is shown in Figure 6 and distinguished by color variations. Based on the thickness, light purple is signified as shallow peat with a 0.8-1m thickness. Dark blue reflected a medium peat with a thickness of 1-2 m. The yellow color suggested a deep peat with a thickness of 2-3 m. Orange to red signified a very deep peat with a 3-4 m thickness. In general, the thickness of peat in the eastern and northern parts was thicker than in the west and south. This was observed from the dominance of the yellow to red in the east and north, while the light purple to dark blue dominated in the west and south.

Table 1. Estimation of peat thickness for each track

Track	Track length (m)	Number of Traces	Thickness (m)
L1	511	2.871	0,8 – 1,1
L2	495	3.015	3,1 – 3,4
L3	500	3.263	2,7 – 3,1
L4	527	3.539	2,5 – 3,0
L5	557	4.310	2,9 – 3,6
L6	261	2.249	2,8 – 3,3
L7	192	1.681	2,8 – 3,2
L8	501	4.114	2,8 – 3,2
L9	510	4.511	2,4 – 2,9
L10	495	3.258	2,2 – 2,9
L11	632	3.079	1,9 – 2,9
L12	887	3.361	3,8 – 4,2
L13	484	2.064	2,7 – 3,2
L14	759	3.585	2,8 – 3,1
L15	837	4.319	2,6 – 3,0
L16	402	2.072	2,7 – 3,7
L17	525	5.143	3,1 – 3,5
L18	496	5.805	2,6 – 3,4
L19	494	5.088	3,0 – 3,3
L20	550	5.165	1,9 – 2,5
L21	328	3.989	1,8 – 2,6
L22	246	3.032	1,8 – 2,1

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Figure 6 shows the distribution map of peat thickness in the study area, categorized from shallow (<1 m) to very deep (>3 m). These characteristics had important implications for carbon storage potential. Areas with thickness of more than 3 m had the potential to possess high carbon stocks compared to the shallow areas (Vernimmen et al., 2020). Peat is also often associated with a greater risk of forest fires, specifically when it dries out due to human activities or climate change. Areas with shallow thickness tended to have a higher fire risk than deep peat. This is because shallow peat dries out more quickly (Nizam et al., 2023). Dried peat is highly fire-prone due to its high organic matter content. The blue and purple areas in the study location are potentially fire-prone.

The uneven distribution of thickness in the study location was caused by several factors, namely topography, drainage, and maturity (Word et al., 2022; Suryani et al., 2022). Low areas or basins were prone to having deeper thicknesses because of their ability to retain more water and support the accumulation of organic material. Poor drainage allowed the accumulation of more organic matter, leading to deeper peat. Maturity also affected its thickness and distribution characteristics. More mature peat generally had a denser and more compact structure because the organic material was subjected to further decomposition. In contrast, young or immature peat tended to be softer and porous and may have a deeper thickness because it has not reached significant compaction (Novrianti & Harisuseno, 2024).

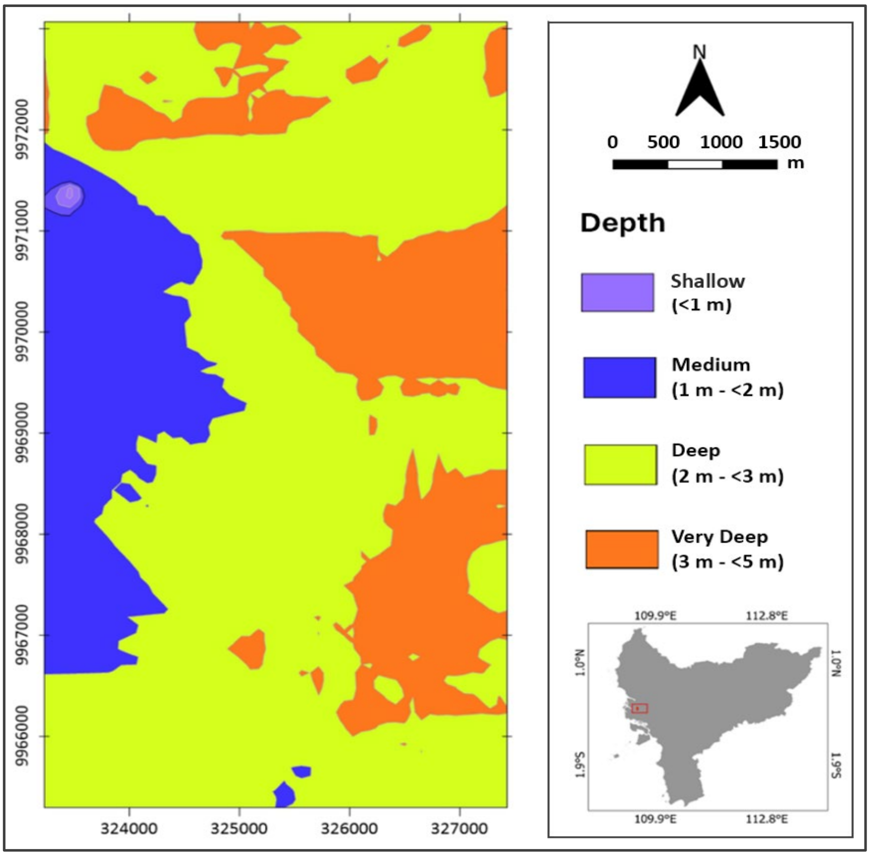

Figure 6. Distribution of peat thickness and its classification

Peat Volume

Volume of peat was obtained based on the distribution of thickness and the area of the study location. The interpolation process through the kriging method was conducted using the Surfer Software to produce a three-dimensional (3D) profile of the peat layer for estimating its volume. The method was used because it can estimate values between data points with a high level of accuracy (Fiantis et al., 2024). Based on the calculation of thickness distribution and the study area, the total volume was estimated to be approximately 4.8 x 10^7 m^3, as shown in Figure 7. This estimated value was influenced by the thickness distribution, which depended on factors such as topography, drainage, and maturity level. With such a significant volume, peatlands have a large capacity to store carbon, playing an essential role in climate change mitigation. Peat possesses the ability to absorb atmospheric carbon for thousands of years. When the lands are disturbed by fire, the stored carbon can be released back into the atmosphere as greenhouse gases, worsening global warming. Therefore, maintaining a moist area is essential to prevent fires, often a problem in tropical peat ecosystems.

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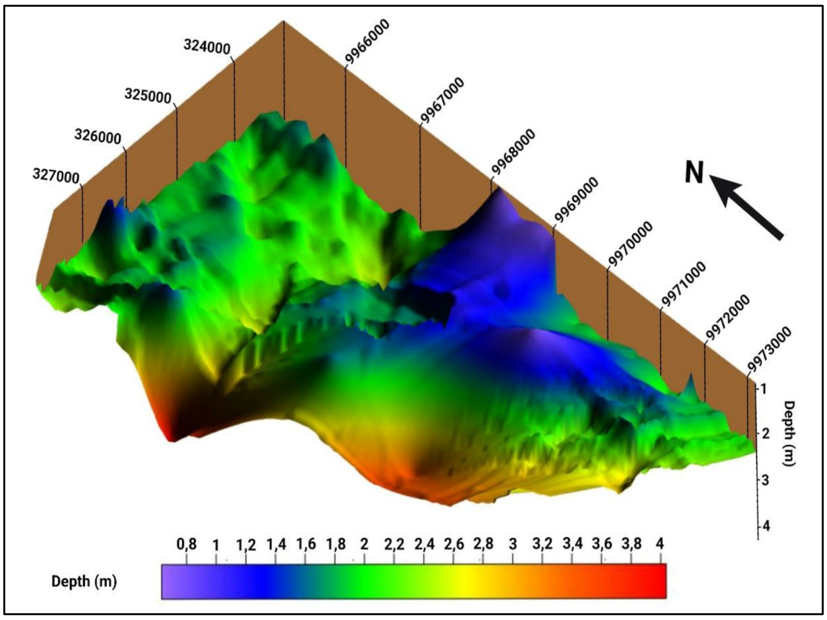

Figure 7. The 3D profile of the peat layer for estimating its volume

4. Conclusion

In conclusion, the GPR method was applicable for estimating peat thickness and volume. The radargram data (raw data) processing consisted of several steps, namely static correction, dewow, Butterworth bandpass, background removal, energy decay, subtracting the average, and manual gain. The thickness of peat was identified by marking the horizontal layer boundaries (horizons) on the radargram data from the manual gain process through horizon picking. The results showed that the subsurface electromagnetic wave propagation velocity at the study location was 0.026 m/ns, with a peat thickness of 0.8-4.2m. The deepest layer was in the east, with a thickness of 3.8-4.2m, while the shallowest was in the west, recording 0.8-1.1m. The results also show that the volume of peat in the study location was 4.8×107 m^3.

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