INTERPLAY BETWEEN RAINFALL, STREAM WATER LEVEL AND SURFACE SOIL MOISTURE QUANTIFIED AT FIELD SCALE USING IN-SITU AND SATELLITE TECHNIQUES.

YOHANNES AGIDE DEJEN February, 2017

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YOHANNES AGIDE DEJEN Enschede, The Netherlands, February, 2017

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ABSTRACT

Surface soil moisture is a crucial state variable in various land surface processes and a significant component of the water balance that controls the partitioning of rainfall into runoff and infiltration. The assessment and quantification of surface soil moisture with respect to time and space can significantly improve catchment water resources management. However, monitoring of soil moisture using in-situ point-based measurements and quantifying its spatial and temporal variability is challenging due to dynamic land surface conditions and meteorological forcing. Remote sensing techniques enable to monitor soil moisture over large areas. The recently launched Sentinel-1 satellite has potential to improve remote sensing products up to a resolution of 10 m. The first objective of this research is to monitor soil moisture variability using a combination of in-situ and remote sensing techniques to overcome the shortcomings of point-based methods.

To measure spatial distribution of soil moisture within agricultural fields and with respect to point-based soil moisture monitoring stations at the edges of fields, fieldwork has been performed from 10 August 2016 to 11 November 2016. The spatial distribution of soil moisture was measured using Hydra probe; and the Hydra probe was calibrated against simultaneously taken gravimetric measurements. The spatio-temporal variability of soil moisture has been analysed at point and field scale, and the spatial representativeness of the point-based soil moisture stations was evaluated against the intensive field measurements. The field measurements were performed at the fields nearby three monitoring stations (labelled ITCSM_02, ITCSM_07, and ITCSM_10). In total, sample were taken from four corn fields, a potato field and grassland.

A soil water index (SWI) is derived from the Sentinel-1 backscatter signal using the change detection algorithm. Then, the soil water index (SWI) values derived from Sentinel-1 backscatter observations are rescaled to surface soil moisture (SSM) by matching the minimum and maximum of Sentinel-1 SWI to insitu measured SSM at the monitoring stations. Subsequently, the accuracy of SWI were evaluated at field scale against in-situ (intensive and station) measurements using coefficient of determination (R²), root mean square error (RMSE), mean absolute error (MAE) and bias. The RMSE of surface soil moisture derived from Sentinel-1 vs labour intensive surface soil moisture measurements ranges from 0.061 to 0.116 m³/m³. Five out of six fields meet the accuracy target of 0.08 m³/m³ for active microwave sensor for agricultural area set by Wagner, (2009). For the potato field (ITCSM_10F2) the target accuracy is not achieved and we attribute this to the fact that the field includes distinct soil rows, which affects the Sentinel-1 observations and makes it difficult to collect reliable ground truth.

The second objective of the research is to study the soil moisture and water level dynamics in response to rainfall events. The role of surface soil moisture on stream water level, and interaction with rainfall was analysed for selected rainfall events at the study catchment by determining the response time and its extent. With different antecedent soil moisture conditions, different in water levels and time to peak have been observed for equal amounts of rainfall. For instance, 2.4 mm rainfall on the time of initial soil moisture for t3 and t4 are 0.164 and 0.341 m³/m³ respectively, and change in water level and time to peak are 0.013 and 0.016 m, and 90 and 135 minutes respectively. Therefore, the degree of response in water level and time to peak is influenced by land surface conditions, which is an indication of the potential use of satellite observation soil moisture for storm runoff characterization.

Key words: Soil moisture, Hydra probe, Soil water index, spatial variability, Response time.

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LIST OF ABBREVIATIONS

ESA	European Satellite Agency
GPS	Geographic positioning system
GRD	Ground range detected
IDL	Interactive data language
ITCSM	ITC soil moisture
IW	Interferometry Wide swath mode
MAE	Mean absolute error
NASA	National aeronautics and Space Administration
R ²	Coefficient of determination
RF	Rainfall
RMSE	Root mean square error
S1	Sentinel-1
SAR	Synthetic Aperture Radar
SM	Soil moisture
SSM	Surface soil moisture
SWI	Soil water index
VWC	Volumetric water content
WL	Water lever

1. INTRODUCTION

1.1. Scientific background

Surface soil moisture is a crucial state variable in various land surface processes, for example exchanges of heat, water, CO_2 , and other trace materials between land surface and overlay atmosphere (Yang, 2004). Therefore, this variable plays an important role in hydrological and meteorological studies, together with weather, climate predictions, water resources and irrigation management, as well as hazard analysis (Cho et al. 2015). In hydrology, surface soil moisture is a significant component of the water balance by controlling the partitioning of rainfall into runoff and infiltration and therefore, has an important effect on the runoff dynamics of catchments (Scipal, Scheffler, & Wagner, 2005). The assessment and quantification of top 5 cm soil moisture over time has significantly improved the prediction of catchment potential and water resources management (Scipal et al., 2005). However, soil moisture monitoring and quantifying its spatial and temporal variability is still challenging due to dynamic land surface conditions and meteorological forcing (Brocca, Melone, & Moramarco, 2008).

Surface soil moisture can be measured via point-based and remote sensing techniques. Point-based surface soil moisture can be measured using gravimetric methods, Soil moisture sensors like Hydra Probe and automated station. These site specific and limited number of point-based measurement technique does not well represent the actual spatial soil moisture variability for large scale. For the last two decades the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have launched satellites equipped with active and passive microwave sensors for monitoring soil moisture information. These mission dedicated Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) microwave sensors improve soil moisture monitoring on global scale (Entekhabi et al., 2010). From an application prospective its main limitation is its resolution, which does not allow surface soil moisture monitoring at field scale (Wagner, Bauer-marschallinger, & Hochstöger, 2016).

In 2014 the European Space Agency launched the Sentinel-1 satellite which has potential to improve the application of microwave remote sensing down to at the scale of an agricultural field. This Synthetic Aperture Radar (SAR) system transmits electromagnetic waves at a wavelength that can range from a few millimetre to tens of centimetres and receives signals backscattered from the target area (Kim & Science, 2013). Actively transmitting and receiving signal with long wavelengths, SAR can operate effectively during day and night, and under most weather conditions(Kim & Science, 2013). Therefore, the launch of this operational satellite has a potential to overcome the challenge to monitor spatio-temporal soil moisture variability at field scale.

The monitoring of surface soil moisture from radar satellites relies on measuring radar backscatter signals from soil surfaces, to yield estimates of dielectric constant that can be converted into the soil moisture content (Wagner et. at., (2009). Availability of (surface) soil moisture estimation from satellite sensors offers a great opportunity to improve the land surface conditions (Brocca et. at., (2009a). The backscattered signal from natural terrain depends, amongst other factors, on surface soil moisture, surface roughness and vegetation. Separation of surface soil moisture, surface roughness and vegetation signal on the backscatter makes the application of Synthetic Aperture Radar (SAR) for soil moisture retrieval complex.

Surface soil moisture retrieval from Synthetic Aperture Radar (SAR) is challenging due to the confounding influence of terrain surface. Multitude approaches have been extensively studied using different backscatter models and SAR techniques (Wagner et al., 2009). Change detection algorithm approach is the most

promising and straight forward to retrieve surface soil moisture from other backscatter signal (Piles, Entekhabi, & Camps, 2009). The assumption of change detection algorithm stated by Wagner et al., (2009), the backscatter change over short time is mainly due to difference in surface soil moisture, while vegetation and roughness assumed constant. Hence, the change in the observed backscatter between two successive images comes from a change in soil moisture content. The accuracy and reliability of remotely sensed surface soil moisture derived from Sentinel-1 backscatter observation using change detection algorithm has to be carefully evaluated with ground truth (Brocca, Melone, Moramarco, Wagner, et al., 2010).

As stated by Brocca, Melone, Moramarco, & Singh, (2009) the role of spatio-temporal surface soil moisture dynamics and the relation with rainfall, and water level can be analysed for small experimental catchments supported by reliable soil moisture estimates from active microwave sensors. The result of this experimental catchment using assimilation of ground-based and remote sensing soil moisture measurement can improve investigation and prediction of hydrological response (Penna, Tromp-Van Meerveld, Gobbi, Borga, & Dalla Fontana, 2011). Apart from the soil moisture content and rainfall amount, the catchment hydrological response depend on site-specific physical and hydro-climatic factors. As result of these site specific factors each catchment has its own runoff response and will respond accordingly to different soil moisture and rainfall events. Further, result derived from detailed hydro-meteorological monitoring in small experimental catchment, has the possibility to make predictions about the hydrological behavior of ungauged watersheds or larger basins (Penna et. at., (2011).

This research focuses on understanding the relationship between rainfall, soil moisture and water level measured in the Voltherbeek, a sub-catchment of the Dinkel, whereby soil moisture derived from the Sentinel-1 images is intended to spatially augment the sparse in-situ measurements. Further, the surface soil moisture and stream water level in response to rainfall is evaluated under different antecedent soil moisture, rainfall intensity and land surface conditions.

The thesis presents point-based soil moisture measurements with gravimetric and dielectric impedance probe, viz. Hydra probe, and spatial representativeness of surface soil moisture at field scale via measurement at the edge of the field; then accuracy and reliability of surface soil moisture derived from Sentinel-1 backscatter observations based on calibrated labour intensive and automated-station measurements using stastical analysis. Finaly, the relationship between rainfall, soil moisture and water level, and the catchment response to rainfall has been analysed.

1.2. Problem statement

Surface soil moisture and rainfall are important components governing the hydrological response. Both surface soil moisture and rainfall are difficult to quantify in space and time, which hampers further optimization of the water availability and management. Satellite data on surface soil moisture can assist in augmenting point measurements to the scale of fields and catchments, enabling a better understanding of the governing hydrological processes. However, surface soil moisture at local scale from satellite data is not yet fully developed and the accuracy needs to be further assessed at field scale. Moreover, the role that surface soil moisture plays in the rainfall-runoff response is not yet fully understood at catchment scale. This research is hence initiated to quantify soil moisture variability and evaluate the relations between rainfall, soil moisture, and water level in the catchment.

1.3. Research objectives

The main objective of this research is to monitor and quantify surface soil moisture patio-temporal variability and analyse hydrological response of soil moisture and stream water level in Voltherbeek catchment.

The specific objectives can be formulated as:

- I. To analysis the surface soil moisture variability at different scales in time and space using labour intensive measurement;
- II. To create a time series of in-situ soil moisture measurements representative at field scale by using a combination of spatially distributed labor intensive measurements and continuous point measurements;
- III. To assess the accuracy of surface soil moisture (SSM) derived from Sentinel-1 backscatter observations with a change detection approach using in-situ surface soil moisture measurements;
- IV. To investigate the relationships between the SSM, rainfall and water level in the catchment.

1.4. Research questions

- Is it possible to upscale the continuous point measurements collected at the edge of a field to the field-scale using a limited set of spatially distributed labour-intensive measurements?
- What is the accuracy of the Sentinel-1 SSM estimated by using a change detection approach when compared to top 5-cm soil moisture measurements?
- How do in-situ measured rainfall, SSM and water level relate to each other in the Voltherbeek catchment?
- How fast is the water level and soil moisture in response to rainfall in the Voltherbeek catchment?

1.5. Thesis and research structure

The report of this thesis is organised in eight chapters. Chapter 1 introduces the scientific background. The study area and the main available dataset are briefly described under chapter 2. Chapter 3 describes the field work, material used for field work, sampling and measurement protocol. Chapter 4 presents Sentinel-1 mission, available dataset and the Soil water index (SWI) from Sentinel-1. Chapter 5 presents the field measurements and an evaluation of the performance of calibrated hydra probe against measurements obtained with a gravimetric method, analyse of surface soil moisture variability at different scales and matches automated station measurement with labour intensive measurements across adjacent fields. Chapter 6 describes the assessment of Sentinel-1 SWI, by rescaling SWI to SSM and comparing with in-situ measurements. Chapter 7 describes the hydrological responses of surface soil moisture and stream water level to rainfall. Chapter 8 gives conclusion and recommendation of this research.

As indicated in the general overview of this research method on Figure 1, surface soil moisture data were collected via in-situ (labour intensive and automated-station) and satellite techniques. Combining two different in-situ point measurements and upscaling to field scale, and rescaling surface water index (SWI) derived from Sentinel-1 backscatter as a reference of continuous point measurement using linear equation is done. Then, evaluate reliability of rescaled surface soil moisture derived from Sentinel-1 backscatter as a reference of in-situ soil moisture at field scale.

Rainfall and stream water level at the outlet of this catchment were measured with Davis bucket rain gauge and AE sensor respectively over the period of field work. Finally, analysis of the relationship between rainfalls, surface soil moisture and stream water level in Volthebeek catchment is made.



Figure 1. Flow chart showing overview of the research method.

2. STUDY AREA AND DATASET

2.1. Study area

The study area selected for this research is located within Twente region eastern part of province Overijssel in the Netherlands. The area is located between $52^{\circ}07' \ 06'' - 52^{\circ}28' \ 11''$ latitude and $6^{\circ}33' \ 00'' - 7^{\circ}03' \ 56''$ longitude. The land cover is dominated by agricultural land use (i.e. corn, grassland and wheat). The elevation falls within the range of 3 to 50 m above sea level. Average temperature varies between 2.2 °C in winter to 16.6 °C in summer (Eden, 2012). The map in Figure 1 shows the study area and the location of three soil moisture monitoring stations.



Figure 2. Highlighted area on the left side map indicate the study area which is located eastern part of the Overijssel province. The right side shows a Google Earth image, whereby the blue points indicate the location of soil moisture monitoring stations from which soil moisture measurements are collected.

2.2. In-situ measurements

2.2.1. Rainfall

Precipitation is the principal meteorological forcing that creates spatial and temporal variability of soil moisture content. In this study the rainfall was measured by a Davis tipping bucket rain gauge station with accuracy measurement of 0. 02 mm installed by ITC within this catchment. Figure 3b shows picture of rain gauge which can record a series of each bucket rainfall with corresponding time. The rainfall recorded from the July 12 to November 11, 2016 is 174 mm. Figure 3c shows downloading rainfall from Davis bucket rain gauge during field work and later this downloaded rainfall is converted to 15 minutes time resolution using Matlab script to fit with the soil moisture and water level data. Within this sub catchment there are two tipping bucket rain gauge stations, one in crop field and the other was on open place.



Figure 3. a) The rainfall data at 15 minute time resolution for Voltherbeek catchment, b) Davis tipping bucket and c) the location of rain gauge and download rain fall data via cable connected with computer.

2.2.2. Water level

The water level data at the outlet of this catchment has been recorded since July 8, 2016 with AE sensor in every five minute. Even though the water level was measured in every five minutes, for this research 15 minutes time step was selected to fit the time resolution with station soil moisture and rainfall measurement. Figure 3 shows the water level converted to convenient time resolution to analyse the relationship of water level with soil moisture and rainfall. The water level in Figure 4a is the response of rainfall on Figure 3a. As indicated in Figure 3a during fieldwork the maximum water level 0.9502 m was recorded on august 12, 2016 at the time of 15:15 and minimum water level 0.8464 m was recorded on September 29, 2016 at mid-day.



Figure 4. a) Stream water level hydrography at the outlet of Voltherbeek catchment in 15 minute time resolution, b) download water level from data logger in the period of field work, and c) stream flow observation during field work.

2.2.3. Soil moisture

In-situ soil moisture and soil temperature monitoring stations in Twente region were installed by the Department of Water Resources, Faculty of Geo-information Science and Earth Observation, University of Twente. This Twente region soil moisture and temperature monitoring station record the soil moisture and temperature at 5, 10, 20 40 and 80 cm depth every 15 minutes. Each soil moisture station consists of one Em50 ECH₂0 data logger which records the data collected by two to four EC-TM ECH₂0 probe, which is measuring dielectric permittivity and converted to volumetric water content via calibration equation (Dente et at., 2011). For this research only top 5 cm soil moisture was considered because Sentinel-1 backscatter is sensitive to soil moisture up to a depth of about 5 cm. Therefore, the reliability of surface soil moisture time series derived from Sentinel-1 backscatter observation was evaluated with ITCSM-monitoring station measurements as a reference (Dente et al., 2011).



Figure 5 a) shows top 5 cm Soil moisture dynamics at three ITCSM monitoring stations since January 1, 2016 and b) shows a sample of ITCSM monitoring station in study area

3. FIELD WORK

3.1. Site and sampling strategy

This fieldwork was conducted from July 10, 2016 to November 11, 2016 on six representative fields nearby the soil moisture monitoring station code ITCSM_02, ITCSM_007 and ITCSM_10 as shown in Figure 2. The selected points on each field were labelled as ITCSM_X_FiPi, where: X represents station number, and Fi and Pi represents the field and point number respectively. As illustrated in Figure 6 the point soil moisture measurement was done using hydra probe and gravimetric method.

3.2. Soil moisture measurements

3.2.1. Hydra Probe soil moisture measurement

For this study, the Hydra probe was used to collect more point measurement as compared to gravimetric method. Figure 6a and 6b show the Hydra probe instrument used to measure the volumetric water content at field. Hydra probe is the simple instrument used to measurement soil moisture and it enhance uniformly management of soil moisture condition. The instrument has four sharp rods of about five cm in length and this rod connected to the logger through a cable. While measuring soil moisture, the rod is inserted vertically in to the soil, this rod affect the reflection of electromagnetic signal and these reflection of signal form a standing wave at transmission line (Stevens Water Monitoring Systems Inc, 2007). This reflected electromagnetic standing wave was displayed in four voltages. These four voltages are a direct signal response of reflected electromagnetic wave (Stevens Water Monitoring Systems Inc, 2007). These four values are processed by a computer program in order to obtain volumetric water content.

3.2.2. Gravimetric soil moisture measurement

One of the most accurate and reliable in-situ soil moisture measurement is gravimetric method (Munoz-Carpena, 2004). However, this method is a labour intensive way of soil moisture measurement. The gravimetric soil moisture was done by collecting undisturbed soil sample from selected point using ring, weighted wet sample, dried for 24 hours at 105 °C and then reweighed. The gravimetric sampling procedures is shown in Figure 6 c to f. The difference between wet sample and dry sample was the weight of water. The equipment required to collect this sample is: ring, hammer, shovel, blade, plastic bag and GPS.



Figure 6. The instrument and technique for intensive soil moisture measurements on the field and analysis in the lab. a. and b. Hydra probe measurements, c., d., e., and f. Taking gravimetric measurement and analysis in the lab.

3.3. Sampling and measurment protocol

Sampling protocol is the most vital for reliable and spatially representative data to validate the soil moisture derived from Sentinel-1 satellite backscatter. The sampling fields, as illustrated in Figure 7, are adjacent to stations ITCSM_02, 07 and 10 and were selected based on land cover. Nearby ITCSM_02 two representative fields (grass and corn) were selected, ITCSM_07 two fields (corn) were selected, and for ITCSM_10 two (corn and potato) fields were selected. Within each field three up to six spatial points were selected depending on the size of the fields for the data collection. (see Figure 7). In each selected location four Hydra probe measurements were conducted, and a gravimetric samples were taken only from odd point numbers as shown on Figure 7d for ITCSM_10F1 field. The soil moisture measured via Hydra probe and gravimetric measurement from odd number as indicated on Figure 7d was used to analyse the performance and reliability of Hydra probe measurements.

The strategy used to collect soil sample and measurement of soil moisture content per point is illustrated in Figure 8. Hydra probe measurement was done at four location between two crop stripe across the row and ring soil sample was taken from nearby the third Hydra probe measurement to evaluate calibrated Hydra probe measurement per intended field. The cross mark on Figure 8 indicate only Hydra probe measurement and star mark indicate both Hydra probe and Gravimetric measurements. This strategy was established for the purpose of studying the spatial and temporal variability of surface soil moisture at the scales of agricultural field and stations.



Figure 7. The yellow point on three figure locate the spatially distributed point measurement and the blue point indicate the SM station. The symbol with read mark indicate measurement method at each point (GH both measurement and H hydra probe measurement).



Figure 8. Soil moisture measurement strategy, blue cross mark locate only Hydra probe measurement and blue star mark locate both Hydra probe and Gravimetric measurements.

4. SENTINEL-1

4.1. Sentinel-1 mission and available datasets

To mitigate the current challenge of water managers to optimize available water resources, recently high spatio-temporal resolution data from European Copernicus Sentinel-1 satellite can be part of the solution as it provides a unique opportunity for operational surface soil moisture mapping.

The ESA Sentinel satellite constellation series was developed by the European Space Agency (ESA) and dedicated space component of the European Copernicus program. This Copernicus program led by the European Union, which is an ambitious operational Earth Observation program providing global, timely and easily accessible information for all user in different application domains (Nagler, Rott, Hetzenecker, Wuite, & Potin, 2015). The goal of European Space Agency (ESA) Sentinel program is to ensure continuity of older Earth observation missions, which are out of service, such as the Envisat mission, or near to the end of their operational life span to guarantee а continuity of ongoing studies https://earth.esa.int/web/guest/missions/esa-future-missions.

Sentinel-1 satellite is an operational SAR to work in conflict-free operational mode with a better accuracy, imaging global landmasses, coastal zones, sea-ice zones, polar areas and shipping routes at high resolution. Specifically the Sentinel-1 mission is designed for continuous and operational applications in the priority areas of marine monitoring, land surface monitoring and emergency management services (Snoeij et al., 2008). It will ensure the reliability required by operational services and create a consistent long-term data archive for applications based on long time series(ESA, 2012). Sentinel-1A, launched on 3 April 2014, is the first of a constellation of two identical satellites sharing the same orbit to improve the revisit time. Both satellites carry dual polarization radar instruments which can improve the extraction of land surface information from backscatter observation. Because of this Sentinel-1 is expected to be very useful for monitoring soil moisture and other dynamic hydrologic process variables (Wagner et al., 2009).

To promote the application of Sentinel data, increased scientific research, growth in Earth Observation markets and job creation, Sentinel-1 data is provided on an open and free of charge to the public by ESA and the European Commission (SUHET, 2013). This data policy and accessibility for public increase the demand of Sentinel and application for different study and contribute for the research of different sectors by enabling and encouraging economically challenged researchers.

Sentinel-1 is one of the satellite series of the Sentinel program which include C-band Synthetic Aperture Radar (SAR) able to operate in four exclusive imaging modes. Among these, the Interferometry Wide swath mode (IW) is the primary operation mode for most applications over land (SUHET, 2013). For this research high resolution L-1 Ground range detected (GRD) data in Interferometric Wide swath (IW) with the spatial resolution of 10 m were used as shown on Table 1 below.

Characteristic	Interferometric Wide Swath (IW) High resolution
Polarizations	Dual VV+VH (over land)
Wavelength	C-band (5.405 GHz)
Pixel spacing	$10 \text{ m} \times 10 \text{ m}$
Temporal resolution	~2-6 days (over study area)
Incidence angle	29.1° - 46°

Table 1. Characteristics of High resolution L-1 Ground range detected Sentinel-1 Interferometric Wide Swath Mode (SUHET, 2013).

4.2. Sentinel-1 soil water index

For this research one of the data source was Sentinel-1 image to extract soil water index (SWI) from surface backscatter. Backscatter is the radar signal that redirects back to the coming direction or radar antenna. This backscatter is a measure of the reflective strength of a target. Figure 9 shows a sample of a pre-processed (masked) Sentinel-1 image (the brown colour indicate masked area which is include building, water, forest, road and Germany). The normalised radar measure from target per unit area is called the backscatter coefficient or sigma naught (σ^0). The soil water index was extracted from Sentinel-1 backscatter observations excluding masked part by the equation below using an Interactive Data Language (IDL) program for 104 image from January 1, 2016 to November 11, 2016. Surface water index from Sentinel-1 image is calculated using equation 1. From the following equation σ^o_{max} and σ^o_{min} represent the maximum and minimum backscatter signal which is indicate relatively the highest and the lowest soil moisture content. The IDL script to extract SWI from Sentinel-1 image are shown in appendix A.

$$SWI = \frac{\left(\sigma_i^0 - \sigma_{\min}^0\right)}{\left(\sigma_{\max}^0 - \sigma_{\min}^0\right)}$$
Eq1

where, SWI is soil water index.

 σ_i° = backscatter measurements at (x, y) coordinate σ_{\min}° = mean -2(stdev) σ_{\max}° = mean +2(stdev)



Figure 9. Sentinel-1 image (brown colour shows masked area, yellow to green indicate the degree SWI.

5. ANALYSIS OF FIELD MEASUREMENTS

5.1. Calibration of Hydra probe measurements

The calibration is needed to be able to convert the dielectric constant measured by the Hydra probe into a volumetric soil moisture content. The probe dielectric measurement depend on soil texture. Therefore, calibration equation is established by correlating the Hydra probe with the gravimetrically determined soil moisture measurements for each station. This is done at various spatial and temporal scale. The matchups between hydra probe measurement day, per field, per station, and for the entire databases to analyse the performance of calibration and quality of the measurements. Across the entire fieldwork period, 18 gravimetric samples have been collected per day, 3 samples per field, 6 per station, total 228 independent measurements. To point out the terminology to represent these scale: 'point' is at location where sample is made; 'field' is a place near to station where point measurements were collected; 'station' is a place include all selected field nearby individual station; and 'study area' is represent the whole study area.

Per measurement day

The statistical analysis result of intensive hydra probe measurement per individual field day is summarized in Table 2. Evaluation for calibrated Hydra probe at different scale was done for 13 days field measurements, and reliability and accuracy was quantified using the: coefficient of determination (R²), root mean square error (RMSE), mean absolute error (MAE), and bias. As shown in Table 2, accuracy and performance on October 19, 2016 indicate low coefficient of determination. On this day the correlation between two different set of measurements was weak with R² and RMSE values of 0.131 and 0.032 m³/m³ respectively. The matchup level of measured soil moisture via Hydra probe and gravimetric is different for each field days. This happen because of different reasons (i.e. small spatial difference between two set of measurement, difficult to collect good sample via ring in extremely wet and dry circumstances, the effect of small tomography). For the fact that the measurement on October 19, 2016 were taken on rainy day. Generally, the R² for each field days greater than 0.633 except field days on October 19 and November 3, 2016. The RMSE and bias for the entire field days less than 0.037 and 0.013 m³/m³ respectively. The scatter plots for each individual measurement are shown in appendix B.

The statistical indicators used to quantify the degree of correlation of Hydra probe as a reference of Gravimetric measurements have the following equations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\theta_p - \theta_g)^2}{n}}$$
Eq2

$$MAE = \frac{1}{n} \sum_{1=i}^{n} \left| \theta_p - \theta_g \right|$$
Eq3

$$Bias = \frac{1}{n} \left(\sum_{i=1}^{n} \theta_p - \sum_{i=1}^{n} \theta_g \right)$$
 Eq4

where, $\theta_{\rm p}$ is Hydra probe measurement in m³/m³ and $\theta_{\rm s}$ is gravimetric measurement in m³/m³.

Field day	Ν	Mean-VWC	R ²	RMSE	MAE	Bias
		m³/m³			m³/m³	
5-Jul	15	0.294	0.929	0.020	0.018	0.002
10-Aug	18	0.228	0.835	0.037	0.032	-0.003
25-Aug	18	0.176	0.952	0.018	0.014	0.000
6-Sep	18	0.186	0.916	0.024	0.019	0.010
15-Sep	18	0.117	0.780	0.027	0.019	0.006
22-Sep	18	0.125	0.750	0.032	0.020	-0.004
30-Sep	18	0.169	0.732	0.032	0.026	0.013
7-Oct	18	0.170	0.814	0.026	0.019	-0.009
14-Oct	18	0.154	0.884	0.017	0.014	-0.005
19-Oct	15	0.345	0.131	0.032	0.026	-0.008
28-Oct	18	0.258	0.633	0.035	0.025	0.001
3-Nov	18	0.256	0.537	0.033	0.026	-0.004
11-Nov	18	0.296	0.789	0.028	0.023	0.010

Table 2. Statistically summarized result for the correlation between Hydra probe and Gravimetric measurement per individual field day.

At field scale

The main purpose for the comparison at the field level was to evaluate the accuracy and performance of thirteen days Hydra probe measurements for each specific field. The scatter plot in Figure 10 shows the R² and performance of calibrated Hydra probe measurements versus gravimetrically determined soil moisture content per each field. The points deviating from the 1:1 line indicate high bias and points nearby 1:1 line indicate better accuracy between two different intensive soil moisture measurement techniques. As illustrated in Figure 10, for ITCSM_2F1, ITCSM_7F1 and ITCSM_7F3, the trend line deviate from 1:1 line when soil moisture content decrease. Inversely for ITCSM10F2, the trend line deviate from 1:1 line when the soil moisture content decrease. That means Hydra probe measurement is underestimate and overestimate in case of extremely high and low soil moisture content respectively. In case of ITCSM_2F2 and ITCSM_10F1 field the trend line has almost the same slope with the 1:1 line, which depicts that the measurement of both methods are linearly correlated. The difference in correlation between gravimetric and Hydra probe measurement for different fields is because of difference in the wetness of the fields and different land cover. The correlation for ITCSM_7F1 and ITCSM_7F3 is relatively weak due to the variation of soil type within field and wet as compared to the rest of the fields.

As illustrated on Figure 10 the scatter plot for ITCSM_2F1 indicates when the soil moisture content increase the trend line deviate from the slope of 1:1 line. This result indicate in case of high soil moisture content, Hydra probe underestimate as compared to gravimetric measurements, and this particular field soil moisture sensitivity in response to rainfall as a result of land cover. The plot of ITCSM_2F2 shows the trend line slope almost the same as 1:1 line. This is the fact that ITCSM_2F2 was relatively dry as compared to ITCSM_2F1 because of interception. Consequently, calibrated Hydra probe perform better on ITCSM_2F2 than ITCSM_2F1.

The reliability and accuracy of calibrated Hydra probe at station scale was evaluated for field scale. Table 2 indicates the quantified summary result of the correlation at field scale between Hydra probe and Gravimetric measurements. Generally field scale Hydra probe measurements display good linear

relationship with gravimetric measurements. Particularly for relatively dry fields (ITCSM_2F1, ITCSM_2F2, ITCSM_10F1, and ITCSM_10F2), as indicated in Table 2, coefficient of determination (R^2) for those field is above 0.851, the RMSE is less than 0.029 m³/m³, MAE less than 0.024 m³/m³, and bias less than 0.012 m³/m³.

Table 3. Statistical sur	mmary for the correlation	n between Hydra pro	obe and gravimetric m	neasurement at field
scale.				

Field	N	Mean_VWC	R ²	RMSE	MAE	Bias
		m³/m³			m³/m³	
ITCSM_2F1	39	0.241	0.905	0.029	0.024	-0.011
ITCSM_2F2	39	0.180	0.904	0.025	0.020	0.012
ITCSM_7F1	39	0.279	0.798	0.040	0.030	-0.010
ITCSM_7F3	36	0.274	0.811	0.040	0.029	-0.009
ITCSM_10F1	39	0.149	0.959	0.018	0.014	-0.002
ITCSM_10F2	36	0.160	0.851	0.026	0.017	0.001







Figure 10. Calibration of hydra probe soil moisture measurement using gravimetrically determined soil moisture content at field scale.

Station scale

The purpose of calibration at specific station is to determine how this point measurement represent the actual soil moisture at station scale. The scatter plot on Figure 11 shows average Hydra probe versus gravimetric measurement per station scale with combined two selected field measurements, and at each station different performance and accuracy have been observed. The result in Table 4 indicate the performance and accuracy of station is better than field scale. This accuracy might be increase as a result of sampling number and consequently decrease the measurement error.

Visual inspection of the scatter plot, the relation is not bad because all point measurements fall nearby the 1:1 line and also the trend line slope almost the same as 1:1 line especially for ITCSM_2 and ITCSM_10. However, qualitative performance evaluation is subjective. Therefore, the performance of Hydra probe was analysed using R², RMSE, MAE and bias.

Table 4 shows the statistics result of correlation between Hydra probe versus gravimetric measurements at station scale. In this case also each station shows different correlation between Gravimetric and Hydra probe measurement because the variability of soil moisture content nearby each station and due to the differences in soil type. The correlation at station scale between two measurements confirm good linear correlation. As indicated in Table 4, the values of R² for all stations is above 0.865, RMSE is less than 0.031 m³/m³, and MAE is less than 0.023 m³/m³, and bias less than 0.003 m³/m³. However, the correlation for station ITCSM_07 was relatively weak, because of variation in clay content on these fields and as a result these locations tend to stay wet for a longer time. Therefore, the accuracy and performance of Hydra probe measurement is low, especially in extremely wet and dry case.

Table 4. Statistically sum	mary result for a	calibration of	hydra probe	versus grav	vimetrically o	determined soil
moisture content at statio	on scale.					

Station	N	Mean_VWC	R ²	RMSE	MAE	Bias
		m³/m³			m³/m³	
Station_02	78	0.211	0.906	0.026	0.021	0.001
Station_07	75	0.252	0.865	0.031	0.023	0.002
Station_10	75	0.165	0.952	0.019	0.015	0.003



Figure 11. Calibration of hydra probe soil moisture measurement using gravimetrically determined soil moisture content at station scale.

Study area

As already discussed in the cases of field and station scale, the calibration for whole study scale was done for evaluating the performance and accuracy of Hydra probe soil moisture measurement at a basin scale. The evaluation of calibrated Hydra probe at basin scale incorporate all measurements in study area. Figure 12 shows linear relationship between Hydra probe and Gravimetric measurement with equation and points along the 1:1 line. As can be observed from the figure, the slope of trend line is somehow gentle than 1:1 line, which indicate the accuracy and performance of Hydra probe at different degree of soil moisture content. In case of low soil moisture content the trend line is above 1:1 line which depicts that the Hydra probe overestimated the soil moisture content. On the other hand, when the soil moisture is higher, the trend line fall below the 1:1 line which is because of the fact that the Hydra probe was less sensitive and as a result the soil moisture measurement was less than actual soil moisture content. Table 5 shows the statistically quantified relationship between the two measurements. The basin scale calibration confirm strong correlation with R² value of 0.906, RMSE and MAE of 0.029 and 0.021 m³/m³ respectively, and 0.001 m³/m³ bias.

		Mean_VWC	R ²	RMSE	MAE	Bias
	Ν	m³/m³			m³/m³	L
Study area	228	0.210	0.906	0.029	0.021	0.001

Table 5. Statistically summary result of general calibration of hydra probe versus gravimetrically determined soil moisture water content at basin scale



Figure 12. General calibration of hydra probe soil moisture using gravimetrically determined soil moisture water content at basin scale.

5.2. Soil moisture spatial and temporal variability

Twente region near-surface soil moisture variability with respect to time and space at different scale is analyzed using the labour intensive soil moisture measurement collected at 33 points for 13 days. These collected ground truth data were used to examine spatio-temporal surface soil moisture variability. To study the spatially and temporally dynamic behaviour of soil moisture, statistical analysis of soil moisture collected at different points at different times is analysed. In this research soil moisture variability were analysed at different spatial scales.

5.2.1. Statistical analysis

The spatial and temporal variability of soil moisture was analyzed to investigate surface soil moisture dynamics at different scale. The temporal variability of soil moisture per specific location during three month field work was assessed by means of surface soil moisture collected for 13 days per specific scale and the deviation of each day measurement from the mean of all measurements per scale. The same is true for the spatial variability, by the spatial mean of intended scale and the deviation of each soil moisture measurement from the mean at the same time.

Point scale

Spatial mean of soil moisture for point i in field j in all sampling day was computed as:-

$$\overline{\boldsymbol{\theta}}_{ij} = \frac{1}{n} \left(\sum_{t=1}^{t=n} \boldsymbol{\theta}_{ijt} \right)$$
 Eq5

where θ_{ijt} is soil moisture observed at point i in field j on sampling day t and n is the total number of sampling days per point in m³/m³.

The high spatial variability soil moisture content within the field j is characterized by high variation between the mean of individual sample point in the field and low variability shows low variation between mean of each point (Brocca, Melone, Moramarco, & Morbidelli, 2010).

As stated by Vanderlinden et al., (2012), the temporal variability of soil moisture at a point i in field j on the sampling day t can be computed using standard deviation, which are formulated by:

$$\sigma_{ij} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(\theta_{ijt} - \overline{\theta_{ij}}\right)^2}$$
Eq6

Where θ_{ijt} is mean soil moisture at a point i in field j on sampling day t, θ_{ij} is mean soil moisture at a point i in field j over a period of field work and σ_{ij} is standard deviation. All values are in m³/m³.

Figure 13 shows the labour intensive mean surface soil moisture per point and deviation from the mean over the study period. As illustrated on Figure 13a the mean soil moisture at all points within the field including point at station range from 0.231 to 0.255 m³/m³. This result implies low spatial variability across the field. The extent of standard deviation from the mean of each point indicate the temporal variability soil moisture at a point. As indicated on Figure 13a for all points the magnitude of standard deviation from the mean soil moisture is high range from 0.081 to 0.093 m³/m³. The upper and lower peak of the bar on the same figure confirm the degree of temporal soil moisture variability with corresponding points. In this field the intensive point measurement at station had almost the same mean soil moisture and standard deviation from the same land cover beside of ITCSM_2F1. Consequently, soil moisture monitoring stations can be well spatially represented for similar land cover as station.

As illustrated on Figure 13b, the intensive point average measurement at station indicate more mean soil moisture content as compared to the rest thee points in ITCSM_2F2 field. The corn field shows lower surface soil moisture content than station point, which is most likely caused by the rainfall intercepted by the corn. The mean intensive soil moisture measurement at three points in ITCSM_2F2 field was almost the same range from 0.180 to 0.184 m³/m³. The difference of this range implies low spatial variability across ITCSM_2F2 field. The standard deviation from the mean at those three fields almost the same range from 0.062 to 0.067 m³/m³ and relatively lower than ITCSM_2F1 field. Therefore, the surface soil moisture within ITCSM_2F2 field less temporarily variable than ITCSM_2F1 field.

Figure 13c and 13d shows point mean surface soil moisture variability within the field and number of point measurements in each field. Figure 13c and 13d shows high spatial and temporal soil moisture variability within the field. The point mean surface soil moisture measurement at ITCSM_7F1P1 shows a range from 0.215 to 0.295 m³/m³ and which implies high spatial variability within the field. The point mean deviation

from mean surface soil moisture is range from 0.052 to 0.094 m³/m³, this figure indicate temporal variability of soil moisture in the field. This is because of the fact that these locations have soil with more clay content and have the tendency to be inundated for short times. On Figure 13c at point 7F1P2, 7F1P3 and 7F1P4 shows relatively similar mean soil moisture content but 7F1P3 more temporarily variable then the other two points. The low standard deviation of point 7F1P2 and 7F1P4 from the mean soil moisture measurement indicate low soil moisture variability of particular point with respect to time. Figure 13c at point 7F1P5 low soil moisture near to ITCSM_07 was higher than the station measurement and less temporarily variable. This may happen due to the effect of small topography and the foliage near to the station. Figure 13d shows five measured points in ITCSM_7F3. From those points soil moisture at point ITCSM_7F3P1 indicated high soil moisture and was temporally variable. Because, this point lies at relatively low elevation and corn was sparse at this location. The other four points within ITCSM_7F3 showed relatively the same mean soil moisture and standard deviation.

Six point measurements were taken per field nearby ITCSM_10 monitoring station as shown on Figure 12. In case of ITCSM_10F1, except the point measurement at station, the rest six points showed relatively low spatial variability of soil moisture and nearly the same high temporal variability at all points in the field. The intensive point measurement near to ITCSM_10 station indicate low mean soil moisture. This might have happened because of the fact that the station is placed at uncropped space between two fields and this raises questions to the spatial representatively of the station's measurements. On the other hand, the ITCSM_10 monitoring station measurements show comparable mean and standard deviation as the field measurements. On Figure 13 (ITCSM_10F2) shows high variability of soil moisture with respect to time and space. The temporal variability of all points in this field was nearly the same. This considerable spatial variability is justifiable by differences in elevation and the growing stage of potato on this field.

Point nearby ITCSM_02		Point nearby ITCSM_07			Point nearby ITCSM_10			
Point	mean/pt	Stdev	Point	mean/pt	Stdev	point	mean/pt	Stdev
ITCSM_02	0.207	0.086	ITCSM_07	0.240	0.074	ITCSM_10	0.168	0.085
Near st_2	0.231	0.093	7_station	0.276	0.056	10_station	0.118	0.074
2F1P1	0.254	0.086	7F1P1	0.295	0.094	10F1P1	0.160	0.084
2F1P2	0.239	0.082	7F1P2	0.267	0.052	10F1P2	0.158	0.083
2F1P3	0.250	0.083	7F1P3	0.253	0.078	10F1P3	0.148	0.082
2F1P4	0.255	0.081	7F1P4	0.258	0.055	10F1P4	0.175	0.084
2F1P5	0.250	0.083	7F1P5	0.215	0.077	10F1P5	0.137	0.086
ITCSM_02	0.207	0.086	ITCSM_07	0.240	0.074	10F1P6	0.155	0.096
2_station	0.231	0.093	7_station	0.267	0.052	ITCSM_10	0.168	0.085
2F2P1	0.180	0.062	7F3P1	0.258	0.067	10_station	0.118	0.074
2F2P2	0.184	0.063	7F3P2	0.202	0.042	10F2P1	0.163	0.084
2F2P3	0.184	0.067	7F3P3	0.198	0.051	10F2P2	0.167	0.079
			7F3P4	0.229	0.058	10F2P3	0.142	0.083
			7F3P5	0.214	0.050	10F2P4	0.117	0.077
						10F2P5	0.113	0.083
						10F2P6	0.153	0.090

Table 6. Summarized result of mean and standard deviation of each location to analysis the spatial and temporal variability at point scale.



Figure 13. Soil moisture spatial & temporal variability at different point scale (The blue point indicate the mean of soil moisture at respective points and the extent of the bar indicate mean deviation from the mean which implies the temporal variability.

Field scale

Spatial mean of soil moisture in field j for all sampling day was computed as:-

1

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$$\overline{\boldsymbol{\theta}}_{j} = \frac{1}{n} \left(\sum_{t=1}^{t=n} \boldsymbol{\theta}_{jt} \right)$$
Eq7

Temporal variability of soil moisture in field j on the sampling day t can be computed as standard deviation from the mean surface soil moisture over period field work.

$$\sigma_j = \sqrt{\frac{1}{n} \sum_{i=1}^n \left(\theta_{jt} - \overline{\theta_j}\right)^2}$$
Eq8

Where θ_j is spatial mean of soil moisture in field j for all sampling days, θ_{jt} is mean soil moisture for field j on the sampling day t, σ_j is standard deviation and n is the number of sampling days per field. All values are in m³/m³.

High soil moisture spatial variability between different fields in the study area is characterized by high variation between the mean of fields, and low variability shows low variation between the mean fields. The field temporal stability of soil moisture is characterized by a low value of standard deviation or minimum deviation each day measurement from the mean of entire period of soil moisture measurement (Dongli, Yingying, Ming, Carlos, & Shuang, 2012)

Figure 14 shows the overall mean of each field and spatio-temporal variability between the fields. The blue point at the centre of bar indicates the mean soil moisture for each intensive field measurements. The upper and lower peak indicate the extent of soil moisture deviation from the mean with respect to time. The more the standard deviation from the mean implies the temporal variability of soil moisture content. Differences among the mean soil moisture between fields indicate the spatial variation of soil moisture content at different fields. ITCSM_2F1 and ITCSM_2F2 are located beside each other nearby ITCSM_02 monitoring station. However, Figure 13 shows high spatial and temporal variability between the two fields. This variation might happened due to the land cover differences during field work. The different in land cover causes surface soil moisture variability because of the difference interception and evaporation. The land cover of ITCSM_2F1 is grass field which is more sensitive in soil moisture for small rainfall than corn field. In corn field, the soil moisture may not show significant response for small rainfall; as a result field average soil moisture was spatially variable. In case of temporal variability, grass field is exposed to soil surface evaporation than corn field, which increases the dynamics of soil moisture in grass field with time and the corn intercept on field ITCSM_2F2 lowering the temporal variability. As such, the deviation of the mean for ITCSM_2F1 is higher than ITCSM_2F2 which is indicates more temporal variability of soil moisture content within the field.

Similarly, fields near to ITCSM_07 monitoring station show different mean soil moisture between fields. In this case, the land cover of both fields during field work was corn. Even if, these fields lie beside each other, the result in Table 7 and Figure 14 show a high soil moisture variability. This variability happened because: 1) ITCSM_7F1 is more clay than the ITCSM_7F3 and for the fact that the clay soil retains soil moisture for a long time, 2) in ITCSM_7F1 out of five point measurements, the location of the first point has the tendency of being inundated in case of high rainfall. As a result of these two reasons the mean soil moisture content in ITCSM_7F1 was higher than ITCSM_7F3 and more temporarily variable than ITCSM_7F3. This temporal variability may be justified by the fact that the inundation water stays only for a short time. This situation increase surface soil moisture temporal variability in the field. ITCSM_7F3 shows low temporal variability as compared the rest five fields.

The field nearby ITCSM_10 monitoring station showed low soil moisture content than the fields nearby the rest two stations. The two fields ITCSM_10F1 and ITCSM_10F2 showed nearly the same mean soil moisture content. Figure 14 and Table 7 indicate high standard deviation which confirm high temporal variability of soil moisture content at field ITCSM_10F1 and ITCSM_10F2.

Figure 14 shows the overall mean of each field and spatio-temporal variability between the fields. The blue point at the centre of bar indicates the mean soil moisture for each intensive field measurements. The upper and lower peak indicate the extent of soil moisture deviation from the mean with respect to time. The more the standard deviation from the mean implies the temporal variability of soil moisture content. The mean difference between fields indicate the spatial variation of soil moisture content at different fields. ITCSM_2F1 and ITCSM_2F2 are located beside each other nearby ITCSN_02 monitoring station. However, Figure 13 shows high spatial and temporal variability between the two fields. This variation might happened due to the land cover differences during field work. The different land cover causes differences in soil moisture for the same amount of rainfall. The land cover of ITCSM_2F1 is grass field which is more sensitive in soil moisture for small rainfall than corn field. In corn field, the soil moisture may not show significant response for small rainfall; as a result field average soil moisture was spatially variable. In case of temporal variability, grass field is exposed to soil surface evaporation than corn field, which increases the dynamics of soil moisture in grass field with time and the corn intercept on field ITCSM_2F2 lowering the temporal variability. As such, the deviation of the mean for ITCSM_2F1 is higher than ITCSM_2F2 which is indicates more temporal variability of soil moisture content within the field.

Similarly, fields near to ITCSM_07 monitoring station show different variability between fields. In this case, the land cover of both fields during field work was corn. Even if, this fields lie beside each other, the result in Table 7 and Figure 14 show high spatial variability in soil moisture. This variability happened because: 1) ITCSM_7F1 is more clay than the ITCSM_7F3 and for the fact that the clay soil retains soil moisture for a long time, 2) in ITCSM_7F1 out of five point measurement, the location of the first two points have the tendency of being inundated in case of high rainfall. As a result of this two reasons the mean soil moisture content in ITCSM_7F1 was higher than ITCSM_7F3 and more temporarily variable than ITCSM_7F3. This temporal variability may be justified by the fact that the inundation water stays only for a short time. This situation decreases the stability of soil moisture in this field in time. ITCSM_7F3 shows low temporal variability as compared with the rest five fields.

The field nearby ITCSM_10 monitoring station showed low soil moisture content than the fields nearby the rest two stations. The two fields ITCSM_10F1 and ITCSM_10F2 showed nearly the same mean soil moisture content. Figure 14 and Table 7 indicate high standard deviation which confirm high temporal variability of soil moisture content at field ITCSM_10F1 and ITCSM_10F2.

Field	Nº. field day	Mean SM(m3/m3)	Standard deviation
ITCSM_02	13	0.231	0.093
2F1	13	0.247	0.084
2F2	13	0.186	0.064
ITCSM_07	13	0.276	0.056
7F1	13	0.262	0.080
7F3	12	0.220	0.059
ITCSM_10	13	0.118	0.074
10F1	13	0.161	0.089
10F2	12	0.143	0.085

Table 7. Summarized spatial and temporal variability of soil moisture content at field scale



Figure 14. Soil moisture spatial & temporal variability at field scale (the blue point on vertical bar indicate the spatial mean of soil moisture respective field and the extent of bar indicate mean deviation from the mean which implies the temporal variability).

5.3. Automated-station vs labor-intensive measurements

The comparison between soil moisture from the automated-stations and labour intensive measurements is the process of checking spatial support of in-situ measurements at different scale.

5.3.1. At station locations

The automated-station measurement was checked with intensive point measurement nearby station to increase on the reliability and accuracy of station measurement. The station measurement might be different from intensive measurement because of the difference measurement techniques. For instance the station measured soil moisture exactly at 5 cm depth and intensive measurement is consider the average soil moisture from 0 to 5 cm depth. The correlation between labour intensive point measurements nearby the station versus automated station measurement was analysed using a scatter plot.

The correlation of the two in-situ measurements per the same location shows different accuracy for each station. As shown on Figure 14 and Table 8, for the location at ITCSM_02 the soil moisture showed relatively good matchup with R² and RMSE values of 0.755 and 0.032 m³/m³ respectively as compared to the other two stations. Contrary, large bias have been observed at this station and subsequently, this large bias increase the error. From the same figure and table the ITCSM_07 soil moisture showed lowest correlation as compared to the rest of the stations, which could be due to the effect of small topography and foliage at the location of ITCSM_07 station. However, low bias have been observed at this station. On the other way the largest deviation have been observed at ITCSM_10 monitoring station. This deviation is high because of the fact that the station is placed at uncropped plot between two fields and the effect of small topography.

Point nearby	Ν	R2	RMSE MAE)		Bias
station				m3/m3	
ITCSM_02	13	0.755	0.039	0.032	-0.069
ITCSM_07	13	0.602	0.048	0.039	0.014
ITCSM_10	13	0.702	0.071	0.061	-0.064

Table 8. Summary of statistical measures for the correlation between automated-stations and intensive measurements nearby the stations.



Figure 15. The relationship between automated-station measurement and point intensive measurement nearby the location of each soil moisture stations.

5.3.2. At field-scale

The next part is to analyse the automated-station measurements with intensive field average measurement to evaluate the spatial soil moisture content representativeness of the automated-station measurements. The correlation of field average intensive measurement nearby each station versus ITCSM monitoring station measurement was analysed using scatter plot. The scatter plot in Figure 16 shows the relationship between field averages versus automated-station measurement at specific field. As shown in the summary result of Table 9 and Figure 16 almost all except ITCSM_2F1 imply weak correlation between these two measurements. This weak relationship might be due to the fact that the exact location of soil moisture station is not in the field. From Figure 16, surface soil moisture for ITCSM_2F1 show the better correlation than the rest of the fields because ITCSM_2F1 was a grass field nearby the ITCSM_02 monitoring station and this station is located on the same land cover beside of ITCSM_2F1. Therefore, the automated-station measurements at this location well represents the field average intensive measurement in ITCSM_2F1.

ITCSM_7F1 and ITCSM_7F3 are located near to ITCSM_07 monitoring station. However, as can be observed from Figure 16 and Table 9, these two field showed different degree of correlation between the two different in-situ measurements. This may have happened for two reasons: 1) during field work, ITCSM_7F1 was relatively wetter than station location due to the difference of soil type in the field and at station location, 2) the ITCSM_07 monitoring station was located beside this field at the boundary between corn and grass fields. Therefore, almost all intensive measurements in ITCSM_7F1 were higher than automated-station measurement. In case of ITCSM_10, in both fields most of field average intensive measurements were lower than the automated-station measurement. Lower intensive measurements could be justified by two reasons: 1) the station is located in small untilled open space between these two fields, 2) in the field, particularly in corn field the whole rainfall does not reach the soil as some part of rainfall will be intercepted by the corn in the field. Generally, the matchup result of automated-station against field scale intensive measurements better performed than against point measurement at station. This is because the

field scale intensive measurement is spatially supported and the number of measurement decrease the measurement error. Table 9 summarizes the statistical analysis results: R², RMSE, MAE and bias for the correlation between field average and station soil moisture measurements.

Table 9. Statistical summary of correlation between automated-station measurement and field average imntensive measurement

Field	N	R ²	RMSE	MAE	Bias		
				m3/m3			
2F1	13	0.847	0.032	0.023	-0.053		
2F2	13	0.744	0.032	0.033	-0.087		
7F1	13	0.447	0.046	0.029	0.005		
7F3	12	0.796	0.019	0.017	-0.035		
10F1	13	0.599	0.055	0.048	-0.032		
10F2	12	0.578	0.057	0.043	-0.039		



Figure 16. The relationship between field average labour intensive measurement and automated-station measurement nearby the specific fields

6. ASSESSMENT OF SENTINEL-1 SWI

6.1. Converting SWI into surface soil moisture

Soil water index (equation 1) are quantitative measurements of water content in the surface layer ranging from zero to one (Bartalis, Naeimi, & Wagner, 2008). Assume the zero values indicate completely dry and one indicate fully saturated. As discussed in section 4.2, the soil water index was extracted using IDL program from Sentinel-1 backscatter observations. The spatial resolution of Sentinel-1 is 10m and its temporal resolution about 3 to 4 days. This soil water index (SWI) derived from the Sentinel-1 backscatter observation value is rescaled to SSM by linearly corresponding the two extreme value of Sentinel-1 SWI and VWC from ITCSM monitoring station and develop the linear equation as:

$$SSM_{s-1} = a * SWI + b$$
 Eq8

Where SSM_{s-1} is rescaled volumetric water content in m³/m³, a is the slope of linear equation between station measurement and *SWI* derived from S1 backscatter observation, *SWI* is relative soil water index extracted from Sentinel-1 on respective days and b the constant value that the linear equation intersect the *SSM* axis at point b.

Table 10 shows the two extreme values from three selected ITCSM monitoring station and the average of two extreme value of SWI extracted from Sentinel-1 which are used to rescale SWI for each of the six selected fields. As indicated on Table 10 each field have its own slope 'a' and intercept 'b' value of the relation between station versus SWI.

		ITCSM_station	S1_SWI Value	Linear relationship	
Field	value			a (slope)	b (intercept)
2F1	max	0.545	0.827	0.544	0.095
	min	0.122	0.049		
2F2	max	0.545	1.000	0.470	0.075
	min	0.122	0.097		
7F1	max	0.484	0.866	0.519	0.035
	min	0.100	0.126		
7F3	max	0.484	1.000	0.469	0.015
	min	0.100	0.182		
10F1	max	0.467	0.892	0.539	-0.014
	min	0.050	0.119		
10F2	max	0.467	0.813	0.584	-0.008
	min	0.050	0.098		

Table 10. Rescaled field average SWI derived from Sentinel-1 backscatter observation to VWC using linear relashinship as areference of automated-station measurement nearby each field.

6.2. Comparison with labor-intensive measurements

As discussed in section 4.2 and 6.1 the SWI extracted from S1 backscatter observation and rescaled SWI to VWC using linear relation (equation 13). Labour intensive soil moisture data was collected weekly during September 2016 to November 2016. The accuracy of Sentinel-1 SSM was evaluated by comparing the surface soil moisture derived from Sentinel-1 with the ground truth soil moisture content from station and labour intensive measurement.

The scatter plots of Figure 17 show the field average surface soil moisture derived from Sentinel-1 against field measurements. Th red symbols on Figure 17 show field average surface soil moisture derived from Sentinel-1 versus field average labour intensive soil moisture measurement, and the blue plot show the correlation of field average surface soil moisture derived from Sentinel-1 versus station soil moisture nearby the field. The accuracy and performance of surface soil moisture derived from Sentinel-1 backscatter observation is analyzed with ground truth soil moisture measurement as a reference. As stated by Wagner et al., (2009) the accuracy target of soil moisture for active microwave sensor is 0.08 m³/m³ for agricultural areas. Table 11 shows number of field day and point measurement per field, and the result of statstical analysis: R², RMSE, MAE and bias for each field.

Table 11 figure out the correlation of field average Sentinel-1 SSM with field average labour intensive and station measurement. From the result of R², RMSE, MAE and bias each field have different correlation and performance. The R² and RMSE value for 2F1, 2F2 and 10F1 is 0.557, 0.662 and 0.530 and 0.061, 0.075 and 0.073 m³/m³ respectively which indicate better correlation between two different set of data as compared to the other fields. RMSE and bias value for 10F2 is 0.116 and 0.097 m³/m³ respectively, which indicate low accuracy as compared to the other fields. This potato field planted with small ridge (raw) during the field work, which is makes difficult to get accurate intensive measurement and increase the RMSE and bias. The correlation of Sentinel-1 with in-situ measurement for ITCSM_7F1 and ITCSM_7F3 fields shows low coefficient of determination. However, the error level of these field meet the accuracy target of 0.08 m³/m³ for active microwave sensor for agricultural land with a bias less than 0.045 m³/m³. Similarly, these fields as discusses in section 5.3 shows low agreement between two in-situ measurements as compared to the other field. The same is true for the correlation between Sentinel-1 versus in-situ soil moisture measurements. This might be happen due to: 1) the difference measurement techniques, and 2) this effect of vegetation on Sentinel-1 backscatter signals.

The correlation of field average Sentinel-1 SSM with field average labour intensive is better than the correlation with station measurement, except for ITCSM_10F2. The labour intensive measurement is spatially distributed over the field, the same is true for Sentinel-1 SWI derived at the coordinate sampling point that is why labour intensive measurement relatively perform better than station measurement. The stations are point measurements and most of them are located at the edge of fields. Hence, the station implies low correlation with field average measurements.

All fields except ITCSM_10F2 the matchup between Sentinel-1 SSM and labour intensive soil moisture measurements meet the accuracy target of 0.08 m³/m³ for active microwave sensor for agricultural area. This bias is the result of rescaling with station measurements as reference and the already showed bias between station and field (figure 15). As indicated on Figure 17 (ITCSM_2F2) the blue point measured on October 19, 2016 deviated from 1:1 line which decrease the correlation between S1 surface soil moisture versus station measurements. On this day Sentilel-1 and station surface soil moisture measurements are 0.463 and 0.159 m³/m³ respectively. October 19, 2016 was rainy day and labour intensive surface soil moisture measurement is 0.330 m³/m³. This type of situation might be happen immediately at the beginning

of rainfall when station measured soil moisture exactly at 5 cm depth, and S1 and labour intensive measurement measured mean soil moisture from 0 to 5 cm.

Field	N	Point /field	mean_vwc	R^2	RMSE MAE		BIAS
			m3/m3			m3/m3	
2F1	13	5	0.248	0.557	0.060	0.042	0.027
2F2	13	3	0.198	0.662	0.075	0.065	0.059
7F1	13	5	0.248	0.041	0.078	0.067	0.030
7F3	12	5	0.226	0.024	0.073	0.064	0.045
10F1	13	6	0.166	0.530	0.073	0.062	0.039
10F2	12	6	0.144	0.351	0.116	0.097	0.097

Table 11. Comparison between field average S1 SSM and labour intensive soil moisture measurement



Figure 17. Comparison the field average S1_SSM with station soil moisture and field average labour-intensive soil moisture measurement at Sentinel-1 overpass.

6.3. Comparison with automated-station measurements

The accuracy and reliability of soil moisture derived from Sentinel-1 is assessed by plotting the field average Sentinel-1 SSM and automated-station measurements on the moment of the satellite overpasses. The time resolution of the automated-station measurements is 15 minute and the Sentinel-1 about three to four days. Therefore, to compare the two soil moisture measurements, first matchup was done on the time resolution by filtering the automated-station measurements on the date and time of Sentinel-1 overpass.

Figure 18 shows the comparison of soil moisture measurement from different techniques. The blue line indicates the relative soil moisture content, the red lines shows SSM after rescaling the SWI derived from Sentinel-1 backscatter observation, and the grey line shows automated-station measurement on the day and time of Sentinel-1 overpass. For this comparison, the automated-station measurement ITCSM_02 and ITCSM_07 are considered for 10 months since January 1, 2016 and for ITCSM_10 only 6 months as the station was replaced in May 2016.

As illustrated on Figure 18 2F1, 2F2, 7F1 and 7F3 rescaled SWI underestimates SSM from January to May as compared to station measurements. But from May to November the Sentinel-1 SSM overestimated the station measurements. The conclusion from this result is that the VWC derived from sentinel-1 backscatter observation underestimate in winter and spring, and overestimate in summer and autumn as compared to automated-station measurement. The uncertainty of Sentinel-1 SSM as compared to ground truth might have happened due to different physical factors: 1) underestimation of winter and spring may happen due to snow and inundation, that affect the redirection of the backscattering signal. The water surface reflect the signal rather than redirect to the coming direction, causing a low backscatter value and consequently a low SSM; and 2) overestimation in summer and autumn may be the result of vegetation cover. The radar receives the total backscatter from soil surface and canopy, and canopy might increase the value of backscatter to radar. 3) Changes in roughness, as a result of ploughing, can cause jumps in the backscatter signal (see between May and August at 2F2 and 7F1).





Figure 18. Comparison between SWI, Rescaled_SWI and automated-station measurement when satellite overpass

The scatter plot on Figure 19 shows the correlation between field average surface soil moisture derived from Sentinel-1 and automated-station measurements. Table 12 shows number of measurements at Sentinel-1 overpasses, and the results of the statistical analysis. From Table 12 statistical result R² value for all field range from 0.108 to 0.355, except field ITCSM_7F3, which indicate ITCSM_7F3 field is not well represented with automated station measurement. RMSE value for all field range from 0.084 to 0.129 m³/m³, and bias range from 0.002 to 0.061 m³/m³.

The comparison result against automated-station measurements shows weaker correlation than against intensive field measurements. This is caused by different factors, for instance vegetation growth, inundation, tillage practices, the length of period that has been considered, spatial location of station and the difference of measurement techniques. As a result, automated-station measurement shows reliability as compared to labour intensive measurement.

Field	N	Station	mean_vwc	R ²	RMSE	MAE	BIAS
			m ³ /m ³			m ³ /m ³	
2F1	104	ITCSM_02	0.276	0.355	0.099	0.081	0.002
2F2	104	ITCSM_02	0.276	0.235	0.116	0.090	-0.021
7F1	104	ITCSM_07	0.252	0.189	0.129	0.112	0.004
7F3	104	ITCSM_07	0.252	0.002	0.106	0.092	0.014
10F1	62	ITCSM_10	0.194	0.179	0.084	0.069	-0.016
10F2	62	ITCSM_10	0.194	0.108	0.109	0.090	-0.061

Table 12. Comparison between field average S1 VWC and automated-station measurement



Figure 19. The correlation between the field average VWC derived from Sentinel-1and the station soil moisture nearby the field.

7. RAINFALL-SOIL MOISTURE-WATER LEVEL

7.1. Hydrological response

This chapter discusses the relation between rainfall, surface soil moisture and stream water level, and analyses hydrological response of surface soil moisture and water level to different rainfall events. Figure 20 is built from in-situ rainfall, surface soil moisture and stream water level collected for the last four months (July to November, 2016).

As indicated on Figure 20a the black dot shows labour intensive soil moisture collected from field nearby the outlet and green dot shows mean Voltherbeek catchment surface soil moisture derived from S1. The blue line on Figure 20a shows automated-station measurement. As explained in section 5.3, the average labour intensive soil moisture measurement somewhat deviate from automated-station measurement. This deviation can be attributed to the fact that ITCSM_07 station is located besides field 1 and the intensive soil moisture measurement points are located in the corn field. The green line on Figure 20b shows stream water level at the outlet of Voltherbeek catchment, and on both Figure 20 a and 20b the grey vertical line shows the magnitude of rainfall in Voltherbeek catchment.

The ellipses on Figure 20a and 20b show rainfall events for which the responses of surface soil moisture and stream water level will further be investigated. At first, investigation of lag time between the peak of rainfall to soil moisture and water level was analysed at four selected events to determine how fast the stream water level and surface soil moisture respond to rainfall. Secondly, sensitivity of surface soil moisture and water level to rainfall as a function of antecedent soil moisture conditions is investigated.



Figure 20. The interaction between rainfall, soil moisture and water level with corresponding time.

7.2. Event analysis

Figure 21 shows a response of surface soil moisture and stream water level for selected date and time t1, t2, t3 and t4 from Figure 20 a and b. Table 13 presents the magnitude of rainfall with date and time, initial soil moisture content, change of surface soil moisture as a result of particular rainfall and time to peak after rainfall event. The rainfall at t1 and t2 are 3.0 mm and 3.8 mm respectively and the change of soil moisture content at t1 and t2 are 0.072 and 0.086 m³/m³. On the other hand, the response time at t1 and t2 is 75 and 45 minute respectively. The response of soil moisture content for the same magnitude of rainfall at different time is different. As summarized in Table 13 the magnitude of rainfall at t3 and t4 is 2.4 mm, but the response of surface soil moisture and time to peak is different. On the date of t3 and t4 with equal rainfall and time to peak, the change of surface soil moisture is 0.062 and 0.071 m³/m³ respectively.

As illustrated on Figure 21 and Table 13 the soil moisture content respond differently for the same magnitude of rainfall; because, the degree of response is not a linear relationship with magnitude of rainfall. The sensitivity of soil moisture in response to rainfall mainly depends on antecedent soil moisture content, land cover and rainfall intensity. The antecedent soil moisture content increases the sensitivity of surface soil moisture for a particular rainfall as a result of interception. Interception decreases rainfall intensity at the ground below the crop. As result, low intensity rainfall increase the response time of top soil moisture content and water level than high rainfall intensity. In case of high rainfall intensity, the response can be observed with short time, for instance the response time on Table 13 at selected time t2.

Table 13 below figures out the magnitude of rainfall with date and time, initial stream water level, change of water level as a result of corresponding rainfall and time to peak water level after particular rainfall. The rainfall at t1 and t2 is 3.0 mm and 3.8 mm respectively and the change of water level at t1 and t2 is 0.021 and 0.012 m, and the response time at t1 and t2 is 165 and 60 minutes respectively. The response of water level for the same magnitude of rainfall at different times is different. As indicated on Table 13 the magnitude of rainfall at t3 and t4 is the same, but the response of water level and time to peak is different. The change of water level and time to peak at t3 and t4 for 2.4 mm rainfall is 0.013 and 0.016 m, and 90 and 135 minutes respectively. Therefore, the response of water level and time to peak is not a linear relationship with the magnitude of rainfall. This is because, the sensitivity of water level in response to rainfall is mainly dependent on antecedent soil moisture content, land cover and rainfall intensity.

The antecedent soil moisture content increase the sensitivity of stream water level in response to rainfall regardless of other factors. The response of stream water level on the date of t1 is larger than the rest three days and longer time to peak than the rest of the days. On this day the response of water level is not only as a result of particular rainfall. The response on this day is from the combination of rainfall on the t1 and subsurface flow, and that is why the time to peak is longer. This is because, there is a lot of rainfall in a week before that particular day (see Figure 20). Another effect is that the land cover of corn increases the response time to peak water level as a result of interception and may keep the rainfall intensity below infiltration rate. This magnifies the response of soil moisture content than water level. The higher the rainfall amount the shorter the response time. Because, if the rainfall intensity is greater than the infiltration rate, the difference between rainfall and infiltration generates runoff which magnifies the response of water level with short time.

Apart from rainfall magnitude and permanent physical characteristics, there are a number of temporally variable factor which have direct influence on the catchment characteristics. These physical and hydrological factors such as rainfall intensity, seasonal change, land cover, vegetation stage, and surface roughness add complexity and event analysis is dynamic with time as a result of these factors.

Selected	Rainfall time and depth		Response of surface soil moisture and stream water level				
time	Time(MDYT)	Rainfall	Initial SM	peak SM	ΔSM	Lag time (min)	
		(mm)	(m3/m3)	(m3/m3)	(m3/m3)		
t1	8/1/16 8:45	3.0	0.189	0.261	0.072	75	
t2	8/19/16 22:00	3.8	0.170	0.256	0.086	45	
t3	9/16/16 3:15	2.4	0.164	0.226	0.062	75	
t4	10/21/16 14:45	2.4	0.341	0.412	0.071	75	
			Initial WL (m)	peak WL (m)	$\Delta WL(m)$	Lag time (min)	
t1	8/1/16 8:45	3.0	0.899	0.920	0.021	165	
t2	8/19/16 22:00	3.8	0.900	0.912	0.012	60	
t3	9/16/16 3:15	2.4	0.880	0.893	0.013	90	
t4	10/21/16 14:45	2.4	0.885	0.901	0.016	135	

Table 13. Summarized th	e magnitude of rainfall	, initial soil moisture	and water level,	, the change soil
moisture and water level,	, and time to peak as a r	esult of a particular	rainfall.	



Figure 21. (a) Shows the response of surface soil moisture and time to peak after peak rainfall, and (b) shows the response of stream water level and time to peak after peak rainfall for selected particular time t1, t2, t3 and t4 from figure 19.

8. CONCLUSION AND RECOMMENDATIONS

8.1. Conclusion

The main objective of this study has been to analyze spatio-temporal surface soil moisture variability, using in-situ soil moisture measurements and surface soil moisture (SSM) derived from Sentinel-1 backscatter observations, and to characterize the relationship between rainfall, top 5 cm soil moisture content and stream water level.

In the Twente region, a number of soil moisture monitoring stations were installed by the Faculty of Geoinformation Science and Earth Observation, University of Twente. In addition, for this research intensive fieldwork was conducted to measure surface soil moisture within six representative fields adjacent to three selected stations. Intensively determined surface soil moisture was used to check the spatial representativeness of the point-based soil moisture monitoring stations. Then, the accuracy and reliability of surface soil moisture derived from Sentinel-1 backscatter is assessed with the in-situ measurements as ground truth and evaluated for compliance with target accuracy (root mean squared error, RMSE of 0.08 m^3/m^3). Finally, the relationship between rainfall, surface soil moisture and stream water level was analysed for the Voltherbeek catchment.

The following conclusions are formulated by answering the research questions defined in chapter 1:

1. Is it possible to upscale the continuous point measurements collected at the edge of a field to the field-scale using a limited set of spatially distributed labour-intensive measurements?

This is largely possible. We have found that the soil moisture in the field is highly correlated to the measurements taken at the edge of the same field. On the other hand, the discrepancies found between the station and intensive measurements can be caused by mismatches in land cover (e.g. ITCSM10, ITCSM02), soil type (e.g. ITCSM_07), local topography (ITCSM_07) and measurement techniques. These factors influence each measurements setup differently. General guidelines for upscaling are, therefore, difficult to formulate.

2. What is the accuracy of the Sentinel-1 SSM estimated by using a change detection approach when compared to top 5 cm soil moisture measurements?

The matchup between spatially distributed (at a location of point measurements) surface soil moisture derived from Sentinel-1 backscatter observation with in-situ (labour intensive and station) measurements was analysed per field scale. In general, the accuracy for Sentinel-1 against labour intensive soil moisture measurement varies from 0.060 to 0.078 m³/m³ which fulfils the accuracy requirement of active microwave sensors for agricultural land (RMSE less than 0.08 m³/m³) with a bias range from 0.027 to 0.059 m³/m³, except ITCSM_10F2. RMSE and bias values for ITCSM_10F2 are 0.116 m³/m³ and 0.097 m³/m³ respectively. This is a potato field planted with ridge (rows), which affects the Sentinel-1 measurements and makes it difficult to get accurate intensive measurements.

Similarly, the accuracy for Sentinel-1 against station measurement varies from 0.07 to 0.13 m³/m³, with a bias less than 0.06 m³/m³. The poorer agreement between Sentinel-1 surface soil moisture and station measurements is caused by various factors. During summer period have been observed high Sentinel-1 backscatter signals, as a result vegetation, tillage practices and roughness. In the winter, low backscatter

signal have been observed as a result of frozen soils and inundation. These factors and length of matchup period decrease the accuracy of Sentinel-1 SSM against automated-stations measurements.

Generally, the matchup result indicate that accuracy level of Sentinel-1 surface soil moisture against intensive measurements is better than against automated-station measurements. As already discussed in the conclusion to research question 1, this is because of the spatial representativeness of stations, difference in land cover and the difference in measurement techniques.

3. How do in-situ measured rainfall, SSM and water level relate to each other in the Voltherbeek catchment?

The relationship between rainfall, surface soil moisture and stream water level was analysed to investigate the catchment in response to rainfall. As illustrated in Figure 20a and 20b, these three variables are interdependent. In addition, for each rain event in the period between August 12, 2016 and November 11, 2016 the response has been observed on surface soil moisture and stream water level. The magnitude of response is not linear with rainfall amount. Because, the response for particular rain event depends on different factors, which are antecedent soil moisture content, type of land cover, and rainfall intensity.

4. How fast are the water level and soil moisture in response to rainfall in the Volterbeek catchment?

To determine how fast the surface soil moisture and stream water level respond to rainfall, four rainfall events were analysed. For selected rainfall events of 3.0 mm and 3.8 mm, change of soil moisture and time to peak are 0.072 and 0.086 m³/m³ and 75 and 45 minutes respectively. Similarly, for equal rainfall (2.4 mm) selected at different time, change of water level and time to peak is 0.013 and 0.016 m, and 90 and 135 minutes respectively after that particular rainfall. Therefore, time to peak of soil moisture content and stream water level as a result of particular rainfall is variable with temporal variability of land surface condition and hydro-meteorological factors.

8.2. Recommendation

Recommendations for further research:

- The spatial representativeness of automated monitoring stations were checked via spatially distributed intensive measurements in field adjacent to the stations. Point selection for fixing automated-stations must consider topography and land use at particular location in addition to soil type and organic matter. Moreover, after it has been placed, continuously check is required for the land cover at the location of station and in the field.
- This study shows that soil moisture is important for the rainfall-runoff relationship and therefore it is important to monitor soil moisture in space and time. Remote sensing with the Sentinel-1 satellites showed to be a promising option for this. Further research is recommended to further improve the soil moisture retrievals from Sentinel-1. A straightforward method was used and the retrievals should be improved by correcting for vegetation and roughness effects. Indeed, during summer period we have observed high backscatter signal as a result of tillage, vegetation and roughness and lower backscatter have been observed in winter as a result of frozen soils.
- With short period available data, soil moisture and water level in response to rainfall were analyzed. To further characterize the catchment's behavior, event analysis needs to be done with consideration of different land surface conditions to determine soil moisture threshold to generate runoff and corresponding runoff coefficient.

- The relationships between rainfall, surface soil moisture and stream water level were analyzed. However, to translate the findings to other catchments, a rating curve must be developed to use discharge instead of water level and the result must be incorporated in a model to improve the prediction of the hydrological response of catchments.
- This study only considered top 5 cm soil moisture. More research is needed to incorporate a deeper soil moisture and base flow to analyze the role of deeper soil moisture on stream flow. Also, research is needed to translate the surface soil moisture from satellites to soil moisture in deeper layers.

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APPENDICES

Appendix A: IDL script to extract SWI from Sentinel-1 image

```
pro extract values point
:-----
   = 1 ; # pixel filter window
win
;-----
; Number of sites
N a = 7 ; number of fields
coords = fltarr(2, N a) ; 1) latitude 2) longitude
station = strarr(N a)
fmt = '(' + strtrim(string(N a*2), 2) + 'F10.4)'
close, 1
openr, 1, 'D:\SM 07\SM 07 F1\SM 07 Points.txt' ; text file with coordinates
readf, 1, coord
close, 1
;-----
             _____
in_path = 'D:\SM_07\S1_Iput_IMAGE\'
NEST_files = file_search(in_path,'*.tif',count = n_nest); read all
available tiff files in the directory
;-----
file o
        = 'D:\SM 07\30 10 16\data SWI.txt'
close, 1
openw, 1, file o
printf, 1, '----Surface soil moisture----'
printf, 1, 'Mean Stdev
                   .
;-----
for f = 0, n_nest-1 do begin ; For all images
;-----
;/ memory allocation output
;-----
t00 = fltarr(2*N a)
t00(*) = -99.
;-----
data = read tiff(NEST files(f), INTERLEAVE = 2, GEOTIFF = GEO)
;------
dims = size(data)
xsize = dims(1)
ysize = dims(2)
output = intarr(xsize, ysize)
;-----
; i lon = GEO.MODELTIEPOINTTAG(3)
;i lat = GEO.MODELTIEPOINTTAG(4)
i_lon = GEO.MODELTRANSFORMATIONTAG(3,0)
i_lat = GEO.MODELTRANSFORMATIONTAG(3,1)
pix size = GEO.MODELTRANSFORMATIONTAG(0,0)
;-----
for a = 0, N a-1 do begin ; For each site
 ------
 ; 1) longitude 2) latitude
 count = 0.
   i = uint((coords(1,a)-i lon)/pix size)
   j = uint((i_lat - coords(0,a))/pix_size)
```

```
;/ define window
  i st = i - win
  if i st LT 0 then i st = 0
  i en = i + win
  if i en GT xsize-1 then i en = xsize-1
  j st = j - win
  if j st LT 0 then j st = 0
  j en = j + win
  if j en GT ysize-1 then j en = ysize-1
  print, i st, j st
  ;-----
  ;/ define window
   if (i st GE 0) and (j st GE 0) and (i en LE xsize-1) and (j en LE ysize-1) then
    begin
    for i = i st, i en do begin
     for j = j_st, j_en do begin
     :---
                 _____
     ;/ determine valid retrieval in the window
     output(i, j) = 10000
       if (data(i,j) GE -500) and (data(i,j) LE 20000) then begin
        count = count + 1
       endif
     endfor ; end q-loop
    endfor ; end p-loop
   if count GT 0 then begin
     ;/ allocate dummy variable for writing raw data
     ;------
     dummy = fltarr(count) ; mean retrieved soil moisture
     count = 0.
     ;-----
                _____
       for i = i st, i en do begin
        for j = j st, j en do begin
          if (data(i,j) GE -500.0) and (data(i,j) LE 20000) then begin
          dummy(count) = data(i,j)/10000.
         count = count + 1
          endif
        endfor ; end q-loop
       endfor ; end p-loop
       t00(a*2+0) = mean(dummy)
t00(a*2+1) = stdev(dummy)
     endif else begin
       t00(a*2+0) = -99.
t00(a*2+1) = -99.
     endelse
  endif
endfor ; a
;printf, 1, file basename(NEST files(f))
printf, 1, t00, FORMAT = fmt
;-----
endfor; t
;-----
close,1
envi_enter_data, output
```

end



Appendix B: Scatter plot between calibrated of hydra probe soil moisture measurement vs gravimetrically determined soil moisture content for individual field days.