# Soil moisture temporal stability and its application in remote sensing products validation

## Using the example of Maqu (China) and Twente (the Netherlands)

Wu Jiexia

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by

Wu Jiexia

Thesis submitted to the International Institute for Geo-information Science and Earth Observation in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation, Specialisation: surface Hydrology

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给亲爱的爸爸妈妈和奶奶

# Abstract

Surface soil moisture plays a key role in hydrology, climate and agriculture; however the conventional in-situ point measurements are not appropriate to represent areal soil moisture in long term, due to high spatial and temporal variability. Remote sensing for example Advanced Microwave Scanning Radiometer (AMSR-E) can give soil moisture information of the surface layer at large scales throughout a long period, however the validation of these products is very critical, because of scale "jump" problem between in situ measurements and remote sensing products.

In this study, soil moisture measurements from two networks, one in Twente (the Netherlands) consisting of 17 stations with available data during study period (from 1$^{st}$ April to 15$^{th}$ November), and the other in Maqu (China) consisting of 20 stations from 30$^{th}$ June 2008 to 12$^{th}$ May 2009 were used to do upscaling for AMSR-E soil moisture products validation.

First, the representativity of stations installed under grassland in the Twente region with heterogeneous land cover types was tested by a 5 days' fieldwork with intensive sampling at 8 stations during September and October 2009.All but 2(station st11 and station st17) stations were proved to be representative. At footprint scale, soil moisture based on stations in this region can represent this region.

Geostatistical interpolation and temporal stability analysis were both to estimate soil moisture spatial distribution. Geostatistical interpolation cannot used in this study due to short soil moisture spatial correlation lengths (<250m) obtained by variogram analysis and big errors caused by interpolation While after applying temporal stability analysis for long term and for different seasons. Representative stations nst13, cst2 and st03, st15 in Maqu and Twente were identified. Correlations between different stations support the results.

Point measurements based on representative station were upscaled to areal soil moisture, by using absolute differences, linear regression and higher order regression, the results was evaluated by RMSE, BIAS, R.

The best upscaling algorithms were applied to validate AMSR-E soil moisture products by using R and RMSE for evaluation. In the Maqu region, at descending time high correlation of 0.73 and low RMSE 4.21%(vol /vol) were observed while quite low correlation and big RMSE 0.003 and 12.53%(vol /vol) for ascending. In the Twente region, correlation at descending time was high about 0.7, while RMSE is  10.18 % (vol/vol), for ascending mode , correlation was also high 0.67, but RMSE was big about 16.32% (vol /vol).

# Acknowledgements

I would like to express my gratitude to all the friends I met in ITC during the past 18 months. It is an unforgettable experience to study and live with a group of professional people with diverse backgrounds.

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I would like to thank people who supported me during fieldwork, my classmate also one of my best friends in WREM Ofwono Matthew, he helped me to do field work when he was also busy with his Msc research, and also the farmers who allowed us to take measurements in their fields.
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I also appreciate the support of Prof. Dr. Wen Jun for the Maqu data, and the team of CAREERI (Cold and Arid Regions Environmental and Engineering Research Institute, Lanzhou, China) who worked on the installation and the maintenance of the Maqu network. And also I would like to express my thanks to Dr. Wu Huanping in China Meteorological Administration (CMA), provided me the meteorology data in Maqu.

Last but not least, I deeply appreciate the contribution to this thesis made in various ways by staffs in WREM Department who gave the basic knowledge of remote sensing, GIS and hydrology, and my friends and colleagues, who I spent most of my life with in ITC, thank you for making my life colourful and

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# 1. Introduction

Soil moisture plays a key role in hydrology, weather and agriculture. It influences the amount of surface runoff, and is an important medium of chemical and physical processes in the soil. It is used in many coupled hydrology-climate models at regional or even global scale. Soil moisture is an influential predictor for agricultural drought extent and floods. Water content in the soil is a significant factor for plant growth. Information about it helps to schedule irrigation.

Due to the applications mentioned above, time series of soil moisture content from field to continental scale is required. The most accurate in-situ measurement method is based on sampling that can be considered as point data. Spatial variability of soil moisture is caused by many variables such as topography, soil texture, and land cover so in most cases it is difficult to characterize it with a finite number of in-situ measurements. Furthermore, these discrete measurements are time-consuming, so this method is not practical for long term monitoring.

Active and passive microwave satellite sensors such as the Advanced Scatterometer, ASCAT(Bartalis et al. 2007), Advanced Microwave Scanning Radiometer, AMSR-E(Njoku et al. 2003), and SMOS (ESA's Soil Moisture and Ocean Salinity) can give soil moisture information of the surface layer at large scales throughout a long period. However the validation of these products is very critical(Prigent et al. 2005). For validation, a coarse-scale areal mean is required based on the in situ measurements, since there is a scale “jump” problem, between the satellite data, such as AMSR-E and ASCAT (>30km) and point measurements (Cosh et al. 2004).

## 1.1. Problem definition

The present work focuses on the following problems:

- Scale mismatch makes validation of remote sensing based on soil moisture data by point measurements difficult.
- Land cover, soil properties, heterogeneous precipitation and topography causes a spatial variability of the soil moisture, which poses uncertainties in the representativity of in situ measurements for large areas.

- Spatial soil moisture distribution may change over time because of the influence of weather and land cover.

## 1.2. Literature review

Upscaling means transferring information from small scale to large scale and typically includes two steps: distributing and aggregating (Bloschl et al. 1995). This concept has been widely used to estimate hydrological parameters for the purpose of modeling and validation. The spatial soil moisture variability is influenced by different variables such as topography, soil texture, land cover, precipitation, porosity, soil temperature, and organic matter, and can be represented by a stochastic framework. Point measurements have to be distributed over an area to visualize spatial distribution, then modeling and geostatistical algorithms can be used to aggregate the distributed information to one value. In this study geostatistical algorithms are used for estimation.

### 1.2.1. Geostatistical interpolation

Geostatistical analysis is usually applied to get information about a variable's spatial distribution information with tools such as semivariogram and kriging (Burgess et al. 1980; Nancy F. Glenn 2003; Bi et al. 2009), spline interpolation (Baxter 2004), moving polynomials, etc. For large area, (Bloschl et al. 1995)demonstrate that if the stations are too far away to make a reliable estimation, a covariate which has a more clear spatial distribution can be used.
However, since interpolation for soil moisture with high spatial variability requires a dense network sampling network (Chen et al. 1995), as was also proved by (Bi et al. 2009) who analyzed the spatial variability of soil moisture in a 400 $m^2$ area with 313 samples pointed out that at a small scaled area with uniform vegetation, soil type and climate condition, geo statistical interpolation can be applied to estimate spatial distribution of soil moisture. However it is costly in labour and finance to apply this method in large-scale soil moisture analysis.

### 1.2.2. Temporal stability analysis

To limit sample size while save the major soil moisture information, (Vachaud et al. 1985) tested time stability in a 2000 $m^2$ area in Grenoble, France, and introduced this method, which is built on the idea that although soil moisture is changing the spatial distribution which presented by locational differences of soil moisture is constant, and the rank of water content for each point is also constant in cumulative density function. If a stable spatial distribution can be identified, statistical variables such as mean, standard deviation can be related to some points in space. Then it was reasonable to use one or more points which have the minimum bias and variability from the spatial average value compared to other points, to predict soil moisture in a certain area. In their research this idea had be proved by experiment, and they thought that soil structure is the main factor that influences soil moisture level.

From then on the feasibility of this method had been examined by many scientists. However there are many problems to be solved before this method is probably used. How to identify the relative point that can present the statistical variable efficiently? Are there any spatial and temporal limitations for this stability? Which factor contributes to this stability?

- **Scale effects**

(Grayson et al. 1998) examined the area ranging from 0.1 to 27 $km^2$ and demonstrated that spatial scales should be considered for temporal stability analysis. (X.Xin. et al. 2008) tested soil moisture temporal stability within two scales ($32km^2$ and $0.05km^2$) and found that it was possible to find such stability on both of the scales, but better results got from the smaller one. On the other hand, they pointed out that irrigation affects temporal stability a lot. To heal the gaps between point measurements and remote sensing products, (Cosh et al. 2004) examined how temporal stability analysis works on an watershed scale about $100km^2$ during two months and good temporal stability was observed within uniform precipitation events. When precipitation cannot cover the whole study area, the spatial distribution changed.

- **Land cover effects**

(Cosh et al. 2005) test soil moisture temporal stability on grassland only, and suggested that the stability should be identified for diverse vegetation seasonally. (Bosch et al. 2006) conducted an experiment at South Central Georgia of the US, where the areas was combined by forest, cotton, peanut and pasture, and they found that soil moisture under different land covers followed a similar trend, and temporal stability can be found at this region.

- **Topography effects**

(Cosh et al. 2005) made his experiment in a rolling area and demonstrate that it is not a significant effect on temporal stability distribution. While a different conclusion has be drawn by (Jacobs et al. 2004) after analyzing the landscape position with soil moisture time stability. He suggested that the most stable sites can be found in mild slopes especially when combined with moderate to moderately high clay content. (Mohanty et al. 2001) examined spatial and temporal variability and temporal stability of soil moisture with different land covers and terrain on southern Great Plains near Oklahoma. They demonstrated that largest spatio-temporal variability and lowest temporal stability was shown on flat topography especially with split wheat and grass fields.

Based on the publications above, geostatistical interpolation is quite sensitive to scale effects and sample density, while temporal stability analysis has less limitation with sample size, but scale, vegetation and topography have considerable contributes to temporal variability of soil moisture. Therefore these effects should be taken into account when applying upscaling methods.

## 1.3. Research objectives

### 1.3.1. General objective

Investigate the temporal stability and the spatial distribution of soil moisture in a humid (Twente, the Netherlands) and cold (Maqu, China) environment. Use the result for upscaling field observations for the validation of coarse resolution AMSR-E soil moisture products.

### 1.3.2. Specific objectives

- Examine representativity of the 17 stations in Twente region
- Estimate the spatial distribution of soil moisture in two large areas (Twente, Maqu) based on in situ measurements;
- Evaluate seasonal changes of spatial soil moisture distribution;
- Identify one or more stations which can represent the whole area.
- Find an appropriate method to characterize the soil moisture dynamics of the whole area based on point measurements;
- Use upscaled soil moisture to validate remote sensing products

## 1.4. Research questions

- Are the 17 stations in Twente network are representative of the whole study area?
- Can the spatial distribution of soil moisture be mapped in detail with the existing observations at the two study areas?
- Does the spatial distribution of soil moisture change significantly during the study period?
- Whether it is possible to identify the representative stations?
- Which algorithm can be used to well estimate the soil moisture dynamics of the selected study areas?
- Is it possible to validate AMSR-E using the upscaled soil moisture obtained from field measurements?

## 1.5. Hypothesis

- The 17 stations in Twente network are representative of the whole area;
- With the stations in two networks it is possible to characterize the spatial dynamics of soil moisture in each study area;
- A stable spatial soil moisture distribution can be obtained by field measurements under certain conditions;

- Representative stations can be identified;
- There is a suitable algorithms used for aggregating the soil moisture measurements;
- The upscaling result can be used for AMSR-E soil moisture validation.

## 1.6. Thesis outlines

This thesis contains 5 chapters and the out lines are as follows:
Chapter1 is a brief introduction to present the background, objectives of the study. Chapter 2 describes study areas, data availability and field work. Chapter 3 introduces the methods use in this study. First, representativity of soil moisture measured by stations in Twente network at station scale and footprint scale were tested by statistical indicators. Then, the application of both geostatistical interpolation and temporal stability analysis on identifying soil moisture spatial distribution are examined. After that temporal stability is applied again to analyze seasonal change of spatial distribution. Later, results of upcaling algorithms are compared and applied to validate the AMSR-E products. Chapter 4 shows the results and discussion of the analysis. Conclusion and recommendation are presented in chapter 5.

# 2. Study area and fieldwork

In this chapter, the two study areas are briefly introduced, including location, topography, climate land cover types and soil properties. Then fieldwork in Twente region to obtain intensive soil moisture measurements is presented.

## 2.1. Description of networks at study areas

In this study, two areas, Twente (the Netherlands), Maqu (China) are selected to validate AMSR-E soil moisture products. Because these two regions have different land cover types, climate conditions, soil properties and topography, and these effects were identified to influence surface soil moisture levels and also soil moisture spatial distribution. In both regions, a network was installed. Details of the two networks are presented in 2.1.1 and 2.1.2.

### 2.1.1. Twente region

The Twente region is located in the eastern part of the Netherlands Figure 2-1 covering an area of 50km by 35 km. The Twente network has been installed by L. Dente in the frame of her PhD research program "Retrieval of soil moisture at global scale from satellite data acquired by passive and active microwave sensors". 20 stations with ECH2O EC-TM Probes installed to collect soil moisture data every 15 minutes. 19 stations out of 20 were installed under grassland while the other one was in forest. Most of the probes took measurements since April 2009. The study period is from 1$^{st}$ April 2009 to 15$^{th}$ November 2009. Because of the problems of probes (st4, st19) and limitation of data availability (st20) during study period, soil moisture at 17 stations, which all installed under grassland were used in this study. Soil moisture data collected by Twente networks, calibrated and pre-processed, have been delivered by L. Dente and used in this study.

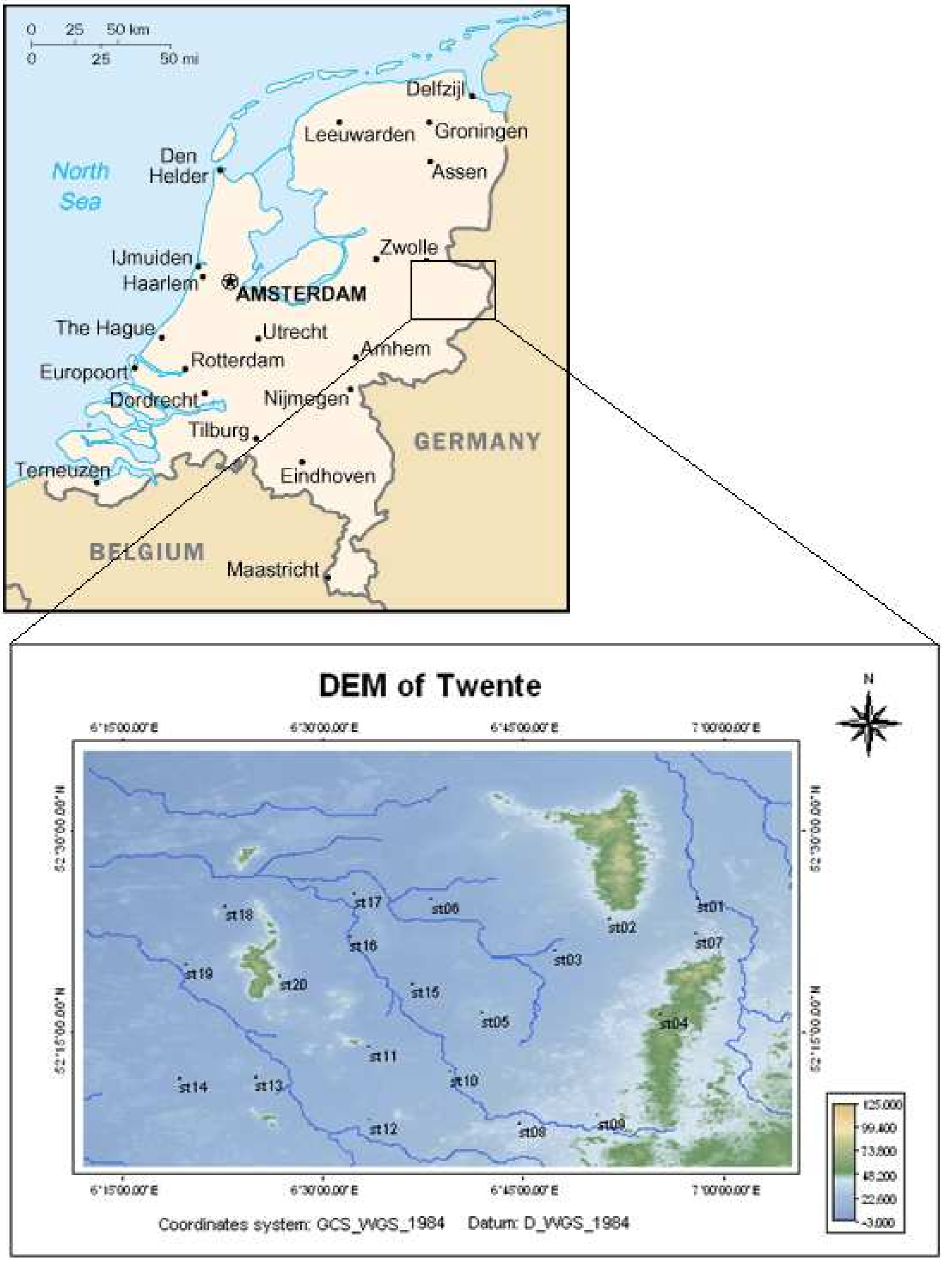



**Figure 2-1 Location and DEM of Twente region**

#### 2.1.1.1. Topography

The Twente region is flat. Figure 2-1 shows the DEM and with the most important drainage of this region, based on SRTM 90 using hydro processing tools in Ilwis. Table 2-1 gives the information of altitude and slope of each station installed in this region as extracted from the DEM.

**Table 2-1 Topography of stations in the Twente region**

| Station ID | Altitude (m) | Slope degree | Slope percentage |
|---|---|---|---|
| ST-01 | 22 | 1 | 1.89 |

| | | | |
|---|---|---|---|
| ST-02 | 29 | 0.6 | 1 |
| ST-03 | 12 | 0 | 0.0 |
| ST-04 | 49 | 1 | 1.7 |
| ST-05 | 19 | 1.1 | 1.4 |
| ST-06 | 9 | 1.1 | 2.0 |
| ST-07 | 23 | 0.8 | 1.4 |
| ST-08 | 33 | 2.8 | 4.9 |
| ST-09 | 35 | 0.5 | 0.9 |
| ST-10 | 17 | 0.4 | 0.7 |
| ST-11 | 12 | 0.2 | 0.3 |
| ST-12 | 14 | 0 | 0.0 |
| ST-13 | 11 | 0.1 | 0.1 |
| ST-14 | 10 | 0 | 0.0 |
| ST-15 | 11 | 0.4 | 0.7 |
| ST-16 | 9 | 0.3 | 0.6 |
| ST-17 | 10 | 0.5 | 1 |
| ST-18 | 7 | 0.3 | 0.7 |
| ST-19 | 9 | 0.5 | 0.9 |
| ST-20 | 33 | 0.8 | 1.4 |

#### 2.1.1.2. Climate

The Twente region has a mean temperature of about 17℃ in the summer and 2℃ in the winter. Precipitation is homogenously distributed throughout the year and it is, on average, about 760 mm. In this region, 12 rain gauges of KNMI are recording daily precipitation and the data are available online (http://www.knmi.nl/klimatologie/monv/reeksen/).

Figure 2-2 describes average temperature and precipitation condition of this region in 2009. The x- axis is different months and left y-axis is precipitation presented in mm, and right y-axis ix temperature in ℃. The precipitation data was calculated based on 12 rain gauges and weighed by Thiessen polygon method. During study period, April was the driest month with precipitation less than 25 mm and more than 125 mm was recorded in July. Temperature of the whole year ranged from 0 ℃ in winter to 20℃ in summer.

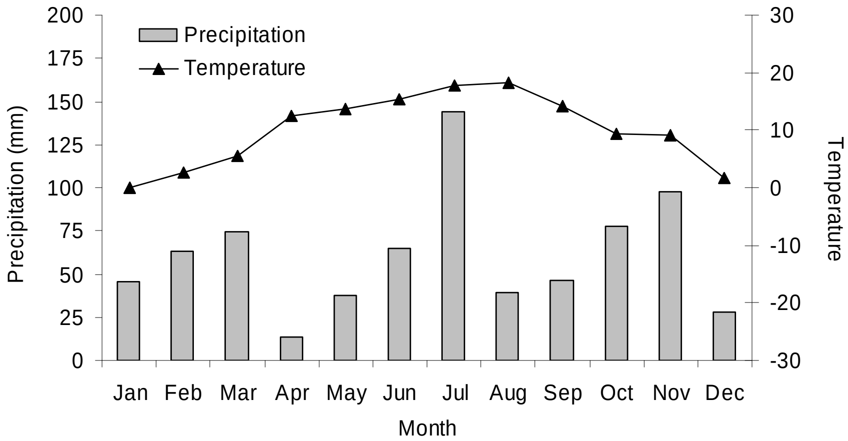



**Figure 2-2 Monthly averaged precipitation and temperature in Twente**

### 2.1.1.3. Land cover

Land cover in Twente region is quite heterogeneous with grassland, corn, forest, bare land and urban area. Figure 2-3 is the land map based on NDVI with pixel size 250m downloaded from (http://rapidfire.sci.gsfc.nasa.gov/subsets/) on 21st September 2009. From this map it is difficult to point out different land cover types the reason may be because the resolution is low and NDVI of different land covers were mixed within one pixel. In Figure2-4, typical land cover types were shown.

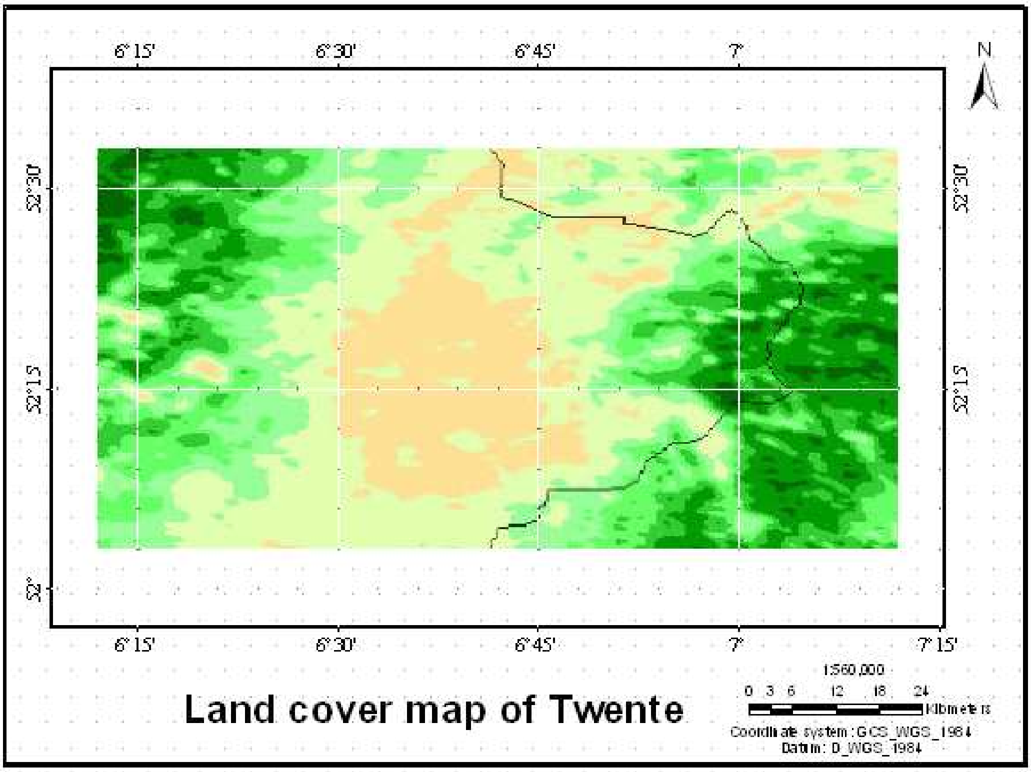



**Figure 2-3 Land cover map of Maqu region**


**Figure 2-4 Typical land cover types in Twente region, Corn fields and grassland(a), forest(b), bare land(c)**

#### 2.1.1.4. Soil properties

The soil properties of stations on top layer in Twente network are listed in Table 2-2. The procedures of measurements are presented in Appendix-1. The measurements were taken in ITC laboratory. Soil properties of st1 are not in the list because of no data. On top layer, very high sand content about 90% was experienced at this region. Organic content at this region was varies from about 2% to 7% at most stations. Station st16 has the highest content, about 10%.

**Table 2-2 Soil properties of stations in Twente region**

| Station ID | Sand (%) | Silt (%) | Clay (%) | Organic matter (%) | Soil texture |
|---|---|---|---|---|---|
| st2 | 86.9 | 9.3 | 3.8 | 5.2 | sand |
| st3 | 80.1 | 9.4 | 10.5 | 4.9 | loamy sand |
| st4 | 82.3 | 12.9 | 4.8 | 3.3 | loamy sand |
| st5 | 85.1 | 9.2 | 5.8 | 7.4 | loamy sand |
| st6 | 88.7 | 8.6 | 2.7 | 5.8 | sand |
| st7 | 84.7 | 7.8 | 7.5 | 2.4 | loamy sand |
| st8 | 95.0 | 3.2 | 1.8 | 6.9 | sand |
| st9 | 88.4 | 8.6 | 3.0 | 4.6 | sand |
| st10 | 88.4 | 9.9 | 1.6 | 4.1 | sand |
| st11 | 85.5 | 11.0 | 3.5 | 5.2 | loamy sand |
| st12 | 90.8 | 6.1 | 3.1 | 2.0 | sand |
| st13 | 89.9 | 7.2 | 2.9 | 7.0 | sand |
| st14 | 73.1 | 19.0 | 7.9 | 3.6 | loamy sand |
| st15 | 90.8 | 9.2 | 0.0 | 5.1 | sand |
| st16 | 83.9 | 16.1 | 0.0 | 10.4 | sand |
| st17 | 94.8 | 3.9 | 1.2 | 1.9 | sand |
| st18 | 83.9 | 13.8 | 2.3 | 2.2 | loamy sand |
| st19 | 88.4 | 10.2 | 1.4 | 4.3 | sand |
| st20 | 98.2 | 1.8 | 0.0 | 4.4 | sand |

### 2.1.2. Maqu region

The Maqu region is located at the first meander of the Yellow River in southeast of Maqu city, Gansu Province in China. The Yellow River, and its tributaries, the black river and the Lang River pass through this region figure 2-5. It covers about 80 km by 45 km. The Maqu network has been installed by L. Dente, Z. Vekerdy and the CAREERI-CAS institute in the frame of the research program “Retrieval of soil moisture at global scale from satellite data acquired by passive and active microwave sensors” and the CEOP-AEGIS project. 20 stations with ECH2O EC-TM Probes installed to collect soil moisture data every 15 minutes. Soil moisture data at 5 stations (cst1-cst5) were available since May 2008, and 15 stations (nst1-nst15)were installed in June 2008. In this region, study period is from 30th June 2008 to 12 May 2009. The data collected by Maqu network, calibrated and pre-processed, have been delivered by L. Dente and used in this study.

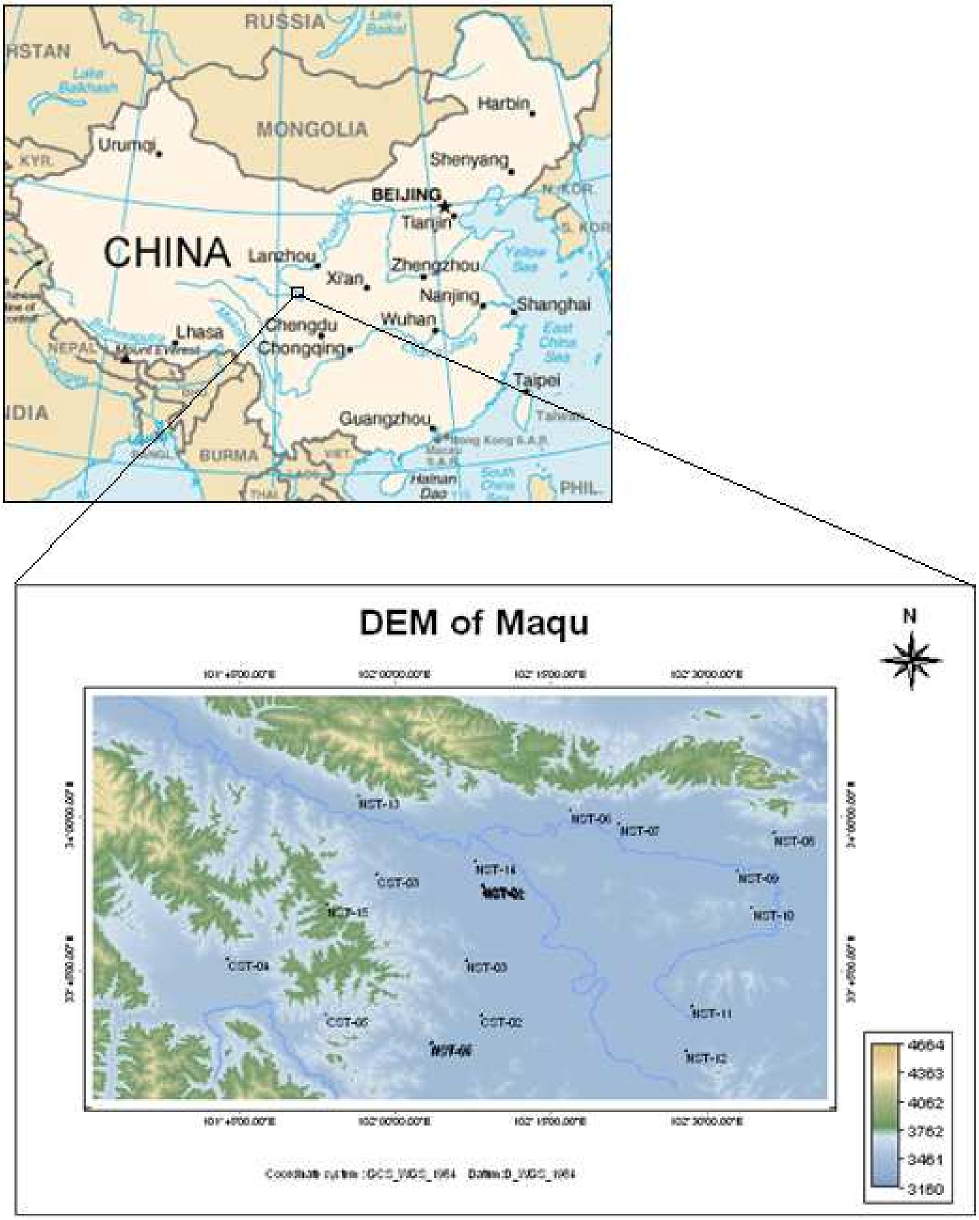



**Figure 2-5 Location and DEM of Maqu region**

## 2.1.2.1. Topography

Topography at the eastern and central part of the Maqu region is rolling or flat with an average elevation of 3100 m a.m.s.l., whilst the terrain is mountainous in the west with peaks up to 4664m. The DEM and drainage map (Figure 2-4) of this region was based on SRTM 90 using the hydro processing tool in Ilwis.

**Table 2-3 Topography in Maqu region**

| Station ID | Landscape | Altitude | Slope degree | Slope percentage | Slope aspect |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| NST-01 | river_valley | 3430 | 0.5 | 0.9 | E |
| NST-02 | river_valley | 3434 | 2 | 3.4 | NE |
| NST-03 | hill_slope | 3513 | 3.0 | 5.3 | E |
| NST-04 | river_valley | 3447 | 1.8 | 3.1 | NE |
| NST-05 | hill_slope | 3476 | 6.7 | 11.8 | S |
| NST-06 | river_valley | 3428 | 3.0 | 5.2 | E |
| NST-07 | river_valley | 3429 | 4.0 | 7.1 | NE |
| NST-08 | valley | 3473 | 2.3 | 4.2 | SE |
| NST-09 | river_valley | 3433 | 2.0 | 3.5 | NW |
| NST-10 | hill_slope | 3511 | 10.5 | 18.5 | W |
| NST-11 | river_valley | 3442 | 1.3 | 2.3 | S |
| NST-12 | river_valley | 3440 | 0.9 | 1.8 | SE |
| NST-13 | valley | 3519 | 3.3 | 5.7 | S |
| NST-14 | river_valley | 3432 | 1.4 | 2.6 | NE |
| NST-15 | hill_slope | 3751 | 18.1 | 32.8 | NE |
| CST-01 | river_valley | 3431 | 2.0 | 3.6 | SW |
| CST-02 | river_valley | 3449 | 1.5 | 2.6 | W |
| CST-03 | hill_valley | 3507 | 0.8 | 1.4 | S |
| CST-04 | hill_valley | 3504 | 2.6 | 4.7 | S |
| CST-05 | hill_valley | 3542 | 0.4 | 0.8 | S |

#### 2.1.2.2. Climate

In Maqu, summer is wet while winter is cold and dry. Only one station is located near the study area. The meteorology data was measured at station 51074 Figure 2-6 provided by China Meteorological Administration (CMA)

**Figure 2-6 Location of rain gauge in Maqu**

Figure 2-7 shows the precipitation and temperature of Maqu region collected by this station. From June to September, high precipitation level was recorded, especially in June and September, while in winter; low precipitation was observed from November to February. Temperature of this region follows the same trend with precipitation, high in summer about 10 ℃ while in winter it decreased to about -5℃.

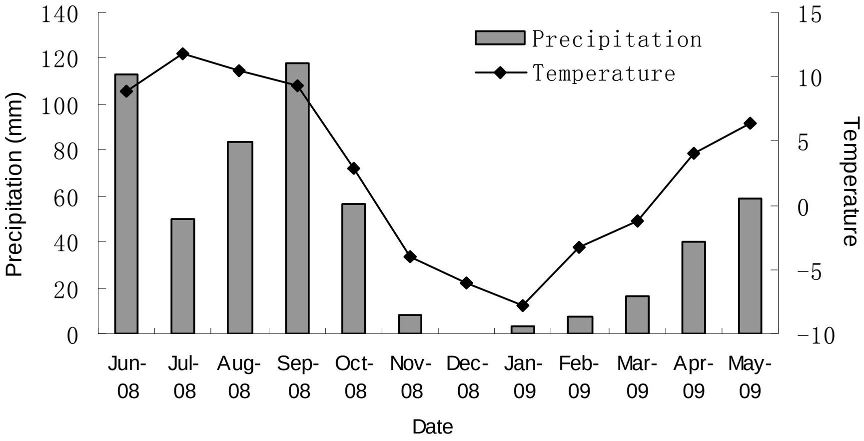



**Figure 2-7 Monthly averaged precipitation and temperature in Maqu**

### 2.1.2.3. Land cover

This region is covered by homogenous grassland with some wetlands figure 2-8, this map was based on Landsat 5 NDVI image taken in April 2007, which was downloaded from website http://landsat.datamirror.csdb.cn/list.run?action=list&products=L45TM and classified by ERDAS. In this map, grassland 1 presents grassland on valley, and grassland 2 presents grassland on hills with slopes. Figure 2-9 shows pictures of typical land cover types in Maqu region

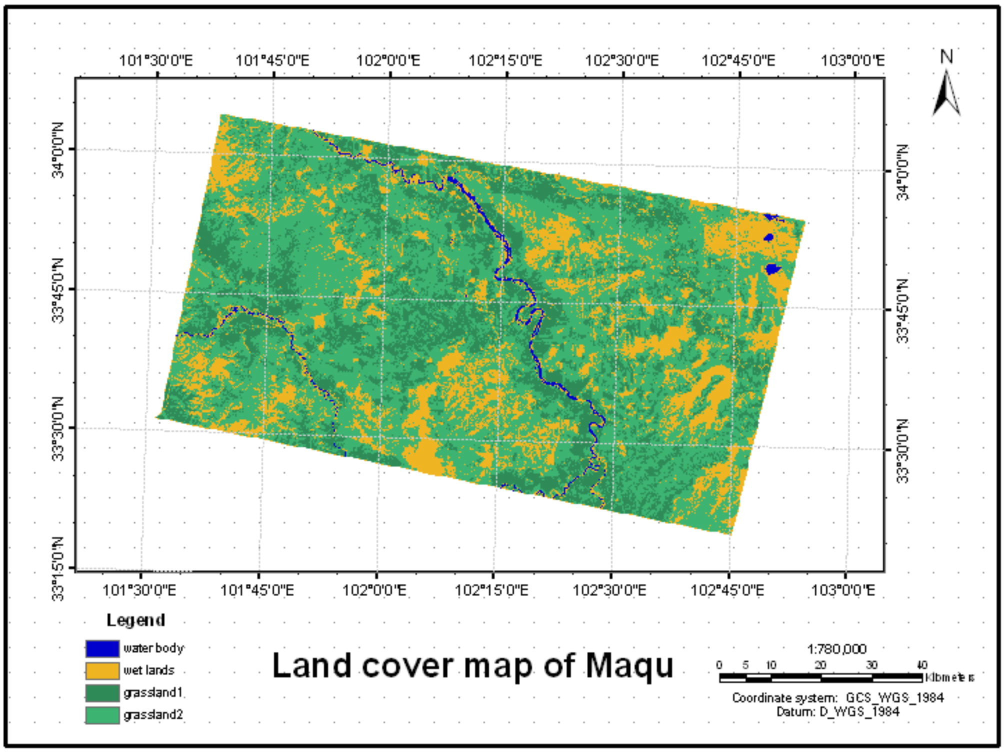



**Figure 2-8 Land cover map of Maqu region**

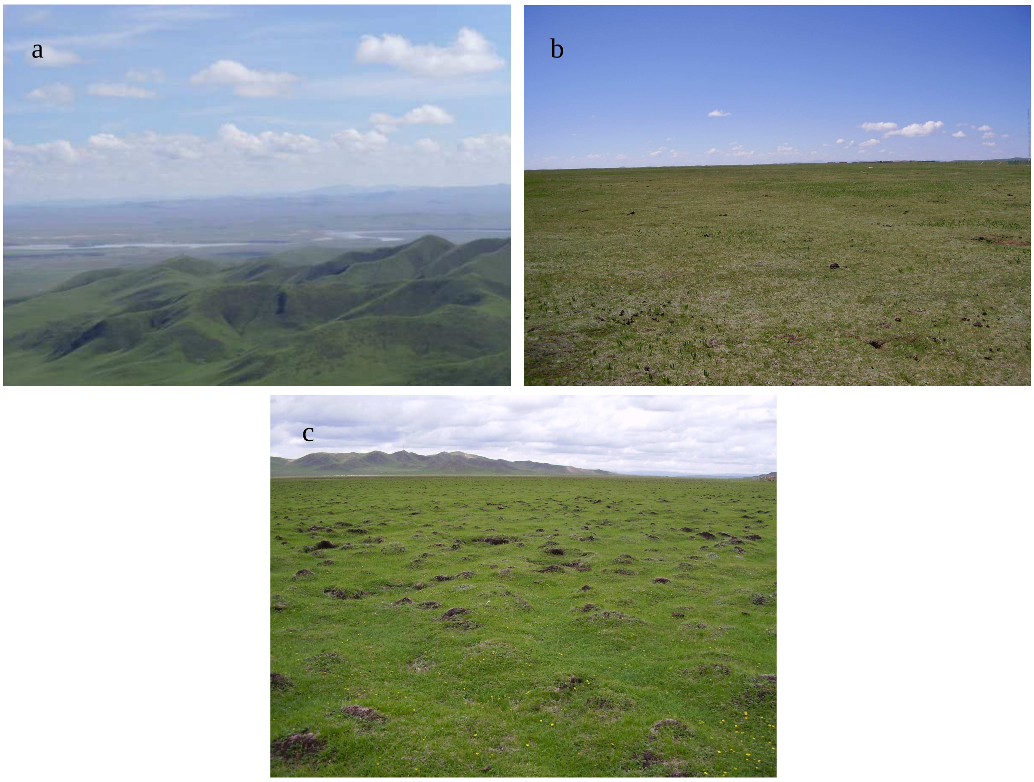



**Figure 2-9 Typical land cover types in Maqu region, hills and river (a), grassland(b), wetland(c)**

#### 2.1.2.4. Soil properties

Soil texture of most stations at this region is silt loam (Table 2-4). Organic matter at most of the places is low except nst 4 and nst11, which are located near wetlands.

**Table 2-4 Soil properties at the top layer of the stations in Maqu region**

| Station ID | Sand (%) | Silt (%) | Clay (%) | Organic matter (%) | Soil texture |
|---|---|---|---|---|---|
| NST-01 | 15.4 | 61.4 | 23.2 | 1.8 | silt loam |
| NST-02 | 15.4 | 61.4 | 23.2 | 1.8 | silt loam |
| NST-03 | 13.5 | 66.8 | 19.7 | 4.9 | silt loam |
| NST-04 | 7.9 | 55.7 | 36.6 | 22.9 | silt loam |
| NST-05 | 14.4 | 64.7 | 20.9 | 2.3 | silt loam |
| NST-06 | 13.5 | 66.8 | 19.7 | 2.3 | silt loam |
| NST-07 | 13.5 | 66.8 | 19.7 | 2.3 | silt loam |
| NST-08 | 18.2 | 66.0 | 15.8 | 3.4 | silt loam |
| NST-09 | 6.4 | 32.3 | 61.3 | 1.7 | sandy loam |
| NST-10 | 14.6 | 49.4 | 36 | 2.4 | loam-silt loam |
| NST-11 | 12.6 | 72.5 | 14.9 | 13.6 | silt loam |
| NST-12 | 13.0 | 54.3 | 32.8 | 3.9 | silt loam |
| NST-13 | 15.9 | 66.6 | 17.5 | 2.9 | silt loam |
| NST-14 | 17.6 | 62.5 | 19.9 | 3.0 | silt loam |
| NST-15 | 18.6 | 75.0 | 6.4 | 5.6 | silt loam |

## 2.2. Description of in situ experiment

In the Twente region, according to description in 2.1.1, soil properties at top layer are similar between stations, and topography is flat almost everywhere but land cover at this region is quite heterogeneous. The 17 stations used to estimate areal soil moisture of this region are all installed in grassland. Since large differences of soil moisture value may be observed under different land cover types, the information lost at other land covers (eg. Corn, bare land, forest) may cause errors. Therefore, a fieldwork for representativity examination of stations at this region is needed.

In the Maqu region, according to description in 2.1.2, soil properties at top layer are similar among all the stations; land cover is homogeneous grassland with wetland at some places. Stations have been installed at both land cover places, topography is rolling at this region, and stations in this network can well represent typical landscapes. Therefore, representativity examination is not as necessary as in the Twente region in this study.

The aims of representativity examination are as follows:

- Checking whether soil moisture values measured by stations, which were usually installed at border of grasslands, are representative to soil moisture in the same and the neighbouring fields or not, especially fields with different land cover types.
- Checking whether the soil moisture values recorded by 17 stations under grassland can represent the results combined with different land covers.

Due to the aims above, to avoid soil moisture differences influenced by precipitation events and land cover change, sampling duration should be short. In this study, the sampling duration was within one day, and same work has been repeated for 5 times, on 22$^{nd}$ September, 1$^{st}$ October, 9$^{th}$ October, 21$^{st}$ October and 28$^{th}$ October 2009. Surface soil moisture was measured both by Theta probes and gravimetric method. Considering time limitation, 8 stations among 17 in the Twente region were sampled to test representativity. The selection was influenced by the location of in-situ, the 8 stations should spread uniformly over the Twente region, and other reasons like soil texture, and site access were also taken into consideration.

In each of the 8 stations, 3 fields (the field where the station installed and two fields next to it with possibly different land cover) were sampled. Field attributes are listed in Table 2- 5 represent typical combinations of soil texture and land cover in the Twente region.

**Table 2-5 Field attributes**

| Station ID | Soil texture | Land cover | Location of sensor (Dutch RD coordinates) |
|---|---|---|---|
| St3 | Loamy sand | Grassland/corn/bare land | 250509.5, 485563.1 |
| St5 | Loamy sand | Grassland/corn/bare land | 244506.6,476887.8 |
| St7 | Loamy sand | Corn/bare land | 262418.7,488157.2 |
| St8 | Sand | Grassland/corn/bare land/forest | 247915.6,461598.4 |
| St11 | Loamy sand | Grassland / forest | 235006.1,471987.4 |
| St12 | Sand | Grassland/corn/bare land | 235219.2,461881.2 |
| St17 | Sand | Grassland | 233416.3,493027.5 |
| St18 | Loamy sand | Grassland/corn/bare land | 222502.1,491182.4 |

In each field, Three points with homogeneous vegetation and gentle slope were tested along one transect with interval about 20 to 30 m. Considering spatial variability of soil moisture 9 measurements were taken at each point.

In Figure 2-10, (a) illustrates the distribution of 8 stations in the Twente region. (b) and (c) are examples of the sampling points at station st17 and station st03. Sampling points at each station is presented in Appendix-2.Red points show the locations of the sensors, while the yellow marks were the points where intensive measurements were taken by theta probes. Therefore, within one day 9 measurements *3 points *3 field *8 stations, 648 measurements in total were taken. One or two soil moisture values were taken at one station by gravimetric method for Theta-probes calibration. All the measurements taken in Twente region were collected between 9 am and 5 pm each day. Coordinates of each site were received by GPS.

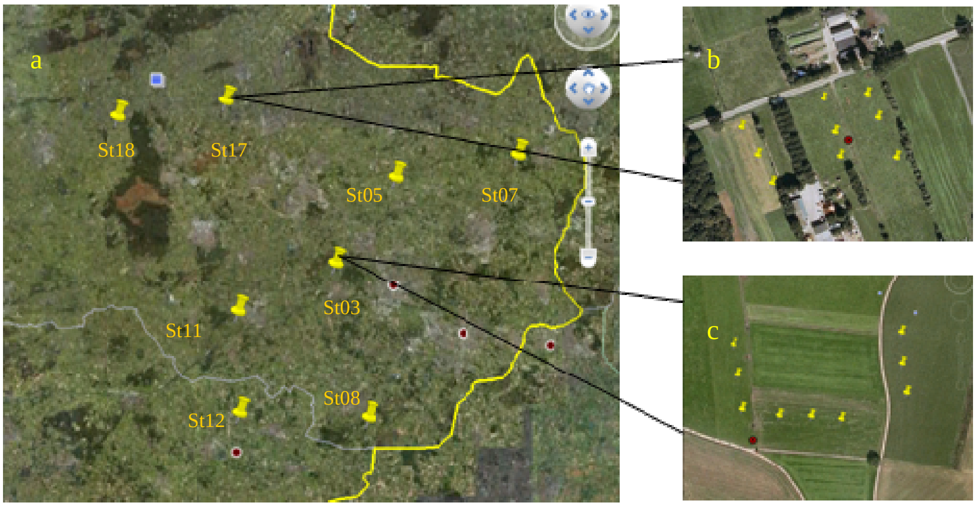



**Figure 2-10 Distribution of sampling stations, Location of 8 stations selected (a) sampling points at station17 (b), and station03 (c)**

## 2.3. Soil moisture measurement

In this part, calibration of in-situ soil moisture collected by Theta-T probe and AMSR-E soil moisture data used in this study are introduced.

### 2.3.1. In situ measurement for soil moisture

In this study, Theta-T probe was used to do field measurements intensively and be calibrated by gravimetric method (Figure 2-11). The methods of two measurements are presented in Appendix-3.The two datasets collected by two measurements show a good linear relation with $R^2$ of 0.8262. As Figure 2-11 shows, only 3 out of 85 values are outliers. Slight bends were observed when soil moisture is lower than 15% and higher than 30%, a logarithmic relation is also applied with an $R^2$ 0.8299. Since no obvious improvement when applying a logarithmic relation, to make the calculation easier, in this research linear model is used to calibrate Theta-T probes.

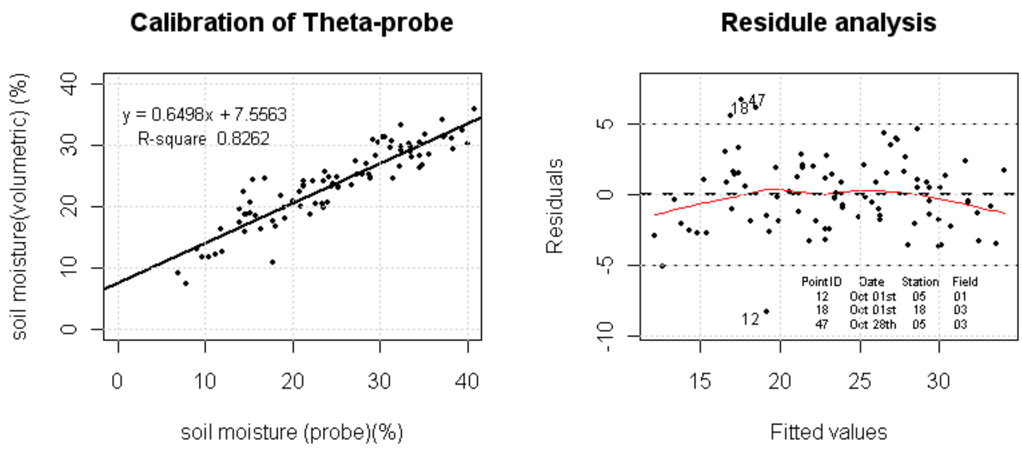



**Figure 2-11** **Theta-probe calibration and residual analysis**

### 2.3.2. Remote sensing of soil moisture

The advanced microwave scanning radiometer (AMSR-E) flown on Aqua provides passive microwave measurement. VUA-NASA applies the Land Surface Parameter Model (LPRM) (Owe et al. 2001) using 6.9 GHz and 10.7 GHz channel to retrieve soil moisture from brightness temperature. In this research, their AMSR-E soil moisture products were downloaded from (http://www.falw.vu/~jeur/lprm/).

# 3. Research methods

## 3.1. Representativity examination

Data collected by the calibrated Theta-probe was used to define whether the data measured by the ECH2O EC-TM sensors are representative to the whole area in Twente. 8 stations were selected out of the 17. The analysis consisted of two parts:

- Examine representativity of 8 stations at station scale by comparing field datasets with the one got from the corresponding sensor at the same time.
- Examine representativity of 17 stations at the footprint scale by spatial statistics based on three datasets (soil moisture data from field work at 8 stations, soil moisture data from installed sensor at 8 stations, soil moisture data from installed sensor at 17 stations) on the five days of the field campaigns.

### 3.1.1. Soil moisture representativity examination at station scale

81 soil moisture measurements (9 measurements* 3 points*3 fields) were taken per station on each day of the field campaign. Generally, measurements at one station lasted for 30 minutes to 1 hour depending on the land cover, during which only two or three records were taken by sensor. The following statistical analysis aims at quantifying the representativity

- **Parametric analysis**

To find out how probabilities associated to a group of continuous independent variables cumulative density function (CDF) is always calculated. It is a S-shape curve to tell the probability of value less than x is obtained(Qi 2002). Its slope is probability density. This algorithm always based on certain distributions such as normal distribution, gamma distribution, exponential distribution to quantify probabilities.

Normal distribution is an essential distribution for probability. It is widely use when the target variables are random selected or influenced by many independent factors and none of them is influential. Equation 4-1 is the function used to calculate density function.

$$f(x,\mu,\sigma)=\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right) \qquad 3\text{-}1$$

$\mu$ is the average of variables, x is individual variable and $\sigma$ is standard deviation

And the equation 3-2 is the function for CDF

$$F(x,\mu,\sigma)=\frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{x} e^{-\frac{(y-\mu)^2}{2\sigma^2}}\,dy, -\infty < x < \infty \qquad 3\text{-}2$$

In this study, an indicator 'pnorm' was used to shown representativity. Histograms are built for each station and also each type of land cover at one station during 5 days. Examples are shown in Figure 3-1:

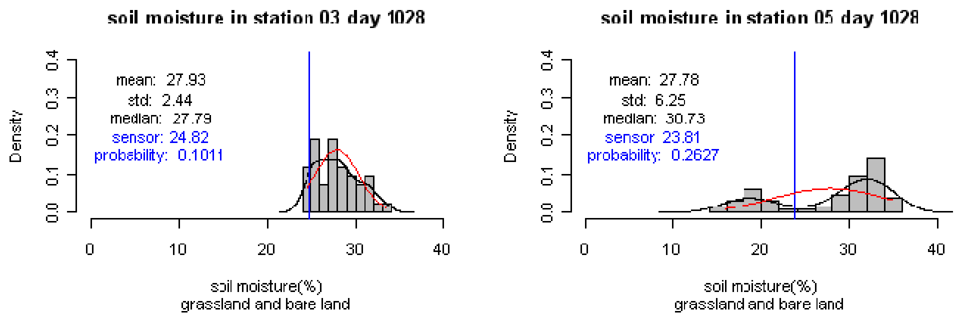



**Figure 3-1 Examples of pnorm analysis**

(Day 1028 means $28^{th}$ October)

Based on the histogram, a probability density function (black curve) was calculated and approximated by a normal distribution (red curve), using the mean and the standard deviation of the measurements. Then the cumulative probability was defined from the density function. 'pnorm' is cumulative probability minus 0.5 (centre of normal distribution) ranging from -0.5 to 0.5. This indicator tells whether the value measured by the recording sensor is underestimated or overestimated compared with the expected value 0.5, in terms of normalized distance. In the following analysis, threshold to identify representativity by 'pnorm' is -0.3, +0.3 according to the histograms based on intensive field measurements.

For example, in the case of Figure 3-1, at station 03 the cumulative probability of the sensor is about 0.1, and the corresponding 'pnorm' is -0.4, while at station 05 cumulative probability is 0.26 then the corresponding 'pnorm' is -0.24, according to the thresholds, the sensor is not representative at station 03 on $28^{th}$ October, but representative at station 05. It means the sensor value is too high to be representative. The histograms for each station on each day are presented in Appendix-5.

To avoid errors due to unknown distribution, a more robust method was also used in this part of the work, as shown below:

$$f(x) = \frac{x - Median}{IQR} \qquad 3\text{-}3$$

Here x is the sensor value, while median and IQR is calculated by field work data. In probability distribution, median is more robust than mean. Inter Quartile Range (IQR) tells the differences between the first the quarter and the third quarter. To some extent, it presents the statistical dispersion of variables. For continuous distribution CDF can be used to calculate IQR:

$$IQR = CDF^{-1}(0.25) - CDF^{-1}(0.75) \quad 3\text{-}4$$

For this indicator, 'Diff/IQR', the thresholds applied in this study is -1 and 1. If Diff/IQR is much higher than 1 or lower than -1 then the sensor value is not representative. When Diff/IQR is close to 0, it means the sensor value is representative.

- **Non-parametric analysis**

When the variables are not continuous, discrete probability can be used. In this research, soil moisture values we collected at one station may not be normally distributed. We can find obvious skewness and bimodal distributions in some cases, so analysis based on normal distribution may cause big error. By this method, Theta-probe measurements at one station on one day are ranked together with the sensor value. After ranking, by comparing the rank of sensor value and total number of measurements, representativity can be identified. The threshold for representativity is the middle half. For example on 22$^{nd}$ September the rank of sensor at station st03 is 64/64, this means the sensor value is the highest among all the measurements at same station same day. The acceptable rank should be between 16/64 to 48/64 in this case. Therefore sensor value at 22$^{nd}$ September at station st03 was not representative. This method based on rank is much simpler than parametric analysis. Since most of the soil moisture data are not normally distributed, this method is useful

### 3.1.2. Soil moisture representativity examination on footprint scale

Three datasets are compared to identify whether the sensor values can represent the whole area or not.

- **Box plot**

Box plot is used to display the difference between populations without any assumption of underlying statistical distribution. It is non-parametric. Box plot is a graph based on a five-number summary (McGill et al. 1978). Figure 3-1 shows an example of box plot of normal distribution compared with its density function:

:

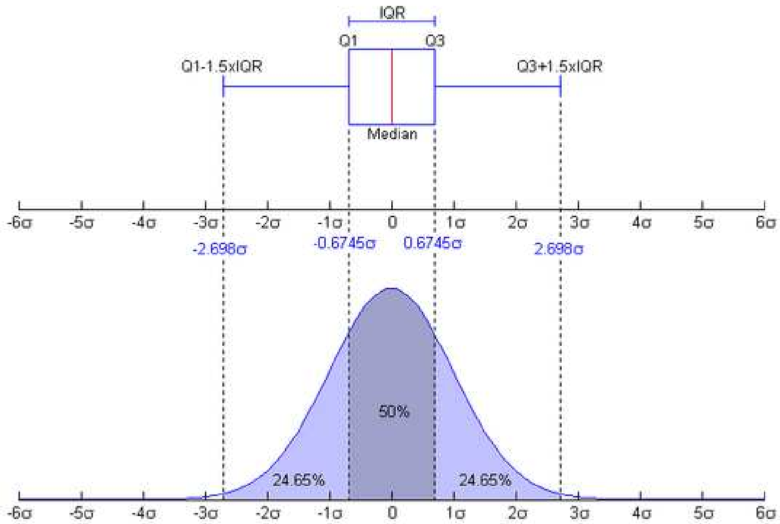



**Figure 3-2 Box plot with density function (Wikipedia)**

- **T-test**

T test is first published by W. S. Gossett in 1908 and perfected by R.A. Fisher later (Michael 2007). Fisher pointed out that for small –sample statistics the results should be obtained based on sample variance and population variance. Function for calculation is shown in 3-5

$$t = \frac{mean\_diff}{se_{diff}} = \frac{\overline{Y}_A - \overline{Y}_B}{se_{diff}} \qquad 3\text{-}5$$

$\overline{Y}_A, \overline{Y}_B$ are mean of two variables. $se_{diff}$ is standard error of the difference between two mean values. If the two variables are independent, then variance of the two variables equals to the sum of the separate variances. The function to get $se_{diff}$ is presented in 3-6:

$$se_{diff} = \sqrt{\frac{s_A^2}{n_A} + \frac{s_B^2}{n_B}} \qquad 3\text{-}6$$

$s_A, s_B$ are standard error of two variables relatively. $n_A, n_B$ are the sample size of the two variables. In this test the null hypothesis is that the two means are same. Generally, 5% probability as the threshold was used to reject the hypothesis.

## 3.2. Soil moisture spatial distribution on footprint scale

Geostatistical interpolation and temporal stability analysis are used to estimate spatial distribution of soil moisture at two areas.

### 3.2.1. Geostatistical interpolation

Variogram analysis is a frequently used method to describe the spatial distribution of variables. In this research, it was used to evaluate the spatial distribution of soil moisture.

The semi-variogram is square of the increments of a variable with a distance, known as lag (Buchter et al. 1991). It is defined as:

$$\gamma(h) = \frac{1}{2N} \sum_{i=1}^{N} \left( \left| Z(x_i) - Z(x_i + h) \right|^2 \right) \qquad 3\text{-}7$$

$\gamma(h)$ is called the semi-variogram, N is the number of pairs of data separated by the lag h.

Trend surface which simply consider variables based on spatial coordinates with first and second order polynomial were also used in this study.

### 3.2.2. Temporal stability analysis

(Guber et al. 2008) demonstrated that no advantage is obtained when high frequency soil moisture measurements are used for the temporal stability analysis. So in the present research daily averages were used. Furthermore, (Guber et al. 2008) divided the whole year into four seasons and based their stability analysis on the Mean Relative Difference (MRD) and Standard Deviation of the Relative Difference (SDRD), which are described below.Mean relative difference is defined by (Vachaud et al. 1985) and it is calculated as,

$$\bar{\delta}_i = \frac{1}{n} \sum_{j=1}^{n} \frac{S_{i,j} - \bar{S}_j}{\bar{S}_j} \qquad 3\text{-}8$$

Where $\bar{\delta}_i$ is MRD, $S_{i\,j}$ is the measured soil moisture at site $i$ at time $j$ of $n$ records of the study period. $\bar{S}_j$ is the computed average among all sites at time j. MRD is calculated to show the difference between each site and the average soil moisture in a certain period. To know how variable the relationship is, SDRD $\sigma(\delta_i)$ is used here,

$$\sigma(\delta_i) = \sum_{i=1}^{n} \left( \frac{\delta_i - \bar{\delta}_i}{n-1} \right)^{\frac{1}{2}} \qquad 3\text{-}9$$

From MRD and standard deviation, each site can be ranked and it is possible to find one or more stations with mean relative difference near zero and a low standard deviation.

If in this analysis, one station is determined to be appropriate the correlation coefficient (Cosh et al. 2004) between two stations can be used to check the results, whether the station chosen has high correlation with other stations ? Correlation coefficient is calculated as follows:

$$r_{i,i'} = \frac{\sum_j (S_{i,j} - \overline{S}_i)(S_{i',j} - \overline{S}_{i'})}{\sqrt{\sum_j \left(S_{i,j} - \overline{S}_i\right)^2} \sqrt{\sum_j \left(S_{i,j'} - \overline{S}_{i'}\right)^2}} \qquad 3\text{-}10$$

Where $S_{i,j}$ is soil moisture value for station *i* at time *j* and $S_{i',j}$ is soil moisture in station *i'* at time *j*. $\overline{S}_i$ is the average soil moisture value for station *i* during the whole period. $\overline{S}_{i'}$ is the average soil moisture value for station *i'* during the whole period.

(Schneider et al. 2008) averaged two to four most acceptable point measurements and they found results received from four were more close to the spatial mean. It is possible to give different weights by a simple multivariate linear regression based on a cost function between soil moisture point measurements and spatial mean.

## 3.3. Upscaling operators

To estimate areal soil moisture at large area, using point measurements may have low precision or even bring bias. Therefore it is better to scale up the point measurements. Even if the point measurements fit the spatial averaged soil moisture well, low precision may also be obtained because there are constant offset between these datasets(De Lannoy et al. 2007). Three methods below are all based on the relationship between time- invariant measurements of point and spatial average.

- Absolute differences

(De Lannoy et al. 2007) used absolute differences from results of temporal stability to correct point measurements. In temporal stability analysis, mean relative differences were calculated to identify the station which is most close to spatial mean. In this step, this parameter is again be used to convert point measurements to spatial average. Equation 3-11 gives the way for transformation from point measurements to areal soil moisture:

$$\hat{y}_j = \frac{S_{i,j}}{\overline{\delta_i} + 1} \qquad 3\text{-}11$$

$S_{i,j}$ is the soil moisture of point measurement at station *i*, time *j*. $\overline{\delta}_i$ is mean relative differences of at station *i*. $\hat{y}_j$ is areal soil moisture after upscaling.

- **Linear regression**

This method assuming that there is a linear relation between point measurements and spatial averaged measurements. The equation for calculation is shown in

$$\hat{y}_j = aS_{i,j} + b \qquad 3\text{-}12$$

*a* and *b* are constant parameters for linear regression.

- **Higher order regression**

To fit a higher order moments of the point scaled data and spatial average, higher order regression are also applied. 3-13, 3-14 give the equation of second order regression:

$$\hat{y}_j = aS_{i,j} + bS^2_{i,j} + c \tag{3-13}$$

$$\hat{y}_j = a + bS_{i,j} + cS^2_{i,j} + dS^3_{i,j} \tag{3-14}$$

To evaluate the results bias, RMSE, correlation can be used to compare the upscaled dataset with average soil moisture. Which method gives best results compared with spatial average. The way for calculation R is same with 3-10, and RMSE and BIAS are shown in 3-15, 3-16

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \tag{3-15}$$

$$BIAS = \left|\frac{1}{N}\sum_{i=1}^{N} y_i - \frac{1}{N}\sum_{i=1}^{N}\hat{y}_i\right| \tag{3-16}$$

N is total number of measurements, $y_i$ is spatial averaged soil moisture, $\hat{y}_i$ is upscaled soil moisture.

## 3.4. Remote sensing products validation

AMSR-E overpass times are 1:30 AM and 1:30 PM at local time of the descending and ascending tacks, respectively. The in-situ data collected at the same time by the selected representative stations were used for the validation of the AMSR-E based SM products. Scatter plots and regression analysis of the time series were used to compare the differences of the in-situ and the AMSR-E products. Then RMSE and R were applied to quantify the differences between datasets.

# 4. Results and discussion

This chapter present the results and discussions of this study based on the measurements listed in chapter 3. First results from representativity examination are presented (4.1), then soil moisture spatial distribution is estimated by two methods to get the idea whether they can well present the study area or not (4.2), in 4.3 upscaling was applied based on point measurements, and the results from different upscaling methods and stations were discussed. After that, the upscaled soil moisture were used to compare with remote sensing products.(4.4)

## 4.1. Representativity examination

In this part, first time series of soil moisture was compared with precipitation in Twente region, to identify the weather condition of the 5 days for intensive measurements, then, the station representativity was tested both at station scale and footprint scale.

### 4.1.1. Time series of SM and rainfall in Twente region

The weather condition of the Twente region in September and October 2009 is shown in the Figure 4-1. The upper half of the figure represents the soil moisture recorded by 8 stations where the fieldwork was carried out. Measurements were taken in every 15 minutes. The lower part of the figure is a record of daily precipitation, based on 12 rain gauges spreading over the area. Among all the stations, station st17 observed the lowest soil moisture during the whole period; while station st11 recorded the highest. At the beginning of this period, low soil moisture values were observed, ranging 5% to about 20%. The heaviest rain was recorded on 8$^{th}$ October, and after that soil moisture increased dramatically. Spatial distribution changed as well, soil moisture at station st11 increased sharply to about 35%, while the moisture condition at station st17 had no much change, shifting around 10%. The order of the stations changed also.

Due to practical reasons, most of the field campaigns were in October, when the precipitation was relatively high. Nevertheless, on the first day, September 22$^{nd}$ (day 22), the area was drying out. No rainfall was recorded in the 5 antecedent days. On October 1$^{st}$ (day 31), it was raining slightly even a few hours before our field work. The third day of field work (day 39) was one day after a heavy rain; more than 20 mm per day was recorded by most of the rain gauges. Weather condition on October 21$^{st}$ (day 51) was similar to the first field work day. However soil moisture was much higher. The last day of field work (day 58) was in wet condition with a slight rain the day before. Therefore in this study, the first 2 days are identified as in dry condition while the other 3 as in wet condition.

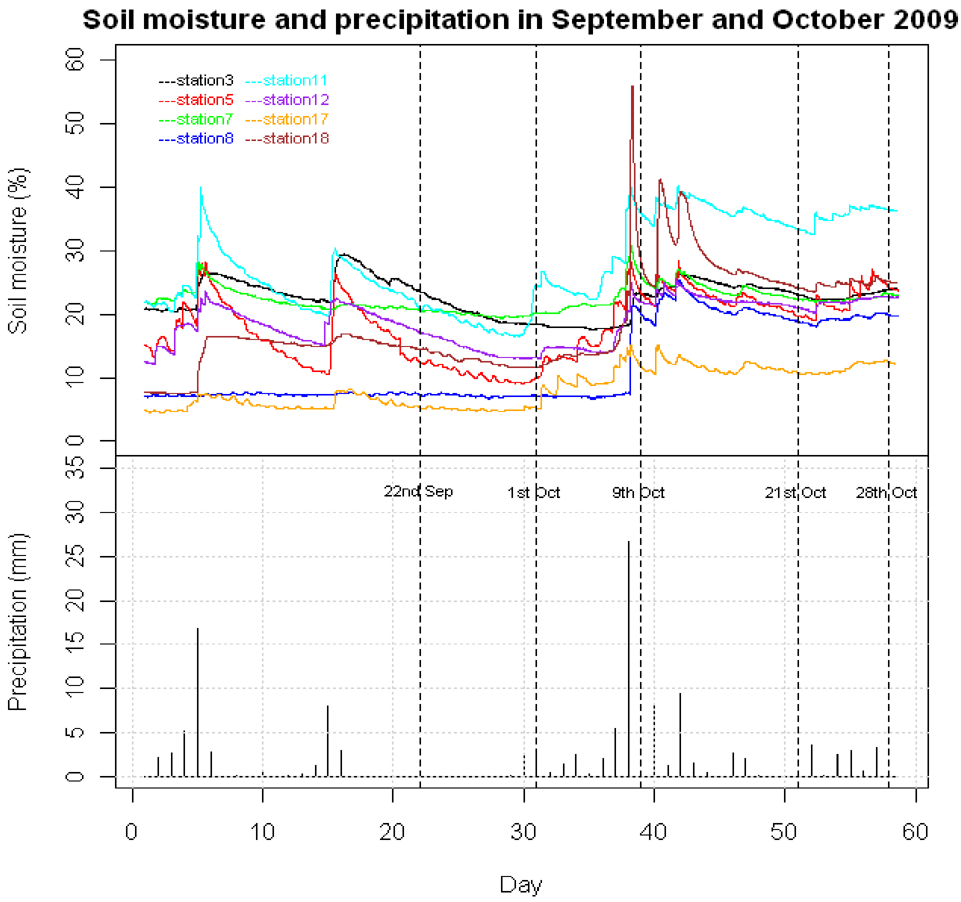



**Figure 4-1 Soil moisture at 8 stations at 5cm depth and precipitation in Twente region from September to October 2009**

Table 4-1 shows the correlation matrix of soil moisture of the 5 days of filed work. High correlation coefficients (about 0.9) are shown between the last three days (which were in wet conditions), indicating similar spatial distributions. The correlation coefficients between October 1$^{st}$ and other days are the lowest, indicating less similar spatial distributions

**Table 4-1Correlation matrix of SM between different days**

| | 22$^{nd}$ Sep | 01$^{st}$ Oct | 09$^{th}$ Oct | 21$^{st}$ Oct | 28$^{th}$ Oct |
|---|---|---|---|---|---|
| **22$^{nd}$ Sep** | 1.000 | | | | |
| **01$^{st}$ Oct** | 0.791 | 1.000 | | | |
| **09$^{th}$ Oct** | 0.754 | 0.605 | 1.000 | | |
| **21$^{st}$ Oct** | 0.719 | 0.606 | 0.915 | 1.000 | |
| **28$^{th}$ Oct** | 0.714 | 0.553 | 0.868 | 0.902 | 1.000 |

### 4.1.2. Soil moisture representativity examination at station scale

In the following, an analysis of the individual stations is presented by 5 aspects, PDF shape, pnorm, rank, diff, Diff/IQR (in tables below dates with red means sensor value at that day are representative):

- **Station st03**

At station st03, three fields (two grass fields and one corn field) were tested. Corn was cut just before 1st October. The results of the statistical analysis are listed in Table 4-2. The three methods yield the same results here: on the first two days the sensor values were much higher than field measurements. While when the weather condition was wet on October 09th the sensor value became representative. The last two days were not comparable because one field was not accessible for measurements.

**Table 4-2 Results of the representativity analysis at station st03**

| Date | 22nd Sep | 01st Oct | 09th Oct | 21st Oct* | 28th Oct* |
|---|---|---|---|---|---|
| **Land cover** | Grass, corn | Grass, bare | Grass, bare | Grass | Grass |
| **PDF shape** | Bimodal | Unimodal | Bimodal | unimodal | unimodal |
| **Pnorm (to 0.5)** | 0.5 | 0.42 | -0.06 | -0.43 | -0.4 |
| **Rank** | 64/64 | 57/64 | 25/64 | 5/43 | 4/43 |
| **Diff** | 8.17 | 2.31 | -0.64 | -1.88 | -3.95 |
| **Diff/IQR** | 1.86 | 1.73 | -0.3 | -2.44 | -1.45 |

* Based on data of two fields, since one field was not accessible for measurements

- **Station st05**

At Station st05 the land cover is same as station 03; two grass fields and one corn field were included in the measurements. The results are presented in Table 4-3. On September 22nd and October 01st the sensor values were too low to be representative. While on the other three days the sensor values are representative.

**Table 4-3 Results of the representativity analysis at station st05**

| Date | 22nd Sep | 01st Oct | 09th Oct | 21st Oct | 28th Oct |
|---|---|---|---|---|---|
| **Land cover** | Grass, corn | Grass, bare | Grass, bare | Grass, bare | Grass, bare |
| **PDF shape** | Unimodal | Unimodal | Bimodal | bimodal | bimodal |
| **Pnorm (to 0.5)** | -0.5 | -0.5 | -0.33 | -0.27 | -0.24 |
| **Rank** | 1/64 | 1/64 | 15/64 | 17.5/50 | 19/64 |
| **Diff** | -4.02 | -5.14 | -4.06 | -3.88 | -3.97 |
| **Diff/IQR** | -3.01 | -3.34 | -1.05 | -0.8 | -0.73 |

- **Station st07**

At Station st07 all the fields around it are corn, and station was installed on the edge of one these fields. The corn was harvested just before 21st October. Three methods give different results here. On 22nd September and 21st October, sensor values were not representativy according to Pnorm (0.44,-0.34) and Rank (60/64, 9/64), while acceptable by Diff/IQR(0.94,0.97), Since Diff/IQR are close to 1, and the histograms of the two days shows they are not representative.

**Table 4-4 Results of the representativity analysis at station st07**

| Date | 22nd Sep | 01st Oct | 09th Oct | 21st Oct | 28th Oct |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| **Land cover** | Corn | Corn | Corn | Bare | Bare |
| **PDF shape** | Unimodal | Unimodal | Bimodal | Bimodal | Bimodal |
| **Pnorm (to 0.5)** | 0.44 | 0.09 | 0.1 | -0.34 | -0.44 |
| **Rank** | 60/64 | 31/64 | 39/64 | 9/64 | 4/64 |
| **Diff** | 3.91 | 0.95 | 0.85 | -3.93 | -5.51 |
| **Diff/IQR** | 0.94 | 0.11 | 0.77 | -0.97 | -1.47 |

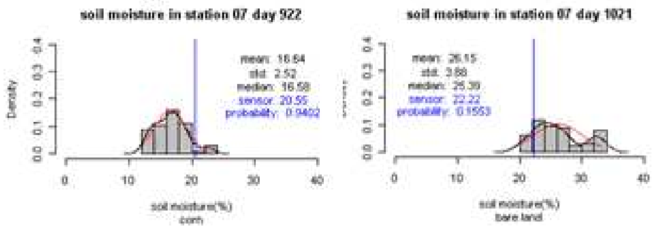



**Figure 4-2 Histograms of soil moisture at station st07 on 22nd September and 21st October**

- **Station st08**

At station st08three fields with different land covers were tested. Corn was cut since 01st October. As shown in Table 4-5, on the first two days, sensor values are lower than all the field measurements. On the other three days the sensor values are representative.

**Table 4-5 Results of the representativity analysis at station st08**

| **Date** | **22nd Sep** | **01st Oct** | **09th Oct** | **21st Oct** | **28th Oct** |
|---|---|---|---|---|---|
| **Land cover** | Grass, corn, forest | Grass, bare, forest | Grass, bare, forest | Grass, bare, forest | Grass, bare, forest |
| **PDF shape** | Bimodal | unimodal | Bimodal | unimodal | unimodal |
| **Pnorm (to 0.5)** | -0.44 | -0.5 | -0.04 | 0.09 | -0.05 |
| **Rank** | 3/64 | 1/64 | 24/64 | 37/64 | 29/64 |
| **Diff** | -3.55 | -9.51 | -0.34 | 0.58 | -0.27 |
| **Diff/IQR** | -1.3 | -7.6 | -0.45 | 0.14 | -0.18 |

- **Station st11**

At station st11 two grass fields and one forest were tested. Here, sensor values are much higher than the field measurements. The analysis based on IQR shows that the station is representative, but this is due to the broad value range at this station. Figure 4-3 gives an example of soil moisture distribution at this place on which the large value range can be observed.

**Table 4-6 Results of the representativity analysis at station st11**

| **Date** | **22nd Sep** | **01st Oct** | **09th Oct** | **21st Oct** | **28th Oct** |
|---|---|---|---|---|---|
| **Land cover** | Grass, forest | Grass, forest | Grass, forest | Grass, forest | Grass, forest |
| **PDF shape** | Bimodal | bimodal | Bimodal | unimodal | unimodal |
| **Pnorm (to 0.5)** | 0.4 | 0.45 | 0.47 | 0.45 | 0.47 |
| **Rank** | 58/64 | 64/64 | 64/64 | 64/64 | 64/64 |
| **Diff** | 8.24 | 8.90 | 11.15 | 10.31 | 11.76 |
| **Diff/IQR** | 0.54 | 1.08 | 0.93 | 0.88 | 1.22 |

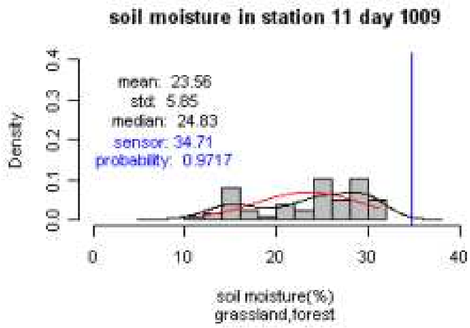



**Figure 4-3 Soil moisture distribution at station 11 on 9th October**

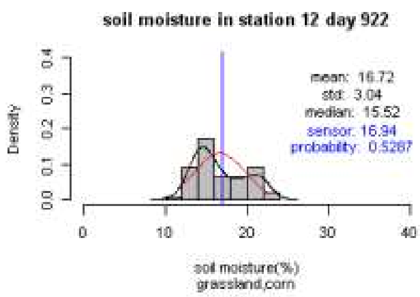
- **Station st12**

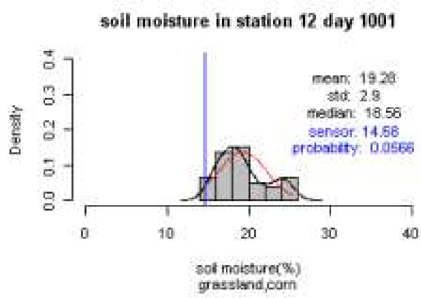
The three methods give different results here. According to probability analysis and ranking, the representativity is acceptable only on the first day. While if we consider IQR and difference between sensor value and mean, it is representative on all the five days.

**Table 4-7 Results of the representativity analysis at station st12**

| Date | 22nd Sep | 01st Oct | 09th Oct | 21st Oct | 28th Oct |
|---|---|---|---|---|---|
| **Land cover** | Grass, corn | Grass, corn | Grass, corn | Grass, corn | Grass, bare |
| **PDF shape** | Bimodal | bimodal | Unimodal | bimodal | unimodal |
| **Pnorm (to 0.5)** | 0.03 | -0.44 | -0.33 | -0.35 | -0.31 |
| **Rank** | 37/57 | 5/64 | 10/64 | 10/64 | 11/64 |
| **Diff** | 0.22 | -4.60 | -2.25 | -2.99 | -2.82 |
| **Diff/IQR** | 0.37 | -1.22 | -1.91 | -0.47 | -0.66 |

To estimate which method gives a more reliable result at this station, let's turn to the histograms of soil moisture measured in field work and the corresponding sensor values (Figure 4-4); most of the distributions are bimodal and the different results are caused by the obvious skewness. According to this observation and also the analysis above, we can conclude that the sensor value is not representative on 01st October, while on other days it is representative.



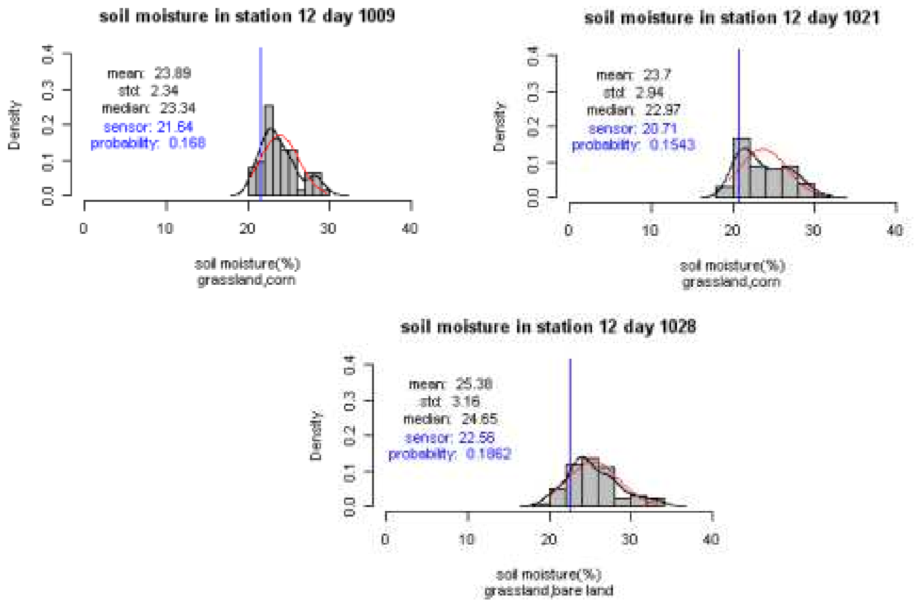



**Figure 4-4 Soil moisture distribution in station st12**

- **Station st17**

At Station st17 the fields chosen here are covered with grass. As shown in Table 4-8, sensor values are much lower than field measurements on all the days, according to all indicators. This station is not representative.

**Table 4-8 Results of the representativity analysis at station st17**

| Date | $22^{nd}$ Sep | $01^{st}$ Oct | $09^{th}$ Oct | $21^{st}$ Oct | $28^{th}$ Oct |
|---|---|---|---|---|---|
| **Land cover** | Grass | Grass | Grass | Grass | Grass |
| **PDF shape** | bimodal | bimodal | unimodal | bimodal | unimodal |
| **Pnorm (to 0.5)** | -0.5 | -0.49 | -0.5 | -0.5 | -0.5 |
| **Rank** | 1/64 | 1/64 | 1/64 | 1/64 | 1/64 |
| **Diff** | -14.05 | -11.31 | -17.59 | -17.97 | -18.56 |
| **Diff/IQR** | -4.19 | -1.45 | -10.11 | -11.56 | -9.89 |

- **Station st18**

At station st18 two grasslands and one corn field were tested. Corn was cut after $01^{st}$ October. As shown in Table 4-9, on the first two days, sensor values are lower than all the field measurements. On the other three days the station measurements are representative.

| Date | $22^{nd}$ Sep | $01^{st}$ Oct | $09^{th}$ Oct | $21^{st}$ Oct | $28^{th}$ Oct |
|---|---|---|---|---|---|
| **Land cover** | Grass, corn | Grass, bare | Grass, bare | Grass, bare | Grass, bare |
| **PDF shape** | unimodal | unimodal | bimodal | Bimodal | Bimodal |
| **Pnorm (to 0.5)** | -0.5 | -0.5 | 0.02 | -0.05 | -0.17 |
| **Rank** | 1/64 | 1/64 | 27/64 | 22/64 | 24/64 |
| **Diff/IQR** | 2.4 | -4.03 | 0.22 | -0.32 | -0.2 |

**Table 4-9 Results of the representativity analysis at station st18**

### 4.1.3. Time series of representativity

In this part representativity of stations with same land cover types are compared during five days. Form the analysis above, ‘pnorm ‘has a same range from -1 to 1 for each station and can tell the representativity well was selected to present representativity time series. In station st03, st05, st08, st018 land cover types are similar, grassland and corn, and after October 1st corn was cut. Figure 4-5 shows how representativity changed in time, based on the days of the field campaigns.

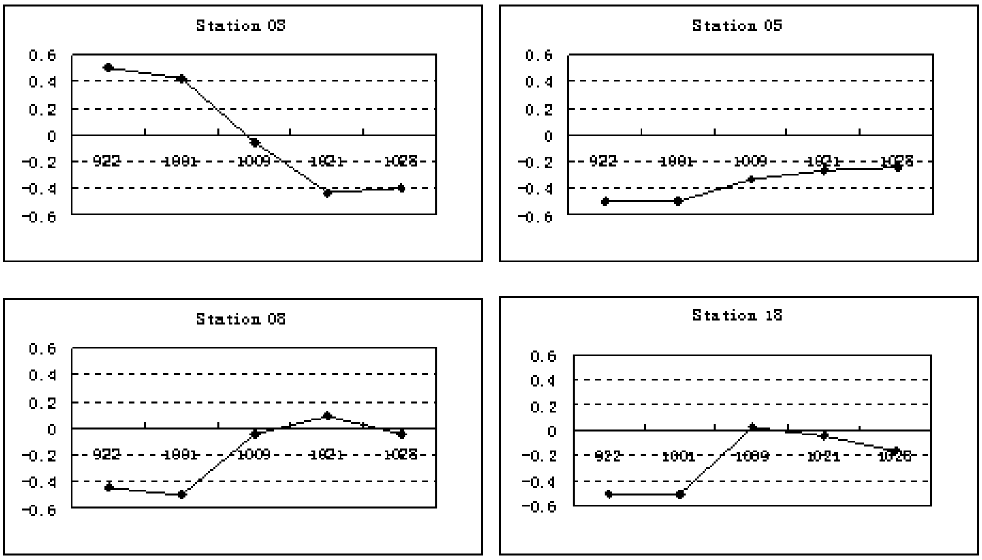



**Figure 4-5** **Time series of station representativity at stations st03, st05, st08 and st18**

By comparing the results for stations st05, st08, st18, it can be concluded that the sensor values are lower than the field measurements in the beginning of the period, while at station 03 it is much higher. The calculated ‘pnorm’ for 01st October was similar to the one on 22nd September, although the land cover was different. However, representativity improved a lot after 9th October when the weather condition became wetter. Here I omit station 03, because no bare land on last two days, because of the data missing at two fields on last two days.

Figure 4-6 presents how soil moisture under different land covers change in dry and wet conditions at station 5. The histograms on the left are based on soil moisture measured on 01st October (dry condition), giving the information of all three fields (top), grass fields (middle) and bare land (bottom), respectively. As we see, soil moisture values of grass land and bare land were almost within the same range. On the right side of the figure, graphs represent the situation on 28th October (wet condition). Data collected from grass land was obviously higher than that from bare land. The same rule was found in each station with mixed land covers. Appendix-5. In this figure, soil moisture measured by Theta-probes is higher than installed sensor, although they both took measurements under grass.

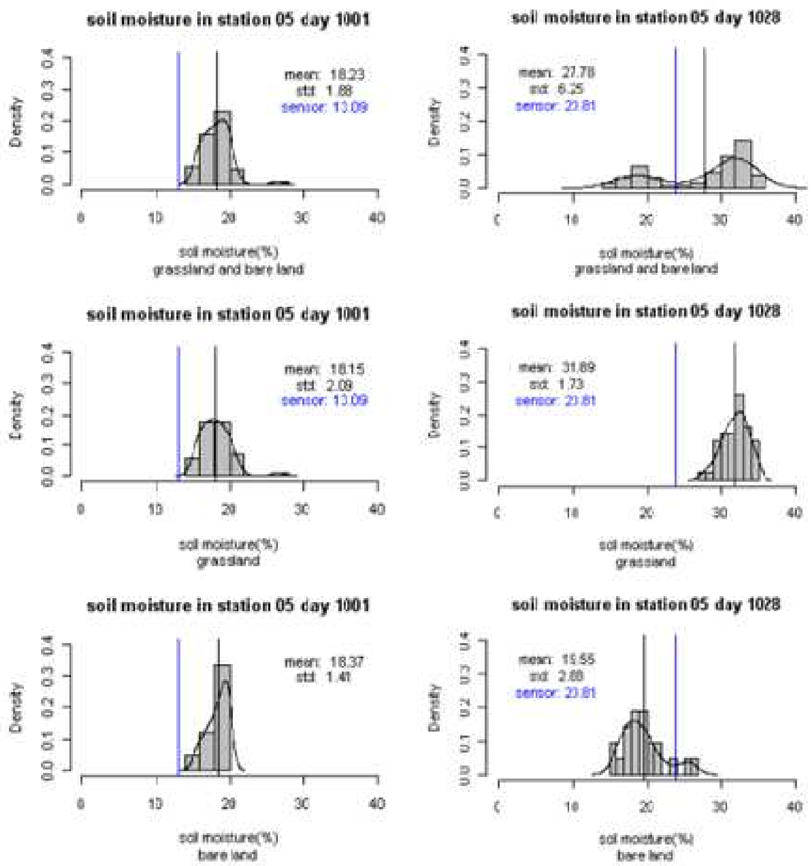
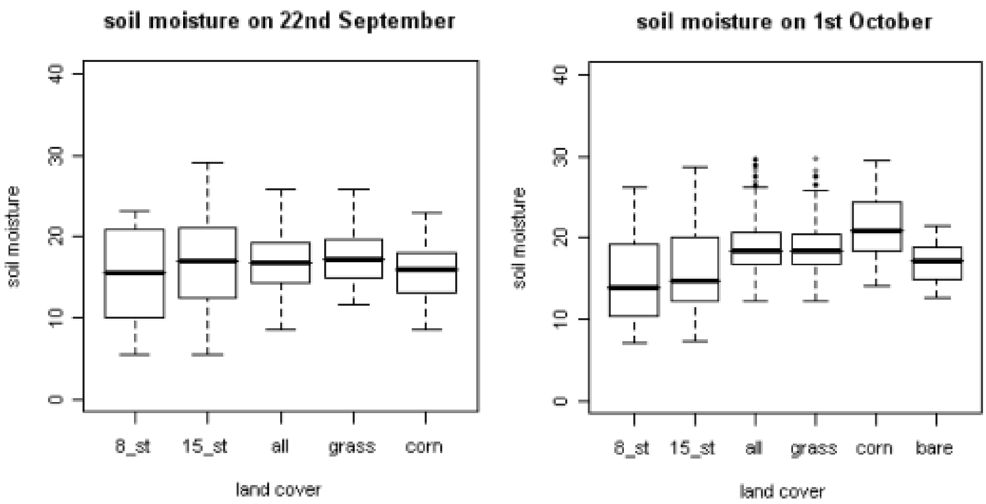



**Figure 4-6** **Soil moisture distribution at station 5 on 1st October and 28th October**

### 4.1.4. Soil moisture representativity examination on footprint scale

The box plots in figure 4-7 compares soil moisture distribution on different land covers and also collected by different equipments in Twente region. During the fieldwork period, soil moisture values are only available at 15 stations, so data from 15 stations are used to compare with 8 stations selected for representativity examinations.



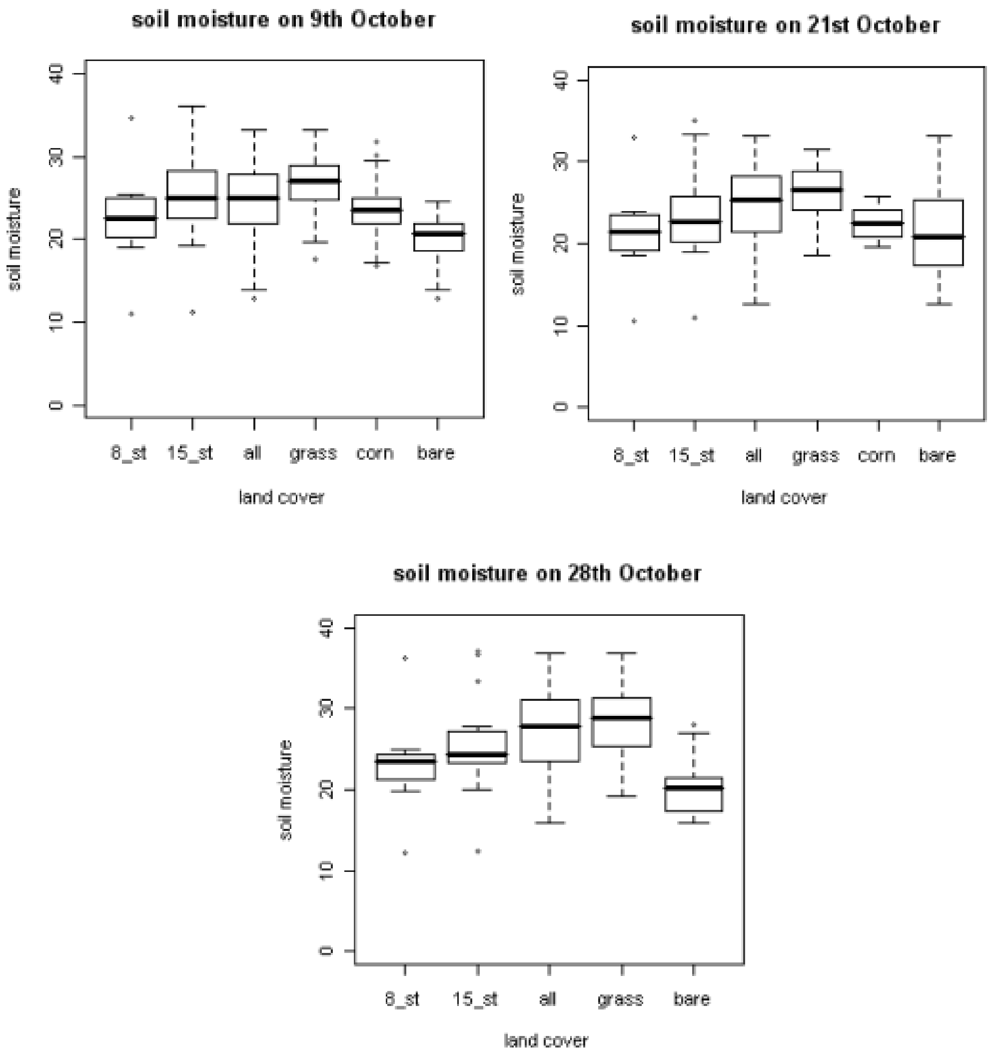



**Figure 4-7** **Box plots for soil moisture on five days**

In each sub-figure, the first two box plots are based on the sensor values of the 8 stations used in the fieldwork and the 15 stations respectively. The third ones are all the measurements from field work in one day regardless of land cover differences. To quantify the differences, t-test was used. The results are listed in table 4-10:

**Table 4-10** **t-test results for representativity**

| | Field _ sensor (8) | | Sensor (15) _ sensor (8) | |
|---|---|---|---|---|
| | **t** | **p-value** | **t** | **p-value** |
| **22nd September** | -0.32 | 0.75 | -0.68 | 0.50 |
| **01st October** | -1.56 | 0.15 | -0.56 | 0.58 |
| **09th October** | -0.58 | 0.57 | -1.00 | 0.33 |
| **21st October** | -1.10 | 0.30 | -0.83 | 0.41 |
| **28th October** | -1.29 | 0.23 | -0.85 | 0.40 |

The results from 8 stations and 15 stations are similar, which means the stations we chose for field work can represent stations installed in Twente region. Generally, sensor values are lower than field measurements. The null hypothesis in this t-test is that there is no significant difference between means of the two datasets. Since the p-values are all much larger than 0.05, which was identified to be the level of rejecting, we cannot reject the hypothesis. Thus there is no significant difference between the means of the field measurements, the sensor values, and the 8 tested stations and all the stations working in Twente region on each day.

#### 4.1.5. Summary and Discussion of representativity

Based on all the analysis in 4.1.2, sensors installed at station st11 and station st17 were not representative on all the 5 tested days. Station st11 overestimated while st17 underestimated soil moisture. It suggested removing these stations. No station showed a perfect representativity during all the tested days. However it is obvious that the more stations are shown to be representative on the last 3 days which were identified as in wet condition. same result got from 4.1.3, and from the histograms of soil moisture, difference of soil moisture under different land cover types increased when the weather getting wetter. That may be caused by higher evaporation and infiltration on top layer of bare land in wet condition, because of the lack of the protective effect of the vegetation. This separation causes high standard deviation which contributes to good representativity in wet condition with mixed land covers. However, obvious differences were found between soil moisture value based on station and Theta- probes even when with measurements were taken on grassland, the reason behind may be the spatial variability, since the stations were installed at the border of fields, and also may caused by the different layers they measured. Stations were installed to measure soil moisture at the depth of 5cm, while Theta-T probe give the information at the depth of 0cm to 6 cm.
At footprint scale, stations installed can represent the intensive soil moisture well, although the station values are relatively lower than Theta-T probes.

### 4.2. Soil moisture spatial distribution on footprint scale

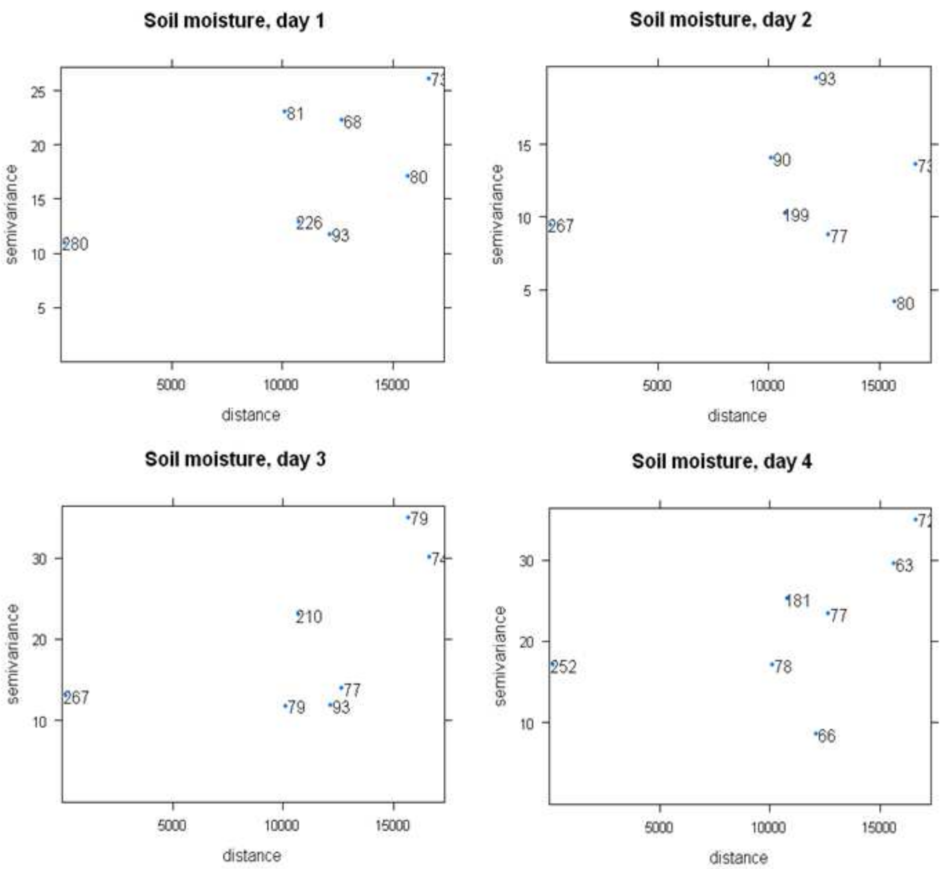
Two methods geostatistical interpolation and temporal stability analysis were used to estimate the spatial distribution of soil moisture In Twente and Maqu regions. The results are presented as follows

#### 4.2.1. Geostatistical interpolation

In this part, the possibilities of interpolation for well estimating spatial soil moisture distributions were tested at two areas. In Twente region, intensive in-situ measurements allow the application of semi-variogram for spatial correlation identification, which is useful to find a model for interpolation. Errors areBoth of the two areas are trend surface he results of interpolation

#### 4.2.1.1. Twente region

In Figure 4-8, semi-variograms based on the field work measurements in the Twente region on the five field measurement days are presented with a lag distance of 1000 m. No clear spatial distribution of the soil moisture can be observed in them with such large lags. There were no point pairs found with separation distances from 1km to 10 km. Semi-variances at the shortest lag are in the same order of magnitude as beyond 10 km, where there is no clear pattern; so it can be concluded that it is not possible to find a fitting kriging model for interpolation with the available data



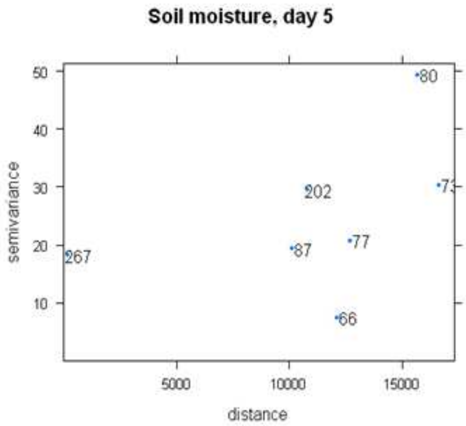



**Figure 4-8 Semi-variogams of soil moisture in Twente region at large scale**

To understand the spatial correlation of soil moisture, same method was applied to shorter lag distances too. Figure 4-9 shows the semi-variograms of soil moisture within 500 meters with lag distance steps of 50 m. In day 1 and day 2 no clear spatial distribution can be observed. The semi-variograms suggest some periodicity, but this might be false. However a clear pattern on the last three days can be obtained up to about 250 m. These three days were relatively wet. This means that in wet condition, the spatial correlation length of soil moisture at this region is longer than in dry conditions, caused by frontal precipitation.

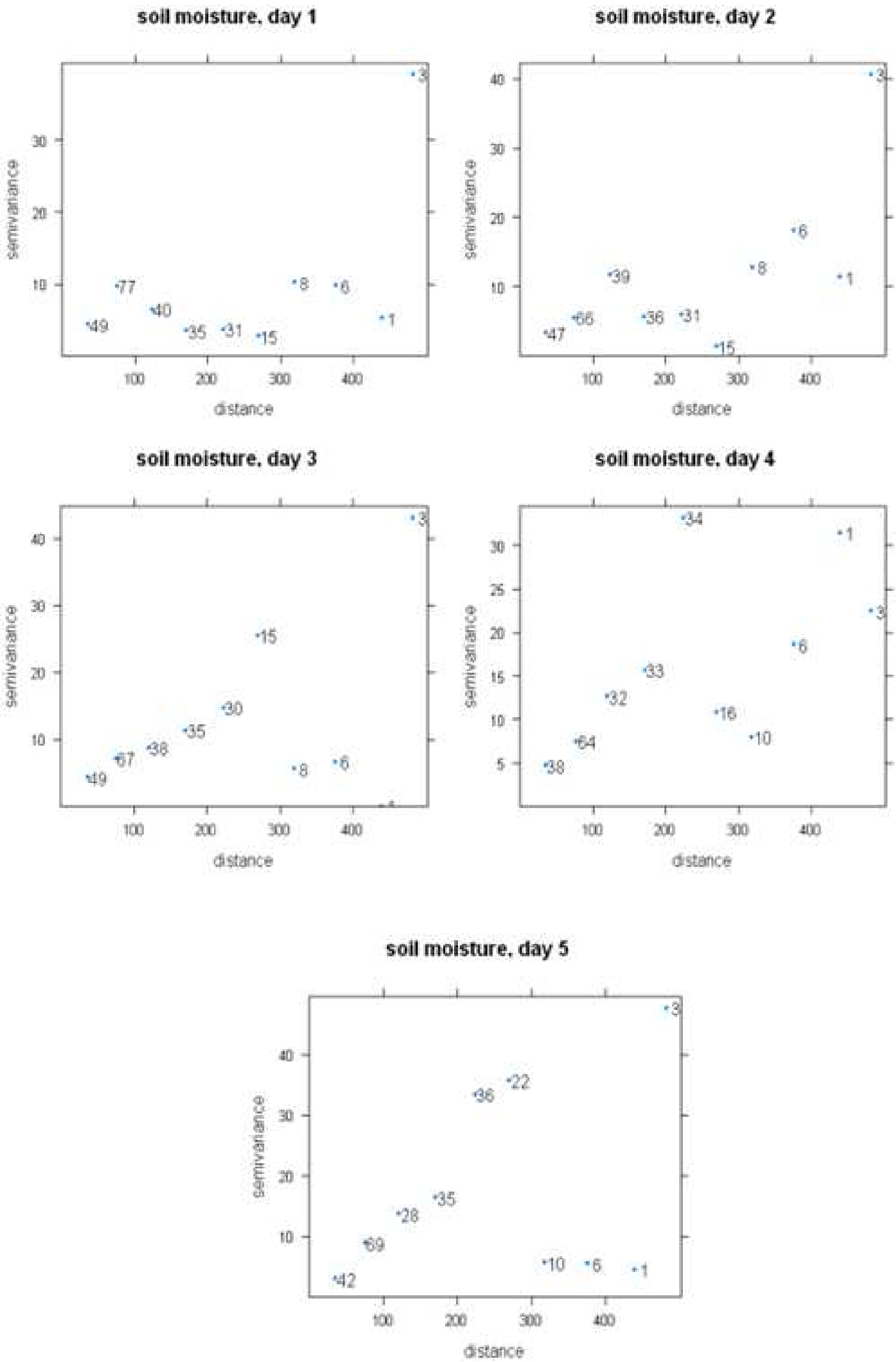



**Figure 4-9 Semi-variogams of soil moisture in Twente region within 500m**

This part spatial correlation within 250 m with steps of 20m was tested to analyse the spatial distribution in day1 and day2 which were in dry condition. A nicer pattern of soil moisture on day 1 was shown up to 100 m distance, while on day 2 still nothing can be concluded. It may be because of a slight rain before several hours of the measurements. The vegetations above soil caused the heterogeneity of precipitation effects to soil moisture. Nice spatial distributions were shown for day 3, day 4 and day5 with a smaller step figure 4-10.

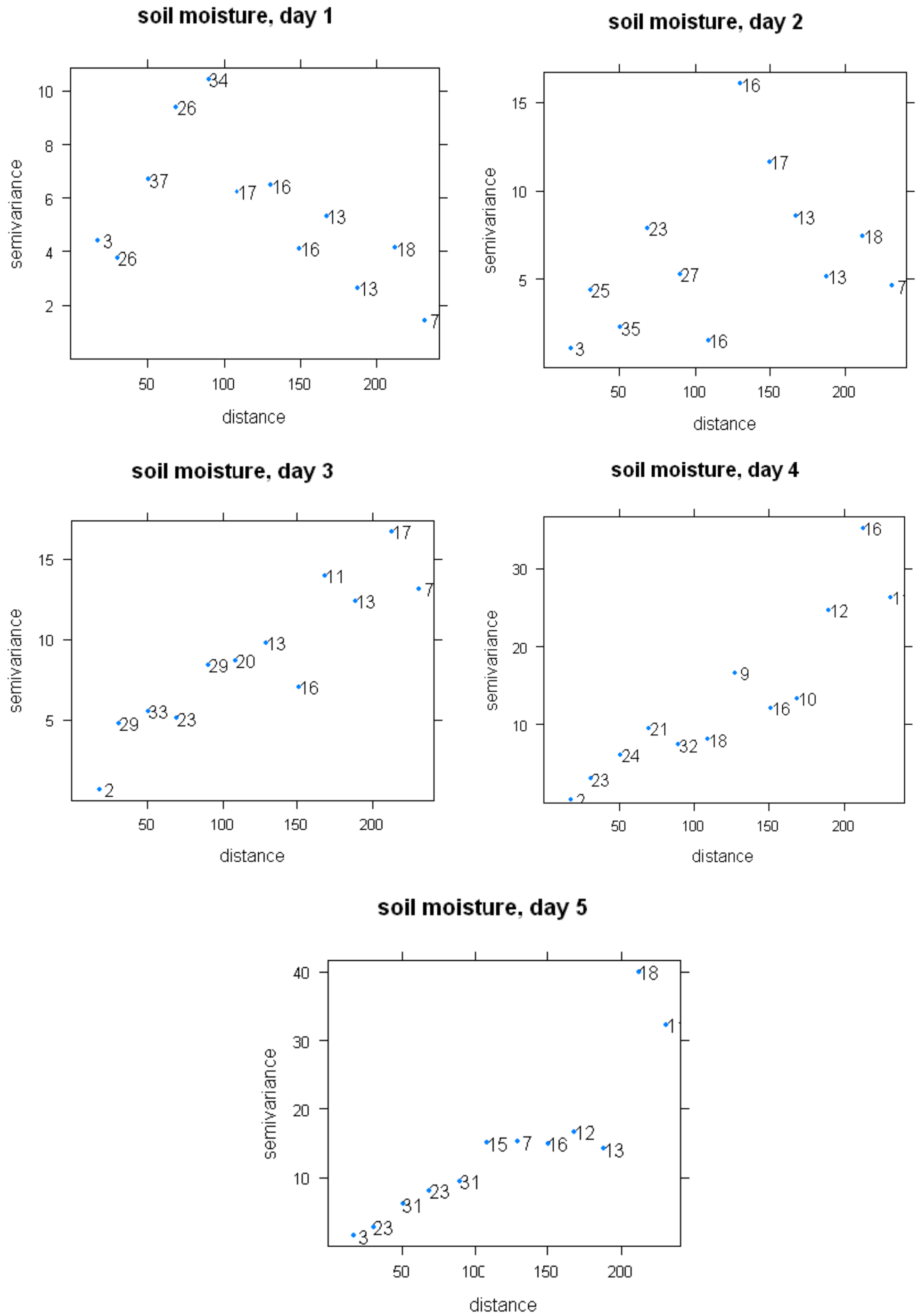



**Figure 4-10 Semi-variogams of soil moisture in Twente region within 250m**

According to the semi-variogram analysis, in this region, the spatial correlation length (the range of the semi-variogram) of the soil moisture is too short compared to the average separation distance of the observation stations in this research. Therefore, as it was mentioned before, kriging cannot be used for interpolation of soil moisture in Twente region.

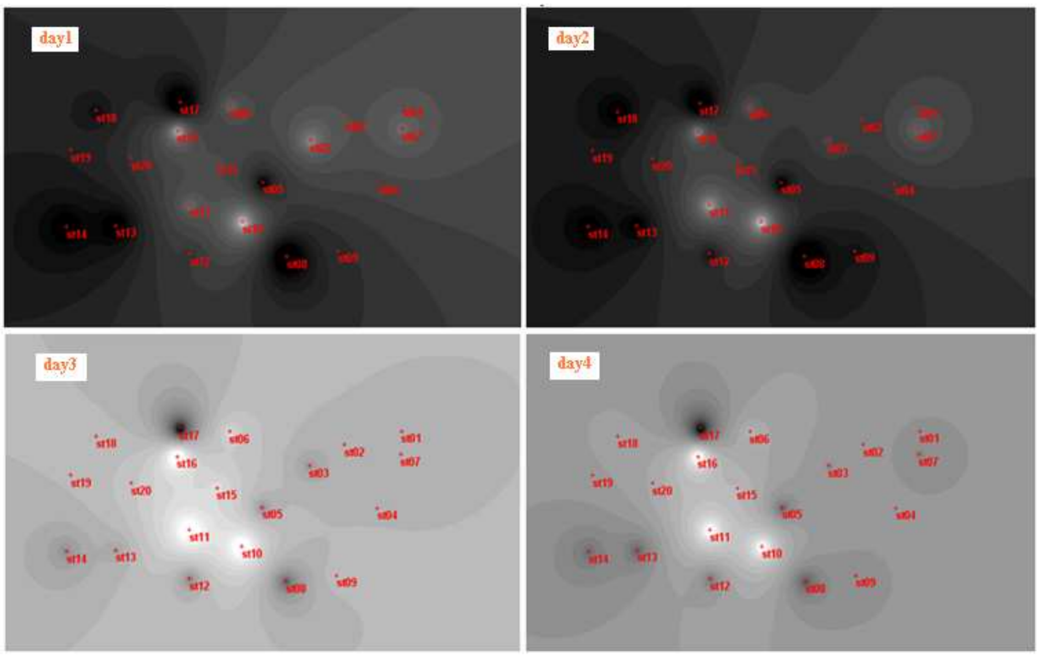
To test regional trends, trend surface fitting was used. These surfaces did not show temporal stability; furthermore, big errors occurred by both first order and second order models. RMSE values were very high for all the 5 days (Table 4-11).

**Table 4-11 RMSE of interpolation results on 5 days in Twente region**

| | day1 | day2 | day3 | day4 | day5 |
|---|---|---|---|---|---|
| First order | 6.23 | 5.95 | 6.28 | 6.06 | 6.02 |
| Second order | 5.53 | 5.01 | 5.28 | 5.18 | 4.83 |

(Day1 is 22$^{nd}$ September 2009, day2 is 01$^{st}$ October 2009, day3 is 09$^{th}$ October 2009, day4 is 21$^{st}$ October 2009, day5 is 28$^{th}$ October 2009)

Figure 4-11 shows soil moisture distribution after interpolation based on inverse distance method for the five days, with same legend. Low soil moisture was presented in black and high with white. According to the above analysis, interpolation does not show the spatial distribution in detail, using such a few data in large area. However, these maps show patterns stable in time, no matter whether in wet or dry condition, which was proved by the fact, that the ranks of soil moisture values of these stations were persistent. Station st17, which is located at the NNW edge, always recorded the lowest moisture value, while stations st10, st11, st16 which are at the centre of the area, had the highest water content. Other stations, generally the ones located at southern part were drier than the stations in the north. This phenomenon indicated that there is a temporal stability of soil moisture distribution in this region.



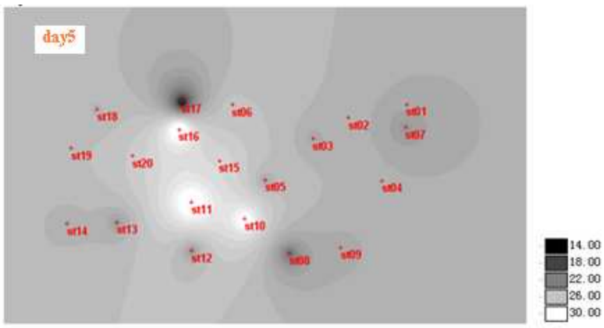



**Figure 4-11 Spatial distribution of soil moisture of 5 days in Twente region**

#### 4.2.1.2. Maqu region

In this region, we don't have intensive measurements to apply a semi-variogram analysis for spatial correlation examination. However, the results of fitting trend surfaces were similar to the Twente region. We choose 5 days, which have the same data availability of stations and different weather conditions. Results showed large errors Table 4-12 and the spatial distributions for different days were similar. In this region, to show the pattern clearly, a different legend was used for day1 from the other 4 days). Stations located at the center of region were always wet, and other stations are also shown to have rank stability at this region. Figure 4-12

**Table 4-12 RMSE of interpolation results on 5 days in Maqu region**

| | day1 | day2 | day3 | day4 | day5 |
|---|---|---|---|---|---|
| First order | 5.94 | 5.60 | 8.06 | 4.92 | 4.08 |
| Second order | 5.95 | 5.64 | 7.97 | 4.96 | 4.08 |

(Day1 is 22nd September 2008, day2 is 01st October 2008, day3 is 09th October 2008, day4 is 21st October 2008, day5 is 28th October 2008)

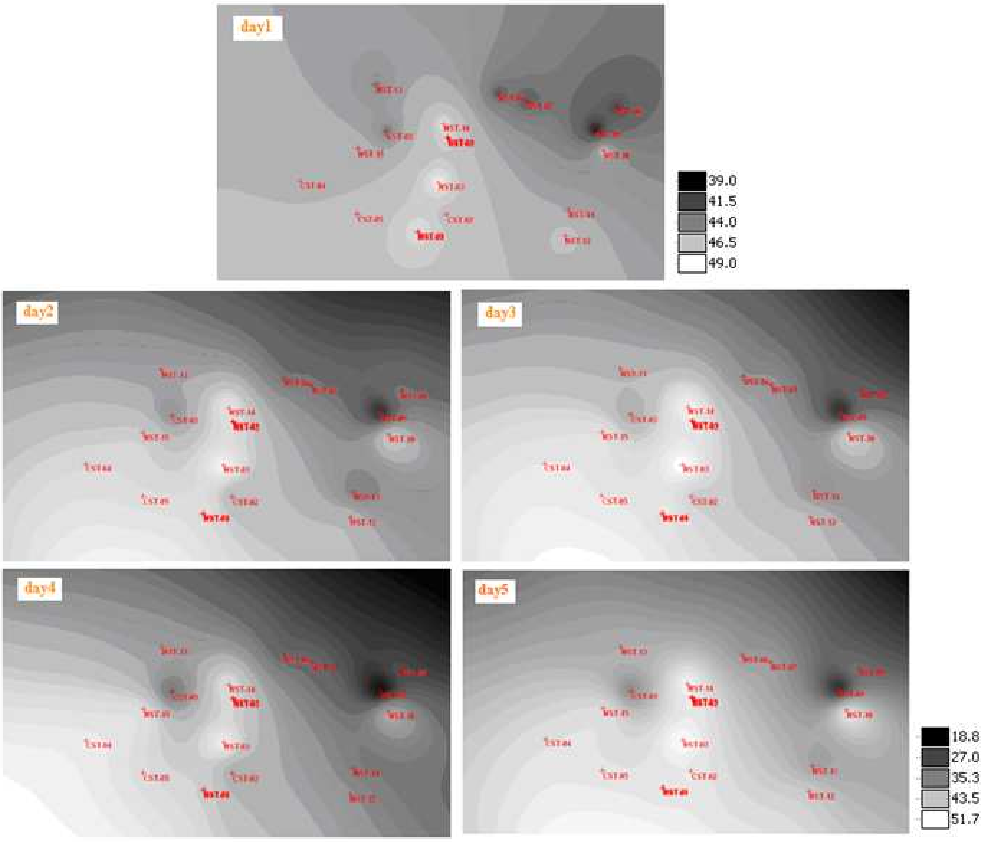



**Figure 4-12 Spatial distribution of soil moisture of 5 days in Maqu region**

### 4.2.2. Temporal stability analysis

In this part, temporal stability presented by MRD and SDRD was tested at these two areas for the whole study periods. Considering the seasonal influences, temporal stability of each station was also tested by seasons, which is identified by weather conditions (temperature and precipitation. Correlations between each station at one area were calculated to find the representative stations.

#### 4.2.2.1. Maqu region

- **MRD and SDRD**

First the temporal stability was applied for the whole study period, Figure 4-13. Station nst15 is shown with big variance which means this station is not temporally stable. The most representative station can be selected from nst1, nst13, cst4. Data in nst1 and cst4 is available only for a short period. Therefore station nst13 was selected as the representative station which can be used for long term estimation of spatial averaged soil moisture.

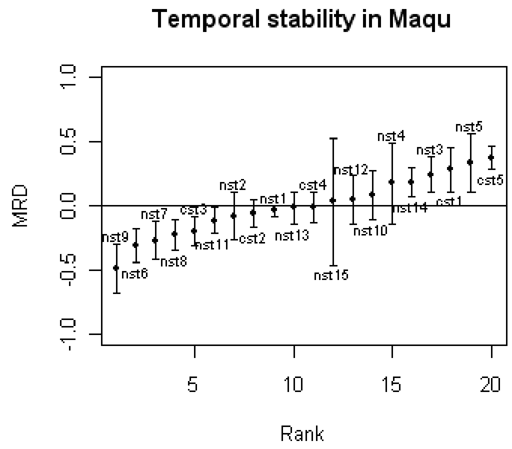



**Figure 4-13 Mean relative difference plot for Maqu region (from 30th June 2008 to 12th 2009)**

Considering that soil moisture spatial distribution may change as the weather conditions change, temporal stability analysis was applied to different parts of study period. According to Figure 4-14, this study period can be separated into four sub-periods, however due to the limitation of data availability, in this study the first two sub-periods were analysed as one.

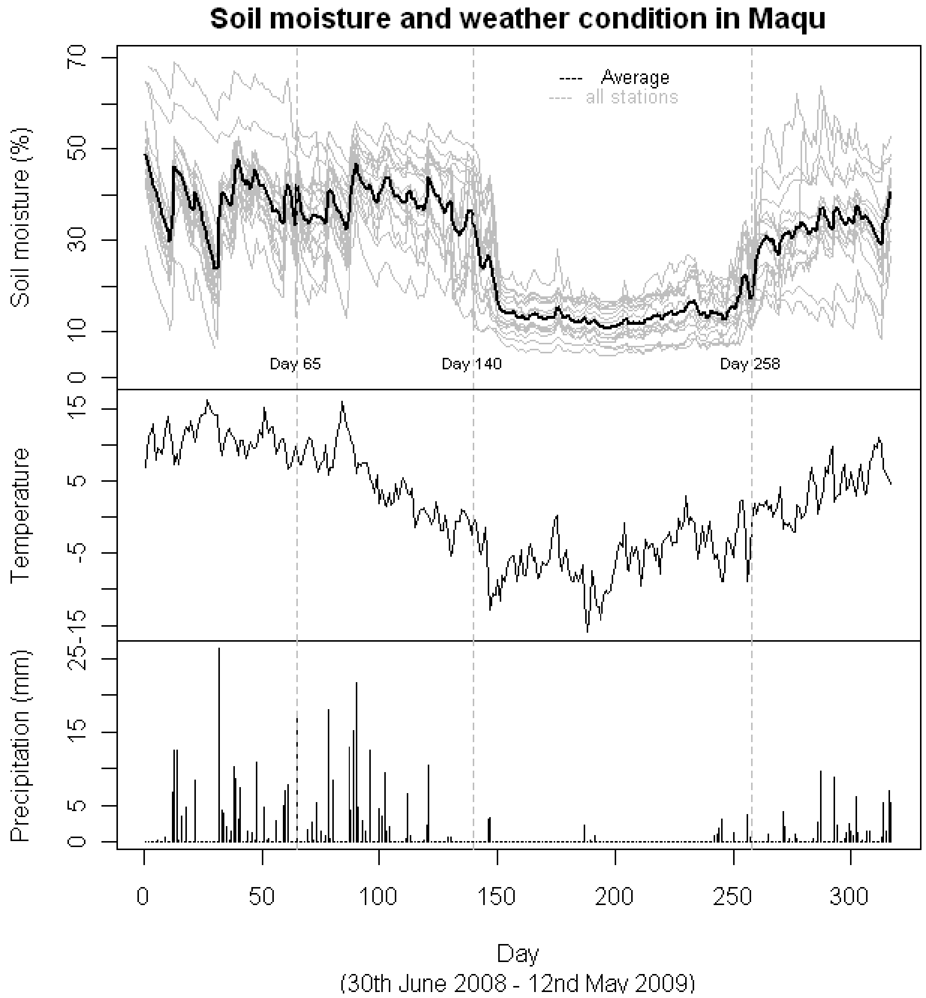



**Figure 4-14 Time series of soil moisture at all stations and spatial average in Maqu comparing with Temperature and precipitation**

Therefore, the first sub-period is from 30th June 2008 (Day1) to 16th November (Day140), which is almost summer and autumn. During this period, temperature was above 0 degree, and large amount of precipitation events were recorded. The second period is from 17th November (Day umber141) to 16th March (Day 258). This sub-period is cold and dry, with temperature below 0 degree and few precipitation events can be seen as winter time. The last sub-period is from 17th March 2009 (Day number 259) to 12th May 2009(Day number 316). In this sub-period, weather is getting warmer and wetter and can be recognized as spring.

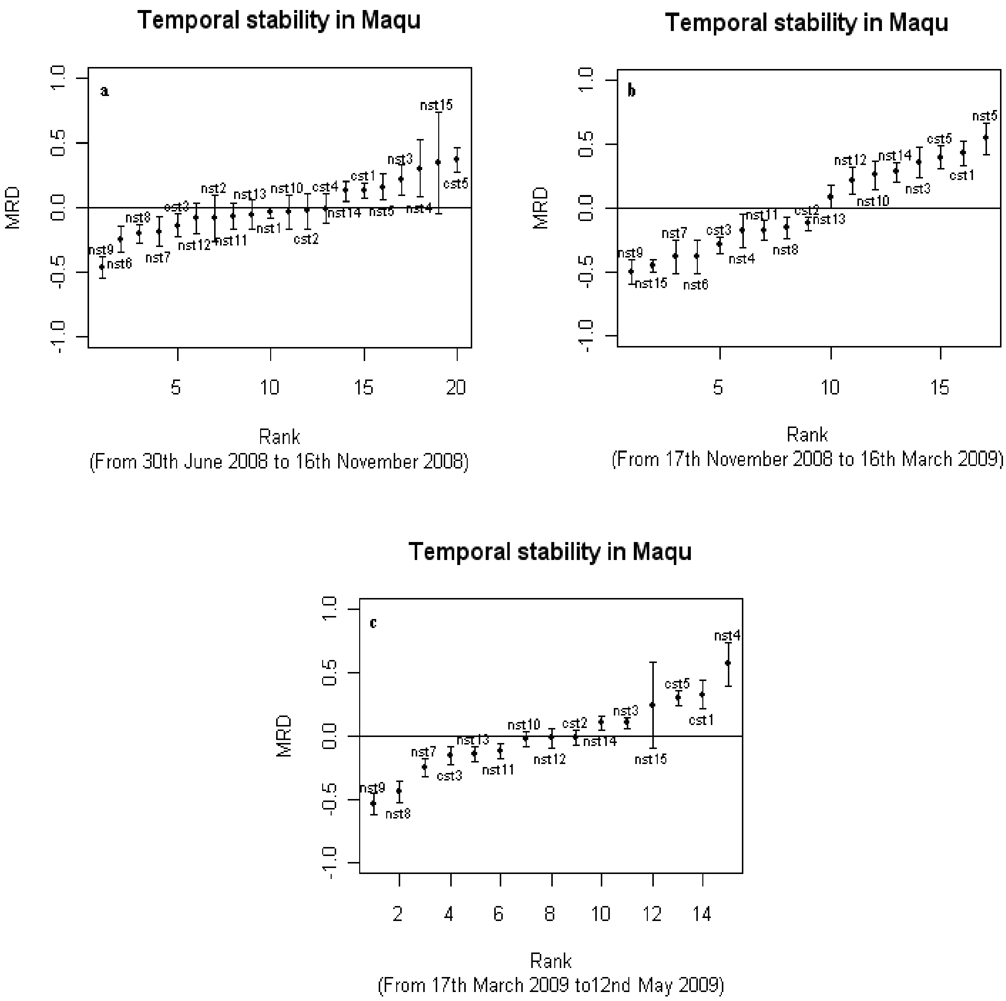



**Figure 4-15  Mean relative difference plot for Maqu region**

(a, b, c, are sub-period 1,2,3 respectively)

According to Figure 4-15, there is no obvious spatial distribution change between three sub periods. Station nst9 always recorded lower values compared to others. This may be due to the fact that the soil at nst9 is very sandy, contains about 61% of sand, which is almost 2 to 3 times higher than that of other stations. The values of nst6 and nst7 are lower than the average as well. The locations of these stations may be the reason; these three stations are all installed in the northeast part of the area, quite close to river. On the contrary, cst1, cst5 and nst3 are always wetter than the average values. No distinct characteristics can be found in these stations. Variation of stability is quite small for most of the stations during the study period except nst15 and nst10. Nst15 and nst10 were installed in an area with a steep slope of 32% and 18% higher in the mountains. In sub-period 1 and 3, both of these stations are much wetter than the average soil moisture of the area and have large variations; while in sub-period 2, they recorded lower values compared to the mean.  The most representative station at each sub-period is cst2. Although MRD for nst13 is very close to 0 when considering the whole period, it is relatively lower in sub-period 1and 3 but a little higher in sub-period 2. At the same time cst2 with a MRD a little bit lower than 0 is very constant in both of the two conditions. In that case both of the two stations were used as representative stations for future analysis. Time series of soil moisture values at station nst13 and cst2 are presented with spatial average in Figure 4-16, both of the two representative stations recorded soil moisture close to spatial average and follows a similar trend at most of the study period.

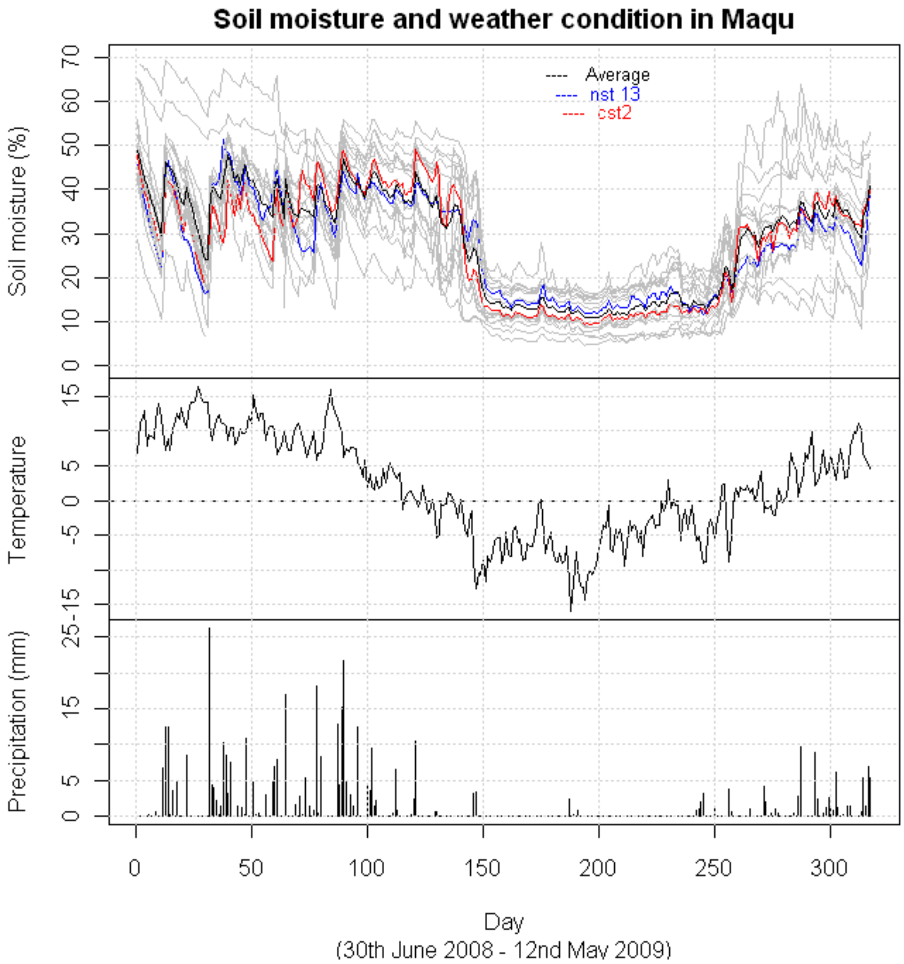



**Figure 4-16 Temperature and precipitation with soil moisture time series at all stations comparing with representative one and field average**

- **Correlation coefficient analysis**

Table 4-13 shows the correlation of soil moisture within two stations during the same period, very high correlations are observed between different stations. Lower correlations are shown in station nst1, nst2, cst4, cst5 where there is data missing. The representative stations we choose in previous analysis are nst 13 and cst 2 very high correlation coefficients were obtained, range from 0.62 to more than 0.9. Similar results can be obtained by this analysis.

**Table 4-13 Correlation coefficients between stations in Maqu region during study period**

| | nst1 | nst2 | nst3 | nst4 | nst5 | nst6 | nst7 | nst8 | nst9 | nst10 | nst11 | nst12 | nst13 | nst14 | nst15 | cst1 | cst2 | cst3 | cst4 | cst5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| nst1 | 1.00 | 0.84 | 0.73 | 0.27 | 0.89 | 0.84 | 0.79 | 0.86 | 0.84 | 0.85 | 0.74 | 0.73 | 0.80 | 0.82 | 0.18 | 0.98 | 0.70 | 0.86 | 0.75 | 0.89 |
| nst2 | | 1.00 | 0.41 | 0.59 | 0.79 | 0.73 | 0.73 | 0.77 | 0.54 | 0.61 | 0.63 | 0.62 | 0.57 | 0.56 | 0.56 | 0.79 | 0.50 | 0.58 | 0.51 | 0.26 |
| nst3 | | | 1.00 | 0.86 | 0.98 | 0.92 | 0.90 | 0.89 | 0.90 | 0.93 | 0.91 | 0.90 | 0.93 | 0.97 | 0.79 | 0.94 | 0.95 | 0.92 | 0.62 | 0.98 |
| nst4 | | | | 1.00 | 0.90 | 0.90 | 0.90 | 0.76 | 0.76 | 0.81 | 0.89 | 0.81 | 0.82 | 0.87 | 0.89 | 0.93 | 0.85 | 0.88 | 0.06 | 0.92 |
| nst5 | | | | | 1.00 | 0.92 | 0.90 | 0.93 | 0.92 | 0.95 | 0.90 | 0.94 | 0.94 | 0.96 | 0.78 | 0.97 | 0.96 | 0.92 | 0.64 | 0.98 |
| nst6 | | | | | | 1.00 | 0.98 | 0.95 | 0.91 | 0.91 | 0.92 | 0.86 | 0.92 | 0.95 | 0.86 | 0.94 | 0.93 | 0.95 | 0.41 | 0.93 |
| nst7 | | | | | | | 1.00 | 0.89 | 0.85 | 0.87 | 0.93 | 0.83 | 0.90 | 0.93 | 0.90 | 0.90 | 0.89 | 0.94 | 0.38 | 0.93 |
| nst8 | | | | | | | | 1.00 | 0.91 | 0.87 | 0.92 | 0.83 | 0.86 | 0.89 | 0.81 | 0.81 | 0.86 | 0.89 | 0.89 | 0.91 |
| nst9 | | | | | | | | | 1.00 | 0.95 | 0.92 | 0.92 | 0.90 | 0.93 | 0.70 | 0.89 | 0.92 | 0.89 | 0.92 | 0.91 |
| nst10 | | | | | | | | | | 1.00 | 0.90 | 0.94 | 0.92 | 0.95 | 0.73 | 0.92 | 0.96 | 0.92 | 0.78 | 0.95 |
| nst11 | | | | | | | | | | | 1.00 | 0.90 | 0.91 | 0.95 | 0.91 | 0.91 | 0.91 | 0.97 | 0.80 | 0.95 |
| nst12 | | | | | | | | | | | | 1.00 | 0.89 | 0.93 | 0.72 | 0.93 | 0.92 | 0.89 | 0.70 | 0.94 |
| nst13 | | | | | | | | | | | | | 1.00 | 0.94 | 0.79 | 0.91 | 0.90 | 0.91 | 0.93 | 0.96 |
| nst14 | | | | | | | | | | | | | | 1.00 | 0.83 | 0.95 | 0.97 | 0.97 | 0.86 | 0.98 |
| nst15 | | | | | | | | | | | | | | | 1.00 | 0.80 | 0.78 | 0.90 | 0.55 | 0.85 |
| cst1 | | | | | | | | | | | | | | | | 1.00 | 0.94 | 0.92 | 0.76 | 0.96 |
| cst2 | | | | | | | | | | | | | | | | | 1.00 | 0.94 | 0.69 | 0.98 |
| cst3 | | | | | | | | | | | | | | | | | | 1.00 | 0.83 | 0.94 |
| cst4 | | | | | | | | | | | | | | | | | | | 1.00 | NA |
| cst5 | | | | | | | | | | | | | | | | | | | | 1.00 |

#### 4.2.2.2. Twente region

- **MRD and SDRD**

In this region, soil moisture data was collected at 17 stations from 1st April to 15th November 2009. In previous chapter, I suggested to remove station 11 and station 17. However, since sensor in station 11 overestimated the field soil moisture while station 17 underestimated, there was not much difference in the spatial average based on 17 stations or 15 stations, and the same was experienced in the temporal stability analysis. Thus, I still use the data collected from all the stations available.

Figure 4-17 shows temporal stability of soil moisture at each station in the Twente region.

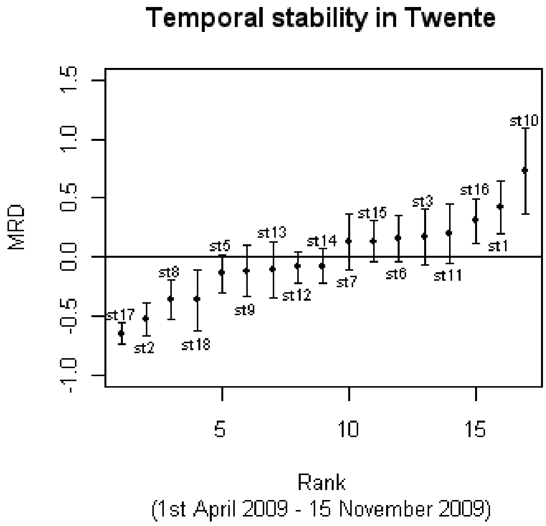



**Figure 4-17 Mean relative difference plot for Twente region**

In this region, it is not easy to find a station with MRD close to 0 and low SDRD. Station15, station14 and station12 are relatively representative (-0.15<MRD<0.15, SD<0.2). Since there is data missing in station14 and station12, station15 was selected as the representative station.

Since this region is covered by intensive corn fields and other vegetation types, spatial distribution may change along with plant growth. Thus it is practical to divide this period into three parts by seasons. Figure 4-18 gives the soil moisture temporal structure in Twente region with temperature and precipitation, three sub-periods are shown here, the first sub-period is from 1st April 2009 (DOY91) to 31st May 2009 (DOY151), this sub-period is almost spring In Twente, with little precipitation. The second sub-period is from 1st June 2009(DOY152) to 31st August 2009(DOY246), during these days, precipitation is intensive and temperature is high. Therefore this sub-period can be seen as summer, and the third period from 1st September 2009(DOY246) to 15th November 2009(DOY322) can be recognized as autumn.

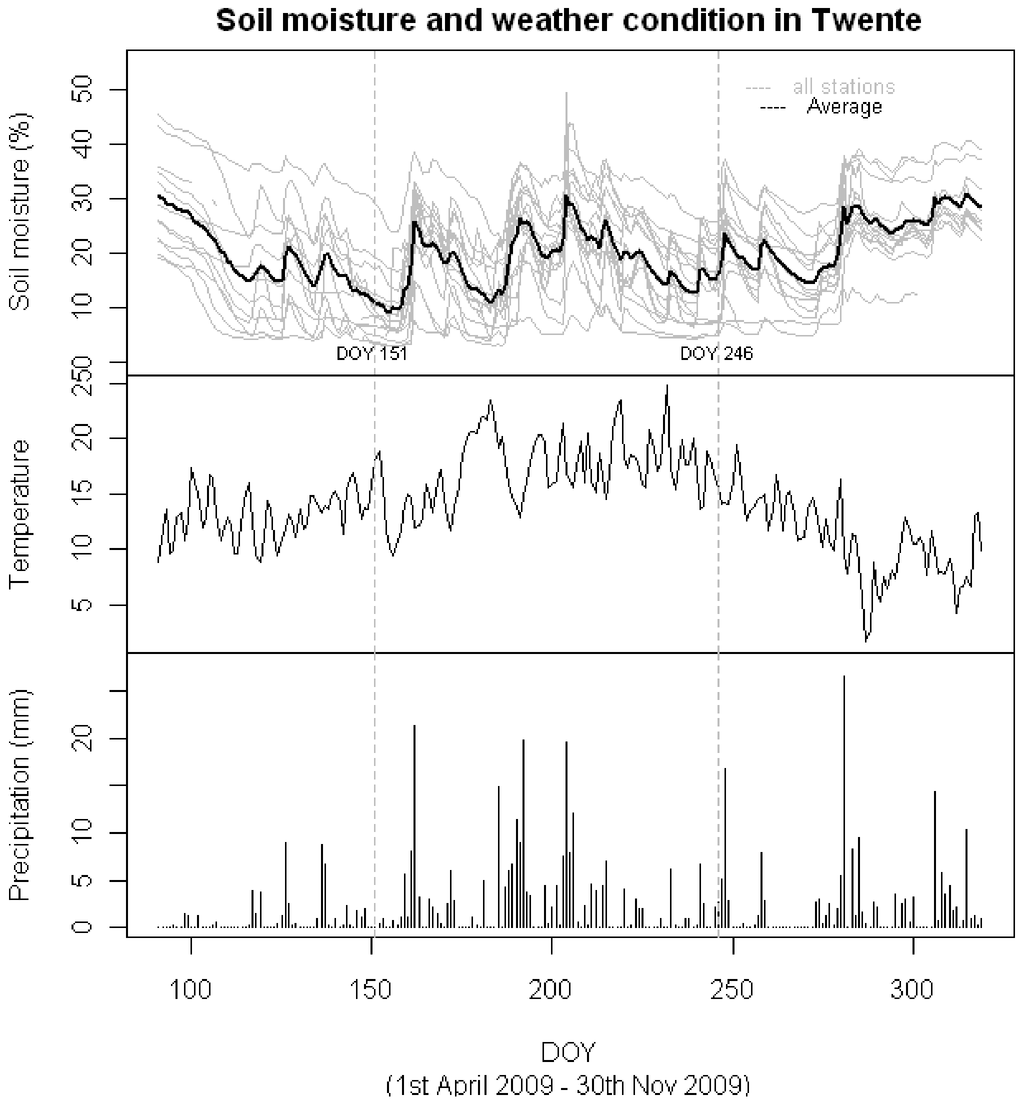



**Figure 4-18 Time series of soil moisture at all stations and spatial average In Twente comparing with Temperature and precipitation**

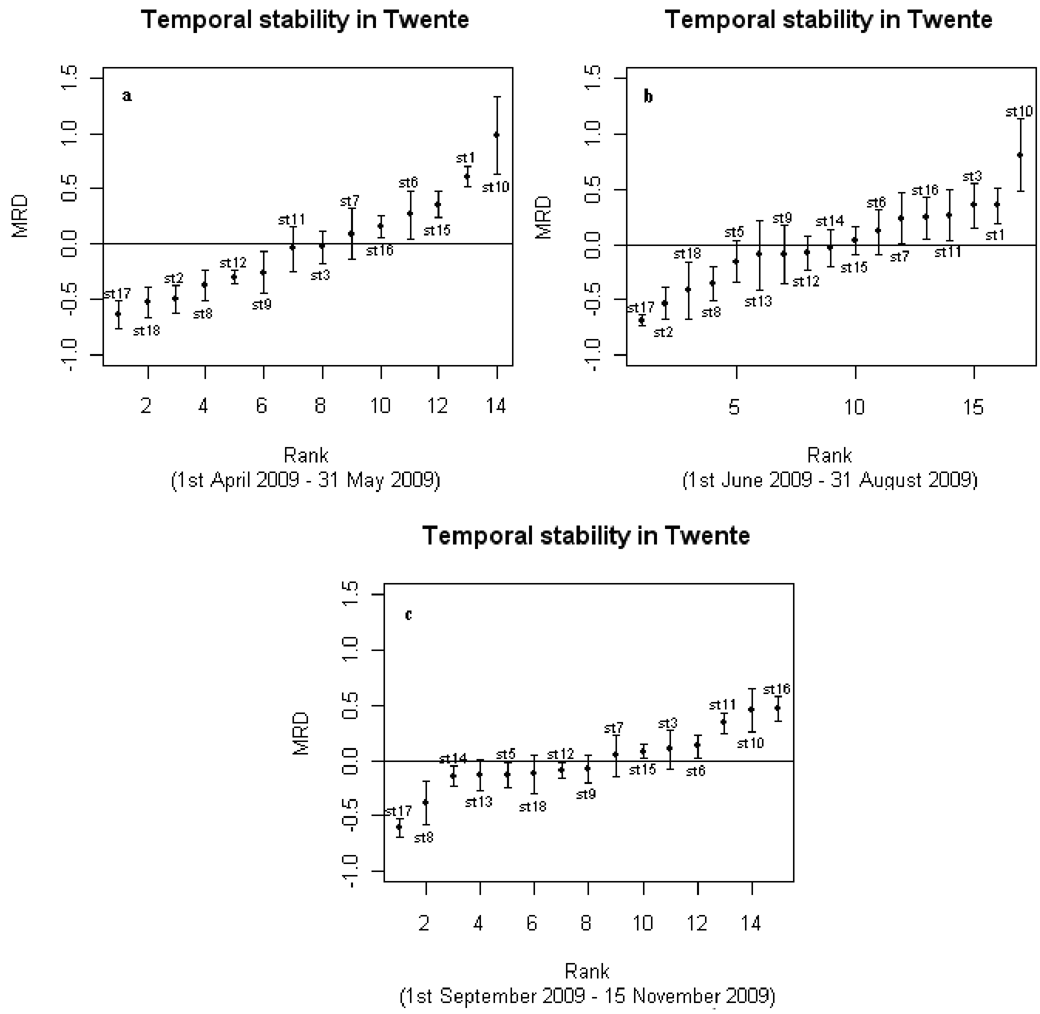



**Figure 4-19 Mean relative difference plot for Twente region**

In Figures 4-19(a) (b) and (c), three graphs show the temporal stability of three sub-periods in Twente region. By comparing the results, the spatial distribution of soil moisture in this region during different seasons are similar. Station st18, station st8 and station st5 were always lower than the average, while station st16, station st6 and station st10 were relatively wetter. The originally chosen representative station is not acceptable in the first period, while station st3 was quite close to mean. Thus, station st15 and the combination of station st3 and station st15 were used in the further analysis to represent this region.

Figure 4-20 presents soil moisture time series with temperature and precipitation during the study period. Station st15 and station st3 were selected as representative stations in the previous analysis. However, none of the stations were fully satisfactory during spring. Big errors were found at station st15 while st 3 lost the real trend of the spatial mean..

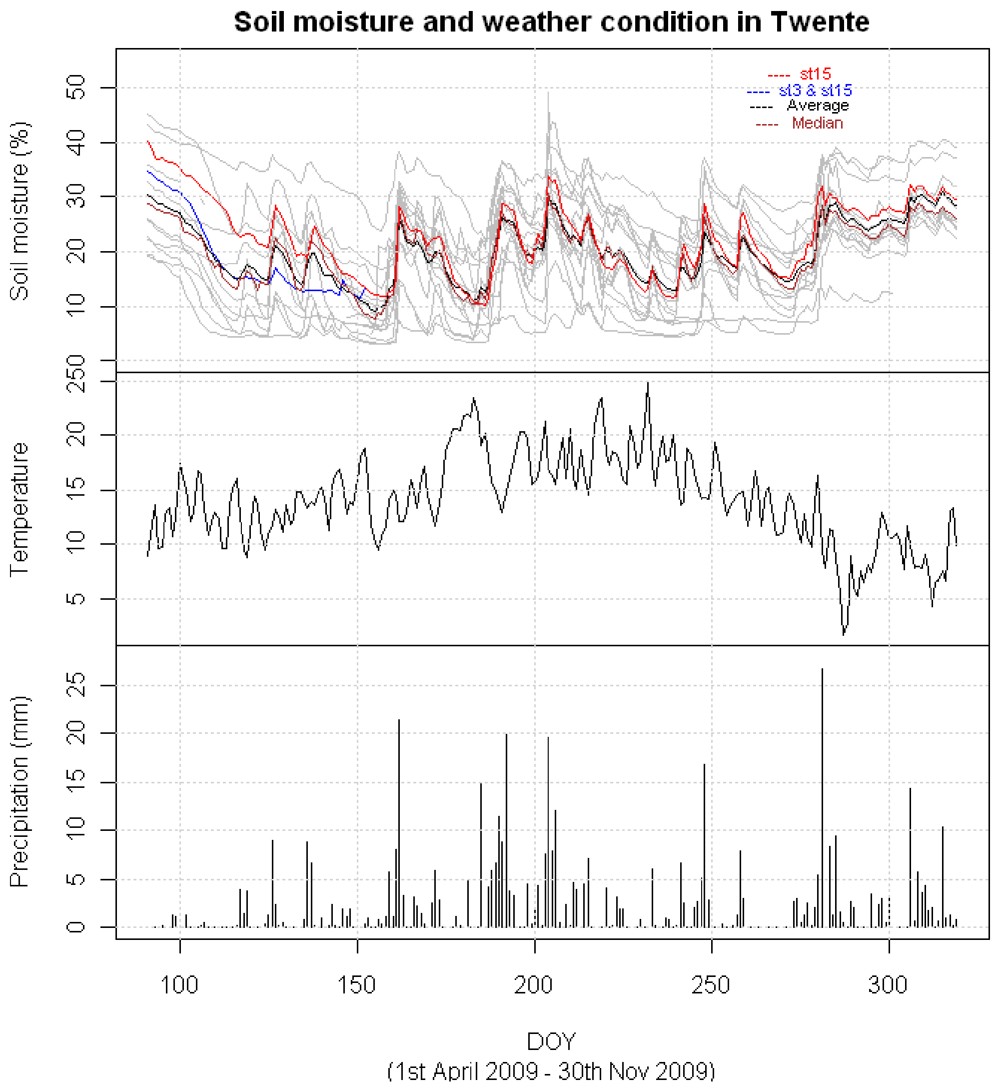



**Figure 4-20 Temperature and precipitation with soil moisture time series at all stations comparing with representative one and field average**

- **Correlation coefficient analysis**

Table 4-14 shows the correlation matrix of the soil moisture measured at the stations during the studied period. The correlation coefficients in this region are relatively low; most of them are between 0.5 and 0.8. The lowest correlations are shown in pairs containing station st07. The representative station we choose in the previous analysis is station st15; Correlation coefficients between this station and others are around 0.6 - 0.8.

**Table 4-14 Correlation coefficients between stations in Twente**

| | st1 | st2 | st3 | st5 | st6 | st7 | st8 | st9 | st10 | st11 | st12 | st13 | st14 | st15 | st16 | st17 | st18 | st3&st15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| st1 | 1.00 | 0.77 | 0.53 | 0.69 | 0.66 | 0.24 | 0.83 | 0.60 | 0.90 | 0.51 | 0.71 | 0.49 | 0.75 | 0.88 | 0.62 | 0.75 | 0.60 | 0.79 |
| st2 | | 1.00 | 0.68 | 0.74 | 0.59 | 0.51 | 0.78 | 0.77 | 0.65 | 0.69 | 0.54 | 0.53 | 0.73 | 0.76 | 0.72 | 0.81 | 0.66 | 0.69 |
| st3 | | | 1.00 | 0.72 | 0.56 | 0.68 | 0.70 | 0.68 | 0.50 | 0.76 | 0.79 | 0.45 | 0.68 | 0.57 | 0.73 | 0.56 | 0.63 | 0.77 |
| st5 | | | | 1.00 | 0.80 | 0.78 | 0.79 | 0.84 | 0.80 | 0.88 | 0.80 | 0.82 | 0.87 | 0.94 | 0.85 | 0.69 | 0.73 | 0.95 |
| st6 | | | | | 1.00 | 0.70 | 0.63 | 0.66 | 0.70 | 0.69 | 0.71 | 0.67 | 0.71 | 0.78 | 0.84 | 0.59 | 0.72 | 0.75 |
| st7 | | | | | | 1.00 | 0.54 | 0.77 | 0.37 | 0.80 | 0.71 | 0.65 | 0.72 | 0.45 | 0.76 | 0.40 | 0.67 | 0.65 |
| st8 | | | | | | | 1.00 | 0.77 | 0.75 | 0.73 | 0.77 | 0.70 | 0.87 | 0.81 | 0.75 | 0.74 | 0.71 | 0.78 |
| st9 | | | | | | | | 1.00 | 0.58 | 0.80 | 0.74 | 0.73 | 0.86 | 0.69 | 0.78 | 0.62 | 0.74 | 0.69 |
| st10 | | | | | | | | | 1.00 | 0.48 | 0.80 | 0.73 | 0.86 | 0.86 | 0.57 | 0.57 | 0.44 | 0.88 |
| st11 | | | | | | | | | | 1.00 | 0.88 | 0.68 | 0.82 | 0.63 | 0.89 | 0.68 | 0.84 | 0.85 |
| st12 | | | | | | | | | | | 1.00 | 0.62 | 0.71 | 0.84 | 0.75 | 0.64 | 0.70 | 0.63 |
| st13 | | | | | | | | | | | | 1.00 | 0.81 | 0.82 | 0.67 | 0.56 | 0.56 | 0.76 |
| st14 | | | | | | | | | | | | | 1.00 | 0.87 | 0.76 | 0.58 | 0.65 | 0.77 |
| st15 | | | | | | | | | | | | | | 1.00 | 0.80 | 0.75 | 0.64 | 0.76 |
| st16 | | | | | | | | | | | | | | | 1.00 | 0.72 | 0.88 | 0.96 |
| st17 | | | | | | | | | | | | | | | | 1.00 | 0.67 | 0.56 |
| st18 | | | | | | | | | | | | | | | | | 1.00 | 0.77 |
| st3&st15 | | | | | | | | | | | | | | | | | | 1.00 |

### 4.2.3. Summary and discussion of spatial distribution

Variogram analysis got spatial correlation length of Surface soil moisture in the Twente region is only 250m in wet condition 4.2.1, and in dry condition a spatial correlation length is shorter, this can be a reason why in wet condition soil moisture representativity is better in wet condition as presented in 4.1.2 and 4.1.3. However this correlation length is too short compare with the distances between stations in this network. Geostatistical interpolation based on trend surface brings big errors when estimating spatial soil moisture pattern in large area, therefore the spatial pattern shown in Figure 4-11 and Figure 4-12 cannot tell the soil moisture between stations. Thus geostatistical interpolation cannot applied to estimate soil moisture distribution with small sample size in large region However there is a rank temporal stability by comparing the tested days. Same situation was observed in Maqu. This stability supports the use of temporal stability analysis.

Temporal stability analysis shows that when considering the stability of a long term, it is easier to find a representative station in the Maqu region than in the Twente region 4.2.2. When focus on temporal stability change between seasons , the representative station in the Maqu region changed, that means the representative station selected for long term estimation has temporal instability between seasons, in this study, since MRD differences between seasons at nst 13 is small, both of the stations nst13 and cst2 were selected for upscaling. Nst15 and nst10 was tested instable, since both of them are located at a place with higher slope, slope may be the reason, which causes temporal instability of soil moisture in this region. However no more data needs to be obtained to prove that. In Twente region, the station st15 is the most representative station, however large bias was found in spring, in which no station can well represent the area, MRD at station st03 recorded close to spatial mean. The reason may be, heterogeneous precipitation in spring, since small precipitation was recorded. Therefore in Twente region point measurements for upscaling can be based on st03 and st15 in spring and st15 in summer and winter.

## 4.3. Upscaling operators

Upscaling using 3 methods were applied in both of the two regions. Detail presented in 4.3.1 for Maqu region, and 4.3.2 for Twente region.

### 4.3.1. Maqu region

To upscale the soil moisture values measured at a point to the scale of an AMSR-E pixel, statistical methods are used. In the Maqu region, cst2 and nst13 were selected as representative stations for upscaling. $R^2$ of the linear regression between nst13, cst2 and spatial average are 0.91 and 0.92, respectively. Second order polynomials show better fits with both data series, with adjusted $R^2$ 0.93 and 0.94. However, no advantage was observed when using third order polynomials or higher. Table 4-15 give the parameters of the used transformation methods.

**Table 4-15 Transformation parameters to upscale point measurements**

| | Linear relationship $\hat{y}_j = aS_{i,j} + b$ | | Second order $\hat{y}_j = aS_{i,j} + bS^2_{i,j} + c$ | | | MRD $\hat{y}_j = \frac{S_{i,j}}{\bar{\delta}_i + 1}$ |
|---|---|---|---|---|---|---|
| | a | b | a | b | c | $\bar{\delta}_i$ |
| nst13 | 1.033 | 0.3888 | 2.2069 | −0.0214 | −13.286 | -0.109 |
| cst2 | 0.8975 | 3.9801 | 1.768 | −0.0165 | −4.9541 | -0.058 |

Figure 4-21 shows how the soil moisture point measurements are transformed to spatial average by three statistical methods. As we see, the upcaling results – based on the same station using three different methods – show similar trends and bias compared with the spatial average, while more differences were obtained from different stations. The upscaled soil moisture at station nst13 is smoother than that based on station cst2

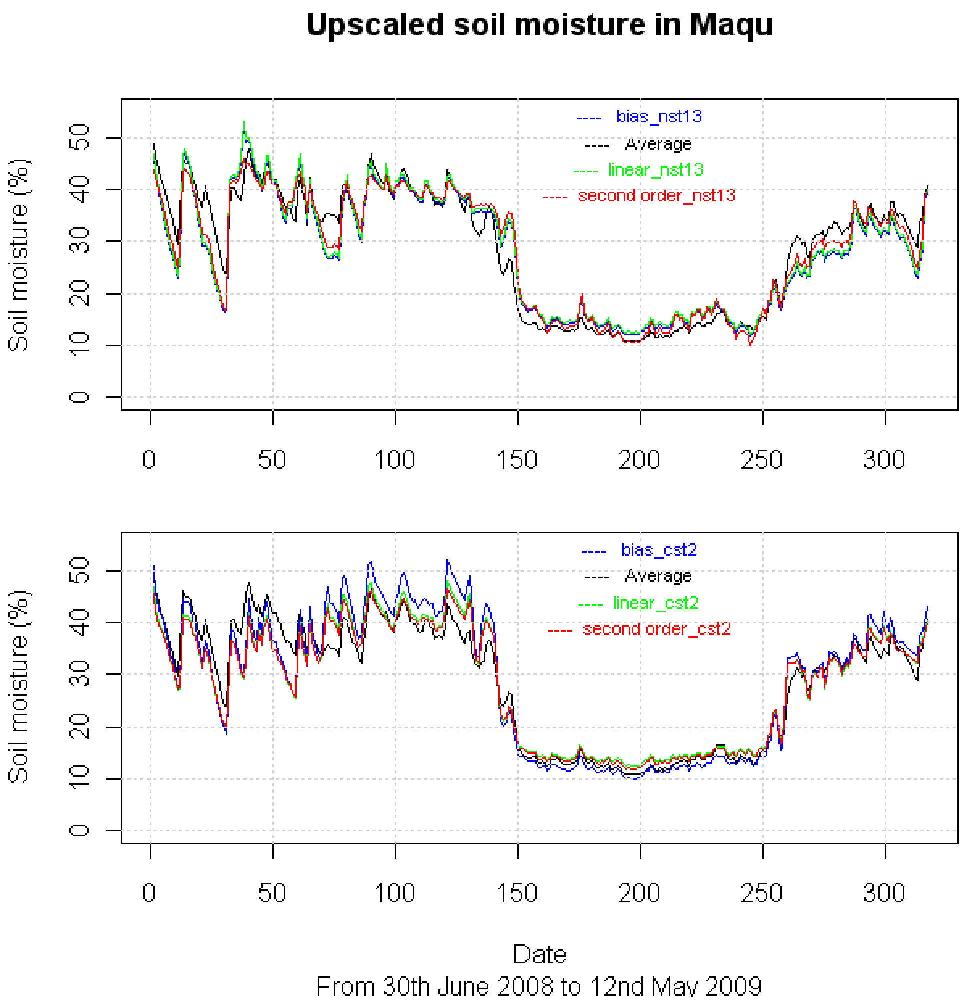



**Figure 4-21 Temporal structure of soil moisture after upscaling through three methods from nst13 and cst 2 in Maqu**

Correlation coefficient (R), root mean square error (RMSE) and absolute mean difference (BIAS) are calculated between spatial average and upscaled data by three different methods are listed in Table 4-16.

**Table 4-16 RMSE, BIAS, R between observed field average soil moisture of Maqu region and point measurements upscaled measurements from nst13 and cst2**

| | nst13 | | | | cst2 | | | |
|---|---|---|---|---|---|---|---|---|
| | Point measurements | Absolute differences | Linear relation | second order | Point measurements | Absolute differences | Linear relation | second order |
| R | 0.95 | 0.95 | 0.92 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 |
| RMSE | 3.81 | 3.65 | 3.58 | 3.07 | 3.72 | 3.92 | 3.30 | 3.15 |
| BIAS | 1.27 | 0.74 | 0.25 | 0.30 | 1.16 | 0.54 | 0.01 | 0.24 |

Correlation coefficient R is similar for each transformation method. Second order polynomials performed better than the other two conversions when considering RMSE, while smallest bias was obtained from linear transformation. In summary, the second order polynomial using station cst2 was the best choice for upscaling at this region.

### 4.3.2. Twente region

To convert the point scaled soil moisture value to footprint scale, statistical corrections are used. In Twente region station st15 and combination of station st03 and station st15 were selected to do upscaling. $R^2$ of linear regression between two point scaled measurements and spatial average were 0.79 and 0.90 respectively. After matching higher order polynomials, best fit was found by using third order regression with $R^2$ 0.8 between station st15 and spatial average, and second order regression with $R^2$ 0.79 between station st15 combined with station st03. Table 4-17 give the parameters of each transformation method.

**Table 4-17 Transformation parameters to upscale point measurements**

| | Linear relationship $\hat{y}_j = aS_{i,j} + b$ | | Higher order $\hat{y}_j = a + bS_{i,j} + cS^2_{i,j} + dS^3_{i,j}$ | | | | Absolute differences $\hat{y}_j = \frac{S_{i,j}}{\bar{\delta}_i + 1}$ |
|---|---|---|---|---|---|---|---|
| | a | b | a | b | c | d | $\bar{\delta}_i$ |
| St15 | 0.7143 | 3.8033 | 14.946 | −0.9311 | 0.0749 | −0.0011 | 0.304 |
| St15&03 | 0.8975 | 3.9801 | 6.6127 | 0.5019 | 0.006 | | 0.834 |

Figure 4-22 shows how the point-scaled soil moisture is transformed to spatial average by three statistical methods. The x-axis is time axis and y presents the soil moisture value in volumetric percentage. The upper half of the figure is upscaled soil moisture based on station 15, while the lower half of the figure shows upsclaed soil moisture based on combination of station st15 and st03. All the data sets show low level of agreement before DOY150. The results of upscaling by absolute difference bring a large bias with spatial average. Soil moisture combines with station st15 and station st03 after linear and second order regression fit well to spatial mean after DOY170.

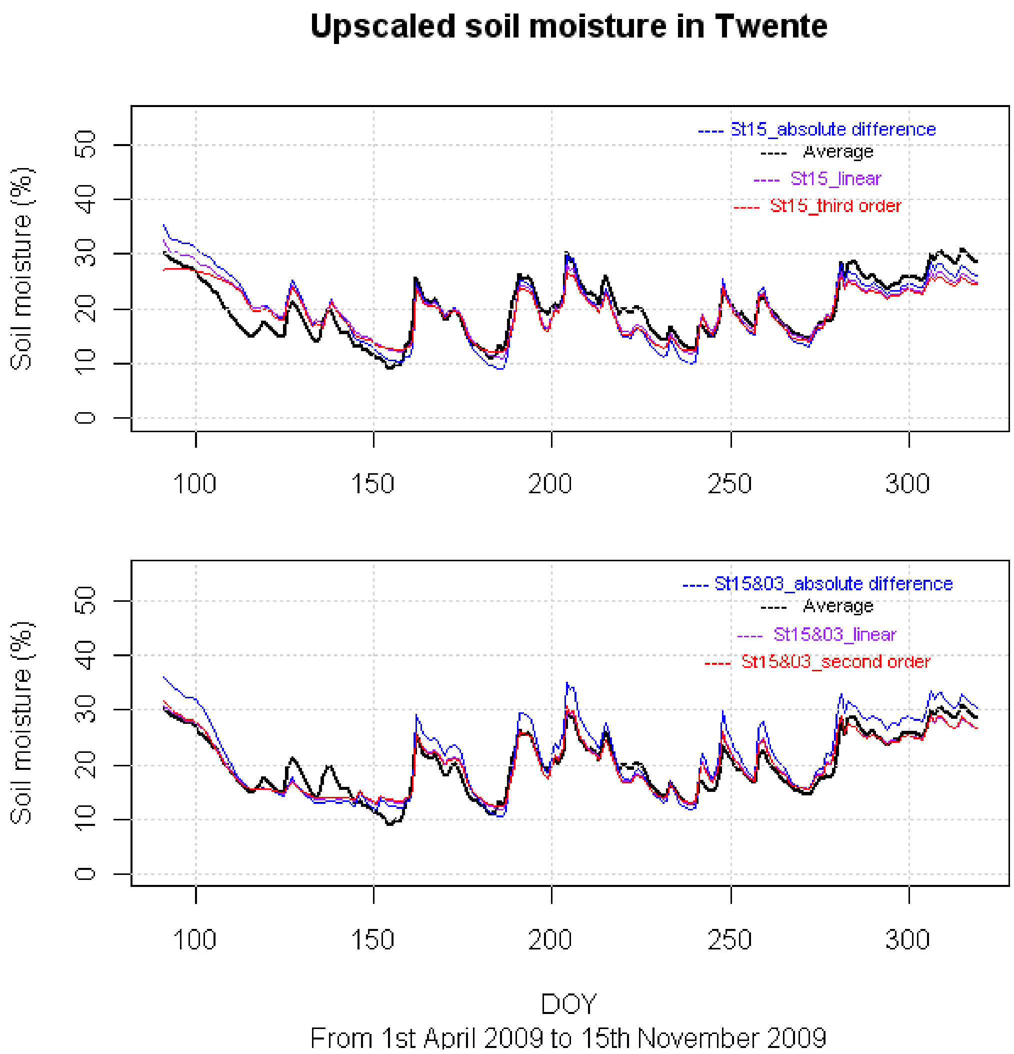



**Figure 4-22 Temporal structure of soil moisture after upscaling through three methods from station 15 and station 3 in Twente region**

Correlation coefficient, root mean square error and absolute mean difference are calculated between spatial average and upscaled data by three different methods are listed in table 4-18.

**Table 4-18 RMSE, BIAS, R between observed field average soil moisture of Twente region and point measurements, upscaled measurements**

| | Station 15 | | | | Station 15 and station 3 | | | |
|---|---|---|---|---|---|---|---|---|
| | Point measurements | Absolute differences | Linear relation | third order | Point measurements | Absolute differences | Linear relation | second order |
| R | 0.89 | 0.89 | 0.89 | 0.89 | 0.95 | 0.90 | 0.95 | 0.89 |
| RMSE | 4.17 | 2.75 | 2.50 | 2.56 | 2.46 | 2.94 | 1.68 | 2.54 |
| BIAS | 2.71 | 0.02 | 0.00 | 0.54 | 0.85 | 0.84 | 0.00 | 1.76 |

In summary, the results shown by R are similar for each transformation method. Linear transformation performs slightly better than other methods with small bias and RMSE. The best results by comparing the statistic indicators and time series results; soil moisture combined by station st03 and station st15 after linear transformation was selected to validate remote sensing products

### 4.3.3. Discussion of upscaling

In this part, three upscaling methods were applied to identify the best way to transform point measurements to areal soil moisture. Second order regression and linear regression was selected as the best method for upscaling in Maqu and Twente, respectively. However there are limitations of these upscaling methods, which may cause bias when applying to further analysis.

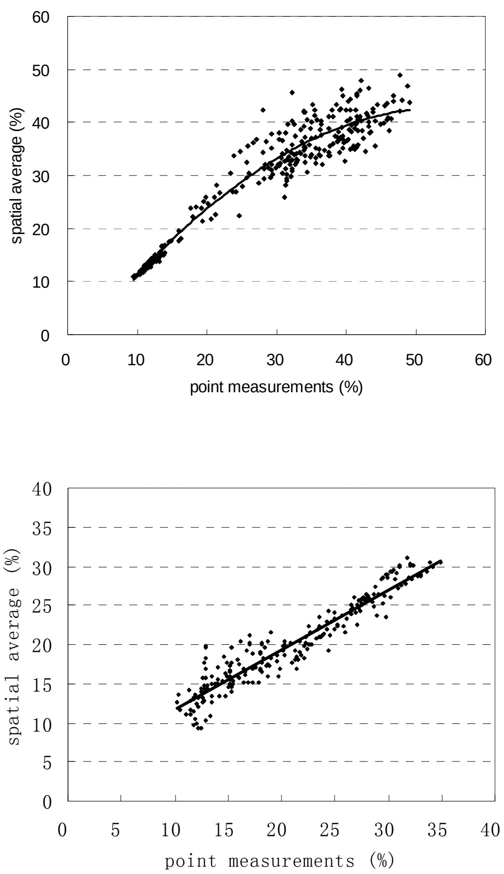



**Figure 4-23 Analysis of best upscaling methods**

In Figure 4-23, the left box is residual analysis of second order regression based on station cst2 in Maqu region. This method estimated soil moisture well at lower moisture values, and at higher than 40%, this upscaling method underestimated the areal values. The right one is for linear regression based on combination of st15and st03 In Twente. There are obvious overestimation and underestimation of areal soil moisture lower and higher than 13%, which may decrease the moisture differences after upscaling in this soil moisture range.

## 4.4. Remote sensing products validation

In this part, upscaled soil moisture values based on representative stations are compared with AMSR-E data both at descending and ascending time. The in-situ soil moisture was collected at the same time when satellite overpassing the areas. The results and discussion are presented below.

### 4.4.1. Maqu region

Figure 4-24 shows the time series of soil moisture both collected by in-situ measurements and AMSR-E at the same time. The x-axis is the time axis and the y-axis of the upper two figures present the soil moisture as a percentage and the third one shows precipitation. There is no AMSR-E overpass on every day. To remove noise of AMSR-E data, moving average of 3 days was used for smoothing. The in-situ data in this region was based on soil moisture values at station cst2 after second order regression. High level of agreement is there in between the in-situ and the AMSR-E soil moisture data in descending mode. Both respond to precipitation events reasonably well. When soil moisture is very high (>40%) the in-situ measurement is less sensitive than AMSR-E. The agreement of in-situ and AMSR-E at ascending time is worse, especially at winter time when the temperature was below $0^{o}C$. Figure 4-25 shows the scatter plots of In-situ soil moisture and AMSR-E products at the Maqu region. High correlation coefficient of 0.73 with a RMSE of 4.21% is obtained at descending time, while very low correlation about 0.003 and big RMSE of 12.53% for ascending. This latter might be attributed to problems with temperature/emissivity definition of the model applied to the SM derivation from the AMSR-E data.

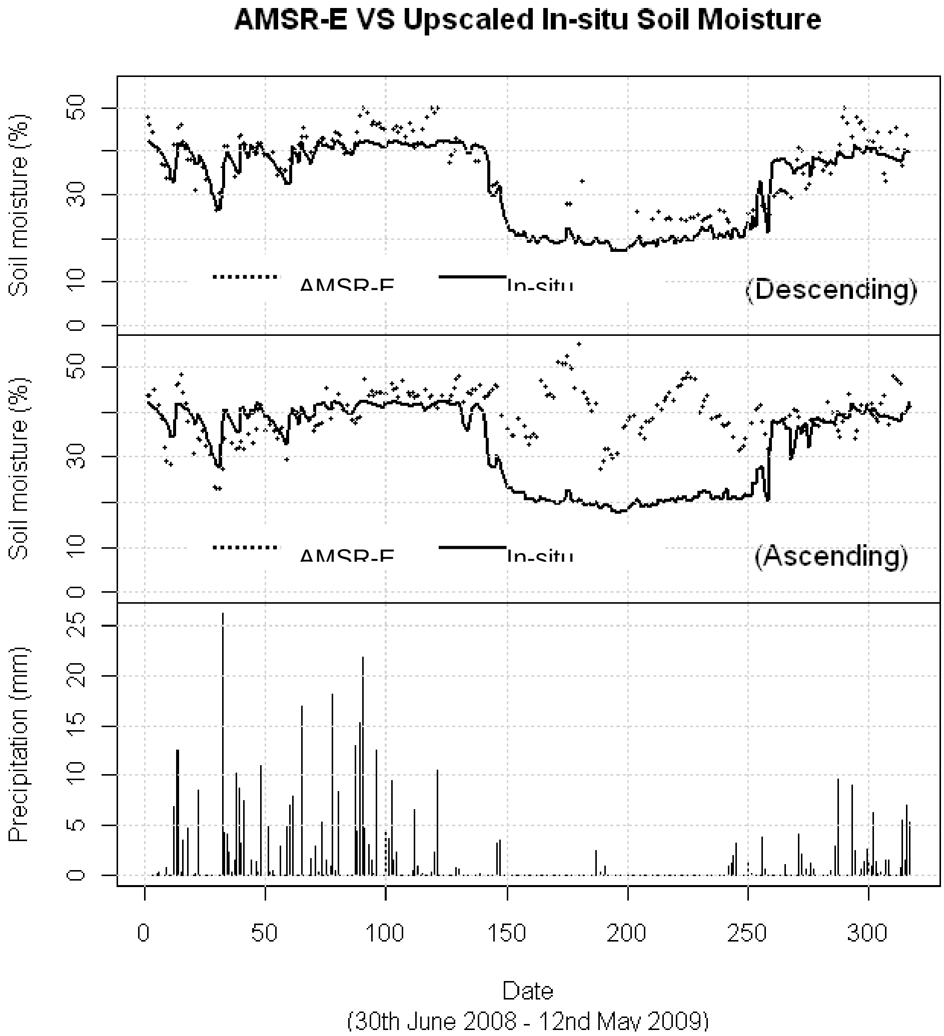
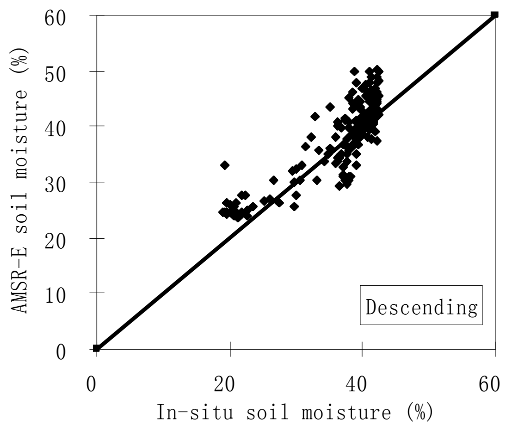



**Figure 4-24 Time series plots of the in-situ measured and AMSR-E results at AMSR-E descending and ascending overpass time in Maqu region during study period**



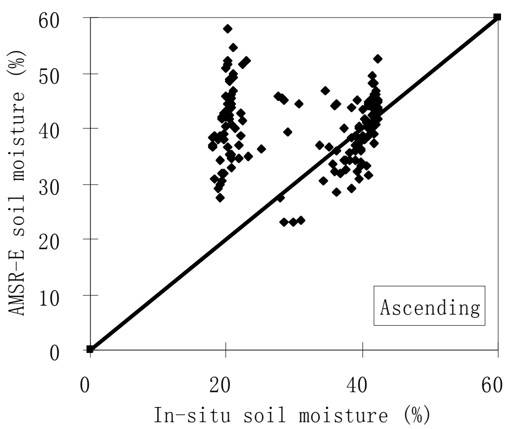




**Figure 4-25 Scatter plots of In-situ soil moisture and AMSR-E products in Maqu region during study period**

### 4.4.2. Twente region

Figure 4-26 is similar to figure 4-24, but gives the information about the Twente region. The in-situ data in this region was based on soil moisture values collected at station nst13 when satellite was overpassing the area, and was upscaled with linear regression. On most days, AMSR-E gives a higher soil moisture value than in-situ measurement. There is an obvious bias can be observed. Both of the two measurements have response to precipitation and the bias decreases when there is a precipitation. The bias between AMSR-E and in-situ measurements is larger at ascending time. Figure 4-27 shows scatter plots of In-situ soil moisture and AMSR-E products in Twente region. High correlation coefficient of 0.70 with RMSE of 10.18 % was obtained for the descending time. Similar results are found at ascending time, with correlation about 0.67 and a larger RMSE of 16.32%.

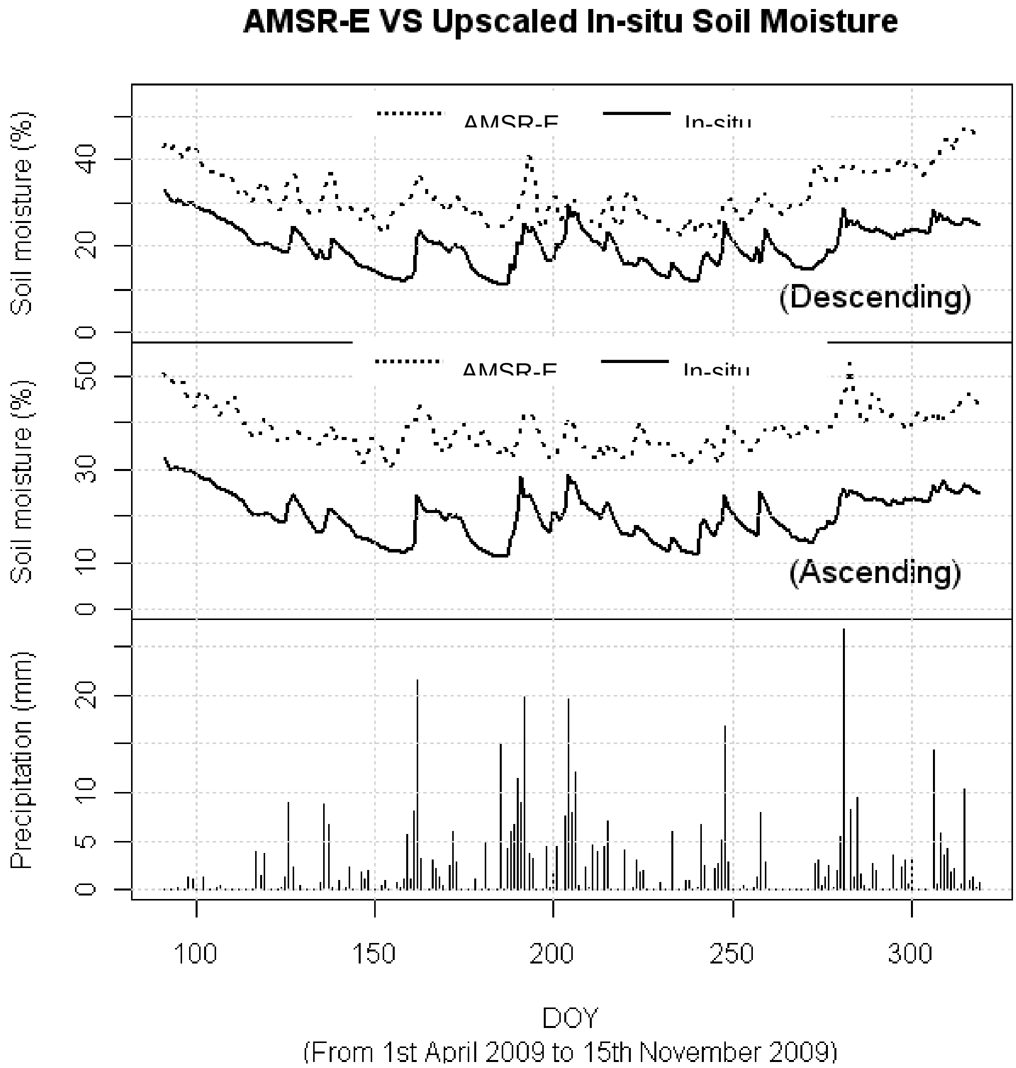
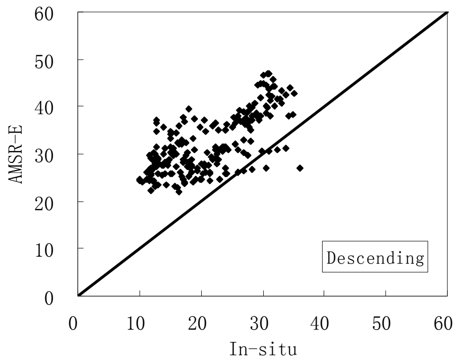



**Figure 4-26 Time series plots of the in-situ measured and AMSR-E results at AMSR-E descending and ascending overpass time in Twente region during study period**



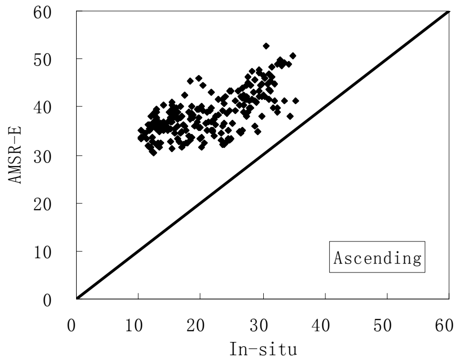




**Figure 4-27 Plots of In-situ and AMSR-E soil moisture in Twente region during study period**

### 4.4.3 Discussion of validation

In the following, the discussion focuses on the differences between the AMSR-E based soil moisture values and the in situ measurement based upscaling results by analysing the possible reasons in each method.

- AMSR-E

At both areas, higher level of agreements between in-situ and AMSR-E were obtained at descending mode than at ascending mode, because in the AMSR-E soil moisture retrieval algorithms, soil and vegetation temperatures are assumed equal, at night, soil and vegetation temperature had smaller differences, which brings less error than at noon. (Njoku et al. 2003)

At the Maqu region, in winter, large bias was observed because when temperature is below 0 degree, soil is frozen, and the emissivity of soil increased, which results in increased brightness temperature obtained by the satellite (Wigneron et al. 2003).

In the Twente region, large bias was obtained at both ascending and descending mode, the bias may be caused by the different land cover types. C-band is sensitive to soil moisture under short vegetation (Jackson et al. 2002) . When the vegetation depth increase, attenuation of radiation from soil increase, soil moisture retrieved by AMSR-E at C-band and X-band may have problem (Njoku et al. 2003). Since in this region, there are grassland, agriculture land, also forest and urban, the heterogeneity of land cover types may be the reason.

- Upscaled in-situ data

Soil moisture values based on one station is practically impossible to perfectly present the state of a large area.

At the Maqu region, when the soil moisture values are above 40%, the upscaled in-situ measurements are less sensitive. The reason lies in the limitation of the upscaling method (regression dampens extreme values) as discussed in 4.3.3.

# 5. Conclusions and recommendations

## 5.1. Conclusions

8 stations among 17 were tested whether the stations installed under grassland to measure soil moisture were representative at the station scale and to the whole area in the Twente region where the land cover is heterogeneous. Intensive measurements under 4 land cover types (grass land, maize, forest and bare land) were conducted on five days with different weather conditions during September and October 2009. Representativity of the soil moisture monitoring sensor was better in wet condition than in dry conditions. Most of the stations were proved representative in these days except station 11 and station 17. Soil moisture values measured by stations under grassland can well represent the moisture condition of different land covers in the Twente region as presented in 4.1.

Variogram analysis in 4.2.1.1 shows that spatial correlation distance of soil moisture on top layer of Twente region is about 250 m in wet conditions and even shorter in dry conditions, which is too short compared to the distances between the stations. In both regions big errors were obtained by trend surface interpolation when estimating soil moisture spatial distribution. These results suggest geostatistical interpolation not to be used in estimating soil moisture spatial distribution based on networks with small number of stations In Twente and Maqu region.

Temporal stability analysis in 4.2.2 was applied to estimate soil moisture spatial patterns as well. In Maqu region, all stations but two (nst15, nst11) show temporally stable. Station nst13 was tested close to spatial averaged soil moisture values and with less variation during the whole study period, from 30$^{th}$ June 2008 to 12$^{th}$ May 2009, while station cst2 performed better in case of variable weather conditions. In this region topography is rolling, but no significant effects of this could be identified on the soil moisture spatial pattern. Same result for little Washita river watershed in Oklahoma, USA in 2002 was obtained by (Cosh et al. 2006).

In the Twente region, it is more difficult to identify one site which is representative to the spatial average of soil moisture than in the Maqu region. Representativity of station st15 was the best when consider the whole study period, from 1$^{st}$ April to 15$^{th}$ November. However large bias between soil moisture at station st15 and spatial average was observed in spring. Station st3 recorded similar moisture values to spatial mean in spring but showed a different trend 4.2.3. Correlation estimation of these two regions gave the same results with temporal stability analysis.

Three algorithms, (absolute differences, linear regression and higher order regression) were applied to upscale the soil moisture value based on most representative stations to spatial average. In Maqu region, station cst2 after second order regression with (slightly) higher correlation (R=0.96) and low bias (RMSE=3.15, BIAS=0.24) in 4.3.1and station st15 after linear regression (R=0.89, RMSE=2.5, BIAS =0) in 4.3.2 in Twente region were selected to represent in-situ areal soil moisture.

In-situ soil moisture measurements based on selected representative stations were upscaled and compared to the AMSR-E based soil moisture data (derived with the VUA-NASA method, and then smoothed with a moving average of 3 days) at both descending and ascending mode. Time series and scatter plots show that in the Maqu region, high level of agreement was obtained at descending time with correlation of 0.73 and RMSE of 4.21%(vol /vol), while large bias was observed in winter time for the ascending mode. As presented in 4.4.1Correlation coefficient and RMSE in the ascending mode were 0.003 and 12.53%(vol /vol), respectively. In Twente region, higher soil moisture values were obtained by AMSR-E than in-situ measurements, both in the descending and ascending mode. Higher correlation was obtained in the descending mode (R=0.70) than in the ascending mode (R=0.67). Large biases were found, 10.18 % (vol/vol), 16.32% (vol /vol) for descending and ascending, respectively in 4.4.2. Both in-situ and remote sensing data showed response to precipitation events at both study areas.

## 5.2. Recommendations

Representativity was tested at 8 stations during September and October in this study, to identify the representative situation, better to test all the stations in a network, and the test should also be conducted in other seasons of the year.

The bias between stations and Theta-T probe measurements under same land cover, maybe caused by spatial variability and the soil depth they took measurement. To find the reason, it is proposed to measure soil moisture using Theta-T probe at the same place where stations were installed.

Temporal stability was tested in less than one year at two areas, since soil moisture spatial distribution may change by seasons, it is proposed to analysis the stability conditions for a whole year, and validate the result by another year at least.

In this study statistic correction was applied, however, soil moisture was highly dependent on temperature, precipitation and the moisture value of day before. Upscaling algorithms based on time series should also be considered.

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**Appendix-1 Soil properties measurements**

- **Soil texture**

Soil texture and organic content are two essential factors which influence water content in soil.

Soil texture which means the percentage of clay, silt and sand in sample is an important physical property of soil. According to table 3 (USDA 2008), these soil separates can be identified by their particle size:

**Table 19 Soil texture classification**

| Particles | Grain Size |
|---|---|
| Sand | 2.00-0.05 mm |
| Silt | 0.050-0.002 mm |
| Clay | 0.002 mm or less |

**Figure 28 Measuring soil texture in lab**

Soil samples collected from 19 stations at top layer were analyzed. The procedures of soil texture identification are as follows:

1. Dry samples by heaters
2. Break down clumps by pestle. Take 20 grams of sample and pass through 2mm sieve to

separate grains. Note down weight of grains

3. Place soil samples in beakers and pour 100mL of 5%Calgon solution into beakers to remove organics in soil sample.
4. After reaction, add 300ml water into beakers and heat for an hour to remove remaining $H_2O_2$. After cooling down, centrifuge and siphon of settlements
5. Transfer settlements into plastic bottles,add20ml dispersing agent, and shake about 16 hours
6. Separate fractions with different size.

- **Organic matters**

The measurement used Walkley-Black procedure(Schumacher 2002). It is combustion of organic matter with potassium dichromate and sulphuric acid. The residual is titrated against ferrous sulphate.

The procedures are as follows:

1. Add 1g of soil sample into a 500 ml wide- mouth Erlenmeyer flask.
2. Add 10 ml dichromate solution. ($K2Cr_2O_2$) (including blanks)
3. Add 20 ml sulphuric acid and stand on a pad for 30 min.
4. After cooling down, add 250ml and 10ml phosphoric acid.
5. Add 1 ml indicator and titrate with ferrous sulphate solution.

**Appendix-2 Sampling points distribution at all 8 stations**

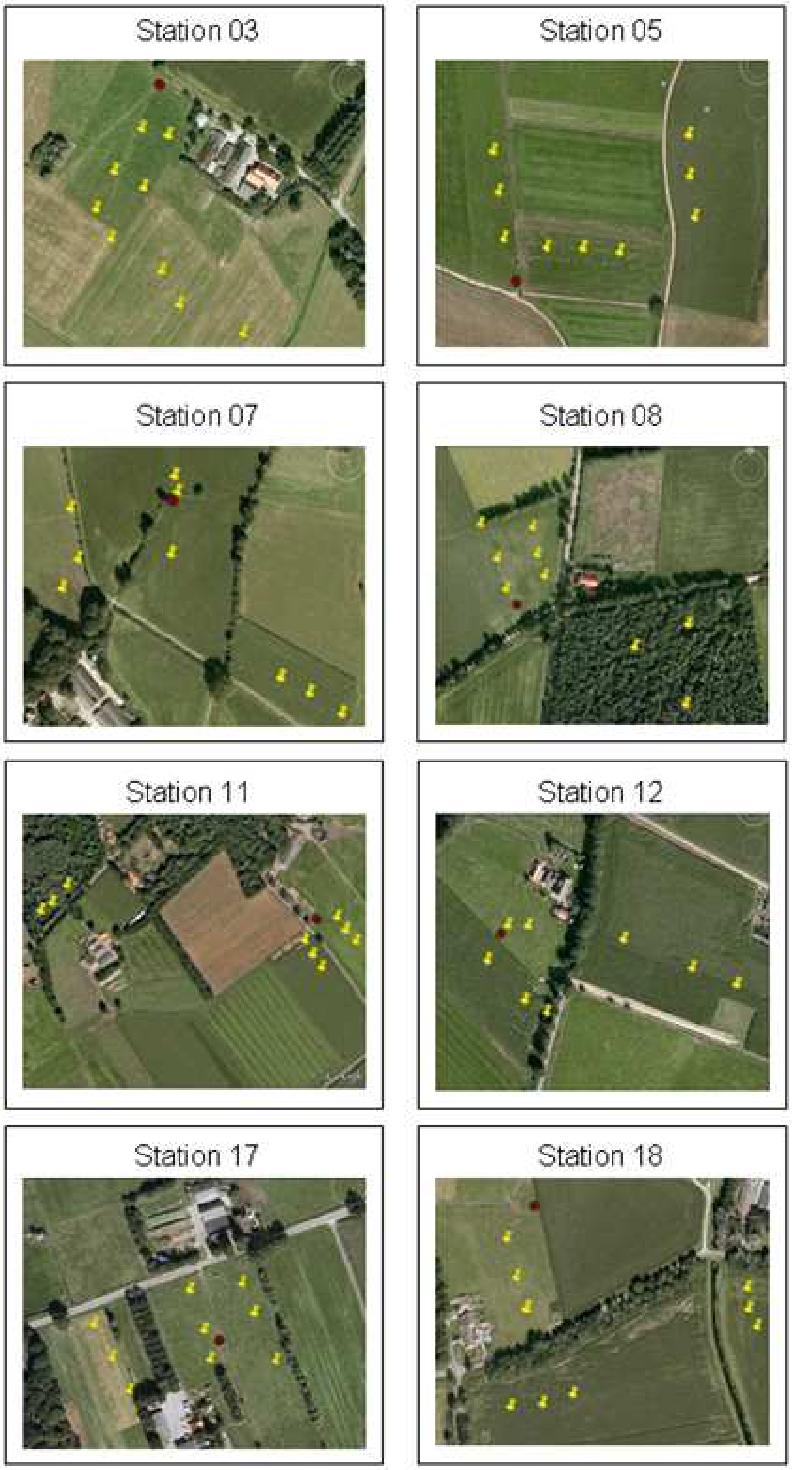


**Figure 29 Sampling points distribution at all 8 stations**

**Appendix-3 Soil moisture measurements**

- **Indirect method**

Most of methods for soil moisture measurements are indirect. In this research, Theta-T probe method was used to obtain intensive soil moisture data. Figure 1 shows Theta probe type ML2x which can measure volumetric soil moisture at 0cm to 6cm in depth with accuracy within 1% and the way it works in field. An oscillator is used to generate signal with a high frequency electromagnetic wave travel along a transmission line and part of energy is reflected back after reaching place with different impedance. The reflected sig
nal interacts with the incident signal, and the original amplitude changed, and then producing a voltage standing wave along the TL which is influenced by permittivity of the media which is air, water and minerals in this case. Since when the frequency of electromagnetic wave is in the range of (50M~10GHz), dielectric properties of air and minerals are constant. Volumetric water content is a major factor that may influence permittivity. At one end of probe, 4 rods Made of 3mm diameter resilient are arranged. Three of them form a electrical shield in a circle around the central one.  By this method data can be collected by simply inserting the rods into soil, and get soil moisture immediately.

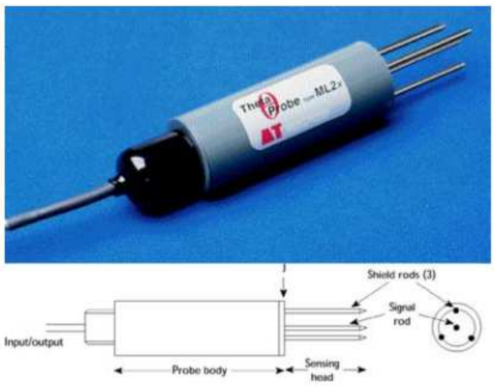


**Figure 30 Theta-T probe**

- **Direct method**

A direct method to measure soil moisture is calculating change in weight before and after drying soil samples. Procedures of this measurement are as follows:

1. Weigh a tare and note down its weight as (*wt*)
2. Place a soil sample on a weighed tare and record the weight (*wt + wet weight*)
3. Put both sample and tare into oven with 105℃ for 24 hours.
4. Weigh the sample and record the weight (*wt + dry weight*)
5. Remove soil and weigh empty ring. Note down as (*wr*)

Expression of soil moisture can be based on mass and volume. In this study, Gravimetric method which gives information weight of water in weight of sample was used and then expressed by volumetric soil moisture. The way to calculate soil moisture by following formula (DeAngelis 2007):

$$\theta_d = \frac{(wt + wetweight) - (wt + dryweight)}{(dryweight + wt) - wt - wr}$$

$$bulkdensity = \frac{(dryweight - wr - wt)}{volume\_soil}$$

$$\theta_{vd} = \theta_d \times bulkdensity$$

$\theta_d$ is water content in soil sample based on mass. $\theta_{vd}$ is water content in soil sample based on volume. Since most of the variables in hydrology such as precipitation, evapotranspiration are expressed volumetrically, volumetric water content are more widely used.

**Appendix-4 Histograms of soil moisture station measurements**

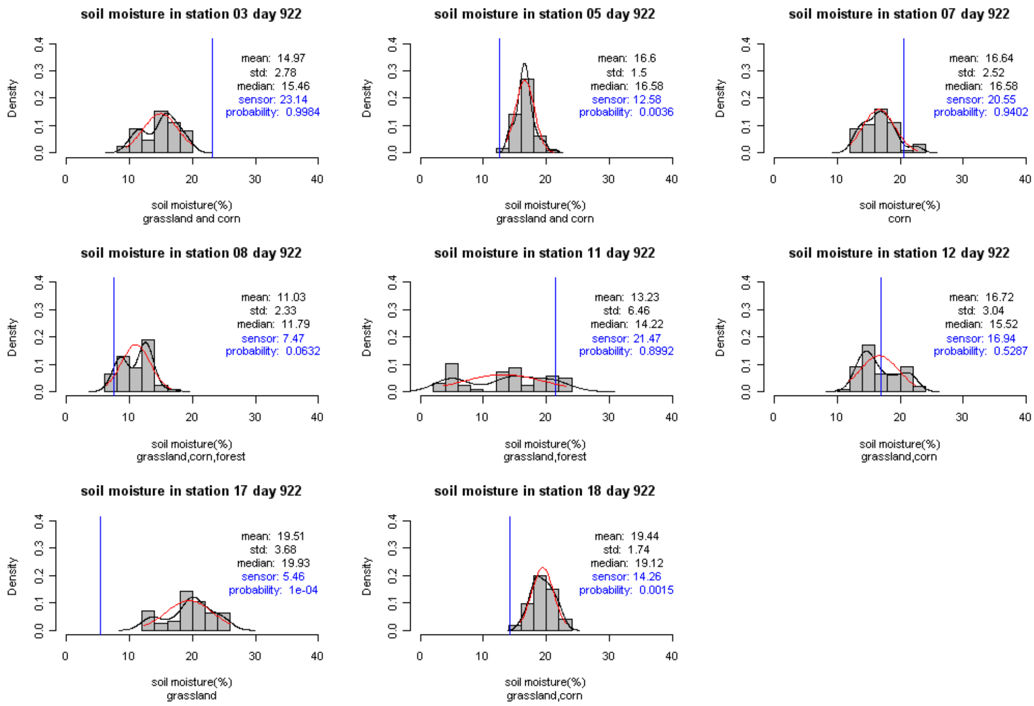


**Figure 31 All fields on 22nd September 2009**

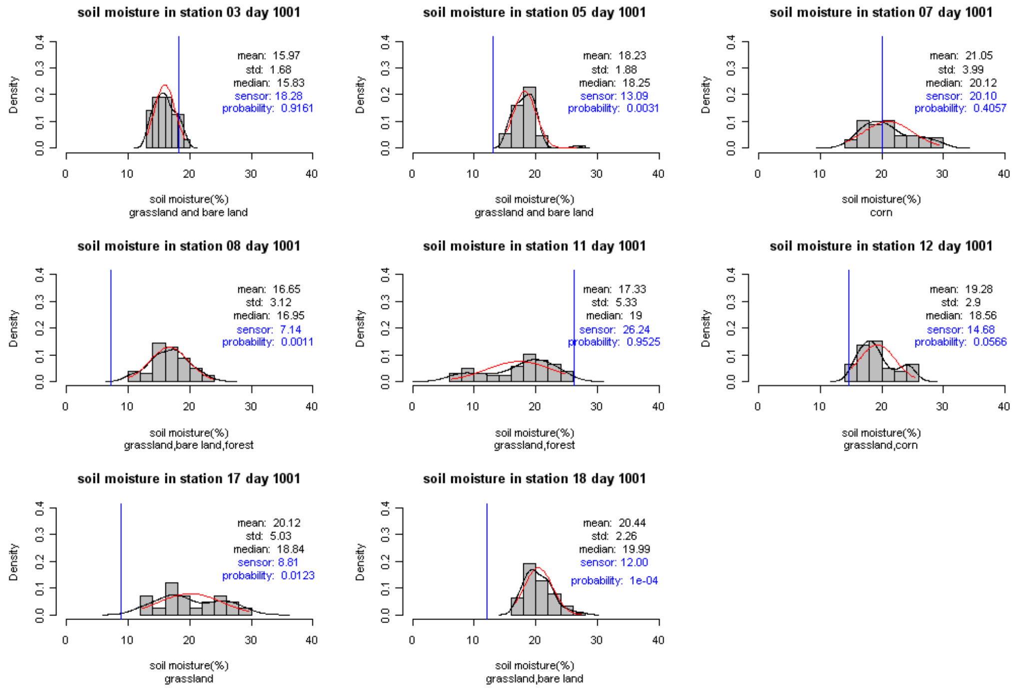


**Figure 32 All fields on 01st October 2009**

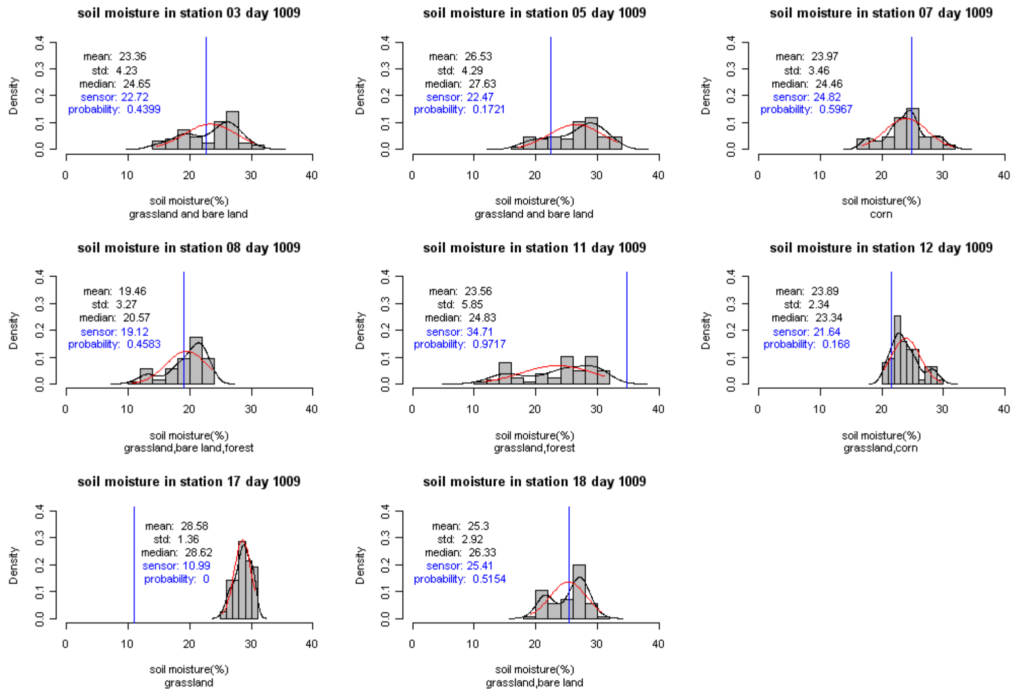


**Figure 33 All fields on 09th October 2009**

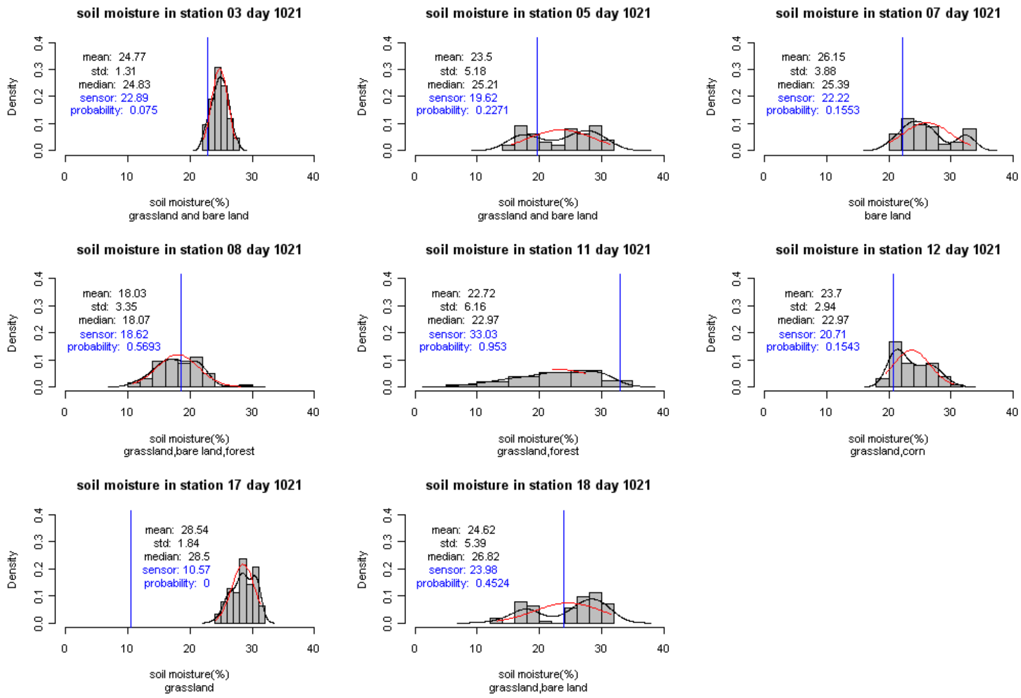


**Figure 34 All fields on 21st October 2009**

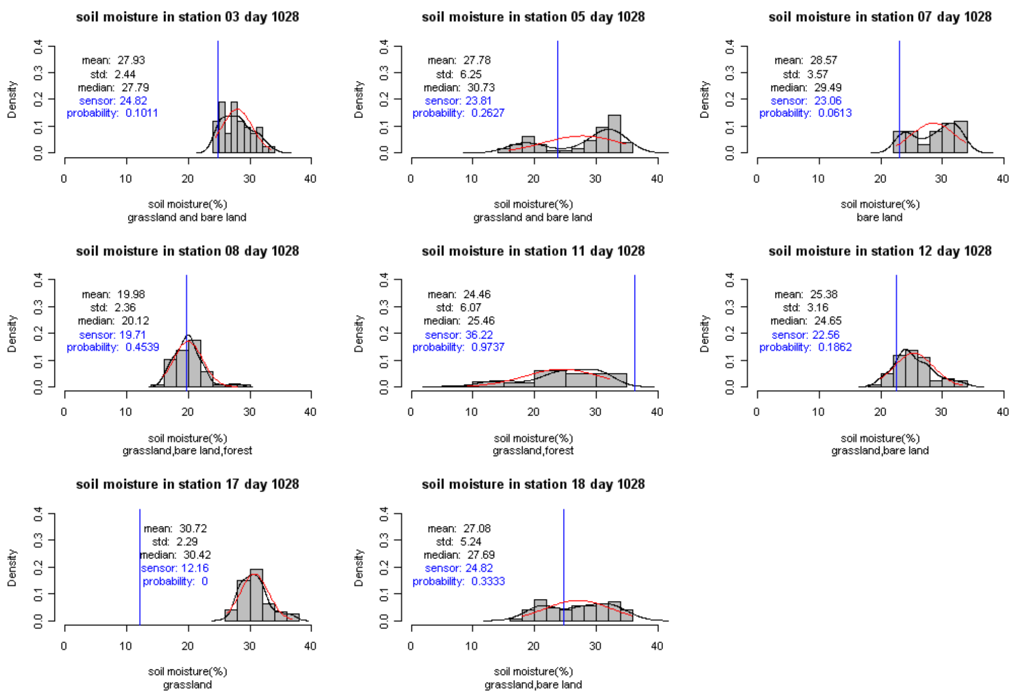


**Figure 35 All fields on 28th October 2009**

## Appendix-5 MRD and SDRD at each station at Maqu region

| 30th June 2008 to 12th May 2009 | | | | 30th June 2008 to 16th November 2008 | | | | 17th November 2008 to 16th March 2009 | | | | 17th March 2009 to 12th May 2009 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rank | Station ID | MRD | SDRD | Rank | Station ID | MRD | SDRD | Rank | Station ID | MRD | SDRD | Rank | Station ID | MRD | SDRD |
| 1 | nst9 | -0.491 | 0.192 | 1 | nst9 | -0.465 | 0.087 | 1 | nst9 | -0.493 | 0.097 | 1 | nst9 | -0.535 | 0.082 |
| 2 | nst6 | -0.305 | 0.131 | 2 | nst6 | -0.248 | 0.099 | 2 | nst15 | -0.446 | 0.051 | 2 | nst8 | -0.432 | 0.084 |
| 3 | nst7 | -0.270 | 0.150 | 3 | nst8 | -0.204 | 0.076 | 3 | nst7 | -0.373 | 0.132 | 3 | nst7 | -0.246 | 0.076 |
| 4 | nst8 | -0.228 | 0.123 | 4 | nst7 | -0.192 | 0.113 | 4 | nst6 | -0.373 | 0.132 | 4 | cst3 | -0.154 | 0.071 |
| 5 | cst3 | -0.198 | 0.106 | 5 | cst3 | -0.141 | 0.090 | 5 | cst3 | -0.287 | 0.064 | 5 | nst13 | -0.139 | 0.058 |
| 6 | nst11 | -0.117 | 0.101 | 6 | nst12 | -0.085 | 0.122 | 6 | nst4 | -0.175 | 0.126 | 6 | nst11 | -0.114 | 0.057 |
| 7 | nst2 | -0.076 | 0.183 | 7 | nst2 | -0.084 | 0.179 | 7 | nst11 | -0.170 | 0.073 | 7 | nst10 | -0.021 | 0.062 |
| 8 | cst2 | -0.058 | 0.113 | 8 | nst11 | -0.072 | 0.101 | 8 | nst8 | -0.154 | 0.081 | 8 | nst12 | -0.013 | 0.081 |
| 9 | nst1 | -0.040 | 0.041 | 9 | nst13 | -0.061 | 0.112 | 9 | cst2 | -0.118 | 0.052 | 9 | cst2 | -0.005 | 0.060 |
| 10 | nst13 | -0.019 | 0.132 | 10 | nst1 | -0.040 | 0.041 | 10 | nst13 | 0.088 | 0.090 | 10 | nst14 | 0.105 | 0.051 |
| 11 | cst4 | -0.012 | 0.116 | 11 | nst10 | -0.037 | 0.127 | 11 | nst12 | 0.217 | 0.111 | 11 | nst3 | 0.108 | 0.040 |
| 12 | nst15 | 0.026 | 0.487 | 12 | cst2 | -0.029 | 0.135 | 12 | nst10 | 0.261 | 0.114 | 12 | nst15 | 0.244 | 0.337 |
| 13 | nst12 | 0.043 | 0.188 | 13 | cst4 | -0.009 | 0.116 | 13 | nst14 | 0.288 | 0.077 | 13 | cst5 | 0.303 | 0.059 |
| 14 | nst10 | 0.079 | 0.189 | 14 | nst14 | 0.123 | 0.076 | 14 | nst3 | 0.356 | 0.120 | 14 | cst1 | 0.327 | 0.111 |
| 15 | nst4 | 0.169 | 0.321 | 15 | cst1 | 0.130 | 0.063 | 15 | cst5 | 0.400 | 0.089 | 15 | nst4 | 0.571 | 0.171 |
| 16 | nst14 | 0.183 | 0.111 | 16 | nst5 | 0.156 | 0.103 | 16 | cst1 | 0.435 | 0.094 | | | | |
| 17 | nst3 | 0.244 | 0.144 | 17 | nst3 | 0.206 | 0.118 | 17 | nst5 | 0.544 | 0.130 | | | | |
| 18 | cst1 | 0.280 | 0.175 | 18 | nst4 | 0.296 | 0.218 | | | | | | | | |
| 19 | nst5 | 0.333 | 0.225 | 19 | nst15 | 0.344 | 0.391 | | | | | | | | |
| 20 | cst5 | 0.368 | 0.094 | 20 | cst5 | 0.367 | 0.097 | | | | | | | | |

## Appendix-6 MRD and SDRD at each station at Twente region

| 1st April 2009 to 15th November 2009 | | | | 1st April 2009 to 31st May 2009 | | | | 1st June 2009 to 31st August 2009 | | | | 1st April 2009 to 15th November 2009 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rank | Station ID | MRD | SDRD | Rank | Station ID | MRD | SDRD | Rank | Station ID | MRD | SDRD | Rank | Station ID | MRD | SDRD |
| 1 | st17 | -0.650 | 0.092 | 1 | st17 | -0.641 | 0.124 | 1 | st17 | -0.685 | 0.049 | 1 | st17 | -0.604 | 0.081 |
| 2 | st2 | -0.525 | 0.140 | 2 | st18 | -0.529 | 0.144 | 2 | st2 | -0.533 | 0.150 | 2 | st8 | -0.383 | 0.197 |
| 3 | st8 | -0.368 | 0.168 | 3 | st2 | -0.507 | 0.127 | 3 | st18 | -0.415 | 0.259 | 3 | st14 | -0.139 | 0.091 |
| 4 | st18 | -0.367 | 0.263 | 4 | st8 | -0.375 | 0.145 | 4 | st8 | -0.351 | 0.153 | 4 | st13 | -0.133 | 0.138 |
| 5 | st5 | -0.138 | 0.161 | 5 | st12 | -0.304 | 0.061 | 5 | st5 | -0.153 | 0.191 | 5 | st5 | -0.130 | 0.113 |
| 6 | st9 | -0.121 | 0.216 | 6 | st9 | -0.257 | 0.189 | 6 | st13 | -0.094 | 0.310 | 6 | st18 | -0.123 | 0.179 |
| 7 | st13 | -0.109 | 0.239 | 7 | st11 | -0.047 | 0.202 | 7 | st9 | -0.085 | 0.263 | 7 | st12 | -0.086 | 0.069 |
| 8 | st12 | -0.084 | 0.131 | 8 | st3 | -0.031 | 0.144 | 8 | st12 | -0.071 | 0.151 | 8 | st9 | -0.072 | 0.124 |
| 9 | st14 | -0.076 | 0.145 | 9 | st7 | 0.088 | 0.233 | 9 | st14 | -0.030 | 0.168 | 9 | st7 | 0.045 | 0.189 |
| 10 | st7 | 0.133 | 0.237 | 10 | st16 | 0.153 | 0.098 | 10 | st15 | 0.033 | 0.124 | 10 | st15 | 0.086 | 0.057 |
| 11 | st15 | 0.134 | 0.169 | 11 | st6 | 0.265 | 0.217 | 11 | st6 | 0.114 | 0.198 | 11 | st3 | 0.101 | 0.173 |
| 12 | st6 | 0.156 | 0.190 | 12 | st15 | 0.355 | 0.119 | 12 | st7 | 0.238 | 0.236 | 12 | st6 | 0.129 | 0.108 |
| 13 | st3 | 0.166 | 0.240 | 13 | st1 | 0.610 | 0.093 | 13 | st16 | 0.243 | 0.187 | 13 | st11 | 0.341 | 0.092 |
| 14 | st11 | 0.197 | 0.248 | 14 | st10 | 0.978 | 0.348 | 14 | st11 | 0.267 | 0.227 | 14 | st10 | 0.457 | 0.192 |
| 15 | st16 | 0.304 | 0.193 | | | | | 15 | st3 | 0.353 | 0.202 | 15 | st16 | 0.466 | 0.113 |
| 16 | st1 | 0.423 | 0.224 | | | | | 16 | st1 | 0.357 | 0.163 | | | | |
| 17 | st10 | 0.728 | 0.364 | | | | | 17 | st10 | 0.809 | 0.329 | | | | |