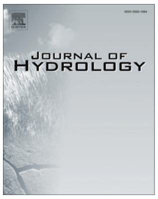
Journal of Hydrology 537 (2016) 260–270

Contents lists available at ScienceDirect

Journal of Hydrology

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



Impacts of thickening unsaturated zone on groundwater recharge in the North China Plain

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ARTICLE INFO

Article history:
Received 30 October 2015
Received in revised form 19 March 2016
Accepted 21 March 2016
Available online 29 March 2016
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Renato Morbidelli, Associate Editor

Keywords:
Groundwater recharge
Soil water balance
Unsaturated flow
North China Plain

SUMMARY

Unsustainable groundwater development shown by rapid groundwater depletion in the North China Plain (NCP) underscores the need to quantify spatiotemporal variability in groundwater recharge for improved management of the resource. The objective of this study was to assess spatiotemporal variability in recharge in response to thickening of the unsaturated zone in the NCP. Recharge was estimated by linking a soil water balance (SWB) model, on the basis of monthly meteorological data, irrigation applications, and soil moisture monitoring data (1993–2008), to the water table using a deep unsaturated zone flow model. The dynamic bottom boundary (water table) position was provided by the saturated zone flow component, which simulates regional pumping. The model results clearly indicate the effects of unsaturated zone thickening on both temporal distribution and magnitude of recharge: smoothing temporal variability in recharge, and increasing unsaturated storage and lag time between percolation and recharge. The thickening unsaturated zone can result in average recharge reduction of up to ~70% in loam soils with water table declines ⩾30 m. Declining groundwater levels with irrigation sourced by groundwater converts percolation to unsaturated zone storage, averaging 14 mm equivalent water depth per year in mostly loam soil over the study period, accounting for ~30% of the saturated groundwater storage depletion. This study demonstrates that, in thickening unsaturated zones, modeling approaches that directly equate deep drainage with recharge will overestimate the amount and underestimate the time lag between percolation and recharge, emphasizing the importance of more realistic simulation of the continuity of unsaturated and saturated storage to provide more reliable estimates of spatiotemporal variability in recharge.

1. Introduction

In many semiarid regions where irrigated agriculture relies heavily on groundwater, understanding the distribution of regional groundwater recharge is extremely important for more sustainable management of aquifers subjected to water table declines (Scanlon et al., 2006). Temporal variability in recharge is a response to climate variability and land use change; and may be affected by the flow and storage in the unsaturated zone (McMahon et al., 2006; Hunt et al., 2008; Scanlon et al., 2010a, 2010b; Crosbie et al., 2013; Le Coz et al., 2013). Recharge estimation techniques often focus on drainage below the root zone assuming that the unsaturated zone flux at the base of the root zone represents actual recharge (Gurdak and Roe, 2010). Fluctuation in the underlying groundwater table was either not considered, or assumed to be sufficiently deep to not influence the base of the modeled soil column. This modeled lower boundary condition cannot reliably represent the spatiotemporal variability in the groundwater table depth and the continuity between unsaturated and saturated storage (Carrera-Hernández et al., 2012). Moreover, the travel time of soil moisture through the unsaturated zone and the time lags of actual recharge (timing of arrival of pressure front at the water table resulting from pressure changes at the land surface)

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http://dx.doi.org/10.1016/j.jhydrol.2016.03.049
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(e.g., Grismer, 2013; Rossman et al., 2014), are key factors affecting temporal variations in recharge. However, most previous studies equate drainage or percolation below the root zone and recharge at the water table and commonly ignore time lags between the two (e.g., Kendy et al., 2003; Lu et al., 2011). Although unsaturated storage change is generally affected by the root zone soil water content variations, a significant amount of stored water may change its status from saturated to unsaturated when the water table declines; and the deep unsaturated storage will play a more important role as the total storage capacity of the unsaturated zone increases (Bastiaanssen, 2003; Seibert et al., 2003; Acharya et al., 2012). Commonly used groundwater recharge estimation methods, such as soil water balance and unsaturated zone studies (e.g., natural and artificial applied tracer techniques) would overestimate recharge and underestimate the timing of recharge. Thus, coupling the unsaturated zone flow process and the groundwater flow to assess the effects of the thickening unsaturated zone is necessary to improve the understanding of recharge variations in areas where significant groundwater depletion has occurred.

The North China Plain (NCP) is a classic example of a depleting groundwater resource, where irrigation has severely depleted groundwater at a rate of ~4 km^3/yr since the 1960s and a water table decline of ~0.3 m/yr over the entire plain (up to ~1 m/yr for some local regions). This makes the NCP a global hotspot of groundwater depletion caused by irrigation (Zheng et al., 2010; Wada et al., 2012; Cao et al., 2013; Werner et al., 2013). The unsaturated zone thickness in agricultural areas has increased from 2 to 15 m in the 1970s to 30–60 m in the piedmont region in the west in the 2000s (Zhang et al., 2004). Numerous previous studies have estimated groundwater recharge in the NCP using multiple methods (e.g., Kendy et al., 2003; Wang et al., 2008; Lu et al., 2011; Tan et al., 2014); however, the impact of the thickening unsaturated zone on groundwater recharge at regional scales has not been addressed. Motivation of this study, therefore, originated with the need to assess the influence of increasing unsaturated zone thickness on recharge and to incorporate the process into hydrological modeling.

The primary objective of this study was to simulate the process of deep percolation through the thickening unsaturated zone and hence evaluate the impacts of a thickening unsaturated zone (water table declines) on groundwater recharge. Unique aspects of this study include integration of a relatively straightforward soil water balance (SWB) model using monitored soil moisture as input with a coupled unsaturated and saturated zone flow model to estimate groundwater recharge and application of this model over 16 years to assess recharge response to variations in precipitation and applied irrigation. To our knowledge, such regional groundwater recharge estimation across the NCP that considers the influence of a continuous water table decline has not been attempted before and should have important implications for groundwater-fed irrigated areas in other semiarid regions.

2. Background to the study site

The NCP has an area of ~140,000 km^2 (see supplementary Fig. S1) and contributes ~22% of winter wheat and ~15% of summer maize (also called corn) production in China in 2012 (National Bureau of Statistics of China, 2013). Currently, an estimated 70% of groundwater exploitation in the plain is used for winter wheat irrigation, which is grown in the dry season (Li et al., 2005). Mean annual precipitation in the NCP is ~560 mm (1951–2008), ranging from 420 mm/yr in dry years to 780 mm/yr in wet years (Fig. S2). Mean annual precipitation decreases from ~580 mm in the northwest to ~520 mm in the southeast (Fig. S3a). Although previous studies suggested a declining trend in precipitation of ~1.1 mm/yr from 1958–1998, the trend is not statistically significant (Fu et al., 2009). The annual irrigation requirement to sustain current crop production averages ~160 mm for winter wheat and 40 mm for summer maize (Yang et al., 2010). The sediment sources and depositional processes play a large role in controlling present-day soil textures in the NCP (Wu, 1999); primary soil textures including loam, loamy sand, and clay (accounting for ~90% of the plain area), which generally grade from coarser textures in the piedmont region and in paleochannels to finer textures in the plains (Wu, 1999) (see Fig. S3b).

The area of the NCP that is equipped with irrigation is 6.5 million ha (mha, 65,000 km^2), representing ~50% of the NCP. Most (~70% to 80%) irrigation in the NCP is sourced by groundwater. The remaining 20–30% is supplied by surface water delivered from the Yellow River to the south, extending ~3 to 8 km away from the river. Groundwater has not been depleted in these regions and water tables are shallow (1–3 m deep, Fig. S4). Lateral subsurface flow from the Taihang Mountains is another important source of recharge to the aquifer system in the NCP (Kendy et al., 2004), and is estimated to range from 1.5 to 4.0 km^3/yr (Wang et al., 2008; China Geological Survey, 2009; Cao et al., 2013).

The NCP is divided into three main hydrogeological zones from the Taihang Mountains on the west to the Bohai Sea on the east: piedmont region, central plain, and coastal plain (Wu et al., 1996). The piedmont region (~17% of the NCP area) is a diluvial plain created by flooding and consisting of numerous connected diluvial fans, with altitudes of 60–110 m above mean seal level (amsl) and slopes of 2–5‰. The central plain consists of alluvial fans and alluvial plains, occupying 70% of the NCP, were formed from depositional processes related to the Yellow, Hai, and Luan Rivers and their tributaries (Wu et al., 1996; Xu et al., 1996).

The water table decline caused by extensive groundwater pumping (Fig. S5) has resulted in 11 cones of depression in the shallow unconfined aquifer, totaling 11,000 km^2 (8% of the NCP area) in 2009 (Fei et al., 2009; Yang et al., 2013). The water table declines in the centers of these cones of depression range from 20 to 65 m from predevelopment (~1950s) to 2009 (Yang et al., 2013). The impact of irrigation on the groundwater table decline is greatest in the piedmont region, and results in six cones of depression totaling 4400 km^2. Water table declines $\geqslant$10 m extend over 20% of the NCP area, and declines $\geqslant$20 m extend over ~5% of the NCP area (Fig. S6). The total area of water table dropping <2 m (no water table decline) account for 14% of the NCP and concentrates in the coastal plain and the irrigated area along the Yellow River (Figs. S4 and S6).

3. Methods

Recharge was simulated by integrating a SWB model (coded by the authors) and a coupled unsaturated zone flow and groundwater flow model (UZF-MODFLOW) (Niswonger et al., 2006). A simulation period of 16 years (1993–2008) was selected considering the significant water table decline and data availability. The SWB model was used to calculate the potential groundwater recharge (percolation) below the root zone. Percolation water calculated was transmitted to the water table by the unsaturated zone flow (UZF) Package (Niswonger et al., 2006) available for the widely used groundwater flow model MODFLOW (Harbaugh, 2005). The modeled spatiotemporally variable water tables by MODFLOW, therefore, provide the variable bottom boundary in the unsaturated zone flow model.

The water balance for the soil root zone, in the absence of significant runoff, is represented by:

$$R_p = P + I_r - ET_a - \Delta\theta \tag{1}$$