Spatio-Temporal Evolution and Time Stable Features of Soil Moisture in Different Hydro-climatic Regions

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Introduction

Ground-based point measurements and remotely sensed soil moisture data from the air-borne remote sensors (e.g., Polarimetric Scanning Radiometer, PSR, and Electronically Scanned Thinned Array Radiometer, ESTAR) have been used in various soil moisture field campaigns to investigate the spatio-temporal evolution and time-stable characteristics in different hydro-climatic scenarios. Past studies have helped understand how the various hydrologic controls like soil, topography, vegetation, and climate affect soil moisture dynamics across a large region and determine the time-stable locations which are representative of a field, footprint, or watershed. The purpose of this study is to conduct a time stability analysis of soil moisture at different spatial scales (point-scale and footprint-scale) in two different hydro-climatic regions: the Walnut Creek watershed (Iowa), and the Little Washita watershed (Oklahoma). The data used in the analysis consist of *in-situ* and remotely sensed soil moisture data from Southern Great Plains hydrology experiments (SGP97 and SGP99) conducted in Little Washita watershed, and Soil Moisture Experiments (SMEX02 and SMEX05) in Walnut Creek watershed. The study also aims to determine the physical factors controlling the dynamics and time-stable characteristics of soil moisture. Results obtained can be effectively used to reduce the number of *in-situ* sampling points while designing short duration field-scale hydrology experiments for remote sensing validation purposes. Further, the findings can help in designing long-term hydrologic monitoring networks in different hydro-climatic regions.

Methodology

Time Stability Analysis: According to Vachaud et al. (1985), time stability is the time-invariant association between spatial location and classical statistical parametric values of different soil properties. Two statistical metrics normally used to conduct the time stability analysis are:

1) Mean Relative difference, $\bar{\delta}_{i,j} = \frac{1}{n_t}\sum_{t=1}^{n_t}\frac{\theta_{i,j,t} - \bar{\theta}_{j,t}}{\bar{\theta}_{j,t}}$

where, $\bar{\theta}_{j,t}$ (% v/v) is the field mean soil moisture calculated as: $\bar{\theta}_{j,t} = \frac{1}{n_{j,t}}\sum_{i=1}^{n_{j,t}}\theta_{i,j,t}$

t = total number of days soil sampling was done (**t** = 1, 2, …. ,$\mathbf{n_t}$); $\theta_{i,j,t}$ = volumetric soil moisture content (VSM) measured at location **i** (**i** = 1, 2, …..,$\mathbf{n_{j,t}}$) in field **j** at time **t**.

2) Root mean square of relative difference, $RMSE_{i,j} = \left(\bar{\delta}_{i,j}^2 + \sigma(\delta)_{i,j}^2\right)^{1/2}$

where, $\sigma(\delta)_{i,j}^2$ is the variance of the relative difference calculated as: $\sigma(\delta)_{i,j}^2 = \frac{1}{n_t - 1}\sum_{t=1}^{n_t}\left(\frac{\theta_{i,j,t} - \bar{\theta}_{j,t}}{\bar{\theta}_{j,t}} - \bar{\delta}_{i,j}\right)^2$

Locations having high time stable features have $\bar{\delta}_{i,j}$ close to zero and low RMSE value.

Results and Discussions

1) Theta probe data (point-scale)

a) Walnut Creek watershed, IA

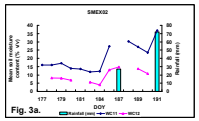


Fig. 3a.

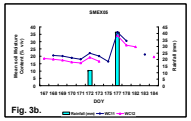


Fig. 3b.

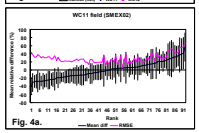


Fig. 4a.

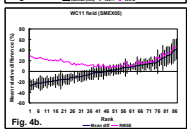


Fig. 4b.

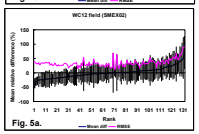


Fig. 5a.

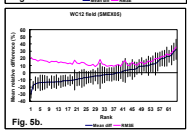


Fig. 5b.

WC11 field has a higher mean soil moisture and lower variability compared to WC12 field. This may be due to the presence of strong drainage features and a higher sand content in WC12 field. WC11 field has higher time stability compared to WC12 field. In WC11, 18 out of 32 time stable locations from SMEX02 maintained their time stability during SMEX05 also. In WC12 field, 14 out of 27 locations from SMEX02 were time stable during SMEX05 (see Fig.1). (Note: Figs. 3, 4 and 5a from Jacobs et al., 2004).

b) Little Washita watershed, OK

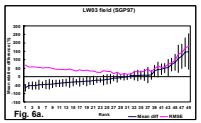


Fig. 6a.

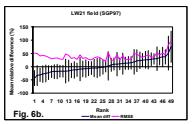


Fig. 6b.

Field LW03 having sandy loam soil exhibited better time stable features compared to the two silt loam fields (LW13 and LW21). LW21 field with flat topography showed worst time stability features than LW03 and LW13 fields having gently rolling topography.

(Note: LW13 field not shown here due to space limitations. Fig. 6a-b from Mohanty and Skaggs (2001)).

2) Remote Sensing data (footprint-scale)

a) Walnut Creek watershed, IA – PSR data

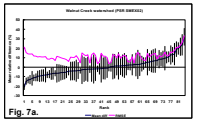


Fig. 7a.

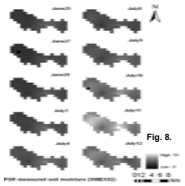


Fig. 8.

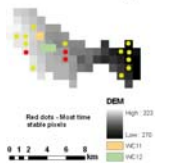


Fig. 7b.

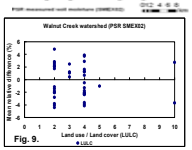


Fig. 9.

Nearly 58% of the total pixels captured the watershed mean soil moisture (within ± 5% VSM). The three most time stable pixels are located at high elevation close to the maximum. Further analysis shows that pixels exhibiting high time stable features are located at a very high elevation, close to the water divide. Very few time stable pixels lie within the watershed having intermediate elevations. A possible reason for this could be attributed to the lateral drainage features of these pixels due to their role as a source, not a sink in the watershed. Interestingly, these time stable pixels do not have a definite crop type (similar to the findings of Cosh et al.,2004). Results obtained from multiple linear regression analysis of the time stable pixels (within ± 5% VSM) showed that elevation could be one of the physical controls affecting time stability of the pixels. (Note: analysis results and tables not shown here).

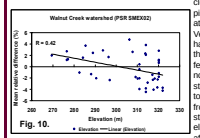


Fig. 10.

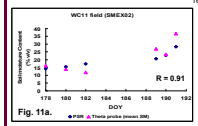


Fig. 11a.

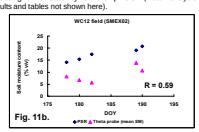
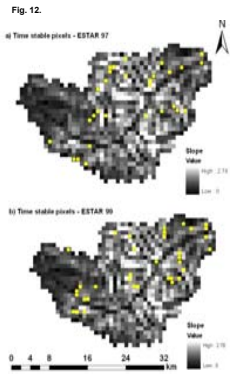


Fig. 11b.

PSR estimated soil moisture matches fairly well with the theta probe data in WC11. In WC12 field, PSR consistently overestimated necessitating improved calibration.

b) Little Washita watershed, OK – ESTAR data

Fig. 12.



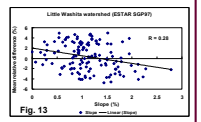


Fig. 13

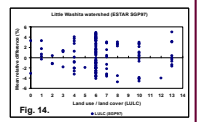


Fig. 14.

Many of the pixels showing better time stability have higher slope and are located in close proximity to the water divide, during both SGP97 and SGP99. Multiple linear regression analysis results indicate that slope could be one of the physical controls affecting pixel-scale time stability in this region. This is similar to the findings of Jawson and Niemann (2007) in their EOF analysis of SGP97-ESTAR dataset. Also, crop cover does not seem to have a definite effect on the time stability of pixels.

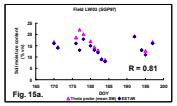


Fig. 15a.

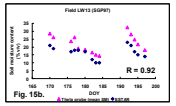


Fig. 15b.

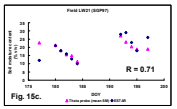


Fig. 15c.

ESTAR (SGP97) measured soil moisture matches well with the theta probe data for LW03 field having silty loam soil, gently rolling topography and rangeland cover. LW13 field shows a consistent underestimation of soil moisture at the footprint scale, while in field LW21, few of the ESTAR measurements are scattered around the in-situ data. Thus, for LW13 and LW21 fields, ESTAR measurements need better calibration.

(Note: Fig. 15a-c from Mohanty and Skaggs (2001)).

Study Area

1) Walnut Creek watershed (Iowa)

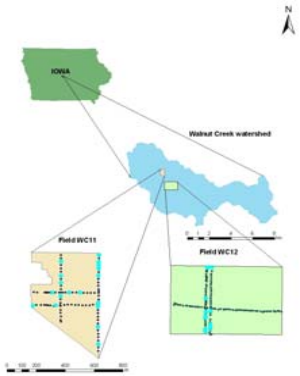


Fig. 1. Sampling points in WC fields in Walnut Creek watershed (Iowa) during SMEX02 and SMEX05 campaigns (Highlighted locations are time stable during both SMEX02 and SMEX05).

a) Walnut Creek, IA

Area ~ 100 km²

Climate – mostly humid

Avg. Annual Precipitation ~ 835 mm

Topography - low relief (~ 270-323m)

LULC – Corn and soybean

Soil texture – varies from fine sandy loam to clay, with majority classified as silt loam

Soil moisture data:

Theta probe – **SMEX02 & SMEX05**

PSR (~ 800m X 800m) - **SMEX02**

b) Little Washita, OK

Area ~ 610 km²

Climate – Sub-humid

Avg. Annual Precipitation ~ 750 mm

Topography – moderately rolling (~ 321-459 m)

LULC - rangeland, pasture, wheat

Soil texture - varies considerably, with large areas having both coarse and fine textures

Soil moisture data:

Theta probe – **SGP97**

ESTAR (~ 800m X 800m) – **SGP97 & SGP99**

b) Little Washita watershed (Oklahoma)

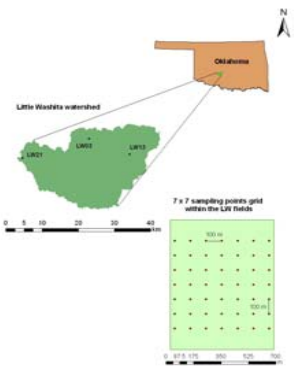


Fig. 2. Sampling points grid within LW fields in Little Washita watershed (Oklahoma) during SGP97 campaign (see Inset).

Conclusions

- WC11 field exhibits better time stability compared to WC12 field. In both the fields approximately 50% of time stable locations from SMEX02 maintained their time stability during SMEX05 also. Some of the time stable locations were located at higher elevation. Presence of drainage features cause a reduction in mean soil moisture and an increase in variability in field WC12.
- Sandy loam field (LW03) is more time stable compared to the two silt loam fields (LW13 and LW21). LW21 field with flat topography (wheat/grass cover) showed worst time stability features than LW03 and LW13 fields having gently rolling topography (rangeland cover).
- Analysis of PSR data from SMEX02 showed that the time stable pixels were located at higher elevations close to the maximum value with most of them being close to the water divide. This may be on account of the lateral drainage features of these pixels due to their role as a source, not a sink in the watershed.
- Elevation could be one of the physical controls affecting soil moisture time stability at footprint-scale in Walnut Creek watershed having comparatively flat topography. In Little Washita watershed where the topography is moderately rolling, slope may be one of the physical factors controlling pixel-scale time stability of soil moisture.
- Analysis of various ground and remote sensing datasets from two different hydro-climatic regions showed that the drier locations tend to have lower variability and RMSE values compared to the wetter ones. This fact can be helpful while designing hydrology experiments.

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Vachaud, G., Desilans, A. P., Balabanis, P., and M. Vauclin (1985). "Temporal Stability of Spatially Measured Soil-Water Probability Density-Function." Soil Science Society of America Journal 49(4): 822-828.The geostatistical analyst toolbox from ArcGIS is a very powerful tool for performing deterministic or stochastic geostatistical analysis on a given data.

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