

## **Chapter 4 : IMPROVING SPATIAL REPRESENTATION OF SOIL MOISTURE THROUGH THE INCORPORATION OF AN IMPROVED SINGLE-CHANNEL ALGORITHM WITH DIFFERENT DOWNSCALING APPROACHES**

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### **4.1 INTRODUCTION**

The primary goal of this chapter is to enhance the SCA by substituting the existing methods with an optimized roughness parameter and a temporally enhanced VWC product. The Enhanced SCA (E\_SCA) soil moisture product is then employed in three downscaling methods to verify the accuracy of E\_SCA for disaggregation.

SMAP soil moisture disaggregation is a broad topic of research; many researchers have already given a lot of time in this field [71, 119-122]. P. W. Liu et al. [119] have presented a study to disaggregate the SMAP enhanced soil moisture product (9 km) by implementing a Thermal Inertia approach, Lian He et al., [120] utilized Sentinel-1 radar data to downscale the SMAP radiometer soil moisture data, while Montzka et al., [121] presented a different downscaling approach based on the soil moisture sub-grid variability, and Fangmin et al., [122] construct a non-linear regression relation between soil moisture and other surface auxiliary data. On the other hand, Li Fang et al. [71] presented an intercomparison study of various downscaling approaches for SMAP soil moisture product. Das et al. [13, 62], introduced a new approach to disaggregate SMAP soil moisture up to 9, 3, and 1 km by using Sentinel-1 backscattering data products instead of SMAP radar backscattering. These products are now available on a global scale, but the temporal resolution is 12 days, except for the 9-km product. This product is available on a daily basis but still has a coarse spatial resolution for many applications related to land management and agriculture. These are some recently published studies that utilized

different approaches for soil moisture downscaling and used the direct SMAP soil moisture data for disaggregation. The baseline algorithm of SMAP L2 soil moisture is also SCA; however, some parameters used in the algorithm are computed on a global basis, where they may have different values for different types of regions. One of the critical parameters is the roughness parameter [123]. The present study used optimized roughness parameters values to better estimate soil moisture. Another improvement from the baseline algorithm is the estimation of VWC using NDVI with better temporal resolution (Daily NDVI) instead of NDVI with a temporal resolution of 16 days. Therefore, using the estimated SMAP soil moisture through the E\_SCA in place of the direct SMAP soil moisture product can enhance the spatial variability of downscaled soil moisture also. Thus, the present study attempts to enhance the accuracy of SCA by improving two crucial parameters and then employ the estimated soil moisture by E\_SCA and SMAP L2 soil moisture one by one in different downscaling algorithms (Triangle method, ATI, and Dispatch algorithm) to enhance the downscaling results. This chapter also gives an intercomparison of these three approaches for disaggregation.

## **4.2 DATASETS**

### **4.2.1 In-situ Measurements**

The in-situ soil moisture measurements are taken from the field sampling campaign described in section 2.3.2 of chapter 2.

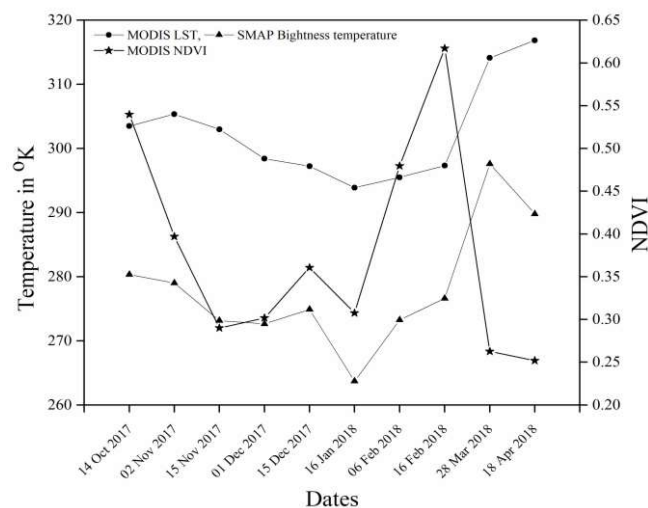
### **4.2.2 SMAP Data**

The present study utilizes SPL1CTB\_E (Brightness temperature) and SPL2SMP\_E (soil moisture) observations on the 9 km EASE-2 grid for soil moisture estimation and downscaling. Details of SPL1CTB\_E and SPL2SMP\_E data products are presented in J. Chaubell et al., [124] and P. E. Neil et al., [5]. The SPL1CTB\_E data product was

assimilated for the SCA algorithm to estimate the soil moisture content to be used in the downscaling algorithms. Simultaneously, SPL2SMP\_E was incorporated directly as an input in different downscaling methods.

### 4.2.3 MODIS Data

MYD11A1 and MOD09GA products of MODIS sensors aboard Aqua and Terra satellites, respectively, were obtained through the website of MODIS Land Processes Distributed Active Archive Center (LPDAAC) (<https://lpdaac.usgs.gov/>). Bands 1 (Red band) and 2 (NIR band) of MOD09GA product are used for computing the daily NDVI values. MRT (MODIS Reprojection Tool) was used for the reprojection and resampling of MODIS LST and reflectance images. Although the chosen dates of the study are mostly cloud-free but still to exclude the effect of clouds from the images of MODIS LST, the quality flag, through QC information data of MODIS LST product was used. The quality flag information helps to rectify the MODIS LST images with the exclusion of low-quality pixels. The maximum acceptable error in the values of LST is  $\pm 2$  K only [125].



**Figure 4.1** Temporal variations of MODIS LST, NDVI and SMAP Brightness temperature.

The temporal variation of MODIS LST and MODIS NDVI, along with the SMAP brightness temperature for the chosen time series, is shown in Figure 4.1. The lowest mean LST and brightness temperature values were found on 16 Jan 2018 due to the winter season. At the same time, the lowest mean NDVI value is found in April due to the harvesting of wheat crops and the highest observed NDVI was found for February because of the fully matured wheat crop.

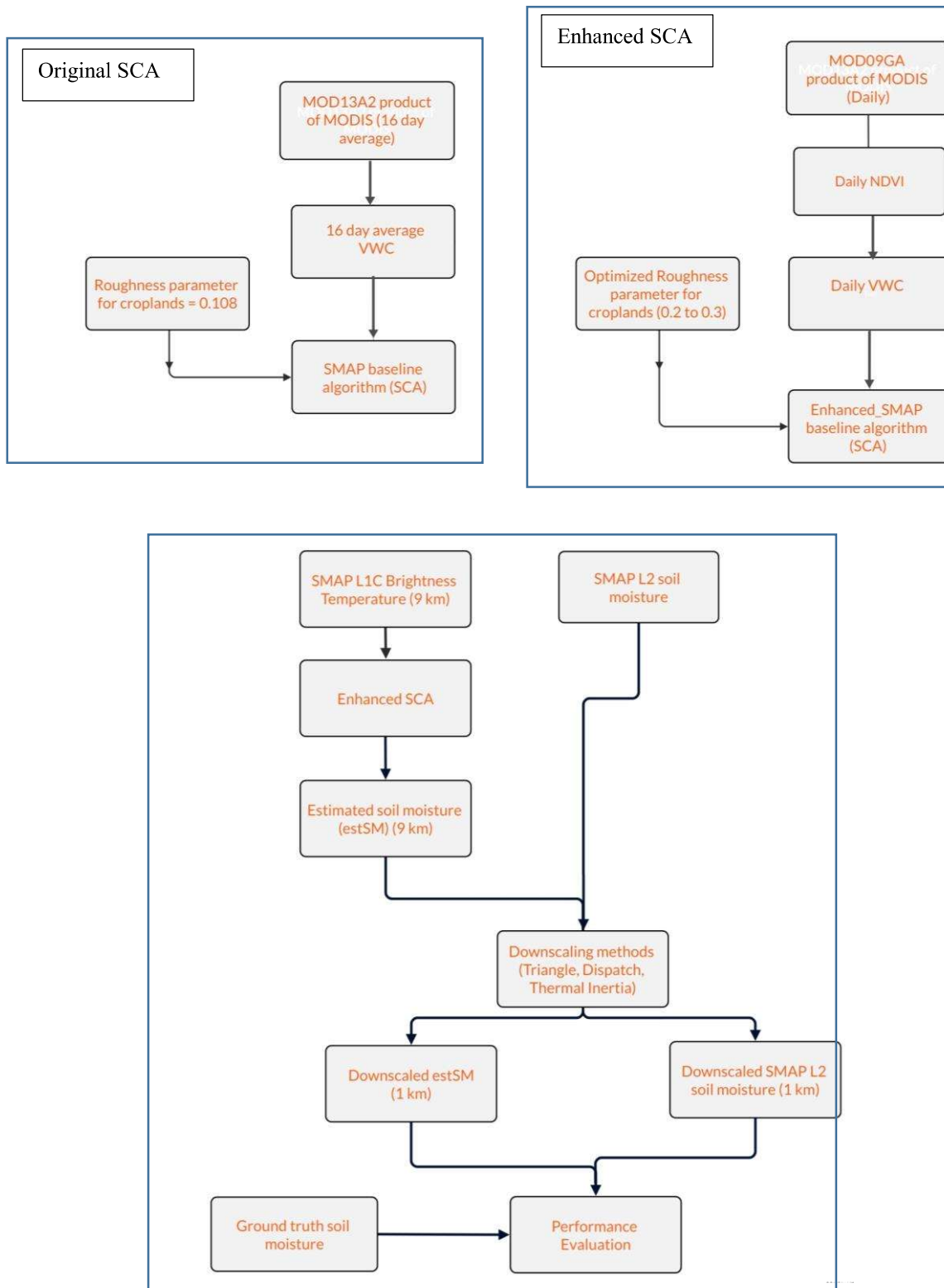
### **4.3 METHODOLOGY**

This chapter presents an improvement in the accuracy of SCA and downscaling of the SMAP soil moisture with three different algorithms. SMAP L2 soil moisture and the estimated soil moisture through E\_SCA have been used for downscaling up to 1 km. Figure 4.2 describes the complete workflow of this study.

#### **4.3.1 Satellite soil Moisture retrieval**

The baseline algorithm of SMAP L2 soil moisture product is SCA. However, the roughness value given in the Look-Up Table (LUT) of SMAP ATBD [59] for cropland is around 0.1, which is always found lower than the ground measurements. Therefore, the present study used an optimized roughness value to adopt a suitable roughness value.

The VWC, a function of NDVI, is also an essential parameter for estimating soil moisture through SCA. The baseline algorithm of SMAP L2 soil moisture is currently using MOD13A2 MODIS product, which provides NDVI at the temporal resolution of 16 days. A better NDVI product with a higher temporal resolution, MOD09GA, is used to



**Figure 4.2** Schematic diagram representing the improvement in SCA and the downscaling of estSM through E\_SCA and SMAP soil moisture.

compute NDVI. The images of band 1 (Red) and band 2 (NIR) of this product are used to calculate the NDVI through the expression

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \quad (4.1)$$

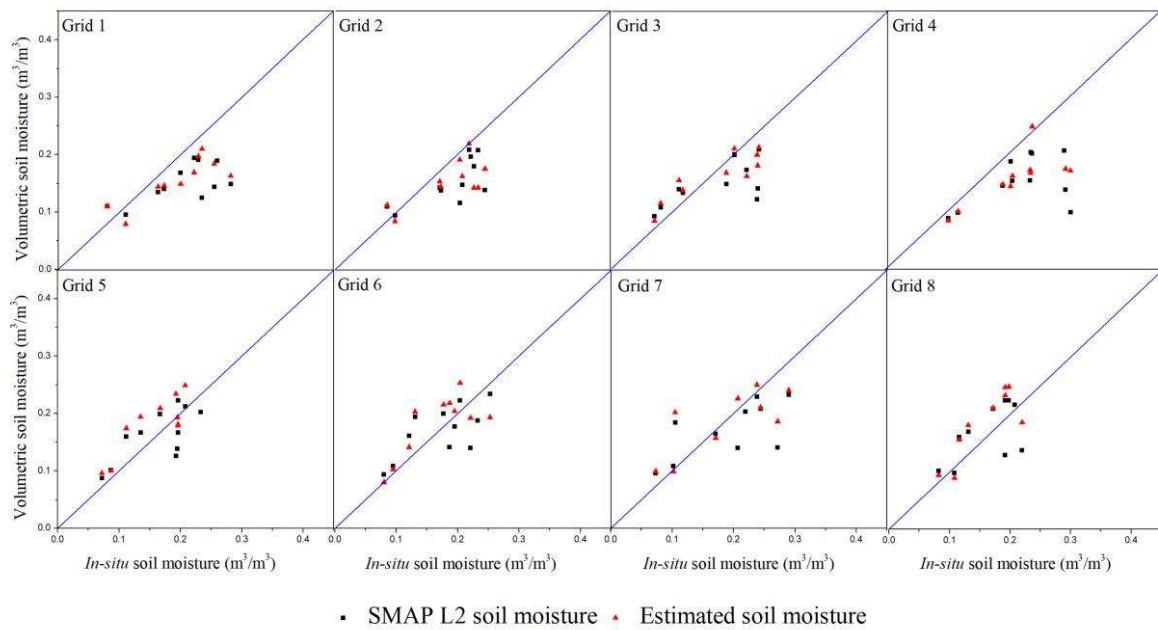
The computed NDVI using equation (4.1) is then used in equation (2.5) (Chapter 2) for the estimation of daily VWC. The E\_SCA with the above-mentioned changes improves the soil moisture estimation compared to the direct SMAP L2 soil moisture. The SCA, based on the zeroth-order RTM, has been described in detail in section 2.5.1 of chapter 2.

The estimated soil moisture (estSM) by E\_SCA is then used as an input for different downscaling processes: the Triangle method, the Dispatch method, and the Approximation of Thermal Inertia (ATI) theory. These approaches are described in section 2.5.2 of chapter 2.

## 4.4 RESULTS AND DISCUSSION

### 4.4.1 Comparison of SMAP L2 soil moisture and estimated soil moisture with the in-situ soil moisture datasets

The accuracy of soil moisture data values is initially assessed by comparing the direct SMAP soil moisture product and estSM with the in-situ soil moisture data. This comparison is shown in a scatter plot in Figure 4.3, which includes eight plots for eight different grids. Compared to the SMAP L2 soil moisture product, the estSM was found to be better along the 1:1 line in all eight plots. The performance evaluation in terms of correlation coefficient (R), RMSE, bias, and the slope is shown in Table 4.1. The correlation between SMAP L2 soil moisture and in-situ soil moisture is found to be lower than that of the estSM and ranges from 0.45 to 0.71. The estSM through E\_SCA shows improved results with a correlation coefficient ranging from 0.72 to 0.88. The overall RMSE for the estimated soil moisture was also found better than SMAP L2 soil moisture,



**Figure 4.3** Comparison of SMAP L2 and estimated soil moisture with the in-situ soil moisture for eight grids.

**Table 4.1** The statistical comparison between SMAP L2 and estimated soil moisture with the ground truth soil moisture in terms of correlation coefficient (R), RMSE, bias, and slope.

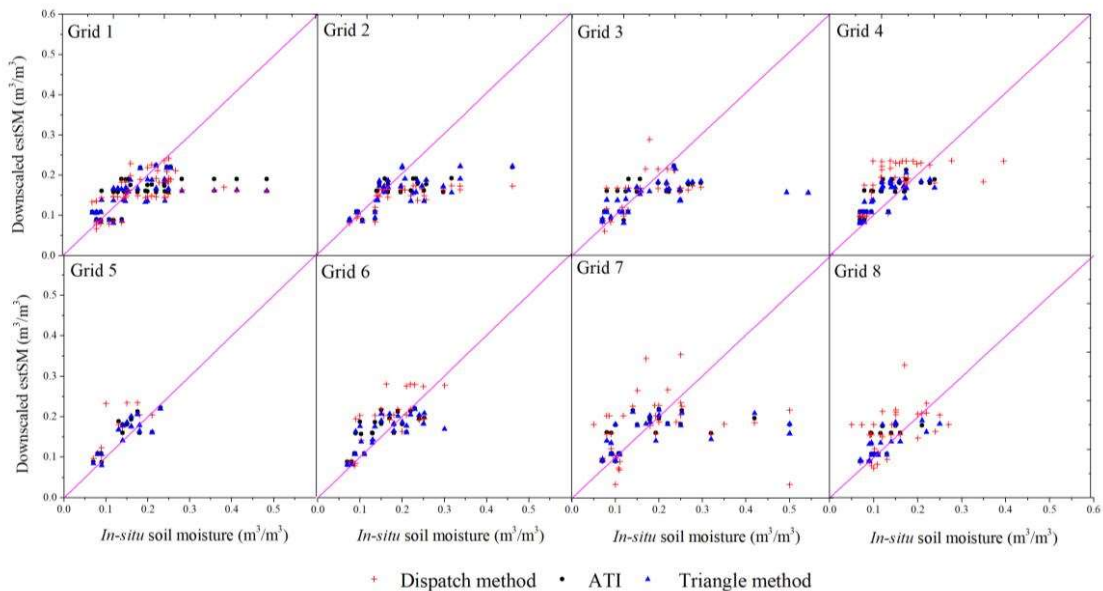
Grid	SMAP L2 soil moisture				Estimated soil moisture			
	R	RMSE	Bias	Slope	R	RMSE	Bias	Slope
<b>1</b>	0.65	0.070	-0.052	0.34	0.82	0.054	-0.039	0.51
<b>2</b>	0.71	0.052	-0.037	0.54	0.72	0.050	-0.034	0.50
<b>3</b>	0.66	0.052	-0.022	0.39	0.88	0.036	-0.008	0.54
<b>4</b>	0.45	0.090	-0.068	0.30	0.74	0.069	-0.056	0.51
<b>5</b>	0.70	0.037	-0.001	0.59	0.84	0.037	0.024	0.82
<b>6</b>	0.69	0.041	-0.004	0.53	0.77	0.038	0.013	0.74
<b>7</b>	0.66	0.058	-0.022	0.43	0.76	0.049	-0.004	0.54
<b>8</b>	0.59	0.042	0.005	0.61	0.84	0.040	0.026	1.05
<b>Average</b>	0.64	0.055	-0.025	0.47	0.80	0.047	-0.010	0.65

with the average RMSE of 0.047 and 0.055 for estimated and SMAP L2 soil moisture, respectively. All grids show a higher slope for estSM (0.65) than SMAP (0.47) except for

grid 2. The bias between estSM and ground truth soil moisture was found better for most grids except for grids 5, 6, and 8.

#### 4.4.2 Performance analysis of different downscaling algorithms using estimated soil moisture

As shown the relatively weak performance of original SMAP L2 soil moisture compared to estSM in the previous section, the downscaling algorithms were first evaluated using estSM. The results obtained by downscaling the estSM using the Dispatch method, Triangle method, and ATI are shown in Figure 4.4. The approach based on the Thermal Inertia theorem significantly improves the results compared to the Dispatch and Triangle method. The Dispatch algorithm overestimated soil moisture values for most of the grids except grids 1 and 2. Results of the Triangle method are concentrated around the results of the ATI. The statistical analysis results in terms of correlation coefficients (R), RMSE, bias, and slope are shown in Table 4.2. The second and third columns of Table 4.2 show the



**Figure 4.4** Spatial comparison of downscaled estSM (y-axis) using Dispatch, ATI, and Triangle method with the in-situ soil moisture (x-axis) for the selected eight grids.

**Table 4.2** Performance analysis of different downscaling algorithms including Dispatch, Triangle, and ATI when used with estSM, in terms of Correlation coefficient (R), RMSE, bias, and slope. The Correlation between MODIS derived land surface parameters (LST and NNDVI), and in-situ soil moisture is also presented in the second and third columns, respectively.

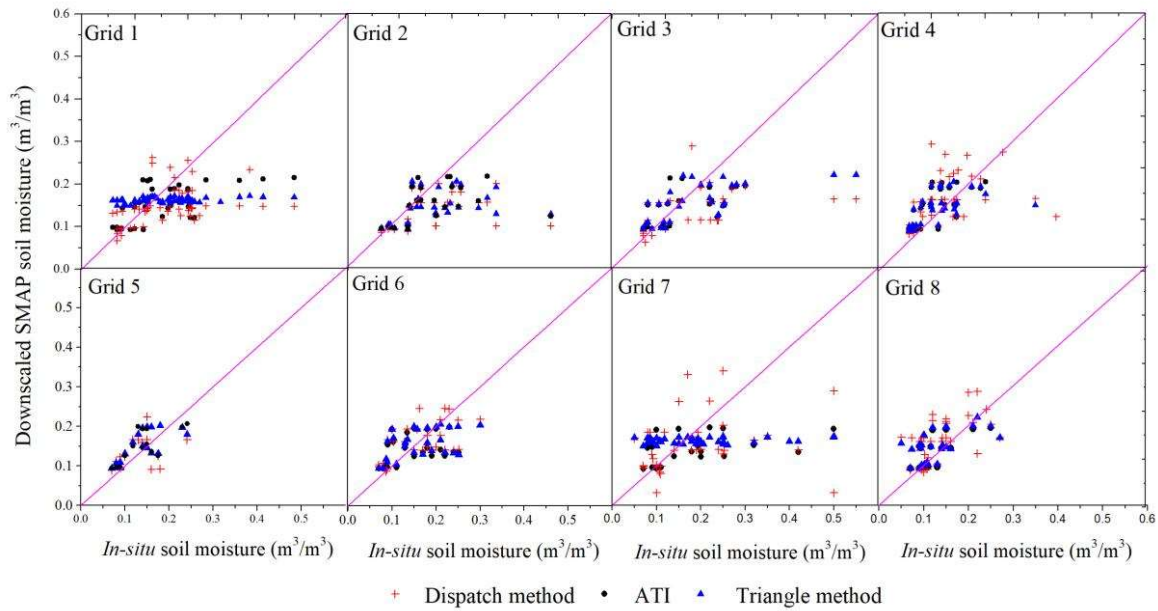
Grid	NDVI		Dispatch					Triangle					ATI					
	LST	R	R	RMSE	Bias	Slope	R	RMSE	Bias	Slope	R	RMSE	Bias	Slope	R	RMSE	Bias	Slope
<b>1</b>	-0.61	0.36	0.49	0.08	-0.036	0.25	0.51	0.08	-0.029	0.22	0.62	0.08	-0.022	0.27				
<b>2</b>	-0.53	0.29	0.66	0.09	-0.057	0.24	0.69	0.08	-0.045	0.33	0.73	0.07	-0.036	0.34				
<b>3</b>	-0.63	0.33	0.61	0.06	-0.013	0.41	0.56	0.11	-0.044	0.19	0.71	0.06	-0.014	0.38				
<b>4</b>	-0.54	0.33	0.58	0.07	0.032	0.42	0.80	0.03	0.016	0.64	0.77	0.04	0.022	0.62				
<b>5</b>	-0.72	0.29	0.73	0.06	0.044	0.87	0.84	0.03	0.012	0.78	0.82	0.03	0.016	0.75				
<b>6</b>	-0.75	0.16	0.61	0.07	0.032	0.74	0.73	0.04	0.001	0.48	0.77	0.04	0.015	0.57				
<b>7</b>	-0.64	0.17	0.22	0.12	-0.010	0.14	0.52	0.11	-0.030	0.19	0.57	0.09	-0.018	0.24				
<b>8</b>	-0.62	0.28	0.56	0.06	0.023	0.55	0.77	0.03	0.009	0.59	0.76	0.03	0.018	0.79				
<b>Average</b>	-0.63	0.28	0.56	0.08	-0.008	0.45	0.68	0.06	-0.014	0.43	0.72	0.05	-0.002	0.53				

correlation of MODIS LST and NDVI with ground truth soil moisture. The overall

correlation coefficient of the Dispatch algorithm is the lowest (0.56), whereas the highest (0.72) is found for the ATI. However, the values of RMSE, bias and slope for the Dispatch and the Triangle methods are significantly low compared with the results of the ATI. The average values of RMSE, bias and slope for the ATI are 0.05, -0.002, and 0.53, respectively. As described in the methodology section, soil moisture values are directly proportional to the temperature in the ATI method. It also depends on the values of NDVI, but there were three different SM-LST relations for different ranges of NDVI. While in the Dispatch and the Triangle method, the soil moisture is directly dependent on the values of NDVI and LST, both. So, on a slight change in NDVI, the Thermal inertia-based approach does not show much variation [126] compared to the Dispatch and Triangle methods. Thus, the performance of the ATI in terms of the correlation coefficient, RMSE, bias, and slope is significantly more dependent on the correlation of LST with in-situ soil moisture rather than NDVI. As shown in Table 4.2, the LST is highly correlated with in-situ soil moisture in comparison to NDVI. Therefore, the methods which include the same weight of NDVI and LST (Dispatch and Triangle method) show comparatively poor performance. Although, the performance of the different downscaling algorithms also varies from the grid to grid, dependent on the correlation of land factors (LST and NDVI) with the ground truth soil moisture (Table 4.2) and the accuracy of the estimated soil moisture (Table 4.1).

#### **4.4.3 Performance analysis of different downscaling algorithms using SMAP L2 soil moisture**

The downscaling algorithms' performance is then assessed using direct SMAP L2 soil moisture. The comparison of different downscaling methods for SMAP soil moisture to in-situ soil moisture is shown in the scatter plot (Figure 4.5). Where downscaled SMAP soil moisture (y-axis) is represented as the function of in-situ soil moisture (x-axis). The



**Figure 4.5** Spatial comparison of downscaled SMAP soil moisture (y-axis) using Dispatch, ATI, and Triangle method with the in-situ soil moisture (x-axis) for the selected eight grids.

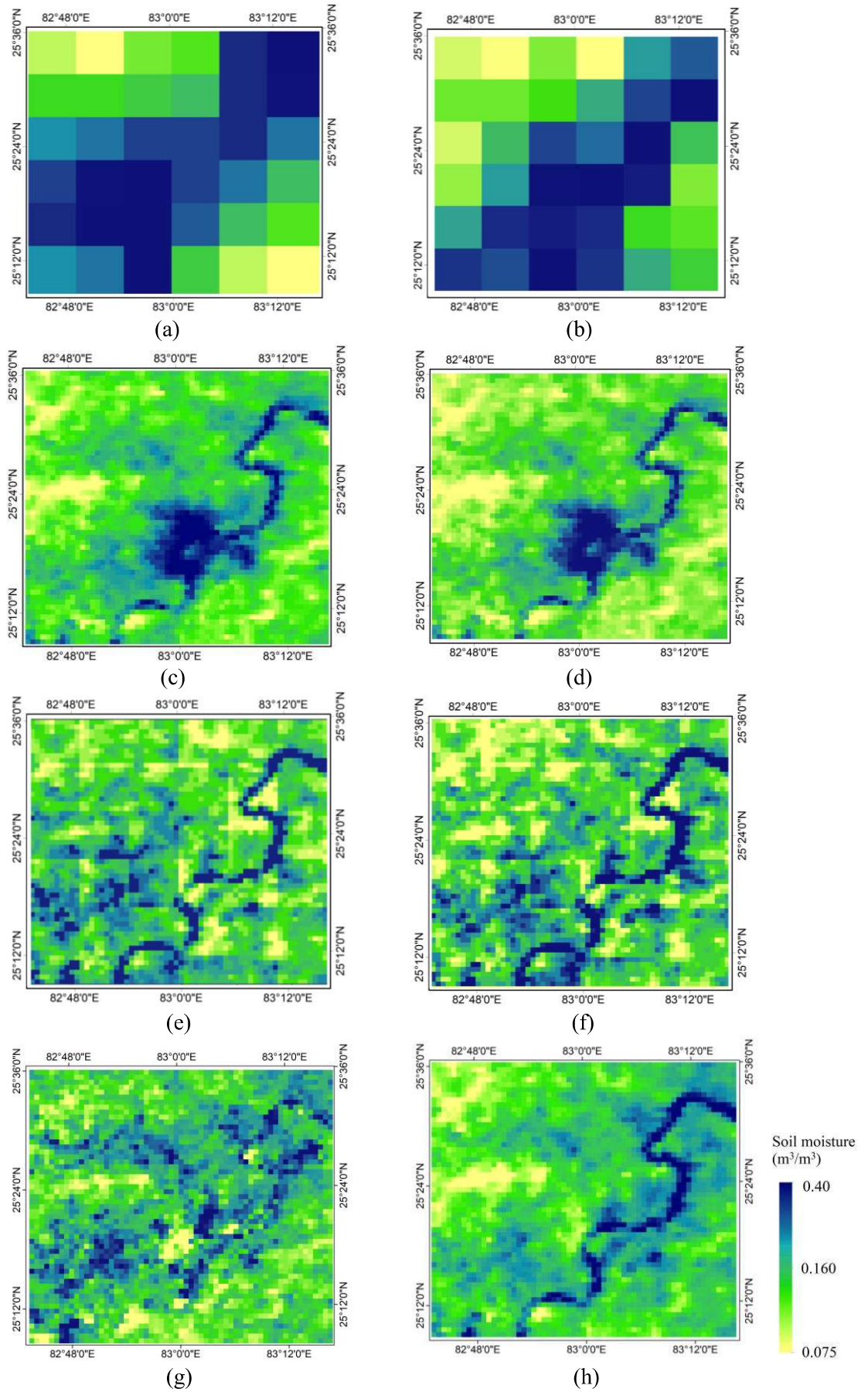
results obtained with the Triangle method and the ATI are better distributed along the 1:1 line than the Dispatch method. The data values obtained with the Triangle and the ATI method are almost similar, but the best results were obtained using the ATI. Each grid shows different results due to the different characteristics, correlation of LST and NDVI with soil moisture, and the SMAP L2 soil moisture data product's performance. Values of the correlation coefficient, RMSE, bias, and slope for different disaggregation methods and each grid (Table 4.3) indicate that the ATI approach performs well compared to the Triangle and the Dispatch method. The Dispatch, Triangle, and the ATI's overall correlation coefficients are found to be 0.36, 0.46, and 0.60, respectively. The RMSE values for the ATI are the lowest and ranged from 0.05 to 0.10; similarly, in the case of bias and slope, the ATI method performs well, and the values found in the range from -0.007 to -0.041 and 0.18 to 0.66, respectively.

**Table 4.3** Performance analysis of different downscaling algorithms including Dispatch, Triangle, and ATI when used with SMAP soil moisture, in terms of Correlation coefficient (R), RMSE, bias, and slope.

Grid	Dispatch				Triangle				ATI			
	R	RMSE	Bias	Slope	R	RMSE	Bias	Slope	R	RMSE	Bias	Slope
<b>1</b>	0.36	0.09	-0.044	0.19	0.32	0.09	-0.030	0.02	0.60	0.08	-0.030	0.28
<b>2</b>	0.26	0.10	-0.059	0.12	0.48	0.10	-0.049	0.30	0.45	0.09	-0.041	0.19
<b>3</b>	0.44	0.11	-0.054	0.18	0.40	0.10	-0.037	0.30	0.65	0.06	-0.018	0.36
<b>4</b>	0.40	0.07	0.016	0.31	0.28	0.07	0.004	0.03	0.72	0.04	0.021	0.65
<b>5</b>	0.33	0.05	0.002	0.28	0.70	0.04	0.012	0.56	0.73	0.04	0.010	0.59
<b>6</b>	0.36	0.07	0.008	0.37	0.52	0.05	-0.006	0.30	0.39	0.05	-0.007	0.25
<b>7</b>	0.22	0.12	-0.026	0.13	0.32	0.11	-0.030	0.02	0.53	0.10	-0.037	0.18
<b>8</b>	0.51	0.07	0.033	0.67	0.66	0.04	0.018	0.50	0.73	0.04	0.015	0.66
<b>Average</b>	0.36	0.09	-0.016	0.28	0.46	0.08	-0.015	0.25	0.60	0.06	-0.011	0.40

#### **4.4.4 Comparison of the performance of SMAP L2 soil moisture and the estimated soil moisture in the downscaling methods**

The SMAP L2 soil moisture product and estSM values were utilized in the three different downscaling methods (Triangle, Dispatch, and ATI). The results of disaggregation were validated with the ground truth measurements shown in the previous sections. The Thermal Inertia based method shows the best result with both the soil moisture products, either SMAP L2 or estSM, when compared with the Triangle and the Dispatch methods. The scatter plots, shown in Figures 4.4 and 4.5, illustrate that the downscaled estSM shows improved results than the downscaled SMAP soil moisture with all three algorithms and all the grids except only grid 3. The downscaled estSM for grid 3 does not show that much noticeable improvement than downscaled SMAP L2 soil moisture for the Triangle and the ATI, but it performs better for the Dispatch algorithm. The statistical analysis of the downscaled estSM and SMAP soil moisture, shown in Tables 4.2 and 4.3, also concludes that estSM improves statistical variables' values over the SMAP L2 soil moisture. The overall correlation coefficients for downscaled estSM are 0.56, 0.68, and 0.72 for the Dispatch, Triangle, and ATI, respectively. Whereas for SMAP L2 soil moisture, its values are 0.36, 0.46, and 0.60 for the Dispatch, Triangle, and ATI, respectively. Similarly, if the values of RMSE, bias, and slope are being compared, the downscaled results of estSM have better performance than SMAP soil moisture. The best averaged RMSE, bias, and slope for estSM and SMAP L2 soil moisture are 0.05 and 0.06, -0.002 and -0.011, and 0.53 and 0.40, respectively, with the ATI method. The spatial distribution map for SMAP L2 soil moisture, estSM, and 1 km rescaled soil moisture using three prescribed algorithms with the original SMAP L2 soil moisture and the estSM for 18 April 2018 are shown in Figure 4.6. The images of downscaled soil moisture (from Figure 4.6(b) to (d) and 4.6(f) to (h))



**Figure 4.6** Spatial maps of (a) SMAP L2 soil moisture, (b) estSM and downscaled and downscaled SMAP L2 soil moisture using (c) ATI (c) Dispatch and (d) Triangle method, downscaled estSM using (d) ATI (g) Dispatch and (h) Triangle method.

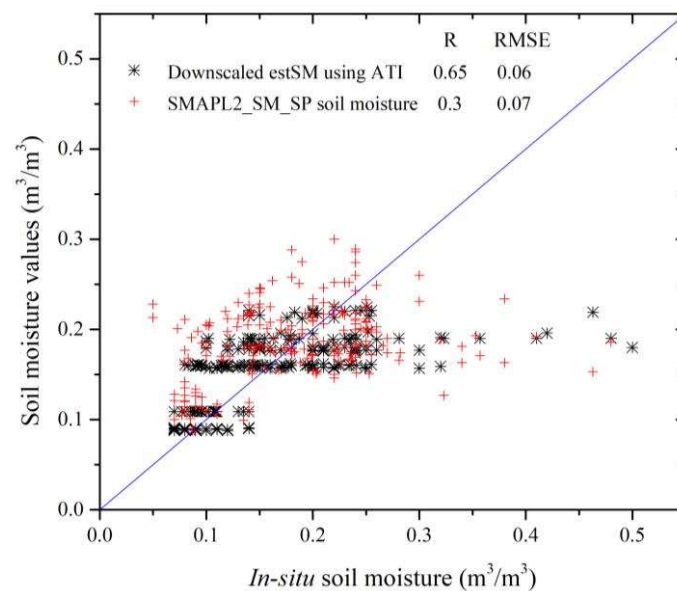
show more detailed information than the original image of SMAP L2 soil moisture (Figure 4.6(a)) and estSM (Figure 4.6(e)) at the resolution of 9 km. The Ganges River is clearly shown in all the maps of downsampled soil moisture, while it cannot be clearly seen in the original SMAP L2 soil moisture and the estSM map. The spatial pattern of downsampled soil moisture using the Thermal Inertia based approximation (Figure 4.6(b) and (f)) significantly enhances the spatial variability of soil moisture in comparison to the Dispatch (Figure 4.6(c) and (g)) and the Triangle methods (Figure 4.6(d) and (h)). The soil moisture distribution map for the downsampled SMAP L2 data product and the downsampled estSM are shown in Figures 4.6(b), (c), (d), and 4.6(f), (g), (h), respectively. These figures show that the spatial distribution maps for the downsampled estSM provide a better interpretation of soil moisture than downsampled SMAP L2 soil moisture for all three approaches.

#### **4.4.5 Comparison with the active-passive microwave soil moisture product of SMAP**

The above results show that the ATI is the best downscaling approach among the three prescribed methods with the estSM; therefore, in this section, the downsampled results of ATI are compared with the active-passive microwave soil moisture of SMAP (SMAPL2\_SM\_SP) [62]. This product is produced with the combination of SMAP L-band TB and Sentinel 1A/B C-band  $\sigma^0$  and is now available globally at the spatial resolution of 3 km and 1 km with a temporal frequency of 12 days. But its temporal frequency varies for different regions, and the revisit frequency for the selected area is 2 to 3 days. Due to this discontinuous coverage, the product is not completely coinciding with the field data sampling. The availability of the product with the ground sampling is shown in Table 4.4.

**Table 4.4** The available dates of SMAPL2\_SM\_SP data product along with the ground data sampling.

Dates of Field Sampling	Available Dates of SMAPL2_SM_SP data product
14/Oct/2017	13/Oct/2017
02/Nov/2017	01/Nov/2017
15/Nov/2017	-
01/Dec/2017	30/Nov/2017
15/Dec/2017	16/Dec/2017
16/Jan/2018	17/Jan/2018
06/Feb/2018	05/Feb/2018
16/Feb/2018	16/Feb/2018
28/Mar/2018	-
18/Apr/2018	18/Apr/2018



**Figure 4.7** Comparison between downscaled estSM using ATI and active-passive microwave soil moisture product of SMAP.

In the present study, the 1 km product was used to compare with downscaled soil moisture. The comparison between downscaled estSM using ATI and the

SMAPL2\_SM\_SP soil moisture is shown in the scatter plot (Figure 4.7). This comparison indicates that the downscaled estSM using ATI performs better than the SMAPL2\_SM\_SP with the correlation coefficient of 0.65 and the RMSE of 0.06.

#### **4.5 CONCLUSION**

The primary goal of this chapter is to enhance the accuracy of SCA and then the downscaling results by using the estSM in the downscaling algorithms instead of direct SMAP L2 soil moisture data values and to investigate the better downscaling approach among the Triangle, Dispatch, and the ATI.

The comparison of estSM and SMAP L2 soil moisture indicates that estSM performs better than initial SMAP L2 soil moisture for each grid due to the inclusion of suitable roughness values and VWC with better temporal resolution. The results of disaggregation approaches were also significantly improved with the estSM over the SMAP L2 soil moisture for all grids. The comparison among these algorithms indicates that the Thermal Inertia based approach is the best performing approach among the prescribed techniques. The spatial distribution pattern of the downscaled soil moisture pointedly enhances the soil moisture variability than the appearance of coarse resolution SMAP L2 soil moisture or estSM. Among the images of downscaled soil moisture, the estSM provides a more detailed and precise value of downscaled soil moisture than SMAP L2 soil moisture. The main reason for error with the SMAP L2 soil moisture is not performing well with the in-situ soil moisture compared to estSM. Hence, using estSM instead of direct SMAP L2 soil moisture in the downscaling algorithms significantly improves the results.

This study adopted the modified SCA and several downscaling approaches to find the best approach. Therefore, the depth discrepancy between the satellite soil moisture and the in-situ soil moisture can be improved by using the better temporal resolution of NDVI and

the optimized value of the roughness parameter in SCA. Further, this study can be beneficial for the future satellite mission, namely Terrestrial Water Resources Satellite (TWRS) [127], a combined mission of optical and radar observations, by including ATI to achieve high-resolution soil moisture as it performed better among the other methods based on optical datasets.

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