Journal of Hydrology 527 (2015) 305–315

Contents lists available at ScienceDirect

Journal of Hydrology

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

Estimating groundwater recharge using deep vadose zone data under typical irrigated cropland in the piedmont region of the North China Plain

Leilei Min [a], Yanjun Shen [a,*], Hongwei Pei [a,b]

[a] Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050021, PR China

[b] University of the Chinese Academy of Sciences, 19A, Yuquan Road, Beijing 100049, PR China

ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form 17 April 2015
Accepted 27 April 2015
Available online 6 May 2015
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Xunhong Chen, Associate Editor

Keywords:
Groundwater recharge process
Deep vadose zone
North China Plain

SUMMARY

Groundwater recharge can be accurately estimated by understanding the soil water flow process in the deep vadose zone. In this study, soil water content and soil matric potential were measured in situ in the deep vadose zone (~8 m) under typical irrigated cropland in the piedmont region of the North China Plain and were used to analyze the soil water dynamics and calibrate a transient matric flow model. Using the calibrated model, the long-period average groundwater recharge was estimated, and the influences of the lower boundary depth and time scale (length of study period) on the recharge were assessed. The study showed that the response time of the water table (with a buried depth of 42 m) to water input might be no more than 1 year because the velocity of the wetting front could be as high as 0.13 m/day below the root zone. However, the lag time could be more than 15 years because of the slower velocity of the soil water displacement. The variation in the recharge flux with depth was significant over shorter time scales. Therefore, for more representative estimated recharge with a maximum deviation less than 20% from the 38-year mean value, research should be conducted over a long period (>12 years). However, the average annual recharge showed almost no change with depth at the 38-year scale, and a depth of 2 m below ground surface could be used as an interface for estimating recharge at the 38-year scale. The simulated annual recharge at a depth of 2 m ranged from 59 mm to 635 mm with a mean value of 200 mm. The variation in water input (precipitation and irrigation) was the main reason for the variation in annual recharge at the depth of 2 m. This approach improves our understanding of the recharge process in the deep vadose zone in this region, and the results of this work could aid development of effective groundwater resources management.

1. Introduction

Groundwater recharge is of fundamental importance in evaluating groundwater resources and meeting agricultural water requirements. In an area with a deep water table, downward soil water flux from the bottom of the root zone (deep drainage) is often referred as potential recharge (Rushton, 1988; de Vries and Simmers, 2002; Radford et al., 2009; Wohling et al., 2012). Generally, if deep drainage is not hampered by low-conductivity horizons in the deep vadose zone or flow to nearby local depressions (where it runs off or evaporates), it could eventually completely recharge the groundwater with a delay (de Vries and Simmers, 2002). However, soil water flux in deep vadose zone usually varies with depth and time because of variations in water input (precipitation and irrigation) pulses, variations in evapotranspiration, and changes in deep soil water storage (Hubbell et al., 2004; West and Truss, 2006; Timms et al., 2012). Therefore, the deep vadose zone plays an important role in groundwater recharge process. The soil water dynamics and soil water flux in deep vadose zone have attracted much attention (Hubbell et al., 2004; Rimon et al., 2007; Dahan et al., 2009; Kurtzman and Scanlon, 2011; Turkeltaub et al., 2014), but further studies are necessary to better understand the process of groundwater recharge.

The piedmont area of the North China Plain is a high-yield agricultural area with widely distributed farmland (Shen et al., 2002; Sun et al., 2010). Grain production in this area is maintained by groundwater over-exploitation (Yuan and Shen, 2013). As a result, the excessive exploitation of groundwater resources has caused a continuous decline in the water table. Vertical recharge caused

* Corresponding author. Tel./fax: +86 311 85825464.
E-mail address: yjshen@sjziam.ac.cn (Y. Shen).

http://dx.doi.org/10.1016/j.jhydrol.2015.04.064
0022-1694/

by precipitation and irrigation is the dominant recharge mechanism in the piedmont area (von Rohden et al., 2010), which is also the key hydrological process that connects precipitation, irrigation and groundwater. Therefore, estimation of vertical groundwater recharge is a prerequisite for sustainable development of groundwater resources.

In recent years, unsaturated zone methods (physical methods, tracer methods and numerical modeling) for estimating groundwater recharge have been fully tested and broadly applied. In the piedmont area of the North China Plain, these methods have been used to estimate the groundwater recharge in irrigated areas (Xue and Gao, 1987; Qiu, 1992a; Kendy et al., 2003; Wang et al., 2008; Lu et al., 2011; Ma et al., 2011; Lin et al., 2013; Tan et al., 2014). Based on these studies, the potential groundwater recharge rates over short time scales (a short-term length of the study period, i.e., one to several years) at fixed low boundary depths (~2 m) are generally well understood. However, the recharge process in the deep vadose zone (variation in flux with depth, velocity of the wetting front, etc.) is less understood. Most of these studies only used datasets from shallow depths or sparse sediment samples of the deep vadose zone, and as a result, the dynamic process of groundwater recharge in the deep vadose zone could not be revealed. In addition, the mean value of multi-year recharge could not be accurately estimated from these studies since the findings in different studies might display considerable differences given that these works were conducted at different time scales (with different water inputs) and at variable low boundary depths. The modeling method is useful for estimating groundwater recharge. However, research that used both water content data and matric pressure data (rather than soil water content only) for model calibration is limited, which leads to less credible parameters and induces uncertainty into the results (Šimůnek and Hopmans, 2002). Using the dataset from the deep vadose zone combined with a numerical model, both the dynamic nature of the soil water flow (velocity of the wetting front, variation in flux with depth, etc.) and the effects of water input, time scales and depth of lower boundary on the recharge could be elucidated.

The objective of this study was to investigate the groundwater recharge process in the deep vadose zone (~8 m) under typical irrigated cropland in the piedmont region of the North China Plain. To achieve this objective, in situ monitoring data, chloride mass balance (CMB), soil water budget, and numerical simulation were used to: (i) interpret the characteristics of the soil water dynamics and evaluate the response time of the water table to water input, (ii) calibrate the transient unsaturated flow and estimate the long-period average groundwater recharge using the calibrated model, and (iii) assess the impact of the lower boundary depth and time scale on the soil water flux.

2. Materials and methods

2.1. Experimental sites and instrumentation setup

The experiments were conducted at the Luancheng Experimental Station for Agro-ecosystems at the Chinese Academy of Sciences (37°53′N, 114°41′E, altitude of 50.1 m), which is located in the middle of the piedmont area in the North China Plain (Fig. 1a), with a semi-arid to semi-humid monsoonal climate. The mean annual precipitation is 496 mm (1971–2013), most of which occurs from July to September, and the mean annual temperature at the station is 13.2 °C (1971–2013). A one-year double cropping agro-system, i.e., winter wheat and summer maize, is predominantly adopted in this region. Generally, 3–5 irrigation applications of ~80 mm each are carried out in the winter wheat growing season, and 0–2 irrigation applications of ~80 mm each

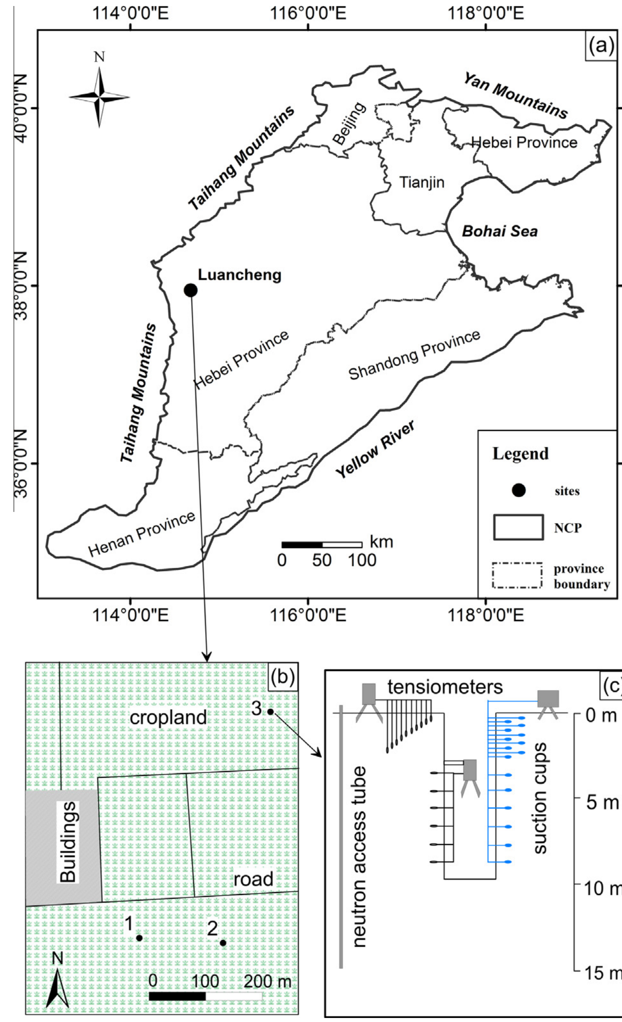

Fig. 1. Location of the experimental site in the North China Plain (a), observation positions at the site (b), and schematic of soil profile instrumentation (c). Points 1, 2 and 3 in (b) are the locations of the monitoring well, eddy covariance system, and deep vadose zone monitoring systems, respectively.

are carried out in the summer maize growing season (Zhang et al., 2003, 2011; Sun et al., 2010). The water table depth has increased dramatically from 11 m in 1975 to 42 m in 2013 at a drawdown rate of approximately 0.84 m per year.

The ET was measured (Fig. 1b) by an eddy covariance system composed of a CSAT3 sonic-anemometer (Campbell Scientific, Inc.) and a LI7500 H2O/CO2 gas analyzer (Li-Cor, Inc.) installed at a height of 3 m above the ground surface. The latent heat flux was measured every 30 min. A deep vadose zone monitoring system was established based on an old open caisson (constructed in the 1970s with an inner diameter of 150 cm and a depth of 900 cm) in which the inner sidewall was brick lined (Fig. 1c). Soil water content and matric potential in the deep vadose zone were measured, and the soil solution was sampled. A borehole constructed with a 15.2-m deep aluminum access tube was used to measure soil water content through a neutron probe (IH-II, Institute of Hydrology, Wallingford, UK) at 10-cm intervals from a depth of 0 to 100 cm and at 20-cm intervals from a depth of 100 to 1500 cm. The matric potential was measured by tensiometers at 20-cm intervals from a depth of 0 to 200 cm and at 100-cm intervals from a depth of 200 to 800 cm. The porous ceramic cup of the tensiometer was placed at a location approximately 1 m from the sidewall (Fig. 1c). Both soil water content and matric potential