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Soil Moisture Retrieval from Soil Moisture Active Passive (SMAP) Satellite: A Validation and Error Analysis Using Ground-Based Observation Over Bangladesh

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ABSTRACT

The Soil Moisture Active Passive (SMAP) mission, the latest satellite dedicated to soil moisture monitoring, provides global soil moisture maps through simultaneous L-band radar and radiometer measurements. This study aimed to support the ongoing authentication of SMAP soil humidity products by inter-comparing five products: L4_SM, L3_SM_P_E, L3_SM_P, L2_SM_P_E, and L2_SM_P. Ground-based soil moisture data from nine locations in Bangladesh—Cumilla, Ishwardi, Mymensingh, Dinajpur, Rajshahi, Rangpur, Joydebpur, Khulna, and Sreemongal weather stations were used for validation. The analysis also investigated potential sources of error in SMAP products. Results revealed that L4_SM had the lowest error values among the five products, with ubRMSE (5.3001 m^3/m^3), RMSE (5.3077 m^3/m^3), and Bias (-0.2841 m^3/m^3). However, these values fell short of the SMAP mission's accuracy goal of 0.04 m^3/m^3, primarily due to the use of point location data for validation. The correlation factor between in-situ observations and L4_SM soil moisture was probabilistically significant ($r = 0.63$, $p < 0.01$). Among the evaluated products, L4_SM demonstrated a relatively better agreement with ground observations and could contribute to enhancing the SMAP algorithm's accuracy. Further research, particularly involving core validation sites, is recommended to address the identified error sources and improve the precision of SMAP soil moisture retrievals.

Keywords: SMAP, Soil Moisture, L-band, RMSE, Bias, Correlation Co-efficient.

INTRODUCTION

Soil moisture is universally acknowledged as a vital parameter for characterizing surface drought conditions, evaluating plant productivity, and contributing significantly to the global energy cycle. [1] Soil moisture refers to the amount of water present in the pore spaces between soil particles, typically expressed as a percentage of the soil's total mass or volume. Soil moisture is the volume of water. held in the pores between soil particles, typically expressed as a percentage of the soil's total mass or volume. Surface soil moisture denotes the water content in the top 5 centimeters of soil, during root-zone soil moisture. refers to the water within the upper 200 centimeters, accessible to plants for absorption. [2] Numerous scientific disciplines have made substantial use of it, including meteorology, hydrology, civil engineering, forestry, and agronomy. [3] The moisture found in the topsoil is very crucial for atmospheric cycles demand and short-term precipitation which regulates evapotranspiration, plant water availability and eventually, plant growth. [4] In Bangladesh, soil moisture appears as a significant limiting factor in soil–atmosphere coupling and land management by influencing pattern and propensity of droughts and floods. Therefore, it is crucial to gather data on the geographic and temporal variations in near-surface soil moisture across Bangladesh. Traditionally the soil moisture data has been collected by meteorological weather stations. While they are useful for pinpointing soil moisture, their precision is limited by the fact that the ground surface varies greatly from place-to-place. Moreover, in situ observation of soil moisture in wide scale is not always empirical which lacks the data of this variable on the basis of spatial variabilities and time evolution. To overcome such constraints, researchers have employed remote sensing and land-surface moisture modeling. Microwave remotely sensed data, including passive and active, has been used successfully to infer soil moisture at enormous spatial and temporal scales during the last several decades. [5], [6] To monitor soil moisture, microwave remote sensing techniques using active systems involve transmitting microwave signals and analyzing the reflected signals from Earth's surfaces like synthetic aperture radar are preferable to passive sensors due to the higher spatial resolution they provide in their observations. [7], [8] In contrast, radar backscatter is severely influenced by the such as vegetation cover, surface roughness, and terrain features. Radiometers and other passive microwave sensors are preferable to active ones when it comes to mapping soil moisture over long periods. However, a passive sensor's spatial resolution (tens to hundreds of kilometers) is often relatively narrow, severely restricting its use in certain real-world contexts, such as local-scale agricultural production assessment. To acquire globally accurate surface soil moisture data with high precision that can mostly satisfy the requirements of meteorological applications. In January 2015, NASA initiated the Soil Moisture Active Passive (SMAP) mission, a specialized satellite designed to assess soil moisture. by integrating the distinct advantages and sensitivities of both radiative and reflective detection techniques. [9] The SMAP satellite is equipped with two sensors: a 1.26 GHz L-band radar and a 1.41 GHz L-band radiometer. The radar provides fine-resolution backscatter measurements at 3 kilometers, while the radiometer captures coarse-resolution brightness temperature data at 36 kilometers. The L-band (1–2 GHz) is measured ideal for measuring soil moisture in the upper layers, as it demonstrates minimal sensitivity to atmospheric and weather-related disturbances, while also possessing the capability to effectively penetrate vegetation of low to moderate density, making it ideal for accurate soil moisture estimation in such conditions. [10], [11] SMAP provides three primary types of soil moisture estimates from remote sensing: active, passive, and active-passive.

Additionally, the SMAP radiometer has been made publicly available as an enhanced soil moisture product. [8], [12]

Although the radar has remained out of service due to an instrument malfunction since July 2015, Integrated active-passive soil moisture measurements continues to be collected by integrating the SMAP radiometer with other active measurements, As seen with the ongoing Sentinel-1 C-band remote sensing data, thereby enabling cross-platform soil moisture estimates to be derived and maintained. [2] Considering the regularity with which SMAP products are updated, consumers must be made aware of the validity of the latest versions. In addition, the feedback (such as probable error causes) provided by the validation findings may be used to further optimize the algorithms. Since the soil moisture products of SMAP were made available to the public at the start of November 2015, there have been efforts to evaluate their efficacy. [13] The beta version of the SMAP radiometer's soil moisture data was initially tested in areas with and without a dense soil moisture network. The findings revealed that the SMAP product, in most cases, exhibited a strong agreement with ground measurements, successfully meeting the mission's established threshold of 0.040 m^3m^{-3}, thereby validating its accuracy for soil moisture estimation. [8] This study aims to assist in the ongoing verification of SMAP soil moisture datasets by utilizing in situ soil moisture data from nine weather stations in Bangladesh—Cumilla, Ishwardi, Mymensingh, Dinajpur, Rajshahi, Rangpur, Joydebpur, Khulna, and Sreemongal. The focus will be on comparing and validating the performance and inter-comparison of five SMAP soil moisture products: L4_SM, L3_SM_P_E, L3_SM_P, L2_SM_P_E, and L2_SM_P.

MATERIALS AND METHODS

Study Area and Ground-based Measurements

Total nine meteorological stations such as Cumilla (Lat 23.4345, Lon 91.1845), Ishwardi (Lat 24.1502, Lon 89.0398), Mymensingh (Lat 24.7260, Lon 90.4260), Dinajpur (Lat 25.6461, Lon 88.6544), Rajshahi (Lat 24.3603, Lon 88.6540), Rangpur (Lat 25.7329, Lon 89.2530), Joydebpur (Lat 23.9888, Lon 90.4044), Khulna (Lat 22.7319, Lon 89.0828), and Sreemongal (Lat 24.2949, Lon 91.7439) were selected as the study area (Figure:1).

This study utilizes in-situ soil moisture data collected by the Bangladesh Meteorological Department (BMD) at nine locations during the winter seasons from 2015 to 2020. The BMD currently operates 35 stations that monitor soil moisture at varying depths of 5, 10, 20, 30, and 50 cm below the soil surface. Given the penetration depth of microwave signals in the L-band, only the topsoil moisture measurements at 5 cm are considered for analysis in this research.[12]. SMAP Soil Moisture Products: Data for five SMAP soil moisture products (Table:1)—L4_SM, L3_SM_P_E, L3_SM_P, L2_SM_P_E, and L2_SM_P—were collected from https://worldview.earthdata.nasa.gov/ (Figure:2) for nine-point locations from 2015 to 2020 during the winter season.

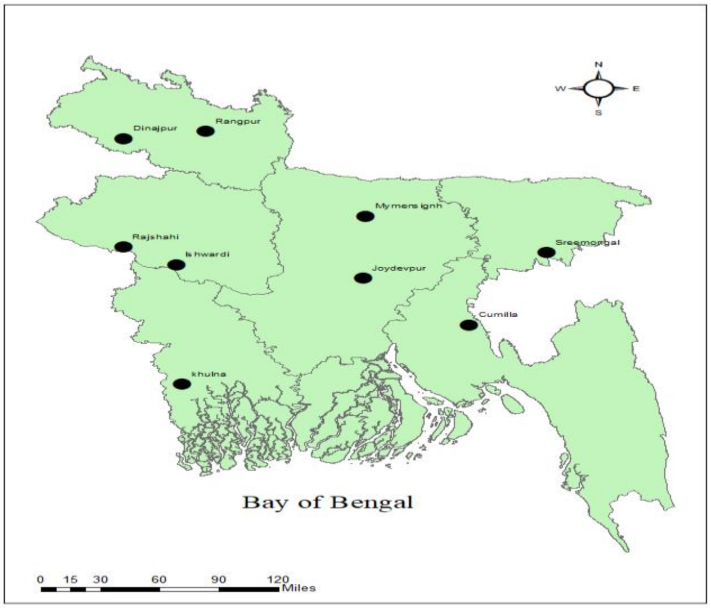

Figure 1: Study Area

Table 1: SMAP Data Products

Data product short name	Short Description	Gridding (Resolution)	Granule extent
L4_SM	Surface and root zone soil moisture	9 kilometres	3 hours - Global
L3_SM_P_E	Daily global composite radiometer soil moisture	9 kilometres	Daily- Global
L3_SM_P	Daily global composite radiometer soil moisture	36 kilometres	Daily- Global
L2_SM_P_E	Radiometer soil moisture	9 kilometres	Half - Orbit
L2_SM_P	Radiometer soil moisture	36 kilometres	Half - Orbit

This study has utilized ground data from nine sites provided by the Bangladesh Meteorological Department to examine the accuracy of five soil moisture products from SMAP: L4_SM, L3_SM_P_E, L3_SM_P, L2_SM_P, and L2_SM_P. Validating the accuracy of remotely sensed products is a crucial process that relies on "ground truth" data, which is typically derived from in ground-based measurements that undergo thorough accuracy verification processes. [4], [14]

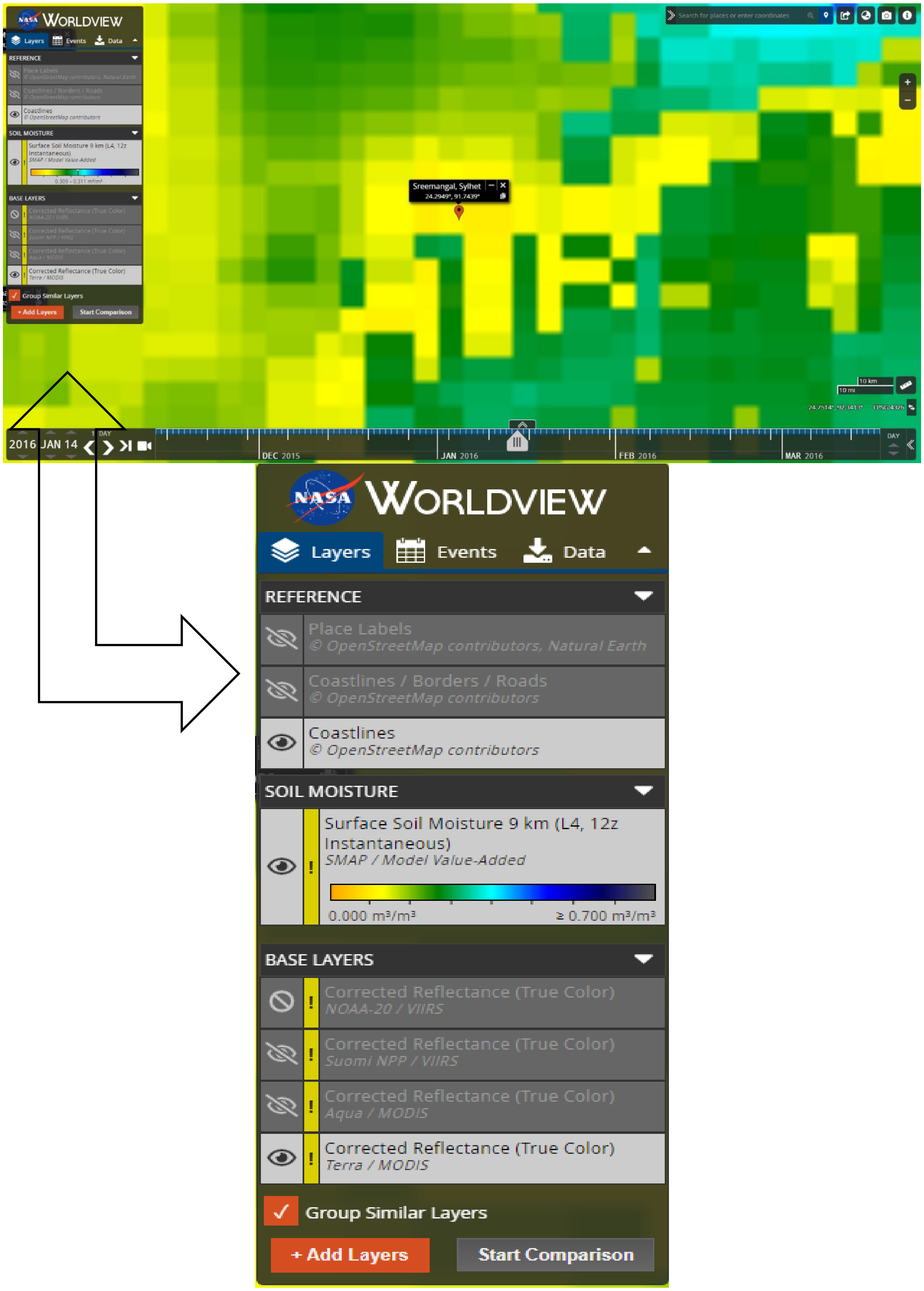

Figure 2: Sample of SMAP Soil Moisture Data for L4_SM_M (Sreemongal)
Source: (https://worldview.earthdata.nasa.gov/)

Four error metrics—Root Mean Square Error (RMSE), average bias (Bias), unbiased Root Mean Square Error (ubRMSE), and the correlation coefficient (r)—are employed to quantitatively compare the in-situ data with the SMAP soil moisture products, providing a comprehensive assessment of their accuracy and performance. These metrics are described as follows [14]:

i. RMSE:

$$\mathrm{RMSE} = \sqrt{E\{(\theta_{smap}(t) - \theta_{in-situ}(t))^2\}}$$

ii. Bias:

$$\mathrm{Bias} = E\left\{\theta_{smap}(t)\right\} - E\{\theta_{in-situ}(t)\}$$

iii. ubRMSE:

$$\mathrm{ubRMSE} = \sqrt{E\{((\theta_{smap}(t) - E\left\{\theta_{smap}(t)\right\} - (\theta_{in-situ}(t) - E\{\theta_{in-situ}(t)\}))^2\}}$$

iv. Correlation Coefficient (r):

$$r = \frac{E\{\left(\theta_{smap}(t) - E\left\{\theta_{smap}(t)\right\}\right).(\theta_{in-situ}(t) - E\{\theta_{in-situ}(t)\})\}}{\sigma_{smap} \cdot \sigma_{in-situ}}$$

Where:

- E = the operator for linear averaging
- t = Observational time
- θ_{smap}(t) = SMAP products observed at time t
- $\theta_{in\text{-}situ}$ (t) = measurement data were taken in-situ at time t.
- σ_{smap} = standard deviations of SMAP soil moisture products
- σ_{true} = standard deviations of in-situ measurements
- r = correlation coefficient
- MS Excel and R programming was used in this study.

RESULT

The present study (Table:2) revealed that L4_SM had the lowest values of ubRMSE (5.3077), RMSE (5.3001), and Bias (-0.2841). L4_SM had a strong positive correlation r=0.637 with in-situ soil moisture. The significant variation among L4_SM and in-situ observed soil moisture was found at the 5% level of significance. On the other hand, L3_SM_P_E, L3_SM_P, L2_SM_P_E, and L2_SM_P had higher values of ubRMSE, RMSE, and Bias.

Table 2: The five SMAP soil moisture products are compared with in-situ observed soil moisture in Bangladesh, N denotes the number of samples, and the p-value indicates the significance level.

Products	ubRMSE (m^3m^{-3})	RMSE (m^3m^{-3})	Bias (m^3m^{-3})	r	N
L4_SM	5.3001	5.3077	-0.2841	0.637***	420
L3_SM_P_E	7.5676	24.4493	21.9820	0.445***	420
L3_SM_P	7.9348	24.1700	21.5644	0.378***	420
L2_SM_P_E	7.9345	19.7887	16.8720	0.352***	420
L2_SM_P	8.3789	19.7708	16.6517	0.318***	420

"***" The correlation is significant at the p<0.001 level.

L4_SM, L3_SM_P, L2_SM_P_E, and L2_SM_P exhibited a weak positive correlation with the in-situ observed soil moisture, with L4_SM showing the lowest correlation, while L3_SM_P demonstrated the strongest correlation among the five products. Furthermore, all five products—L4_SM, L3_SM_P_E, L3_SM_P, L2_SM_P_E, and L2_SM_P—were found to be statistically significant at the 5% level, indicating their reliability in capturing soil moisture variations.

Regression Analysis of SMAP Products Compared to In-situ Observed Soil Moisture

The regression coefficients' intercept and slope are calculated using the regression analysis technique. The coefficients of determination (R^2) have also been estimated. The R^2 values show the goodness of the data (Figure:3). The data set was used to investigate the performance of the SMAP products. According to the scattered diagram, L4_SM had the highest R^2 0.4044 and L2_SM_P had the lowest R^2 0.1042So, L4_SM was the fittest SMAP product than others.

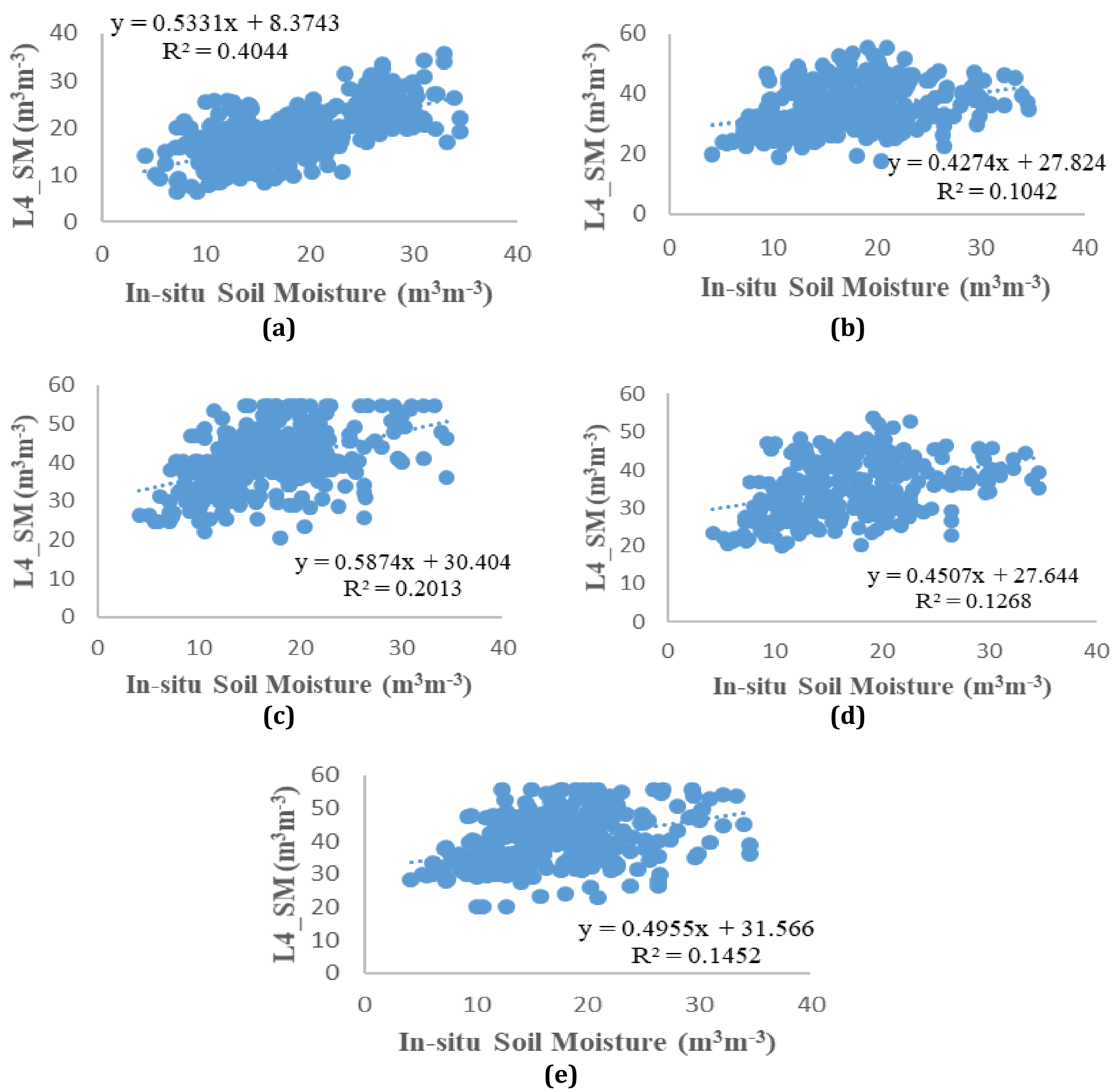

Figure 3: (a-e) scattered diagram between SMAP products and in-situ observed soil moisture.

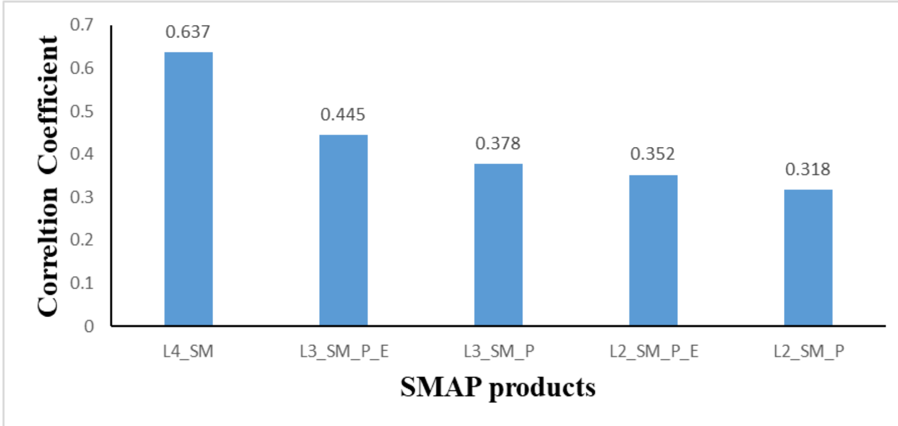

Figure 4: Correlation Between SMAP Products and In-situ Observed Soil Moisture.

The above analysis (Figure:4) depicts the correlation coefficient between SMAP Products and in-situ observed soil moisture. L4_SM had the highest values of correlation coefficient 0.637 and L2_SM_P 0.318.

Soil Moisture Scenario of Bangladesh

Figure:5 shows the highest soil moisture values in the southwestern part of Bangladesh and the lowest values in the northwestern part. Medium soil moisture values are observed in the central and eastern regions. The northern region exhibits lower soil moisture levels compared to the southern region of Bangladesh.

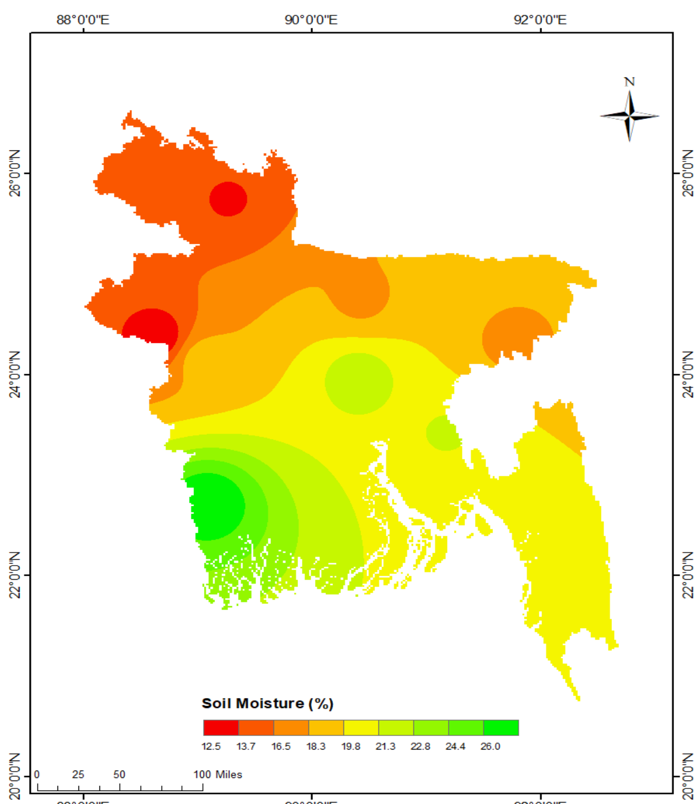

Figure 5: L4_SM Soil Moisture map over Bangladesh from 2015 to 2020 for the winter season.

DISCUSSION

The strategy for validating soil moisture data products through point-specific observations allowed for a swift and accurate evaluation of SMAP soil moisture products immediately after data acquisition. A crucial element of the calibration and validation process was the rigorous screening of sites to ensure they met the validation requirements set by SMAP before the availability of the SMAP data. L4_SM, 9 km: The L4_SM product demonstrated the best performance among the five SMAP soil moisture products evaluated in this study. It had the lowest ubRMSE (5.3001 m^3m^{-3}), RMSE (5.3077 m^3m^{-3}), and bias (-0.2841 m^3m^{-3}). However, these values still exceeded the SMAP mission requirement of 0.04 m^3m^{-3}.Zhang et al. (2017) documented ubRMSE values of 0.14 m^3m^{-3}, RMSE of 0.22 m^3m^{-3}, and a Bias of -0.06 m^3m^{-3}, none of which satisfied the SMAP mission criterion of 0.04 m^3m^{-3}. The correlation coefficient r=0.637 demonstrated a robust positive relationship with in-situ soil moisture data and was statistically significant at the 5% level, with a p-value of less than 0.001. This performance suggests that the L4_SM product is the most reliable of the five, capturing soil moisture variability more effectively. Nevertheless, the errors observed indicate room for improvement, particularly in reducing bias and error magnitude. The relatively better performance of L4_SM may be attributed to its integration of advanced modeling and assimilation techniques.

L3_SM_P_E, 9 km: The L3_SM_P_E product showed moderate performance compared to the others. It had a ubRMSE of 7.5676 m^3m^{-3} and an RMSE of 24.4493 m^3m^{-3}, both of which were significantly higher than the SMAP mission requirement. The bias of 21.9820 m^3m^{-3} indicated a consistent overestimation of soil moisture. The correlation coefficient r=0.445, while positive, was lower than that of L4_SM, suggesting reduced accuracy in replicating the variability of in-situ soil moisture observations. The errors in L3_SM_P_E are likely linked to the spatial resolution of the product and the limitations of the data assimilation techniques used. Its performance suggests that while it is somewhat reliable, it requires further refinement for accurate soil moisture monitoring. [12] observed ubRMSE values of 0.026 m^3m^{-3}, RMSE of 0.064 m^3m^{-3}, and Bias of -0.059 m^3m^{-3}, all of which satisfied the SMAP mission requirement of 0.04 m^3m^{-3}. The overall correlation coefficient was r = 0.933, reflecting a strong positive correlation with in-situ observed soil moisture.

L3_SM_P, 36 km: The L3_SM_P product exhibited similar performance to L3_SM_P_E, with a ubRMSE of 7.9348 m^3m^{-3} and an RMSE of 24.1700 m^3m^{-3}. The bias of 21.5644 m^3m^{-3} indicated a significant overestimation of soil moisture, and the correlation coefficient (r) of 0.378 reflected a weaker relationship with in-situ observations compared to other products. These results indicate that L3_SM_P struggles to capture the nuances of soil moisture variability accurately. This is consistent with the notion that lower-level products, such as L3_SM_P, may have limitations in their ability to process and refine data compared to higher-level products like L4_SM. The overestimation and relatively lower correlation suggest the need for enhanced algorithms to improve its reliability. In comparison [14] reported ubRMSE values of 0.32 m^3m^{-3}, RMSE of 0.034 m^3m^{-3}, and Bias of -0.012 m^3m^{-3}, which met the SMAP mission requirement of 0.04 m^3m^{-3}. Additionally, their overall correlation coefficient was r = 0.914, reflecting a strong positive correlation with in-situ observed soil moisture.

L2_SM_P_E, 9 km: The L2_SM_P_E product showed slightly better results than L3_SM_P but still fell short of meeting the SMAP mission requirements. It had a ubRMSE of 7.9345 m^3m^{-3} and an

RMSE of 19.7887 m^3m^{-3}, both higher than the desired thresholds. The bias of 16.8720 m^3m^{-3} indicated overestimation, though to a lesser extent compared to L3_SM_P. The correlation coefficient (r) of 0.352 indicated a weak positive relationship with in-situ soil moisture observations. This weak correlation reflects the product's inability to accurately capture spatial and temporal soil moisture dynamics. The relatively high error metrics suggest that L2_SM_P_E may require significant refinement in its retrieval algorithms and data assimilation processe. [12] reported ubRMSE values of 0.109 m^3m^{-3}, RMSE values of 0.031 m^3m^{-3}, and average Bias of -0.079 m^3m^{-3}, all of which met the SMAP mission requirement of 0.04 m^3m^{-3}. The correlation coefficient was r = 0.361, indicating a moderate positive correlation with ground-based observed soil moisture. [15] found ubRMSE values of 0.029 m^3m^{-3}, RMSE values of 0.031 m^3m^{-3}, and Bias values of -0.301 m^3m^{-3}, all meeting the SMAP mission requirement of 0.04 m^3m^{-3}. The correlation coefficient was r = 0.942, reflecting a strong positive correlation with in-situ observed soil moisture at TxSON. Additionally, for Kenaston, the ubRMSE was 0.026 m^3m^{-3}, RMSE was 0.043 m^3m^{-3}, and Bias was -0.350 m^3m^{-3}. While the ubRMSE and Bias met the SMAP mission requirement, the RMSE was very close to the threshold. The correlation coefficient was r = 0.774, demonstrating a strong positive correlation with in-situ observed soil moisture.

L2_SM_P, 36 km: The L2_SM_P product had the weakest performance among the five products evaluated. It recorded the highest ubRMSE (8.3789 m^3m^{-3}) and RMSE (19.7708 m^3m^{-3}), both exceeding the SMAP mission requirements. The bias of 16.6517 m^3m^{-3} further highlighted a significant overestimation of soil moisture. The correlation coefficient (r) of 0.318 was the lowest among all products, indicating a weak positive correlation with in-situ soil moisture data. The poor performance of L2_SM_P suggests that it is the least suitable for operational soil moisture monitoring in the study region. This may be attributed to the lack of advanced data assimilation techniques or lower spatial and temporal resolutions compared to higher-level products. [5] found ubRMSE values of 0.041 m^3m^{-3}, RMSE values of 0.051 m^3m^{-3}, and Bias values of -0.030 m^3m^{-3}. Both the ubRMSE and RMSE met the SMAP mission threshold of 0.04 m^3m^{-3}, but the Bias did not. The correlation coefficient was r = 0.942, indicating a strong positive correlation with ground-based observed soil moisture at Reynolds. Similarly, at Kenaston, the values were ubRMSE 0.028 m^3m^{-3}, RMSE 0.049 m^3m^{-3}, and Bias -0.350 m^3m^{-3}. While the ubRMSE and Bias met the SMAP mission threshold of 0.04 m^3m^{-3}, the RMSE was very close to the requirement. The correlation coefficient was r = 0.724, showing a strong positive correlation with in-situ observed soil moisture found ubRMSE values of 0.129 m^3m^{-3}, RMSE values of 0.031 m^3m^{-3}, and Bias values of -0.079 m^3m^{-3}, all of which met the SMAP mission threshold of 0.04 m^3m^{-3}. The correlation coefficient was r = 0.361, indicating a strong positive correlation with in-situ observed soil moisture. [15] The overall findings were poor than [5], [10], [14], [16]etc. because of other study use core validation sites for measuring in-situ observed soil moisture for validation of SMAP satellite products but in this paper point location use to measure in-situ observed soil moisture for validation of SMAP satellite products. Point location data easy to access at any place any time from SMAP which fulfilled the now casting of soil moisture.

CONCLUSION

It is important to assess the reliability and possible errors in SMAP soil moisture products to improve their accuracy and usability in research and practice. This study compares five SMAP soil moisture products—L4_SM, L3_SM_P_E, L3_SM_P, L2_SM_P_E, and L2_SM_P—using in-situ data from nine locations in Bangladesh and examines the potential sources of errors in these products. The results indicate that L4_SM exhibited the lowest values for ubRMSE (5.3001 m^3m^{-3}), RMSE (5.3077 m^3m^{-3}), and Bias (-0.2841 m^3m^{-3}) compared to other SMAP products, though these values did not meet the SMAP mission requirement of 0.04 m^3m^{-3}. The higher error values can be attributed to the use of point location data for validation in this study. The correlation coefficient between in-situ observed soil moisture and L4_SM was r = 0.63, which was statistically significant at the 5% level (p-value < 0.001). L4_SM showed a relatively good response compared to other SMAP products, indicating its potential for improving the accuracy of soil moisture retrievals when further refined within SMAP algorithms. However, this study has several limitations. The lack of sufficient observed soil moisture data and the absence of some SMAP satellite data were addressed by filling in gaps with average values from before and after the missing data points. Extreme values were replaced with average values. Furthermore, point location data was used for validation, and further research using core validation sites is recommended to improve the robustness of the findings.

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