SMAP L2 SOIL MOISTURE PASSIVE VALIDATION USING IN-SITU MEASUREMENTS FROM THE TWENTE REGION, THE NETHERLANDS

RAHWA LUKAS
February 2016

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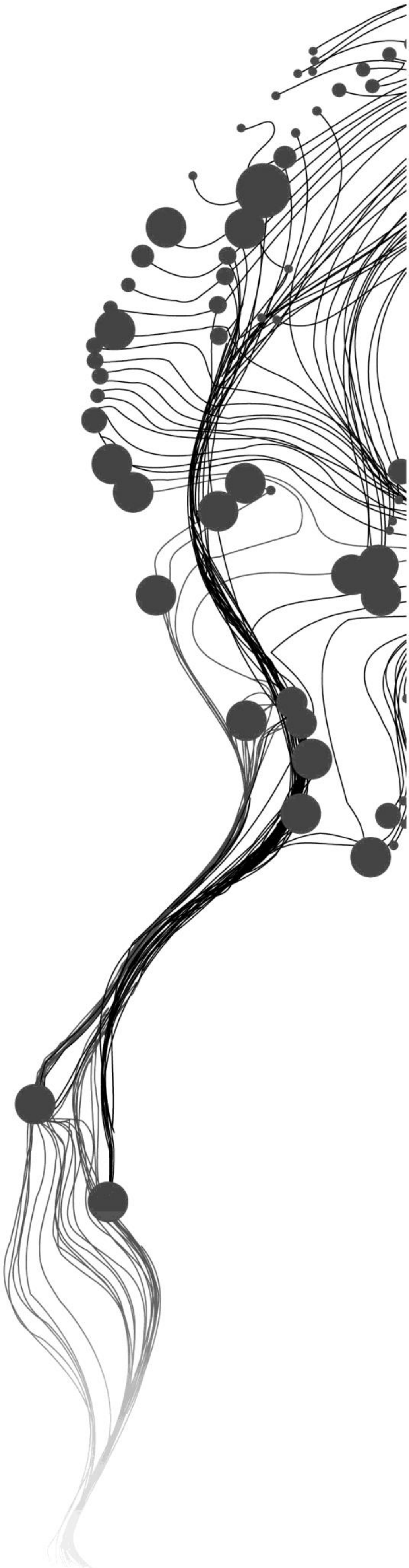

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RAHWA LUKAS
Enschede, The Netherlands, February 2016

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Water Resources and Environmental Management

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ABSTRACT

Soil moisture is a key variable in land surface processes and plays an important role in hydrology, weather and agriculture. It influences the partitioning of rainfall into runoff, infiltration and evapotranspiration. However, in-situ point measurements of soil moisture are spacres and each value is only representative of a small area because of the spatial soil moisture variability is caused by spatial heterogeneity in soil, land cover and atmosphere inputs. Remote sensing techniques for monitoring soil moisture such as SMAP Level 2 Soil Moisture Passive (L2_SM_P) can provide spatial and temporal observation of surface soil moisture at global and regional scale.

Twente monitoring station was selected as one core international validation site of SMAP soil moisture products, which consists of 20 stations that covers 50 x 40 km area. Intensive fieldwork was carried out to undertake soil moisture measurements at 11 fields within 5 selected stations and 11 sampling days in Twente region. Soil moisture was measured at different land covers and soil types using theta probe and a gravimetric soil samples. The measured soil moisture from the field used to characterize spatial and temporal patterns of soil moisture near the monitoring station and to provide reference volumetric soil moisture concurrent with SMAP satellite overpasses.

General calibration method with polynomial regression equation was applied to calibrate theta probe soil moisture measurements using gravimetric soil samples in order to achieve small errors. Statistical and temporal stability analysis were employed to estimate and characterize the spatial variability of soil moisture at field, station and regional scale. The accuracy of SMAP L2_SM_P soil moisture was assessed by comparing with in-situ soil moisture data from network stations and field data.

According to the statistical analyses, the cropped fields are found to be the driest and the grassland fields are the wettest. With different land cover, land use and soil type the soil moisture has shown different mean and variability. Most points in the fields show the lowest variability to the spatial average of field and station scale. The soil moisture at sampling location shows high variability to the spatial average of regional scale. The spatial variability of soil moisture increase with the extent of regional scale, with an average spatial coefficient of variation 0.334, and the temporal coefficient variation for individual fields on average ranges from 0.196 to 0.234. The temporal variability of soil moisture is higher as compare to the spatial variation of soil moisture. The soil moisture measured from the in-situ network and field measurements correlated with a coefficient of determination 0.37 and root mean square error 0.04 m^3m^{-3}.

The temporal dynamics of L2_SM_P soil moisture products is generally in agreement with in-situ soil moisture measurements. However, the retrieval soil moisture underestimates in-situ soil moisture measurements. The validation of L2_SM_P soil moisture against individual stations leads to coefficients of determination of 0.54 and 0.52 for the station SM-05 and SM-13 respectively with root mean square error of 0.067 m^3m^{-3} and 0.049 m^3m^{-3}. The validation result against spatial average of 8 selected stations leads to coefficient of determination 0.46 with root mean square error 0.076 m^3m^{-3}, and against spatial average of fieldwork data 0.32 with RMSE 0.09. These error levels do not meet the SMAP L2_SM_P accuracy target of 0.04 m^3m^{-3}. Twente monitoring stations missing a lot of data causes uncertainty for the validation of L2_SM_P soil moisture. The scale mismatch between the individual stations and L2_SM_P can be the reason to the uncertainty. The bias corrected L2_SM_P soil moisture leads to decrease the root mean squared error to 0.04m^3m^{-3} using individual stations SM-05 and SM-13, and are to 0.04 m^3m^{-3}.using spatial average of 8 station and field measurements.

Key words: SMAP, L2_SM_P, Soil moisture, Spatial variability, Theta probe

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CHAPTER ONE

1. INTRODUCATION

Soil moisture is a key variable in land surface processes and plays an important role in hydrology, weather and agriculture. It influences the partitioning of rainfall into runoff, infiltration and evapotranspiration(Bosch et al.,2006; Famiglietti et al., 1999). Therefore measuring surface soil moisture with the required spatial and temporal resolution and accuracy is important information for hydrometeorological and agriculture applications (Das et al., 2014; Velde et al., 2014).

Soil moisture measurements can be performed via in-situ techniques (theta probe and gravimetric) (Vereecken et al., 2014) and estimated from remote sensing data (Panciera et al., 2014). Point scale in situ measurement is representative of for specific site, the large spatial variability of soil moisture is not well represented (Njoku et al.,2003). For weather forecasting and hydrological application representatives soil moisture for large region needs (Scipal et al., 2008). Remote sensing, if achievable with sufficient accuracy and reliability, can provide spatial and temporal observations of surface soil moisture at global and regional scale (Kornelsen & Coulibaly, 2013). Active and passive microwave satellite sensors such as Soil Moisture and Ocean Salinity (SMOS)(Dente et al., 2012), Soil Moisture Active Passive (SMAP) (Kornelsen & Coulibaly, 2015) and Advanced Microwave Scanning Radiometer for the Earth Observation System(AMSR-E) (Sahoo et al.,2005) can provides soil moisture across large domains over a certain period of time.

National Aeronautics and Space Administration (NASA) launched the Soil Moisture Active Passive (SMAP) satellite in on 31 January 2015 . The innovative measurement approach of SMAP is consists of L-band Synthetic Aperture Radar (SAR) and radiometer integrated into a single observation system combining active and passive remote sensing to obtain high-resolution(9-km) soil moisture mapping (Das et al., 2014; Entekhabi et al., 2014; Panciera, 2009). SMAP enables global mapping of soil moisture and freeze/thaw state every 2-3 days on nested 3, 9, and 36 km earth grids (Akbar & Moghaddam, 2015; Panciera et al., 2014). SMAP aims at providing soil moisture in the top of 5 cm for vegetation water content ≤ 5 kg with volumetric accuracy of 0.04 m^3m^{-3} excluding regions of snow and ice.

The SMAP Level 2 radiometer passive(L2_SM_P) measures the natural microwave emission from of the brightness temperature of land surface. The SMAP radiometer brightness temperature, which is derived surface soil moisture at coarser resolution 40 Km output on fixed 36 km grid and higher sensitivity to soil moisture (Das et al., 2014; Entekhabi et al., 2014). The L2 radar active (L2_SM_A) measures the energy backscatter from land surface , which is capable to detect high resolution (3 km). But the high resolution (3km) of L-band radar SAR reduced there sensitive to soil moisture especially over densely vegetated area and rough surface (Das et al., 2014; Entekhabi et al., 2014). The SMAP soil moisture product combining the relative strength of active(radar) and passive(radiometer) microwave remote sensing to drive high resolution (9 km) soil moisture product (L2_SM_A/P) that meets SMAP requirements.

Unfortunately, the high Power Amplifier of the SMAP radar experienced an anomaly which caused the radar to stop transmitting on July 7, 2015. All subsequent attempts to power up the radar were unsuccessful to date. At this time the SMAP mission continues to produce high-quality science measurements supporting SMAP's objectives with its radiometer instrument (NASA, 2015).

SMAP mission planned to delivered 15 distributable data products representing four levels of data product: Level 1 calibrated, geolocated surface brightness temperature and radar backscatter measurements; Level 2 and Level 3 surface soil moisture products both from radiometer measurements on a 36 km grid and from combined radar/radiometer measurements on a 9 km grid; Level 3 freeze/thaw products from radar measurements on a 3 km grid; and Level 4 surface and root zone soil moisture and Level 4 Net Ecosystem Exchange (NEE) of carbon on a 9 km grid. Detail description of SMAP data product found in the Algorithm Theoretical Basis Document (O'Neill et al.,2014).

In this study Level 2 Soil Moisture Passive (L2_SM_P) soil moisture product is used. The L2_SM_P is an L-band radiometer obtain time ordered measurements of brightness temperature as output on fixed 36 km Equal-Area Scalable Earth-2(EASE2) grid. The grid spacing is close to the spatial resolution of 40 km of the SMAP radiometer footprint. The L2_SM_P soil moisture product meet the SMAP target accuracy of 0.04 m^3m^{-3} volumetric soil moisture (O'Neill et al., 2014). Validation forms an important aspect of the SMAP mission as it will enable assessment of accuracy of the forthcoming data products based upon which improvements can made. Also knowledge of the accuracy of data can facilitate its use in hydrometeorological and agricultural applications. Twente monitoring stations selected as one core international site to validate SMAP L2_SM_P soil moisture products. Additionally intensive fieldwork have been carried out in 11 fields with selected 5 stations in Twenty study area to relate the SMAP L2_SM_P soil moisture measurements to the ground based measurements.

Twente region holds a regional scale soil moisture monitoring network that include 20 station recorded soil moisture and temperature every 15 minutes (Dente et al., 2011), which provide data for validation of satellite (SMAP). The spatial characteristics of point scale of these station networks are not ideal for validation of coarse (36km) resolution of SMAP L2_SM_P. Statistical analysis and spatial sampling techniques help to select representative point measurement at satellite scale soil moisture (Cosh et al., 2004).

1.1. Research problems

In-situ soil moisture commonly used to validate satellite soil moisture products data of different footprints. A means to validate satellite products through footprint scale mean values is determined from in-situ measurements. However, this validation approach is challenging as in-situ measurements is conducted at scales that are smaller than satellite footprints(Jacobs et al., 2004). Twente in-situ monitoring network are important in validating soil moisture products of the SMAP L2_SM_P soil moisture product. Additionally, soil moisture measurements were collected from 11 field sites which is important for validation of SMAP. Twente monitoring stations are sparsely distributed, hence the measurement locations are only representative for a specific point because of the spatial soil moisture variability caused by spatial heterogeneity in soil, land cover and atmosphere inputs. Therefore, the mean of a collection of in-situ soil moisture measurements involves uncertainty when it is used as representatives for spatial domains such as satellite footprints. It is important to understand this uncertainty to be able reliably quantify the accuracy of SMAP L2-SM-P soil moisture products. Time stability analysis, statistical techniques and spatial sampling techniques help to quantify the spatial and temporal variability of soil moisture and to identify point scale measurement that can representative of spatial domain.

In this researches SMAP L2_SM_P soil moisture product was used. The L2_SM_P soil moisture product provides global measurements of surface soil moisture with volumetric accuracy of 0.04 m^3m^{-3} (Entekhabi et al., 2015). Validation of the L2_SM_P soil moisture product is very important to assess the accuracy and quantify uncertainty of L2_SM_P soil moisture product for their uses in hydrometeorological and agricultural applications. Soil moisture products from satellite have to be validate because the retrieval algorithms, parameters are not thoroughly develop and verified (Bosch et al., 2006). However, the accuracy and quality of SMAP L2_SM_P soil moisture product has not yet been validated worldwide. Twente monitoring station is selected as one of the SMAP core international validation sites.

1.2. Research objectives

1.2.1. General objectives

The main objective of this research is to quantify the uncertainty of radiometer-only (36 km) SMAP L2_SM_P soil moisture product using intensive in-situ measurements in the Twente region, Netherlands.

1.2.2. Specific objectives

The specific objectives for the proposed research are:

- To calibrate impedance probe soil moisture measurement using soil moisture measurement determined by weighing and drying soil samples;
- To analyse the spatial soil moisture variability across time and space using field soil moisture measurements;
- To quantify how well measurements are taken at individual stations represent its proximity;
- To validate SMAP L2 passive SM product towards in-situ soil moisture data.

1.3. Research questions

- How reliable is soil moisture measured with an impedance probe after calibration against values determined gravimetrically from soil?
- How does soil moisture vary spatially and temporally across various spatial domains during the study period?
- How well does the Twente monitoring network represent the actual soil moisture conditions in the region?
- Does the SMAP L2_SM_P soil moisture product fulfil the target accuracy requirements of 0.04 m^3m^{-3} ?

1.4. Research hypothesis

- Spatial soil moisture variability measured in the field is constant
- Twente stations network are representative of the whole study area.
- The validated SMAP L2_SM_P soil moisture product provides soil moisture estimates at an accuracy better than 0.04 m^3m^{-3}.

1.5. Innovation

The novelty of this research is the validation of L2_SM_P soil product for the Twente region that is generated from SMAP observations, which is a satellite that was launched on 31 January 2015.

1.6. Resarch and thesis structure

This thesis contains 8 chapters and the out lines are:
Chapter 1 gives a general introduction .Chapter 2 gives the literature review about the spatial variability of soil moisture and remote sensing for monitoring soil moisture. Chapter 3 gives a brief description of the study area, Twente soil moisture monitoring network data and the description of L2_SM_P. Chapter 4 gives brief description of the field work and materials used for field work. Chapter 5 discusses the calibration method for theta probe, the result, and discussion of calibration theta probe. Chapter 6 described Spatial soil moisture variability at different spatial scale. Chapter 7 present the validation of L2_SM_P results and discussion. Conclusion and recommendation are presented on chapter 8.

The procedures that followed in this research is shown in flow chart:

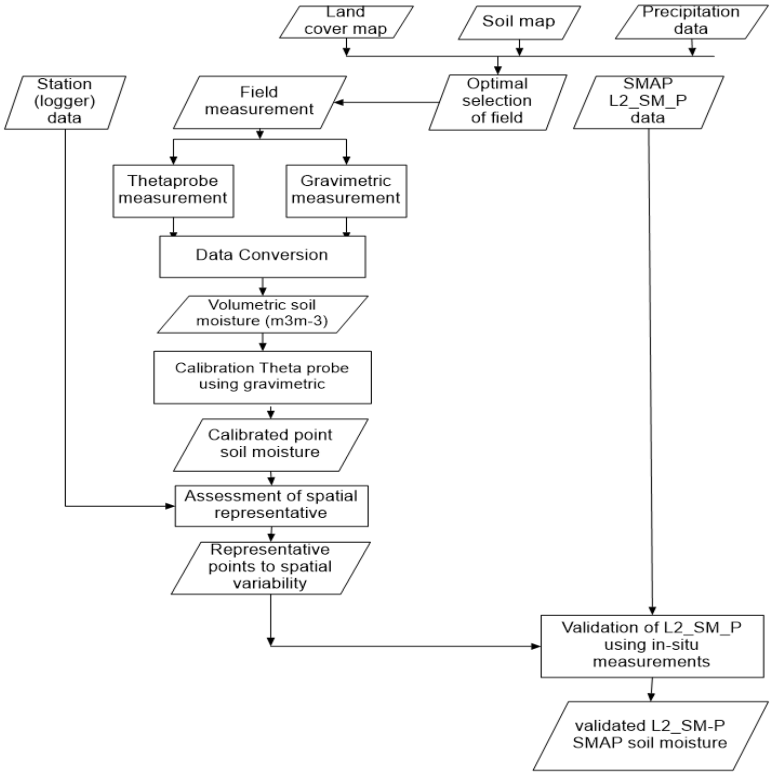

Figure 1-1 Flow chart for methodology applied and the processes followed during the study

CHAPTER TWO

2. LITRATURE REWIEW

2.1. Soil moisture spatial variability

Understanding soil moisture variability across spatial –temporal scales is of great significance in many scientific disciplines (Cosh et al, 2004; Jacobs et al, 2004; Kaleita et al, 2005).The time stability concept introduced by Vachaud et al. (1985) can be used to minimize the number of observation points without loss of information if soil moisture field maintains its spatial pattern over time. Brocca et al. (2010) carried out statistical, spatial variability and temporal stability analysis to characterize soil moisture. They found that soil moisture spatial variability increases with the size of the area. Cosh et al. (2004) investigated watershed scale temporal and spatial stability of soil moisture in the Walnut Creek Watershed, Iowa, USA. Representative point measurements was used to estimate the watershed scale (25 km) soil moisture average and they concluded that representative measurement sites could be used to estimate the watershed scale (~25 km) soil moisture average for long time periods similar to the conditions of the study period. According to Cosh et al. (2004) sites can be identified through temporal stability analysis, which can predict large-scale moisture averages from only a few sensors located at representative sites.

De Lannoy et al. (2007) proposed techniques to limit representative error of point of soil moisture observation as estimates for spatial mean soil moisture in optimizing production inputs for Economic and Environment Enhancement (OPE3). They argued that a sensor can be used as representative for a spatial domain if mean relative difference and standard deviation is close to zero.

2.2. Remote sensing for monitoring soil moisture

Soil moisture can be measurement can be undertaken by remote sensing techniques and in-situ methods. These measurement methods apply different procedures and principles to determine soil moisture. In situ point-based measurement method is time consuming, costly and do not represent the spatial distribution of soil. Technological advances in remote sensing mitigate this shortcoming and have offered different techniques to measure soil across a wide area over long time. The Remote sensing soil moisture measurement techniques include visible, thermal and microwave based on their spectrum properties(Wang & Qu, 2009).

2.2.1. Visible radiation

The visible radiation remote sensing measures soil moisture content based on reflectance of the solar radiation from the earth in the visible range of wavelength that ranges from 0.4 and 2.5 µm (Wang & Qu, 2009). This method is not accurate because as compared to others because the presence of noise elements that confuse interpretation of collected data (Engman, 1991).

2.2.2. Thermal radiation

Thermal radiation measures soil moisture by measuring soil surface temperature. It measures the thermal emission of the Earth with an electromagnetic wavelength region between 3.5 and 14 µm (Curran, 1985). Thermal remote sensing is dependent on the surface temperature which can be affected by the thermal inertia of the soil. The thermal inertia, in turn, is dependent upon thermal conductivity and heat capacity which increases with soil moisture (Engman, 1991).

2.2.3. Microwave radiation

Microwave remote sensing works in the in microwave region of the electromagnetic radiation between 0.5 and 100 cm. It estimates soil moisture based on a contrast that exists between the dielectric constant values for dry and wet soil. The soil dielectric constant increases as soil moisture content increases depending on soil particle (Dobson et al.,1985; Engman, 1991; Lakhankar et al., 2009). Microwave is advantageous as compared to the other techniques as they can sense through cloud cover and, in a vegetation canopy.There are two approaches in microwave satellite remote sensing: passive and active microwave approaches (Engman, 1991).

Passive microwave sensors of soil moisture measure the thermal emission from the soil surface. The variation in the intensity of the radiation depends on the dielectric properties and surface temperature (Forman et a.l, 2014; O'Neill et al.,2014). The other microwave remote sensing method is active microwave. It is observation of backscattering and it has the potential to measure soil moisture content in near surface soil layer (Walker et al., 2004). The backscattering observation is dependent on topography, soil texture, surface roughness and soil moisture.

CHAPTER THREE

3. STUDY AREA AND DATA SET

3.1. Twente region

Twente region is located in the eastern part of the Province Overijssel in the Netherlands. It is bounded between 52⁰05' -52⁰27'N, 6⁰05'-7⁰00'E. Figure 3-1 shows the study area of Twente region which includes also part of the Province Gelderland. The map in Figure 3-1 shows location and soil map of Twente region. Topography of Twente region is almost flat with an elevation varying from 3 and 50 m above sea level(Dente et al., 2012).

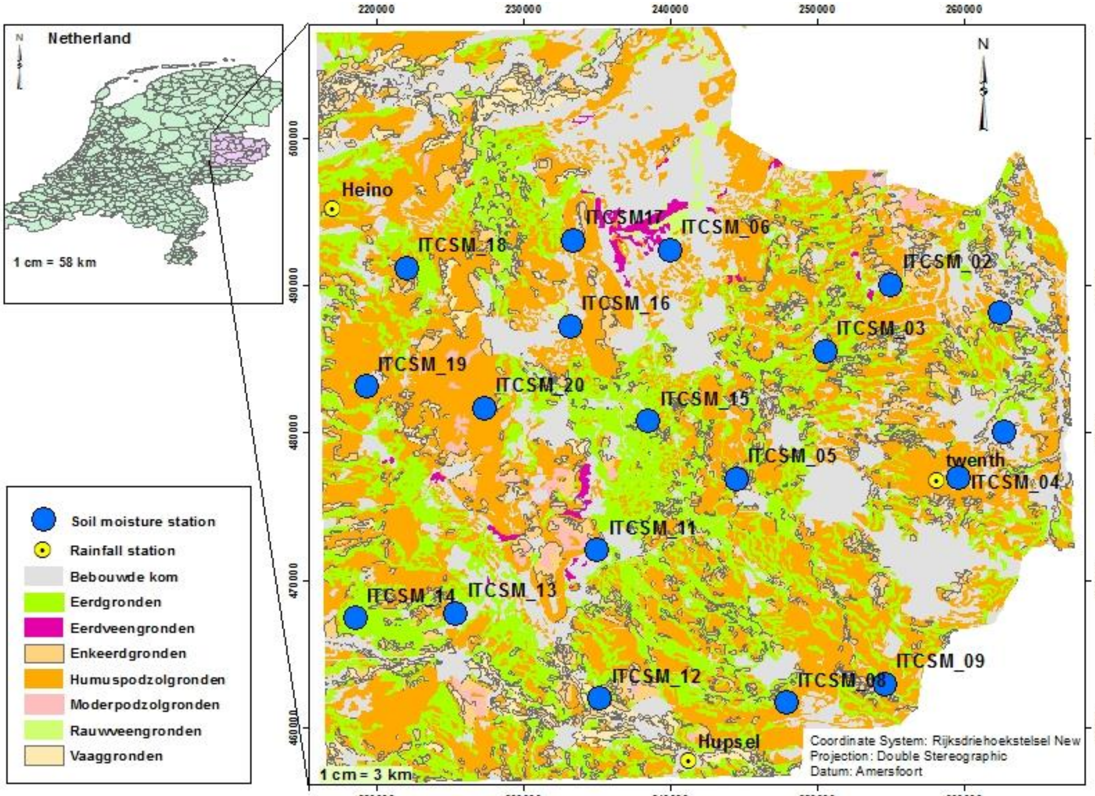

Figure 3-1 Soil map(from ITC data supplied during module exercise) and Twente soil moisture monitoring network (stations shown as blue circles) and meteorological stations from the KNMI indicated yellow circles (Source:)

Precipitation is the most important meteorological forcing for soil moisture content and distribution (Crow et al., 2014). The seasonal variation in potential evapotranspiration (PET) compared with precipitation is critical in the temporal variation of soil moisture (Wilson et al.,2004). The Twente region climate classified as temperate maritime with an average annual precipitation of 760 mm. In this study, three rain gauges from water board district called "Vechstromen" were used which records precipitation at a time interval of 20 minutes. Figure 3-2 shows the seasonal comparison of potential evapotranspiration(PET), precipitation with response of rainfall deficit. As shown in the Figure 3.2 the precipitation start to decline from the beginning of April as the evapotranspiration increase. The atmosphere forcing could result to decrease soil moisture content even there is rainfall event. The reference ET is the potential ET of a reference crop typically 5-8 cm tall grass (Allen, 1998). The KNMI uses the Makkink equation to compute the reference ET. The precipitation and PET data is available online http://www.knmi.nl/klimatologie/monv/reekden.

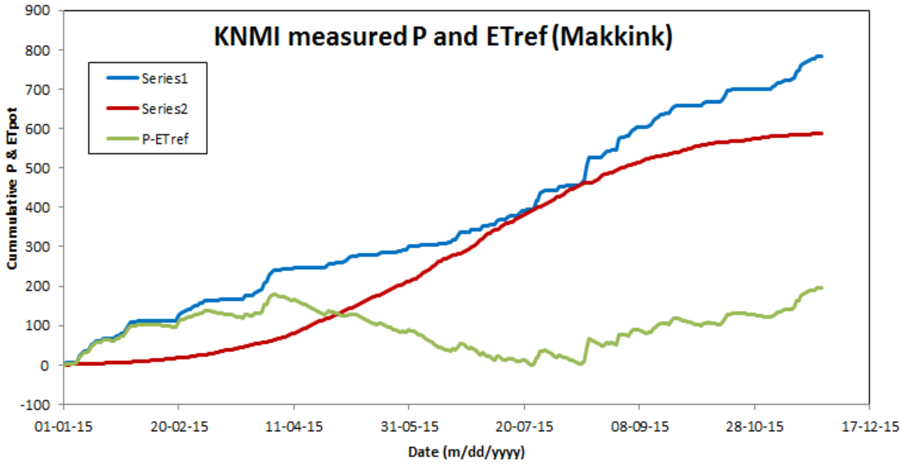

Figure 3-2 Cumulative precipitation, reference evapotranspiration and rainfall deficit of Twente region in 2015 on daily basis

Soil heterogeneity affects soil moisture content through various factors, among which the hydraulic conductively have a dominant influences in soil water flow, variation in soil texture and soil water holding capacity are the other factor (Jacobs et al., 2004; Kim et al., 1997). According to Dente et al. (2011) the soil property of Twente monitoring stations ranging from sand to loamy sand with low clay content. The soil map shown in Figure 3-1 indicate there is spatial variability of soil type in the region.

Land cover characteristics are important for understanding soil moisture variability, which influences evapotranspiration and deep percolation (Mohanty & Skaggs, 2001). The influence of Land cover (vegetation) on spatial variation in soil moisture is more dynamic as compared to soil and topographic factors (Crow et al., 2014). Figure 4-1 shows land cover map of Twente region. Land cover classification has great role for analysing soil moisture as they directly affects the infiltration capacity of soil and the amount of evapotranspiration (Crow et al., 2014). The land cover map (Figure 4-1) was used to reclassify the land cover in to five groups. In Figure 3-3 the area in km² covered by each group is shown, which demonstrates that the majority of the region is covered by grass followed by agriculture and forest.

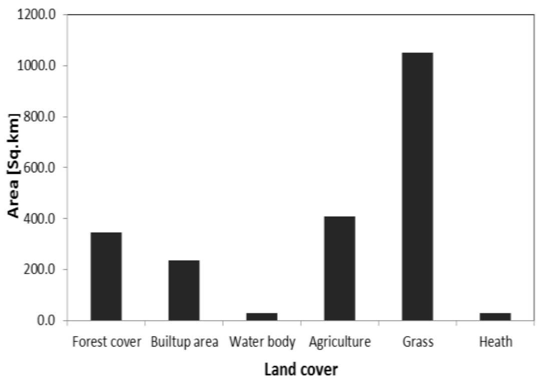

Figure 3-3 Classified land cover of Twente region

3.2. Soil moistre monitoring network

Twente in-situ soil moisture network is established to provide validation data for the satellites and for long term estimation of soil moisture conditions across the region. The Twente soil moisture monitoring network consists of 20 stations that are programmed to record (ECH2O EC-TM probes) soil moisture and soil temperature measurements every 15 minutes. The stations are distributed across an area of approximately 50 km x 40 km as shown in Figure 3-1. Each station consists of one EM50 ECH2O data logger (by Decagon),which is recording the data collected by two to four EC-TM ECH2O probes (by Decagon) measure both soil moisture and soil temperature(Dente et al., 2011). One station is installed in forested area, three in corn fields and the sixteen stations located in grassland (Dente et al., 2011). The data sets collected in the Twente region were used by Dente et al.(2012) for validation of SMOS soil moisture and by Sabaghy (2013) to validate soil moisture maps retrieved through combining coarse resolution with SAR product, over the Twente.

Twente monitoring station missing a lot of data in this year 2015, station SM 06& 17 complete data missing, and stations: SM1,6,7,8,10,11,15,17,19 missing significant amount of data. This creates uncertainty to the validation of L2_SM_P soil moisture product. From those 20 stations 8 stations (SM-04, 05,09,12,13,14,16,20) have almost complete data. These stations selected and used for the validation of L2_SM_P soil moisture and also to see whether there are representative for the surrounding area by comparing with field soil moisture data (described in section 6.6).

Figure 3-4shows soil moisture measurements on the top of 5 cm for the selected 8 stations in the year of 2015 with response of rainfall. It is observed from the figures that high soil moisture content for all stations in winter due to low evapotranspiration as shown in Figure 3-2. During summer some pick rainfall events resulted in increasing soil moisture in some stations (SM-09, 05,16). Stations (SM-05, 09, 13, 16) show fluctuations in soil moisture data in response to rainfall. This is good indication for the reliability of the collected data.

3.3. SMAP Level 2 Soil Moisture Passive product (L2_SM_P)

The L2_SM-P is an L-band (frequency: 1.41 GHz; polarizations: horizontal, vertical and third and fourth Stokes parameters) soil moisture product is half-orbit product, passive microwave. The L2_SM_P soil moisture product is passive microwave from April 01 to December 12,2015 were used in this study.

The L2_SM_P is an L-band radiometer derived from time ordered measurements of brightness temperature product (L1C_TB)as output on fixed 36 km Equal-Area Scalable Earth-2(EASE2) grid. SMAP passive microwave soil moisture had used a number of viable soil moisture retrieval algorithm that can be used with SMAP T_B data. The L2_SM_P L band radiometer algorithms for retrieval soil moisture with less error and with less uncertainties under vegetation condition(O'Neill et al., 2014)

The retrieval algorithm of soil moisture is based on *tau-omega* model at constant incident angle TB data. Five soil moisture retrieval algorithm used for SMAP L2_SM_P product mentioned in the Algorithm Theoretical Basis Document Level 2&3(O'Neill et al., 2014). The presence of open water within SMAP L2_SM_P radiometer corrected prior at SMAP L1T_B observation

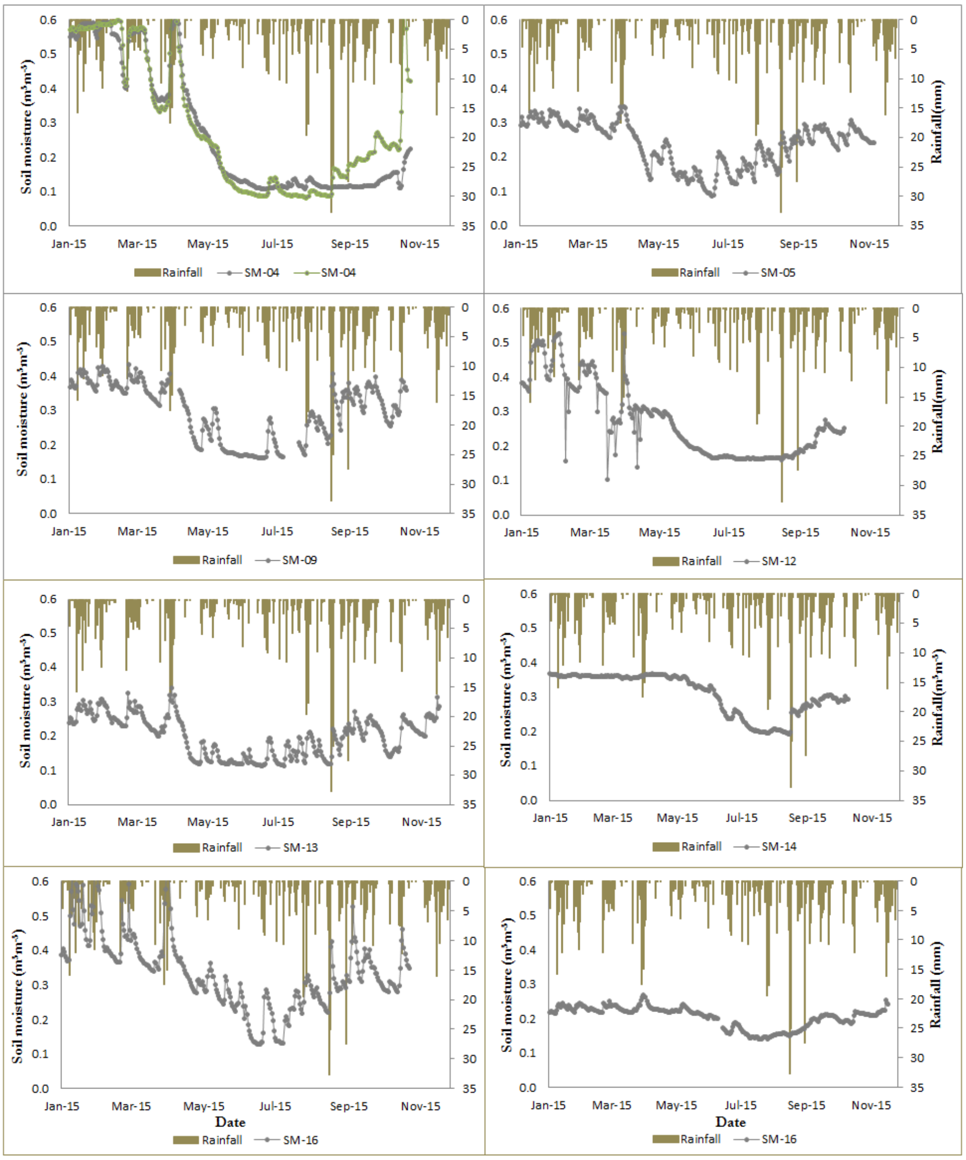

Figure 3-4 soil moisture measured from Twente monitoring network and rainfall data from KNMI

3.4. SMAP Level 2 Soil Moisture Passive product (L2_SM_P)

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CHAPTER FOUR

4. FIELDWORK

The fieldwork was designed to measure soil moisture in the months of September, October and November of 2015. The fieldwork was conducted in the SMAP radiometer grid cell, located in the eastern part of the Overijssel Province of the Netherlands as shown in Figure 4-1 Five stations were selected to collect soil moisture data which are located in eastern part of SMAP gird pixel cell, shaded part in Figure 4-1.The measurements of soil moisture was done using theta probe and gravimetric method.

The main objective of this intensive field work were:(1) to characterize spatial and temporal patterns of soil moisture near the monitoring station (2) to provide reference volumetric soil moisture concurrent with SMAP satellite overpass. Due to the above reason, intensive field work was carried out at eleven fields to collect soil moisture measurements. The measurements of soil moisture was done using theta probe and gravimetric method These samples were taken in corn, grass and fallow barely over a different soil moisture conditions

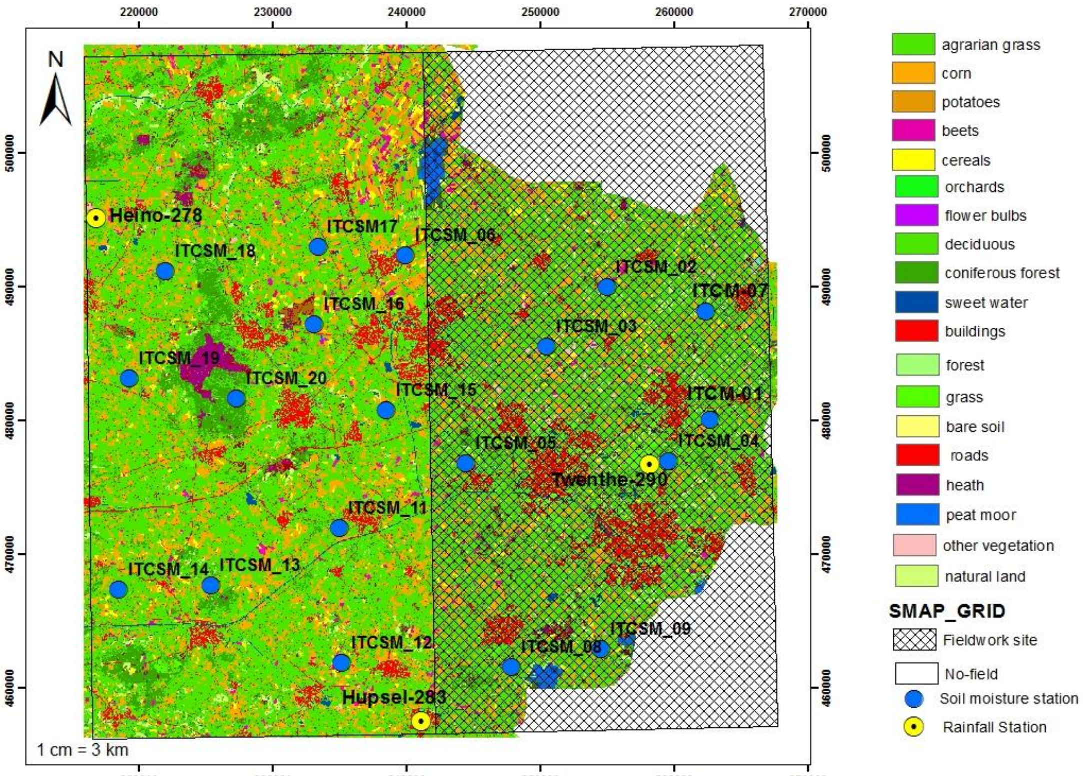


Figure 4-1 Land cover map, rainfall and soil moisture stations with SMAP grid cell. The shaded region indicates that where the fieldwork carried out to measure soil moisture. Source of land cover (http://gisopenbaar.overijssel.nl/viewer/app/bodematlas/v1)

4.1. Soil moisture measurment

Gravimetric method and thetaprobe instrument were used to measure soil moisture in field.

4.1.1. Gravimetric determination of the soil moisture content

Gravimetric is a direct soil moistures measurement method. In this method the soil moisture was determined by collecting soil samples from representative sites, weighted , dried in an oven for 24 hours at 105 ^{0}C, and then the oven dried sample was reweighted to determine the mass of water removed. The soil moisture content of the samples collected were calculated as the difference between the moist weight and oven-dried weight of the samples (Kinzli et al., 2012; Blake, 1965). Figure 4-2. Shows the procedure followed to collect soil samples for gravimetric soil moisture measurement method.

The gravimetric soil moisture content θ_g can be calculated as (Eq 1)

$$\theta g = \frac{Mw}{Ms} \qquad \text{Eq 1}$$

Where M_w is mass of wet soil (g) and Ms is mass of dry soil (g)

Volumetric soil water content can be expressed as (Eq 2)

$$\theta v = \frac{Vw}{Vs} \qquad \text{Eq 2}$$

Where volumetric soil water content, Vw is volume of water (m^3m^{-3}) and Vs is volume of sample (m^3m^{-3})

The relationship between gravimetric and volumetric water content expressed as (Eq 3)

$$\theta v = \theta g \frac{d_b}{d_w} \qquad \text{Eq 3}$$

Where db is bulk density of dry soil (g cm^{-3}), dw is density of water (g cm^{-3})

Figure 4-2 Gravimetric Sampling method

4.1.2. Thetaprobe soil moisture measurement

There are different techniques to measure soil water content on field including : soil-water dielectrics, neutron probe, Time- domain reflectometry (TDR) and radiological (Kaleita et al., 2005). In this study, the Theta probe ML2x was used to conduct intensive measurements of soil moisture content. Thetaprobe (Figure 4-3) responds to changes in the apparent dielectric constant. It uses a simplified voltage standing wave method to determine the relative impedance of its sensing head, which consists of 4 separate 5-cm stainless steel roads. During measurement, it will be inserted vertically into the soil, the impedance of the rod array affects the reflection of the 100 MHz signal, and these reflections combine with the applied signal to form a voltage standing wave along the transmission line. Thetaprobe forms sensitive and precise measure of soil content as the output is an analogue voltage proportional to the difference in amplitude of the standing wave at two points (Dellta-T Device Ltd, 1999).

Figure 4-3 Theta probe soil moisture measurement

4.2. Sampling strategy

Reasonable and reliable collection soil samples is the most important for the validation of remote sensing (SMAP) soil moisture product (Wang et al., 2014) and to compare with station soil moisture. 6 stations (SM-3,SM-04,SM-05,SM-07,SM-08 and SM-09) were selected for sampling based on soil type and land cover which can also represent other stations. The sampling procedure in each field generally followed the pattern shown in Figure.4-4.

From these five stations, elven fields were selected to measure soil moisture content. These fields were identified during the fieldwork (SM-03F1&SM-03F2, SM-04F1&SM-04F2 SM-07F1,SM-07F2&SM-07F3, SM-08F1&SM-08F2 and SM-09F1&SM-09F2) and they are listed in Table 1. SM-03F1 & F2, SM-04F2 and SM-08F2 were grassland fields. SM-04F1 is grassland field for grazing with water level above the surface and it is sloppy area. 08F1 and SM-07F3 are agricultural corn fields. The corn in the field SM-08F1 was cut and the field tilled during the fieldwork (25-09-2015), due to this the soil moisture measurement suspended and started again on 09-10-2015 in this field, and the corn in the field SM-07F3 was cut in the last period of the field work. The fallow barely fields are SM-07F1&F2 and SM-09F1&F2. SM-07F1&F2 are fallow barley field with water above the surface and tilled, mixed with organic material and planted during the field work time. The SM-05 station after collecting data for two days change station to SM-03 due to agricultural activity. The soil property of the stations described in section 2.5. Soil moisture differences between the fields can be expected to be a combination of these characteristics.

Sampling strategy was developed to study the soil moisture variability at field scale. Near each station 2 to 3 fields were selected and in each field, samples were collected at an interval of 20 m to 30 m at 6 location. Whereby at each location five measurements were taken to consider the local spatial soil moisture variability. As such at least 30 points for small fields and 60 points for large fields were collected. The soil moisture measurements from the top 0-5 cm were made with the Thetaprobe (ML2X Theta probe).Thetaprobes measure a dielectric constant for the soil and converts this to volumetric soil moisture based up on a factory provided calibration equation(Gaskin & Miller, 1996). Soil moisture was also measured gravimetrically at 3 sampling points. At each sampling point, 5 theta probe measurements were collected and a gravimetric sample was collected at the 3rd theta probe sampling point for calibration purposes . Gravimetric samples were collected from 0–5 cm depth at each site, weighed, oven dried and reweighed, and then gravimetric moisture calculations was made. Volumetric soil moisture was calculated from gravimetric soil sample for calibration of the measurement obtained from theta probe.

Sampling was suspended in some fields due to agricultural activity. In total more than 3352 theta probe measurements of soil moisture were made on 11 fields (five stations). Surface soil moisture was sampled in each day between (~ 9:00 a.m-15:00pm) during field work.

Table 1 Location of soil sampling fields along with their land cover, soil type (Dente et al., 2011), altitude and agricultural activity.

Station	Soil type	Fields	Latitude	Longitude	Land cover	Agricultural activities
SM-03	Loamy sand	Field1	52.349473°	6.789137°	Grassland	Grass cut week 28 Sept – 2 October
		Field2	52.348672°	6.790383°	Grassland	Grass cut week 28 Sept – 2 October
SM-04	Loamy sand	Field1	52.271832°	6.923137°	Grassland	
		Field2	52.270574°	6.921401°	Grassland	
SM-07	Loamy sand	Field1	52.372494°	6.962558°	Harvested barely	barely harvested before 11 Sept and tilled and planted
		Field2	52.372542°	6.965006°	Harvested barely	barely harvested before 11 Sept and tilled and planted
		Field3	52.369686°	6.967465°	Corn	Corn harvested week
SM-08	sand	Field1	52.135902°	6.743411°	Corn	Corn harvested week 3 Oct
		Field2	52.134276°	6.744520°	Grassland	grass cut before 11 Sept
SM-09	sand	Field1	52.146214°	6.841841°	Fallow barely	barely harvested before 11 Sept
		Field2	52.145547°	6.840690°	Fallow barely	barely harvested before 11 Sept

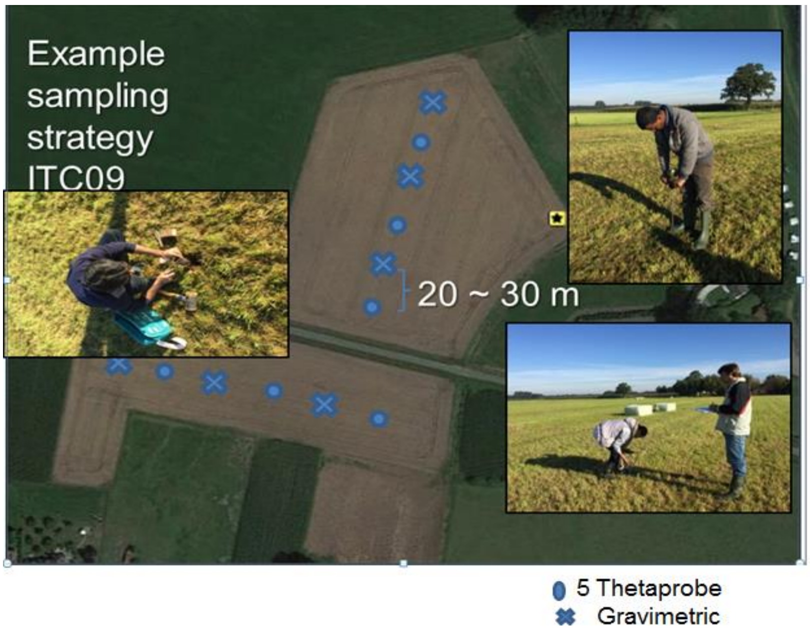


Figure 4-4 Sampling strategy for soil moisture in each field with 5 thetaprobe +1 matching gravimetric

CHAPTER FIVE

5. CALIBRATION OF THETA PROBE MEASURMENTS

The most widely accepted method for soil moisture estimation is gravimetric sampling but this is a time intensive procedure (Cosh et al., 2005). The quick and easy impedance probe (theta probe) measurements support to collect more number of samples that enables accurate characterization of mean and variability of soil moisture content (Famiglietti et al., 1999). Theta probe was used in this study to do intensive field measurements. Theta probe estimates soil moisture using dielectric characteristic of soil and water. From the dielectric constant volumetric water content reads directly from the theta probe sensor(Dellta-T Device Ltd, 1999). A factory calibration for mineral soil was used to convert dielectric constant to volumetric soil moisture directly from the sensor. However, in order to provide more reliable soil moisture measurements theta probe needs calibration against reference soil moisture determined using gravimetric sampling. The method applied for the two measurements are explained in subsection 4.1.1-4.1.2. There are three different methods for calibration of theta probe using gravimetric samples: field specific, soil specific and generalized calibration. Generalized calibration equation is valid for mineral soils, typical errors of ± 0.05 m^3m^{-3}, this accuracy can be increased to ± 0.02 m^3m^{-3} using a soil specific calibration (Cosh et al., 2005; Dellta-T Device Ltd, 1999).

For the selection of the calibration method, comparison were performed between the theta probe and the gravimetrically determined soil moisture measured in specific soil type and individual days. This comparison was analysis using statistics: coefficient of determination(R^2), Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and bias, based on which the calibration method was selected. Linear and polynomial regression equations are appropriate for calibration of theta probe soil moisture measurement (Kinzli et al., 2012). A linear and polynomial regression were established with 170 collected volumetric soil samples and theta probe measurements from all six stations (fourteen fields) across six sampling days for calibration purpose analysed using excel sheet. The fourteen fields includes the soil moisture collected from station SM-05.

The statistical analysis was carried out using coefficient of determination(R^2), Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and bias, between calibrated theta probe soil moisture and volumetric soil moisture determined by gravimetric samples.

The linear and polynomial calibration equation is given as:

$$\theta_{\mathrm{Pr}obe} = a*\theta_{gv} + b \qquad \text{Eq4}$$

$$\theta_{gv} = a*\theta^2{}_{probe} + b*\theta_{probe} + c \qquad \text{Eq 5}$$

$$\theta_{probe} = a*Ln(\theta_{probe}) + b \qquad \text{Eq 6}$$

The statistics analyses used the performance of the calibration(goodness of fit) are given :

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\theta_{probe} - \theta_{gvsm})_i^2} \qquad \text{Eq 7}$$

$$Bias = \frac{1}{n}\sum_{i}(\theta_{probe} - \theta_{gvsm}) \qquad \text{Eq 8}$$

5.1. Measurement by soil type

During the field work the soil moisture measurements and collection of soil samples was carried out at each stations soil type as discussed in section 4.2, the soil type of each station is given in Table 1. Therefore, the comparison was made between theta probe and gravimetric volumetric soil moisture based on each station soil type for selection of calibration method. Figure 5-1 shows the scatter plot of soil moisture measured by theta probe against volumetric soil moisture measured calculated from the gravimetrical sample with liner fit and corresponding equation. As shown in Figure 5-1 points in SM-03 and SM-04 deviate from the 1:1line (solid line) when the soil moisture increase. This indicates the response of the theta probe is low when the soil is wetter. The comparison between theta probe soil moisture and gravimetric volumetric soil moisture range from R^2 0.6 to 0.9 and high MAE and bias shows in table 2. The result indicates that the linear relation between theta probe and gravimetric volumetric soil moisture based on soil type is lower. This may the influence of soil type is limited on this study area.

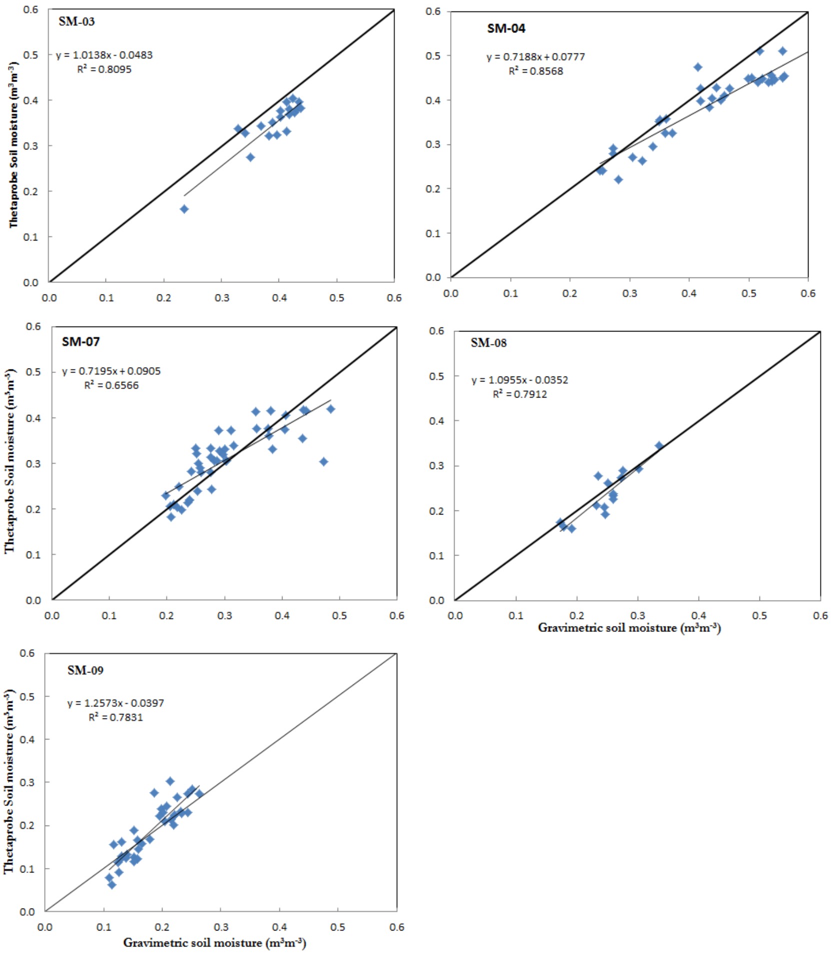


Figure 5-1 Relationship between volumetric soil moisture measured with theta probe and determined from soil samples plotted separately for each station soil type

Table 2 Summary statistics for the relationship between theta probe and gravimetrically determined volumetric soil moisture on each station soil type

Station	Soil type	R^2	RMSE (m^3m^{-3})	MAE (m^3m^{-3})	Bias (m^3m^{-3})
SM-03	Loamy sand	0.809	0.049	0.044	0.353
SM-04	Loamy sand	0.857	0.062	0.050	0.365
SM-07	Loamy sand	0.657	0.046	0.034	0.248
SM-08	sand	0.791	0.027	0.022	0.205
SM-09	sand	0.783	0.024	0.019	0.125

5.2. Measurements by day

For the selection of the calibration method, comparison were also performed between the theta probe and the gravimetrically determined soil moisture measured in individual days. Figure 5-2 shows the scatter plot of soil moisture measured by theta probe against volumetric soil moisture determined from the gravimetric samples on each of the six days for all soil type. The plot for each six days shows that the points deviate from the 1:1line (solid line) when the soil moisture increase. The correlation for all soil type, correlate theta probe to volumetric soil sample ranges from R^2 0.81 to 0.97 and low MAE and bias gives in Table 3. The results indicate that there is a very good linear relation between theta probe and volumetric soil moisture for on each six days measurements. When compared the plot for each stations soil type that described in the above (section 5.1) R^2 ranged from 0.6 to 0.9 and high MAE and bias (Table 2), than the plot on each of the six days. For this reason, a single calibration curve was considered to be appropriate for all sampled during the fieldwork.

Table 3 Summary statistics for the relationship between theta probe and gravimetrically determined volumetric soil moisture on each six days

Date	R^2	RMSE (m^3m^{-3})	MAE (m^3m^{-3})	Bias (m^3m^{-3})
11-09-15	0.925	0.032	0.025	0.015
17-09-15	0.883	0.039	0.029	0.013
24-09-15	0.817	0.045	0.037	-0.015
25-09-15	0.867	0.054	0.003	0.010
30-09-15	0.970	0.047	0.039	0.038
02-10-15	0.936	0.042	0.033	0.021

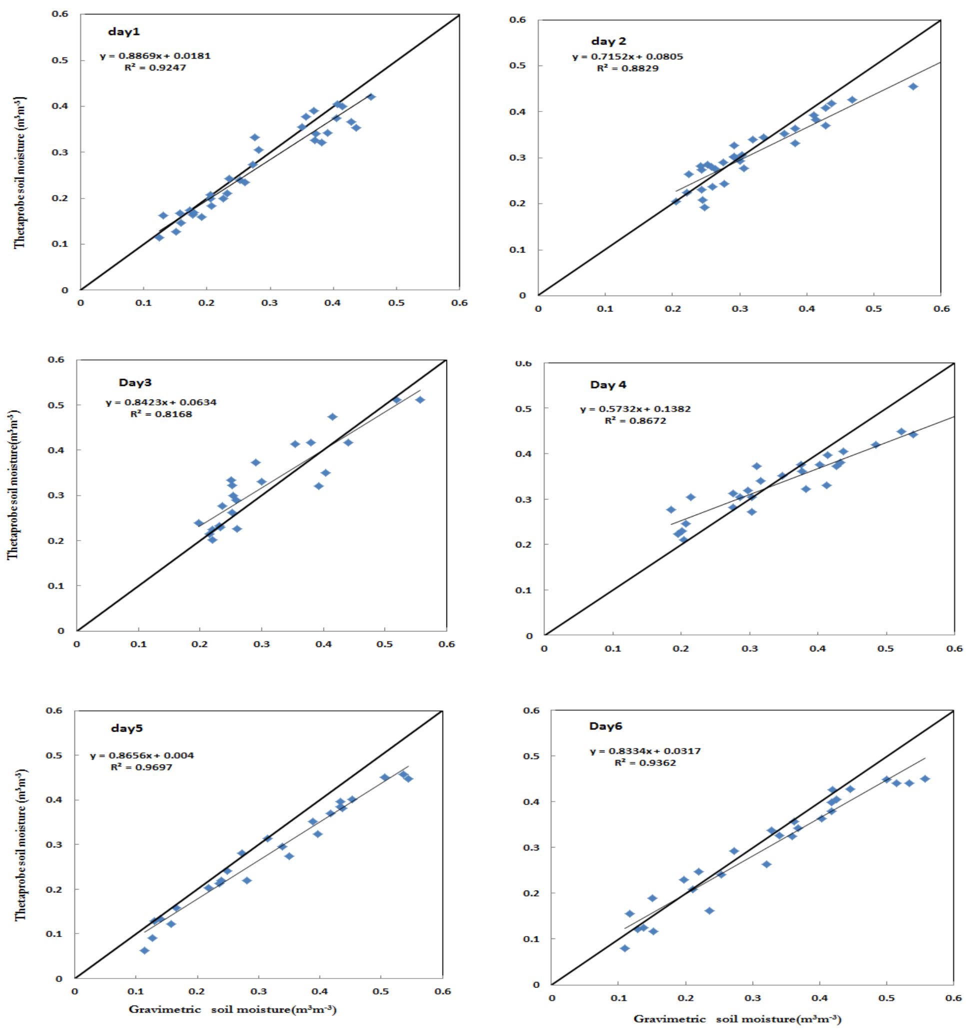


Figure 5-2 Relationship between the volumetric soil moisture measured with theta probe and determined from soil samples plotted separately for each measurement day.

5.3. General calibration

As discussed in the above, for the selection of calibration method the comparison was performed between the theta probe soil moistures and the gravimetric volumetric soil moisture based on the soil type and daily measurements. From the analyses it is decided to use generic calibration method for all sampled during the fieldwork.

Theta probe measurements were linearly related to the gravimetric volumetric soil moisture for the development of calibration equation shows Figure 5-3 (a). with the fit lines and the corresponding equation. The points deviate from the 1:1 line (solid line) when the soil moisture increase. The points deviate from the 1:1 line for all comparison described in the above. This indicates the response of the theta probe is low when the soil is wetter.

Applying generic calibration with linear regression coefficient to the theta probe, R^2 0.91 and MAE with respect gravimetric volumetric soil moisture 0.031 m^3m^{-3} gives in Table 4 and the bias removed shows in Figure 5-3 (b).

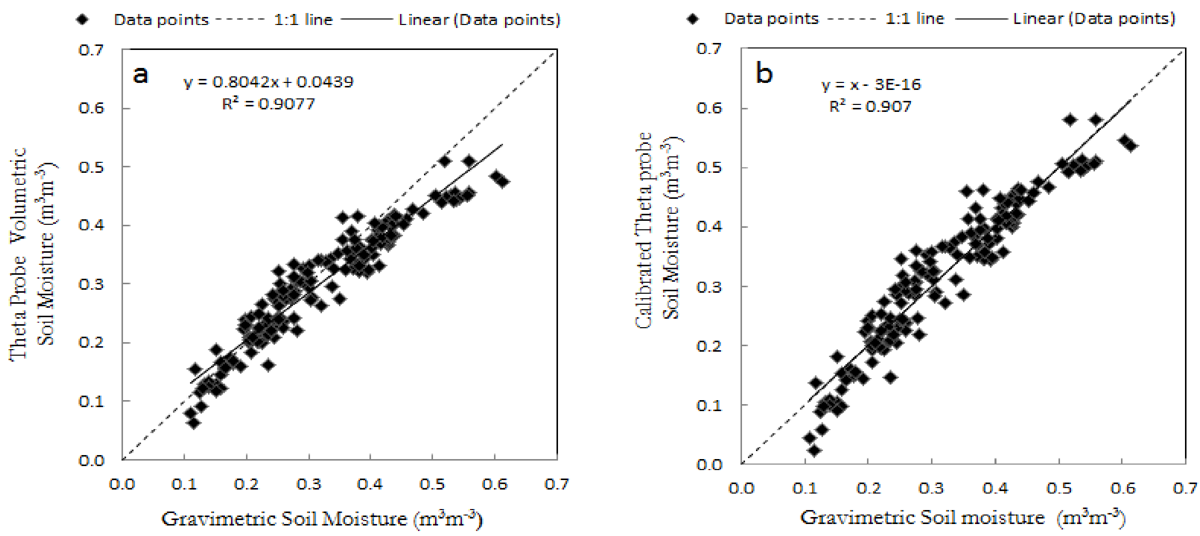


Figure 5-3 (a) Linearly related theta probe to gravimetric based volumetric soil moisture for the development of calibration equation; (b) calibrated theta probe versus gravimetric based volumetric soil moisture.

Figure 5-4 shows polynomial relationship between theta probe measurements and gravimetric volumetric soil moisture for the development of calibration equation. Applying general calibration with polynomial regression coefficient to the theta probe, R^2 0.92 and MAE with respect gravimetric volumetric soil moisture 0.025 m^3m^{-3} gives in Table 4 and the bias removed shows in Figure 5-4(b). The plot in Figure 5-4(b) shows after calibrated theta probe using polynomial equation plotted to see the relation between the calibrated theta probe and gravimetric soil moisture with liner fit.

Since the polynomial relation shows good performance, polynomial calibration equation is used to calibrate theta probe. Therefore, calibration of theta probe is necessary in order to provide a good estimation of soil moisture, as the calibration remove the bias.

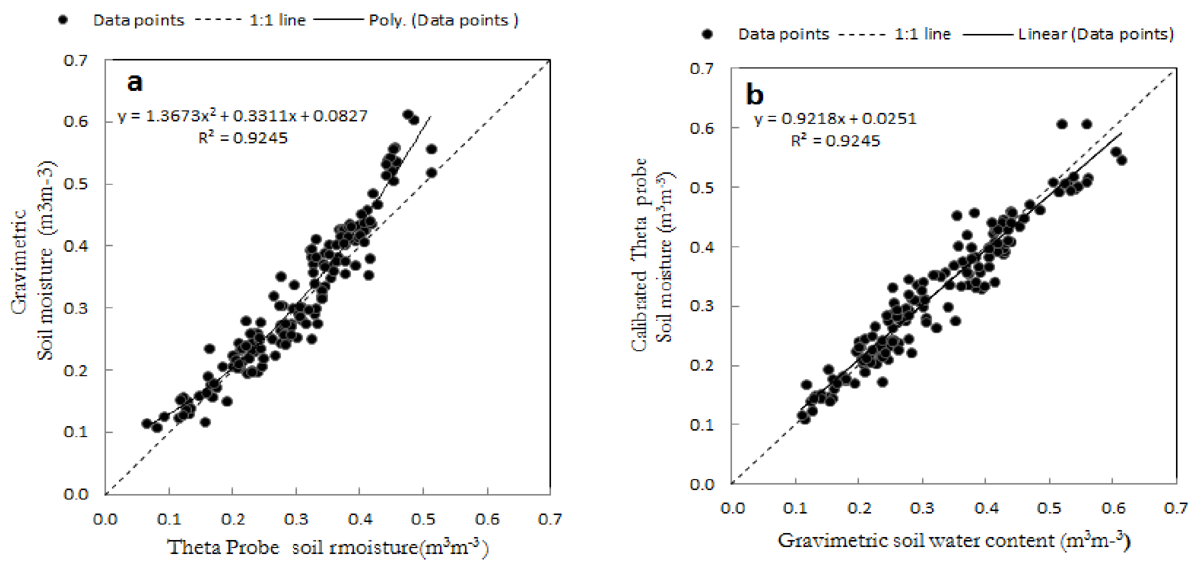


Figure 5-4 (a) Polynomial related theta probe to gravimetric based volumetric soil moisture for the development of calibration equation; (b) after calibrated theta probe using polynomial equation related to gravimetric based volumetric soil moisture with liner fit.

Table 4 Calibration coefficient and summary statistics data for theta probe calibration

	Calibration coefficient						
	a	b	c	R2	RMSE (m^3m^{-3})	MAE(m^3m^{-3})	Bias(m^3m^{-3})
Liner	0.804	0.044		0.908	0.037	0.031	0.000
polynomial	1.359	0.333	0.083	0.924	0.032	0.025	0.000

5.4. Calibration and validation of theta probe using Geo cal / val model

Theta probe soil moisture measurements were calibrated and validated using volumetric soil samples determined from gravimetric soil samples by applied Geo cal/val model. The date was subdivided into calibration (Cal) and validation (Val) data sets for the calibration and the validation of the theta probe. The process of subdivision was done by developing IDL code. According to Salama et al., (2012) the optimal cal/val sets are obtained when mean,μ, and standard deviation, σ, of each set are equal to those of the original data set. Each independent Cal/Val pair is used to derive the coefficients (from the Cal-data set) and the accuracy (from the val set) by applying liner and logarithmic regression equation. The empirical coefficient slope a and intercept b for calibration gives in Table 5. The statistical analysis for the validation result gives in Table 6.

Geo cal/val follow a stochastic approach to generate many slope and intercept empirical coefficient. Theta probe calibrated using the volumetric soil moisture that derived from gravimetric soil sample by applying the liner regression coefficient (Eq 4) and logarithmic equation(Eq 6). The slope and intercept for liner and logarithmic relation gives in the Table 5

Table 5 Empirical calibration coefficient develop by linear and by logarithmic relationship

Fitting line	Coefficient	**mean**	**median**	**min**	**max**	**Standard deviation**	**Kurtosis**	**Skewness**
Linear	slope a	0.794	0.794	0.400	1.294	0.038	13.455	0.356
	intercept b	0.049	0.049	-0.083	0.198	0.012	12.355	0.414
Logarithmic	slope a	0.238	0.238	0.100	0.354	0.008	14.921	0.118
	intercept b	0.592	0.592	0.427	0.740	0.011	13.500	-0.174

The validation data set which help to assess the accuracy of calibration independently. Comparing the validation result between the liner and logarithmic relationship shows that the validation using liner relation obtained an R^2 of 0.87 with MAE of 0.036 m^3m^{-3} in a mean value and the validate theta probe shows 7.7% outlier gives in Table 7. The validation result using logarithmic relation obtained R^2 0.89 with MAE 0.033 m^3m^{-3} and the validate theta probe shows 12.2% outliers.

The calibration result of theta probe applying general calibration method of polynomial regression coefficient using gravimetric soil sample and the calibration and validation using Geo cal/val was comparable. Hence, in this study, only the polynomial regression coefficient was used to calibrate theta probe soil moisture measurement due to time constraint to apply the Geo cal/val result.

Table 6 Summary statistics for validation of theta probe (a) liner relationship, (b)logarithmic relationship

Fitting line	Coefficient	**mean**	**median**	**min**	**max**	**Standard deviation**	**Kurtosis**	**Skewness**
Linear	slope	1.077	1.074	0.251	2.701	0.086	9.144	0.677
	intercept	-0.024	-0.024	-0.415	0.238	0.028	8.573	-0.624
	R2	0.875	0.875	0.134	0.994	0.026	30.571	-2.146
	MAE	0.036	0.036	0.014	0.121	0.004	28.048	2.034
Logarithmic	slope	1.122	1.117	0.441	4.099	0.090	30.578	1.565
	intercept	-0.035	-0.034	-0.853	0.157	0.025	32.050	-1.644
	R2	0.878	0.879	0.111	0.999	0.031	26.438	-2.087
	MAE	0.033	0.032	0.006	0.218	0.005	66.741	2.927

CHAPTER SIX

6. SPATIAL SOIL MOISTURE VARIABILITY

This chapter explains the spatial-temporal variability of surface soil moisture in Twente study area using field soil moisture measurements which are described in chapter three. The objective is to estimate the spatial and temporal soil moisture variability at field, station and regional scale using intensive field measurements. For this purpose, the data collected from 11 fields (SM-08F1&F2, SM-09F1&F2, SM-07F1, F2&F3, SM-04F1&F2 and SM-03F1&F2) is used which were collected during 11 sampling days. During fieldwork, the repeated observation of soil moisture at field scale is performed, this helped to identify representative point for the study area. The information(result) from this chapter is essential for the validation of SMAP L2_SM_P soil moisture discussed in chapter six.

A statistical and temporal stability analysis was performed to assess the space–time variability of soil moisture at field, station and regional scale. As the analysis deals with different spatial scales, for simplicity the terminology used in this research are: a "point" is the location where sampling is made; a "field" is the place where a number of point measurement collected; and a " station" is where a number of fields in indidviaual station are located and "Regional scale" is a collection of fields (stations) which represent for the whole study area .

6.1. Statistical analysis

The soil moisture spatial and temporal variability assessment has been addressed through the analysis of the soil moisture spatial variability using statistical approach (Brocca et al, 2012).The statistical analysis consists of both spatial and temporal mean, standard deviation and coefficient of variation of soil moisture(Brocca et al., 2010, 2012; Famiglietti et al., 1999; Jacobs et al., 2004). The spatial variability of soil moisture was calculated at a different spatial scales (field, station and regional scale) which included all collected soil moister data at each field at each day.

The spatial mean of soil moisture for field j and on a given sampling day t $\bar{\theta}_{jt}$ is computed as:

$$\bar{\theta}_{jt} = \frac{1}{N_p}\sum_{i=1}^{Np}\theta_{ijt} \quad \text{...} \qquad \text{Eq9}$$

Where $\bar{\theta}_{ijt}$ is soil moisture observed at point i, field j and sampling day t, N_p is a number of points at field j.

The spatial mean of each sampling day $\bar{\theta}_t$, which represent for the whole study area is defined as:

$$\bar{\theta}_t = \frac{1}{N}\sum_{j=1}^{N}\bar{\theta}_{jt} \ , \qquad \text{Eq 10}$$

Where N is the number of fields, and the temporal mean for specific field $\bar{\theta}_j$ can be computed as:

$$\bar{\theta}_j = \frac{1}{M}\sum_{t=1}^{M}\bar{\theta}_{jt} \quad . \qquad \text{Eq 11}$$

Where M is number of sampling days

The standard deviation, σ_t and coefficient of variation (CV_t) are computed. The coefficient variation each sampling day in space, CV_t is computed as:

$$CV_t = \frac{\sigma_t}{\theta_t} = \frac{\sqrt{\frac{1}{N-1}\sum_{j=1}^{N}(\bar{\theta}_{jt} - \bar{\theta}_t)^2}}{\bar{\theta}_t} \qquad \text{Eq 12}$$

Where σ_t is the standard deviation

The local coefficient variation (CV*t local*) is for each sampling day, computed by averaging that determine for each field, gives:

$$CV_{tlocal} = \frac{1}{N}\sum_{j}^{N}\left(\frac{\sigma_{jt}}{\theta_{jt}}\right) \qquad \text{Eq 13}$$

The CV*t local* is the average of the coefficient of variation computed for each N of fields

6.2. Temporal stability analysis

In order to understand the soil moisture spatial variability between sampling location in the study area, temporal stability analysis was performed to determine which point can represent for specfic scale (field, station and regional scale). Soil moisture spatial variability can be generated through soil type, topography, vegetation and metrological force (Entin et al., 2000).

Vachaud et al.(1985) used the temporal stability analysis which identifies stable measurement that predicts large scale average over long time scales. If the spatial distribution of soil moisture shows temporally stable, then its estimation over large areas will be possible through a limited number of measurements (Brocca et al., 2010). Temporal stability of soil moisture analysed using field measurements at different spatial scale through the statistical approach of relative difference.

The relative difference was calculated using the relative difference between individual soil moisture measurements at point i and day t. The relative difference, δ_{it}, is calculated as:

$$\delta_{it} = \frac{\theta_{it} - \bar{\theta}_t}{\bar{\theta}_t} \qquad \text{Eq 14}$$

The mean relative difference, $\bar{\delta}_i$ and standard deviation of relative difference, $\sigma(\delta_i)$ for each point i (Brocca et al., 2010; Cosh et al., 2008; Jacobs et al., 2004) are calculated as:

$$\bar{\delta}_i = \frac{1}{M}\sum_{t=1}^{M}\delta_{it}$$ Eq 15

$$\sigma(\delta_i)^2 = \frac{1}{M-1}\sum_{t=1}^{M}(\delta_{jt} - \bar{\delta})$$ Eq 16

The mean relative differences at a sampling point identifies whether the soil moisture measurements at that location is greater or less than the average condition of the soil moisture. A site considered representative of the large scale average if the mean relative difference is near zero and if the standard deviation is low (Brocca et al., 2010; Cosh et al., 2004; Jacobs et al., 2004).

6.3. Field-scale

The main statistical analysis of soil moisture sampling are computed and the results obtained by applying the statistical and temporal stability analysis are discussed for each field site. The "field scale" is computed by averging the soil moisture observed at point *i*, for field *j* on each sampling day using Eq 9.

To explain the spatial and temporal variability of soil moisture within each field plotted as a time series and coefficient variation from each 11 field show in Figure 6-1. From the figure can see the difference in mean soil moisture and variably between each field. A wet trend was observed during the beginning of fieldwork period. The mean moisture content of grassland fields SM-04 (F1 &F2) and SM-03 (F1&F2) were wetter than other fields. The cropped fields SM-08F1, SM-09F1 and F2 and SM-07F3 were the dries this might they exposed to evapoternaspiration and driange makes to dries the soil. At the beginning of the fieldwork period SM-04F1 field were much wetter, with mean moisture content values ranging from 0.420 to 0.583 m^3m^{-3}. The driest fields were SM-08 (F1&F2), SM-09 (F1&F2) and SM-07F3 with mean soil moisture values ranging from 0.138 to 0.311 m^3m^{-3}. As mentioned in sampling strategy section 4.2 and Table 1, there were differences in land cover, land use and soil type in the field sites. The fallow barely fields (SM-07 F1&F2) which have compacted clay and occasionally standing water was tilled and planted during the field work are characterize by intermediate mean soil moisture with high variability. The grassland fields SM-04F2 and SM-08F2 shows high variability in Figure 6-1 b and the crop field SM-07F3 shows increasing the variability with increase soil moisture during 8 October.

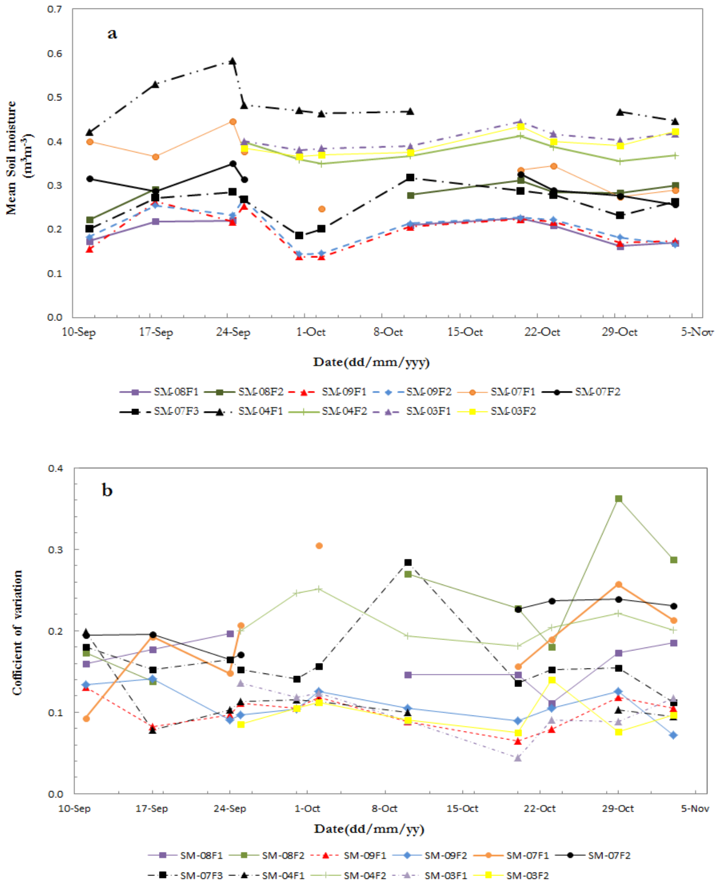


Figure 6-1 Mean and coefficient variation moisture content within each field (a) field mean soil moisture, (b) coefficient of variation

The relationship between areal average soil moisture and standard deviation and the coefficient variation is important in the analysis of soil moisture spatial variability (Bosch et al., 2006; Brocca et al., 2010; Famiglietti et al., 1999). The analysis identfy the dependecey of soil moisture variability on mean soil moisture. Figure 6-2 shows that the standard deviation against the mean of soil moisture for each field in different land covers. The scatter plot shows that the individual soil moisture measurements differ both with respect to soil moisture mean and variability relate to the land cover, land use and soil type. The greatest variability were observed in grassland fields (SM-08F2, SM-04F2) and the grassland fields used for grazing with water above the surface and slopy area (SM-04F1) with soil moisture standard deviation varying between 0.038 up to 0.11m^3m^{-3}. The fallow barely fields (SM-07 F1&F2) which have compacted clay and occasionally standing water was tilled and planted during the field work. Due to this the fallow barely fields SM-07F1&F2 surface soil moisture show high variability varying betwen 0.037 and 0.078 m^3m^{-3}. The croped fields SM-08F1,SM-09F1&F2,SM-07F3 observed the lowest variability with standard deviation value Varies between 0.012 and 0.043. The grassland fields SM-03F1&F2 is the wettest fields and had lowest variability.

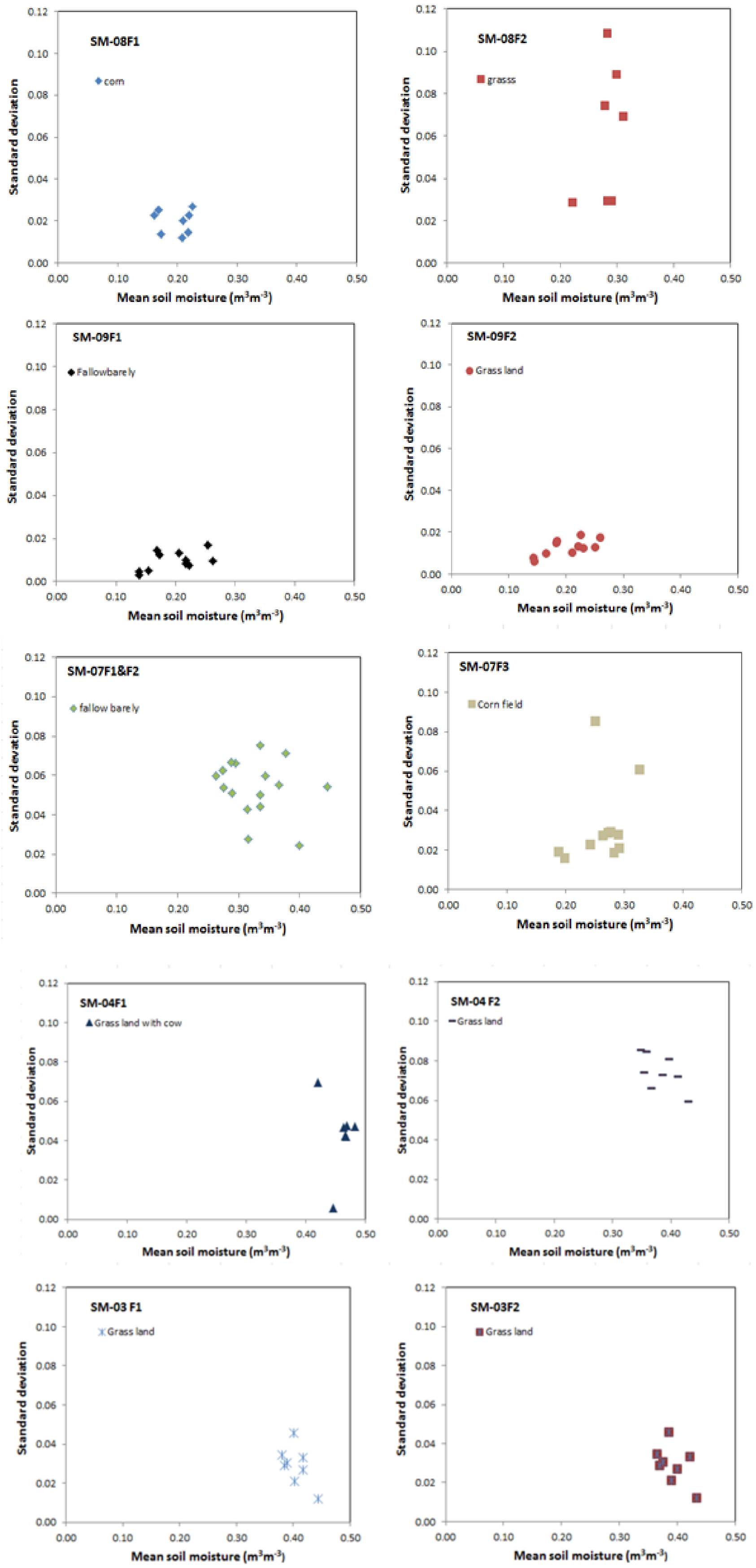


Figure 6-2 Mean (m^3m^{-3}) and standard deviation(m^3m^{-3}) of soil moisture within each field on different land cover

Figure 6-3 (a and b) shows the relationship between the standard deviation of moisture content within each fields and its mean for grassland and cropped fields. The Figure 6-3(a) shows a rough decreasing in standard deviation as mean soil moisture increase for grassland fields, and for cropped fields (figure 6-3 b) shows that increasing in standard deviation as mean soil moisture increase.

Figure 6-3 (b and c) shows the relationship of coefficient variation and mean soil moisture. The grassland shows decreasing in coefficient variation as increase the mean soil moisture (figure 6-3 c), and the cropped field shows increase in coefficient of variation as mean soil moisture increase. In the grassland (figure 6-3c) decreasing in coefficient of variation controlled by increasing moisture content rather than the standard deviation as computed using eq 13. The relationship between mean soil moisture and the coefficient variation indicate that the grassland fields have high variability in dry condition and decrease with increasing moisture content. The cropped fields have low variability under dry condition.

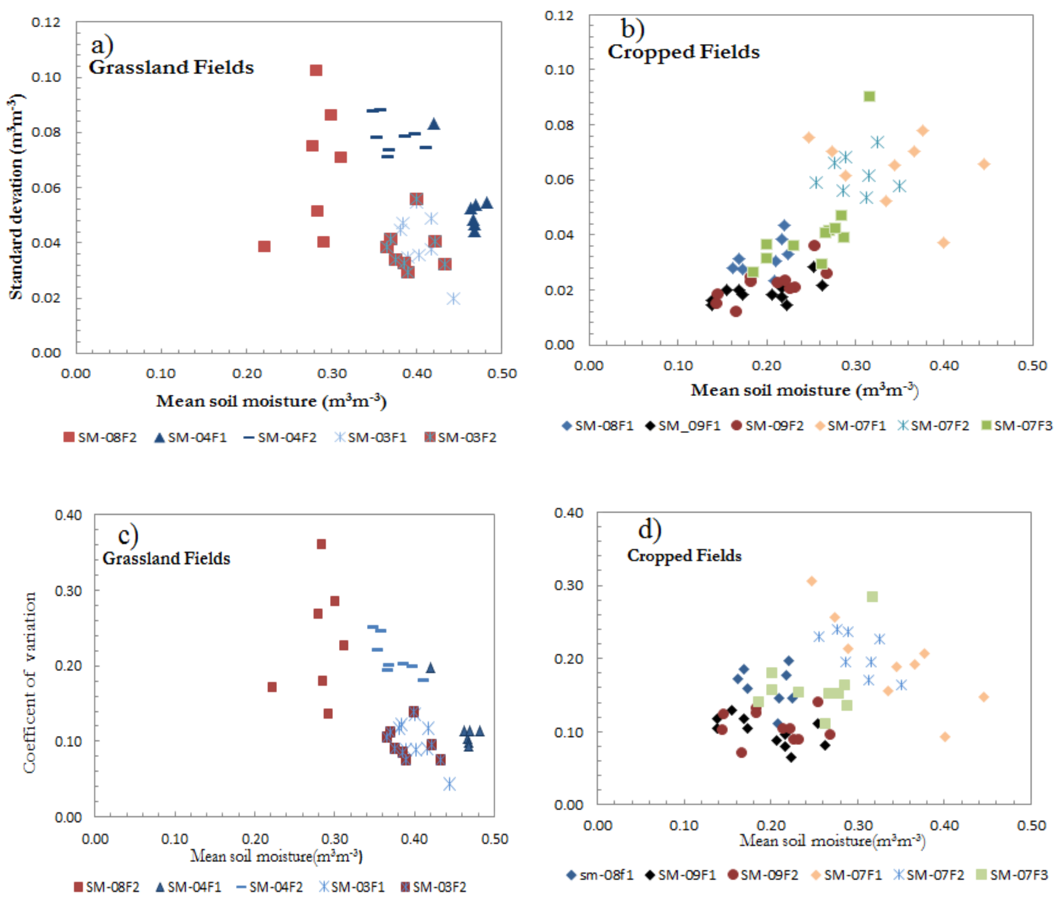
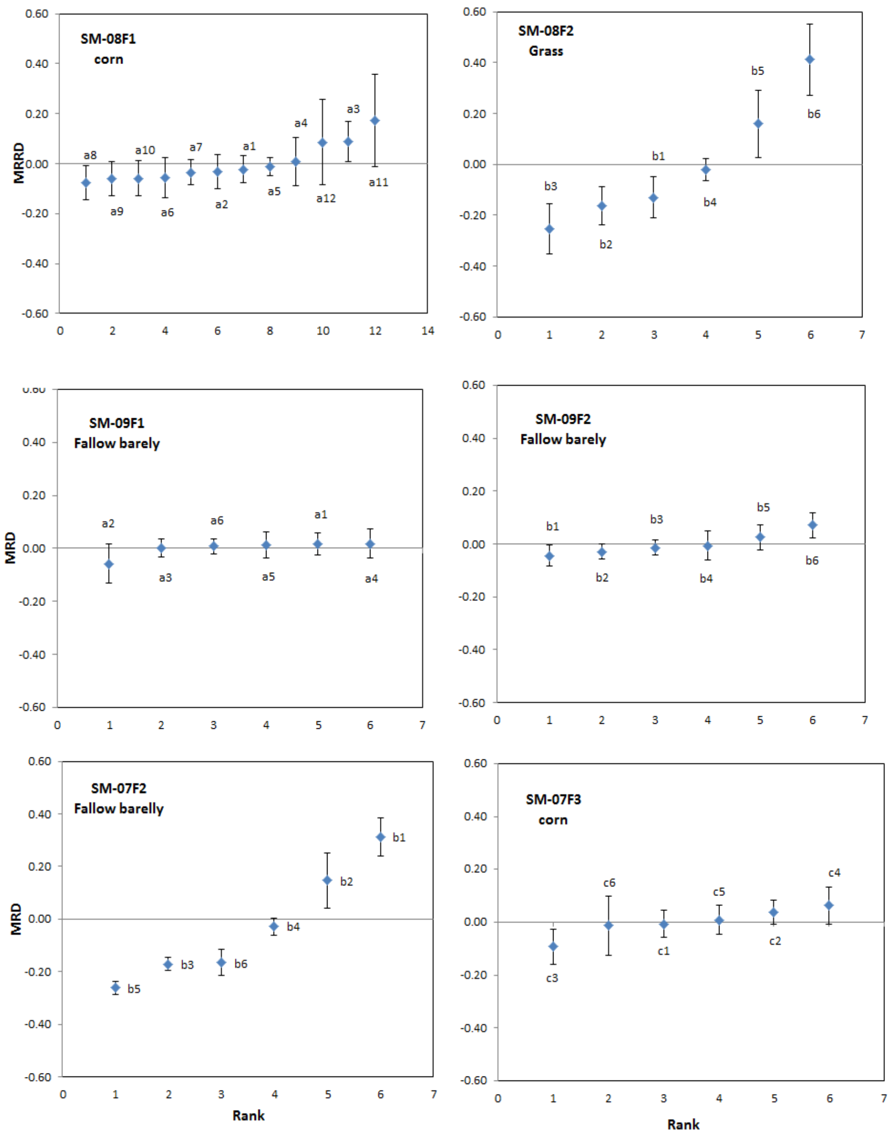


Figure 6-3 Standard deviation (m^3m^{-3}) versus mean oil moisture (m^3m^{-3}) (a)for grassland fields, (b) for cropped fields, coefficient of variation versus mean soil moisture (m^3m^{-3})(c) for grassland fields, and (d) for cropped fields

Figure 6-4 shows the rank order of Mean Relative Differences(MRD)(Eq 15) with one Standard Deviation (STD(MRD)(Eq 16) calculated for each point locations within each 11 fields. Temporal stability analysis performed to determine point-scale soil moisture measurements for representing field scale averages, which are important to characterise the soil moisture variability. Temporal stability is defined as having mean relative difference close to zero and low standard deviation (Brocca et al., 2010; Cosh et al., 2004). The plot shown within alphabet a, b and c in Figure 6-4 indicate that point soil moisture measurements in each field which collected during fieldwork. The cropped fields SM-08F1, SM-09F1&F2, SM-07F3 and the grassland SM-03F1&F2 shows lowest variability. The grassland fields SM-04F2, SM-08F2 and the fallow barely field SM-07F2 shows the highest variability at point location to the mean of the field. From all fields the fallow barely fields SM-09F1&F2 obtained value with close to zero mean relative difference and low variability for all point location. The grassland fields SM-03F1&F2 also shows low variability of soil moisture. The grassland SM-08F2 and SM-04F2 shows the higher variability of mean relative difference almost for all point location.

As the results shows that most of the fields have point locations with a value close to zero mean relative difference and low variability. This indicates that the within each field there are points that can represent the field mean soil moisture content.



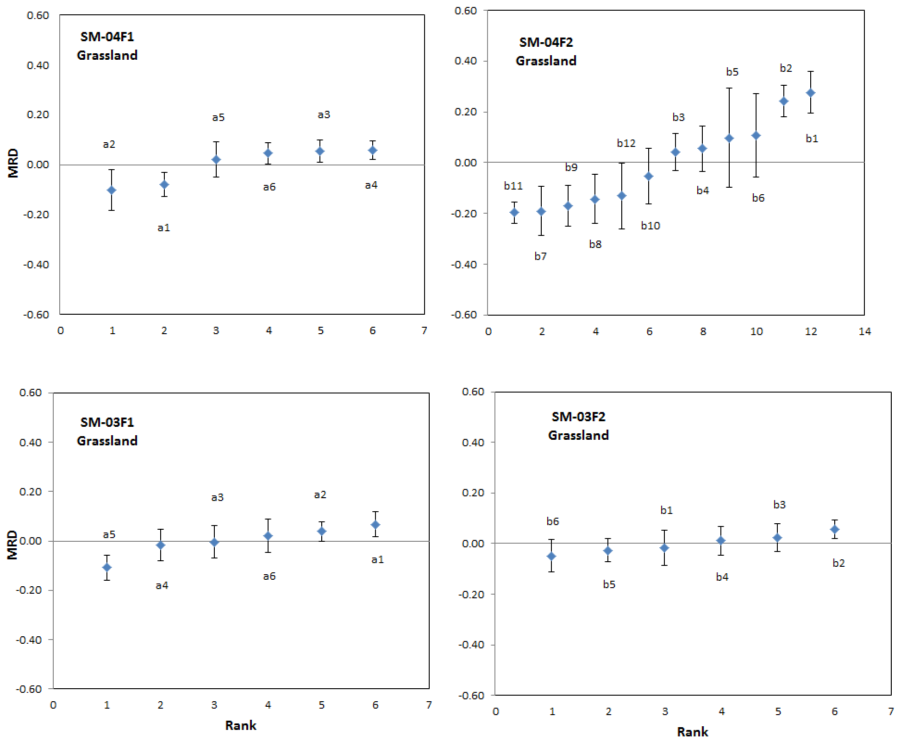


Figure 6-4 Rank order mean relative difference where error bars indicate± standard deviation for the field scale (labels indicates for each sampling location within each fields).

6.4. Station scale

Soil moisture measurements consists of 11 sampling days at 11 fields conducted at 5 different stations as described in section 4.2. The time series of soil moisture in Figure 6-5 was computed by averaging a number of fields observed at each station for each sampling day, plotted in the response of rainfall event during the study period. Rainfall information has been discussed in the section of 3.1 to illustrate the spatial distribution of rainfall and evapotranspiration with the response of rainfall deficit. There were several rainfall events, followed by high evaporation as indicate in Figure3-2, which causes to decrease soil moisture in some fields even if there is rain. The temporal evaluation of mean soil moisture shows that individual stations differ both with respect of soil moisture mean and variability shows in Figure 6-5 a &b. The differences in soil moisture mean and variability is due to the soil type and land cover. Station SM-08 is an average of corn field (SM-08F1) and grassland fields(SM-08F2) and station SM-09 is an average of the fallow barely fields(SM-09F1 and f2) shows the same trend and driest response to atmospheric forcing, during 24-09-15 the soil moisture decrease in SM-08 and SM-09 when comparing with other fields (figure 6-5a). This is because, the corn field when the rain fall intercepted by corn leaf and evaporate does not reach the soil surface, this causes to dry out the soil moisture. The fallow barely field is a bare soil fields which is much more exposed to evaporation. So, this leads to become dries out soil. Staion SM-04 is an averge of grassland fields with loamy sand and station 5(SM-05) (which is stop collecting of soil moisture due to agriculture activity) shows high soil moisture during the binging of the study time.

Figure 6-5 (b) station SM_08 were the driest fields and shows intermediate variability. Station SM-09 was the driest field and had lowest variability. The grassland field for grazing and ground water out in surface level with loamy sand fields (SM-04) were much wetter and had much variability, and (SM-03) is the average of SM-03F1and F2 grassland with loamy sand were systematically wetter and slightly variable. Station SM-07 is average of SM-07F1,F2 and F3 had much greater variability shows in Figure 6-5 (b).

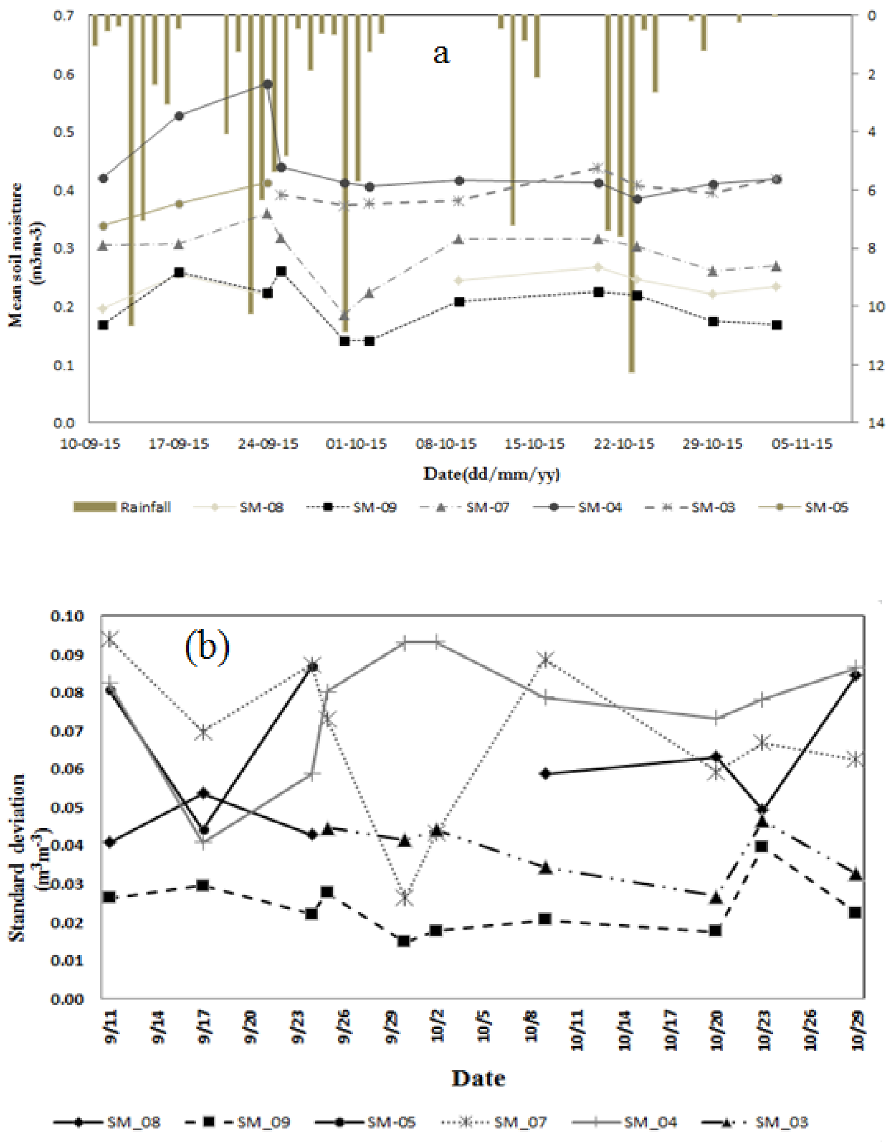


Figure 6-5 Soil moisture content for station scale (a) mean (m^3m^{-3}), (b) standard deviation m^3m^{-3}

The temporal stability analysis also performed to identify how point measurements represent for the station scale average. Figure 6-6 shows the rank ordered mean relative difference with ± standard deviations for station scale. The points in the station SM-03 and SM-09 have lowest variability to the station average. SM-08 and SM-07 shows higher variability at sampling point to station average. Some points in stations SM-08 have low variability but not close to zero MRD . SM-04 have some points close to zero MRD with the low variability that can represent to the mean of station scale.

From all the study areas, SM-09 and SM-03 showed greatest time stability with the lowest variability at point location to the mean of the station scale. The study area SM-08, SM-07 and SM-04 showes highest variability to the mean of the station. As mentioned in the above the land cove and land use for each study area have effect to the soil moisture variability.

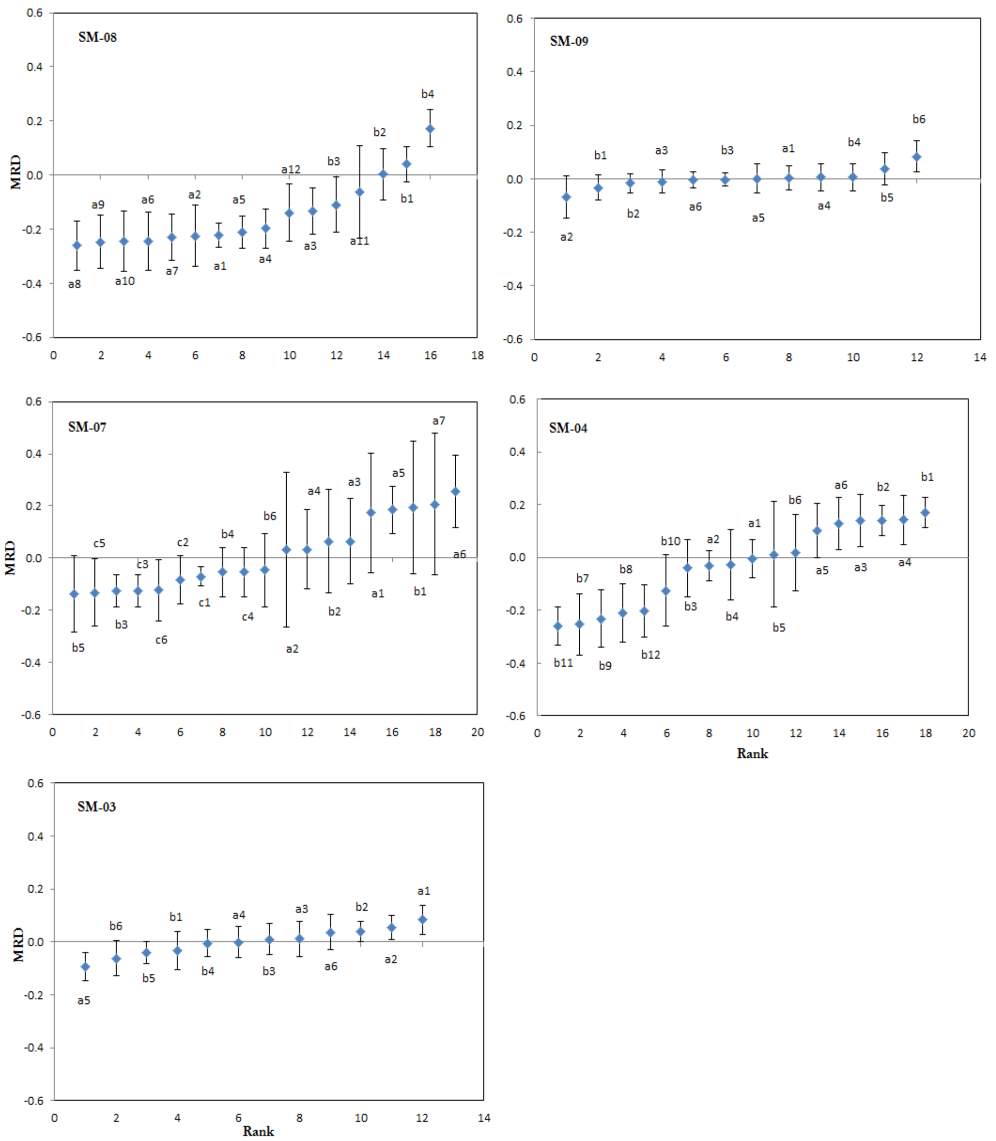


Figure 6-6 Rank order mean relative difference where error bars indicate± standard deviation for the station scale(labels indicates for each sampling location within each stations).

6.5. Regional scale

Regional scale soil moisture computed by an average of soil moisture observed at the 14 fields including SM-05 (which collect data in the beginning) using eq 10. The main statistical analysis for each sampling day and also the third and fourth statistical moments (Skewness and kurtosis) in regional scale are given in Table 7. Coefficient of variation calculated for the whole study area on each sampling day and also for each field. The coefficient of variation is important statistical analysis to describe spatial and temporal soil moisture variability (Brocca et al., 2010, 2012; Famiglietti et al., 1999; Jacobs et al., 2004a). As given in Table 7 the coefficient of variation for the whole area (regional scale) found the maximum value of 0.456 and a minimum value of 0.223 and on average equal to 0.334 calculated using (eq 12). The spatial local coefficient variation, which computed for the individual field using (eq 13) found a value of maximum 0.174 and minimum 0.120 and on average equal to 0.146. The result indicates that the spatial coefficient of variation for the regional scale higher than the local coefficient variation, which confirms with the previous study Brocca et al., (2012). Therefore, the spatial soil moisture variability increases as the size of the area increase. The temporal coefficient of variation for the individual field (Appendix-4) the highest on average for fields of SM-08F2, SM-07F1&F2 and SM-04F2 ranging from 0.196 to 0.234. The result indicates the temporal variability of soil moisture is higher than the spatial variability.

Table 7 statistical properties of the soil moisture data collected at 14 fields during the field work in study area, which is representative of regional scale

Date	Mean (m^3m^{-3})	Standard Deviation (m^3m^{-3})	Coefficient of variation	kurtosis	Skewness
11-09-15	0.275	0.104	0.380	-1.680	0.421
17-09-15	0.323	0.092	0.284	1.866	1.325
24-09-15	0.343	0.131	0.381	-0.102	0.833
25-09-15	0.349	0.078	0.223	-0.924	0.214
30-09-15	0.292	0.133	0.456	-2.011	-0.102
02-10-15	0.287	0.121	0.421	-1.591	0.031
10-10-15	0.314	0.093	0.297	-1.144	0.207
20-10-15	0.322	0.085	0.264	-1.394	0.241
23-10-15	0.304	0.078	0.257	-1.546	0.211
29-10-15	0.290	0.102	0.352	-1.007	0.324
03-11-15	0.299	0.108	0.360	-1.287	0.191

Figure 6-7 shows the rank order of Mean Relative Differences(MRD) with one Standard Deviation (STD(MRD) calculated for individual 11field. Temporal stability analysis performed here to determine each field soil moisture measurements for representing regional scale averages, which are important to characterise the soil moisture variability at large scale. SM-08 F2 and SM-07F1 shows the highest variability to the mean of regional scale. Most fields shows lowest variability but not close to the mean relative differences.

The intensive field measurements of soil moisture from 5 stations (11 fields) were covered a range of soil moisture conditions from wet to dry fields. Generally, the statistical, spatial and temporal analysis results indicate that the soil moisture variability increases with the extent of the area from field scale to regional scale.

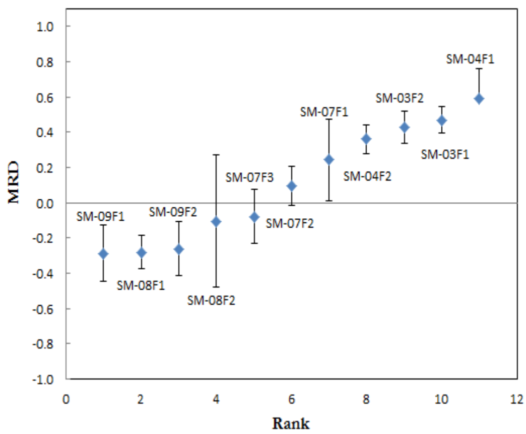


Figure 6-7 Rank order mean relative difference where error bars indicate± standard deviation for the regional scale(labels indicates for 11 fields).

6.6. Matching stations with intensive field measurments

Twente monitoring station was established to provide validation data for the satellite and for long term estimation of soil moisture throughout the region recorded soil moisture every 15 minutes. Intensive fieldwork was performed to collect soil moisture data and used to compare with Twente monitoring station. Statistical and temporal stability analysis helps to examine the reliability of monitoring stations (Bosch et al., 2006). However, Twente monitoring station missing a lot of data in this year, so it is difficult to analysis using temporal stability due to the limitation of data avilabilty. Statistical analysis of spatial average of in-situ soil moisture performed to compare with field data and SMAP satellite.

Twente monitoring station have 20 stations, and significant amount of data were missing from stations:SM-01,07,08,10,11,15,19. The soil moisture data completely missing from the stations SM-06 and 17. The fieldwork were conducted on the stations SM-03,04,07,08,and 09, but station SM- 07,08 and 09 missing the soil moisture data during the period of fieldwork. The examination of this stations where the fieldwork were carried out is difficult because of missing data, therefore the field data used to examine how representative of other stations. In order to compare the station measurements with the fieldwork measurements, first plot the time series of 8 station which have almost complete record of soil moisture data during the fieldwork period. Secondly, the matchup was performed between the spatial average of field data and spatial average of all station data measurements when data are available during the fieldwork period.

Figure 6-8 shows time series of soil moisture of individual 8 stations (SM-04,05,09,12,13,14,16 and 20) which have the almost complete record of soil moisture plot in the response of precipitation recorded from three rain gage during study period(from September to November 4). The soil moisture station recorded soil moisture every 15 minutes and the rain gage every 20 minutes this recorded then averaged to daily base. From the 8 stations, station SM-16 shows the highest soil moisture response to the rainfall. SM-04 was one of the station where fieldwork was carried out and shows lowest soil moisture. All other fields show the almost same trend with the response of rainfall.
The field work was conducted in the month September, October and the last day in November, because during this month perception expected to increase .During the fieldwork the soil moisture data collected from station field 4(SM-04F1&F2) were the highest mean soil moisture data and from the station field 9(SM-09F1&f2) were the lowest mean soil moisture as shown in Figure 6.1(a) and Figure 6.5(b). However, the data from station sensor 4(SM-04) shows the lowest valve as compare with station 9(SM-09),which is different from the fieldwork soil moisture data.as shown in Figure 6-8.

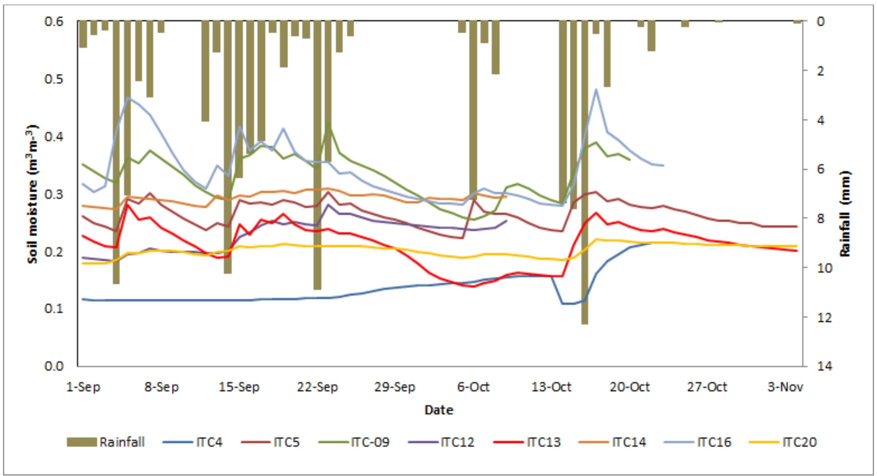


Figure 6-8 Soil moisture at individual 8 station and precipitation during field work period

Figure 6-9(a) shows the comparison between the spatial average field work and the spatial average of 8 stations, which have complete data during field work, correlation coefficient (r) 0 70, RMSE 0.06 m^3m^{-3} and MAE 0.06 m^3m^{-3}. Figure 6-9 (b) shows the comparison between the spatial average of field data and spatial average of all station which have data during fieldwork time. Good correlation coefficient (r) of 0.61 obtained with low RMSE of 0.04 m^3m^{-3} and MAE 0.034 m^3m^{-3}.

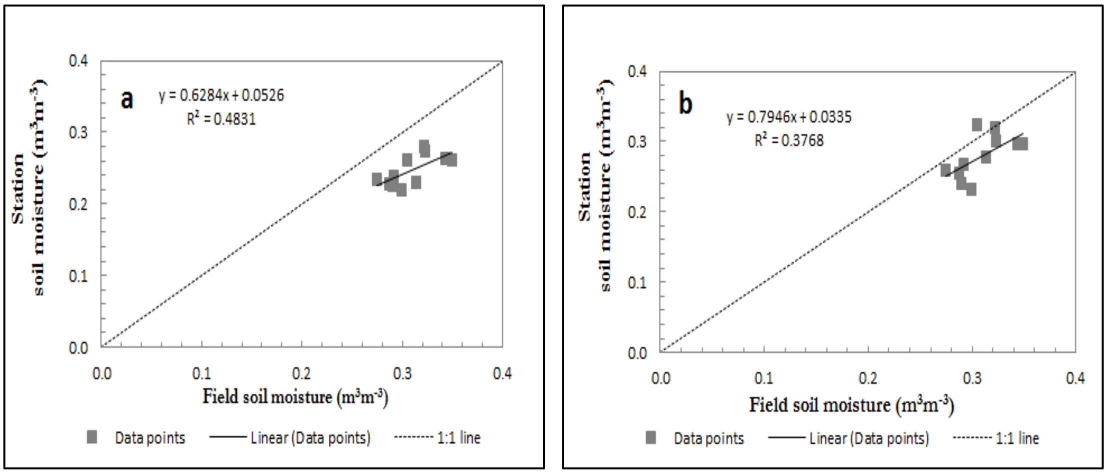


Figure 6-9 comparison between field measured soil moisture data at 11 fields and station soil moisture (a) spatial average of field data with spatial average of 8 station(which have almost complete data), and (b) spatial average of field data with spatial average of all stations. Soil moisture (when data available)

CHAPTER SEVEN

7. VALIDATION OF SMAP LEVEL 2 PASSIVE SOIL MOISTURE

This chapter focuses on the validation of SMAP L2_SM_P radiometer (passive) soil moisture product using Twente monitoring stations and field data which described in chapter 5. The validation site location for SMAP L2_SM_P soil moisture showed in Figure 4-1. The time series of SMAP L2_SM_P obtained in Twente region from April 01 to December 12,2015. The descending L2_SM_P soil moisture retrieval accuracy was validated against in-situ network at SMAP overpass time and field measurements wich obtained on daily measurments. Fristly,the time series of SMAP L2_SM_P prduct was compared aginst the selected 8 station spatial average(wich have almost complete data) and against in-situ spatal average of with in SMAP grid cell (all stations wich have avilable data) and also with spatial average of field data.

Secondly, the reliability of L2_SM_P soil moisture assessed, scatter plot L2_SM_P and measured soil moisture from station and field. The SMAP L2_SM_P compared aginst 8 individual stations, against of spatial average of 8 stations and against of spatial average of all stations with in SMAP grid cell (wich have avilable data) and also spatial average of field soil moisture data. The in-situ network soil moisture data was taken at SMAP overpass time.

Statistics such as the Root Mean Square error (RMSE),coefficient of determination (R^2), bias and Mean Absolute Error (MAE) are calculated from the matchups between the time series of L2_SM_P soil moisture within each individual 8 stations, with in-situ spatial average and 8 stations spatial average.

Bias correction applied to the retrieved L2_SM_P by using in-situ network station and field measurements. The in-situ network used to correct the retrieved L2_SM_P soil moisture, by assuming the in-situ network is unbiased. Statistical analyses used to recalculate the error level RMSE and MAE using the bias corrected.

7.1. Analysis of time series

The accuracy of L2_SM_P soil moisture product assessed by plot time series of L2_SM_P against measured soil moisture from stations and field showed in Figure 7-1 & 7-2. The time series of L2_SM_P soil moisture compare with time series of individual and spatial average of in-situ measurement for the whole study area (when the station data available) and spatial average of field data shown in Figure 7-1.

The time series of L2_SM_P soil moisture compare with spatial average of in-situ measurement for the whole study area (when the station data available) and spatial average of field data shown in Figure 7-2a. Also the time series of L2_SM_P soil moisture compare with spatial average 8 station (which have almost complete data) and spatial average of field data shown in Figure 7-2b. As mentioned in section 6.6, a lot of data missing from each stations and 8 station out of 20 have almost complete data.

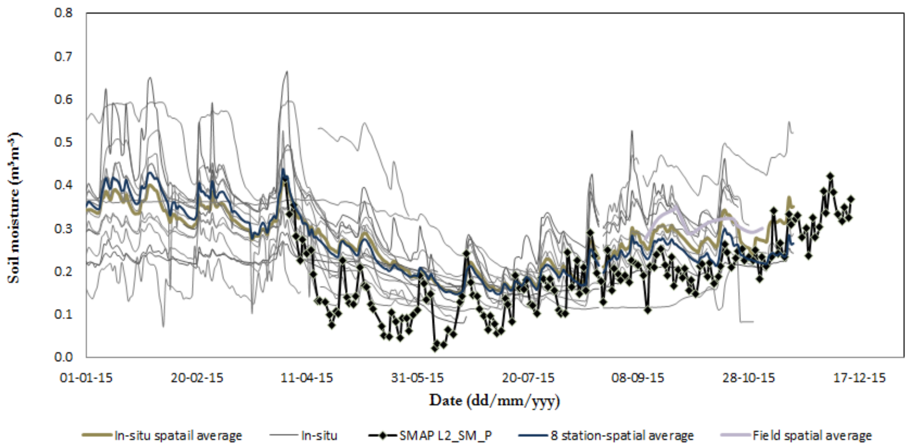


Figure 7-1 The SMAP L2_SM_ P soil moisture from descending overpass compared with in-situ spatial average, 8 station spatial average, individual in-situ measurements and field spatial average (on daily measurements)

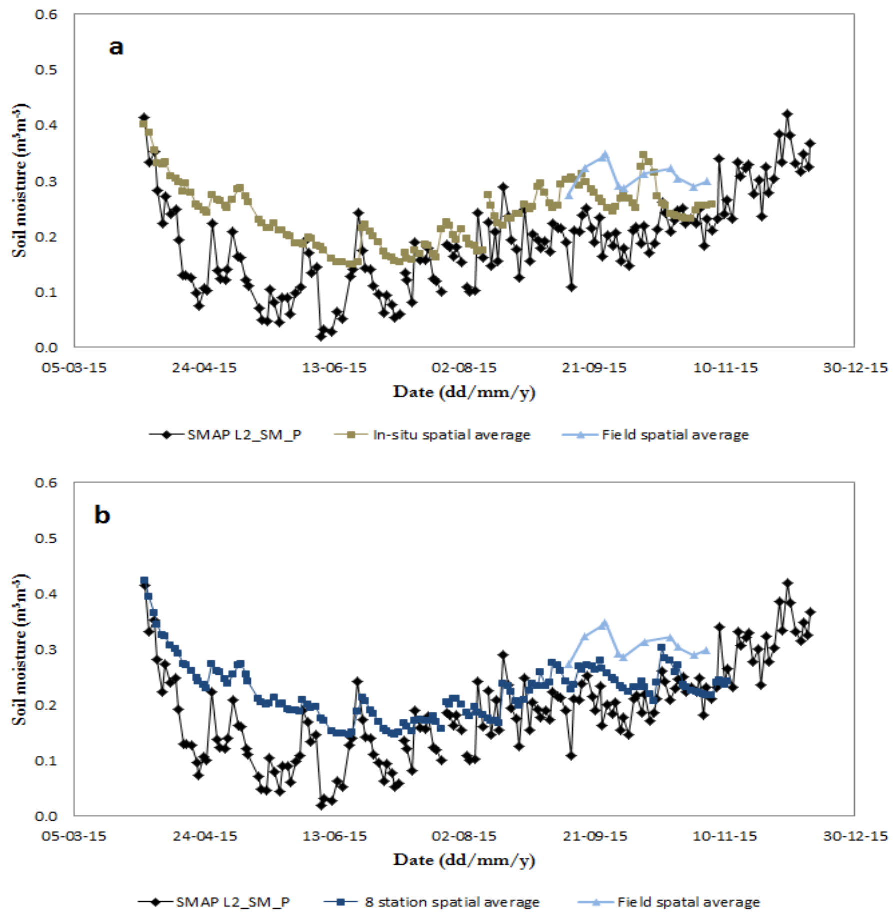


Figure 7-2 (a) Comparison of retrieved L2_SM_ P soil moisture with in-situ spatial average(when the stations data available) and field spatial average, and(b) comparison of retrieved L2_SM_P soil moisture with 8 station spatial average (which have almost complete data) and field spatial average.

The time series of SMAP L2_SM_P soil moisture data obtained (start) from 01-04-2015 up to 13-12-2015. The time series SMAP L2_SM_P soil moisture product generally shows the same trend with in-situ spatial average and 8 station spatial average Figure 7-2 (a and b). Time series of L2_SM_P shows high soil moisture value at the beginning of April. The L2_SM_P soil moisture become decreases and have low soil moisture values in summer followed the same tend with in-situ spatial average and 8 stations spatial average. L2_SM_P have a maximum value of soil moisture measurements in the beginning of April (0.415 m^3m^{-3}) and in autumn (0.420 m^3m^{-3}). The 8 spatial average have also maximum soil moisture value in the beginning of April (0.423) and in autumn (October to half November)(0.304 m^3m^{-3}). L2_SM_P soil moisture value starting increasing from November to the half of December (autumn), which is in-situ data not available at this time for comparison. The retrieval soil moisture and the measured shows the minimum value of soil moisture during spring and summer. The seasonal comparison shows that the L2_SM-P is in agreement with in-situ spatial average and 8 stations spatial average. But generally the retrievaled soil moisture underestimate the measured soil moisture and during summer period shows the very low value of soil moisture. The in-situ measures the soil layer in the 0-5 cm depth. The microwave radiation of L2_SM_P measures soil moisture at the top of soil layer (O'Neill et al., 2014) and this leads to underestimation in dry season as the upper part is dryer than the deeper, and overestimation during the rainy season. But the time series L2_SM_P shows underestimation for all seasons.

There are a lot of missing data in station soil moisture. This causes errors on the validation of L2_SM_P using in-situ measurements. Generally, L2_SM_P soil moisture data underestimate the in-situ spatial average, 8 station spatial average and field spatial average on the whole period. The L2_SM_P soil moisture shows variation when compare to in-situ measurements in Figure 7-2 (a and b), shows very low value of soil moisture retrieved compare to in-situ measurements. This might be the SMAP L2_SM_P measured soil moisture on top of 0-5 cm on the top dry part before getting the wet condition on the depth. This affects for the retrieval of L2_SM_P to become more dry when compare to in-situ measurements.

7.2. Matchups

The accuracy of SMAP L2_SM_P product is assessed, by scatter plot L2_SM_P soil moisture against the soil moisture measured at individual 8 station, spatial average of 8 station, all in-situ stations spatial average at SMAP overpass time and also against spatial average of field soil moisture data that measured on daily base. The statistics analysis:R^2, RMSE, bias, MAD calculated from the matchup given in Table 9.

Figure 7-3 shows the comparison between L2_SM_P and individual of 8 soil moisture station. The scatter plot and Table 8 shows that the R^2 value varies from 0.02 (SM-14) to 0.54(SM-05). For the SM-05,13 and 16 shows closer agreement than other stations. SM-05 and SM-13 shows the better correlation coefficient(r) compare to the other stations. The comparison between SM-05 in-situ soil moisture and L2_SM_P shows correlation coefficient(r) 0.78 which equivalent to R^2 0.54 and SM-13 correlation coefficient (r) 0.72 which is equivalent R^2 0.52. This SM-13 shows a better correlation with low RMSE 0.049 m^3m^{-3} and MAE 0.039 m^3m^{-3} gives in Table 8. A decreasing in R^2 0.02 with high RMSE 0.156 m^3m^{-3} and MAE 0.134 m^3m^-3 resulted for SM-14. The computed bias indicates positive biases towards individual in-situ measurements, each of 8 stations overestimates the retrieved L2_SM_P soil moisture ranges from 0.027(SM-20) to 0.135(SM-16) m^3m^{-3} in Table 9. Figure 7-3 indicates large deviations from 1:1 line between retrieved and measured soil moisture

Generally, the comparison between L2-SM-P soil moisture and the individual stations shows lower R^2 with high RMSE. These can have several factor to decrease the agreement between the L2_SM_P and individual soil moisture. The validation of satellite soil moisture products requires continuous in-situ measurements which can represent the spatial average of the study area. However, Twente monitoring stations missing a lot of data causes uncertainty for the validation of L2_SM_P soil moisture. The scale mismatch between the individual stations and L2_SM_P can be the reason to make uncertainty. As describe in many previous studies (Brocca et al., 2012; Crow et al., 2014) the scale mismatch can make uncertainty on the validation of coarse resolution of satellite.

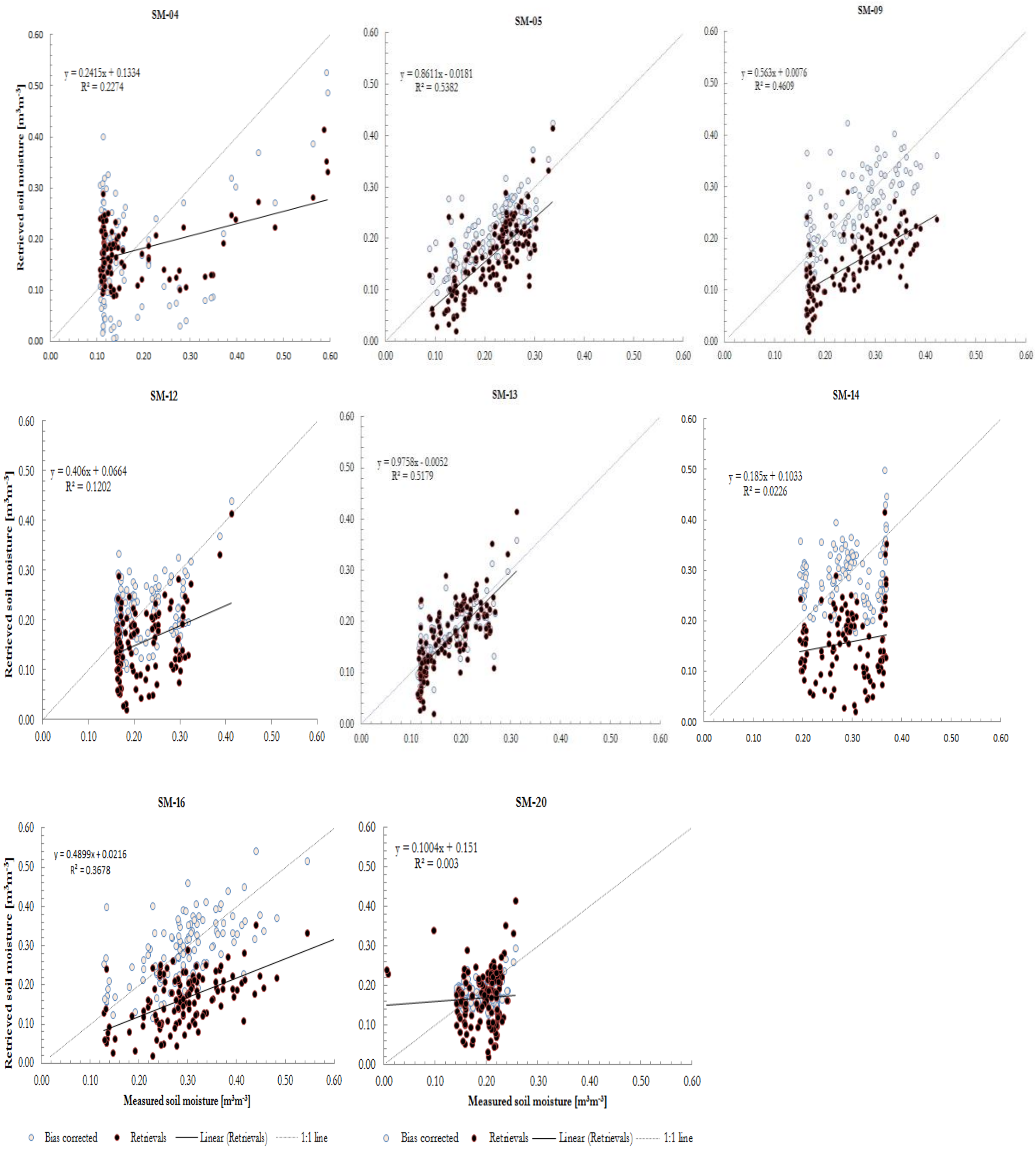


Figure 7-3 Retrieved L2_SM_P soil moisture against soil moisture measured at individual stations

Table 8 Summary of statisticsR2, RMSE, MAE, Bias computed between the L2_SM_P soil moisture and in-situ measurements of 8 individual stations (which have almost complete data), and spatial average of 8 stations.

Validation using individual stations					Validation using spatial average of 8 station			
Stations	R^2	RMSE (m^3m^{-3})	MAE (m^3m^{-3})	Bias (m^3m^{-3})	R^2	RMSE (m^3m^{-3})	MAE (m^3m^{-3})	Bias (m^3m^{-3})
SM-04	0.02	0.100	0.078	0.013	0.46	0.076	0.064	0.064
SM-05	0.54	0.067	0.056	0.047				
SM-09	0.45	0.119	0.109	0.106				
SM-12	0.12	0.096	0.076	0.063				
SM-13	0.52	0.049	0.039	0.009				
SM-14	0.02	0.156	0.134	0.132				
SM-16	0.45	0.150	0.137	0.135				
SM-20	0.003	0.079	0.059	0.021				

Figure 7-4a shows the matchup between L2_SM_P soil moisture and 8 stations spatial average, obtained correlation coefficient (r) of 0.68 with equivalent R^2 0.46. Figure 7-4b shows the matchup between SMAP L2_SM_P and all in-situ station spatial average. The correlation coefficient of 0.62 with the equivalent of R^2 0.38 obtained between SMAP L2_SM_P and all in-situ station spatial average. Also, the matchup preformed between SMAP L2_SM_P and spatial average of field soil moisture measurements correlate coefficient(r) of 0.32 wich equivalent with R^2 0.10 gives in Table 9. The scatter plot between L2_SM_P soil moisture and 8 stations spatial average shows increasing in R^2 compare to each individual stations(SM-04, SM-09, SM-12, SM-14, and SM-20).

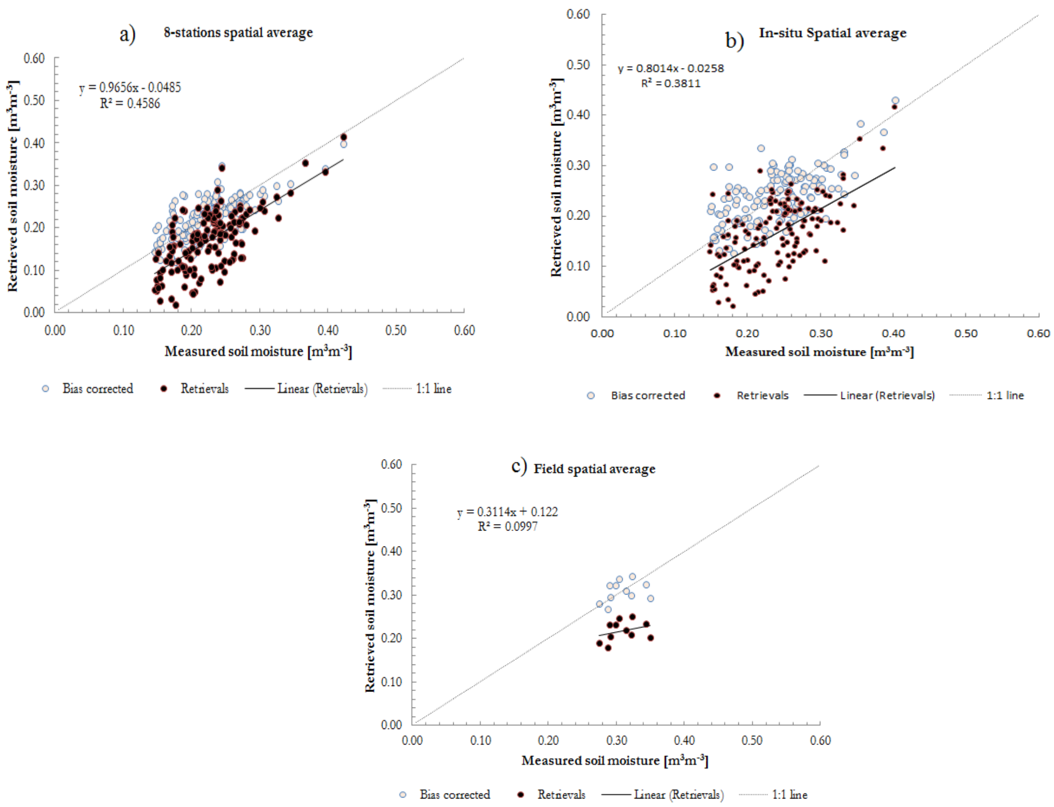


Figure 7-4 Retrieved L2_SM_P soil moisture against the soil measured (a) 8 station spatial average (which have almost complete data), (b) in-situ spatial average(all stations when data available), and(c) field spatial average

Table 9 Summary of statisticsR2, RMSE, MAE, Bias computed between the L2_SM_P soil moisture and in-situ measurements of spatial average field data and spatial average of all stations.

Validation using spatial average of field data				Validation using in-situ spatial average			
R^2	RMSE (m^3m^{-3})	MAE (m^3m^{-3})	Bias (m^3m^{-3})	R^2	RMSE (m^3m^{-3})	MAE (m^3m^{-3})	Bias (m^3m^{-3})
0.10	0.094	0.091	0.091	0.38	0.097	0.082	0.072

These error levels do not meet the SMAP L2_SM_P accuracy target of 0.04 m^3m^{-3}. Bias correction applied to the L2_SM-P. The statistical analysis recalculated using the bias corrected L2_SM_P. The bias correction processes remove the errors in RMSE and MAE. The bias corrected L2_SM_P leads to decrease the root mean square error ranged before correction from 0.067 to 0.160 m^3m^{-3} to 0.043 to 0.092 m^3m^{-3} after bias correction using individual stations gives in Table 10. The bias corrected of L2_SM_P using 8 spatial average reduce from 0.076 to 0.04 m^3m^{-3} after correction. After the bias correction, the accuracy requirements of the SMAP L2_SM_P 0.04 m^3m^{-3} meet for the stations SM-05 and SM-13 and 8 stations spatial average gives in Table 10.

Table 10 Statistics (RMSE and MAE)after bias correction

Validation using individual stations			Validation using spatial average of 8 station	
Stations	RMSE	MAE	RMSE (m^3m^{-3})	MAE (m^3m^{-3})
SM-04	0.118	0.096	0.040	0.032
SM-05	0.043	0.033		
SM-09	0.058	0.045		
SM-12	0.066	0.054		
SM-13	0.038	0.029		
SM-14	0.074	0.062		
SM-16	0.071	0.057		
SM-20	0.035	0.028		

CHAPTER EIGHT

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. Conclusions

Twente monitoring stations selected as one core international validation site for the SMAP soil moisture product contains of 20 stations. The stations were established to provide validation data for the satellite(SMAP) and for long term measurements of soil moisture throughout the region. The stations missing a significant amount of data in 2015. Intensive fieldwork was carried out to measure soil moisture at 11 fields within selected 5 stations using theta probe and gravimetric soil samples. The measured soil moisture from the field used to characterize spatial and temporal patterns of soil moisture near the monitoring station and to provide reference volumetric soil moisture concurrent with SMAP satellite overpasses.

Impedance probe (theta probe) soil moisture measurements are calibrated using volumetric soil moisture determined from gravimetric samples in order to achieve small errors and removes bias caused by the soil type. For the selection of the calibration method, comparison were performed between the theta probe and the gravimetrically determined soil moisture measured in specific soil type and individual days. The comparison results in high coefficient of determination, R^2 values ranging from 0.81 to 0.97, and low mean absolute error, MAE ranging from 0.003 to 0.04 m^3m^{-3}, whereby the best performance was obtained for measurements collected on individual days. From the analyses, it is decided to use general calibration method by applying the linear and polynomial regression equation. The general calibration method with the linear regression coefficients leads to a calibrated theta probe with coefficient of determination, R^2 0.91 and mean absolute error MAE 0.031 with respect to the gravimetrically determined soil moisture. The polynomial calibration results in an R^2 0.92 and mean absolute error 0.025 m^3m^{-3}. Since the polynomial relation shows good performance, polynomial calibration equation is used to calibrate theta probe.

The spatial and temporal soil moisture variability is controlled by land cover, land use and soil type, which is observed at 11 fields. The statistical analyses indicate that considerable soil moisture variability was observed at different spatial scale. Generally, the grassland fields were the wettest and the cropped fields were the driest . The grassland fields used for grazing with water above the surface and slopy area (SM-04F1) were characterized by higher mean soil moisture with a higher field variability. The grassland field in fairly flat sandy area (SM-08F1) has an intermediate mean soil moisture and high variability. The fallow barely fields (SM-07 F1and F2) which have compacted clay and occasionally standing water was tilled and planted during the field work are characterize by intermediate mean soil moisture with high variability. The other fields shows lower variability with different mean soil moisture at different spatial scales The analyses indicates that soil moisture varied more with land use than land cover. The spatial variability of soil moisture increases with the extent of area at regional scale, with an average spatial coefficient of variation equal to 0.334, while the spatial local coefficient of variation for individual fields on average equal to 0.146. The temporal coefficient of variation for individual fields vary from 0.196 to 0.234. The temporal variability of soil moisture is higher as compare to the spatial variation of soil moisture.

Temporal stability analysis was applied to characterize spatial patterns of soil moisture at a different scale. The agriculture fields SM-09F1andF2,SM-08F1,SM-07F3 and the grassland fields SM-03F1andF2 were the lowest variability at sampling location to the mean of field and station scale. This fields show at point sample location with mean relative difference close to zero and low variability, which is representative for field average and stations average. Whereas the point at each fields shows high variability to the spatial mean of regional. Generally, from the statistical and temporal analysis it can be conclude that the point measurements at each sampling location shows low variability to represent for field scale and station scale. The soil moisture variability increases with the extent of area.

Repeated soil moisture measurement carried out at 11 fields within selected 5 stations. Twente monitoring stations provide long-term estimation of soil moisture throughout the region. The field soil moisture measurement compared with in-situ network with R^2 0.37 and low RMSE 0.04 obtained.

The Level 2 Soil Moisture Passive(L2_SM_P) soil moisture accuracy assessed by comparing with in-situ measurements collected from the stations and field measurements in Twente region in 2015. The temporal dynamics of the L2_SM_P soil moisture products generally shows in agreement with in-situ network soil moisture. The matchup between the L2_SM_P and individual soil moisture station resulted in a coefficient of determination(R^2) 0f 0.54 for SM-05 station with root mean square error of 0.067 m^3m^{-3} and station SM-13 resulted in a coefficient of determination (R^2) of 0.52 with root mean square error of 0.049 m^3m^{-3}. This validation result for this two station SM-05 and SM-13 were the better compare to other stations. The validation result between L2_SM_P and 8 stations spatial average (which have almost complete data) resulted in a coefficient of determination R^2 0.46 and root mean square error 0.076 m^3m^{-3}, and with in-situ spatial average(all station with SMAP grid pixel and when data is available) with coefficient of determination R^2 0.38 with root mean squared error of 0.092 m^3m^{-3}. The validation resulted by comparing the retrieved with field spatial average an R^2 of 0.32 with root mean squared of 0.09 m^3m^{-3}. The matchup result indicates low R^2 and large root mean square and bias observed in the whole season. Twente monitoring stations missing a lot of data causes uncertainty for the validation of L2_SM_P soil moisture. The scale mismatch between the individual stations and L2_SM_P can be the reason to make uncertainty.

The error levels do not meet the SMAP L2_SM_P accuracy target of 0.04 m^3m^{-3}. The bias corrected L2_SM_P leads to decrease the root mean square error to 0.04 m^3m^{-3} using individual stations SM-05 and SM-13, and to 0.04 m^3m^{-3}.using spatial average of 8 station and field measurements.

8.2. Recommendations

- The spatial and temporal variability were observed by land cover , land use and soil type, a more detailed observation and analysis may necessary to evaluate if the variability is due to soil texture, land cover or topography.
- The soil moisture data from in-situ measurements resulted in uncertainty to the validation of L2_SM_P due to missing a lot of data. Therefore, the in-situ network soil moisture data need to check the collection of the data from the Twente network to use for validation of satellite and to determine long term soil moisture data.
- Further analyses are required in order to understand the case of to get lower validation result.

LIST OF REFERENCES

Akbar, R., & Moghaddam, M. (2015). A Combined Active – Passive Soil Moisture Estimation Algorithm With Adaptive Regularization in Support of SMAP. *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSINGS*, *53*(6), 3312–3324.

Allen, R. G. (1998). FAO Irrigation and Drainage Paper Crop by. *Irrigation and Drainage*, *300*(56), 300. doi:10.1016/j.eja.2010.12.001

Bosch, D. D., Lakshmi, V., Jackson, T. J., Choi, M., & Jacobs, J. M. (2006). Large scale measurements of soil moisture for validation of remotely sensed data: Georgia soil moisture experiment of 2003. *Journal of Hydrology*, *323*(1-4), 120–137. doi:10.1016/j.jhydrol.2005.08.024

Brocca, L., Melone, F., Moramarco, T., & Morbidelli, R. (2010). Spatial-temporal variability of soil moisture and its estimation across scales. *Water Resources Research*, *46*, 1–14. doi:10.1029/2009WR008016

Brocca, L., Tullo, T., Melone, F., Moramarco, T., & Morbidelli, R. (2012). Catchment scale soil moisture spatial–temporal variability. *Journal of Hydrology*, *422-423*, 63–75. doi:10.1016/j.jhydrol.2011.12.039

Cosh, M. H., Jackson, T. J., Bindlish, R., Famiglietti, J. S., & Ryu, D. (2005). Calibration of an impedance probe for estimation of surface soil water content over large regions. *Journal of Hydrology*, *311*(1-4), 49–58. doi:10.1016/j.jhydrol.2005.01.003

Cosh, M. H., Jackson, T. J., Bindlish, R., & Prueger, J. H. (2004). Watershed scale temporal and spatial stability of soil moisture and its role in validating satellite estimates. *Remote Sensing of Environment*, *92*(4), 427–435. doi:10.1016/j.rse.2004.02.016

Cosh, M. H., Jackson, T. J., Moran, S., & Bindlish, R. (2008). Temporal persistence and stability of surface soil moisture in a semi-arid watershed. *Remote Sensing of Environment*, *112*(2), 304–313. doi:10.1016/j.rse.2007.07.001

Crow, W. T., Berg, A. a, Cosh, M. H., Loew, A., Mohanty, B. P., Panciera, R., … Walker, J. P. (2014). Upscaling Sparse Ground-Based Soil Moisture Observations for the Validation of Coarse-Resolution Satellite Soil Moisture Products, (2011), 1–20. doi:10.1029/2011RG000372.1.INTRODUCTION

Das, N. N., Entekhabi, D., & Njoku, E. G. (2011). An Algorithm for Merging SMAP Radiometer and Radar Data for High Resolution Soil Moisture Retrieval. *IEEE Transactions on Geoscience and Remote Sensing*, *in press*(5), 1–9. Retrieved from http://smap.jpl.nasa.gov/files/publications/TGRS-2009-00901_Active_Passive_Algorithm.pdf

Das, N. N., Entekhabi, D., Njoku, E. G., Shi, J. J. C., Johnson, J. T., & Colliander, A. (2014). Tests of the SMAP combined radar and radiometer algorithm using airborne field campaign observations and simulated data. *IEEE Transactions on Geoscience and Remote Sensing*, *52*(4), 2018–2028. doi:10.1109/TGRS.2013.2257605

De Lannoy, G. J. M., Houser, P. R., Verhoest, N. E. C., Pauwels, V. R. N., & Gish, T. J. (2007). Upscaling of point soil moisture measurements to field averages at the OPE3 test site. *Journal of Hydrology*, *343*(1-2), 1–11. doi:10.1016/j.jhydrol.2007.06.004

Dellta-T Device Ltd. (1999). Theta Probe Soil M0isture Sensor Manual. Retrieved November 9, 2015, from delta-t.co.uk

Dente, L., Su, Z., & Wen, J. (2012). Validation of SMOS soil moisture products over the Maqu and Twente Regions. *Sensors (Switzerland)*, *12*(8), 9965–9986. doi:10.3390/s120809965

Dente, L., Vekerdy, Z., Su, Z., & Ucer, M. (2011). *Soil Moisture and Soil Temperature Monitoring Network*. University of Twente Faculty of Geo-Information Science and Earth Observation (ITC).

Dobson, M., Ulaby, F., Hallikainen, M., & El-rayes, M. (1985). Microwave Dielectric Behavior of Wet Soil-Part II: Dielectric Mixing Models. *IEEE Transactions on Geoscience and Remote Sensing*, *GE-23*(1), 35–46. doi:10.1109/TGRS.1985.289498

Engman, E. T. (1991). Applications of microwave remote sensing of soil moisture for water resources and agriculture. *Remote Sensing of Environment*, *35*(2-3), 213–226. doi:10.1016/0034-4257(91)90013-V

Entekhabi, B. D., Njoku, E. G., Neill, P. E. O., Kellogg, K. H., Crow, W. T., Edelstein, W. N., … Zyl, J. Van. (2015). *The SoilMoistureActive Passive (SMAP) Mission* (Vol. 98).

Entekhabi, D., Das, N., Njoku, E., Yueh, S., Johnson, J., & Shi, J. (2014). Algorithm Theoretical Basis Document L2 & L3 Radar/Radiometer Soil Moisture (Active/Passive) Data Products. Retrieved August 16, 2015, from http://smap.jpl.nasa.gov/documents/

Entin, J. K., Robock, A., Vinnikov, K. Y., Hollinger, S. E., Liu, S., & Namkhai, a. (2000). Temporal and spatial scales of observed soil moisture variations in the extratropics. *Journal of Geophysical Research*, *105*(D9), 11865. doi:10.1029/2000JD900051

Famiglietti, J. S., Devereaux, J. a., Laymon, C. a., Tsegaye, T., Houser, P. R., Jackson, T. J., … Van Oevelen, P. J. (1999). Ground-based investigation of soil moisture variability within remote sensing footprints during the Southern Great Plains 1997 (SGP97) Hydrology Experiment. *Water Resources Research*, *35*(6), 1839–1851. doi:10.1029/1999WR900047

Forman, B. a, Reichle, R. H., & Derksen, C. (2014). Estimating Passive Microwave Brightness Temperature Over Snow-Covered Land in North America Using a Land Surface Model and an Artificial Neural Network. *Geoscience and Remote Sensing, IEEE Transactions on*, *52*(1), 235–248. doi:10.1109/TGRS.2013.2237913

Gaskin, G. J., & Miller, J. D. (1996). Measurement of Soil Water Content Using a Simplified Impedance Measuring Technique. *Journal of Agricultural Engineering Research*, *63*, 153–159. doi:10.1006/jaer.1996.0017

Jacobs, J. M., Mohanty, B. P., Hsu, E. C., & Miller, D. (2004a). SMEX02: Field scale variability, time stability and similarity of soil moisture. *Remote Sensing of Environment*, *92*, 436–446. doi:10.1016/j.rse.2004.02.017

Jacobs, J. M., Mohanty, B. P., Hsu, E. C., & Miller, D. (2004b). SMEX02: Field scale variability, time stability and similarity of soil moisture. *Remote Sensing of Environment*, *92*(4), 436–446. doi:10.1016/j.rse.2004.02.017

Kaleita, A. L., Heitman, J. L., & Logsdon, S. D. (2005). Field calibration of the Theta Probe for Des Moines lobe soils. *Applied Engineering in Agriculture*, *21*(5), 865–870.

Kim, C. P., Stricker, J. N. M., & Feddes, R. A. (1997). Impact of soil heterogeneity on the water budget of the unsaturated zone. *Water Resources Research*, *33*(5), 991–999. doi:10.1029/97WR00364

Kinzli, K.-D., Manana, N., & Oad, R. (2012). Comparsion of laboratory and field calibration of a soil-moisture capacitance probe for various soils.

Kornelsen, K. C., & Coulibaly, P. (2013). Advances in soil moisture retrieval from synthetic aperture radar and hydrological applications. *Journal of Hydrology*, *476*, 460–489. doi:10.1016/j.jhydrol.2012.10.044

Kornelsen, K. C., & Coulibaly, P. (2015). Design of an Optimal Soil Moisture Monitoring Network Using SMOS Retrieved Soil Moisture. *IEEE Transactions on Geoscience and Remote Sensing*, *53*(7), 3950–3959. doi:10.1109/TGRS.2014.2388451

Lakhankar, T., Krakauer, N., & Khanbilvardi, R. (2009). Applications of microwave remote sensing of soil moisture for agricultural applications. *International Journal of Terraspace Science and Engineering*, *2*(1), 81–91.

Mohanty, B. ., & Skaggs, T. . (2001). Spatio-temporal evolution and time-stable characteristics of soil moisture within remote sensing footprints with varying soil, slope, and vegetation. *Advances in Water Resources*, *24*(9-10), 1051–1067. doi:10.1016/S0309-1708(01)00034-3

NASA. (2015). NASA Soil Moisture Radar Ends Operations, Mission Science Continues. Retrieved September 3, 2015, from http://smap.jpl.nasa.gov/news/1247/

Njoku, E. G., Jackson, T. J., Lakshmi, V., Chan, T. K., & Nghiem, S. V. (2003). Soil moisture retrieval from AMSR-E. *IEEE Transactions on Geoscience and Remote Sensing*, *41*(2 PART 1), 215–228. doi:10.1109/TGRS.2002.808243

O'Neill, P. E., Chan, S., Njoku, E., Jackson, T., & Bindlish, R. (2014). Soil Moisture Active Passive (SMAP) Algorithm Theoretical Basis Document SMAP Level 2 & 3 Soil Moisture (Passive) Data Products. Retrieved September 12, 2015, from http://smap.jpl.nasa.gov/documents/

Panciera, R. (2009). *Effect of Land Surface Heterogeneity on Satellite Near- Surface Soil Moisture Observations*. University Of Melbourne,Australia.

Panciera, R., Walker, J. P., Jackson, T. J., Gray, D. A., Tanase, M. A., Ryu, D., … Hacker, J. M. (2014). The Soil Moisture Active Passive Experiments (SMAPEx): Toward Soil Moisture Retrieval From the SMAP Mission. *IEEE Transactions on Geoscience and Remote Sensing*, *52*(1), 490–507. doi:10.1109/TGRS.2013.2241774

Sabaghy, S. (2013). Soil moisture retrieval from combined Active / Passive Microwave Observations over the Regge and Dinkel Soil moisture retrieval from combined Active / Passive Microwave Observations over the Regge and Dinkel.

Sahoo, A. K., Zhan, X., Arsenault, K., & Kafatos, M. (2005). Cross-validation of soil moisture data from AMSR-E using field observations and NASA's land data assimilation system simulations. Retrieved from https://www.researchgate.net/publication/238675503_Cross-validation_of_soil_moisture_data_from_AMSR-E_using_field_observations_and_NASA's_land_data_assimilation_system_simulations

Salama, M. S., Van Der Velde, R., Van Der Woerd, H. J., Kromkamp, J. C., Philippart, C. J. M., Joseph, a. T., … Su, Z. (2012). Technical Note: Calibration and validation of geophysical observation models. *Biogeosciences*, *9*(6), 2195–2201. doi:10.5194/bg-9-2195-2012

Scipal, K., Drusch, M., & Wagner, W. (2008). Assimilation of a ERS scatterometer derived soil moisture index in the ECMWF numerical weather prediction system. *Advances in Water Resources*, *31*(8), 1101–1112. doi:10.1016/j.advwatres.2008.04.013

Vachaud, G., Passerat De Silans, A., Balabanis, P., & Vauclin, M. (1985). Temporal Stability of Spatially Measured Soil Water Probability Density Function1. *Soil Science Society of America Journal*, *49*(4), 822. doi:10.2136/sssaj1985.03615995004900040006x

Velde, R. Van Der, Salama, M. S., Eweys, O. A., Wen, J., & Wang, Q. (2014). Active / Passive Microwave Observations Over the East of the Netherlands. *IEEE Journal of Selected Topics in Applied Eath Observation and Remotesensing*, 1–18.

Vereecken, H., Huisman, J. A., Pachepsky, Y., Montzka, C., van der Kruk, J., Bogena, H., … Vanderborght, J. (2014). On the spatio-temporal dynamics of soil moisture at the field scale. *Journal of Hydrology*, *516*, 76–96. doi:10.1016/j.jhydrol.2013.11.061

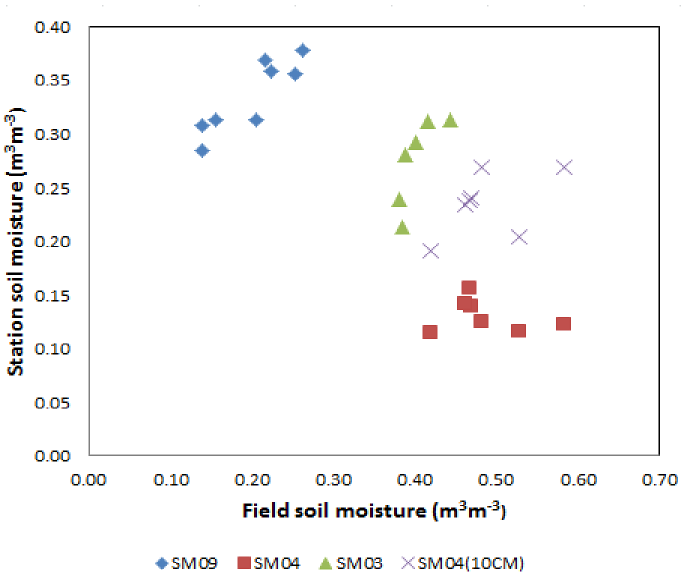
Walker, J. P., Houser, P. R., & Willgoose, G. R. (2004). Active microwave remote sensing for soil moisture measurement: a field evaluation using ERS-2. *Hydrological Processes*, *18*(11), 1975–1997. doi:10.1002/hyp.1343

Wang, L., & Qu, J. J. (2009). Satellite remote sensing applications for surface soil moisture monitoring: A review. *Frontiers of Earth Science in China*, *3*(2), 237–247. doi:10.1007/s11707-009-0023-7

Wilson, D. J., Western, A. W., & Grayson, R. B. (2004). Identifying and quantifying sources of variability in temporal and spatial soil moisture observations. *Water Resources Research*, *40*(2), n/a–n/a. doi:10.1029/2003WR002306

APPENDICES

Appendix 1: Scatter plot between each stations and the field work data.



Appendix: Example of sampling strategy in some of the selected fields

Appendix 3: Example of selected fields for soil moisture measurement

Appendix 4: Mean, standard deviation and Coefficient variation of soil moisture measurement for each fields

		SM-08		SM-09		SM-05		SM-07			SM-04		SM-03	
	SPATIAL	mean(field1)	Mean(field2)	Mean(Field1)	Mean(field2)	Mean(field1)	Mean(field2)	Mean(Field1)	Mean(field2)	Mean(field3)	Mean(field1)	Mean(field2)	Mean(field1)	Mean(field2)
11-09-15	0.275	0.173	0.222	0.155	0.183	0.409	0.269	0.400	0.316	0.201	0.420			
17-09-15	0.323	0.218	0.292	0.262	0.254	0.400	0.352	0.366	0.287	0.271	0.529			
24-09-15	0.343	0.220		0.217	0.232	0.413		0.446	0.350	0.285	0.583			
25-09-15	0.349			0.253	0.268			0.376	0.313	0.267	0.482	0.398	0.400	0.385
30-09-15	0.292			0.138	0.143					0.186	0.469	0.358	0.380	0.366
02-10-15	0.287			0.138	0.146			0.247		0.201	0.463	0.349	0.384	0.369
10-10-15	0.314	0.210	0.278	0.206	0.213					0.317	0.467	0.367	0.389	0.375
20-10-15	0.322	0.224	0.311	0.223	0.227			0.335	0.325	0.287		0.412	0.444	0.433
23-10-15	0.304	0.208	0.284	0.217	0.221			0.344	0.289	0.278		0.386	0.416	0.400
29-10-15	0.290	0.162	0.283	0.169	0.182			0.274	0.276	0.231	0.467	0.354	0.402	0.389
03-11-15	0.297	0.169	0.300	0.174	0.166			0.289	0.256	0.262	0.446	0.368	0.417	0.422
		-0.370	-0.194	-0.437	-0.334	0.490	-0.021	0.456	0.149	-0.269	0.529			

SM-08		SM-09		SM-05		SM-07			SM-04		SM-03
STD(Field1	STD(Field2)	STD(Field1)	STD(Field2)	STD(Field	STD(Field3)	STD(FIELD1)	STD(Field2)	STD(Field)3	STD(Field1)	STD(Field2)	STD(Field1)
0.028	0.038	0.020	0.024	0.048	0.024	0.037	0.062	0.036	0.083		
0.039	0.040	0.022	0.036	0.035	0.029	0.070	0.056	0.041	0.041		
0.043		0.021	0.021			0.066	0.058	0.047	0.060		
		0.028	0.026			0.078	0.053	0.041	0.055	0.080	0.054
		0.014	0.015					0.026	0.054	0.088	0.045
		0.016	0.018			0.075		0.031	0.053	0.088	0.047
0.031	0.075	0.018	0.022					0.090	0.047	0.071	0.035
0.033	0.071	0.014	0.020			0.052	0.074	0.039		0.075	0.020
0.023	0.051	0.017	0.023			0.065	0.068	0.042		0.079	0.038
0.028	0.102	0.020	0.023			0.071	0.066	0.036	0.048	0.078	0.036
0.031	0.086	0.018	0.012			0.062	0.059	0.029	0.044	0.074	0.049

SM-08		SM-09		SM-05		SM-07			SM-04		SM-03		
CV(Field1)	CV(Field2)	CV(Field1)	CV(Field2)	CV(Field2	CV(Field3)	CV(FIELD1)	CV(Field2)	CV(Field)3	CV(Field1)	CV(Field2)	CV(Field1)	CV(Field2)	CV local
0.159	0.173	0.130	0.133	0.116	0.088	0.093	0.195	0.180	0.198				0.147
0.177	0.138	0.082	0.141	0.089	0.081	0.193	0.196	0.152	0.078				0.133
0.197		0.096	0.090	0.000		0.148	0.165	0.164	0.102				0.120
		0.111	0.096			0.207	0.170	0.152	0.114	0.200	0.136	0.085	0.141
		0.105	0.103					0.141	0.115	0.246	0.118	0.105	0.133
		0.118	0.125			0.305		0.157	0.114	0.251	0.123	0.112	0.163
0.146	0.270	0.088	0.105					0.284	0.100	0.194	0.090	0.090	0.152
0.146	0.228	0.065	0.090			0.156	0.227	0.136		0.181	0.044	0.075	0.135
0.111	0.180	0.079	0.105			0.190	0.237	0.152		0.203	0.090	0.140	0.149
0.173	0.362	0.118	0.126			0.257	0.239	0.154	0.103	0.221	0.089	0.076	0.174
0.185	0.287	0.105	0.071			0.213	0.230	0.112	0.095	0.201	0.117	0.096	0.156