Agricultural Water Management 188 (2017) 36–49

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Soil water content monitoring for irrigation management: A geostatistical analysis

J. Burdette Barker[a,*], Trenton E. Franz[b], Derek M. Heeren[c], Christopher M.U. Neale[d], Joe D. Luck[e]

[a] Biological Systems Engineering Department, University of Nebraska-Lincoln, 14 L.W. Chase Hall, 3605 Fair St., Lincoln, NE 68583-0726, United States
[b] School of Natural Resources, University of Nebraska-Lincoln, Robert B. Daugherty Water for Food Global Institute Faculty Fellow, 303 Hardin Hall, 3310 Holdrege St., Lincoln, NE 68583-0973, United States
[c] Biological Systems Engineering Department, University of Nebraska-Lincoln, Robert B. Daugherty Water for Food Global Institute Faculty Fellow, 241 L.W. Chase Hall, 3605 Fair St., Lincoln, NE 68583-0726, United States
[d] Robert B. Daugherty Water for Food Global Institute at the University of Nebraska, Biological Systems Engineering Department, University of Nebraska-Lincoln, 2021 Transformation Dr., Suite 3220, Lincoln, NE 68588-6203, United States
[e] Biological Systems Engineering Department, University of Nebraska-Lincoln, 204 L.W. Chase Hall, 3605 Fair St., Lincoln, NE 68583-0726, United States

ARTICLE INFO

Article history:
Received 7 December 2016
Received in revised form 19 March 2017
Accepted 21 March 2017
Available online 14 April 2017

Keywords:
Cosmic ray neutron probe
Monitoring locations
Soil water content
Temporal stability
Variable rate irrigation

ABSTRACT

With the increasing attention to site-specific or variable rate irrigation management, it is helpful to reconsider the quantity and placement of soil water monitoring locations in this context. Volumetric soil water content (θ_v) was monitored using a neutron probe (NP) at 72 locations in a center pivot irrigated field in eastern Nebraska. Variance reduction and temporal stability analyses were performed on θ_v from shallow (~top 46 cm) and full profile (~122 cm) readings for four monitoring cycles in the 2015 growing season and 2016 preseason. Eleven additional cycles were included for a subset of the data for the temporal stability analysis. The spatial correlation scale for θ_v was found to be less than the closest spacing of monitoring locations in the study (i.e. <37 m). For this field site, approximately three neutron probe monitoring locations were required to determine mean soil water depletion (±2 cm) for the field or for a management zone. Little economy would be gained in variance reduction for areal mean θ_v from using a stratified network for management areas of reasonable size in a center pivot irrigated field. Temporally stable monitoring locations were identified. However, relatively low-cost spatial predictor variables, including elevation, deviation from mean elevation, apparent electrical conductivity, and mean relative difference of interpolated cosmic ray neutron probe surveys, were not consistent predictors of NP mean relative difference. The small range of variability of θ_v within the study field is thought to be a contributing factor. It is possible that for fields with similar variability, or for site-specific irrigation where zones have been selected to reduce within-zone variance, that sensor quantity is more important than sensor placement in quantifying the areal mean θ_v for irrigation management.

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1. Introduction

Soil water content and/or potential measurement can be helpful for irrigation scheduling (Evett, 2007). Hedley and Yule (2009) acknowledged the utility of incorporating soil water into site-specific irrigation management. Traditional soil water techniques provide only point measurements of soil water. Such point measurements may not be representative of a field or sub area of a field if poorly selected. However, the use of dense grids of soil water sensors for irrigation management is impractical from economic, logistical, and data management standpoints. This is a challenge for both conventional irrigation and site-specific irrigation management.

The question of how many soil water content sensors is sufficient to characterize the areal mean soil water content is addressed by Evett et al. (2009). However, their study focused on research plot spatial scales, which are much smaller than in many production fields. Tollner et al. (1991) developed a method for determining the number of soil water locations needed to reduce the 95% confidence interval to within 20% of a defined range. They defined this

* Corresponding author.
E-mail addresses: burdette.barker@huskers.unl.edu (J.B. Barker), tfranz2@unl.edu (T.E. Franz), derek.heeren@unl.edu (D.M. Heeren), cneale@nebraska.edu (C.M.U. Neale), jluck2@unl.edu (J.D. Luck).

http://dx.doi.org/10.1016/j.agwat.2017.03.024
0378-3774/© 2017 Published by Elsevier B.V.

range for neutron probe measurements in their analysis as being water contents corresponding to soil water potentials from 10 to 80 kPa. They used moisture release curves to compute the range. Tollner et al. (1991) recommend four to six neutron probe monitoring locations in "uniform soils" as being "adequate" (see also Evett, 2007). Tollner et al. (1991) suggest that their recommended number of locations was applicable for the range of field sizes in their conditions, which ranged from about 0.2 ha to about 35 ha in area.

1.1. Variance reduction factor

Another approach to examining the number of measurement locations necessary to quantify an areal mean can be borrowed from rainfall network design and analysis (Morrissey et al., 1995; Rodríguez-Iturbe and Mejía, 1974). In such studies, the reduction in the estimate of the variance of the areal mean relative to the point variance resulting from monitoring at multiple locations is evaluated. This reduction has been called a variance reduction factor (*VRF*) (Manfreda and Rodríguez-Iturbe, 2006; Morrissey et al., 1995; Rodríguez-Iturbe and Mejía, 1974). The *VRF* for single storm events is defined by Rodríguez-Iturbe and Mejía (1974) as: $\sigma_N{}^2 = VRF(\sigma_p{}^2)$; where $\sigma_p{}^2$ is the point variance (the point standard deviation being σ_p), calculated from all measurements for a given event and $\sigma_N{}^2$ is the variance of the arithmetic mean of the measurements (the corresponding standard deviation being σ_N), with the subscript N corresponding to the number of point samples within the area, A (see also Manfreda and Rodríguez-Iturbe, 2006). Thus, if the variance associated with making a point measurement is known, the reduction in variance resulting from taking multiple measurements in space can be determined, provided a correlation function is known (Rodríguez-Iturbe and Mejía, 1974). In their analysis, Rodríguez-Iturbe and Mejía (1974) included a simple correlation function which is given with notation following Morrissey et al. (1995) as: $\rho(d) = exp(-d/h)$; where $\rho(d)$ is the correlation for two points at a distance, d, apart, and h is the "e-folding distance" (Rodríguez-Iturbe and Mejía, 1974). The *VRF* method was developed by Rodríguez-Iturbe and Mejía (1974) as a means of calculating the trade-off between the number of monitoring locations and accuracy of the resulting measured areal mean.

This same methodology can be used to optimize the number of monitoring locations for soil water and other environmental variables at the field or management zone level, if a suitable correlation function is identified (Manfreda and Rodríguez-Iturbe, 2006). Rodríguez-Iturbe and Mejía (1974) provided graphical solutions to the *VRF* formulation for randomly placed and "stratified" monitoring network designs. Under conditions of small areas, or large h, a stratified design may necessitate fewer monitoring locations than a random design (Rodríguez-Iturbe and Mejía, 1974).

1.2. Temporal stability analysis and ancillary variables

If the number of monitoring locations necessary to quantify the areal mean soil water can be identified using *VRF* methods, then the question of where soil water should be monitored still remains. It may be possible to identify monitoring networks that improve upon stratified or random sensor placement as was examined by Rodríguez-Iturbe and Mejía (1974). Temporal stability analysis is a common method employed to identify spatially representative areas (Evett, 2007; Vachaud et al., 1985; Wang et al., 2015). Temporal stability analysis involves analyzing measurements from many spatially distributed soil water sites in relation to the spatial mean over time. Temporally stable locations may be defined as those that remain relatively consistent in rank relative to other locations in time (Vachaud et al., 1985). The temporally stable locations, particularly those that closely approximate the aerial mean, may be used as representative monitoring locations. Thus, temporal stability analysis may be used as a tool for objectively locating representative areas of a field for soil water monitoring (Guber et al., 2008; Kaleita et al., 2007; Li and Shao, 2014; Starr, 2005). Employing temporal stability analysis represents a possible improvement over what is likely a more subjective process.

Both temporal stability and *VRF* analyses require relatively spatially intensive soil water measurements. This requirement makes such analyses impractical outside of research. One possible alternative is the inclusion of ancillary datasets including elevation maps and apparent electrical conductivity surveys. Numerous studies have considered relating temporal stability analysis with other spatial variables (Vanderlinden et al., 2012). In their review of temporal stability studies, Vanderlinden et al. (2012) concluded that temporal stability is affected by multiple factors and that methods for identifying temporally stable monitoring locations need to be further developed. Cosmic-ray neutron probe (CRNP) surveys (Dong et al., 2014; Franz et al., 2015; Zreda et al., 2012) have not been examined, as far as we are aware, in the published literature as a potential dataset for this purpose.

1.3. Cosmic ray neutron probes

CRNPs function by measuring counts of fast cosmic ray neutrons near the land surface (Zreda et al., 2008). As fast neutrons are moderated by the presence of hydrogen, there is an inverse relationship between fast neutrons near the land surface and soil water content (Zreda et al., 2008). This is in contrast to the positive relationship typical of conventional neutron moisture gauges, which measure thermalized neutrons. Zreda et al. (2008) demonstrated that fast neutron concentrations near the ground surface are more sensitive to changes in soil water content than are thermal neutrons. CRNPs are estimated to have a footprint radius on the order of 130–300 m (Desilets and Zreda, 2013; Köhli et al., 2015). CPNRs are sensitive to a depth typically less than 30 cm, being dependent on soil water content and other factors (Franz et al., 2012; Köhli et al., 2015). The CRNP footprint is notably large relative to the potential size of water management zones within an agricultural field. However, approximately 63% of the CRNP measured response is typically from radius of about 50–150 m from the probe (Desilets and Zreda, 2013; Köhli et al., 2015). Furthermore, if CRNP measurements are collected at a fine enough spatial resolution, it may be possible to generate gridded soil water maps that provide insight into spatial soil water patterns. This can be accomplished using a mobile CRNP unit, or rover, such as that described by Chrisman and Zreda (2013). CRNP rovers have been shown to be effective at mapping soil water at a scale of 1 km (Franz et al., 2015). CRNP rover surveys represent a method of producing spatial soil estimates of the upper root zone that may be feasible for an agricultural service provider.

Spatial maps of volumetric water content from CRNP surveys could be produced for input into a temporal stability analysis to improve point soil water monitoring network design. Chrisman and Zreda (2013) used a form of temporal stability analysis on interpolated CRNP surveys in the Tucson Basin of Arizona. They then used the spatial pattern of variability in soil water from the CRNP surveys to model spatial soil water in time using a stationary CRNP. This study, however, did not compare the temporal stability analysis from the CRNP with point soil water content measurements. We are unaware of any studies that have attempted to employ temporal stability on CRNP surveys to approximate temporally stable point monitoring locations. CRNPs have recently been used to estimate root zone soil water content using an exponential filter (Peterson et al., 2016). CRNPs have also been used to help close the water balance with corresponding eddy covariance towers (Schreiner-McGraw et al., 2016). The study presented here will continue to

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