Space-Time Characterization of Near-Surface Soil Moisture Across Varying Spatial Scales in an Agricultural Landscape during SMEX02

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Introduction

Near-surface soil moisture is a key state variable of the hydrological cycle as it plays a significant role in the global water and energy balance by affecting several hydrological, ecological, meteorological, geomorphological, and other natural processes. Soil moisture varies greatly across space and time. Various geophysical factors (e.g., soil texture, topography, vegetation, precipitation, etc.) and their interactions contribute towards the spatio-temporal evolution of soil moisture at different scales. Therefore, understanding the spatial/temporal distribution of soil moisture and the ensuing dynamics is crucial for numerous hydrological research and applications (e.g., flood forecasting, climate modeling, and land management practices). The **Objective** of this study is to understand the space-time variability and dynamics of near-surface soil moisture at varying spatial scales in an agricultural landscape in Iowa. The data for the analysis come from two different spatial measurement support scales: point-scale and remote sensing footprint-scale (800 m x 800 m), obtained during the Soil Moisture Experiment 2002 (SMEX02) conducted in Iowa. At the field-scale, theta probe based soil moisture measurements were used, whereas at the watershed- and the regional-scale, airborne Polarimetric Scanning Radiometer (PSR) derived soil moisture fields were used for the study. Similar studies have been conducted in the past in the Southern Great Plains region which has mostly a pasture/rangeland cover with a rolling topography. On the other hand, the SMEX02 experimental domain has a somewhat flat topography with an agricultural land cover.

Methodology

a) Variogram analysis: The analysis involves computing an experimental semivariogram for the soil moisture data obtained for each sampling date, and thereafter, fitting a theoretical semivariogram model to the experimental semivariogram. The traditional semivariogram estimator, $\gamma^*(h_i)$ is defined as

$$\gamma^*(h_i) = \frac{1}{2N(h_i)} \sum_{i=1}^{N(h_i)} [\theta(z) - \theta(z+h_i)]^2$$

; $N(h_i)$ is the no. of pairs of soil moisture $[\theta(z), \theta(z+h)]$ measurements separated by a lag range h_i.

b) Empirical Orthogonal Function (EOF) analysis: For a spatio-temporal dataset (e.g., soil moisture fields), the EOF method can be used to decompose the observed variability into a set of orthogonal spatial patterns (called EOFs), which are invariant in time, and a set of time series (called Principal Components or PCs), which are invariant in space. In EOF analysis, the PCs and EOFs of a data set are generated by conducting an eigenanalysis of the covariance matrix of the data set.

$$x_i(t) = s_i(t) - \frac{1}{m}\sum_{j=1}^{m} s_j(t) \longrightarrow R = \frac{1}{m} X^T X \longrightarrow R*E = L*E \longrightarrow F = X*E$$

$x_i(t)$: spatial anomaly of soil moisture observation $s_i(t)$ at location **i** and time **t**; **j**: an index of locations; **m**: total no. of observation locations.

R(n x n): covariance matrix; **X(m x n)**: matrix containing spatial anomalies of soil moisture; **E(n x n)**: matrix consisting of eigenvectors of **R**; **L (n x n)**: diagonal matrix containing the eigenvalues; **T**: matrix transpose; **n**: total no. of sampling days.

Columns of **E** is a time series called PCs; **F(m x n)** contains the associated EOF patterns, and eigenvalues of **L** indicates the amount of variance explained by each EOF/PC pair.

Study Area and Data

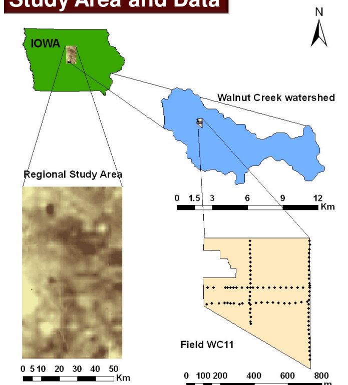

Fig. 1. SMEX02 regional study area including the Walnut Creek watershed and the WC11 field in Iowa.

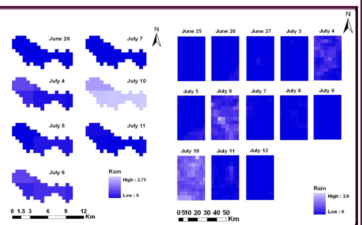

Fig. 2. NEXRAD precipitation data for Walnut Creek watershed and SMEX02 regional site in Iowa.

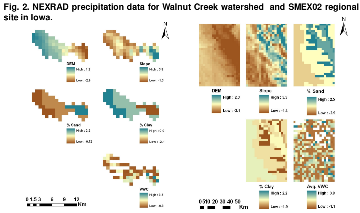

Fig. 3. Normalized topographic, soil, and vegetation attributes of Walnut Creek watershed and SMEX02 regional site.

Results and Discussions

a) WC11 field (Theta probe data ~ point-scale)

Table 1: Parameters and Goodness of Fit of Isotropic Theoretical Models Fitted to Experimental Semivariograms of theta probe measured soil moisture data

Date	Model Type[a]	Nugget C_0	Sill C_0+C	Nugget/Sill $C_0/(C_0+C)$	Model Range[b] (m)	Practical Range[c] (m)	r^2
26-Jun	E	5.50	48.70	0.113	32	97	0.576
27-Jun	S	2.10	43.73	0.048	103	103	0.483
28-Jun	S	14.20	41.64	0.341	146	146	0.726
29-Jun	S	8.07	26.65	0.303	113	113	0.588
30-Jun	S	5.24	29.06	0.180	175	175	0.899
1-Jul	S	8.26	16.53	0.500	230	230	0.706
3-Jul	E	10.48	26.92	0.389	153	459	0.845
5-Jul	S	8.29	18.13	0.457	140	140	0.694
7-Jul	S	9.12	19.66	0.464	111	111	0.288
8-Jul	S	8.80	17.61	0.500	199	199	0.700
9-Jul	S	8.24	21.05	0.391	173	173	0.799
10-Jul	S	1.26	4.71	0.267	64	64	0.415

*Precipitation events: 6th July ~ 27 mm; 10th July ~ 72 mm

Correlation length increases consistently during the dry down period from 26th June – 3rd July (except for 29th June, 2002). The correlation length values are lower on the days when the soil moisture content is higher. The correlation length value is the lowest on 10th July when the soil moisture content is the highest due to the precipitation event.

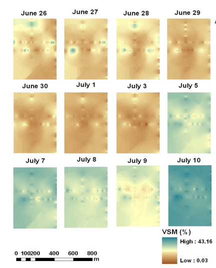

Fig. 4. Soil moisture evolution map of WC 11 field during SMEX02 .

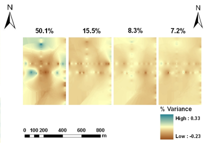

Fig. 5. First four spatial EOF patterns and the variance explained by each EOF/PC pair in WC 11 field.

The first four EOFs together explain about 81% of the total variability, whereas the first three EOFs explain approximately 74% of the total variance (Fig. 5). The rest of the EOFs each explain less than 5% of the total variance (Fig. 6). The weighted PCs are obtained by multiplying the PCs by the amount of variance explained by them. Thus, the weighted PCs give a measure of the relative importance of the EOFs in describing the variance in each day's soil moisture pattern.

Further, the weighted PCs exhibit temporal variations which can be associated with the occurrence of rainfall events and the ensuing dry down periods [*Jawson and Niemann*, 2007]. In WC11 field, the primary EOF is dominant throughout the observation period during SMEX02 (Fig. 7).

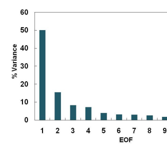

Fig. 6. Scree plot of % variance explained by the spatial EOF patterns for WC 11 field.

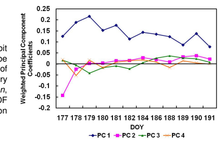

Fig. 7. Weighted principal component coefficients time series for WC 11 field.

The primary EOF explains 67% of the total variance on wet days, while on the dry days, it explains about 55% of the total variability (Fig. 8). The primary EOF on dry days resembles the primary EOF pattern generated from the complete soil moisture data set (Fig. 5).

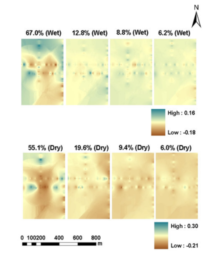

Fig. 8. First four EOFs of soil moisture anomalies for WC11 field under wet and dry conditions.

b) Walnut Creek watershed (Remote Sensing data ~ 800 m x 800 m)

Table 2: Parameters and Goodness of Fit of Isotropic Theoretical Models Fitted to Experimental Semivariograms of PSR based soil moisture fields

Date	Model Type[a]	Nugget C_0	Sill C_0+C	Nugget/Sill $C_0/(C_0+C)$	Model Range[b] (m)	Practical Range[c] (m)	r^2
25-Jun	G	0.01	19.61	0.001	5690	9855	0.999
27-Jun	G	0.12	16.86	0.007	6860	11882	0.999
29-Jun	G	0.09	13.83	0.007	4940	8556	0.999
1-Jul	G	0.04	12.37	0.003	4250	7361	0.996
4-Jul	G	0.36	8.98	0.040	3640	6305	0.999
8-Jul	G	0.00	2.07	0.000	1490	2581	0.510
9-Jul	G	0.22	4.66	0.047	2150	3724	0.985
10-Jul	G	0.01	4.19	0.002	1250	2165	0.483
11-Jul	G	0.01	27.00	0.000	1670	2893	0.480
12-Jul	G	0.01	7.65	0.001	1700	2944	0.951

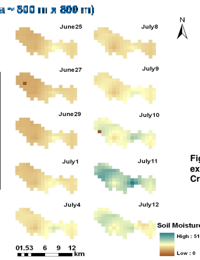

Fig. 9. PSR derived soil moisture evolution map of Walnut Creek watershed during SMEX02 .

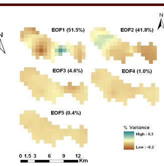

Fig. 10. First five EOFs and the variance explained by each EOF/PC pair in Walnut Creek watershed during SMEX02.

The first two EOFs together explain more than 93% of the total variance. The rest of the eight EOFs each explain less than 5% of the total variance. The watershed received a relatively uniform high rainfall on 10th July, 2002 (Fig. 2). The soil moisture pattern on 11th July shows above average soil moisture content in north-western and south-eastern part of the watershed (Fig. 9). From Fig. 10, EOF1 and EOF2 have high values in the south-eastern and north-western part of the watershed, respectively.

The effect of primary EOF (EOF1) is dominant throughout the observation period, except for the last day when EOF2 is more dominant (Fig. 12). The influence of both EOF1 and EOF2 rises sharply after the July 10th rainfall event.

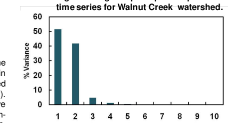

Fig. 11. Scree plot of % variance explained by the spatial EOF patterns for Walnut Creek watershed.

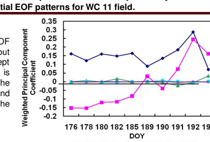

Fig. 12. Weighted principal component coefficients time series for Walnut Creek watershed.

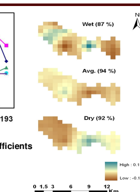

Fig. 13. Primary EOFs generated from dry, average, and wet days.

Table 3: Correlations between EOFs and regional characteristics for full data set

	Elevation	Slope	% Sand	% Clay	VWC
EOF1	-0.18	0.02	0.19	-0.22	-0.05
EOF2	0.75	-0.53	-0.54	0.56	-0.22
EOF3	0.15	-0.09	-0.31	0.27	0.10
EOF4	-0.24	0.26	0.21	-0.20	0.22
EOF5	0.41	-0.20	-0.27	0.30	0.07

Table 4: Correlations between primary EOFs and regional characteristics for wet, avg., and dry days

	Elevation	Slope	% Sand	% Clay	VWC
EOF1 (dry)	0.51	-0.28	-0.44	0.47	-0.09
EOF1 (avg.)	-0.63	0.36	0.47	-0.51	0.11
EOF1 (wet)	0.38	-0.34	-0.24	0.23	-0.16

The primary EOF itself explains more than 90% of the total variability on both the average and dry days, while for the wet days, it explains about 87% of the variance (Fig. 13). The primary EOF for the wet days has high values in the north-western and south-eastern parts within the watershed. This EOF pattern is similar to the 11th July soil moisture pattern (Fig. 9). The primary EOF pattern for the dry days is similar to the primary EOF pattern obtained for the complete soil moisture data set for the 10-day period (Fig. 10).

c) SMEX02 Regional Site (Remote Sensing data ~ 800 m x 800 m)

Table 5: Parameters and Goodness of Fit of Isotropic Theoretical Models Fitted to Experimental Semivariograms of PSR based soil moisture fields

Date	Model Type[a]	Nugget C_0	Sill C_0+C	Nugget/Sill $C_0/(C_0+C)$	Model Range[b] (m)	Practical Range[c] (m)	r^2
25-Jun	E	0.55	6.77	0.081	13300	39900	0.973
27-Jun	S	0.37	7.32	0.051	21500	21500	0.967
29-Jun	S	0.68	6.83	0.100	19000	19000	0.982
1-Jul	E	1.57	18.22	0.086	21300	63900	0.992
4-Jul	E	1.90	52.20	0.036	19000	57000	0.979
8-Jul	E	0.26	19.25	0.014	8400	25200	0.986
9-Jul	E	0.01	18.81	0.001	6500	19500	0.990
10-Jul	E	4.70	45.09	0.104	12900	38700	0.950
11-Jul	E	12.40	133.00	0.093	39500	118500	0.987
12-Jul	E	8.10	97.20	0.083	34100	102300	0.981

[a]G: Gaussian, E: exponential, S: spherical.

[b]Model Range for Gaussian model is ≈ $3^{0.5}A_0$, for exponential model is $3A_0$, and for spherical model is A_0.

[c]Practical range indicates the actual correlation length.

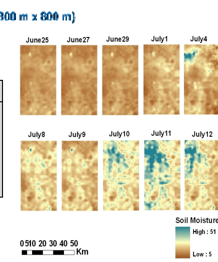

Fig. 14. PSR derived soil moisture evolution map of SMEX02 regional study site.

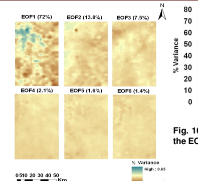

Fig. 15. First six EOFs and the variance explained by each EOF/PC pair at SMEX02 regional site.

EOF1 explains more than 70% of the total variability. The regional site received a uniform high rainfall on 10th July, 2002, while the precipitations events on 4th and 6th July had localized high rainfall values. EOF1 has high values clustered in the north-west region of the study site similar to the above average soil moisture values in the north-western region of the soil moisture patterns from 10th -12th July, 2002.

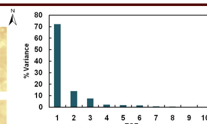

Fig. 16. Scree plot of % variance explained by the EOF patterns for SMEX02 regional site.

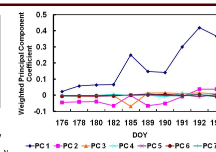

Fig. 17. Weighted principal component coefficients time series for SMEX02 regional site.

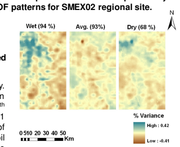

Fig. 18. Primary EOFs generated from dry, average, and wet days.

EOF1 is dominant throughout the observation period. The influence of EOF1 rises sharply after each rainfall event and wanes during the dry down periods (Fig. 17). EOF1 explains more than 90% of the total variability for both the wet and average days, while for the dry days, only 68% of the variance is explained by the primary EOF (Fig. 18). EOF1 for the wet days is similar to the primary EOF pattern generated from the complete soil moisture data set (Fig. 15), as well as the soil moisture patterns for the wet days, i.e., 10th-12th July, 2002 (Fig. 14).

Table 6: Correlations between EOFs and regional characteristics for full data set

	Elevation	Slope	% Sand	% Clay	VWC
EOF1	0.36	-0.31	-0.27	0.42	-0.07
EOF2	0.20	-0.06	-0.12	0.27	-0.07
EOF3	-0.03	-0.06	-0.05	-0.03	-0.03
EOF4	0.60	-0.08	0.04	-0.15	-0.04
EOF5	0.22	-0.01	-0.07	0.11	-0.02
EOF6	0.05	-0.10	-0.05	0.06	-0.04
EOF7	0.19	-0.06	-0.17	0.03	-0.01

Table 7: Correlations between primary EOFs and regional characteristics for wet, avg., and dry days

	Elevation	Slope	% Sand	% Clay	VWC
EOF1 (dry)	0.23	-0.19	-0.15	0.26	-0.02
EOF1 (avg.)	-0.09	0.20	0.16	-0.16	0.01
EOF1 (wet)	0.38	-0.32	-0.29	0.44	-0.02

Conclusions

- At the field-scale, an isotropic spherical/exponential model with a nugget provides a fairly good fit to the daily *in situ* soil moisture semivariograms.
- At the watershed-scale, an isotropic Gaussian model with a nugget provides a reasonably good fit to the daily soil moisture semivariograms, whereas at the regional-scale, the exponential and spherical models with nuggets provided a good fit.
- At the regional-scale, both the sill and correlation length values are higher on wet days compared to the dry days. However, at the field- as well as the watershed-scale, the trend is opposite with the correlation length values increasing with decrease in soil moisture content.
- At the field-scale it took four EOFs to explain about 90% of the total variability, and EOF1 was dominant throughout the observation period compared to the rest of the EOF patterns.
- At the watershed-scale, both EOF1 and EOF2 were dominant explaining about 93% of the total variance. On the other hand, at the regional-scale, the primary EOF (EOF1) itself explained more than 70% of the total variability.
- It is evident from the analyses that the seemingly complex soil moisture patterns can largely be explained by a very small number of underlying orthogonal spatial structures.
- Correlation analysis showed that both topography and soil texture have mixed effects on the variability explained by the dominant EOFs, at the watershed- and the regional-scale.

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