Exploring the potential of soil moisture maps using Sentinel Imagery as a Proxy for groundwater levels in peat

W C Adinugroho¹*, R Imanuddin¹, H Krisnawati¹, A Syaugi², P B Santosa³, M A Qirom³, and L B Prasetyo⁴

¹Forest Research and Development Center, Forestry and Environment Research, Development and Innovation Agency, Jl. Gunung Batu No 5 Bogor, 16610, Indonesia
²Peatland Restoration Agency of Indonesia, Jl. Teuku Umar No.10, RT.1/RW.5, Gondangdia, Kec. Menteng, Jakarta, 10350, Indonesia
³Forestry and Environment and Forestry Research and Development Institute of Banjarbaru, JL. Ahmad Yani, KM. 28, 7, Landasan Ulin Tim., Landasan Ulin, Banjarbaru, Kota Banjar Baru, Kalimantan Selatan 70721, Indonesia
⁴Faculty of Forestry, IPB University, Dramaga, Bogor, Indonesia

* wahyuk2001@yahoo.com (ORCID ID: 0000-0003-0687-5679)

Abstract. Degraded peatlands are extremely vulnerable to the threat of fires and have been a major source of national greenhouse gas emissions. Maintaining a certain level of water in peatlands is an essential measure of disaster vulnerability in peatlands. During the dry season, when the lower part of the peat still retains water, fires only occur on the surface and are relatively easy to extinguish. However, one of the limiting factors in peatland management and its more comprehensive application has been the availability of sufficient and spatially distributed Groundwater Level (GWL) data. This study explores the soil moisture map as a proxy for peat condition indicators that correlate with groundwater level. The case studies conducted at Tumbang Nusa Research Forest and Peat Hydrological Unit of Kahayan Sebangau show that peatland conditions can be estimated through biophysical parameters detectable from remotely-sensed data. Soil Moisture Map (SMM) can be produced with a higher resolution (Sentinel 1 = 10m) using the free and open tools SEPAL based on cloud computing infrastructure. The Support-Vector-Regression machine learning approach is used to estimate soil moisture. There is a correlation between SMM and GWL. However, the response to land cover varies. There is high uncertainty in densely forested areas where the sensors cannot penetrate the canopy. As a result, in its implementation, the SMM can be combined with the vegetation index, which can describe trends of land cover changes.

1. Introduction
Peatlands cover approximately 2-3 percent of the world's land area [1–3]. However, they can store twice as much carbon as the world's forests [2,4]. Indonesia is home to roughly 47 percent of the world's tropical peatlands[4]. The latest detailed information of the peatland area in Indonesia is 13.41 million ha. Peatlands range in depth from 50 to 1,050 cm with a dominance depth of 50–300 cm (69%) [5]. The most recent peatland area is less than the previous estimate of 15–27 million ha [6–8]. Forests and peatlands are currently one of the most pressing issues in the forestry sector in Indonesia. Despite their essential role as carbon storage, some areas have deteriorated. Sumatra and Kalimantan have the
fastest rates of peatland degradation [7,9]. Deforestation and drainage of Indonesia's peatlands are already occurring as a result of logging, agriculture, and fires [10,11]. Land preparation through burning exacerbates peat damage and makes peat a source of Greenhouse Gas (GHG) emissions [12,13]. Peatland degradation has also resulted in socio-economic issues, particularly for communities living around and within peatlands, whose livelihoods rely on the natural resources provided by these ecosystems [14]. Peat-based related greenhouse gas emissions are significant, accounting for approximately 10% of total emissions from the agriculture, forestry, and other land-use sectors (AFOLU) and 5% of the global emissions. Efforts to improve the accuracy of emission estimates continue [15,16].

Tropical peat has distinctive and specific characteristics due to differences in constituent material content, thickness, maturity, and the surrounding environment [17]. Because of these distinguishing and specific characteristics, peatlands are regarded as marginal lands that have an impact on damage. This point of view must be changed by implementing sustainable management to reduce the vulnerabilities, especially the fire threat.

Degraded peatland, which has no vegetation cover, dries out quickly due to the unique characteristics of peat [18]. This condition causes capillary water to move from below, unable to be held in the pore due to the heat of the soil surface, causing it to evaporate or dry quickly, and burn easily. Degraded peatlands are very vulnerable to the threat of fires. Peat fires contributed to one source of the national greenhouse gas emissions[19]. Maintaining a certain level of water in peatlands is an essential indicator of disaster vulnerability in peatlands. During the dry season, when the lower part of the peat still retains water, fires only occur on the surface and are relatively easy to extinguish. The study [18] demonstrates that the incidence of fires is closely related to changes in Groundwater Level (GWL). Fires are frequently started in areas with low GWL, less than -30 cm [20]. In this regard, GWL has been widely used as an essential indicator for predicting fire events [21,22]. Furthermore, GWL information is also required in peatland management and restoration [23]. However, the availability of massive and spatial GWL data has been one of the limiting factors in its more comprehensive application.

GWL field measurement data in Indonesia is generally high cost, and only available from a few, dispersed locations, is not available in long time-series data, and is of limited quality. Many measurement stations are located in relatively accessible locations to protect and maintain the equipment, which may not be ideal from a scientific standpoint when representing GWL across various types of land cover and land use. These factors pose challenges and gaps when using the field data to estimate broader GWL across the landscape and assess peatland status. The depth of the groundwater table and soil moisture are inextricably linked [10,24]. A correlation between field measurement data from GWL and soil moisture is the basis for using soil moisture as a proxy in GWL monitoring. This study aims to explore the potential of soil moisture maps using Sentinel imagery as a proxy for groundwater levels in peat. It is expected to solve the spatially limited availability of GWL data, despite the fact that it is required as an indicator of peat vulnerability.

2. Methodology
The study was conducted using a desk study and field survey, which was then analysed descriptively and quantitatively.

2.1. Site description
The study was conducted at Peat Hidrology Unit (PHU) Kahayan - Sebangau in Pulang Pisau regency, Central Kalimantan province (Figure 1). Previously, this PHU area was known as Block C PLG One Million Hectares between the Kahayan River and the Sebangau River. Pulang Pisau regency is the most fire-prone area in Central Kalimantan with an average density of ~3 hotspots per year, 10-3 under El Nino conditions, of which around 50% is in Block C or PHU Kahayan - Sebangau.
2.2. Methods

The soil moisture map was created using Copernicus Sentinel-1 intensity data [25], which uses machine learning-based mapping of high resolution, global surface soil moisture content. The soil moisture was estimated using the Support-Vector-Regression machine learning approach, with in-situ data from the International Soil Moisture Network (ISMN) used to train the model. PYSMM Soil Moisture Mapping Algorithm from [26] was submitted and the code documentation can be found here: https://pysmm.readthedocs.io/en/latest/ with edits and improvements made by the SEPAL team.

Data from groundwater level measurements at 16 BRG stations were used to analyse the relationship between groundwater level and the resulting peat moisture map. This study used Peat Hydrological Unit Map, Topographic Contour Map, Canal Network Map from Badan Restorasi Gambut/BRG (Peat Restoration Agency), and Sentinel-1 and Sentinel-2 Satellite Imageries. QGIS Desktop 3.14.0, Google Earth Engine, and Sepal platforms were used for image processing. System for Earth Observation Data Access, Processing, and Analysis for Land Monitoring (SEPAL) is an online platform and open-source software that allows users to easily access and process satellite data, and perform a series of customised geospatial analyses for various needs.

![Figure 1. Map of PHU Kahayan - Sebangau study site](image)

3. Results and discussions

PHU Kahayan - sebangau was used as a case study to explore the creation of soil moisture maps using remote sensing and analyse their potential uses.

3.1. Characteristics of PHU Kahayan – Sebangau

The peat ecosystem area of PHU Kahayan - Sebangau covers an area of ±311,323 ha, which includes cultivation and protection functions. The protection function becomes the dominant function of the peat ecosystem in the PHU Kahayan – Sebangau area. According to the results of BRG’s peat depth modeling, the peat depth ranges from 50 cm to 649 m (Figure 2a). There are many canal networks in this PHU area, as shown in Figure 2b from the results of the canal network mapping by BRG.
The results of the evaluation of the characteristics of inland peat at several points in the PHU Kahayan - Sebangau revealed the level of decomposition of surface peat (0 - 20 cm) classified as sapric (fiber content ~ 30%) with a bulk density of 0.17 - 0.26 g cm$^{-3}$.

![Figure 2](image)

**Figure 2.** Characteristics of PHU Kahayan - Sebangau: a) Peat depth, b) Canal Network

The land cover in PHU Kahayan – Sebangau consists of forest, shrubland, agricultural land, estate, barren land, Built-up land, and water bodies. There was a significant change in conditions in 2015 compared to 2020 (Figure 3). The barren land area in 2015 was covered by vegetation in 2020, even though it was only shrubs. Changes in cover conditions in 2015 and 2020 can also be seen from the NDVI vegetation index (Figure 4). The green color looks denser in 2020 than in 2015.

3.2. Soil moisture map

Assessment of the success of rewetting in stopping peatland degradation can be seen from high GWL and decreased subsidence rates [27,28]. GWL measurement in peatlands and canals is a high-priority activity that must be completed to assess changes in peat conditions, the impacts of drainage in various parts of the system (such as peat domes), fire risk, and estimates of carbon emissions, restoration requirements, and outcomes [28]. Although GWL is critical to halting peatland degradation, the optimal depth varies depending on the physical properties of the peat (i.e., water retention, unsaturated conductivity), which is related to the level of peat wetting (fibric, hemic, and sapric).
Figure 3. Land cover in PHU Kahayan – Sebangau: a) 2015, b) 2020

FAO has demonstrated that in situations of data scarcity, soil moisture values estimated from satellite data are a reasonable proxy for estimating GWL and demonstrate progress in restoration measures. Soil moisture estimation in remote sensing using microwave-based radar sensors such as Sentinel-1 is an indirect method that can overcome the challenges associated with measuring GWL in the field. The information obtained when microwaves interact with physical objects on the Earth's surface can indicate moisture content, salinity levels, and physical characteristics (shape, size, and orientation). The scattering properties of the soil depend on the level of surface roughness and the vertical distribution of soil moisture content [29].

In addition to the SAR’s sensor sensitivity to soil moisture [30], SAR is also not affected by cloud cover, which is a significant advantage to overcome the tropics, which are frequently cloudy [31]. As an active sensor, SAR can also operate all day and night because it does not require an external light source such as the sun. Furthermore, the frequency of observations, for example, Sentinel-1 passes through Indonesian territory every 12 days, provides excellent temporal resolution to observe changes [28]. Figure 5. shows the results of the soil moisture map at PHU Kahayan – Sebangau using Sentinel-1 imagery processed using the Soil Moisture Map (SMM) module on the sepals.
Figure 4. NDVI Vegetation Index from Sentinel image 2: a) 2015, b) 2020

Figure 5. Soil moisture map: a) February 2019, b) August 2019
3.3. Trend soil moisture

Figure 6. depicts the trend of soil moisture in PHU Kahayan from 2015 to 2020. It is clear that there is a pattern of increasing and decreasing soil moisture values throughout the year. The month with the highest humidity value is February, while the lowest humidity occurs in August. This condition can also be seen in Figure 5. This is closely related to the season; February is the rainy season while August is the dry season. After August, there was an increase in soil moisture and the arrival of the rainy season until February. After February, the soil moisture began to decline in tandem with the dry season, which lasted until August. This indicator can be used to assess preparedness for vulnerability on peatlands. From 2015 to 2020, there is an increasing trend of soil moisture which can demonstrate the positive impact of interventions to increase the groundwater level through canal blocking.

![Figure 6. Soil moisture in PHU Kahayan from 2015 to 2020](image)

3.4. Correlation of soil moisture from soil moisture map vs. GWL

A positive correlation (r = 0.547) is observed between soil moisture generated by the soil moisture map and GWL (Ground Water Level) in the PHU Kahayan-Sebangau (Figure 7). Table 1 shows the Pearson correlation between soil moisture and GWL. This correlation indicates that as soil moisture increases, so does GWL. The existing GWL monitoring stations are primarily located on agricultural land cover to cover them with vegetation. This factor may also cause this low correlation. Sentinel-1 data is C band SAR data is limited in areas with vegetation cover because the higher frequency sensor cannot penetrate the canopy. Several other studies have also found a correlation between soil moisture and GWL. There is a strong correlation between GWL and radar backscatter values in the Mega Rice Project area in Central Kalimantan, Indonesia [32]; degraded peatlands in Sarawak, Malaysia [30], and boreal peatlands in Alaska [33]. In all of these studies, an increase in GWL (in other words, an increase in soil moisture) was positively correlated with an increase in backscattering values.
Table 1. The Pearson correlation of soil moisture vs. GWL

| Correlations | GWL (m) |
|--------------|---------|
| SoilMoisture (%Vol) | Pearson Correlation | .597** |
|                  | Sig. (2-tailed)     | .000   |
|                  | N                  | 138    |

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 7. Graph of soil moisture derived from soil moisture map and GWL

4. Conclusion
Soil Moisture Map (SMM) can be produced with a higher resolution (Sentinel 1 = 10m) using the free and open tools SEPAL based on cloud computing infrastructure. There is a correlation between SMM and GWL. However, the response to land cover varies. There is high uncertainty in areas covered with dense vegetation where the sensors cannot penetrate the canopy. The vegetation index can detect the changes in land cover trends. As a result, in its implementation, the SMM can be combined with the vegetation index as a proxy for estimating GWL on peat.

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