04JEI00034
1726-2135/1684-8799

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Journal of Environmental Informatics 4 (1) 28-36 (2004)

Representative Soil Water Benchmarking for Environmental Monitoring

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ABSTRACT. Soil moisture is a key hydrological factor affecting the fate and transport of pollutants in soils as well as greenhouse gas emissions. There is strong spatial variability in field soil water, which requires monitoring many locations to capture the salient features of soil water in the field. The objective of this study was to examine whether there are temporally stable soil moisture patterns in a field and whether a representative moisture benchmark site can be identified from these patterns. The experiments were conducted on a black soil at Alvena, northeast of Saskatoon, SK, Canada. Soil moisture was monitored at 95 measurement sites with a portable Capacitance Probe (CP) along a 612 m rolling transect, from April to September in 2001and 2002. Temporal stability of spatial patterns in soil moisture for depths of 30, 60, 90, 120 and 160 cm were determined using temporal means and standard deviations of the differences between individual and spatial average values of soil moisture along the transect. The spatial patterns of soil water storage were stable in different locations for each depth. Contrary to reports in the literature, clay content showed the least amount of control of spatial patterns. Coefficient of variation and standard deviation of soil moisture both decreased with increasing soil moisture. Soil moisture benchmark sites identified in this study represent field mean soil moisture and can be used for environmental monitoring and modeling.

Keywords: Benchmark, soil moisture, spatial variability, temporal stability

1. Introduction

Soil water is the principle limiting factor in semi-arid agricultural production and a key element in environmental health. Soil water affects the transport of sediment, toxins and chemicals to environmentally sensitive areas such as surface water bodies and ground water. In addition to flowing water, antecedent soil moisture has an effect on water infiltration, percolation to lower depths, runoff and evapotranspiration (Gómez-Plaza et al., 2000; Mohanty et al., 2000).

Soil water is influenced by topography, soil properties such as texture and vegetation, water routing processes, depth to water table and meteorological conditions (Western and Blöschl, 1999; Gómez-Plaza et al., 2001). The complex interaction of these variables can lead to large spatial heterogeneity of soil water and can vary greatly on field as well as point scales (Gómez-Plaza et al., 2000).

Due to the spatial variability of soil water in a field, a complete picture of spatial patterns requires numerous samples. Fortunately, the knowledge of the mean and variance are sufficient for most practical applications. Randomly taking a few dozen samples is one of the popular methods to obtain the average and variance of soil water. This method is not only time consuming and costly but the random nature precludes returning to the same sample point on consecutive occasions, making it difficult to study long term changes in field water regimes.

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Benchmarking of soil water addresses the problems associated with random sampling. A benchmark site is a single reference point that is returned to for successive sampling and against which, comparative analysis of changes in soil properties is made. Traditionally, benchmark sites are selected because a site "looks" representative. This is arbitrary and selected sites may deviate from the average behavior of the field. There is a need for identifying benchmark sites that are representative of field average soil water content for agronomic and environmental applications.

Traditional sampling methods assume a random nature to spatial soil water variability, and can only provide estimates of field mean and variance. However, factors controlling soil water exhibit non-random patterns. Spatial patterns in topography, weather, soil, and vegetation within a field or catchment impact water flux patterns giving rise to patterns in soil moisture (Grayson and Western, 1998). These patterns of soil moisture may persist over time. To describe these time-persistent spatial patterns, Vachaud et al. (1985) introduced the concept of temporal stability, defined as the temporal invariance in the relationship between spatial location and statistical measure of soil moisture, most often the mean (Grayson and Western, 1998). Temporal stability was proposed as a method of reducing the number of sampling observations needed to characterize a field by Vachaud et al. (1985). An assumption is made that a point in the field will fall into a statistical rank and will keep that rank for subsequent measurements; therefore, a point that represents the field average will continue to do so over a period of time (Vachaud et al., 1985). Vachaud et al. (1985) reported that temporal stability of soil moisture is realistic because the controlling factors such as soil texture and hydraulic properties affecting soil water are in themselves stable with respect to time.

The finding of time stable sites has been reported recently (Grayson and Western, 1998; Gómez-Plaza et al., 2000). Grayson and Western (1998), found that spatial patterns of soil water are not persistent for the entire catchment although there were a number of time stable points within the catchment called Catchment Area Soil Moisture Monitoring (CASMM) sites. However, CASMM sites were not directly obtained from visual observation of the topography, soil, and vegetation. Gómez-Plaza et al. (2000) found time stable point sources that were in aspect neutral positions within the field. In addition, Gómez-Plaza et al. (2000) found that time stability exists at the transect scale for a bare field, albeit not very strongly. In the same study area, the temporal stability broke down when vegetation was introduced as a variable (Gómez- Plaza et al., 2000, 2001). This would indicate that in vegetated areas, myriad soil factors are affecting ground cover and vegetation, thus impacting local control of soil moisture (Gómez-Plaza et al., 2001).

As research has progressed, a distinction has been made between wet and dry periods, or preferred states in soil moisture patterns (Kachanoski and de Jong, 1988; Grayson et al., 1997; Western and Blöschl, 1999). Grayson et al. (1997) classified the controls for different recharge and depletion states as local and non-local. Local controls dominate in dry conditions when evapotranspiration is greater than precipitation. Local controls include the differences in vegetation and soil properties such as texture. Vachaud et al. (1985) were the first to suggest soil texture as a dominant control on time stable water redistribution and soil moisture. Texture becomes important in semi-arid areas with moisture deficits and water redistribution dominated by vertical flow with no connection between adjacent points (Vachaud et al., 1985; Gómez-Plaza et al., 2001). Soil texture is dominant in local control when no vegetation is present and said texture is more determinate in wet periods than in conditions when field evaporation prevails. When there is a moisture surplus, that is, precipitation is greater than evapotranspiration, non-local controls will dominate redistribution (Grayson et al., 1997). These controls are related to upslope topography and include catchment area, aspect, depth and soil profile curvature (Gómez-Plaza et al., 2001). Western and Blöschl (1999) attributed these differences in local and non-local controls to the high degree of organization during wet periods that consist of connected bands of high soil moisture in drainage lines. Moisture in these drainage lines is laterally redistributed by both overland and subsurface flow. However, during dry periods there is limited spatial organization and this spatial variation seems to be mainly random. Contrary to this, it was recently stated by Martínez-Fernández and Ceballos (2003) that temporal patterns are most persistent during dry periods.

There are no definitive criteria for selecting a benchmark site such that it represents the entire field mean and variance. There is conflicting information on what scale temporal stability exists and the factors controlling it. To the best of our knowledge, only one other study (Martínez-Fernández & Ceballos, 2003) examines multiple depths for the measurement of soil water content or storage. It is therefore apparent that a comprehensive study is needed to further test conflicting conclusions that may be derived from discrepancies in depth measurements. In addition, there are no reports on selecting benchmark sites based on the concept of temporal stability. Therefore, the main objectives of this study are: (1) to identify whether there are time stable sites and if there are, whether time stable sites vary with depth; and (2) whether it is possible to identify a time stable site from the readily measured soil and topographic properties.

1.1. Theory

To find temporally stable benchmark sites we calculated the relative difference, δ_t (j), at location *j* at time *t* at *N* measured locations as:

$$\delta_t(j) = \frac{\Delta_{jt}}{\overline{S_t}} \tag{1}$$

where

$$\Delta_{jt} = S_t(j) - \overline{S_t} \tag{2}$$

and

$$\overline{S_t} = \frac{1}{N}\sum_{j=1}^{N} S_t(j) \tag{3}$$

for each location, at each sampling time. Taking the mean of these observations gives the mean relative difference, $\overline{\delta_j}$, calculated as:

$$\overline{\delta_j} = \frac{1}{m}\sum_{t=1}^{m} \delta_t(j) \tag{4}$$

where *m* is the number of sampling days. Standard deviation $\sigma\left(\delta_j\right)$ of relative differences away from the mean relative difference were then calculated as:

$$\sigma\left(\delta_j\right) = \sqrt{\frac{\sum\left(\delta_t(j) - \overline{\delta}_j\right)^2}{m-1}} \tag{5}$$

Similarly, Vachaud et al. (1985) and Gómez-Plaza et al. (2000) used the non-parametric Spearman's test to determine temporal stability. Let R_{ij} be the rank of the variable S_t(j) at location *j* at time *t* and $R_{jt'}$ the rank of the identical variable at the same location but at time *t'*. Spearman's rank correlation coefficient is calculated by:

$$r_s = 1 - \frac{6\sum_{i=1}^{n}(R_{jt} - R_{jt'})^2}{n(n^2-1)} \tag{6}$$

where n is the number of observations. A value of $r_s = 1$ corresponds to identity of rank for any site, or perfect time stability between times t and t'.

2. Materials and Methods

The study was carried out in a semi-arid area near Alvena, Saskatchewan, Canada. The site was located 70 km northeast of Saskatoon, SK on a gently rolling (5-10% slope) field. The field was managed under a crop/fallow rotation and was under spring wheat in 2001, and left fallow in 2002, tilled using conventional methods. Nitrogen is typically applied during seeding at a single rate of 50 kg·ha^{-1}. The annual precipitation averages around 350 mm, accumulating mostly as snowmelt in spring and rainfall in summer. With potential evapotranspiration reaching 624 mm per year, water deficits can be as high as 274 mm. It was extremely dry in both 2001 and 2002; the total precipitation for the year 2001 was 159 mm (45% of long term average) while it was the driest year on record for Saskatchewan in 2002.

A soil survey was carried out in July, 2002. The field was formed on silty Glacio-lacustrine parent material comprised mainly of Orthic Black Chernozems, but also including Orthic Regosols on the knolls all belonging to the Blaine Lake Association (Acton and Ellis, 1978). The soils were classified from 5.5 cm cores taken by a truck-mounted hydraulic punch and classified based on the Canadian System of Soil Classification (Soil Classification Working Group, 1998). Texture analysis was performed using the simplified hydrometer method (Gee and Bauder, 1979). The average texture is that of a silty clay loam with an A horizon averaging 11 cm. A-horizon depth ranges from below 90 cm in the deepest depression to non-existent on the knolls. A summary of clay content, organic carbon and bulk density is provided (Table 1).

Table 1. Summary of Clay Content, Organic Carbon, and Bulk Density at 0-10 cm Depth for the Studied Field

	Clay Content	Organic Carbon	Bulk Density
	g/100 g soil	g/100 g soil	Mg·m^{-3}
Mean	29.6	2.2	1.1
Standard Deviation	5.0	0.7	0.1
Minimum	20.4	1.0	0.9
Maximum	41.1	3.8	1.3

A single, 612 m transect running north-south was monitored from April to September in both 2001 and 2002. The transect had 95 capacitance probe tubes spaced at 6 m intervals and were installed to cover several knoll-depression cycles. The capacitance probe tubes were installed to a depth of 160 cm in the spring of 2001. Tubes were installed by removing a 160 cm soil core, of just slightly larger outside diameter than the tubes using a truck mounted hydraulic punch. Tubes were fitted with factory supplied installation guides, which allow for installation to full depth without filling the tube with soil. Tubes were installed leaving 10 cm above ground and the proper receptacle fitting was cemented into place.

Water content measurements were made using a capacitance probe (CP). Measurements were taken at least weekly and up to three times a week between April and September in 2002. CP technology works on the principle of dielectric constants and measures the relative differences in constants of four components of soil: free water at 20 °C and standard pressure (80.4), bulk soil (3 - 7), air (1) and bound water (~ 4) (Paltineanu and Starr, 1997). Scaled frequency, which has a direct relationship with the dielectric constant of soil, was measured at each tube using the Sentek Diviner 2000 (Sentek Pty Ltd., 2000). The Diviner provides 16 measurements at 10 cm intervals for a total depth of 160 cm. In some cases only 40 cm were measured, most likely due to tubes bent during installation, or from imperceptible damage incurred over the winter. The Diviner was calibrated with field gravimetric sub-samples taken at 0 - 20 cm, 20 - 40 cm and 40 - 60 cm increments, corresponding generally to textural layers of the soil profile. Samples were taken on 8/01/02, 8/14/02, 9/14/02, and 5/23/03. Gravimetric moisture values were later converted to volumetric water contents (θ_v). The following relationship was used to relate scaled frequency reading to the volumetric soil water content measurements:

$$SF = a \cdot \theta_v^{\,b} \tag{7}$$

where SF is the scaled frequency and can be calculated from:

$$SF = \frac{F_a - F_s}{F_a - F_w} \tag{8}$$

where F_a, F_b, and F_s are the frequency readings in air, water, and soil, respectively.

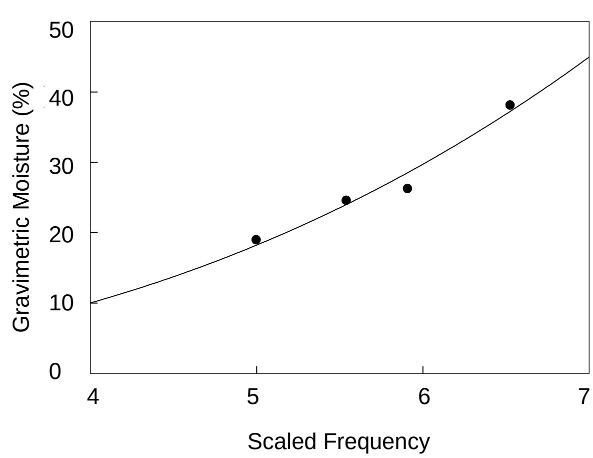


Figure 1. Capacitance probe calibration curve for a single location with scaled frequency versus gravimetric moisture sampled on four different days ($R^2 = 0.96$).

Generally, a site specific calibration curve is needed for each measurement location. A typical calibration relationship is shown in (Figure 1). Gravimetric moisture samples are plotted against scaled frequency and in this case show a good relationship ($R^2 = 0.96$). This verifies that capacitance calibrations for the field are acceptable.

The mean relative difference and the standard deviation of the daily mean were calculated for depths of 30 cm, 60 cm, 90 cm, 120 cm, and 160 cm. The mean relative difference was then ranked in ascending order and graphed. Points that are sufficiently close to 0 and had small standard deviations given by the error bars were selected from the graph. These potential time stable points were then subjected to a t-test of the mean and points that do not fall within the specified 95% confidence interval were subsequently rejected. The premise is that points will fall into a rank and will retain that rank; in other words, will consistently represent the mean soil moisture as given by the small standard deviation.

The field was surveyed in May, 2002 using a laser theodolite. Five parallel transects 612 m in length were established running north-south with a lateral distance of 6 m east-west between sample points. Elevation was measured at 6 m intervals along each transect for a total of 512 points in an area of 1.836 ha. This data was then used to produce the topographic information for analysis of results. Three topographic parameters were used to define the wetness index. The curvature was calculated from the elevations using the following approximations (Sinai et al., 1981; Pennock et al., 1994; Shary et al., 2002):

$$M \approx \frac{\partial^2 Z}{\partial X^2} + \frac{\partial^2 Z}{\partial Y^2} = \Delta^2 Z \qquad (9)$$

The derivatives in Equation (9) were approximated as:

$$\Delta^2 Z = \frac{Z_{i+1,j} + Z_{i-1,j} - 2Z_{i,j}}{\Delta X^2} + \frac{Z_{i,j+1} + Z_{i,j-1} - 2Z_{i,j}}{\Delta Y^2} \qquad (10)$$

where Z is elevation, i represents the indices for the x coordinates (along the transect) and j represents the indices for the y coordinates (perpendicular to the transect).

The wetness index of Beven and Kirkby (1979) was calculated as:

$$w = \ln\left(\frac{\gamma}{\tan\beta}\right) \qquad (11)$$

where γ is the contributing area per unit contour length and $\tan\beta$ is the local slope of the landscape elements.

3. Results and Discussion

Examples of spatial and temporal variations of soil moisture values (30 cm depth) for two selected dates (05/13/02 and 9/14/02) at each probe location with respect to elevation are presented in Figure 2. These dates represent a relatively dry and moist day, respectively. Despite differences in moisture levels, distribution of soil water content exhibited spatial redistribution patterns. That is, soil moisture values in the depression are higher than those on the knolls. Persistent dry conditions tend to homogenize spatial redistribution patterns. Note that to the far right (north) end of the field on the southern aspect, moisture levels in depression area were lower than expected, most likely due to the south facing slope as well as drying winds originating in the south on hot days.

Time-stable sites for soil water storage (total amount of water stored in a given soil depth) existed for the studied field. This is given by the mean relative difference (Equation 4) and standard deviation (Equation 5) for soil water storage at different depths (Figure 3). Sites that are close to the mean with corresponding small standard deviations were selected as time-stable sites, according to Vachaud et al. (1985). A standard two-tailed t-test about the mean was then performed on the chosen sites. Sites that have a mean significantly different from zero are rejected as time stable sites at a 95% confidence interval. The sites that were chosen are summarized in (Table 2). Note that site 11 was the only site that occurred at two separate depths (Table 2) and occurs in a position with no dominant aspect in the field despite the exaggerated appearance (Figure 2). Other sites, however, occur in less neutral locations such as site 40 in a north facing depression area, and site 33 on a south facing shoulder area.

Table 2. A Summary of Temporally Stable Sites for the Complete Data Set at Depths of 30, 60, 90, 120, and 160 cm, Including Rejected Sites Based on a T-Test (Sites Occurring outside the ±1.96 Critical Value Were Rejected)

Depth	Probe	Rank	Mean	Std. Dev	T-test*
30 cm	94	45	-0.01	0.10	-1.0
	59	50	0.01	0.10	1.30
	50	52	0.01	0.10	2.30
60 cm	11	52	-0.03	0.03	-1.35
	84	55	-0.02	0.06	-2.86
90 cm	40	58	-0.01	0.01	-0.70
	33	60	0.01	0.10	0.70
	13	63	0.03	0.05	5.14
120 cm	102	53	-0.02	0.09	-1.82
	34	52	-0.03	0.03	-9.76
160 cm	11	55	-0.01	0.07	-1.18
	29	53	-0.02	0.06	-3.46

Note: *Statistical Significance at $\alpha = 0.05$.

The finding of temporally stable sites is supported by others (Vachaud et al., 1985; Kachanoski and de Jong, 1988; Grayson and Western, 1998; Gómez-Plaza et al., 2000; Martínez-Fernández and Ceballos, 2003). Point source time stable sites were located by Gómez-Plaza et al. (2000) while

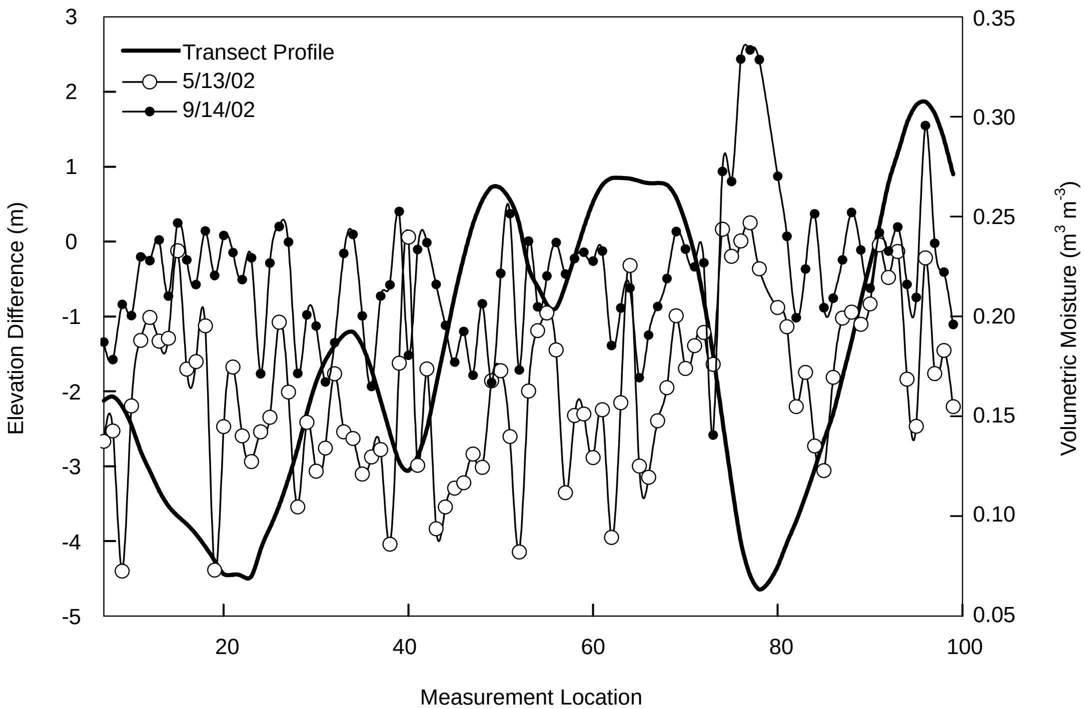


Figure 2. Moisture patterns for two days in relation to an exaggerated longitudinal profile (solid line, left axis) of studied transect.

overall spatial patterns did not display consistent patterns. This is similar to Grayson and Western (1998) who found that transect scale temporal stability did not exist while point scale temporal stability exists because there was no spatial pattern that could be shown.

Table 3. Spearman's Rank Correlations Illustrating Persistence of Spatial Patterns

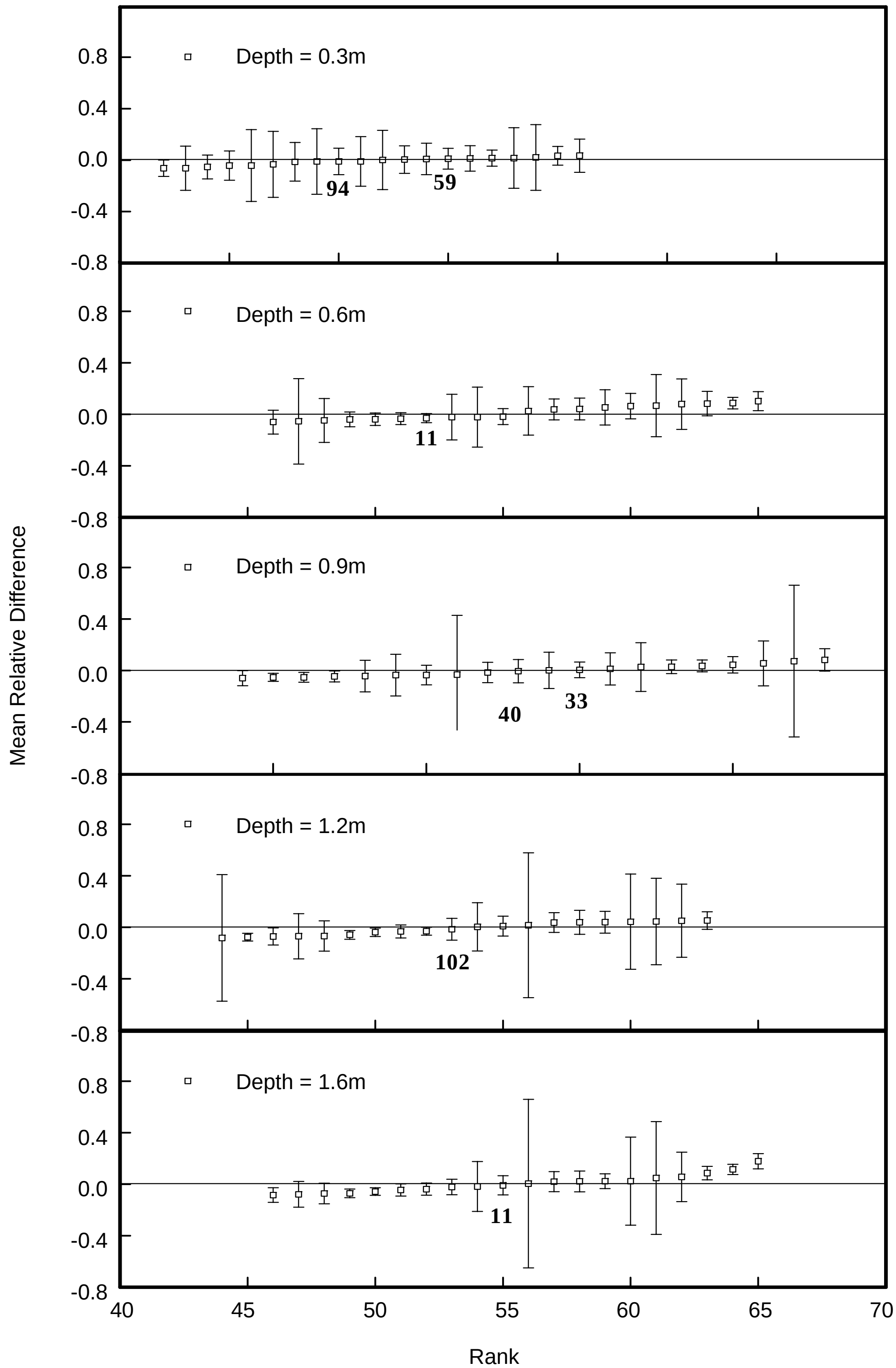
Data	8/01/02	6/13/02	8/14/02	7/24/02	9/14/02
8/01/02	1	0.66	0.52	0.50	0.65
6/13/02		1	0.56	0.49	0.70
8/14/02			1	0.46	0.50
7/24/02				1	0.36
9/14/02					1

Temporal persistence of spatial patterns was examined for selected days using the Spearman's rank correlation (Table 3). The results show a good correlation with a high correlation coefficient of 0.70 between soil water storage measured on 6/13/02 and 9/14/02 and a low correlation coefficient of 0.36 between water storage measured on 7/24/02 and 9/14/02. The overall mean correlation coefficient for these days is 0.54.

Variability for daily mean soil moisture values are presented in (Figure 4). As the mean moisture content increases there is a corresponding decrease in the coefficient of variation (CV) while standard deviation (SD) remains constant. The exception to this is the increase in both CV and SD for the wettest point. This was the wettest mean recorded at 0.28 ($m^3 \cdot m^{-3}$) and inferences about an increase in variability were difficult to make on a single observation. These findings are in contrast to those of Martínez-Fernández and Ceballos (2003) who found a high correlation between the mean soil moisture and moisture variance; the opposite of our findings.

There is very little correlation between soil water storage and any of the standard local (texture) and non-local (elevation, catchment area, wetness index, curvature) controls on soil moisture. Most surprising is a very weak correlation between texture and moisture storage, with a mean coefficient of determination of 0.02. On some days there was a good correlation between contributing area and storage. Contributing area showed the most consistent relationship on days that were relatively wetter, with coefficients of determinations ranging from 0.09 (6/21/02) to 0.25 (8/14/02), the exception being 0.03 on 6/26/02. Overall, on the drier days soil water storage has very poor relationships with all parameters. An exception existed for contributing area, which has a coefficient of determination of 0.37 with soil water storage on 5/21/02. Water storage on this date also showed good relationships with elevation (0.186) and wetness index (0.18).

There was a consistent lack of dominance exerted by tex-



Notes: Vertical bars correspond to associated time standard deviation;
Each point corresponds to a measuring location.

Figure 3. Ranked intertemporal relative deviation from the mean spatial water storage at 30 cm, 60 cm, 90 cm, 120 cm, and 160 cm depths.

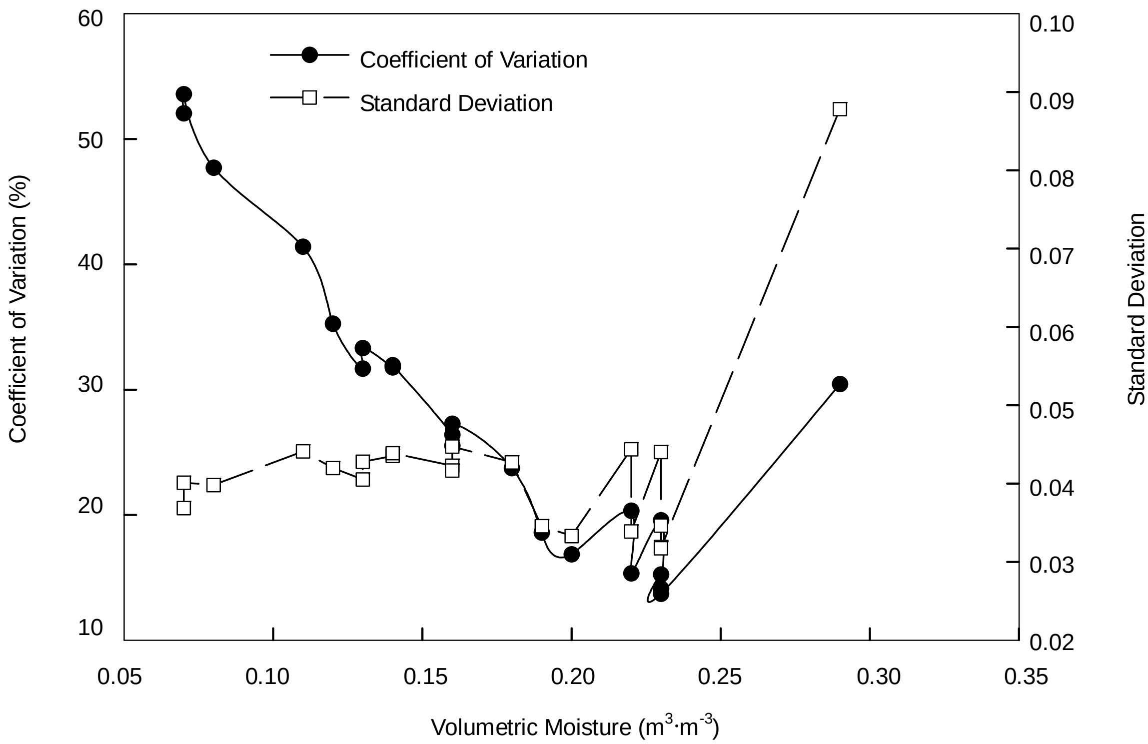


Figure 4. Daily mean moisture variability showing standard deviation from the daily mean and coefficient of variation vs. increasing mean moisture measurements.

ture and topography. Average overall coefficients of determination for local and non-local controls were: texture (0.02) and non-local controls of elevation (0.065), contributing area (0.09), wetness index (0.047) and curvature (0.02) for 30 cm storage. This would suggest that not one single factor is responsible for the observed spatial patterns. Contributing area, a non-local control, is most consistent in explaining patterns. This is reasonable because in the prairie region the most significant recharge and redistribution event is the spring snowmelt. Recharge preferred states are characterized by non-local controls (Grayson et al., 1997). Contributing area, a non-local control, reflects the upslope area contributing runoff of snowmelt to a point. Conversely, water loss during the summer months is governed by evaporation. Evaporation is controlled by temperature, humidity and wind speed. In sheltered depressions relative to knolls, humidity gradients and wind speeds are lower. Therefore, in depressional areas, evaporational losses will not be as great as knoll positions. Evaporative losses are indirectly related to contributing area and elevation in that the greater the contributing area and lower the elevation, the further downslope a point is. Therefore depressions are subject to less evaporative demand relative to the knoll. This may serve to explain why contributing area exhibited the most consistent control on soil moisture.

The use of differing depths in identification of temporal soil moisture stability is not widely studied. There is a lack of research on the finding of time stable depths and their relation to the most commonly studied soil variables. Grayson and Western (1998) reported that there were no significant effects of measurement depth between measured data sets. Similarly, no stability patterns were found with respect to depth according to Martínez-Fernández and Ceballos (2003). Our results concur, and have shown that there were substantial differences in measurement depths, and the sites were not even adjacent in terms of spatial location. Since semi-arid water redistribution is dominated in summer months by vertical flow with little connection between points (Gómez-Plaza et al., 2001), it should follow that deeper time stable depths should be located in relative proximity to the overlying sites. This is not the case, and is most likely due to "hydrological inertia" (Martínez-Fernández and Ceballos, 2003) where the factors controlling temporal stability at surface depths do not have as pronounced an effect and greater lag time on soils at depth.

There is no discernible pattern along the transect with respect to occurrence of these sites. Time stable sites occurred on both north and south aspects and were also found on shoulder, mid and low slope positions. Grayson and Western (1998) expected that sites that represent field means should be found in field neutral locations, including slope and aspect. This was not the case in the present work. While slope aspect does have an effect on moisture levels in the field studied, especially at the northern end of the field with a southern aspect, where the slope is quite steep, aspect does not seem to be the dominant control. Temporally stable sites occur independent of slope aspect and slope position.

Gómez-Plaza et al. (2001) found that moisture patterns could be explained by soil texture. Mohanty et al. (2000) state that soil texture will dominate control on soil water in the mid to low water pressure range and in the absence of vegetation. The results from this study are not in agreement with their findings as there was a lack of relationship between moisture in the first 30 cm and texture, specifically clay content. We found a very weak correlation between clay content and soil moisture patterns. Supporting this are Si and Farrell (2004) who found a poor correlation between crop yield and soil texture for a dry year. This would also indicate a poor relationship between soil water and texture. The evidence is suggestive that drought conditions were severe enough to minimize the control of texture and non-local controls on time stability of soil moisture storage. Although clay content varied by around 30% at some points, the textural class only ranged from silty clay loam to silty clay, with the majority of the field being silty clay loam. It is cautiously suggested that even with fluctuations in clay content, silt content served to smooth out variations and homogenize the field in terms of textural class. This may serve to lessen the control that texture would have on spatial patterns.

The concept of using temporal stability to benchmark soil moisture measurement sites is an attractive one. Monitoring a single site that would give representative information on field drainage rates and water content, for example, is far more efficient than traditional methods. Sites that accurately represent the field mean soil moisture exist for this field, but cannot be identified *a priori* using common variables. Consistently dry conditions could be responsible for the lack of an easily identified dominant control on temporal stability. It was reported by Martínez-Fernández and Ceballos (2003) that during dry conditions, temporal stability was greatest, as given by a small mean relative difference. Despite this, it was possible in our case that the record drought conditions served to eliminate any connections between points. This would minimize spatial patterns, and overshadow any dominant control thus negating the possibility of determining benchmark sites *a priori*.

4. Conclusions

A representative soil water benchmark site has the potential to provide important information for environmental monitoring. Temporally stable spatial patterns within the field led to the determination of benchmark sites for various depths that were representative of field mean soil moisture. Time stable sites showed poor relationships to soil and topographic properties suggesting the absence of a single dominant control. The most consistent control was catchment area, a non-local control indirectly affecting evaporative losses. Future studies should look at the effect of controls on all depths in an effort to determine time stable sites *a priori* as well as upscaling of point source temporal stability. Benchmark sites**,** whether they represent mean or extreme values**,** can greatly improve sampling efficiency and can provide useful information for environmental monitoring.

Acknowledgments. This work was supported by funding from the Natural Science and Engineering Research Council (NSERC). The authors would like to acknowledge Shaun Campbell for assistance in the field and in the lab.

References

Acton, D.F. and Ellis, J.G. (1978). The soils of the Saskatoon map area, 73-B, Saskatchewan. *Sask. Inst. Pedology Publ.*, 54.

Beven, K.J. and Kirkby, M.J. (1979). A physically-based, variable contributed area model of basin hydrology. *Hydrol. Sci. Bull.*, 24, 43-69.

Gee, G.W. and Bauder, J.W. (1979). Particle size analysis by hydrometer: A simplified method for routine textural analysis and a sensitivity test of measurement parameters. *Soil Sci. Soc. Am. J.*, 43, 1004-1007.

Gómez-Plaza, A., Martinez-Mena, M., Albaladejo, J. and Castillo, V.M. (2001). Factors regulating spatial distribution of soil water content in small semi-arid catchments. *J. Hydrol.*, 253(1-4), 1261-1277.

Gómez-Plaza, A., Alvarez-Rogel, J., Albaladejo, J. and Castillo, V.M. (2000). Spatial patterns and temporal stability of soil moisture across a range of scales in a semi-arid environment. *Hydrol. Process.*, 14(7), 1261-1277.

Grayson, R.B. and Western, A.W. (1998). Towards areal estimation of soil water content from point measurements: time and space stability of mean response. *J. Hydrol.*, 207(1-2), 68-82.

Grayson, R.B., Western, A.W., Chiew, F.H.S. and Blöschl, G. (1997). Preferred states in spatial soil moisture patterns: local and non-local controls. *Water Resour. Res.*, 33(12), 2897-2908.

Kachanoski, R.G. and de Jong, E. (1988). Scale dependence and the temporal persistence of spatial patterns of soil water storage. *Water Resour. Res.*, 24 (1), 85-91.

Martínez-Fernández, J. and Ceballos, A. (2003). Temporal stability of soil moisture in a large-field experiment in Spain. *Soil. Sci. Soc. Am. J.*, 67, 1647-1656.

Mohanty, B.P., Famiglietti, J.S. and Skaggs, T.H. (2000). Evolution of soil moisture spatial structure in a mixed vegetation pixel during the Southern Great Plains 1997 (SGP97) hydrology experiment. *Water Resour. Res.*, 36(12), 3675-3686.

Paltineanu, I.C. and Starr, J.L. (1997). Real-time soil water dynamics using multisensor capacitance probes: Laboratory calibration. *Soil Sci. Soc. Am. J.*, 61, 1576-1585.

Pennock, D.J., Anderson, D.W. and De Jong, E. (1994). Landscape-scale changes in indicators of soil quality due to cultivation in Saskatchewan, Canada. *Geoderma*, 64, 1-19.

Shary, P.A., Sharaya, L.S. and Mitusov, A.V. (2002). Fundamental quantitative methods of land surface analysis. *Geoderma*, 107, 1-32.

Si, B.C. and Farrell, R.E. (2004). Scale-dependant relationship between wheat yield and topographic indices: A wavelet approach. *Soil Sci. Soc. Am. J.*, 68(2), 577-587.

Sinai G., Zaslavsky, D. and Golany, P. (1981). The effect of soil surface curvature on moisture and yield-beer Sheba observation. *Soil Sci.*, 132, 367-375.

Soil Classification Working Group (1998). The Canadian system of soil classification. *Agric. Agric-Food Can. Publ.*, 1646, 187 (Revised).

Vachaud, G., Passerat De Silans, A., Balabanis, P. and Vauclin, M. (1985). Temporal stability of spatially measured soil water probability density function. *Soil Sci. Soc. Am. J.*, 49, 822-828.

Western, A.W. and Blöschl, G. (1999). On the spatial scaling of soil moisture. *J. Hydrol.*, 217, 203-224.