Development of a Web-Based Analytical Framework for Soil Moisture Estimation Using Multipolarized SAR Data

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Keywords: Remote Sensing, Synthetic Aperture Radar, Soil Moisture, Water Cloud Model, Web-Based System.

Abstract

This study developed a novel framework to estimate and visualize soil moisture using KOMPSAT-5 synthetic aperture radar (SAR) data in a real-time web-based environment. We investigated two approaches: one combining NDWI derived from KOMPSAT-3A optical data with SAR backscatter, and another relying solely on the Radar Vegetation Index (RVI) computed from KOMPSAT-5 dual-polarized imagery. Through a modified Water Cloud Model (WCM), we compared the two methods against ground-truth measurements in wheat fields located in the Wimmera region of Australia. Results showed that both NDWI+SAR and RVI+SAR achieved similar levels of accuracy (R2 ranging from 0.6865 to 0.6951), suggesting that a SAR-only approach can be a valid alternative when optical data are unavailable or affected by atmospheric conditions. Our integrated web system further automates tasks such as SAR preprocessing, vegetation index calculation, and map overlay, enabling users to interpret soil moisture trends and dynamic changes over time with minimal effort. Looking ahead, future satellites such as KOMPSAT-6, providing higher resolution and full polarization data, may enhance the performance of SAR-only models. This study thereby demonstrates a scalable and practical solution for soil moisture monitoring and broader agricultural or environmental applications.

1. Introduction

Since the launch of Korea Multi-Purpose Satellite-1 (KOMPSAT-1, also referred to as Arirang-1) in 1999, South Korea has consistently advanced its Earth observation satellite technology, achieving notable successes both academically and industrially. These domestically developed satellites, widely recognized for their utility in fields such as agriculture, environmental monitoring, climate research, and disaster management, have undergone continuous evolution. High-resolution optical imagery from KOMPSAT-2, KOMPSAT-3, and KOMPSAT-3A, in particular, has been extensively used in geographical and environmental research, urban development, and national defense applications. Going forward, the national space program aspires to extend its satellite-based observation capabilities by launching KOMPSAT-6, next-generation medium-sized satellites, and microsatellite constellations. These prospective missions are expected to deliver improved spatial resolution as well as advanced polarimetric and hyperspectral imaging technologies, further increasing the impact of satellite data for both research and operational use (Lee, 2024).

Despite these advancements, fully harnessing the capabilities of satellite data remains challenging due to a number of issues. One of the most pressing problems is the fragmented management of datasets across diverse government agencies and research organizations. This often leads to inconsistent data formats and, in some cases, duplicates of identical imagery for the same region and time period. Consequently, researchers and practitioners can experience significant bottlenecks when attempting to locate or process the required datasets in a timely manner. In addition, certain agencies restrict data accessibility based on security considerations or internal policies, while others provide user interfaces that are poorly suited for practical implementation. These shortcomings underscore the necessity for an integrated system that can organize, store, and analyze multi-source satellite data in a coherent and user-friendly manner (Kim, 2023).

In recent years, web-based tools have emerged as a powerful means to streamline data integration and facilitate real-time sharing. By centralizing data management in a server-based environment, these platforms eliminate the need for users to install specialized software or undergo complicated setup procedures. Researchers, policymakers, and other stakeholders can thus access large and varied datasets from any internet-enabled location, making it easier to conduct complex analyses or carry out time-series investigations. This shift has the added benefit of encouraging interdisciplinary collaborations, as individuals working on different aspects of a project from agriculture to climate modeling can simultaneously explore the same online repository of geospatial data and derived products.

Soil moisture estimation represents a critical application domain for satellite data, intersecting with research topics that include hydrological modeling, evapotranspiration analysis, precision agriculture, and broader climate change studies. Nonetheless, optical satellites alone face inherent limitations, particularly their inability to capture data at night or through extensive cloud cover. Synthetic Aperture Radar (SAR) satellites, such as KOMPSAT-5, provide a strong alternative, offering all-weather, day-and-night imaging capabilities. These features make SAR highly suitable for continuous soil moisture monitoring, especially in agricultural regions where seasonal cloud cover can pose a significant obstacle to timely data collection (Tao et al., 2022). By delivering consistent, weather-independent measurements, SAR-based approaches can fill crucial data gaps that would otherwise compromise analyses of water resource dynamics or crop health.

Against this backdrop, the present study introduces a straightforward web-based tool rather than a conversation-driven or chatbot interface that focuses on using KOMPSAT-5 SAR data to compute soil moisture indices and display the results in an interactive online environment. The core objective of this system is to simplify the process of obtaining, processing, and interpreting soil moisture information without requiring specialized technical expertise or multiple software installations. Researchers and practitioners can upload relevant satellite images, perform automated computations to retrieve soil moisture estimates, and visualize the outcomes on a map-based interface that supports basic interactivity, such as zooming and panning. By consolidating these functionalities in a user-friendly web application, the system aims to remove many of the practical barriers associated with multi-source satellite data analysis, thereby making it easier to track and understand spatiotemporal changes in soil moisture conditions.

Ultimately, this effort builds upon ongoing national satellite programs and the expanding global interest in Earth observation technologies, demonstrating how a simple yet robust web-based platform can serve diverse user communities. By taking advantage of SAR data’s unique strengths particularly under cloudy or nighttime conditions and providing an accessible interface for data exploration and analysis, the proposed tool enhances the reliability and scope of soil moisture monitoring. As satellite missions become increasingly sophisticated, such online systems will be well-positioned to handle more complex sensor data, integrate auxiliary datasets (e.g., meteorological or field measurements), and adapt to the evolving needs of climate-impacted regions worldwide.

2. Materials and Methods

2.1 Soil Moisture

2.1.1 Study Area

This study was conducted on three wheat cultivation fields located in the Wimmera region of Australia. Field experiments were carried out in 2019, with soil moisture sensors installed at depths of 20–50 cm from May (prior to sowing) to November (harvest period) to obtain in situ observations. The collected data encompassed different growth stages, including early, mid, and late growing seasons, and were utilized to validate the soil moisture estimation model proposed in this study.

2.1.2 Satellite Data

In this study, both KOMPSAT-3A optical imagery and KOMPSAT-5 SAR imagery were utilized, as summarized in Table 1.

To align with the timing of field observations, KOMPSAT-5 SAR data were acquired at approximately two-month intervals from May to November 2019, collecting VV and HV polarization data. These acquisitions covered the entire wheat growth cycle, ranging from bare soil conditions to the ripening stage. The collected SAR imagery was resampled to a spatial

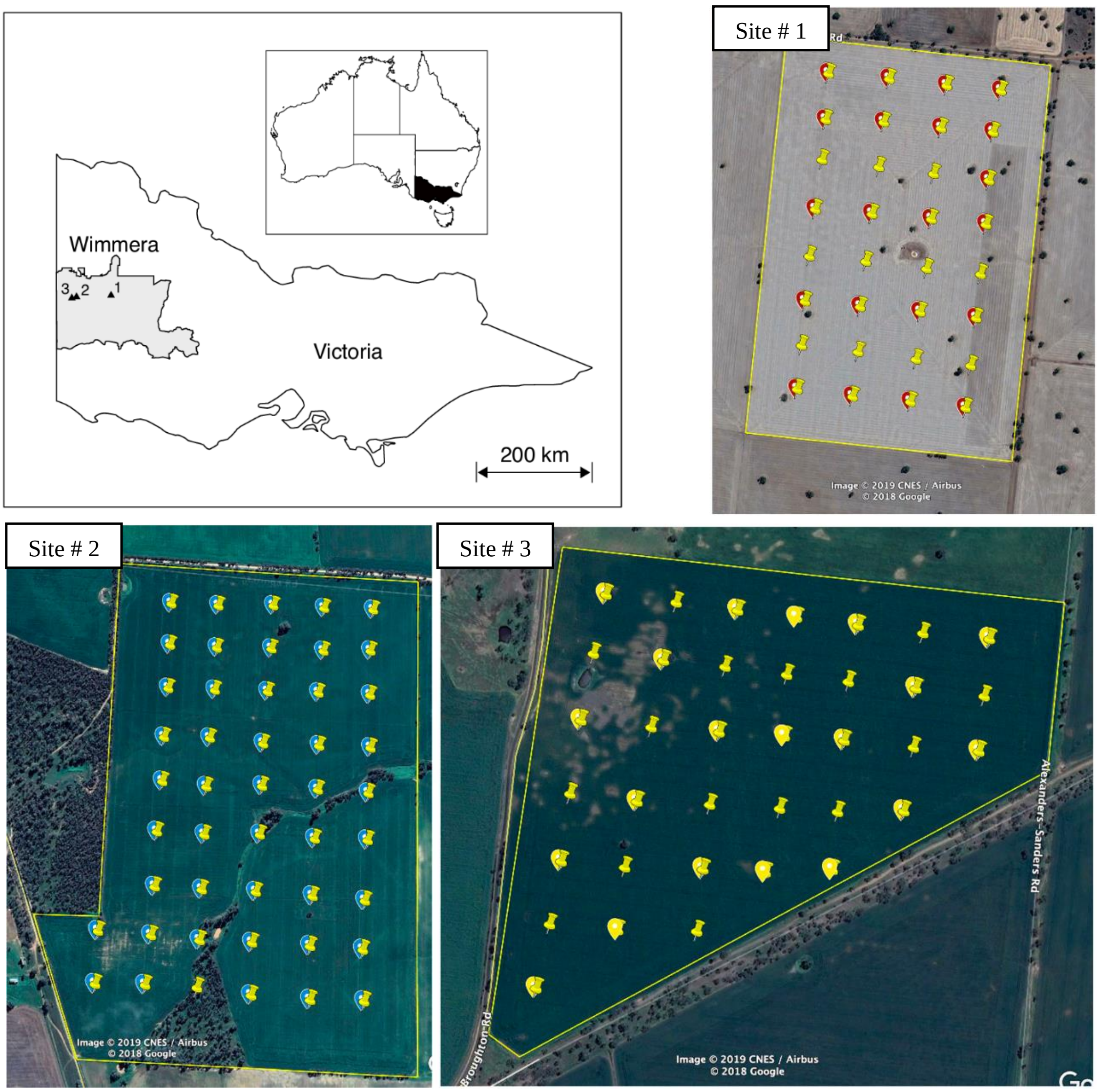


Figure 1. Study area of the soil moisture estimation experiment in the Wimmera, Australia.

resolution of 3 m and underwent radiometric calibration, terrain correction, and speckle filtering to obtain backscatter coefficients (σ^0) in dB units with an incidence angle of approximately 40°.
Meanwhile, the optical data were derived from KOMPSAT-3A, covering the same observation period (May–November 2019) and including red, green, and near-infrared (NIR) spectral bands. To estimate soil moisture in agricultural regions, vegetation moisture content (VMC) was incorporated into the model using the Normalized Difference Water Index (NDWI), which was computed from the green and NIR bands. The acquired KOMPSAT-3A and KOMPSAT-5 remote sensing data were subsequently converted into NDWI and Radar Vegetation Index (RVI), respectively, and used as input variables for soil moisture estimation based on the Water Cloud Model (WCM).

Satellite	Date	Polarization	Band
KOMPSAT-5	2019-05-07	HV	X-band
	2019-05-08	VV	
	2019-07-26	HV	
	2019-07-27	VV	
	2019-09-17	VV	
	2019-09-18	HV	
	2019-11-18	HV	
	2019-11-19	VV	
KOMPSAT-3A	2019-05-08	-	Blue
	2019-07-23		Green
	2019-09-11		Red
	2019-11-15		NIR

Table 1. Acquisition details of KOMPSAT-3A and KOMPSAT-5 imagery used in this study

2.1.3 Soil Moisture Estimation

In this study, a modified version of the Water Cloud Model (WCM), originally proposed by Bao et al. (2018), was employed to assess the feasibility of estimating soil moisture using only SAR imagery. The standard WCM formulation is given in **Equation (1)**:

$$SM = k_1 + k_2 \cdot \sigma^0 + k_3 \cdot VI + k_4 \cdot VI^2 + k_5 \cdot VI^3 + k_6 \cdot VI^4 + k_7 \cdot \sigma^0 \cdot VI \cdot sec\theta + k_8 \cdot \sigma^0 \cdot VI^2 \cdot sec\theta \quad (1)$$

where *SM*= Soil Moisture
k = Empirical coefficient
VI = Vegetation index **(**In this study, RVI or NDWI**)**
secθ = Incidence angle
σ^0 = Backscatter coefficient in VV polarization (dB)

Previous WCM-based studies have predominantly estimated vegetation moisture content (VMC) by integrating SAR backscatter coefficients with vegetation indices derived from optical imagery, such as the Normalized Difference Water Index (NDWI). However, simultaneous utilization of optical and SAR sensors poses certain limitations due to differences in observation timing and spatial resolution. Furthermore, optical imagery is highly susceptible to atmospheric conditions, such as cloud cover, making consistent data acquisition challenging (Cho et al., 2021).
To overcome these constraints, this study compared two approaches: (1) the conventional method that integrates NDWI and SAR data, and (2) an alternative method using only the Radar Vegetation Index (RVI), which is derived exclusively from SAR data. NDWI is computed using the green and near-infrared (NIR) bands, as defined in Equation (2):

$$NDWI = (NIR - Green)/(NIR + Green) \quad (2)$$

where *NIR*= Reflectance at the near-infrared wavelength (KOMPSAT-5 Band 4)
Green = Reflectance at the green wavelength (KOMPSAT-5 Band 2)

Meanwhile, RVI is calculated from the VV and HV polarization channels of KOMPSAT-5 SAR, as defined in Equation (3). Unlike NDWI, RVI does not require optical imagery, allowing for all-weather observations while effectively capturing vegetation canopy characteristics (Holtgrave et al., 2020).

$$RVI = \frac{4\sigma^0_{VH}}{\sigma^0_{VV} + \sigma^0_{VH}} \quad (3)$$

where σ^0 = Backscatter coefficient in VV and VH polarization (dB)

Both approaches (NDWI+SAR vs. RVI+SAR) were applied to the modified WCM to estimate soil moisture content. NDWI was computed from the green and NIR bands of KOMPSAT-3A, while RVI was derived from the VV and HV polarization data of KOMPSAT-5 SAR. Through this comparative analysis, the study empirically evaluated whether integrating optical indices with SAR remains advantageous or if SAR-derived indices alone can achieve sufficient soil moisture estimation accuracy.
Thus, this study validated the estimated soil moisture content by comparing in situ observations with:
(1) WCM estimates using NDWI+SAR, and
(2) WCM estimates using RVI+SAR.
By conducting this evaluation, the study aimed to determine whether reliable soil moisture information can be derived with reduced dependency on external atmospheric conditions, such as cloud cover. Additionally, it investigated the practical feasibility of using SAR-only approaches for soil moisture estimation in real-world applications.
To evaluate the accuracy of the soil moisture estimation results, the model-derived estimates were compared with in situ observations by computing the coefficient of determination (R^2) and the Root Mean Square Error (RMSE).
These validation metrics were used to systematically assess the soil moisture estimation performance of the RVI-based modified WCM model and to evaluate the degree of agreement between the estimated values, in situ observations, and the conventional WCM calculation method.

2.2 Web-Based Satellite Image Analysis Service

To effectively utilize satellite-derived data, including soil moisture information, an integrated platform that provides systematic data management and visualization within a single web environment is required. In this study, a web-based system was developed to facilitate the integrated management, analysis, and visualization of various satellite datasets, including KOMPSAT-5 SAR imagery.

2.2.1 Development of a Satellite Data Management System

Satellite imagery varies in terms of acquisition time, spatial resolution, and polarization modes, necessitating a standardized framework for data storage and retrieval. In this study, a structured management system was established to store and index raw satellite images along with their metadata (e.g., acquisition date, spatial coverage, and sensor type), enabling users to efficiently search and utilize desired datasets through a web-based interface.
The system was designed to allow users to quickly locate relevant imagery using spatial queries (e.g., rectangular, polygonal, or circular regions) or by entering addresses and place names. Additionally, a structured versioning mechanism was implemented to systematically manage temporal datasets for time-series analysis.

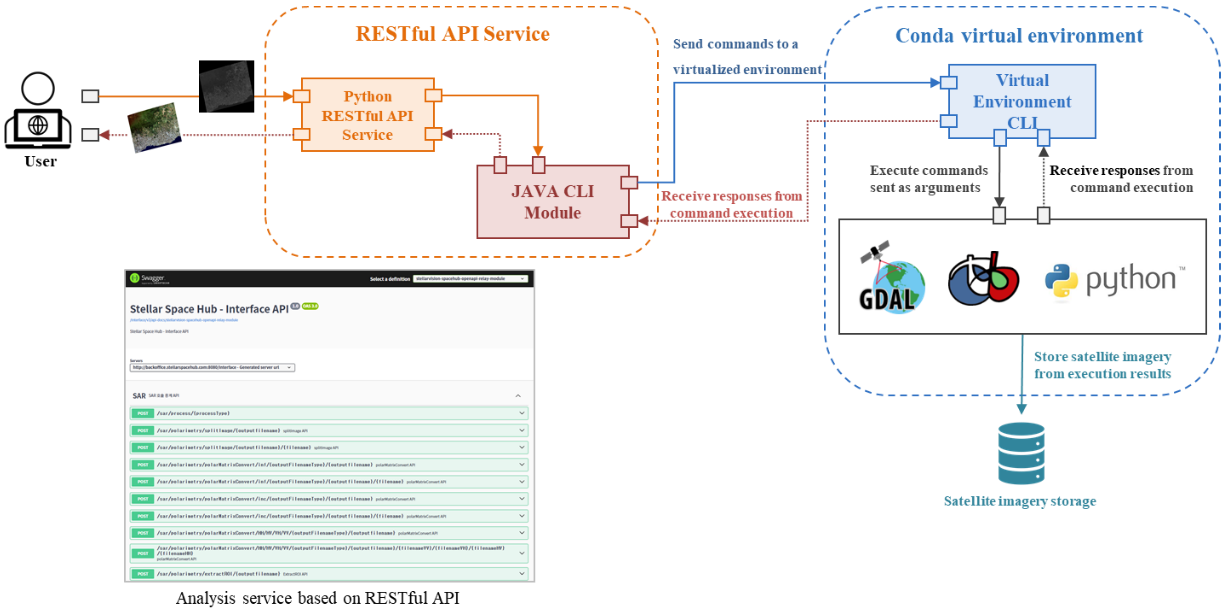


Figure 2. Architecture of the web-based analytical system for satellite data processing and visualization

2.2.2 Design of the Satellite Information Analysis System

The soil moisture estimation algorithm proposed in Section 2.1 was implemented as an independent analysis module, enabling real-time processing within the web environment. Registered satellite imagery is linked to this module, allowing users to execute various processing steps such as SAR radiometric calibration, speckle filtering, and backscatter coefficient extraction via a web-based graphical user interface (GUI) with customizable parameters.

To achieve this, the system leverages open-source geospatial processing tools such as Orfeo Toolbox (OTB) and GDAL, along with Python-based AI models deployed in a Docker-based server environment. The analysis module is designed as a RESTful API, allowing users to submit processing requests through the web interface. Upon receiving a request, the server executes the corresponding module via RESTful API calls and returns the results (Figure 2).

This modular architecture ensures flexibility, allowing the integration of additional algorithms for different frequency bands or sensor types beyond those developed in Section 2.1. By automating and streamlining the analysis workflow, the system enables researchers and practitioners to efficiently derive soil moisture information and apply additional models with minimal effort.

2.2.3 Development of a Visualization System for Analysis Results

The processed satellite imagery is visualized as an overlay on a web-based map interface, allowing users to intuitively analyze spatial and temporal variations. The system supports zooming and panning over regions of interest, enabling users to compare imagery across different acquisition dates to assess changes over time.

Additionally, metadata such as acquisition date, sensor type, and processing parameters are displayed alongside the imagery to facilitate quantitative interpretation by researchers and agricultural practitioners. This integration enhances the usability of the system, providing a comprehensive platform for satellite-based soil moisture analysis and decision-making.

3. Results and Discussion

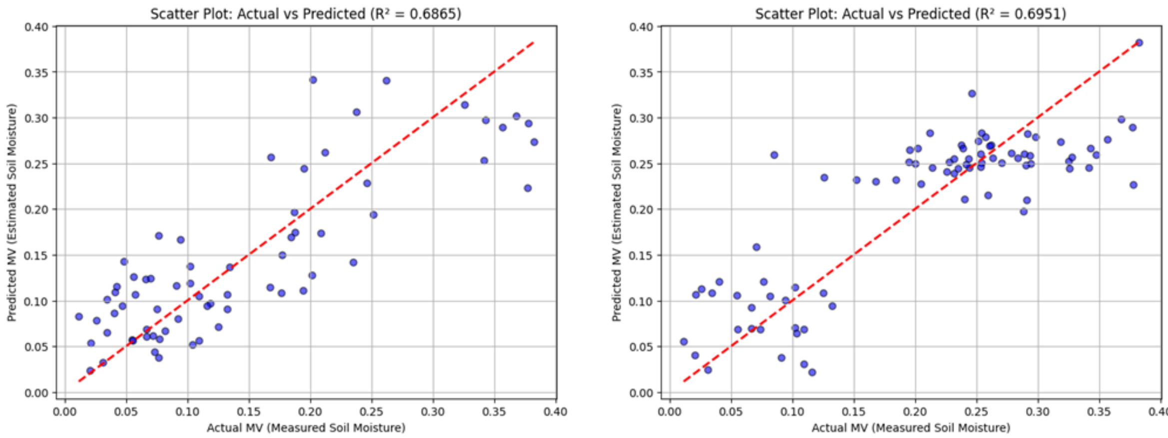
3.1 Soil Moisture Estimation Results

In this study, soil moisture content was estimated using WCM in two distinct ways: one integrating NDWI and another relying solely on RVI. The performance of each approach was evaluated by comparing the estimated soil moisture with in situ measurements, providing a thorough validation in agricultural areas.

The NDWI-based method achieved $R^2 = 0.6951$ with RMSE = 0.0576 m^3/m^3, while the RVI-based method yielded $R^2 = 0.6865$ with RMSE = 0.0583 m^3/m^3 (Figure 3). These error metrics show that both approaches reached comparable accuracy. Although NDWI can capture vegetation moisture directly from optical data, the RVI-based approach offers the advantage of using only SAR, allowing observations under all-weather conditions and circumventing issues like cloud cover. This finding is significant for agricultural applications where time-sensitive data collection is essential, especially in regions prone to prolonged cloudiness.

Even though there is little discrepancy in accuracy between the two methods, NDWI can be especially useful when clear-sky optical imagery is readily available. NDWI is sensitive to water content in vegetation, which can enhance soil moisture estimates by incorporating detailed information on canopy structure. However, its dependency on optical imagery means that adverse weather or atmospheric conditions can limit data acquisition. By contrast, RVI relies entirely on backscatter from SAR, making it possible to observe the land surface regardless of lighting or cloud cover. This all-weather capability ensures that RVI-based methods can provide consistent and frequent updates on soil moisture, a critical factor in water resource management and precision agriculture.

One potential limitation in this study is the lack of precise temporal alignment between KOMPSAT-5 (SAR) and KOMPSAT-3A (optical). Because the two sensors did not always acquire data on the exact same dates, temporal mismatches could have weakened the correlation between soil moisture and vegetation indices, especially for NDWI. Nonetheless, as future missions like KOMPSAT-6 provide data that include full polarization SAR simultaneously with optical imagery, the



(a) (b)

Figure 3. Scatter plots of soil moisture estimation using WCM: (a) RVI-based WCM, (b) NDWI-based WCM.

alignment issue should diminish, and the reliability of both the NDWI-based and RVI-based models is likely to improve.

Taken together, these results confirm that both an NDWI+SAR hybrid method and a SAR-only approach can achieve robust soil moisture estimation in agricultural environments. The ability to rely solely on SAR is particularly valuable in situations where cloud-free optical data are scarce. As sensor technologies evolve and higher-resolution data become more accessible, further improvements in accuracy and applicability are anticipated, paving the way for advanced soil moisture monitoring at larger scales.

3.2 Results of the Web-Based Satellite Image Analysis Service

The web-based satellite image analysis service developed for this study provides an end-to-end framework that encompasses data loading, analysis execution, and result visualization. By consolidating these phases into a single interface, the system lowers the technical barriers to satellite data usage, enabling non-expert users to perform complex analyses with minimal effort.

During the data loading step, users upload KOMPSAT-3A (optical) and KOMPSAT-5 (SAR) imagery through a unified portal. The system organizes the uploaded data, presenting them in a list with essential attributes such as acquisition dates, sensor modes, and spatial resolution. This streamlined approach allows users to select datasets relevant to their specific area of interest without juggling multiple software tools.

In the analysis execution phase, a user-friendly GUI enables the selection of optical or SAR datasets and the configuration of important parameters like polarization modes, optical bands, and preprocessing steps. Once these settings are saved, the server automatically processes the selected datasets to estimate soil moisture via WCM, integrating NDWI or RVI as specified. This modularized design encourages both novices and advanced users to follow standard best practices for instance, performing radiometric calibration, speckle filtering, or geometric corrections without the hassle of command-line tools.

Figure 4 illustrates how users can conduct these analyses through a point-and-click interface. After data processing, the system generates soil moisture maps at the selected spatial resolution. The benefit of combining NDWI- and RVI-based models within one platform is that users can compare the results side by side, assessing potential differences attributable to varying data sources or parameter choices. This comparative visualization serves as a valuable diagnostic tool for identifying potential error sources or optimizing the analysis methodology for specific agricultural conditions.

In the final visualization stage, the system overlays the derived soil moisture maps onto a web-based map viewer, allowing users to inspect results at multiple scales(Figure 5). By toggling between NDWI- and RVI-based outputs, users can observe how each model performs under different conditions. The platform also provides metadata such as acquisition date, preprocessing history, and sensor types, promoting transparency and reproducibility. This interactive environment fosters collaboration among researchers, field technicians, and policy-makers by offering a real-time shared view of the results, complete with zooming, panning, and querying capabilities.

Overall, this web-based service greatly simplifies the soil moisture estimation workflow. It demonstrates how NDWI and RVI can be leveraged in tandem or independently, ensuring that operational demands can be met even when optical data are unavailable. By reducing the reliance on specialized software and enabling seamless comparison between SAR-only and hybrid approaches, the system significantly broadens the scope of satellite-based soil moisture monitoring in agriculture, water resource management, and environmental studies.

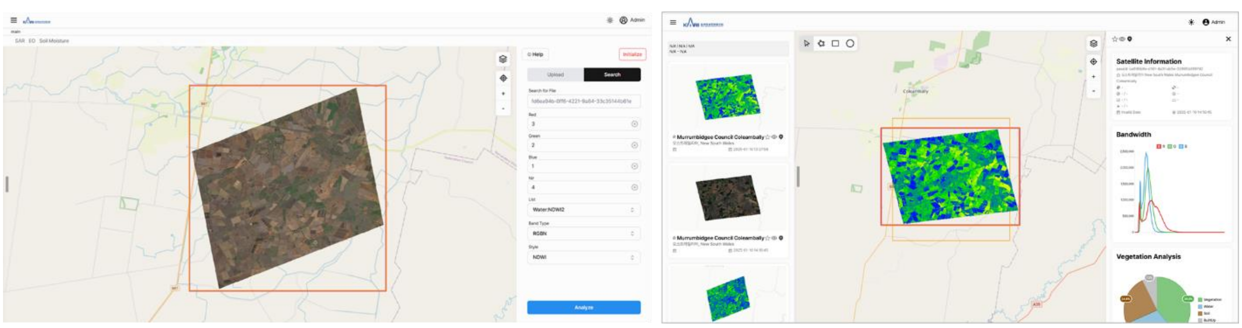
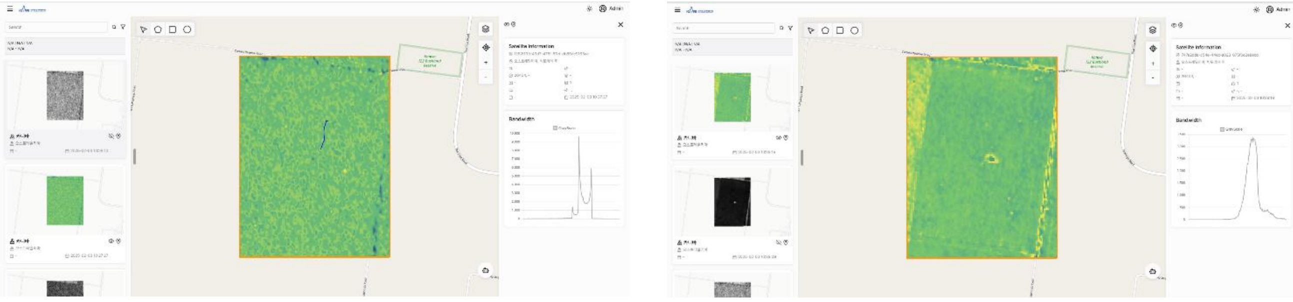


Figure 4. Web-based satellite image visualization and analysis service for soil moisture estimation.



(a) (b)

Figure 5. Web-based visualization of soil moisture estimation results: (a) RVI-based WCM, (b) NDWI-based WCM.

4. Conclusion

This study introduced an integrated system for estimating and visualizing soil moisture in near-real time using KOMPSAT-5 SAR data. The main objective was to compare WCM-based estimation approaches: one combining NDWI with SAR data and another using only RVI. Both methods displayed similar performance in terms of R^2 and RMSE, indicating that SAR alone can be relied upon to deliver accurate soil moisture estimates in agricultural settings where optical data are often hindered by unfavorable weather conditions.

The web-based service developed here centralizes the workflow data loading, analysis, and visualization into a single platform. By allowing users to upload and preprocess satellite data, configure WCM-based analyses, and overlay results in a spatially interactive environment, the system offers a straightforward path to operationalizing soil moisture monitoring. Furthermore, the side-by-side comparison of NDWI- and RVI-derived outputs facilitates immediate assessments of how optical and SAR data can complement or replicate each other under varying circumstances.

Looking ahead, the availability of next-generation satellites such as KOMPSAT-6 providing full-polarization SAR data and synchronized optical imagery is expected to refine both NDWI-based and RVI-based models. Enhanced temporal alignment and finer spatial resolution will likely boost model accuracy, further establishing the value of combined or SAR-only approaches. Ultimately, this study shows that RVI alone can match the performance of NDWI+SAR for soil moisture retrieval, underscoring the adaptability of SAR-focused techniques in regions where cloud cover is prevalent.

In conclusion, this research confirms that adopting a SAR-only method for soil moisture estimation is not only feasible but highly practical, particularly in environments where clear-sky optical observations are limited. By developing a web-based system that integrates all aspects of data handling, analysis, and results visualization, the study highlights a scalable and user-friendly solution. Future work, aided by improved sensor technology and data fusion methods, will undoubtedly enhance the applicability of satellite-based soil moisture monitoring, benefiting precision agriculture, water resource management, and climate-related research on a broader scale.

Acknowledgements

This research was supported by the Korea Aerospace Research Institute, grant number FR24H00.

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