

Chapter 2 : MATERIALS AND METHODOLOGY

2.1 SATELLITE DATASETS

2.1.1 SMAP

SMAP, which stands for Soil Moisture Active Passive, is an orbiting observatory that measures the amount of moisture contained in the soil surface all over the Earth. SMAP was launched in January 2015 and started to operate in April 2015. SMAP was designed with active (radar) and passive (radiometer) measurements. Its operational frequency is 1 – 2 GHz (L-band). In order to attain a broad coverage, the antenna rotates at 14.6 revolutions per minute (around one revolution every 4 seconds). The combination of orbital motion with the spin of the antenna allows it to sweep a small FOV (Field of View) in a sequence of overlapping loops that produce a swath of 1000 km wide. The broad swath enables SMAP to continuously generate a global soil moisture map every two to three days. After every 8 days, a similar swath is revisited. The altitude of the SMAP orbit from the Earth's surface is 685 km.

The spatial resolutions of SMAP radiometer and radar are 36 km and 3 km, respectively. The final SMAP combined output has a spatial resolution of 9 km. After the termination of radar observations, N. N. Das [13] introduced a new approach in which the Sentinel-1 SAR backscattering values replaced radar backscattering values and the resultant product was replaced by the previous one on the website on SMAP.

The Level – 1 product of SMAP (SMAP L1) provides brightness temperature and is available with two spatial resolutions; 36 km and 9 km. The 9 km product is the enhanced version of 36 km. Similarly, SMAP's Level - 2 product (SMAP L2) delivers soil moisture data at 36 km and 9 km spatial resolutions. The SMAP L2 soil moisture data product is

evaluated using SMAP L1 brightness temperature in the baseline algorithm, which is based on the zeroth-order RTM and known as SCA. SMAP L2 product also provides the data values of surface temperature, clay percentage, surface roughness parameter, albedo, and VOD, that are the essential parameters for the accurate modelling of the baseline algorithm of SMAP.

The brightness temperature provided by SPL1CTB and SPL1CTB_E data products of SMAP L-1 are used for the modelling of SCA. The soil moisture values provided by SPL2SMP and SPL2SMP_E data products of SMAP L2 are utilised for validating the predicted soil moisture as well as disaggregation. The description of these datasets is provided in the Table. 2.2.

2.1.2 MODIS

Initially, on December 18, 1999, NASA launched the Terra (EOS AM-1) satellite into Earth's orbit with the MODIS sensor on board. The satellite crosses the equator around 10:30 AM local time while in a near-polar circular orbit 705 kilometres above the Earth's surface. On May 4, 2002, the Aqua satellite was launched with an additional MODIS sensor. The Terra satellite crosses the equator from north to south in the morning, while the Aqua satellite crosses the equator from south to north in the afternoon (01:30 PM). Terra MODIS and Aqua MODIS map the entire Earth's surface every 2 days and acquire data in 36 spectral bands. The wavelength of these bands ranges from 0.4 μm to 14.4 μm with different spatial resolutions, such as; 2 bands have 250 m, 5 bands have 500 m, and 29 bands have 1000 m of pixel size.

MODIS delivers many atmospheric corrected land surface products. The MOD09GA provides daily surface reflectance of seven bands at the spatial resolution of 500m [94]. The wavelength range corresponding to these bands is given in Table 2.1. MOD11A1 and

MOD11B1 provide daily LST at 1 km and 6 km spatial resolution, respectively. MOD13A2 provides a 16-day average of NDVI at a spatial resolution of 1 km. MYD11A1 and MYD11B1 also provide daily LST at 1 km and 6 km spatial resolution, respectively. The description of these datasets is provided in the Table 2.2.

Table 2.1 Wavelength range for Band 1 to 7 of MODIS data product (MOD09GA).

| Band | Wavelength Range |
|------|------------------|
| B1 | 620 – 672 nm |
| B2 | 841 – 876 nm |
| B3 | 459 – 479 nm |
| B4 | 545 – 565 nm |
| B5 | 1230 – 1250 nm |
| B6 | 1628 – 1652 nm |
| B7 | 2105 – 2155 nm |

2.1.3 Sentinel-1 SAR data

The Sentinel-1 mission is a SAR component launched by the ESA on April 3, 2014. Sentinel-1 is a two-satellite constellation (1A and 1B) that operates in the microwave C-band frequency range. The constellation helps to increase the temporal frequency of the satellite from 12 to 6 days. Sentinel-1 SAR captures data over the Earth’s surface in four modes: 1) Strip map (SM), 2) Interferometric Wide swath (IW), 3) Extra Wide swath (EW), and 4) Wave (WV). The IW mode is further splitted into three sub swaths (IW1, IW2, and IW3), which are imaged with the Terrain Observation with Progressive Scans SAR

(TOPSAR) method at a spatial resolution of 5m x 20 m. The IW products have a lengthy coverage and are presented in some slices, making data management more straightforward regarding data storage and computational effort. Each slice acts as a separate product and can be processed separately. Each sub-swath contains nine bursts in the azimuthal direction.

Table 2.2 Satellite data used in the study.

| Data | Data product | Satellite | Spatial Resolution | Temporal Resolution |
|--------------------------------------|---------------------|---------------------------|---------------------------|----------------------------|
| Soil Moisture | SPL2SMP | SMAP | 36 km | Daily |
| Soil Moisture | SPL2SMP_E | SMAP | 9 km | Daily |
| Soil Moisture | SPL2SM_SP | SMAP | 3 and 1 km | 12 days |
| Brightness Temperature | SPL1CTB | SMAP | 36 km | Daily |
| Brightness Temperature | SPL1CTB_E | SMAP | 9 km | Daily |
| Land Surface Temperature (LST) | MOD11A1, MYD11A1 | Terra-MODIS Aqua-MODIS | 1 km | Daily |
| Land Surface Temperature (LST) | MOD11B1, MYD11B1 | Terra-MODIS Aqua-MODIS | 6 km | Daily |
| NDVI | MOD13A2 | Terra-MODIS | 1 km | 16 Days |
| Surface Reflectance | MOD09GA | Terra-MODIS | 500 m | Daily |
| Dual Polarized backscatter intensity | S1A_IW_SLC_1SDV | Sentinel-1 | 5 x 20 m | 6 days |

Sentinel-1 IW product is further available in two data types; GRD (Ground Range Detected) and SLC (Single Look Complex). The SLC products contain focused SAR data, which is geo-referenced through satellite orbit and altitude data. This product includes a single look in each dimension because of the use of complete transmit signal bandwidth and also consists of complex samples which preserve the phase information. The GRD product comprises the focused SAR data that has been sensed, multi-looked, and then projected to the ground range using an Earth ellipsoid model. This product doesn't have phase information and has almost square spatial resolution and square spacing between the pixels with low speckle and poor spatial resolution.

In this thesis, the Sentinel-1 SLC product has been used. The initial product of Sentinel-1 provides data in terms of amplitude and intensity. After pre-processing and calibration, it is converted into a backscattering coefficient or complex form. The description of these datasets is provided in the Table. 2.2.

2.2 GROUND MEASUREMENTS

The instruments used for ground measurements are discussed below,

2.2.1 Steven's water soil sensor: Hydra Probe

The Hydra Probe is a durable soil sensor that uses advanced technologies [95]. It continuously and consistently measures the three most important soil parameters—soil moisture, soil salinity, and soil temperature—all together at the same. It is a "dielectric

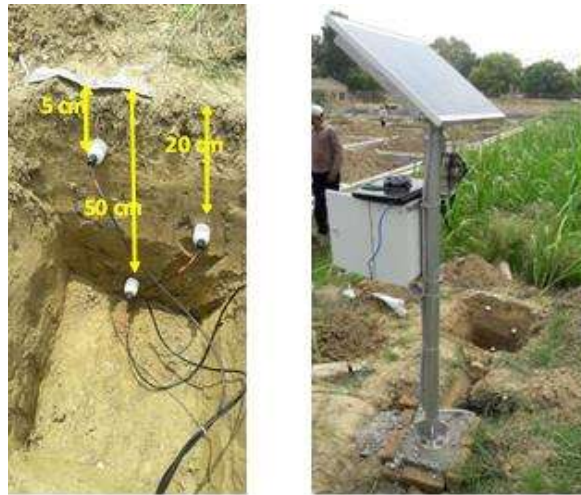


Figure 2.1 Hydra Probe soil sensor installed in the agricultural field of BHU

impedance"-based soil sensor which is produced by the Department of Physics, Dartmouth College, Hanover, United States. Unlike the capacitance or time domain-based soil sensors, it is completely described by the dielectric spectrum at a radio frequency of 50 MHz. It is used by installing it into the soil surface at different heights. For this research, it was permanently installed in the agricultural field of BHU on June 7, 2017. And collect soil moisture information at three depths, 5cm, 20cm, and 50cm, every 15 minutes all over the day. The picture of the installed Hydra Probe in the agricultural field of BHU is given in Figure 2.1.

2.2.2 Hydra GO

The basic phenomenon of Hydra GO is similar to that of Hydra Probe. The main difference is in the data collection process. The Hydra Probe is a permanently installed soil moisture sensor that delivers soil moisture values of a similar place every 15 minutes. Whereas Hydra GO is a portable soil sensor, it can be taken anywhere to detect soil moisture content. It is fitted with a 5 cm portable probe for measuring soil moisture up to a depth of 5 cm. It also includes wireless technology for establishing a connection with a smartphone in order to transmit data values. It can also measure three soil parameters

simultaneously: soil moisture content, soil surface temperature, and soil electrical conductivity [96]. The image Hydra Go soil sensor is shown in Figure. 2.2.



Figure 2.2 The Hydra Go soil sensor

2.3 GROUND SAMPLING CAMPAIGN

During the research period, two field sampling campaign was conducted in the Varanasi district.

2.3.1 From Oct-2017 to Apr-2018 (Ten Dates of seven months)

The field sampling was conducted from October 14, 2017, to April 18, 2018. The monsoon season months (May to September) were excluded from the sampling plan. The sampling was planned on eight equal grids [Figure. 2.3 (black square)] having an area of $9\text{km} \times 9\text{km}$. These eight grids were constructed in accordance with SMAP pixels and can be considered comparable to one SMAP data product pixel. The sampling was carried out on the ten dates of 2017 and 2018 at the interval of 10 to 15 days. Black triangles in Figure 2.3 represent the points where data values were taken from the ground, and 2 to 7 points were chosen from each grid to collect soil moisture samples. Table 2.3 describes the center latitude and longitude along with the number of sampling points for all the grids. Figures

2.4 and 2.5 shows the variation of soil moisture for all the grids and all the dates, respectively. The in-situ soil moisture measurements were taken by a soil sensor named Hydra Go, described in section 2.2.2.

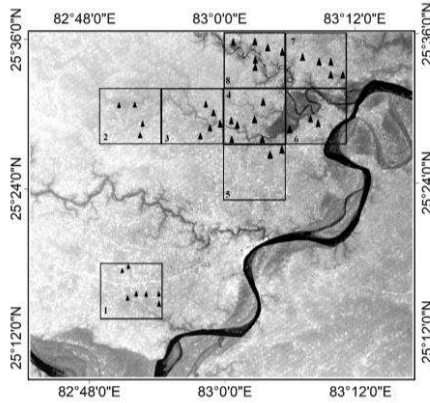


Figure 2.3 Overview of the field sampling plan.

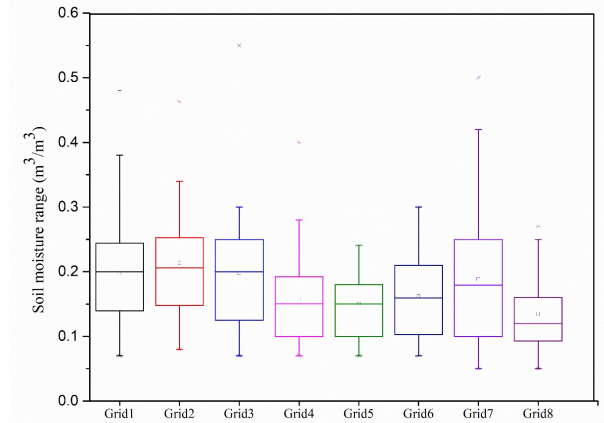


Figure 2.4 Soil moisture values corresponding to different Grids.

Table 2.3 Description of the eight in-situ grids.

| Grid | Center Latitude | Center Longitude | No. of sampling points |
|-------------|------------------------|-------------------------|-------------------------------|
| 1 | 25° 15' 24.48" | 82° 51' 28.52" | 7 |
| 2 | 25° 29' 26.49" | 82° 51' 28.52" | 4 |
| 3 | 25° 29' 26.49" | 82° 57' 4.53" | 5 |
| 4 | 25° 29' 26.49" | 83° 2' 40.53" | 6 |
| 5 | 25° 24' 45.48" | 83° 2' 40.53" | 2 |
| 6 | 25° 29' 26.49" | 83° 8' 16.53" | 3 |
| 7 | 25° 34' 7.49" | 83° 8' 16.53" | 5 |
| 8 | 25° 34' 7.49" | 83° 2' 40.53" | 6 |

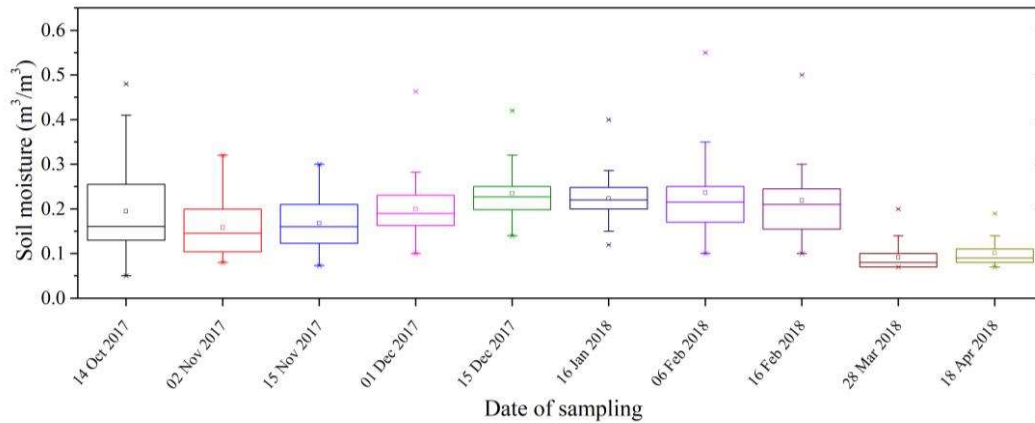


Figure 2.5 Whisker plot for the in-situ measurements of soil moisture.

2.3.2 From Jan-2020 to Feb-2020 (Terminated in between due to COVID)

The field sampling was started on January 2, 2020, with the initial plan of ending in May 2020 as per the complete crop cycle of wheat. However, the field sampling remained half-finished and was terminated on 23 February 2020 due to the COVID pandemic. Still, the data values were collected on the five dates of January and February 2020. The season of the entire campaign was winter, but the last date was closer to the spring season. The sampling locations were covered by several crops such as wheat, maize, mustard, and some

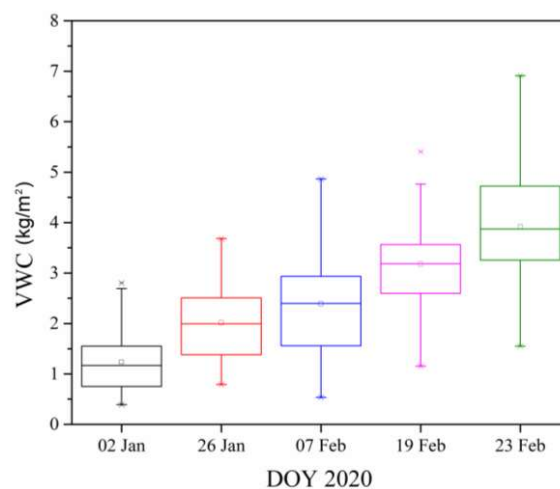


Figure 2.6 Range of VWC for five days of 2020.

vegetables. An average of 60 data points was selected each day. In this sampling campaign, two main variables were collected from each site; VWC and soil moisture. The samples of green vegetation were collected using a 0.5m x 0.5m quadrant. All the green vegetation inside the quadrant was taken out from the land surface and sealed and packed into a bag to ensure no moisture loss. The vegetation samples were used to find their wet weight before placing them in the dehydrator (oven) for three to four days. Then, the samples were taken out to find their dry weight. The difference between the wet and the dry weight allowed us to obtain the VWC. Figure 2.6 demonstrates the range and average values of VWC for the selected dates.

Along with VWC, soil moisture data were also collected using a Hydra Go portable soil sensor. Figure 2.7 shows the range of soil moisture measurements made during the field assessment.

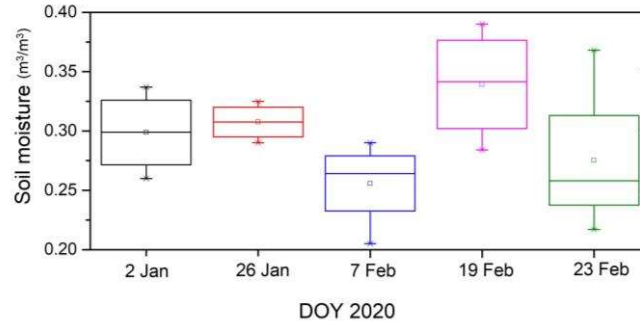


Figure 2.7 Variation of soil moisture for five days of 2020.

2.4 STUDY AREA

This research was conducted in the Varanasi district of eastern Uttar Pradesh, India. This campaign site is prepared for ScatSat-1 calibration and validation and comes under the ISRO PAN India soil moisture network. It is situated in conjunction with three rivers, the Ganges, Varuna, and Assi, and between the altitude of 50 to 70 feet above the river. The Varanasi district's climate is subtropical, with a substantial difference between summer

and winter temperatures. Dry summer begins in mid-March and continues till June, followed by monsoon season (July to September), followed by winter, which starts in October and stays up to February. The months of May to September mainly belong to the monsoon season and are mostly covered by clouds. Thus, these months were excluded from the study. The minimum and the maximum temperatures of Varanasi district in summer ranges from 22°C to 47°C, and for winter season ranges from 5°C to 27°C. The total terrestrial area covered by the district is 1535 km², out of which more than 60% part is covered by agricultural fields, ~12% is fallow land or grassland, approximately 10-11% part is a built-up or urban region, and the rest is covered by trees and water features. Figure 2.8 represents the study area's location in INDIA together with RGB imagery of Sentinel-1, and land cover map, which shows the dominance of agriculture over other classes. The chief crops of the Varanasi district are wheat, paddy, pearl millet, pigeon pea, and maize.

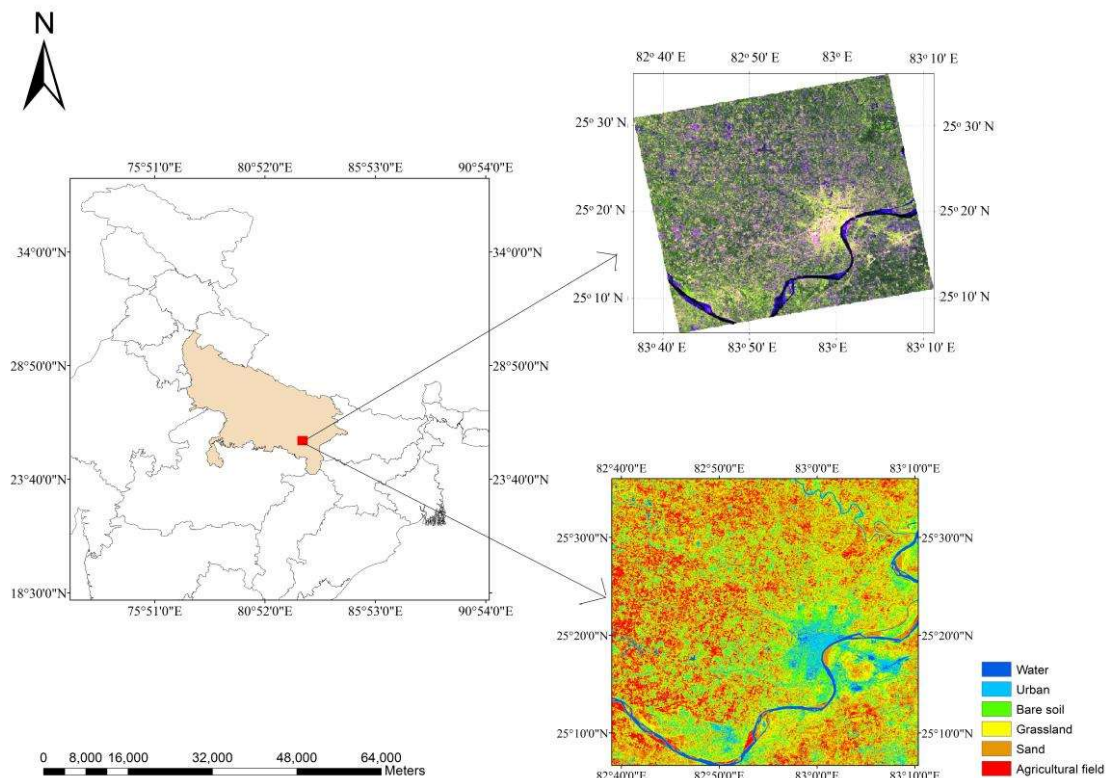


Figure 2.8 Location of the study area in India along with RGB image of Sentinel-1, and Land cover map.

Due to the location at the Indo-Gangetic Plain, the soil is exceptionally fertile, and the often-low-level floods continually replenish the soil. The soil is categorized into four classes according to texture and composition [97];

- (a) Ganga sandy loam,
- (b) Western low land soil,
- (c) Western upland soil,
- (d) Loamy soil

Other physical characteristics of the Varanasi region are described below,

| | | |
|------------------------------|---|---|
| Geographical location | : | 25° 10' 30'' N to 25° 35' 15'' N |
| Latitude | | |
| | | 82° 40' 50'' E to 83° 12' 18'' E |
| | | Longitude |
| Projection | : | UTM (zone – 44, N), WGS 84 |
| Geographical area | : | 1532.91 km² |
| Average rainfall | : | 1110 mm (44 in.) |
| Climate zone | : | Humid subtropical |
| Elevation | : | 81 m |

2.5 METHODOLOGY

2.5.1 Satellite soil moisture retrieval

In microwave remote sensing, RTM is the most appropriate model for soil moisture monitoring. It presents a perfect balance of upwards and downwards radiations from the ground. The zeroth-order RTM or the Tau-omega model has been utilized in this thesis for the assessment of soil moisture as it is more suitable for the low-vegetation area. This model is described below

- **Single-Channel Algorithm (SCA) or Tau-omega model**

The Tau-omega model is appropriate for the chosen study region due to the presence of low or sparse vegetation or agricultural fields. This model includes all possible factors corresponding to the geometry of the soil surface and low vegetation. Two main parameters of this model are, as per its name Tau (τ), VOD or opacity through vegetation, and omega (ω), single scattering albedo. This model has also been utilized as the baseline method for the SMAP soil moisture product, and it has been called SCA. The ATBD [59] of SMAP describes the demonstrating of SCA in detail. According to SCA, microwave emissivity can be stated as,

$$e = \frac{T_B \text{ (Brightness Temperature of SMAP)}}{T \text{ (Surface Temperature)}} \quad (2.1)$$

Where

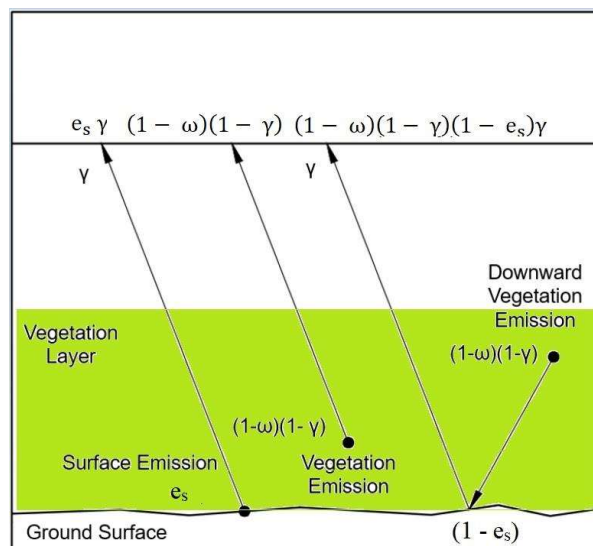


Figure 2.9 Formulation of Tau-Omega model.

$$e = \text{soil emissivity} + \text{Vegetation emissivity} + \text{Reflected vegetation emissivity form soil} \quad (2.2)$$

The formulation of the Tau-omega model can be better understood by demonstrating at Figure 2.9 [98],

The principal equation is

$$e = e_s \gamma + (1 - \omega)(1 - \gamma)[1 + (1 - e_s)\gamma] \quad (2.3)$$

Where ω is the single scattering albedo, representing the scattering fraction in the total extinction efficiency, its reported numerical value for low vegetation at L-band is 0.05. γ is the vegetation attenuation coefficient, representing the attenuation of the radiations as a result of scattering, absorption, and reflection suffered by the waves in vegetation layer. It can be measured by using VOD (τ) and can be stated as,

$$\gamma = e^{(-\tau/\cos\theta)} \quad (2.4)$$

VOD is dependent on VWC as $\tau = b \cdot \text{VWC}$, b is a proportionality constant and be subject to the vegetation conditions and the frequency range. Its reported numerical value for low-vegetation or croplands for the L-band frequency region is 0.25 ± 0.12 . θ is the incident angle of the satellite platform.

The conventional method for estimating VWC depends on MODIS products such as LAI and NDVI. The ATBD of SMAP L2 soil moisture used a relation between VWC and NDVI, developed by Jackson et al., [89] for the evaluation of VWC,

$$\text{VWC} = 1.9134 \text{NDVI}^2 - 0.3215 \text{NDVI} + s \frac{\text{NDVI}_{\max} - \text{NDVI}_{\min}}{1 - \text{NDVI}_{\min}} \quad (2.5)$$

Here, s is the stem factor, and its numerical value for croplands is 3.5.

In equation (2.3), e_s represents the vegetation corrected soil emissivity. After vegetation correction, this emissivity also requires a surface roughness correction.

Choudhury et al. [99] developed a model to study the significance of surface roughness on observed emissivity and successfully quantified the consequence of surface roughness on emissivity as follows,

$$e_s = 1 - (1 - e_0)e^{-h\cos^2\theta} \quad (2.6)$$

The soil surface roughness parameter h , is a function of the standard deviation of surface height and the wavelength of electromagnetic waves, as follows

$$h = 4\sigma^2 \left(\frac{2\pi}{\lambda} \right)^2 \quad (2.7)$$

Here, σ and λ denote the standard deviation of surface height and electromagnetic radiation's wavelength. According to the ATBD of SMAP L2 soil moisture product, h has not been measured using the above formula. Instead, it uses its direct value, which depends on vegetation conditions and frequency ranges. In ATBD, the reported values of h ranges from 0.1 to 0.4 for L-band whereas it is 1.08 for croplands, however the ground observation of northern India shows higher values for agricultural fields. Therefore, its optimized values were utilized in this thesis to determine the appropriate range of the surface roughness parameter.

e_0 in equation (2.6) denotes the emissivity of a smooth soil surface. It can be evaluated through Fresnel's equations [100] as follows,

$$e_{oH} = 1 - \left| \frac{\cos\theta - \sqrt{\varepsilon - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon - \sin^2\theta}} \right|^2 \quad (2.8)$$

$$e_{oV} = 1 - \left| \frac{\varepsilon \cos\theta - \sqrt{\varepsilon - \sin^2\theta}}{\varepsilon \cos\theta + \sqrt{\varepsilon - \sin^2\theta}} \right|^2 \quad (2.9)$$

e_{oH} and e_{oV} represent the smooth soil surface emissivity in horizontal and vertical polarization, respectively. Fresnel's equations show that it is strongly dependent on the soil's dielectric constant (ϵ), and that the soil dielectric constant is strongly dependent on soil moisture. The remote sensing community has introduced various soil dielectric models, such as Dobson [101], Wang & Schmugge [102], and Mironov [103, 104]. The Mironov model is more suitable due to its easier parameterization and fewer input variables than other models. Mironov established two dielectric models, the first one [103] is dependent on frequency and texture at room temperature, and the second one [104] is a temperature- and texture-dependent dielectric model at a frequency of 1.4 GHz. The latter one is more appropriate and used in this study due to its applicability to L-band. It requires only clay percentage and soil temperature as the input parameters. It can be described as follows,

$$\epsilon'_s = n_s^2 - k_s^2 \quad (2.10)$$

$$\epsilon''_s = 2n_s k_s \quad (2.11)$$

Here, ϵ'_s , and ϵ''_s are the real and imaginary parts of the soil dielectric constant, and n_s and k_s denote the refractive index and the normalized attenuation coefficient for moist soil, respectively. They can be represented as the function of the refractive index and the normalized attenuation coefficient for dry soil (n_d, k_d), bound soil water (n_b, k_b), free soil water (n_u, k_u) as follows,

$$n_s = \begin{cases} n_d + (n_b - 1)M_v & M_v \leq M_{vt} \\ n_d + (n_b - 1)M_{vt} + (n_u - 1)(M_v - M_{vt}) & M_v \geq M_{vt} \end{cases} \quad (2.12)$$

$$k_s = \begin{cases} k_d + k_b M_v & M_v \leq M_{vt} \\ k_d + k_b M_{vt} + k_u (M_v - M_{vt}) & M_v \geq M_{vt} \end{cases} \quad (2.13)$$

Where M_v and M_{vt} are the values of volumetric soil moisture and the maximum bound water fraction in the soil layer, respectively.

$$M_{vt} = 0.0286 + 0.00307C \quad (2.14)$$

$$n_d = 1.634 - 0.00539C + 2.75 \times 10^{-5} C^2 \quad (2.15)$$

$$k_d = 0.0395 - 4.038 \times 10^{-4} C \quad (2.16)$$

$$n_b = (8.86 + 0.00321 T) + (-0.0644 + 7.96 \times 10^{-4} T)C \\ + (2.96 \times 10^{-4} - 9.6 \times 10^{-6} T)C^2 \quad (2.17)$$

$$k_b = (0.738 - 0.00903 T + 8.57 \times 10^{-5} T^2) + (-0.00215 + 1.47 \times 10^{-4} T)C \\ + (7.36 \times 10^{-5} - 1.03 \times 10^{-6} T + 1.05 \times 10^{-8} T^2)C^2 \quad (2.18)$$

$$n_u = (10.3 - 0.0173 T) + (6.5 \times 10^{-4} + 8.82 \times 10^{-5} T)C \\ + (-6.34 \times 10^{-6} - 6.32 \times 10^{-7} T)C^2 \quad (2.19)$$

$$k_u = (0.7 - 0.017 T + 1.78 \times 10^{-4} T^2) + (0.0161 + 7.25 \times 10^{-4} T)C \\ + (-1.46 \times 10^{-4} - 6.03 \times 10^{-6} T - 7.87 \times 10^{-9} T^2)C^2 \quad (2.20)$$

C and T are the clay percentage and soil surface temperature, respectively.

2.5.2 Spatial disaggregation of soil moisture

Soil moisture information with high spatiotemporal resolution is necessary for numerous regional, hydrological, and agricultural applications. In this thesis, SMAP soil moisture is disaggregated up to 1 km using various approaches such as the Triangle method, Dispatch method, and Approximation of Thermal Inertia (ATI) theory.

- ***Triangle method***

Firstly, Carlson., [66] developed this method for predicting soil moisture based on the relation between spatiotemporal variability of temperature and the vegetation index for soil moisture. Later, this relationship was highly utilized with LST and NDVI to evaluate and downscale the coarse resolution satellite soil moisture. In this approach, the polynomial regression relation is regressed backward with high-resolution LST and NDVI to obtain

high-resolution soil moisture. The Triangle method can be expressed through a polynomial regression relation as follows,

$$SM = \sum_{i=0}^n \sum_{j=0}^m a_{ij} NDVI^{*(i)} LST^{*(j)} \quad (2.21)$$

Here, SM stands for soil moisture, and LST^* and $NDVI^*$ denote the normalized LST and NDVI, respectively, and can be described as,

$$LST^* = \frac{LST - LST_{min}}{LST_{max} - LST_{min}} \quad (2.22)$$

$$NDVI^* = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (2.23)$$

The subscripts max and min represent the maximum and minimum LST and NDVI values for the whole study region. Here, the first-order polynomial regression is used to rescale SMAP soil moisture.

$$SM = a_{00} + a_{01} LST^* + a_{10} NDVI^* \quad (2.24)$$

Since the MODIS LST and NDVI have a good spatial resolution, evaluating the regression coefficients allowed for the computation of the soil moisture at a high spatial resolution using equation (2.24). Thus, to evaluate the regression coefficients, equation (2.24) can be written as,

$$SM_C = a_{00} + a_{01} \frac{1}{N} \sum_{k=1}^N LST_{H,k}^* + a_{10} \frac{1}{N} \sum_{k=1}^N NDVI_{H,k}^* \quad (2.25)$$

LST_H^* and $NDVI_H^*$ signify the normalized LST and NDVI at the high spatial resolution, and k denotes the total number of high-resolution pixels in a coarse resolution pixel. The

regression relation was derived using 70% of the complete datasets, and the rest of the data values were used for the validation. After successfully obtaining the polynomial relation, the estimated regression coefficients are further employed with high-resolution MODIS LST and NDVI to compute the high-resolution soil moisture,

$$SM_H = a_{00} + a_{01} LST_H^* + a_{10} NDVI_H^* \quad (2.26)$$

- ***Dispatch method***

Dispatch stands for disaggregation based on physical and theoretical scale change and was introduced by Merlin et al., [63] This approach relies on a proxy SEE, which is the proportion of actual to potential evaporation. SEE can be estimated using MODIS LST by separating it into soil and vegetation temperature. The formula for SEE is as follows,

$$SEE = \frac{T_{S,max} - T_S}{T_{S,max} - T_{S,min}} \quad (2.27)$$

Where T_S indicates the soil skin temperature, it can be evaluated in three ways,

1. When the surface temperature is only controlled by soil evaporation (zone A in [63]).
2. When the surface temperature has a combined influence of soil evaporation and vegetation transpiration in the dry season (zone B in [63])
3. When the surface temperature has a combined influence of soil evaporation and vegetation transpiration in the wet season (zone C in [63])

A combined resultant formula for T_S is

$$T_S = \frac{LST - \frac{f_v(T_{v,min} + T_{v,max})}{2}}{1 - f_v} \quad (2.28)$$

Where $T_{v, \min}$, and $T_{v, \max}$ are the vegetation temperature at the minimum, and maximum water stress, the estimation of end members is shown below. f_v is the vegetation parameter that denotes the vegetation conditions. The region covered by dense or thick vegetation corresponds to f_v values greater than 0.5 and values less than 0.5 indicate a low vegetation region, agricultural, or sparse vegetation zone. f_v can be calculated by the following equation,

$$f_v = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (2.29)$$

Where $NDVI_{min}$ and $NDVI_{max}$ denote the minimum and the maximum values of NDVI over a selected study region.

The end members can be estimated as follows

1. $T_{S, \max} = \max (T_{MODIS})$
2. $T_{S, \min} = \min (T_{MODIS})$
3. $T_{v, \min} = \text{minimum vegetation temperature for } SEE = 0 (T_S = T_{S, \max}) \text{ for dry season}$
 $= \min (T_{MODIS}) \text{ for other seasons}$
4. $T_{v, \max} = \text{maximum vegetation temperature for } SEE = 1 (T_S = T_{S, \min}) \text{ for the wet season}$
 $= \text{maximum vegetation temperature for } T_S = T_{S, \max} \text{ for other seasons}$

The formulation for vegetation temperature T_v can be derived from equation (2.28) for evaluating $T_{v, \min}$ (minimum T_v), and $T_{v, \max}$ (maximum T_v) by substituting T_S with $T_{S, \min}$, and $T_{S, \max}$ as per the conditions, which is shown below,

$$T_v = \frac{LST - T_S (1 - f_v)}{f_v} \quad (2.29)$$

The final disaggregation equation can be represented as the subtraction of the coarse resolution SEE from the high-resolution SEE averaged over the pixels and multiplied by the variation of soil moisture related to SEE, and then added to the low-resolution soil moisture product.

$$SM_{high} = SM_c + \frac{\partial SM}{\partial SEE} (SEE - SEE_c) \quad (2.30)$$

Where SEE_c represents the coarse resolution SEE, averaged over the pixels, and $\partial SM/\partial SEE$ represents the variance in soil moisture related to SEE [65],

$$\frac{\partial SM}{\partial SEE} = a \frac{1}{N} \sum_{i=1}^N \frac{SM_{c,i}}{SEE_{c,i}} \quad (2.31)$$

N is the total number of pixels, a is an experimental tuning parameter, and 0.5 is the chosen value for 'a' in this study [65].

- *Approximation of Thermal Inertia Theory*

Bin Fang et al., [72] presented this approach based on the thermal inertial theory, representing a relation between the temperature difference and the daily soil moisture for different vegetation conditions. Thermal inertia is the property of any material that resists time-dependent temperature changes. Therefore, in contrast to materials with low thermal inertia, those with high thermal inertia exhibit comparatively low variation between their maximum and minimum temperatures. Thermal inertia is equal to the square root of the product of the material's bulk thermal conductivity and volumetric heat capacity, and volumetric heat capacity is a product of density and specific heat capacity multiplied together. [72].

$$I = \sqrt{k\rho c} \quad (2.32)$$

Since water has a greater heat capacity than dry soil, a higher water content in the soil leads to a higher thermal inertia and hence has relatively low-temperature changes. Thus,

the low moisture content of the soil correlates to the large difference in minimum and maximum temperatures, (ΔT) and vice versa. ΔT can be written as,

$$\Delta T = T_{max} - T_{min} \quad (2.33)$$

Where T_{max} and T_{min} are the maximum and the minimum temperature throughout the day, respectively. The two overpasses of the MODIS Aqua satellite were considered maximum and minimum temperatures. The MODIS LST corresponding to the 13:30 (day time) overpass was considered as a maximum, and the 01:30 (night time) overpass was considered as a minimum temperature on a whole day.

To build the downscaling technique, a linear regression between daily soil moisture and daily temperature differences that corresponds to specific NDVI intervals at coarse spatial resolution was constructed as follows

$$SM_c = a_0 + a_1 \Delta T_{9km} \quad (2.34)$$

Where a_0 and a_1 are the regression coefficients and SM_c and ΔT_{9km} are the soil moisture and temperature difference at the coarse spatial resolution, respectively. This relation was derived for three intervals of NDVI as 0 – 0.3, 0.3 – 0.6, and 0.6 – 0.9. Then, these computed regression coefficients for different NDVI intervals were then employed with the high spatial resolution (1 km) temperature difference (ΔT_{1km}) to obtain the high-resolution soil moisture.

$$SM_{high} = a_0 + a_1 \Delta T_{1km} \quad (2.35)$$
