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Temporal stability of estimated soil water flux patterns across agricultural fields**

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A b s t r a c t. When a field or a small watershed is repeatedly surveyed for soil water content, sites often can be spotted where soil is consistently wetter or consistently dryer than average across the study area. This phenomenon has been called time stability, temporal stability, temporal persistence, or rank stability in spatial patterns of soil water content or in soil water contents. The temporal stability presents significant interest for upscaling observed soil water contents to obtain average values across the observation area, improving soil water monitoring strategies, and correcting the monitoring results for missing data. The objective of this work was to research the temporal stability in estimated soil water fluxes using extremely frequent multi-depth measurements of soil water content with multisensor capacitance probes installed in soil in multi-year corn production. Data on water contents at 10, 30, 50, and 80 cm depths were collected every 10 min for 20 months of continuous observations from May 2001 to December 2002. Temporal stability was well pronounced for soil water fluxes estimated from soil water balance for the depth of 60 m. Soil water fluxes can be upscaled and efficiently monitored using the temporal stability of soil water patterns.

K e y w o r d s: soil water flux, temporal stability, agricultural fields

INTRODUCTION

When a field or a small watershed is repeatedly surveyed for soil water content, sites often can be spotted where soil is consistently wetter or consistently dryer than average across the study area. This phenomenon has been called time stability or temporal stability (Vachaud *et al.*, 1985), temporal persistence (Kachanoski and de Jong, 1988), or rank stability (Tallon and Si, 2003) in spatial patterns of soil water content or in soil water contents. The temporal stability has been demonstrated for three different time-dependent characteristics of soil water dynamics, namely for (a) water contents at specific depths, (b) soil water storage usually interpreted as the total soil water amount within a range of depths, and (c) soil water fluxes estimated at specific depths. The temporal stability causes time series of soil water contents or fluxes in different locations to have similar shapes while being offset from each other. Although the mechanistic explanation of the temporal stability in spatial soil water patterns has never been given, the presence of this stability has been routinely observed in various very different environments provided measurement locations did not change in time.

Several consequences of temporal stability in soil water patterns (TSSWP) caused recent growing interest to this phenomenon. One consequence is that one or more locations can be found that have the time series of soil water content (soil water storage or estimated soil water flux) very similar to the time series of the average value of soil water content (soil water storage or soil water flux) across the study area. After such location(s) are found, only small number of soil moisture sensors in such locations is needed to monitor the average soil water content across large areas. This aspect of the TSSWP has been actively used in remote sensing of soil moisture because of the opportunity to upscale soil water content from several or even single point measurements to the average soil water content across a footprint area (Mohanty

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and Skaggs, 2001; Cosh *et al*., 2003; Jacobs *et al*., 2004). Other applications included establishing field- or catchment-wide antecedent moisture conditions for runoff simulations (Western *et al*., 2003), relating spatio-temporal variation of soil water to triggering of subsurface flow, as measured by a network of piezometers (Penna *et al*., 2006), and upscaling soil moisture monitoring data in irrigated and dryland crops (Rocha *et al*., 2005; Rolston *et al*., 1991).

Whereas the temporal stability for soil water contents was amply demonstrated, the temporal stability of estimated soil water fluxes was questioned. Reichardt *et al*. (1993) concluded that it was not feasible to estimate mean field behavior with respect to soil water fluxes due to the soil variability, if field-measured hydraulic conductivity and soil water potential are used to estimate the fluxes and gradients. It is not known if the temporal stability of estimated soil water fluxes can be demonstrated, and whether the same locations can be used to estimate time series of average soil water contents and average soil water fluxes.

The objective of this work was to research the temporal stability in estimated soil water fluxes using extremely frequent multi-depth measurements with multisensor capacitance probes installed in soil in multi-year corn production.

MATERIALS AND METHODS

Soil water monitoring

The research site is part of the Optimizing Production inputs for Economic and Environmental Enhancement (OPE3) research site located at the USDA-ARS Beltsville Agricultural Research Center, in Beltsville, Maryland (39° 01' 00" N, 76° 52' 00" W). Data form two fields of the OPE3 site with the total area of 6 ha are used in this work (Fig. 1). The fields are under continuous corn. Each year the tillage practice is the same, fields are being disked about a month prior to a second disking operation that was followed with planting. Soil at these fields has been classified as a coarse-loamy, siliceous, mesic Typic Hapludult with either well or excessively well drainage. On average, the soil has a coarse loamy sand surface horizon (0-25 cm, organic matter 1.2-5.1%), followed by a sandy loam horizon (25-80 cm), and a loam horizon (80-120 cm), with loamy sand and fine textured clay loam lenses between 120 and 250 cm. The latter form a nearly impermeable layer in this soil (Gish *et al*., 2002) that prevents deep leaching and causes lateral movement of water and solutes. This subsurface layer has numerous localized depressions that form braided flow pathways throughout the field that drain toward a riparian wetland and first-order stream.

The multisensor capacitance probes, or MCP (EnviroSCAN, SENTEK Pty Ltd., South Australia) were installed in spring of 1998 to better understand surface and subsurface soil water dynamics. For details on sensor location and installation, see Gish *et al*. (2002). Each sensor was calibrated before installation (Paltineanu and Starr, 1997). This work uses the data from 24 soil moisture multisensor capacitance probes (Fig. 1) that have been installed at depths of 10, 30, 50, 80, 120, 150, and 180 cm and water content was recorded each 10 min for 610 days from May 1, 2001 to December 31, 2002. Depths of sensor installation at different locations are shown in Table 1.

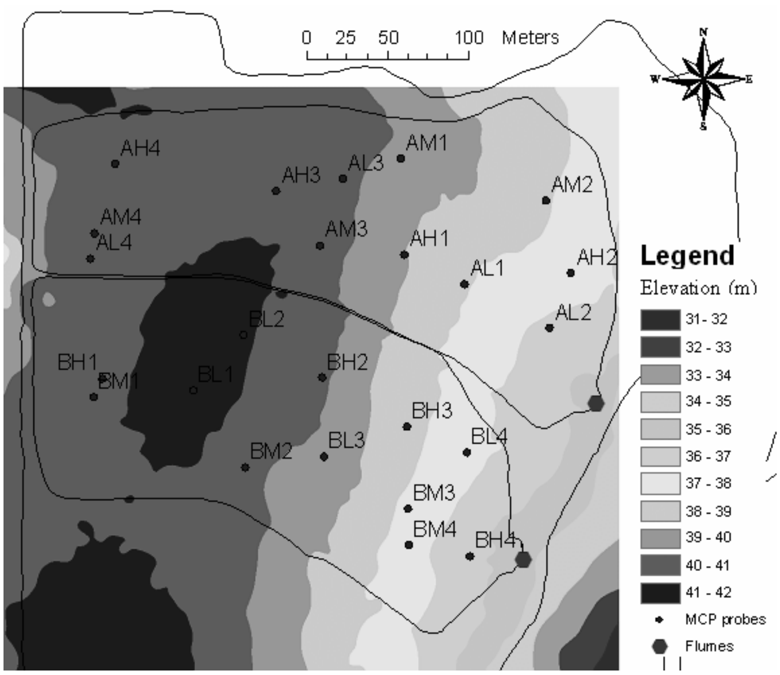

Fig. 1. Layout of fields, elevation map, and soil water probes locations; A, B – the field code; H, M, and L – the range of distances to the impermeable layer (high, medium, and low, respectively), 1 to 4 – replication number.

Evaluating temporal stability of soil water fluxes

Soil water fluxes Q_{ij} (cm h^{-1}), were estimated at the depth of 60 cm at locations of MCP installations where the data were available (Table 1) as:

$$Q_i^j = -\sum_{k=1}^{3}\left(\theta_{ik}^{j+1} - \theta_{ik}^{j}\right)\Delta z / \Delta t + R^j - ET^j, \quad (1)$$

where: θ is the volumetric water content, Δz = 20 cm is the thickness of a soil layer where soil water contents is assumed equal to the MCP reading for a single depth, R_j and ET_j are rainfall and evapotranspiration rates, respectively, cm h^{-1}, between observation times j and j+1, Δt =1 h is the time interval between observations at times j and j+1, subscripts 'i' and 'k' refer to locations and depths, respectively; k=1,2, and 3 refer to depths of 10, 30 and 50 cm.

The flux deviations B_i^j were defined as differences between the estimated hourly fluxes at each location from average estimated hourly fluxes across the field for the same observation interval:

$$B_i^j = Q_i^j - \frac{1}{N_{j3}}\sum_{i=1}^{N_{j3}} Q_i^j, \quad (2)$$

where: N_{j3} is the total number of locations having working probes at depths 10, 30, and 50 cm. Values of hourly precipitation and evapotranspiration were assumed the same for all locations within the field, and therefore the value of B_i^j was actually the difference between the hourly change in water storage in 0-60 cm layer in location i and average hourly change in water storage in 0-60 cm layer across the field between the observation times j and j+1. The temporal stability of the estimated soil water fluxes was characterized for each location by the empirical probability distribution function of the values of B_i^j.

T a b l e 1. Depths of sensor installation by locations

k	Depth (cm)	Location		
		AH1, AH2, AH3, AH4, BH1, BH2, BH3, BH4	AM1, AM2, AM3, AM4, BM1, BM2, BM3, BM4	AL1, AL2, AL3, AL4, BL1, BL2, BL3, BL4
1	10	+	+	+
2	30	+	+	+
3	50	-	+	+
4	80	+	-	+
5	120	-	+	+
6	150	-	+	+
7	180	-	+	+

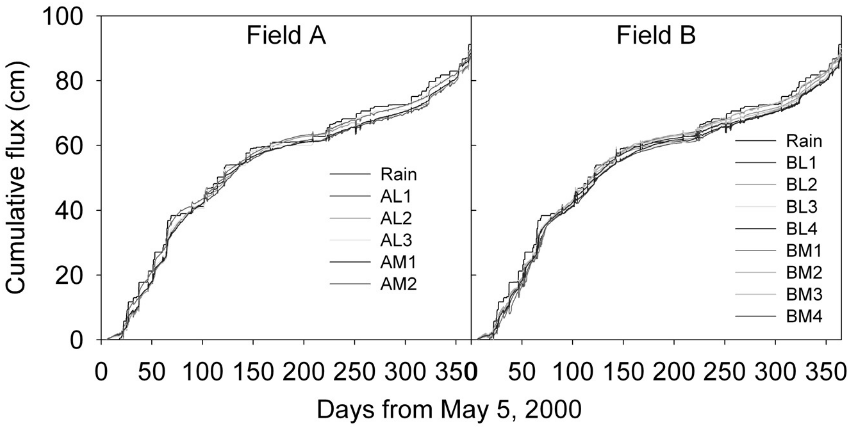

Fig. 2. Cumulative estimated soil water fluxes. Locations are shown in Fig. 1

RESULTS AND DISCUSSION

The cumulative soil water fluxes are shown in Fig. 2. All locations show a similar trend of cumulative fluxes following cumulative rainfall. This reflects the low and infrequent runoff and predominantly strong and short rainfall at the site. Nevertheless, as Fig. 2 shows, the differences between locations can be substantial. This is further illustrated in Fig. 3 where the statistical distributions of the flux deviation values B_i^j are shown. Some locations, *eg* AM2 or BM2 have fluxes larger than the average, and other locations, *eg* BL1 or Al1, have fluxes smaller than the average most of the time. This demonstrates and illustrates the temporal persistence in soil water fluxes. The data on flux deviation are further condensed in Fig. 4 where average and standard deviation of flux deviation values B_i^j flux are shown. Locations with small average and large variability in flux deviations, *eg* BL4, along with locations with relatively large absolute value of the average and small standard deviations, *eg* BL1 and BL2, can be found. The temporal stability-based estimates of the average soil water flux at 60 cm depth were found from data in each location by subtracting the average deviation in this location from the deviations at each observation time. The smallest root- mean-squared error of such estimates was found in locations AM1 and BM4 at fields A and B, respectively (Fig. 5). These were locations that corresponded to the smallest variability in flux deviations as shown in Fig. 4.

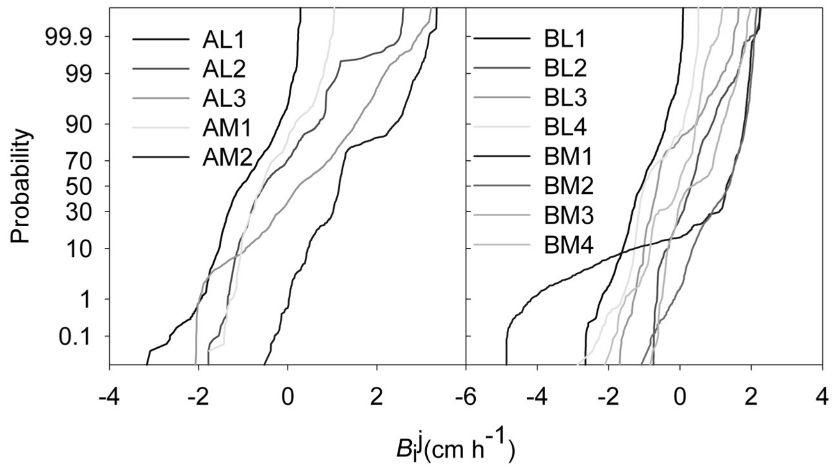

Fig. 3. Probability distributions of flux deviations computed over two-hour intervals across fields A and B. Locations are shown in Fig. 1

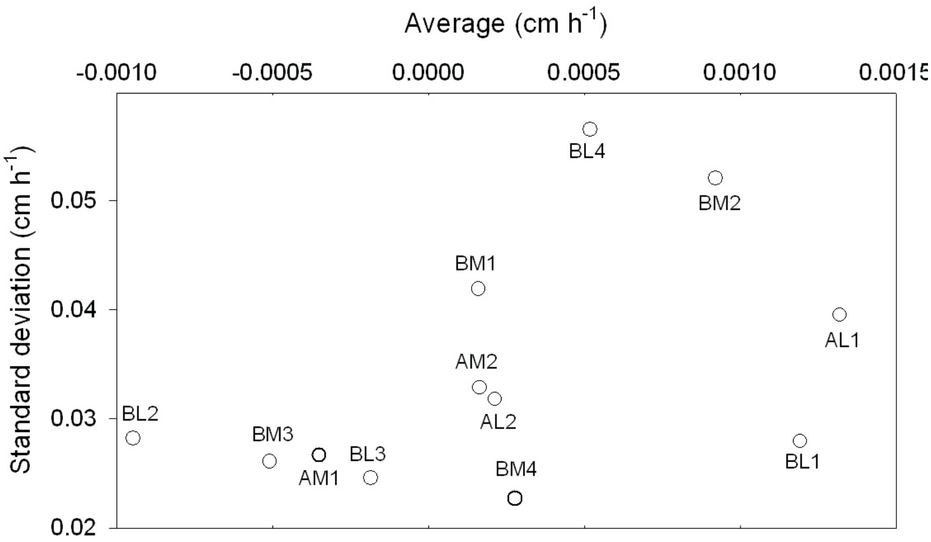

Fig. 4. Statistics of soil water flux deviations from the average flux deviation across fields A and B. Locations of soil water probes are shown in Fig. 1.

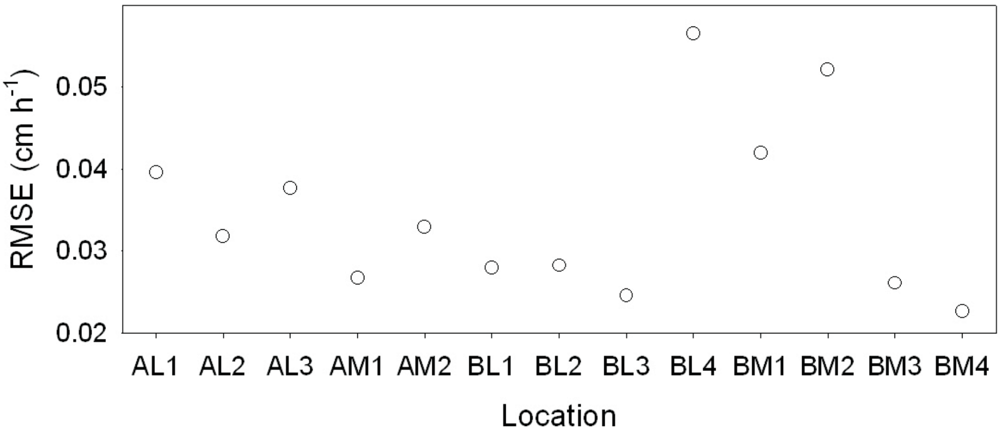

Fig. 5. Root-mean-squared errors of the estimates of the average soil water flux at 60 cm depth based on the temporal persistence. Locations of soil water probes are shown in Fig. 1.

Grayson and Western (1998) have hypothesized that the locations representative for the 'mean' landscape response in terms of soil water contents should be 'mean' with respect to main influences on spatial soil water distribution. At the Tarrawarra catchment, these authors found such locations in areas that are neither strongly convergent nor divergent, tend to be near the mid-slopes, and are in areas that have topographic aspect close to average. Our data demonstrate that similar assumptions can be made regarding locations representing mean soil water fluxes. Indeed, at the field A, the midslopes are the areas where the average deviations from the average flux and the standard deviations of fluxes are relatively low (see AM1, AM2, and AL2 in Figs 4 and Fig. 1). Similarly, in the field B, locations with low average deviations from the average flux and the standard deviations of fluxes are in midslopes (BL3, BM3, BM4 in Fig. 4 and Fig. 1). Locations with the largest deviations of average fluxes from the average flux over the field B are in the divergence area of highest elevations (BL1, BL2, and BM2 in Figs 1 and 4).

Multisensor capacitance probes provide soil water content data with high temporal frequency. From such data, soil water fluxes can be estimated that appear to exhibit temporal stability. We stress that soil water fluxes are estimated rather than measured in this work. The flux estimations with Eq. (1) have unaccountable errors because rainfall and evapotranspiration rate values used in this equation are measured or computed from measurements in locations different from locations of MCP, the accuracy of evapotranspiration estimates is essentially unknown, etc. Uncertain as they are, such soil water balance-based flux estimates are needed and used in the multitude of applications of soil moisture data for groundwater recharge and contaminant hydrology modeling. Limitations and necessary precautions of using Eq. (1) and its analogs are thoroughly discussed *ie* Gee and Hillel, 1988; Zhang *et al*., 2002.

Although the mechanisms behind the temporal stability in soil water patterns need further research, the empirical evidence indicates that this phenomenon is widespread and pervasive. It remains to be seen whether the temporal stability of soil water fluxes is affected by the interannual variations in weather conditions. We have not observed a seasonal effect of the persistence (data not shown).

The similarity in temporal stability of estimated soil water fluxes and soil water contents should not be expected. Flux estimation with Eq. (1) uses the approximation of the temporal derivative in soil water storage. The rainfall and evapotranspiration are set the same for all locations, and therefore spatial variations in estimated flux values are in fact spatial variations of temporal derivatives of soil water storage. There are no reasons to expect similarities in spatial variability of soil water contents and spatial variability of the temporal derivative of soil water storage which is the weighted sum of soil water contents at several depths. Therefore, the temporal stability of soil water contents established for our research site (Guber *et al*., 2008) does not necessarily imply the temporal stability of soil water fluxes.

The temporal persistence in soil water fluxes series can be quantified along with temporal stability. Whereas temporal stability analysis uses statistics of relative water contents or statistics of relative differences in water contents as defined by Vachaud *et al.* (1985), the temporal persistence is characterized using the autoregression of the soil water content time series as suggested by Kachanoski and de Jong (1988). Lin (2006) has developed four conditions of temporal persistence based on the slope and intercept of this autoregression. There have been suggested other characteristics of consistency in temporal patterns of soil water contents, such as rank stability (Vachaud *et al*., 1985), spatial coherency (Kachanoski and de Jong, 1988), variance of relative differences (Martínez-Fernández and Ceballos, 2003; Jacobs *et al*., 2004), and parameters of soil moisture semivariogram (Kaleita *et al*., 2004). Combining characteristics of consistency in temporal patterns of soil water contents to select monitoring locations and fill in missing data presents an interesting avenue of research.

Values of soil water fluxes are of interest for both groundwater recharge estimations and estimations of shallow groundwater input in crop water uptake. The near-real-time monitoring of soil water storage with MCP provides the sufficient information for point estimates of soil water fluxes. Using a large number of MCPs to upscale fluxes to the field scale by averaging is prohibitively costly. However, the short term monitoring to establish a location which is representative for the field-average soil water flux is feasible, since the set of MCP can be reused many times in different locations. Therefore, the temporal persistence in soil water fluxes, if proven, opens the possibility of the efficient monitoring and upscaling soil water fluxes.

CONCLUSIONS

1. This work demonstrates the temporal persistence in soil water fluxes estimated from near-real-time monitoring of soil water contents with multisensor capacitance probes.

2. The efficient upscaling and monitoring of soil water fluxes can be achieved thus providing essential information for both groundwater recharge estimation and estimation of shallow groundwater input in crop water uptake.

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