The Utilization of Sentinel-1 Soil Moisture Satellite Imagery for Crop's Water Requirement Analysis in the Dryland Agriculture

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ABSTRACT

Soil moisture is an essential factor in supporting the crop's growth. The total soil moisture affects plant fertility, which impacts its productivity. The information about soil moisture can be used for crop scheduling to optimize the potential of the harvest and reduce crop failure risk. The utilization of remote sensing data to measure soil moisture can be implemented for routine agricultural practices. This information is important, especially for dryland agriculture such as in the Semanu, Gunung Kidul Regency. Value of soil moisture can be obtained from Sentinel-1 satellite image through the backscattering (σ◦) method, which involves Apply Orbit File, Thermal Noise Removal, Border Noise Removal, Calibration, Speckle Filtering, Range Doppler Terrain Correction, and Conversion to dB. The dB (σ◦) was then processed using the Dubois Model and Topp Model until the importance of soil moisture volumetric value was obtained, known in cm^3/cm^3. In this research, measuring the soil moisture value was also conducted by taking the soil sample tests under gravimetry methods for validation and sensor soil meter for comparison. Using Sentinel-1 to find soil moisture value is an alternative that can be done without conducting ground measurements. It is supported by a high resolution of 10x10 m and a standard error value of ±0,045. Furthermore, Sentinel-1 uses SAR (Synthetic Aperture Radar) possible to penetrate the cloud and land surface covers, even covered by lush vegetation. The backscattering data is, therefore, likely to be continuously generated. Based on the calculation of crops' water requirements by inputting the soil moisture values obtained from the calibrated Sentinel-1 data, the crop scheduling for dryland agriculture in the Semanu region was adjusted. Sentinel-1, which has interval data available every 12 days, is ideal for routine agriculture practices in real time. Therefore, the opportunity for agriculture development through Sentinel-1 is auspicious.

Keywords: *soil moisture, crop water, Sentinel-1, backscattering, Dubois Model, Synthetic Aperture Radar*

1. INTRODUCTION

The increase in food demand due to human population growth needs to be taken seriously, especially in food fulfillment. The potential of dryland to be expanded for alternative food products are relevant. The utilization of remote sensing can be applied to developing cultivation plants in dryland. Using Satellite imagery, like Sentinel-1, can be useful to measure a value of moisture level at certain time series [7]. The soil moisture value is very suitable for monitoring the growth of crops considering the duration of every phase, around ten days.

Data of Satellite imagery is available continuously. So that can be useful for monitoring soil moisture levels to analyze water crop requirements. The level of soil moisture value, known as water availability, is better than rainfall [10].

The stage of crop water requirement can be calculated by evapotranspiration. According to Arsyad [2], evapotranspiration is total water in a crop's area that is used for transpiration, evaporated from soil, water surface, and intercepted. The evapotranspiration value can be calculated as a unit of water thickness (mm) or area (m^3/ha).

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The phase of growth influences the total crop water requirement. According to Doorenbos dan Pruit [5], crop water requirement in every phase can be calculated from the crop coefficient (Kc). The value of Kc for every crop is different according to type and growth phase. The value of Kc maximum occurs when the crop gets into a critical phase [1]. In this phase, crops need more available water for the production process. The essential phases of every crop type are different. Potato crops have a critical phase when producing tuber. Tomato plants go through a critical phase when flowering formation. Tobacco plants experience a critical phase in the vegetative stage. Therefore, the critical phase of the plant is necessary to notice so that the productivity of cultivation is maximal.

Crops with adequate water needs will thrive optimally, thus having an impact on crop productivity. Therefore, the information generated by the Sentinel-1 Satellite Image, namely soil moisture content, can be used to determine agricultural commodities suitable for dry land cultivation. Processing soil moisture content data within one year is used as a reference for calculating the availability of soil moisture content. Then determine the type of commodity cultivated by taking into account the water needs of each plant's growth/development phase [13].

Utilization of Satellite Sentinel-1 Imagery to find out the value of soil moisture because this Satellite uses sensor radar C-Band in the form of a microwave. The microwave wavelength in frequency C-Band is 5,6 cm [3]. The advantage of C-Band radar is the ability to penetrate disturbances in the form of covers such as clouds and vegetation. Therefore, this satellite continuously produces data on soil moisture content without being disturbed by weather/environmental conditions and time [9]. Data acquisition from Sentinel-1 has four modes based on the sweep width and recording azimuth. The four data acquisition modes include Strip map Mode (SM) with a sweep width of 80 km and a spatial resolution of 5 x 5 m; Interferometric Wide Swath Mode (IW) with a sweep width of 250 km and a spatial resolution of 5 x 20 m; Extra-Wide Swath Mode (EW) with a sweep width of 400 km and a spatial resolution of 20 x 40 m; and Wave Mode (WV) with a sweep width of 20 km every 100 km and a spatial resolution of 5 x 5 m in option incidence angle 23^{o} dan 36^{o} [7].

The backscatter value method (backscatter value) is used to obtain the value of *sigma naught* ($\sigma°$). This value results from the interaction of two parameters, namely field parameters, and radar parameters. Field parameters include parallel or cross-polarization of electromagnetic waves during recording. The radar parameter is the polarization of the electromagnetic wave transmitted by the radar antenna [11].

The value of soil moisture content was obtained using the formula from Dubois [6] and Model Topp [12]. The Dubois formula is used to process the backscatter value to obtain the relative soil permittivity value. Meanwhile, the Topp model is used to get the volumetric soil moisture content value based on the relative soil permittivity value.

2. STUDY AREA

This research was conducted by taking several limitations into account to fit the objectives:

a) The study area is located at Kapanewon Semanu, covering the Semanu, Ngeposari, Dadapayu, Candirejo, and Pacarejo Villages.
b) The research was conducted on two land-use types, which are agricultural land (paddy fields and dry fields) and shrubs with a variation of five slopes including 0 – 3%, 3 – 8%, 8 – 15%, 15 – 30%, dan >30%.
c) The satellite image used is Sentinel-1 from April 2021 to April 2022.

3. MATERIAL AND METHODS

3.1. Tools and Material

This research uses a gravimetric soil sampling set to validate the measured soil moisture. A tool for taking soil samples as gravimetric includes a small shovel, hammer, wooden block, sampler ring, dagger, plastic bag, Styrofoam box, ice gel, analytical balance, aluminum crucible oven, and desiccator. A software tool is used to process the sentinel data and landcover retrievals, such as SNAP, Google Earth Engine, and ArcGIS. The use of the SNAP tool is to read the data from Sentinel-1 Satellite Imagery and then to process land cover data and DEM (Digital Elevation Model) to determine research sample points. The data type of Sentinel-1 is level-1 GRD ranging from April 2021 to April 2022.

3.2. Methods

The methodology of this research is represented in Figure 1 below.

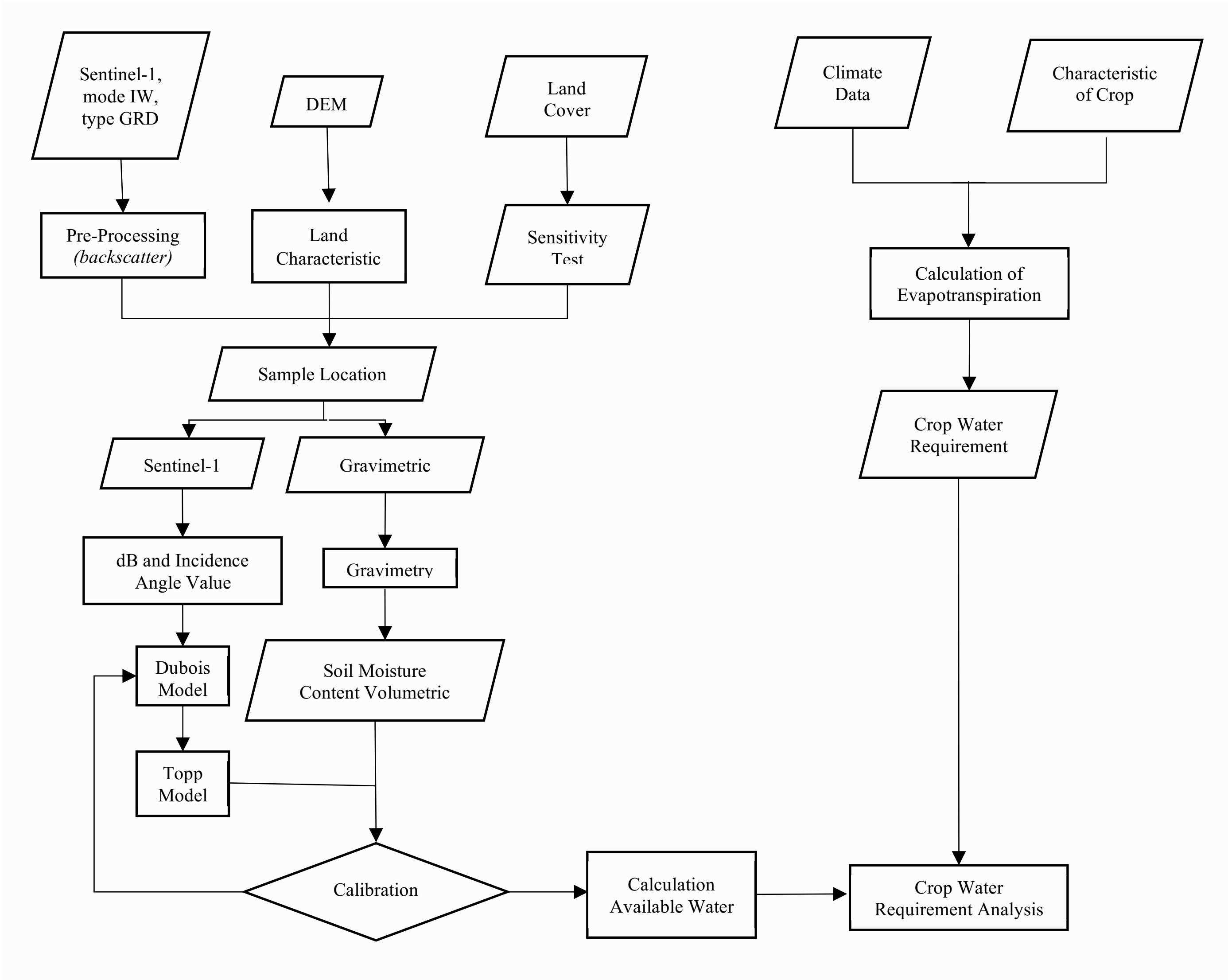

Figure 1 Research methodology

This study used two data on soil moisture content from Gravimetry and Sentinel-1. Gravimetric data was obtained through the process of the oven for 24 hours. Meanwhile, soil moisture content data from Sentinel-1 was obtained through the backscattering process and processing in the Dubois and Topp Models.

3.2.1. Gravimetric

The gravimetric method is used to determine soil moisture content. To measure soil moisture content, soil sampling was carried out five times in March and April 2022. The moisture content is calculated based on the volume of the soil on Equation (1), then the calculation on a mass basis based on Equation (2), and the calculation on a volume basis based on Equation (3).

$$V = \frac{1}{4}\pi d^2 t \tag{1}$$

Where:
V = soil volume (cm^3)
d = diameter ring (cm)
t = high ring (cm)

$$\theta_m = \frac{m_w}{m_s} \tag{2}$$

$$\theta_m = \frac{m_0 - m_1}{m_1} \tag{3}$$

Where:

θ_m = soil moisture content on a mass basis (g)
m_w = water mass (g)
m_s = soil mass (g)
m_0 = soil mass before oven (g)
m_1 = soil mass after oven (g)

$$\theta_v = \theta_m \frac{\rho_{b\cdot}}{\rho_w} \tag{4}$$

$$\theta_v = \frac{m_w}{m_s} \cdot \frac{\frac{m_s}{V}}{\rho_w} \tag{5}$$

Where:
θ_v = soil moisture content on volume basis (cm^3/cm^3)
ρ_w = density of water (g/cm^3)
ρ_b = density of soil (g/cm^3)
V = soil volume (cm^3)

3.2.2. Sentinel-1

The Sentinel-1 Satellite Image data was retrieved from May 2021 – April 2022 and was processed according to the following stages.

3.2.2.1. Backscattering

The moisture content value from Sentinel-1 is determined based on the backscatter value in the decibel unit (dB). The steps to obtain the final soil moisture values follow 1) Image subset of Semanu Sub-district, 2) Apply Orbit File, 3) Thermal Noise Removal, 4) Calibration to generate sigma_0 band values, 5) Speckle Filter to remove interference in the image in the form of black and white spots, 6) Terrain Correction aims to adjust the image geometry by involving DEM, and 7) Convert sigma value to dB.

3.2.2.2. Dubois Model

The backscatter coefficient value (dB) from the backscattering process is processed in Equation (6). It obtains the relative permittivity of the soil.

$$\sigma°_{VV} = 10^{-2.35} \left(\frac{cos^3\theta}{sin^3\theta}\right) 10^{0.046\mathcal{E}\tan\theta} (k.s.\sin\theta)^{1.1} \lambda^{0.7} \quad (6)$$

Where:

σ^0 = backscatter coefficient for VV polarization
θ = projected incidence angle (deg)
$\mathcal{E}$ = relative soil permittivity
s = surface roughness (4.27 cm)
k = $(2\pi/\lambda)$, wavenumber
λ = SAR wavelength

3.2.2.3. Topp Model

The relative soil permittivity generated by the Dubois Model is then processed in the Topp Model. This model obtains the volumetric soil moisture content (cm3/cm3).

$$m_v = -5{,}3 \times 10^{-2} + 2{,}92 \times 10^{-2}\epsilon - 5{,}5 \times 10^{-4}\epsilon^2 + 4{,}3 \times 10^{-6}\epsilon^3 \quad (7)$$

Where:

m_v = volumetric soil moisture content (cm^3/cm^3)
ϵ = relative soil permittivity

3.2.3. Sentinel-1 Calibration

Soil moisture content from Sentinel-1 was measured with statistical tests on moisture content from Gravimetric. The statistical tests are RMSE, Mean Bias, Standard Deviation, and Correlation Coefficient. Equation (8) was obtained from these statistical tests to make corrections to the soil moisture content data from Sentinel-1.

$$KLS = S - 0{,}23 \quad (8)$$

Where:

KLS = soil moisture content corrected from Sentinel-1
S = soil moisture from Sentinel-1
G = soil moisture from Gravimetric

3.2.4. Conversion of Soil Moisture Volumetric to Water Thickness

The soil moisture content of Sentinel-1 has volumetric units. Meanwhile, crop water requirements are expressed in mm/day. Therefore, it is necessary to convert the value of soil moisture content from volumetric units to the soil moisture content in units of water thickness. The equation for converting soil moisture content from volumetric to water thickness follows Equation (9).

$$d = \frac{(KLS - TL)}{100} \ x \ \rho b \ x \ D \quad (9)$$

Where:

KLS = soil moisture content from Sentinel-1 (%)
TL = wilting point (24,5%)
d = total available soil moisture content (mm)
ρb = bulk density (without unit)
D = soil sampling depth (mm)

3.2.5. Crop's Water Requirement (CWR)

Crop water requirements are calculated using monthly evapotranspiration based on Equation (10).

$$ETo = p \ x \ (0{,}46 \ x \ Tmean + 8) \quad (10)$$

Where:

ETo = potential evapotranspiration (mm/day)
p = mean daily percentage (p) of annual daytime hours
$Tmean$ = mean daily temperature (°C)

Next, the potential evapotranspiration according to each phase is calculated based on Equation (11)

$$ETof = \frac{duration \ of \ phase}{duration \ of \ month} \ x \ ETo \quad (11)$$

Where:

$ETof$ = potential evapotranspiration in every phase (mm/day)
Duration of phase= number of days required for each phase (days)
Duration of month= number of days in the month that a phase last (days)

Then, evapotranspiration is calculated to obtain each crop's water requirements based on the characteristics or crop coefficient (Kc). Calculations are carried out based on Equation (12)

$$ETc = ETof\ x\ Kc \quad (12)$$

Where:

ETc = crop water requirement according to phase(mm/day)

4. RESULTS AND DISCUSSION

The Gravimetric and Sentinel-1 methods were obtained from volumetric soil moisture content (cm^3). Moisture content data from the Gravimetric method were collected four times; March 14, 2022, March 26, 2022, April 7, 2022, and April 23, 2022. The recording time of Sentinel-1 has been adjusted to gravimetric data retrieval so that validation and correction tests can be carried out.

Statistical tests were carried out to determine the validity of the soil moisture content of Sentinel-1. The statistical test results are presented in Table 1 below.

Table 1. Statistical Test Results on Sentinel-1 Data Before and After Corrections

Data	RMSE	Mean Bias	Standard Deviation
Before	0.24	0.23	0.045
After	0.07	0	0.045

The results in Table 1 show that before calibration, the average mean bias obtains 0.23, which means the difference between both measurements is 0.23 mm. After calibration, the soil moisture content of Sentinel-1 has a lower RMSE value and mean bias. The results prove that the calibrated Sentinel-1 moisture content is close to Gravimetric measurements. Meanwhile, the standard deviation and correlation coefficient values before and after calibration are less different.

The standard deviation value of 0.045 indicates that the data on soil moisture content does not change the variation in value. As regards the result above, the Sentinel-1 satellite imagery doesn't require calibration when the in-situ test is not possible to conduct. The generated calibration equation can correct the Sentinel-1 soil moisture content value for one year. Soil moisture content within one year expressed in units of water thickness is presented in Figures 2 and Figure 3.

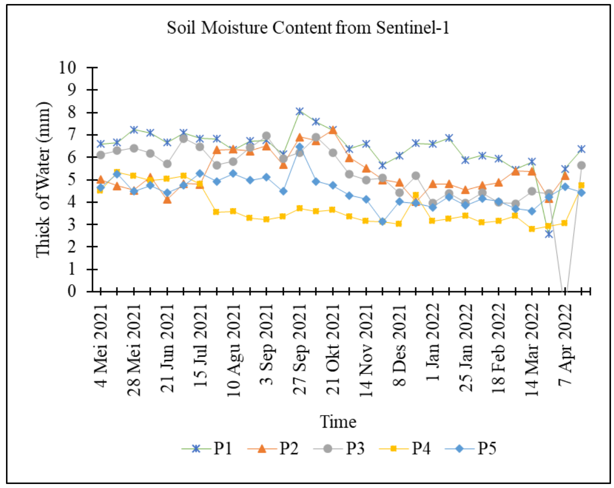

Figure 2 Soil Moisture Content in Dryland Farming

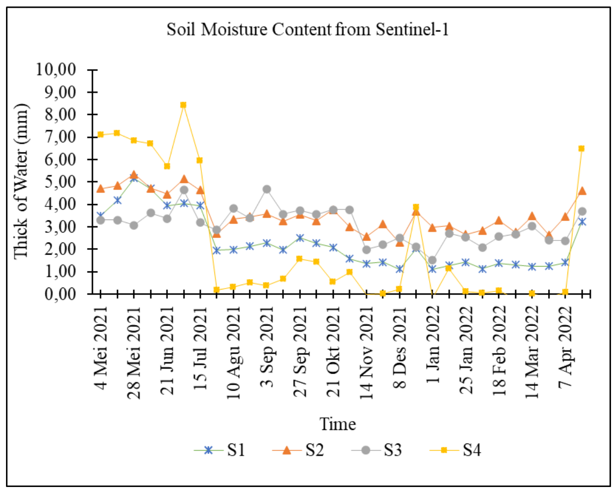

Figure 3 Soil Moisture in Bushland

The results shown in Figure 2 and Figure 3 indicate that the soil moisture content of dryland farming is higher than in bushlands. This is due to land processing activities. According to Darwis [4], cultivated land will make the soil loose, thus creating more pore space in the soil. As a result, the capacity of the soil to store water through the infiltration process will be higher. Meanwhile, uncultivated soil will experience compaction due to the blow of rainwater. Thus, it impacts the soil's low pore space as a place to store water. In addition, it is also known that the soil moisture content on land with a downward slope tends to be higher. This is caused by the movement of rainwater due to gravity to form a runoff so that more rainwater collects on flatter land. On the other hand, rainwater will experience infiltration and storage in the soil, maintaining the soil moisture [4].

Based on the calculation of crop water requirements that refers to the value of evapotranspiration, the amount of crop water in units of water thickness (mm/day) is known. The level of crop water requirements has been calculated based on the growth phase and growing period. The results are presented in Table 2, Table 3, and Table 4 below.

Table 2. Crop Water Requirement January – April (mm/day)

Crop Type	Crop Water Requirement January – April (mm/day)				
	Initial	Vegt	Flower	Seed	Ripe
Paddy	2.56	5.71	5.46	8.37	2.18
Ground Nut	1.15	4.59	6.73	5.77	1.10
Onion	1.60	3.25	4.75	2.37	3.28

Table 3. Crop Water Requirement May-August (mm/day)

Crop Type	Crop Water Requirement May-August (mm/day)				
	Initial	Vegt	Flower	Seed	Ripe
Paddy	2.34	5.07	4.93	7.44	2.11
Ground Nut	1.05	4.25	6.09	5.47	1.06
Onion	1.46	2.95	4.16	2.33	3.01

Table 4. Crop Water Requirement September – December (mm/day)

Crop Type	Crop Water Requirement September – December (mm/day)				
	Initial	Vegt	Flower	Seed	Ripe
Paddy	2.40	5.23	5.35	8.83	2.24
Ground Nut	1.08	4.38	6.67	6.00	1.13
Onion	1.51	3.04	4.29	2.41	3.47

The results in Tables 2, 3, and 4 indicate that paddy commodities are the most crop water needs. In addition, it is also known that from January to April, the water needs of the crops are higher than in other months. This is due to the high evapotranspiration in that month.

The soil moisture content obtained has shown the thickness of the water that crops can use. Thus, an analysis can be carried out to determine the suitability of crop types to the availability of soil moisture in dryland based on Sentinel-1. The results are presented in Figures 4 to 8 below.

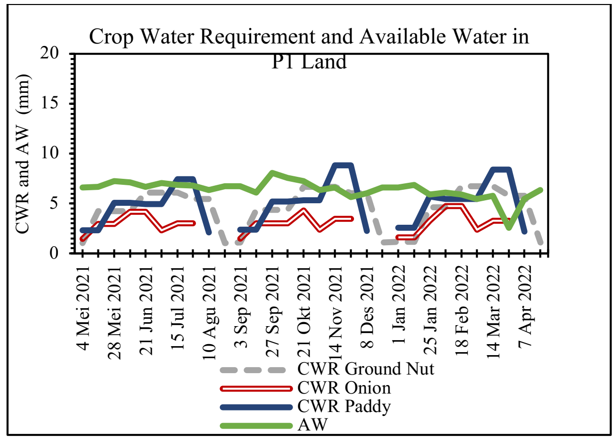

Figure 4. Analysis of Water Requirement and Soil Moisture Content in P1 Dryland Agriculture

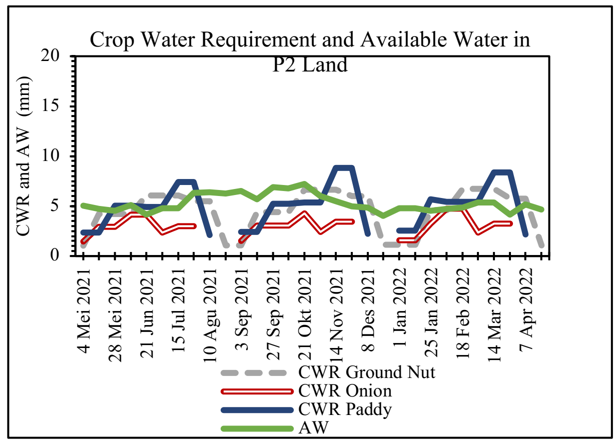

Figure 5. Analysis of Water Requirement and Soil Moisture Content in P2 Dryland Agriculture

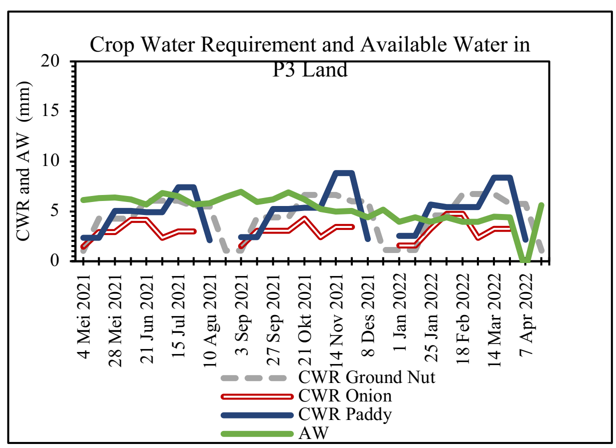

Figure 6. Analysis of Water Requirement and Soil Moisture Content in P3 Dryland Agriculture

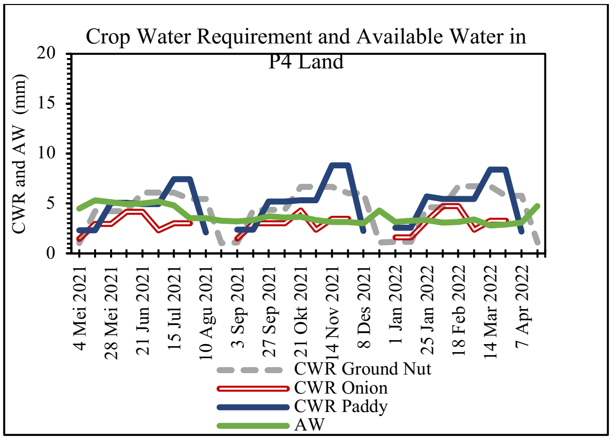

Figure 7. Analysis of Water Requirement and Soil Moisture Content in P4 Dryland Agriculture

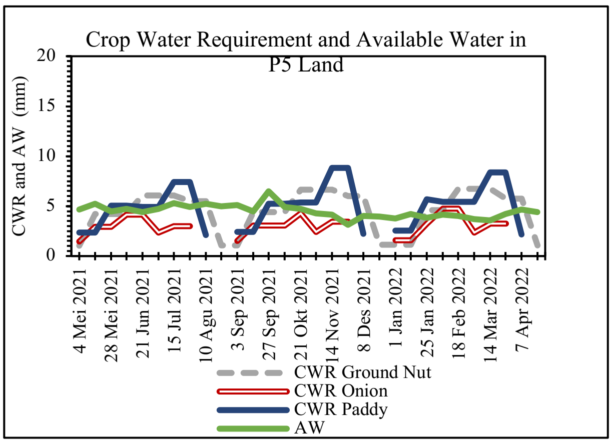

Figure 8. Analysis of Water Requirement and Soil Moisture Content in P5 Dryland Agriculture

The results shown in Figures 4 to 8 indicate that the suitable water needs of crops throughout the year are onion. Based on this analysis, agricultural development for onion cultivation in dry land is the best potential. This is because the water needs of onions are fulfilled on various land slopes. The fulfillment of crop water needs can optimize the process of its growth and productivity.

5. CONCLUSIONS

Sentinel-1 satellite imagery can potentially be used in agricultural development on dryland, especially for moisture content monitoring. The Sentinel-1 Satellite Image is useful for calculating the crop water requirements during the crop phase. It is reliable to be use in different types of land cover and slopes. However, Sentinel-1 showed a higher sensitivity in soil moisture measurement in agricultural land than in bushland.

Based on the results, the onion is the best commodity cultivated in the Semanu region. It reveals that the soil moisture content utilized by onion consistently exceeds the water requirement. Thus, the phase development of crop growth can be fulfilled.

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