Soil water storage benchmarking for environmental monitoring

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Abstract:

Soil water, a key hydrological factor, controls the fate and transport of nutrients and pollutants in soil as well as emission of green house gases from soil. Inherent spatial variability of soil water requires multiple monitoring sites for soil water which is expansive in terms of money, time and labour. The objective of this study was to identify the hydrologically time stable location (benchmark point) and spatial pattern of soil water storage in a hummocky landscape in semiarid climate. Soil water was measured in field for consecutive two years (11 measurements) by Neutron Moisture Meter (NMM) along a 128 point transect established at St Denis National Wildlife Area, Saskatchewan, Canada. Soil water measurements were taken at every 20 cm up to the depth of 1.2 m at every 4.5 m on the transect. The NMM was calibrated for this site and the calibration equation was used to calculate the soil water storage at different depths. High Spearman's rank correlation coefficient between different dates of measurements indicated the spatial similarity of soil water storage pattern over time. Similar environmental events showed more persistent spatial pattern between measurements than different environmental events. The stability or the similarity of the rank of individual observations in the probability distribution functions over time indicated temporal stability of soil water storage pattern. While, 22^{nd} point from the origin of the transect maintained the rank of soil water storage overtime for 0-20 cm with very low measurement variability, 4^{th} point maintained the rank for 0-60 cm and 0-120 cm depth. The similarity or persistency of rank in water storage pattern and the mean water content over field at multiple times helped in identifying representative moisture benchmark site, which can be used for environmental monitoring and modelling, irrigation scheduling, nutrient recommendations and predicting green house gasses.

Keywords: soil water storage, temporal stability, benchmarking, environmental monitoring.

Introduction:

Soil water is the principle limiting factor in semi arid agricultural production and a key element in environmental health. It affects the transport of sediment, toxins and chemicals to environmentally sensitive area such as surface water bodies and ground water. In addition, the factors controlling near surface hydrological processes influences the partitioning of rainfall and snowmelt into infiltration and runoff. It also determines the rate of evapotranspiration by controlling water availability to plants (Gómez-Plaza et al., 2000; Mohanty et al., 2000). Soil water content also determines the greenhouse gas emissions thus taking part in present days climate change. There are several factors and processes controlling the water in soil. These includes soil texture, structure, and organic matter; the slope, curvature, and aspect of topography; type and density of vegetation, different climatological factors and processes like temperature, solar radiation, snowfall, rainfall, evapotranspiration; and depth of ground water table (Western and Blöschl, 1999; Gómez-Plaza et al., 2001; Tallon and Si, 2004). The individual or combined effect of these factors and processes creates large spatial heterogeneity of soil water in field (Gómez-Plaza et al., 2000) thus making it difficult to monitor the soil water storage.

A conventional way of determining the soil water storage in field is by measuring the soil moisture from a number of random locations and averaging them over the field. The more number of samples are measured for water content the better is the prediction about the soil water storage. Not only the sufficient number of samples involves a lot of money and time, this labour intensive method precludes returning to the same sample location on consecutive occasions (Tallon and Si, 2004). This random sampling assumes the soil water to be random and the large spatial variability of soil water in a field requires numerous sampling to present a complete picture of soil water distribution. Fortunately, the factors controlling soil water exhibit non random patterns in field. The existing spatial patterns of controlling factors impact soil water fluxes thus giving rise to patterns in soil water and its storage (Grayson and Western, 1998). The persistency of this pattern over time was first analysed by Vachaud et al. (1985). They introduced this concept as 'temporal stability', which is defined as a time invariant association between spatial location and classical statistical parametric values of soil water, most often the mean (Grayson and Western, 1998). This phenomenon has been also called as temporal persistence by Kachanoski and de Jong (1988) or rank stability by Tallon and Si (2004) in soil moisture spatial pattern. If the pattern is persistent over the whole field, it is known as filed source stability of soil water and if it is persistent at a point, it is known as point source stability of soil water. This time stable point in a field can be described as the benchmark point. This is a non random and reference point.

The concept of this time stability for soil water pattern has been a huge step forward in identifying locations representing the aerial average and extreme values in field and thus reducing the number of sampling or observation to characterize a field. Consequently, the idea of location based sampling and monitoring techniques is very exciting and holds considerable promise for minimizing costs. The objective of this study was to identify the hydrologically time stable location (benchmark point) and spatial pattern of soil water storage in a hummocky landscape in semiarid climate.

Theory:

In identifying hydrologically time stable location or benchmark site, time stability analysis was performed following the method introduced by Vachaud et al. (1985), i.e. by calculating and ranking the mean relative difference and their standard deviation. Nonparametric Spearman's rank correlation test was also conducted between the different measurements and at different depths. If the soil water content at i^{th} location and t^{th} date is $\theta_{i,t}$ and the mean water content is $\overline{\theta}_t$ at the same time, the difference (Δ) between individual determinations is $\Delta_{i,t} = \theta_{i,t} - \overline{\theta}_t$. The mean water content was calculated from $\overline{\theta}_t = \left(\frac{1}{n}\right)\sum_{i=1}^{n}\theta_{i,t}$; where, n is the number of measurement locations (for this study $n = 128$). Then the relative difference $\delta_{i,t}$ was calculated as $\delta_{i,t} = \frac{\Delta_{i,t}}{\bar{\theta}_t}$. The mean of these observations gives the Mean Relative Difference (MRD) and was calculated as $\bar{\delta}_i = \frac{1}{m}\sum_{t=1}^{m}\delta_{i,t}$; where, m is the number of sampling days (for this study, $m = 11$). The standard deviation, $\sigma(\delta_i)$ of relative differences ($\delta_{i,t}$) away from the mean relative differences ($\bar{\delta}_i$) were calculated as $\sigma(\delta_i) = \sqrt{\frac{\sum(\delta_{i,t} - \bar{\delta}_i)^2}{m-1}}$. The MRD were ranked according to numerical values. Let, $R_{i,t}$ be the rank of variable $\theta_{i,t}$ at i^{th} location and t^{th} date and $R_{i,t`}$ the rank of identical variable at the same location but at different time $t`$. The Spearman`s rank correlation coefficients were calculated by $r_s = 1 - \frac{6 \cdot \sum_{i=1}^{n}(R_{i,t} - R_{i,t'})^2}{n(n^2-1)}$; where, n is the number of observations. A value of r_s =1 corresponded to identity of rank for any location, i.e. perfect time stability between dates t and t'. The closer r_s was to 1, the more stable the process was at that specific location (Vachaud et al., 1985).

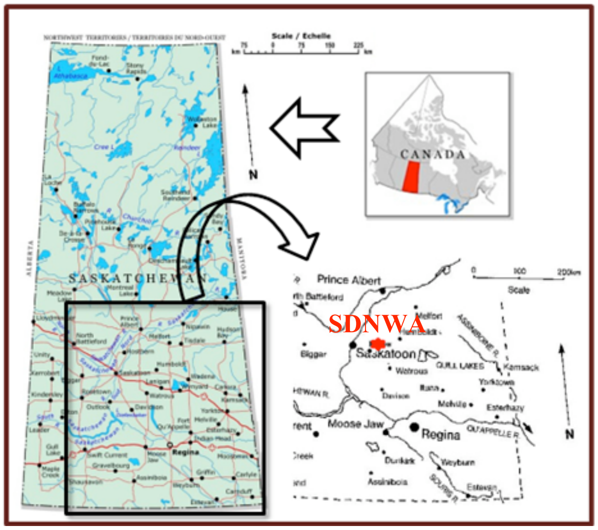

Fig. 1: Geographic location of study site at St. Denis national Wildlife Area, Saskatchewan, Canada.

Materials and Methods:

Site description: A sampling transect, extending north-south direction, was established in the St. Denis National Wildlife Area (SDNWA) (52°12’ N latitude, 106°50’ W longitude), which is located approximately 40 km east of Saskatoon, SK, Canada (Fig. 1). The landscape of this area contains a very complex sequence of slopes extending from different size rounded depressions to irregular to complex knolls and knobs (Pennock, 2005) making the terrain hummocky with 10-15% slopes. Soils of this area is mapped within the Wyandotte Associations which are Dark Brown soils developed from moderately fine to fine textured, moderately calcareous, clayey glacio-lacustrine deposits and modified glacial till (Saskatchewan Centre for Soil Research, 1989). This area is mainly of semi arid in nature with mean annual air temperature (at Saskatoon air port)

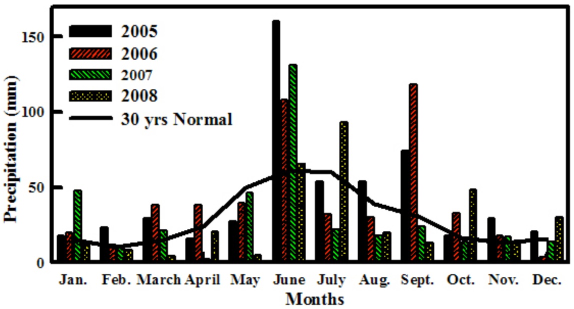

Fig. 2: Monthly precipitation data for the year of 2005, 2006, 2007 and 2008 with 30 year normal from Saskatoon International Airport (40 km west of study site).

is 2°C with the monthly mean of -19°C in January and 18°C in July (AES, 1997). Snow, which covers the area generally in the month of November, has a good contribution towards total precipitation. The 90 year mean annual precipitation is Saskatoon is 360 mm of which 84 mm occurs in winter mostly as snow (AES, 1997). The total precipitation in the year of 2005 and 2006 were 523 mm and 489 mm respectively (Fig. 2), which was higher than 30 years average (350 mm) resulting a good water storage. The total precipitation in the year of 2007 and 2008 (366 mm in 2007 and 331 mm in 2008) were comparatively lower than previous years resulting low water storage in 2008 fall season. The runoff generated by spring snowmelt and the summer rainfall events concentrated in the depressions.

Data collection: An equally spaced (4.5 m) 128 point transect of 576 m long was established over several rounded knolls and seasonal depressions (Woo and Rowsell, 1993) representing different landform cycles including three vegetative depressions (Yates et al., 2006). Detailed information about the study site is available in Yates et al. (2006). In brief, the topographic survey of this site was completed using a Sokkisha Set 5 Electronic Total Station (Sokkisha Co. Ltd. Tokyo, Japan) and a Trimble Pro XRS, Global Positioning System (Trimble Navigation, Sunnyvale, CA). The vegetation of the site is mixed grass seeded by Ducks Unlimited Canada in 2004. The sample points were installed with 5 cm diameter and 1.5 m long PVC tubes using truck mounted hydraulic drills. The open ends of PVC tubes were kept closed with caps to prevent water entry from top. These tubes were used as access tube in measuring soil water content using Neutron Moisture Meter (NMM) in field. A CPN 501 DR Depthprobe (CPN International Inc.) was used to measure the soil moisture at every 20 cm up to 1.2 m. NMM was calibrated in the transect against the volumetric water content at different moisture condition (Fig. 3). The field moisture measurements were recorded at eleven times on 17 July 2007, 7 August 2007, 1 September 2007, 12 October 2007, 2 may 2008, 31 May 2008, 21 June 2008, 16 July 2008, 23 August 2008, 17 September 2008, and 22 October 2008. The soil water storage was calculated by multiplying the depth with moisture content calculated from the calibration relationship. Measured soil water storage was classified as tillage layer water storage (0 to 20 cm depth), root zone water storage (0 to 60 cm depth) and total active root zone water storage (0 to 120 cm depth). In the manuscript, tillage layer, root zone and active root zone will indicate the water storage at 0 to 20 cm, 0 to 60 cm and 0 to 120 cm, respectively.

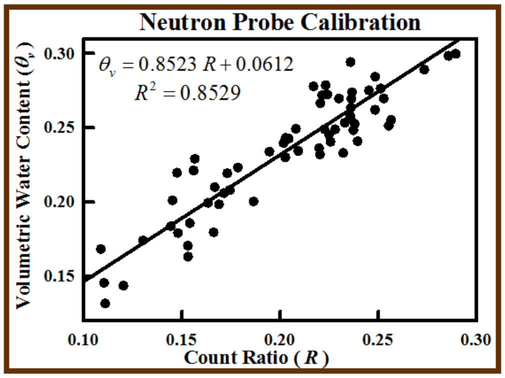

Fig. 3: Neutron Moisture Meter calibration with equation.

Results and Discussion:

The spatial distributions of soil water storage at tillage layer for different dates with respect to elevation are presented in Fig. 4. The average soil water storage at tillage layer was 4.81 cm over two year period. The high or the above average precipitation during 2005 and 2006 stored little high water during 2007 (average 5.22 cm). The average or below average precipitation during 2007 and 2008 resulted in low water storage during 2008 (average 4.58 cm). The measurement locations from 100 m to 140 m from the origin of the transect showed a very high water storage during the early part of the summer season. These locations were within depression that maintained a height of standing water. The water content was calculated strictly based on the bulk density of the soil. As the depression had very high organic matter, the bulk density was very low and the water content calculated at saturation was very high. Similarly high water storage was also observed at 225 m to 250 m from the origin of the transect. The soil water storage in tillage layer clearly showed a pattern with topography during the early part of the summer season. With time, this pattern was almost abolished over space. The high evapotranspiration demand of grass cover during late summer and fall almost equalised the difference between the water content at knoll and depression position. High water content at depression allowed grass to take up high amount of water from the depression making it more water to evapotranspire. On contrary, the little water stored in knoll locations did not allow plant to evapotranspire luxuriously thus loosing little water from the tillage layer. This variable water uptake diminished the pattern with topography during late summer and fall.

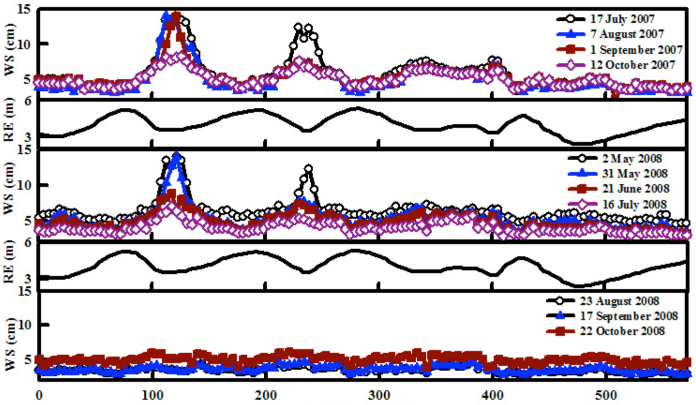

Fig. 4: Spatial distribution of soil water storage for different dates at tillage layer.

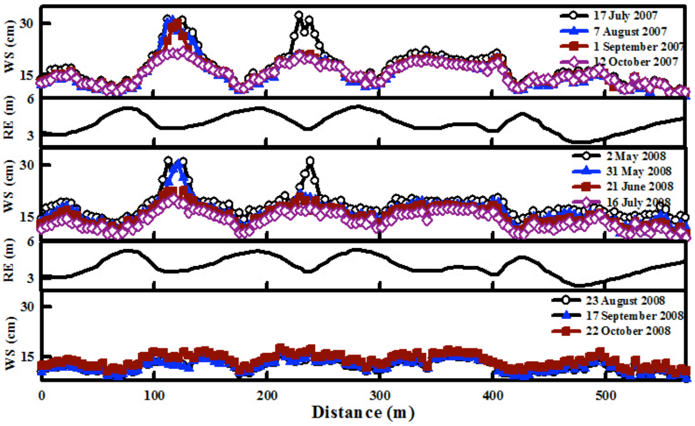

Fig. 5: Spatial distribution of soil water storage for different dates at root zone.

Fig. 5 and Fig. 6 showed the spatial distribution of water storage to the depth of root zone and total active root zone, respectively. The spatial pattern of water storage with topography at root zone and active root zone were similar to the pattern observed at tillage layer. This pattern for

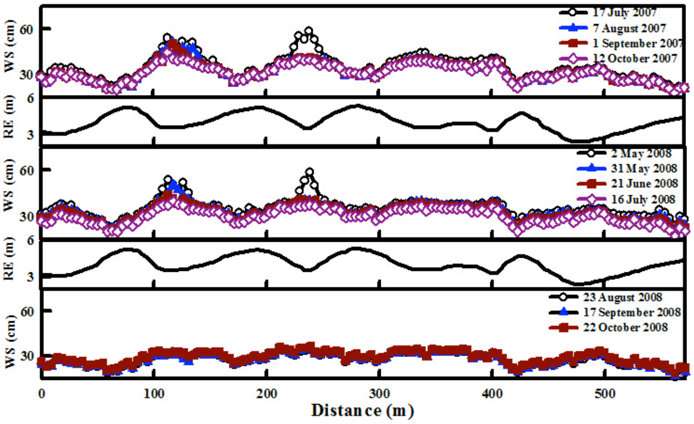

Fig. 6: Spatial distribution of soil water storage for different dates at total active root zone.

root zone and active root zone during late summer and fall was stronger than the pattern existed at tillage layer during same time. Plants generally take up more than 70% of the total water a plant can take up mainly from the first 50% of its root zone. The highest root activity at tillage layer equalised stored water over the transect and lost the spatial pattern while the root zone and active root zone still showed some pattern with topography.

The persistency of this spatial pattern was examined using Spearman's rank correlation. Table 1 showed the rank correlation coefficients between every two measurements for tillage layer. The very high rank correlation coefficients between every two measurements during 2007 clearly indicated a persistency of soil water storage pattern. This indicated the locations with high water storage maintained high water storage over time. The correlations within the measurements during spring and early summer of 2008 showed good rank correlation coefficients between measurements indicating temporal persistency of spatial pattern of soil water storage.

Table 1: Spearman's rank correlation coefficients between every two date of measurements for tillage layer.

	Jul 17 2007	Aug 7 2007	Sept 1 2007	Oct 12 2007	May 2 2008	May 31 2008	Jun 21 2008	July 16 2008	Aug 23 2008	Sept 17 2008	Oct 22 2008
Jul 17 2007	1	0.952	0.949	0.953	0.877	0.891	0.866	0.843	0.658	0.640	0.643
Aug 7 2007		1	0.937	0.942	0.828	0.828	0.809	0.829	0.689	0.679	0.673
Sept 1 2007			1	0.976	0.851	0.865	0.863	0.853	0.681	0.658	0.669
Oct 12 2007				1	0.854	0.867	0.874	0.867	0.698	0.684	0.683
May 2 2008					1	0.910	0.873	0.825	0.653	0.647	0.626
May 31 2008						1	0.956	0.893	0.685	0.657	0.678
Jun 21 2008							1	0.951	0.759	0.729	0.715
July 16 2008								1	0.866	0.831	0.773
Aug 23 2008									1	0.970	0.821
Sept 17 2008										1	0.831
Oct 22 2008											1

Table 2: Performance of benchmark points.

Depth	BM point	Field WS (cm)	BM WS (cm)	Diff. in WS	% diff. WS	% diff. in moisture
Tillage layer	22	4.81	4.93	0.13	2.7	0.65
Root zone	4	14.97	14.69	0.28	1.8	0.46
Active root zone	4	31.34	31.60	0.26	0.8	0.22

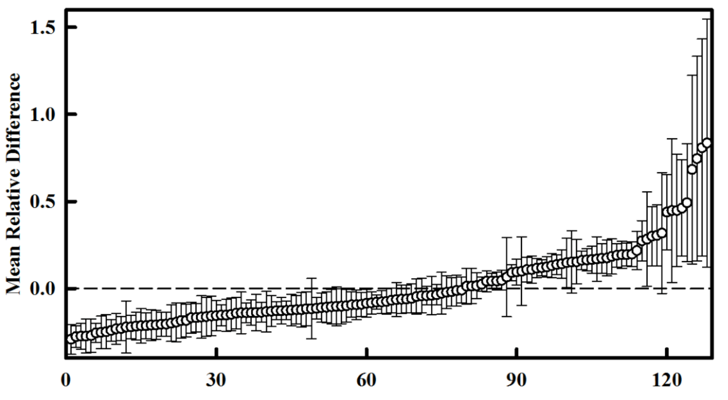

Fig. 7: Ranked relative deviation from the mean soil water storage for tillage layer.

The measurements within the fall season showed good correlation. However, the measurements between the seasons did not show good correlation indicating a season or environmental event based temporal stability of spatial patterns. The processes operating at different events determine the spatial pattern. This stability of spatial pattern was the field source temporal stability.

The stability of overall spatial pattern can lead us in identifying the temporally stable sites. Identification of this point source time stable sites is supported by various authors (Vachaud, et al., 1985; Kachanoski and de Jong, 1988; Grayson and Western, 1998; Gómez-Plaza et al., 2000; Martínez-Fernández and Ceballos, 2003), which can also be defined as benchmark site (Tallon and Si, 2004). Through temporal stability analysis, we can identify the benchmark site by plotting the mean relative difference (MRD) according to their rank. Fig. 7 showed the rank of MRD and the standard deviation (SD) associated with every point for tillage layer. The points with very high MRD with high SD were mainly associated with two depressions. The point with very low MRD and SD was considered as the benchmark point as it explained that the point showed a consistent value over time and the value was almost close to the field mean. Fig. 8 identified 22nd point on the transect as the benchmark site for tillage layer. Similarly the benchmark site for root zone and total active root zone was identified at 4th point on the transect (Fig. 8).

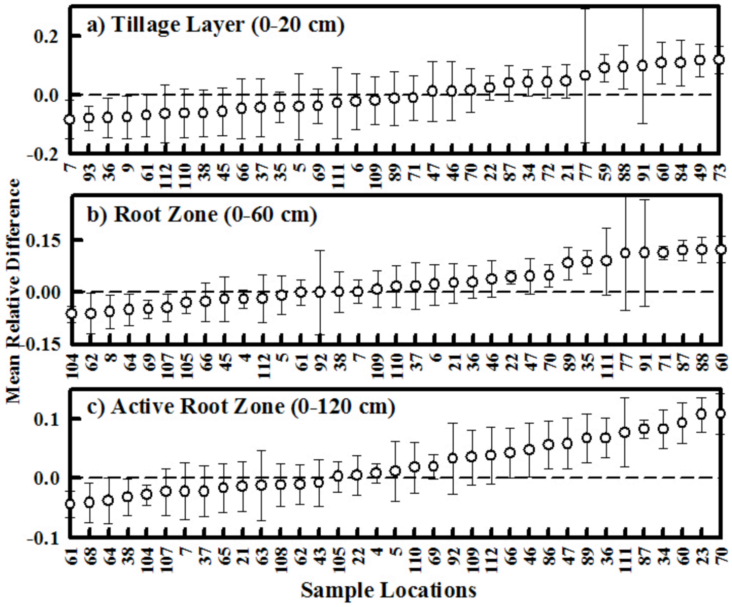

Fig. 8: Zoomed ranked relative deviation from the mean soil water storage for: a) tillage layer; b) root zone; and c) active root zone.

The different benchmark site indicated need of depth specific monitoring point. The performance of the benchmark site was also evaluated and presented in Table 2. The difference between the field average water storage and benchmark point water storage was very low. The percent difference in the moisture content at benchmark point was also calculated. The difference was less than 1% of the moisture content, which clearly indicated that the difference was within the measurement error.

The benchmark site identified from the temporal stability analysis is very attractive and promising. Monitoring a single site for average field soil water storage can save a lot of money, time and labour. The benchmark site measured average soil water stored during spring can be used for fertilizer recommendation. The irrigation schedule can be determined by monitoring the soil water storage at benchmark point. Monitoring and modelling of different hydrological processes can be done using the benchmark site. The prediction of greenhouse gas emission from a field can be done from the monitoring of soil water at benchmark site. This benchmarking is far more efficient than the conventional methods of soil water storage monitoring.

Conclusion:

Identification of benchmark site from the temporal stability analysis has potential for environmental monitoring. In field there were some locations with near average value of field which maintain the rank over time based on the soil water stored at that location with very low variability within the measurements. These hydrologically time stable locations were considered as benchmark points, which represented the field mean soil moisture storage. These points can greatly improve the sampling efficiency by reducing the number of samples or observations for field soil water storage monitoring over the conventional methods. These benchmark sites can provide a lot of useful information for environmental monitoring.

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