Journal of Hydrology 533 (2016) 250–265

Contents lists available at ScienceDirect

Journal of Hydrology

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

Feasibility analysis of using inverse modeling for estimating natural groundwater recharge from a large-scale soil moisture monitoring network

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ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form 7 December 2015
Accepted 10 December 2015
Available online 18 December 2015
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Renato Morbidelli, Associate Editor

Keywords:
Groundwater recharge
Inverse modeling
Vadose zone model
Soil moisture
Automated Weather Data Network

SUMMARY

Despite the importance of groundwater recharge (*GR*), its accurate estimation still remains one of the most challenging tasks in the field of hydrology. In this study, with the help of inverse modeling, long-term (6 years) soil moisture data at 34 sites from the Automated Weather Data Network (AWDN) were used to estimate the spatial distribution of *GR* across Nebraska, USA, where significant spatial variability exists in soil properties and precipitation (*P*). To ensure the generality of this study and its potential broad applications, data from public domains and literature were used to parameterize the standard Hydrus-1D model. Although observed soil moisture differed significantly across the AWDN sites mainly due to the variations in *P* and soil properties, the simulations were able to capture the dynamics of observed soil moisture under different climatic and soil conditions. The inferred mean annual *GR* from the calibrated models varied over three orders of magnitude across the study area. To assess the uncertainties of the approach, estimates of *GR* and actual evapotranspiration (ET_a) from the calibrated models were compared to the *GR* and ET_a obtained from other techniques in the study area (e.g., remote sensing, tracers, and regional water balance). Comparison clearly demonstrated the feasibility of inverse modeling and large-scale ($>10^4$ km^2) soil moisture monitoring networks for estimating *GR*. In addition, the model results were used to further examine the impacts of climate and soil on *GR*. The data showed that both *P* and soil properties had significant impacts on *GR* in the study area with coarser soils generating higher *GR*; however, different relationships between *GR* and *P* emerged at the AWDN sites, defined by local climatic and soil conditions. In general, positive correlations existed between annual *GR* and *P* for the sites with coarser-textured soils or under wetter climatic conditions. With the rapidly expanding soil moisture monitoring networks around the globe, this study may have important applications in aiding water resources management in different regions.

1. Introduction

Knowledge of groundwater recharge (*GR*) is pivotal for numerous reasons, such as sustainable management of water resources and mitigation of groundwater contamination (Böhlke, 2002; Scanlon et al., 2006; Gleeson et al., 2012). However, owing to the highly nonlinear nature of the process, *GR* may vary significantly over space and time (Small, 2005; Scanlon et al., 2006). As such, accurate estimation of *GR* still remains one of the most challenging tasks in the field of hydrology (De Vries and Simmers, 2002; National Research Council, 2004). Over the past several decades, a range of techniques have been developed to quantify *GR* with various degrees of success (c.f., Allison et al., 1994; Scanlon et al., 2002). Although previous studies indicated that tracer approaches might provide the most reliable *GR* estimates (Allison et al., 1994; De Vries and Simmers, 2002), the use of process-based vadose zone models (VZMs) has recently attracted more attention, largely due to the time and cost effectiveness of this method for quantifying *GR* (Small, 2005; Jiménez-Martínez et al., 2009; Carrera-Hernández et al., 2012; Min et al., 2015; Ries et al., 2015; Turkeltaub et al., 2015).

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http://dx.doi.org/10.1016/j.jhydrol.2015.12.019
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Compared to other methods, the use of VZMs demands complicated model parameterizations, particularly the soil hydraulic parameters (SHPs) inputs that are generally unavailable. To resolve this issue, pedotransfer functions (PTFs), which convert readily available or easily measurable soil properties (e.g., soil texture, particle size distribution, and bulk density) to SHPs (Schaap et al., 2001; Wösten et al., 2001), have been routinely used along with VZMs for quantifying *GR* at regional scales (e.g., Keese et al., 2005; Nolan et al., 2007). In spite of the advantages, the reliability of such a method for computing *GR* is greatly constrained by the uncertainties associated with PTFs, particularly in semiarid regions (Faust et al., 2006; Wang et al., 2009a, 2015a). Therefore, it is necessary to seek new approaches to estimating SHPs for computing *GR*, and inverse modeling to infer SHPs from observed soil moisture and/or matric potential data is such an approach (see the reviews by Hopmans and Simunek (1999) and Vrugt et al. (2008)). Recently, studies tested the practical viability of inverse vadose zone modeling for estimating *GR* under different soil, vegetation, and hydroclimatic conditions (Jiménez-Martínez et al., 2009; Lu et al., 2011; Andreasen et al., 2013; Min et al., 2015; Ries et al., 2015; Turkeltaub et al., 2015). By calibrating a VZM to soil moisture data in an agricultural field, Jiménez-Martínez et al. (2009) concluded that the approach of inverse modeling was promising for providing reliable *GR* estimates in semiarid regions. Andreasen et al. (2013) calibrated a 1-D soil–plant–atmosphere model using soil moisture data within a small watershed, and also reached the conclusion that inverse modeling could offer reliable *GR* estimates. Min et al. (2015) showed that *GR* estimated from inverse modeling was comparable to the one obtained from the chloride mass balance method.

Despite previous efforts, earlier inverse modeling studies mostly focused on quantifying local-scale *GR* (e.g., at one location); however, *GR* may spatially vary depending on local soil, vegetation, and hydroclimatic conditions (Keese et al., 2005; Small, 2005; Wang et al., 2015a). Thus, from the perspective of water resources management, it is more valuable to provide spatial information on *GR* at much larger spatial scales. With rapid developments in sensor technology for measuring soil moisture, soil moisture data have become increasingly accessible from large-scale distributed monitoring networks (>10^4 km^2; see Crow et al. (2012) and Ochsner et al. (2013) for the lists of large-scale soil moisture monitoring networks around the globe). Although those soil moisture monitoring networks were originally deployed for other purposes (e.g., monitoring droughts and validating remotely sensed data), they may provide additional societal benefits of estimating spatial distributions of *GR* at low costs (e.g., without additional field work and installing new equipment); however, its feasibility warrants further investigation, which is the primary motivation of this work.

The primary goal of this study was threefold: (1) use a widely-spread soil moisture monitoring network and an inverse modeling technique to estimate the spatial distribution of *GR* in a semiarid region, (2) compare the inverse modeling technique with other methods for quantifying *GR*, and (3) assess soil and climatic controls on *GR*. To ensure the generality of this study, a standard procedure was proposed to parameterize a widely used VZM. This procedure utilized publicly available data and literature values. For calibrating the VZM, long-term daily soil moisture data (i.e., 6 years) were retrieved from the Automated Weather Data Network (AWDN) across Nebraska, USA. It should be stressed here that due to the uncertainties associated with each technique for estimating *GR*, it is critical to compare *GR* results from multiple methods (Scanlon et al., 2002). Thus, *GR* estimated from a number of techniques in the study area was used to cross-validate the inverse modeling results. With the aid of existing soil moisture monitoring networks, this study has important implications for aiding water resources management in different regions around the globe.

2. Materials and methods

2.1. Study area and soil moisture data

The study area covers the state of Nebraska with an area of approximately 2.0 × 10^5 km^2 (Fig. 1). The climate in the region is characterized as a continental semiarid type. From western to eastern Nebraska, mean annual precipitation increases from about 35 cm/year to over 75 cm/year (the mean annual precipitation map can be accessed at http://www.hprcc.unl.edu/index.php).

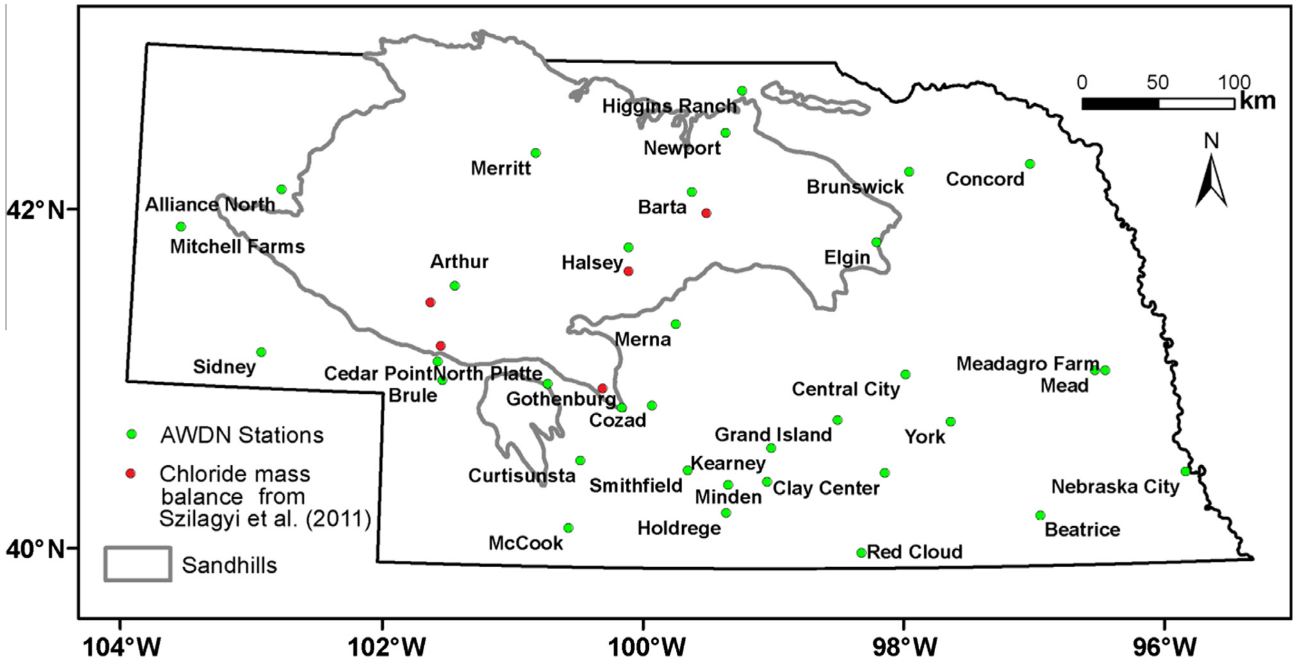

Fig. 1. Location map of soil moisture stations from the Automated Weather Data Network (AWDN) across Nebraska.