

Estimation of Watershed Scale Soil Moisture from Point Measurements During SMEX02

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Abstract

Watershed scale soil moisture estimates are necessary to validate current remote sensing products, such as those from the Advanced Microwave Scanning Radiometer (AMSR). Unfortunately, remote sensing technology does not currently resolve the land surface at a scale that is easily observed with ground measurements. One approach to validation is to use existing soil moisture measurement networks and scale these point observations up to the resolution of remote sensing footprints. As part of the Soil Moisture Experiment 2002 (SMEX02), one such soil moisture gaging system, in the Walnut Creek Watershed, Iowa, provided robust estimates of the soil moisture average for the watershed. Twelve in-situ soil moisture probes were installed across the watershed. These probes recorded soil moisture at a depth of 5 cm from June 29th, 2002 to August 19th, 2002. The sampling sites were analyzed for temporal and spatial stability by several measures including mean relative difference and Spearman rank. Representative point measurements were scaled up to the watershed scale (~25 km) and shown to be accurate indicators with low variance and bias of the watershed scale soil moisture distribution. This work establishes the validity of this approach to provide watershed scale soil moisture estimates in this study region for the purposes of satellite validation. Also, the potential errors in this type of analysis are explored. This analysis is an important step in the implementation of large-scale soil moisture validation using existing networks such as the Soil Climate Analysis Network (SCAN) and several Agricultural Research Service watersheds as a basis for calibrating satellite soil moisture products.

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Introduction

Satellite soil moisture products are being developed from new sensors such as the Advanced Microwave Scanning Radiometers on the NASA Aqua and Japanese Midori-II platforms. These products will be the basis for long term global observations of the Earth surface. The calibration of algorithms and validation of these products are of vital importance at this stage in the development of the technology.

For surface soil moisture, two factors make satellite product validation difficult. The first is a mismatch in scale between satellite footprints (1-50 km) and a ground sample (~5 cm). The second is high spatial variability of soil moisture, which is influenced by various land surface and meteorological factors at different scales. Both factors necessitate a large number of distributed observations within a footprint to accurately estimate the average. The issues described above lead to the conclusion that a large number of ground based in-situ samples will be required to validate a single footprint. It would be difficult to provide such information for a large number of footprints. Two approaches have been used in the past. The first is short term intensive field campaigns such as SGP97, SGP99, and SMEX02. These provide reliable estimates but only for a specific subset of physical and climate conditions. Another approach has been to use data from existing in-situ networks. A problem with this approach is the density of the network. Most provide only a single point within a footprint.

Soil moisture scaling theory (Warrick et al. 1977, Russo and Bresler 1980) demonstrates that estimates of a moisture field can be obtained using point observations; however, this requires extensive surface sampling over long periods of time (Kachanoski and De Jong 1988, Vinnikov et al. 1999, Yoo 2002).

Geostatistical analyses, such as kriging (Burgess and Webster 1980) and semivariogram analysis, also requires a dense sampling network to adequately portray the spatial character of the soil moisture field. Vachaud et al. (1985) first proposed a method of large scale soil moisture estimation by establishing temporal and spatial stability in a 2000 m² grass field in Grenoble, France. This technique investigates the idea that a soil moisture field maintains its spatial pattern over time. If the pattern is stable at long time scales, it is possible to use this pattern to an advantage. The mean of the field at a given time is compared to specific sampling sites within the field to identify locations with a small bias to the mean and a low variability in its relationship to the mean. Once a specific location in an area is demonstrated to accurately estimate the average soil water content for the region, it should be possible to use that point or a reduced number of points for future studies. Their study demonstrated that it is possible to conduct watershed scale soil moisture estimation simply and efficiently. Grayson and Western (1998) extended this research to several additional small watersheds with significant relief ranging in size from 0.1 km² to 27 km². These included the Tarrawarra catchment (Australia), Chickasha (Oklahoma), and Lockyersleigh (Australia). Kachanoski and De Jong (1988) argued that spatial scales must be considered in this type of analysis because of the correlation length scales with a soil moisture field.

These previous projects were conducted over scales (< 27 km²) smaller than most satellite remote sensing technologies (100 - 2500 km²). The scale of temporal stability must be established at larger scales (Kachanoski and De Jong 1988), if this approach is to be used in the validation of large scale remote sensing products. Also, there is a need to extend this research to a larger variety of surface types such as agricultural crops.

The study reported here estimates watershed scale (~100 km²) soil moisture averages for the purpose of validating current remote sensing products by means of point to watershed scaling of in-situ soil moisture sensors. Using three methods of statistical exploration, namely mean relative difference analysis, Spearman rank coefficients and correlation analysis, the temporal and spatial stability of soil moisture for a region can be assessed. For a given season, representative locations can be identified for future regional estimation, greatly reducing the complexity and operational costs of watershed and regional scale monitoring. This work focuses on a

temporary sensor network that was installed during the Soil Moisture Experiment 2002 (SMEX02). This network was in place for two months during the summer of 2002 and serves as a model for future watershed investigations.

In this investigation, we explore the potential of temporal stability theory as a solution to the problem of satellite based soil moisture validation. This may provide a means to effectively design sparse validation networks and may also provide a way to utilize existing in-situ low density networks in validation. In addition, this project will investigate the intricacies of using only a few in-situ points for large scale validation.

Study Region

The intensive study region of SMEX02 was the Walnut Creek watershed and the surrounding area, located south of Ames, Iowa, which is on the order of 100 km². An outline of the watershed is shown in Figure 1. Corn and soybean dominate the land cover, with approximately 50% and 40% respectively. The remaining 10% of the area's land cover is grains and urbanization. The intensive field campaign portion of SMEX02 took place from June 25th to July 12th, 2002. As part of that experiment, 12 Stevens-Vitel Hydra (www.stevenswater.com) probes were installed in 10 study fields near surface meteorological stations, which were located throughout the area as part of the experiment. These stations operated during the field campaign and continued until August 19th, 2002. This extended period of time allowed for a wider range of soil moisture patterns to be observed. This study will demonstrate how SMEX02 contributes to the field of temporal stability.

The soil moisture probes measured the dielectric constant of the soil, from this the volumetric soil moisture was computed from previously determined relationships (Campbell 1990). Each probe was installed at a depth of 5 cm, which is appropriate for comparing soil moisture

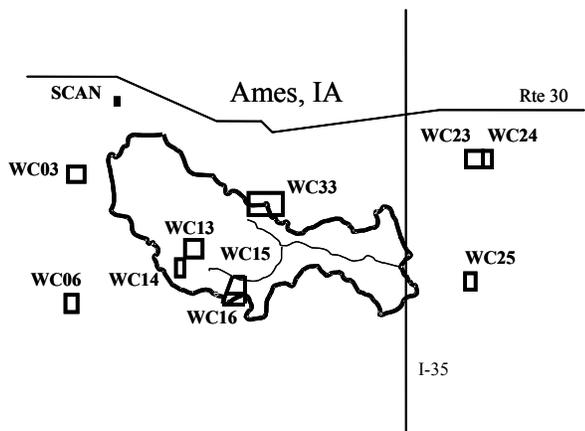


Figure 1. The Walnut Creek Watershed and the surrounding region near Ames, Iowa. The ten WC Fields and the NRCS SCAN station are outlined.

readings to L-band microwave remote sensing estimates (Jackson 1993). The land cover distribution of the sampled fields is as follows: Soybean-WC03, WC13, WC14, WC16, WC13; Corn-WC06, WC15, WC24, WC25, WC33; Grass-SCAN.

In addition to this temporary soil moisture sensor network, there is also a permanent soil moisture profiling station situated northwest of the watershed as part of the Natural Resources Conservation Service-Soil Climate Analysis Network (NRCS-SCAN) (Schaefer and Paetzold 2001). This SCAN site records a suite of meteorological and hydrological variables, including precipitation, soil temperature, and soil moisture. Though the location of this particular site is covered in grass in a low swale within the field which causes abnormally high soil moisture readings occasionally. The site was used in this study to evaluate its potential as a future tool for estimating the soil moisture in this region.

Methods

Current approaches to the estimation of watershed scale surface soil moisture requires a dense network of moisture probes located throughout the region to provide a large number of samples. The most efficient way of reducing this burden is to find a way to predict large scale moisture averages from only a few sensors located at ‘representative’ sites. These sites can be identified through temporal stability analysis. If temporal stability can be established in a watershed, a small number of soil moisture sensor sites can be used to accurately and precisely predict watershed averages. This is accomplished by determining those sites that maintain a consistent

temporal relationship with the watershed average with little variability.

The primary method for determining the temporal stability of a soil moisture field is the mean relative difference plot. This plot represents the ability of a particular soil moisture sensor location to estimate the average over the watershed. Building on Vachaud et al. (1985) and Grayson and Western (1998), this type of analysis was applied to the SMEX02 watershed network. The mean relative difference is defined as

$$\bar{\delta}_{\bullet,j} = \frac{1}{n} \sum_{i=1}^n \frac{S_{i,j} - \bar{S}_{i,\bullet}}{\bar{S}_{i,\bullet}} \quad (1)$$

where $S_{i,j}$ is the i^{th} sample of n samples at the j^{th} site within the study region. $\bar{S}_{i,\bullet}$ is the computed average among all sites for a given date and time, i . This variable gives a direct measure of how a particular site compares to the average of a larger region, whether it is consistently greater or less than the mean and how variable is that relationship. The mean relative difference of each site is then plotted by rank with error bounds of one standard deviation of the relative differences to determine which site best estimates the mean of the watershed. There are two criteria for selecting the ideal site for watershed estimation. Proximity of a site’s mean relative difference to zero indicates it can accurately estimate the watershed average and small standard deviations (narrow error bars) indicate low variance of that estimate. If a site has both of these characteristics, it can be concluded that it accurately and precisely predicts the average watershed soil moisture for long time periods.

It is also important to assess the spatial stability of the soil moisture field which can be accomplished with the Spearman rank coefficient. This coefficient measures the correlation of site rankings from one day to the next. It is defined by

$$r_i = 1 - \frac{6 \times \sum_{i=1}^n (R_{i,j} - R_{i,j'})^2}{n(n^2 - 1)} \quad (2)$$

where $R_{i,j}$ is the rank of the soil moisture, $S_{i,j}$, at location i on day j , with a total of n days. $R_{i,j'}$ is the rank of the same location i for day j' . A value for r_i near 1 indicates a stable soil moisture field, while r_i values near zero indicate a lack of stability. Therefore, an r_i of 1 is computed for pairs of days

that maintain the same ranking among the soil moisture gaging sites. When dealing with an in-situ network, it is necessary to address the temporal resolution. For these purposes, it is only necessary to consider soil moisture from one day to the next. Therefore in this analysis, the Spearman rank coefficient is calculated between each hour of each day (to account for any diurnal pattern in the signal) and then these are averaged together to obtain a single coefficient for each day.

Results

The first step in the analyses is an examination of the time series of surface soil moisture measurements for the Walnut Creek watershed, as shown in Figure 2. This plot shows the individual site and average soil moisture, as a function of time. One can readily observe the variation that exists among the individual points on any specific day. Applying Eq. (1) to the data set resulted in a mean relative difference plot, shown in Figure 3.

Several key results can be drawn from this plot. WC13, a soy field in the center of the watershed, had a mean relative difference close to zero and a small standard deviation, indicating a close correlation between the WC13 soil moisture at 5 cm and the expected average of surface soil moisture across the entire watershed region.

Patterns are visible in Figure 3 when the location of each site is considered. WC23, WC24, and WC25 are all located in the eastern portion of the study region and, from observations made during the experiment, had smaller precipitation amounts. This is determined from the negative mean relative differences for these sites. Negative mean relative differences indicate that the average at that particular site is less than the average across the whole region.

Also, there was a precipitation event on Day 185 which was very heterogeneous across the watershed; therefore, each site received a different amount of rainfall. This resulted in moisture patterns, which would be different from a large scale precipitation event, thereby nullifying any temporal stability. This issue proves to be a problem for watershed scale estimation for particular time periods. Precipitation events can be divided into two scales: Field scale and watershed scale. It is expected that larger events will dominate the moisture field of a watershed at long time scales, but for any small time period, there could be an influence of heterogeneous precipitation

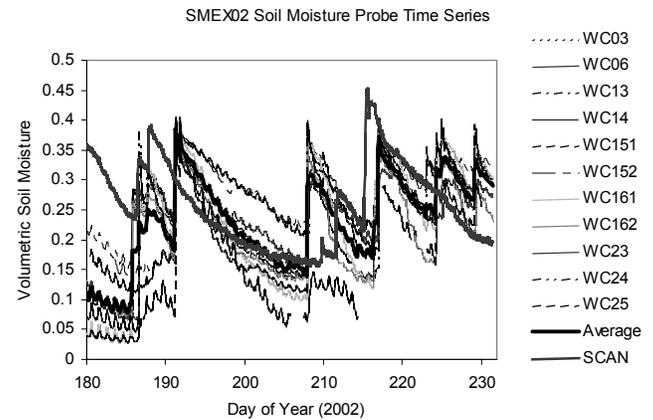


Figure 2. Time series of surface (5 cm) soil moisture for each soil moisture probe in and around the Walnut Creek watershed. The average for each time step is also plotted in bold.

occurring at the smaller field scale. Therefore, using singular point estimates to approximate watershed scale soil moisture should only be considered for long-term validation. Also, it would prove to be unwise to use a single ‘random’ point to estimate regional soil moisture in the short term. For instance, the SCAN site demonstrates a significant bias (nearly 20%) to the regional soil moisture average. However, there is still potential to use the SCAN site as a rough approximation if this bias can be taken into account.

It is also apparent that there was little or no deterministic relationship between mean relative difference and crop type. Soybean and corn fields are scattered across the mean relative difference plot, indicating that the location within the watershed may play a greater role in the selection of a representative site than does land cover type.

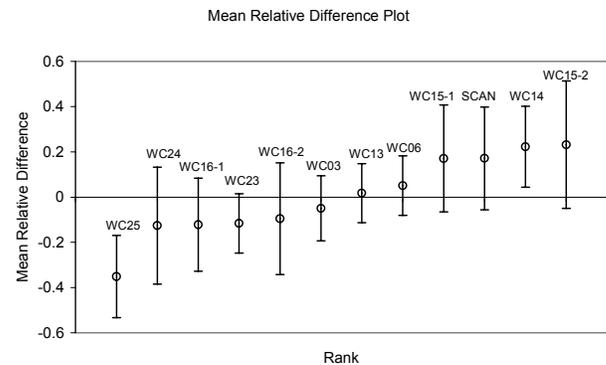


Figure 3. The mean relative difference plot for the SMEX02 soil moisture network. The bars are +/- one standard deviation.

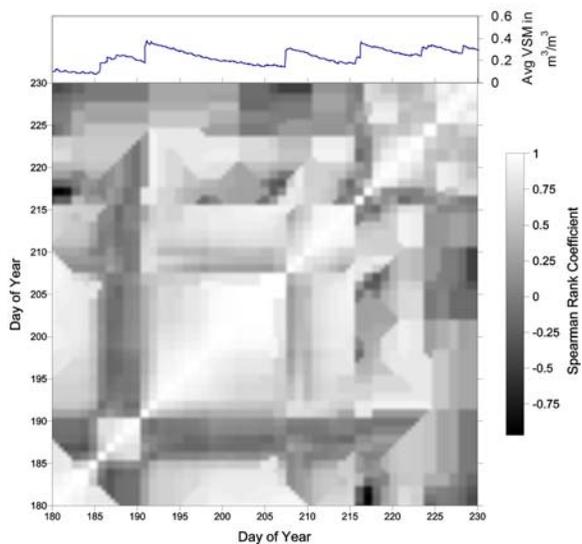


Figure 4. Spearman rank coefficient plot of volumetric soil moisture by day of year. Also included is a plot of the average soil moisture for the watershed for the same time period. Coefficients near 1 indicate strong rank correlation between the dates.

A Spearman rank analysis determined that for most of the study period there is a strong temporal stability across the region. Figure 4 shows a plot of these coefficients over time as well as a plot of the average soil moisture for the watershed. The plot is grayscale; therefore, the whiter the plot, the higher the Spearman rank coefficient. Dark pixels indicate low values and time instability. For several time periods, there is a distinct lack of stability, such as for the days proceeding days 185, 208, and 223. Each of these periods follows a heterogeneous precipitation event, as shown by the drastic changes from high to low Spearman rank coefficients. Conversely, on day 191, there was a larger than watershed scale rain event, which affected each of the sites uniformly. Following this event, an order is observed in the ranking of the magnitudes of the soil moisture at each gaging station, similar to that of the mean relative difference plot. Overall, the plot indicates that there is a persistent pattern to the watershed moisture condition such that for a given homogeneous precipitation event, there is a ranking among the surface soil moisture measurement sites. This temporal stability should prove useful for the prediction of watershed scale soil moisture with a sparse array of in-situ soil moisture measurements.

Site selection was examined in greater detail to try and identify characteristics that make particular sites representative of the watershed. Initial considerations would reveal that closeness to the center of the region

of study is not a necessity, because both WC03 and WC06 have low mean relative differences and are the western most sites. However, if a site is close to the center, it is more than likely receiving the mean precipitation for the region for long periods of time. Land cover type did not appear to be a significant factor because there was no apparent link between soybean, corn, and mean relative difference rank. There is a complex set of variables which appear to affect mean relative difference.

Further investigation into the sensor at WC13 revealed that if only one site was available for estimating average watershed soil moisture, this sensor would be a credible choice. A random sampling of points between the sensor at WC13 and the watershed average had a strong correlation ($R^2 = 0.928$) and low root mean square error ($rmse = 0.028$). The bias was also quite small at 0.006 (m^3/m^3). WC13 was a typical row-crop soybean field with some topography, while WC14, for example, was a drilled or broadcast soybean field with similar topography with a similar precipitation history. The only apparent distinction between these fields was the method of planting, but there is a considerable deviation in their mean relative differences.

Conclusions

Watershed and regional estimates of surface soil moisture are necessary for a wide variety of hydrologic and climatologic studies; however, it is infeasible to gage a system adequately for true measures. Remote sensing provides an attractive alternative. However, these methods must be calibrated and validated. This work demonstrates that single point in-situ measurements can be used to estimate area average values accurately if spatial and temporal stability can be established in the region of interest. It has been shown that for the Walnut Creek watershed the soil moisture pattern during the summer of 2002 was both temporally and spatially stable for uniform precipitation events. A mean relative difference plot established that with accuracy and precision, a single site (WC13) could accurately and precisely estimate the watershed soil moisture average for long time periods. For time periods that are subject to heterogeneous rain patterns, this stability is reduced. Several points may be necessary to accurately characterize the soil moisture for specific time periods. Certainly, the use of one random in-situ point would be a risky proposition. For example, if the SCAN site was used as a representative point, there would be a significant

amount of bias. Fortunately, experiments such as SMEX02 permit the SCAN to be calibrated to the watershed average for long term studies. It is demonstrated that short term field experiments may be an appropriate method for establishing temporal stability and calibrating in-situ field sensors.

For the purpose of validation of remote sensing of surface soil moisture products, the temporal scales are greater than the short episodes of heterogeneous precipitation often experienced in field experiments. Indeed, the time scales of validation span many seasons and a watershed's soil moisture distribution at this time scale is, on average, a result of large-scale weather systems. It can be concluded that for the purposes of validation, temporal stability is a valuable tool for accurate and precise estimation of mean soil moisture.

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