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Temporal stability analysis for estimating spatial mean soil water storage and deep percolation in irrigated maize crops

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ABSTRACT

The temporal stability of soil moisture in irrigated cropland may have profound implications for precision agriculture in arid regions. This study evaluated the temporal variation of components of the soil water balance in irrigated cropland in northwestern China and identified representative locations to reliably estimate the profiles (0–1 and 1–2 m) of spatial mean soil water storage (SWS) and deep percolation below a depth of 2 m. Soil water storages were determined with a neutron probe at 48 locations (31 and 17 in the northern and southern croplands, respectively) on a total of 18 occasions in 2011 and 2012. Crop evapotranspiration, SWS variations and deep percolation were analyzed during the maize growing seasons. Soil water storages in the northern and southern croplands were temporally stable. The location with the lowest standard deviation of relative differences could accurately estimate the spatial mean SWS with a high coefficient of determination ($R^2 > 0.91$, $P < 0.001$) and prediction accuracy (PE > 0.76) and near-zero mean absolute relative error (MARE = 0). The most representative locations were different for the 0–1 and 1–2 m soil layers, but the location for the 0–1 m layer could also generally represent SWS in the 1–2 m layer in the northern and southern croplands. From 21 May to late September in both years, approximately 39 and 22% of the irrigation and rainwater were lost as deep percolation in the northern and southern croplands, respectively. Deep percolation at the most representative locations of spatial mean SWS for the 0–1 m layers could generally estimate the spatial mean deep percolation below a depth of 2 m. This study provides an alternative approach for estimating spatial mean SWS and deep percolation, which is essential for the rational management of scarce resources of irrigation water in a large arid region of northwestern China.

1. Introduction

Information for the components of water balance under irrigated agriculture is crucial for planning irrigation and for exploring water-saving measures at field scales. Quantifying the portioning of irrigation water during the growing period is important for the development, soil water movement and the management of agricultural water (Ji et al., 2007). Precipitation and ice/snow melt from the Qilian Mountains along the Heihe River basin of northwestern China are the sole sources of water available for the entire basin (Wang and Cheng, 1999). As one of the main regions for the production of commodity grain in China, the middle basin consumes ~86% of the total volume of the surface runoff, and ~96% of the water consumed is used for agricultural irrigation (Chen et al., 2003). The drastic population growth and the increasing use of irrigation in the middle basin in recent decades have increased water deficits, which in turn have accelerated ecological degradation downstream (Chang et al., 2006). Irrigation using groundwater has thus become increasingly important for promoting agricultural productivity in the middle basin. A large amount of irrigation water, however, is depleted by severe evaporation and drainage below the root zone due to conventional flood irrigation (Chen et al., 2005; Ji et al., 2007). Popularizing water-conserving irrigation techniques is essential to alleviate the wastage of irrigation water in the middle basin (Wang and Cheng, 1999). One approach to reduce the wastage is to control deep percolation. Minimizing deep percolation may reduce the risk of a high groundwater table and the subsequent salinization of the root zone, and would be vital to the sustainability of irrigated agriculture (Tanji and Kielen, 2002).

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The accurate estimation of crop evapotranspiration, changes in soil water storage (SWS) and deep percolation below the root zone can determine the proper scheduling of irrigation and provide a basis for improving the use efficiency of irrigation water (Li et al., 2003; Pereira et al., 2007; Ma et al., 2013). The spatial variability of SWS, however, presents a challenge for the scheduling of irrigation due to the difficulty in obtaining field averages (Van Pelt and Wierenga, 2001). Site-specific measurements with fine resolution in both space and time are time-consuming, costly and laborious. The analysis of temporal stability may be an alternative strategy to accurately estimate spatial mean SWS with reduced effort (Hu et al., 2012b). The concept of temporal stability was first proposed by Vachaud et al. (1985) and has received considerable attention in studies of soil moisture on various spatial scales in various climatic regions in recent decades (Pachepsky et al., 2005; Guber et al., 2008; Hu et al., 2014). The possible extrapolation of soil moisture data from a certain depth at one location to the entire soil profile at point or slope scales using the concept of temporal stability, has been recently explored by Hu and Si (2014). The study of the temporal stability of soil moisture in irrigated cropland has mostly focused on small fields (Starr, 2005; de Souza et al., 2011; Cosh et al., 2012), and the temporal stability in irrigated cropland larger than tens or thousands of hectares during the growing season is poorly known. The direct measurement of deep percolation is difficult, so modeling plays an increasingly important role in guiding experimentation and decision-making. Deep percolation is usually quantified based on soil water balance under different irrigation strategies for various crops (Moreno et al., 1996; Vázquez et al., 2006; Ji et al., 2007; Kang et al., 2012; Wang et al., 2012). The applicability of Richards' equation models in predicting deep percolation has also been evaluated (Stewart et al., 2006; Jiménez-Martínez et al., 2009; Sella et al., 2011). Richards' equation models, however, require various parameters of the crop and soil hydraulics, so previous studies have mostly focused on small croplands. A simple method for evaluating deep percolation during the growing season in cropland larger than tens or thousands of hectares could thus provide information for the determination of water-saving schedules of irrigation in arid regions.

It would be appealing if spatial mean SWS and deep percolation during the growing season could be predicted from measurements at very few locations. The use of a temporally stable pattern of SWS as a basis for the management of precision agriculture, however, has received little attention. A spatially variable but temporally stable pattern of application of irrigation water could save energy, labor and costs and could benefit the management of scarce resources of irrigation water in arid regions. Therefore, the objectives of this study were: (1) to analyze components of the soil water balance in irrigated maize cropland in an arid region of northwestern China, and (2) to evaluate the temporal patterns of both SWS and deep percolation during the growing periods of maize and identify the representative locations for adequately predicting the spatial means of SWS and deep percolation.

2. Materials and methods

2.1. Study area

The study was conducted at the Linze Inland River Basin Comprehensive Research Station of the Cold and Arid Region Environment and Engineering Institute, Chinese Academy of Sciences. This region is in the middle part of the Heihe River basin in northwestern China and is characterized by desert with fixed or semi-fixed sand dunes, cropland in patchily distributed oases and wetland with severely salinized soil surfaces (Fig. 1). The region has a continental, dry, temperate climate with a mean annual air temperature of 7.6 °C. Mean annual precipitation is 120 mm, ∼60% of which falls from July to September, while only 3% falls during winter. The mean annual potential evaporation is 2360 mm, and the drying index is 15.9 (Zhao et al., 2010). Each year has ∼165 frost-free days. The growing period ranges from March to October. Agriculture relies on conventional flood irrigation sourced from groundwater (Chen et al., 2005; Ji et al., 2007). The desert vegetation in the northern and middle parts of the study area consists of *Halaxylon ammodendron* (C. A. Mey.) Bunge, *Calligonum mongolicum* Turcz., *Tamarix chinensis* Lour., *Nitraria sphaerocarpa* Maxim and *Reaumuria soongorica* (Pall.) Maxim. The predominant species in the wetland are Common Reed (*Phragmites australis* (Cav.) Trin. ex Steud.), Common Leymus (*Leymus secalinus* (Georgi) Tzvel.), *Achnatherum splendens* (Trin.) Nevski, *Kalidium foliatum* (Pall.) Moq. and *N. tangutorum* Bobr. Soils in the northern and southern parts of the study area differ both in the vertical and horizontal directions (Li and Shao, 2013). The zonal soil in the northern margin of irrigated cropland is an Aridisol derived from diluvial–alluvial materials (Su et al., 2010). Siltigi-Orthic Anthrosols have developed under long-term irrigation from sediment-rich water, fertilization and cultivation in the central and southern parts of the study area (Su et al., 2009). The wetland in the southern part of the study area has Inceptisols.

Maize (*Zea mays* L.) for seed production is the staple crop in the study area. The growing period was 155 days from sowing to harvest. Field observations were conducted from germination to harvest. The growing period was divided into four phenological stages: initial, development, mid-season and late season of 30, 50, 42 and 33 days, respectively (Zhao et al., 2010). The maize in the northern cropland was sown on 9–10 and 14–15 April in 2011 and 2012, respectively, and harvested on 11–12 and 14–15 September in 2011 and 2012, respectively. Soil water content was considerably high in the southern cropland, so the spring thaw of frozen soil was later in the southern than in the northern cropland. To facilitate the mechanical operations before sowing and to guarantee germination by avoiding seed mildew and rotting, the sowing and subsequent growing stages in the southern cropland were 15 days later than those in the northern cropland. The groundwater level was shallower in the southern than in the northern cropland. In addition, the differences in soil texture led to different capacities of soil water retention in the northern and southern croplands. The fine-textured soil in the southern cropland was able to hold more water than the coarse-textured soil in the northern cropland. The maize was thus irrigated seven times with 120 mm of water (at 15–17 day intervals) in the northern cropland and four times with 150 mm of water (once a month) in the southern cropland during the growing seasons. The croplands were plowed after harvest in September and kept bare throughout the winter and were irrigated with 150 mm of water sourced from the Heihe River in mid-November of both years to maintain soil moisture.

2.2. Sampling and measurement

Previous studies have shown that roots of maize even can reach to a depth of 2 m (Teare and Peet, 1983; Liu et al., 2009). Therefore, we focused on the temporal variation of components of soil water balance in the 0–2 m soil profile during the growing season in this study.

2.2.1. Measurement of soil moisture

A total of 48 aluminum neutron-probe access tubes were installed at a depth of 3 m in the croplands in April 2011 (Fig. 1), 31 and 17 in the northern and southern parts of the study area, respectively. Volumetric soil water contents (θ, cm^3 cm^{-3}) were determined with a neutron probe at the 48 locations, and the piecewise-constant rule (at 0.1- and 0.2-m intervals for the 0–1