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

Guoliang Cao [a,b,*], Bridget R. Scanlon [c], Dongmei Han [d,*], Chunmiao Zheng [e,f]

[a] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
[b] National Centre for Groundwater Research and Training, Adelaide, SA, Australia
[c] Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, TX 78758, USA
[d] Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[e] School of Environmental Science and Engineering, South University of Science and Technology of China, Shenzhen 518055, China
[f] Department of Geological Science, University of Alabama, Tuscaloosa, AL, USA

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)

* Corresponding authors at: State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China (G. Cao).
E-mail addresses: gliang.cao@gmail.com (G. Cao), handm@igsnrr.ac.cn (D. Han).

http://dx.doi.org/10.1016/j.jhydrol.2016.03.049
0022-1694/

(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 ⩾10 m extend over 20% of the NCP area, and declines ⩾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:

$$R_p = P + I_r - ET_a - \Delta\theta \quad (1)$$

where R_p is potential recharge; P is precipitation; I_r is irrigation; ET_a is actual ET (AET); and $\Delta\theta$ is change in soil water storage. All units are in millimeters per month. The actual ET was calculated by the Complementary Relation Areal Evapotranspiration (CRAE) model (Morton, 1983; Morton et al., 1985) using meteorological data (see Table S1) from 23 stations available for the NCP. The soil water storage was determined from soil water measurements at 104 monitoring stations across the NCP (Fig. S1). Applied irrigation was estimated from documented irrigation quota data and statistical data on irrigated area (see Fig. S7). Details on the data processing of P, I and soil water content, and the formulation of CRAE model can be found in the supplementary material. The R_p rates derived by the SWB based on Eq. (1) are considered as the net potential recharge rates, and negative values may be obtained. These areas are generally considered to be groundwater discharge zones and concentrate in the coastal plain (see Fig. 1). Positive values of R_p from the SWB are input to the UZF model as infiltration rates, and negative values of R_p (upward flux at the bottom of the root zone) is represented as a discharge term in the flow equation solved by the UZF model.

The UZF package simplifies the 1D Richards' equation by removing the diffusive term, assuming that the vertical flux is only driven by gravitational forces. The kinematic wave approximation of the Richards' equation through a homogeneous unsaturated zone, as used in the UZF package, provides an alternative that is well suited to large-scale models (Niswonger et al., 2006; Niswonger and Prudic, 2009). The continuity between the unsaturated zone and the underlying unconfined aquifers is achieved by approximating specific retention with residual water content (θ_r), which is calculated internally by the UZF package as the difference between saturated water content (θ_s) and specific yield (S_y) (Niswonger et al., 2006). Pedotransfer functions (PTFs) developed by Schaap et al. (2001) by using the computer code called ROSETTA were applied to estimate soil hydraulic parameters used in the UZF (Table S1). The saturated water content (θ_s) and saturated hydraulic conductivity (K_s) (Fig. S8) were directly estimated by the PTFs. Details of application procedure of the PTFs and the estimation method of the Brooks-Corey epsilon in the UZF were provided in Section S3.2 in the supplementary material. The hydraulic properties of the aquifers, pumping and lateral flow are derived from the previously constructed regional groundwater flow model (Cao et al., 2013).

Initial water content in the unsaturated zone is generally obtained by running the unsaturated zone model in a steady state

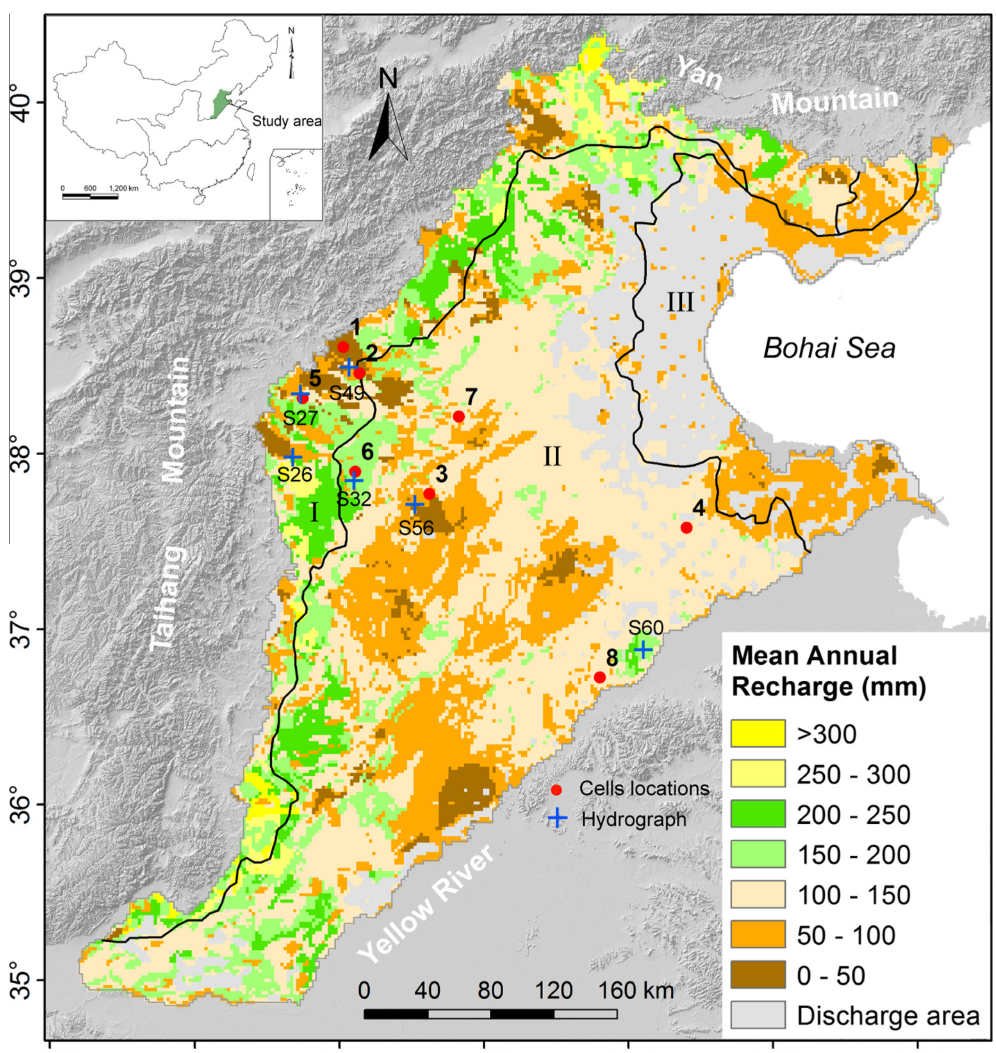

Fig. 1. Calculated mean annual groundwater recharge for 1993–2008 for the NCP. Mean annual recharge over the entire NCP is 110 mm, highest in the piedmont area of ~160 mm, decreasing to ~120 mm in the central plain and ~40 mm in the coastal plain. Locations of unsaturated zone profiles and well hydrographs are shown. Solid black lines are the boundaries of the piedmont region (I), the central plain (II) and the coastal plain (III) (from Wu et al., 1996; Liu et al., 2009).

or reinitializing the simulation multiple times (e.g., Keese et al., 2005; Wang et al., 2009). However, groundwater in the NCP is obviously over-exploited currently, and it is impossible to run the integrated model in a steady state mode to match the initial measured groundwater level distribution. In this study, an initialization period, or spin-up simulation was run to provide reliable initial conditions. The integrated model was firstly run from 1960 to 1992 using estimated groundwater recharge from a previously constructed flow model (Cao et al., 2013) with an initial water content of 0.2. Because the unsaturated zone was generally 1–2 m thick in the 1960 s, errors caused by initial water contents would be corrected rapidly by percolation. The simulated water content and groundwater levels served as the initial conditions for the integrated model in this study.

4. Results and discussion

4.1. Spatiotemporal variability in groundwater recharge

Simulated groundwater recharge is highly variable spatially (Fig. 1). Simulated mean annual recharge (MAR) over the entire NCP is 110 mm, representing 17% of the mean annual precipitation plus irrigation (MAPI). The estimated MAR is highest in the piedmont area (∼160 mm, 24% of MAPI), decreasing to ∼120 mm/yr (18% of MAPI) in the central plain and ∼40 mm/yr (6% of MAPI) in the coastal plain. The contrasts in recharge and precipitation indicate that applied irrigation, ET, and soil texture may be critical factors controlling recharge (Kendy et al., 2003; Wang et al., 2008; Lu et al., 2011; Tan et al., 2014). Annual ET is generally higher than precipitation across the NCP and increases from northwest to southeast (Wu et al., 2012; Yuan and Shen, 2013); therefore, much of the area with the highest groundwater recharge is in irrigated areas with higher irrigation rates, because irrigation results in higher soil water contents enhancing percolation and recharge (Chiew and McMahon, 1991; Qin et al., 2011). In the piedmont region, lower ET relative to precipitation during the summer when there is little or no irrigation (Table S2) suggests that partial recharge is caused by precipitation. In the central and coastal plain, recharge rates rely primarily on applied irrigation.

For the 16-year simulation, groundwater recharge is generally higher in wet years of 1993–1996. The sequence of dry years (1997–2002, ∼100 mm lower than long-term average precipitation) results in reduced groundwater recharge rates because the soil water deficit has to be replenished before deep percolation and recharge can occur (Fig. S9). Temporal variations in recharge are lower in the piedmont region [coefficient of variation (CV) of 0.56] than those in the central plain (CV of 0.70) and coastal plain (CV of 1.01) (Fig. S8) because of its relatively deep water table depth. Temporal viabilities of recharge rates are controlled by variations in precipitation, even though precipitation may not be the primary contributor to the amount.

Errors in precipitation measurements, estimation errors in AET and precision in the applied irrigation increase uncertainty in calculated percolation and ultimately recharge. Estimation error of the averaged annual precipitation in the NCP is approximately 8% of the true mean value (Sun, 2012). The error of ET estimates is 4–19% based on comparison with multiyear ET estimates using energy balance models (Wu et al., 2008, 2012). Errors in precipitation and ET may lead to 20% error in estimates of P minus ET_a in Eq. (1) assuming errors are independent and a 12% error in ET. Annual ET generally exceeds precipitation and irrigation, however, there is great uncertainty in the irrigation data (Yang et al., 2010). Therefore, the 20% error in the percolation estimates provides a lower bound. With respect to unsaturated zone hydrological parameter estimation, Wang et al. (2009) showed that uncertainty in recharge estimation can result from uncertainty in soil hydraulic characteristics estimated using PTFs. Those unsaturated zone flow model parameters estimated using PTFs are based on data sets from the United States of America; therefore, their applicability in the NCP should be evaluated using local soil data sets. Although assuming a vertically homogeneous unsaturated zone makes regional scale modeling feasible, the accuracy in the estimation of recharge should be further evaluated considering heterogeneity.

The area weighted recharge estimates are generally comparable in magnitude with point scale estimates based on environmental tracer data and unsaturated flow modeling, and the previous regional scale estimates using the empirical method (Table S3). Although various recharge estimation techniques had been applied, precise estimation of recharge is difficult because of different levels of unavoidable inherent uncertainty associated with each method (Scanlon et al., 2002); however, those uncertainty estimates provide valuable information for groundwater management (Gurdak and Roe, 2010). None of the previous studies reported uncertainties with recharge estimates; making it difficult to directly compare those previous estimates and the simulated recharge in this study. Although we proposed that unsaturated zone thickening may affect recharge (discussed in later sections), it is not surprising that the recharge estimates are within the wide range of recharge estimated in previous studies using different methods, because areas of intense water table declines (>30 m) are concentrated in cones of depression representing ∼5% of the NCP area. Effects of these localized cones of depression may not be significant if considering the area weighted recharge values.

4.2. Reduction of fraction of recharge with declining water table

The percolation at the base of the soil water zone can be divided into recharge to groundwater and addition to the unsaturated storage; and the available space for unsaturated storage depends on the position of the water table. Therefore, the timing and magnitude of groundwater recharge can be affected by water table declines. The water balance for the unsaturated and saturated zone neglecting the store of water held by capillary forces may be expressed as

$$R_p + S_y \Delta h - \Delta U = V_d \quad (2)$$

and the water balance for the saturated zone can be expressed as

$$R + S_y \Delta h = V_d \quad (3)$$

where R is the recharge; ΔU is increase in unsaturated zone water storage in the time interval; Δh is water table decline; and V_d is amount of vertical drainage. Therefore, all variables are positive numbers when the water table declines. From Eqs. (2) and (3), it is apparent that the actual recharge variations are also related to unsaturated zone flow processes and any increase in deep unsaturated zone water storage would reduce the fraction of recharge (R/R_p) within a time interval. It is noteworthy that all increased unsaturated zone storage would finally become recharge if assuming an infinite time for deep percolation flowing out.

Decreases in recharge related to water table decline may be explained by the coupling method between the unsaturated zone and the unconfined aquifer. The UZF package uses the specific yield to calculate the storage change in an unconfined aquifer and couples the unsaturated zone and the unconfined aquifer by approximating the specific yield as the difference between saturated water content and residual water content (Niswonger et al., 2006). In reality, the release of water is not instantaneous; and the specific yield decreases as the depth to the water table decreases and may vary with the length of the time step during which the water table declines or increases (Healy, 2010). For deep water tables,

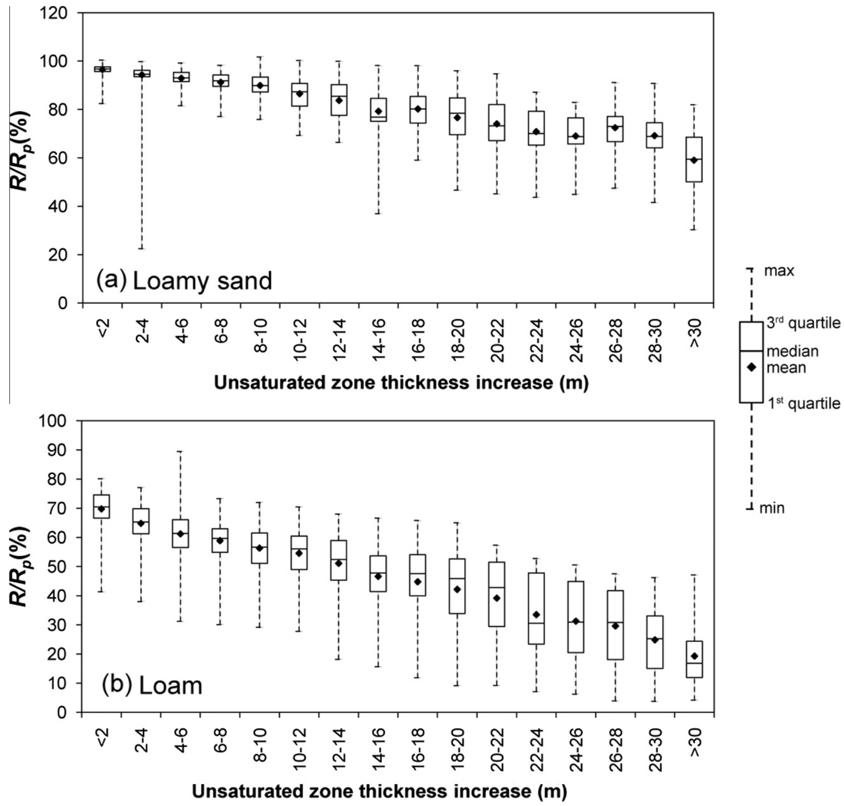

Fig. 2. Variations of the ratio of simulated recharge and potential recharge with changes in unsaturated zone thickness for (a) loamy sand and (b) loam.

Table 1
Characteristics of the profiles and simulated recharge (R), the ratio of recharge and potential recharge (R_p). The lag time is estimated using the transfer function for two simulation periods before/after the primary drought period (1997–2002) (mean lag time for 1994–1996/mean lag time for 2004–2008). Mean lag time is presented for the cases with the coefficient of determination of ⩾0.8. Note that the value of R/R_p may be less than 100% for shallow water table cases due to groundwater evaporation.

Profile	Soil texture	Water table depth (m)	P	I	ET_a	R	R/R_p (%)	Lag time (months)
			(mm/yr)					
1	Loam	30–60	492	41	472	23	16	–
2	Loam	15–40	490	162	479	26	11	–
3	Loam	8–20	471	145	540	91	57	30.6/–
4	Loam	3-4	529	145	598	116	73	25.8/14.0
5	Loamy sand	20–60	502	164	459	175	70	3.6/15.0
6	Loamy sand	20–40	487	190	501	178	78	4.6/9.2
7	Loamy sand	10–20	468	130	548	143	87	5.3/5.3
8	Loamy sand	3–6	534	119	604	136	98	0.5/0.6

when no recharge occurs, the soil water decrease to its residual value during water drainage and the specific yield will be equal to its ultimate value (θ_s–θ_r) (Crosbie et al., 2005; Orellana et al., 2012). Percolation must refill the depleted soil water storage, reducing recharge. For shallow water table depths or cases where recharge occurs, this method may overestimate the specific yield.

The reduction in the ratio of actual to potential recharge (R/R_p) (Fig. 2) indicates that more percolation water is held in the unsaturated zone when the unsaturated zone is thickening. A lower rate of reduction of R/R_p for sandy loam (Fig. 2a) then loam (Fig. 2b) indicates that the reduction in recharge is inversely related to soil hydraulic conductivity. The values of R/R_p can be reduced from 70% to 20% for loam soils when water level declines ⩾30 m (Fig. 2b), meaning the recharge can be reduced by up to ~70%. This can also be understood because higher water flux could occur through the coarser soil column within the same time interval. Because of large spatiotemporal variability in recharge, eight model grid cells were selected in different geographic zones with different soil textures and model input fluxes to represent variations in groundwater recharge (Table 1).

4.3. Recharge variations for profiles with different rates of water table decline

Simulated recharge variations in locations with a thick unsaturated zone and high rates of water table declines (1.8–2.5 m/yr) in the piedmont plain (loam profiles 1 and loamy sand profile 5) clearly indicate that the unsaturated zone affects both the temporal distribution and magnitude of recharge (Fig. 3). The loam profile has a small net atmospheric flux (P-AET) and a small applied irrigation (Fig. 3a). Relatively lower hydraulic conductivity but higher storage capacity in the loam soil converts percolating water to unsaturated water storage (Fig. 3b) precluding recharge. Therefore, the rate of the groundwater table decline exceeds the percolation rate and no percolation reaches the water table (recharge become zero) (Fig. 3c). Groundwater recharge is also reduced to zero for

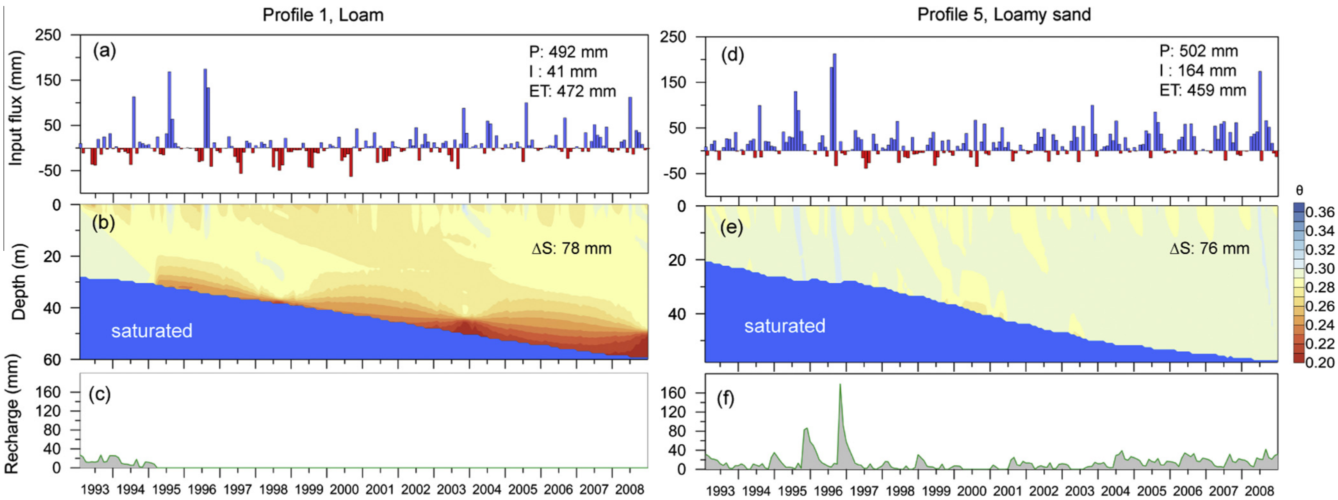

Fig. 3. Percolation, soil water content and recharge in cases of deep groundwater table (20–60 m) in the piedmont region: (a) monthly percolation flux with average annual precipitation, applied irrigation and ET presented, (b) soil moisture dynamics and (c) groundwater recharge variation at profile 1 with loam soil; and (d–f) at profile 5 with loamy sand soil.

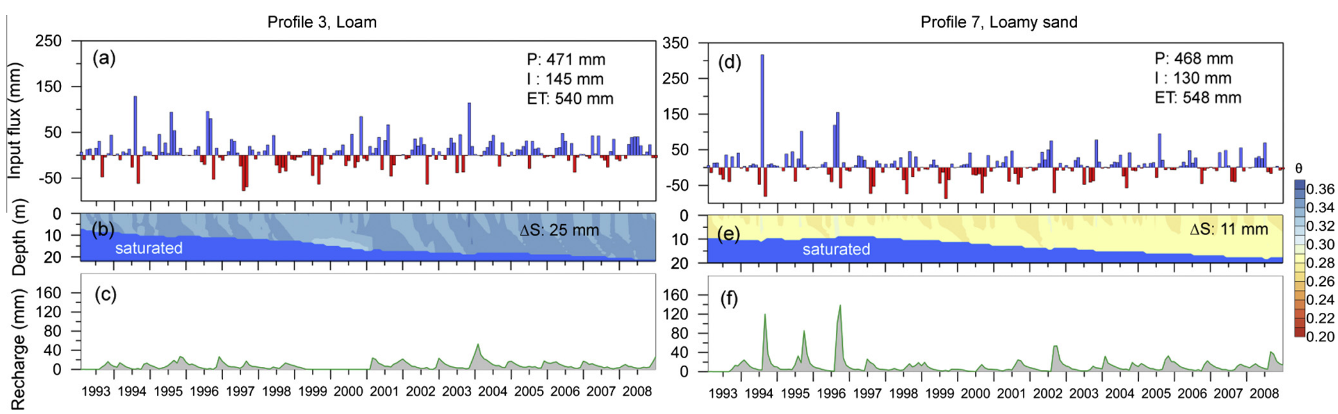

Fig. 4. Percolation, soil water content and recharge at profiles with groundwater table depth of 10–20 m in the central plain: (a) monthly percolation flux with average annual precipitation, applied irrigation and ET presented, (b) soil moisture dynamics and (c) groundwater recharge variation at profile 3 with loam soil; and (d–f) at profile 7 with loamy sand soil.

another loam soil profile with higher applied irrigation (profile 2, Fig. S10), suggesting more important effects of soil texture on percolation in the unsaturated zone. However, this situation can change within the profile of loamy sand with relatively higher applied irrigation (Fig. 3d) which causes more rapid percolation in the unsaturated zone and less water being held as unsaturated storage (Fig. 3e); as a result, recharge still occurs even in areas with rapid water level declines (Fig. 3f).

Recharge for profiles with an unsaturated zone thickness increasing by 10–15 m (0.6–0.8 m/yr) in the central plain shows the impact of specific high infiltration events (profiles 3 and 7, Fig. 4), although the fraction of recharge is reduced. The two profiles have similar amounts of net atmospheric flux and applied irrigation (Fig. 4a and d). The soil moisture depends on the soil texture, and the midrange loam soil texture profile has a larger capacity to hold water in the unsaturated zone (Fig. 4b) than that in the coarse loamy sand profile (Fig. 4e). Calculated recharge in the loam soil profile (Fig. 4c) shows lower temporal variability relative to that in the loamy sand profile (Fig. 4f). Moisture dynamics and groundwater recharge variations are highly correlated with temporal variations in precipitation and applied irrigation for shallow water table depths (profiles 4 and 8, Fig. S11), as all the percolation water can contribute to recharge instantaneously.

The thick unsaturated zone generally delays the arrival time of recharge but also smooths out temporal variations in recharge (Smerdon et al., 2008). In the 16-year simulation, recharge was greatest in September through November that followed the wet summers of 1994 through 1996. The relatively high hydraulic conductivity of the loamy sand results in the rapid recharge increases (Figs. 3f and 4f). In the 1997–2002 period with more frequent drought (Standard Precipitation Index, 12 month SPI $\leqslant -1$) and the following simulation period, increases in recharge from percolation were damped and the impact of specific infiltration events was not observed in simulated recharge (Figs. 3f and 4f). Conversion of percolation to additional soil moisture storage causes recharge to be reduced within a time step; and thicker unsaturated zones (comparison of Figs. 3e and 4e) and finer soil texture (comparison Fig. 4b and e) hold more percolation water resulting in lower recharge.

4.4. Increased time lag associated with unsaturated zone thickening

The unsaturated storage change is also correlated with the time lag between percolation and recharge: longer time lag means a larger fraction of percolation being held as unsaturated storage in a time interval. Although the kinematic velocity (the derivative of the Darcian flux with respect to the water content) represents the rate of pressure wave propagation through the unsaturated zone (Rasmussen et al., 2000) and is relevant to the lag time of recharge, the assumption of unit hydraulic gradient in its calculation requires small variations in percolation during the time step to approach a steady state (Rossman et al., 2014). However, both soil water content and percolation flux varied with time in the simulations in this study. Time series analysis is used to examine the lag times associated with recharge. The recharge time series can be determined using a transfer function to transport drainage water below the root zone to the water table (Besbes and De Marsily, 1984):

$$R(t) = \int_0^t R_p(t-\tau)\Phi(\tau)d\tau \tag{4}$$

where τ is the variable of the integration that represents the time lag of the transfer function; $R(t)$ is the cumulative recharge between times 0 and t; R_p is percolation or potential recharge; and $\Phi(\tau)$ is a linear transfer function. A series of linear reservoirs in which the outflow rate resulting from instantaneous inflow is described by an exponential decay can be used to represent the transfer function; and the transfer function mathematically has the same shape as the gamma probability density function (PDF) (O'Reilly, 2004). The gamma PDF includes three parameters: a shape parameter n, a scale parameter k, and an initial time lag τ_i. The mean value of the PDF function, $nk + \tau_i$, represents the average lag time. Large values of n and k would cause significant attenuation of deep percolation, resulting in smoother time series of recharge (O'Reilly, 2004).

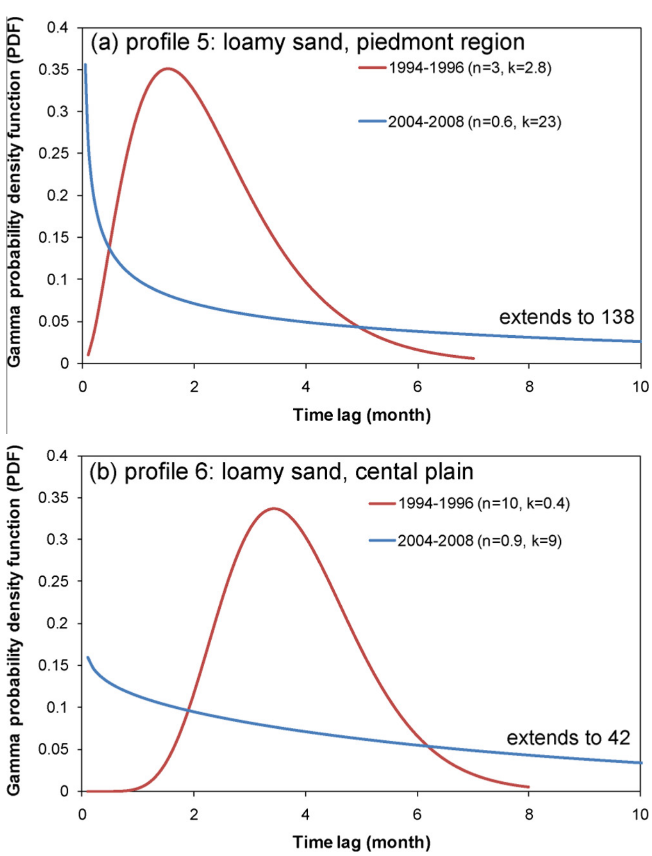

Fig. 5. Transfer functions for the loamy sand soil profiles 5 in the piedmont region and 6 in the central plain (locations shown in Fig. 1). The optimized values for two time series for the shape parameter n, the scale parameter k and the initial time lag τ_i of the transfer function of (O'Reilly, 2004) are labeled.

Transfer functions were compared for the period before and after the dry period of 1997–2003 to assess the effects of increased unsaturated zone thickness on the lag time. Optimized values of the three parameters were determined using the parameter estimation program, PEST (Doherty, 2005) to minimize the difference between the simulated recharge and that obtained through the transfer functions. For the wet periods of 1994–1996, the shape of the transfer function is unimodal (peak at τ value of about 2 and 4 months for profiles 5 and 6, respectively) (Fig. 5). For the period 2004–2008, the transfer shape to exponential decay (n values less than 1). The fraction values of functions have a similar n have no physical analogy, but may suggest that one linear reservoir may effectively represent the relationship between percolation and the smoothed recharge time series. The parameter k in a linear reservoir has the dimension of time and can be interpreted as representative time or turnover time of water in the reservoir. Larger k values for profile 5 for the period 2004–2008 (23 months) than 1994–1996 (~3 months) (Fig. 5a) indicate that increased unsaturated zoon thickness significantly extends the residence time of percolation water in the unsaturated zone, resulting in longer lag times to recharge. Smaller k values for profile 6 (Fig. 5b) than profile 5 for both periods also show that the lag time is longer when the unsaturated zone is thicker. The average lag time imposed on recharge by the unsaturated zone has increased from ~4 months to ~15 months for profile 5, and from ~5 months to ~10 months for profile 6 (Table 1). The simulated groundwater recharge and therefore the lag times can be generally validated by measured water level variations. Considering the difficulty to match the simulated and observed groundwater level variations at specific local scales because of more complicated unsaturated zone flow processes and real aquifer system structures, quite coarse available pumping data, model calibration with respect to various parameters in regional scale was not the scope of this study. Nevertheless, comparison of simulated and monitored water levels in 105 observation wells (totaling 13,900 monitored values) shows an absolute error (MAE) of 6.5 m (see Fig. S12), which is very close to the result that obtained in the previously calibrated regional groundwater flow model (Cao et al., 2013). This suggests that temporal variations in groundwater recharge at the regional scale and changes in recharge time lags can be effectively estimated. These simulated recharge variations and lag times demonstrate 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 recharge process to provide more reliable estimates of spatiotemporal variability in recharge.

4.5. Representative well hydrographs

Representative well hydrographs (Fig. 6) show water level fluctuations related to the recharge mechanisms discussed above. In the piedmont region, representative hydrographs (S26, S27 and S49) show rapid declines (~1.0 m/yr) during the study, except in 1996 and 1997. Groundwater level rises in 1996 and 1997 in the piedmont plain may be explained by lateral mountain block recharge related with higher precipitation in 1995 and 1996. The combined effects of low precipitation in 1997–2007 and increased pumping caused water levels to decline continuously in most parts of the piedmont region. Seasonal variations in the water table show the lowest water levels in June or July due to spring irrigation pumpage, and recovery from autumn to spring in the following year attributed to reduction in irrigation pumpage and possible lateral groundwater recharge. The deep groundwater level (hydrograph S26) shows a decreasing trend without identifiable

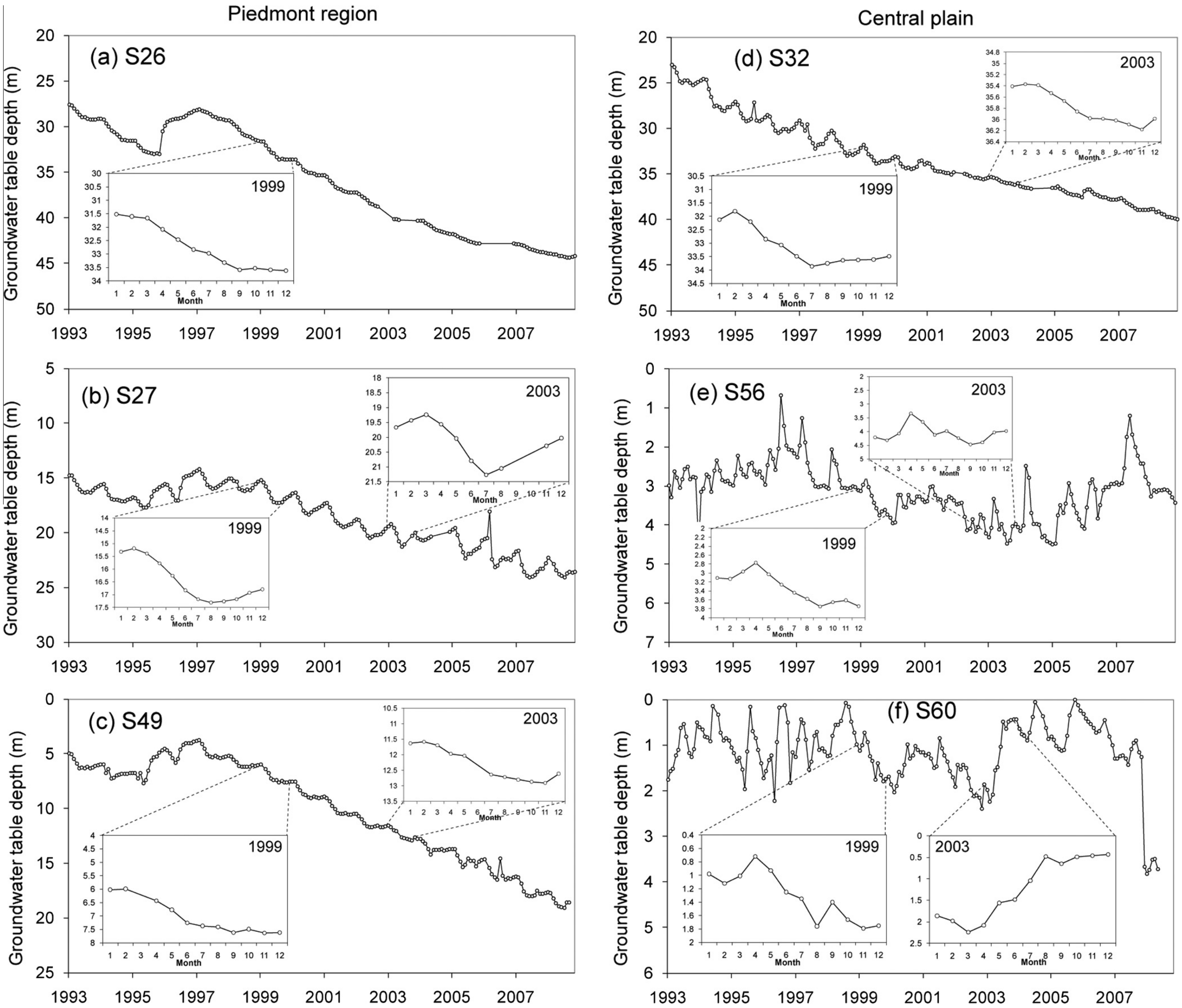

Fig. 6. Groundwater hydrographs from available monitoring wells located near selected profiles locations (shown in Fig. 1): hydrographs S26, S27 and S49 in the piedmont region, hydrographs S32, S56 and S60 in the central plain.

seasonal variations, possibly due to the buffering effect of the thick unsaturated zone or temporally invariant water pumping.

In the central plain (hydrograph S32), obvious seasonal water level variations also occur before 2000: lowest water levels in June or July caused by spring irrigation followed by recovery after irrigation due to pumpage reduction and increases in recharge. After about 2001, the seasonal variations in groundwater level are no longer evident, possibly due to increased lag time in recharge associated with thickening of the unsaturated zone. In regions in the central plain where shallow groundwater is brackish, representative well hydrographs (S56) show water table variations related to irrigation pumped from deep groundwater and ET. Groundwater levels are highest in spring and early summer due to irrigation and decrease during dry seasons with less precipitation but strong ET. The relatively steady annual water table in this region may be attributed to higher ET, and possible enhanced aquifer leakage due to the increasing downward hydraulic gradient. In the southeast part of the NCP where most irrigation is fed by water diversion from the Yellow River (hydrograph S60), groundwater levels are higher during the crop growing season and in wet years when water stage is high in the Yellow River.

4.6. Impact of soil texture on recharge

Differences in soil hydraulic parameters also affect spatial variability in recharge. Unsaturated sediments in the piedmont region of the NCP are generally coarser, consisting of loamy sand, but are finer in central and coastal plains including higher clay contents (Fig. 7). Due to the uneven distribution of percolation/applied irrigation, soil type and water table depth, there is an overlap in simulated groundwater recharge rates between loamy sand and loam: annual recharge for loamy sand averages ~195 mm (standard deviation, SD of 55 mm); averages for loam of ~108 mm (SD of 32 mm). The soil texture effects are analyzed assuming an exponential function modified from Acharya et al. (2012):

$$R = R_p \exp(-\alpha d) \quad (5)$$

where R is recharge rate, R_p is percolation calculated by the SWB model, d is water table depth, and α is a parameter that varies with soil texture. Eq. (5) neglects the flow process in the unsaturated zone, so all quantities are treated as time-averaged values. The relationship between the recharge fraction of percolation in logarithmic scale and water table depth (Fig. 7) shows the expected

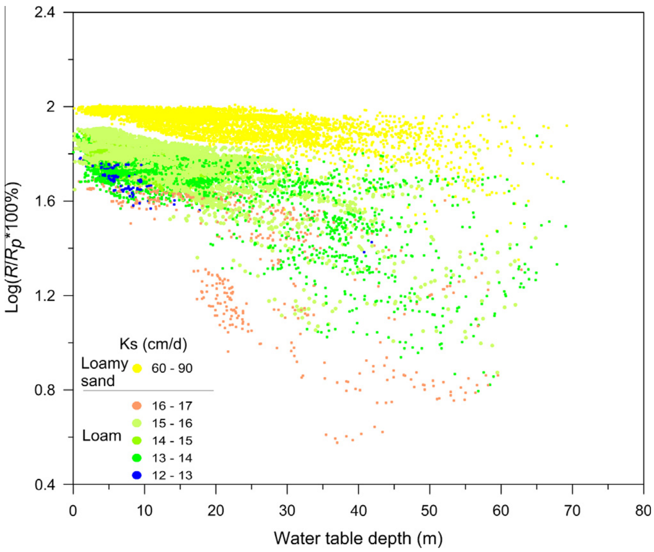

Fig. 7. Relationship between ratio of calculated recharge rate and percolation in logarithmic scale and water table depth for different soil textures.

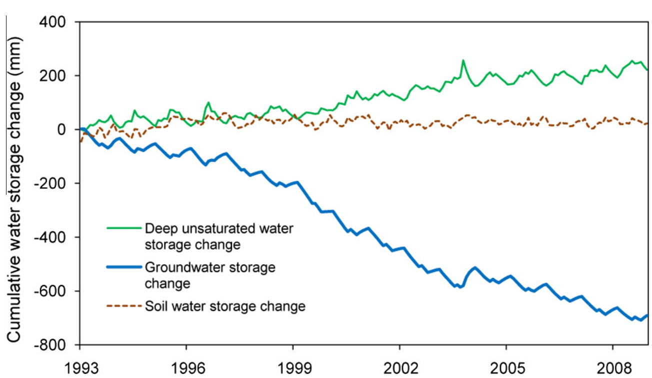

Fig. 8. Cumulative simulated annual water storage change in the top soil (0.5 m depth), unsaturated zone and saturated zone of the NCP for the period of 1993–2008.

relationships between recharge and soil texture: coarser soil resulting in higher percentage of percolation recharging the underlying aquifer. Finer grained soils in the central and coastal plains result in lower hydraulic conductivities. The presence of such sediments could significantly affect downward percolation of water and transport of dissolved agricultural contaminants.

4.7. Unsaturated water storage change

Simulated water storage change in the unsaturated zone increases from 1993 through 2008 (Fig. 8). This increase in storage may be caused by increasing soil water content due to infiltration of high precipitation and irrigation, and/or may result from the increase in unsaturated zone thickness providing more space to intercept percolation. If groundwater recharge is primarily driven by precipitation and the groundwater table is below the root zone as in the present study, groundwater storage is expected to be positively correlated with unsaturated zone storage, as groundwater recharge occurs when soil water content is high. The negative correlation between unsaturated and saturated storage clarifies the effects of groundwater-fed irrigation on the water balance: irrigation from groundwater converts groundwater storage to unsaturated storage. Excessive irrigation from groundwater cannot return to groundwater when the percolation rate is less than the rate of groundwater table decline. Groundwater-fed irrigation also results in more unsaturated zone space to be filled, particularly in a wet year following a drought period. The unsaturated zone water storage increase caused by high precipitation in 2003 after the drought period of 1997–2002 accounted for ~18% of the total unsaturated water storage increase in the 16 yr simulation period. The slow increase in unsaturated zone storage from 2003 to 2006 can be explained by a reduction in groundwater pumpage and water table decline.

Simulated mean annual storage increase in the unsaturated zone is ~14 mm equivalent water depth (corresponding to 0.2 m/yr of water table decline with an area weighted S_y of 0.07) (1993–2008) across the NCP, accounting for ~30% of the saturated groundwater depletion (Fig. 8), and is highest in the piedmont region (up to 120 mm/yr). It is noted that this unsaturated storage change estimate does not include the component of saturated storage converted to unsaturated storage (residual water storage) when the water table declines. The simulated unsaturated storage change in this study suggests that the increase in unsaturated storage is a notable water balance component and the cumulative deep unsaturated storage may be much greater than the root zone soil water storage in irrigated regions sourced primarily by groundwater. Conventional methods using specific yield in groundwater budget analysis do not consider unsaturated storage change; therefore, both deep unsaturated water storage and deep aquifer storage should be constrained when evaluating groundwater storage depletion caused by irrigation pumping. In addition, any possible strategy that could return the accumulated deep drainage to the production cycle before accessing the water table would benefit groundwater management.

5. Conclusions

The estimated spatiotemporally averaged mean groundwater recharge in the NCP is 110 mm/yr (1993–2008), which represents 17% of the MAPI. This recharge rate broadly agrees with previous recharge estimates based on field studies using different methods (e.g., environmental tracers). Although pumping groundwater for irrigation has a net negative effect on the water balance because of enhanced ET, the significant connection between higher groundwater recharge and irrigated cropland indicates that irrigation is a primary source of groundwater recharge. Spatially averaged recharge in the piedmont region (~160 mm/yr) is higher than that in the central plain (~120 mm/yr) and much higher than that in the coastal plain (~40 mm/yr). Temporal variations in recharge indicate the importance of irrigation in replenishing the antecedent unsaturated storage loss and therefore increasing groundwater recharge.

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. For thick unsaturated zone, groundwater recharge can be reduced significantly associated with unsaturated storage increases in a specified time step. In the piedmont region and western part of the central plain, the overall effect of groundwater pumping for irrigation is decreasing saturated groundwater storage but increasing unsaturated storage through thickening the unsaturated zone. Much finer soil texture is more likely to preclude drainage from irrigation that would result in recharge. The dominant loam soil causes unsaturated storage increasing over the NCP by ~14 mm equivalent water depth per year (corresponding to 0.2 m/yr of water table decline) in the study period. The simulated recharge results from this study should prove that importance of taking the thickening unsaturated zone into account when quantifying spatiotemporal variability in recharge in the NCP and similar regions suffering great groundwater depletion.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant Nos. 41401012 and 41371057). Special thanks are given to the editor, Dr. Brian D. Smerdon and anonymous reviewers for their constructive comments leading to a significant improvement of the paper.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2016.03.049.

References

Acharya, S., Jawitz, J.W., Mylavarapu, R.S., 2012. Analytical expressions for drainable and fillable porosity of phreatic aquifers under vertical fluxes from evapotranspiration and recharge. Water Resour. Res. 48 (11), W11526.

Bastiaanssen, W., 2003. Retrieving soil moisture storage in the unsaturated zone using satellite imagery and bi-annual phreatic surface fluctuations. Irrig. Drain. Syst. 17 (3), 141–161.

Besbes, M., De Marsily, G., 1984. From infiltration to recharge: use of a parametric transfer function. J. Hydrol. 74 (3–4), 271–293.

Cao, G., Zheng, C., Scanlon, B.R., Liu, J., Li, W., 2013. Use of flow modeling to assess sustainability of groundwater resources in the North China Plain. Water Resour. Res. 49 (1), 159–175.

Carrera-Hernández, J.J., Smerdon, B.D., Mendoza, C.A., 2012. Estimating groundwater recharge through unsaturated flow modelling: sensitivity to boundary conditions and vertical discretization. J. Hydrol. 452–453, 90–101.

Chiew, F., McMahon, T.A., 1991. Groundwater recharge from rainfall and irrigation in the Campaspe River Basin. Soil Res. 29 (5), 651–670.

China Geological Survey, 2009. Investigation and Assessment of Sustainable Utilization of Groundwater Resources in the North China Plain. Geological Publishing House, Beijing (in Chinese).

Crosbie, R.S., Binning, P., Kalma, J.D., 2005. A time series approach to inferring groundwater recharge using the water table fluctuation method. Water Resour. Res. 41 (1), W01008.

Crosbie, R.S., Scanlon, B.R., Mpelasoka, F.S., Reedy, R.C., Gates, J.B., Zhang, L., 2013. Potential climate change effects on groundwater recharge in the high plains aquifer, USA. Water Resour. Res. 49. http://dx.doi.org/10.1002/wrcr.20292.

Doherty, J., 2005. Model Independent Parameter Estimation, fifth edition of user manual. Watermark Numerical Computing, Brisbane, Australia.

Fei, Y., Miao, J., Zhang, Z., Chen, Z., Song, H., Yang, M., 2009. Analysis on evolution of groundwater depression cones and its leading factors in North China Plain. Resour. Sci. 31 (3), 394–399 (in Chinese with English abstract).

Fu, G.B., Charles, S.P., Yu, J.J., Liu, C.M., 2009. Decadal climatic variability, trends, and future scenarios for the North China Plain. J. Climate 22 (8), 2111–2123.

Grismer, M.E., 2013. Estimating agricultural deep drainage lag times to groundwater: application to Antelope Valley, California, USA. Hydrol. Process. 27 (3), 378–393.

Gurdak, J.J., Roe, C.D., 2010. Review: recharge rates and chemistry beneath playas of the high plains aquifer, USA. Hydrogeol. J. 18 (8), 1747–1772.

Harbaugh, A.W., 2005. In: MODFLOW-2005, the U.S. Geological Survey Modular Groundwater Model—The Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16. USGS, Reston, Virginia.

Healy, R.W., 2010. Estimating Groundwater Recharge. Cambridge Univ. Press, U.K.

Hunt, R.J., Prudic, D.E., Walker, J.F., Anderson, M.P., 2008. Importance of unsaturated zone flow for simulating recharge in a humid climate. Ground Water 46 (4), 551–560.

Keese, K.E., Scanlon, B.R., Reedy, R.C., 2005. Assessing controls on diffuse groundwater recharge using unsaturated flow modeling. Water Resour. Res. 41 (6), W06010.

Kendy, E., Gérard-Marchant, P., Walter, M.T., Zhang, Y., Liu, C., Steenhuis, T.S., 2003. A soil-water-balance approach to quantify groundwater recharge from irrigated cropland in the North China Plain. Hydrol. Process. 17 (10), 2011–2031.

Kendy, E., Zhang, Y., Liu, C., Wang, J., Steenhuis, T., 2004. Groundwater recharge from irrigated cropland in the North China Plain: case study of Luancheng County, Hebei Province, 1949–2000. Hydrol. Process. 18 (12), 2289–2302.

Le Coz, M., Favreau, G., Ousmane, S.D., 2013. Modeling increased groundwater recharge due to change from rainfed to irrigated cropping in a semiarid region. Vadose Zone J. 12 (2), 1–12.

Li, H.M., Inanaga, S., Li, Z.H., Eneji, A.E., 2005. Optimizing irrigation scheduling for winter wheat in the North China Plain. Agric. Water Manage. 76 (1), 8–23.

Liu, F., Cui, J., Chen, L., Zhao, Y., Qin, Y., Wu, C., 2009. A view on geomorphologic zonalization of North China Plain. Geogr. Geol. Inf. Sci. 25 (4), 100–103 (in Chinese with English abstract).

Lu, X., Jin, M., van Genuchten, M.T., Wang, B., 2011. Groundwater recharge at five representative sites in the Hebei plain, China. Ground Water 49 (2), 286–294.

McMahon, P.B., Dennehy, K.F., Bruce, B.W., Böhlke, J.K., Michel, R.L., Gurdak, J.J., Hurlbut, D.B., 2006. Storage and transit time of chemicals in thick unsaturated zones under rangeland and irrigated cropland, high plains, United States. Water Resour. Res. 42 (3), W03413.

Morton, F.I., 1983. Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. J. Hydrol. 66 (1–4), 1–76.

Morton, F.I., Ricard, F., Fogarasi, S., 1985. Operational Estimates of Areal Evapotranspiration and Lake Evaporation: Program WREVAP. Inland Waters Directorate, National Hydrology Research Institute, Environment Canada, Ottawa, Ont.

National Bureau of Statistics of China, 2013. China Statistical Yearbook 2012. China Statistics Press, Beijing.

Niswonger, R.G., Prudic, D.E., Regan, R.S., 2006. Documentation of the Unsaturated-Zone Flow (UZF1) Package for Modeling Unsaturated Flow between the Land Surface and the Water Table with MODFLOW-2005. U.S. Geological Survey Techniques and Methods 6-A19. U.S. Geological Survey, Reston, Virginia.

Niswonger, R.G., Prudic, D.E., 2009. Comment on" evaluating interactions between groundwater and vadose zone using the HYDRUS-based flow package for MODFLOW" by Navin Kumar C. Twarakavi, Jirka Simunek, and Sophia Seo. Vadose Zone J. 8 (3), 818–819.

O'Reilly, A.M., 2004. A method for simulating transient ground-water recharge in deep water-table settings in central Florida by using a simple water-balance/transfer-function model, U.S. Geological Survey Scientific Investigations Report 2004-5195.

Orellana, F., Verma, P., Loheide, S.P., Daly, E., 2012. Monitoring and modeling water-vegetation interactions in groundwater-dependent ecosystems. Rev. Geophys. 50 (3), 2011RG000383.

Qin, D., Qian, Y., Han, L., Wang, Z., Li, C., Zhao, Z., 2011. Assessing impact of irrigation water on groundwater recharge and quality in arid environment using CFCs, tritium and stable isotopes, in the Zhangye Basin, Northwest China. J. Hydrol. 405, 194–208.

Rasmussen, T.C., Baldwin, R.H., Dowd, J.F., Williams, A.G., 2000. Tracer vs. pressure wave velocities through unsaturated saprolite. Soil Sci. Soc. Am. J. 64 (1), 75–85.

Rossman, N.R., Zlotnik, V.A., Rowe, C.M., Szilagyi, J., 2014. Vadose zone lag time and potential 21st century climate change effects on spatially distributed groundwater recharge in the semi-arid Nebraska Sand Hills. J. Hydrol. 519 (Part A(0)), 656–669.

Scanlon, B.R., Healy, R.W., Cook, P.G., 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J. 10 (1), 18–39.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M., Simmers, I., 2006. Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol. Process. 20 (15), 3335–3370.

Scanlon, B.R., Reedy, R.C., Gates, J.B., 2010a. Effects of irrigated agroecosystems: 1. Quantity of soil water and groundwater in the southern high plains, Texas. Water Resour. Res. 46 (W09537).

Scanlon, B.R., Reedy, R.C., Gates, J.B., Gowda, P.H., 2010b. Impact of agroecosystems on groundwater resources in the Central High Plains, USA. Agric., Ecosyst. Environ. 139 (4), 700–713.

Schaap, M.G., Leij, F.J., van Genuchten, M.T., 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251 (3–4), 163–176.

Seibert, J., Rodhe, A., Bishop, K., 2003. Simulating interactions between saturated and unsaturated storage in a conceptual runoff model. Hydrol. Process. 17 (2), 379–390.

Smerdon, B.D., Mendoza, C.A., Devito, K.J., 2008. Influence of subhumid climate and water table depth on groundwater recharge in shallow outwash aquifers. Water Resour. Res. 44 (8), W08427.

Sun, X., 2012. In: Effects of observation error on precipitation measurement and trend estimates over North and Northeast China, Thesis. Nanjing University of Information Science and Technology, Nanjing, p. 76, in Chinese with English abstract.

Tan, X., Wu, J., Cai, S., Yang, J., 2014. Characteristics of groundwater recharge on the North China Plain. Groundwater 52 (5), 798–807.

Wada, Y., van Beek, L.P.H., Bierkens, M.F.P., 2012. Nonsustainable groundwater sustaining irrigation: a global assessment. Water Resour. Res. 48, W00L06.

Wang, B.G., Jin, M.G., Nimmo, J.R., Yang, L., Wang, W.F., 2008. Estimating groundwater recharge in Hebei Plain, China under varying land use practices using tritium and bromide tracers. J. Hydrol. 356 (1–2), 209–222.

Wang, T., Zlotnik, V.A., Imunek, J., Schaap, M.G., 2009. Using pedotransfer functions in vadose zone models for estimating groundwater recharge in semiarid regions. Water Resour. Res. 45 (4), W04412.

Werner, A., Zhang, Q., Xue, L., Smerdon, B., Li, X., Zhu, X., Yu, L., Li, L., 2013. An initial inventory and indexation of groundwater mega-depletion cases. Water Resour. Manage. 27 (2), 507–533.

Wu, C., Xu, Q.H., Zhang, X.Q., Ma, Y.H., 1996. Palaeochannels on the North China Plain: types and distributions. Geomorphology 18 (1), 5–14.

Wu, B., Xiong, J., Yan, N., Yang, L., Du, X., 2008. ETWatch for monitoring regional evapotranspiration with remote sensing. Adv. Rater Sci. 19 (5), 671–678 (in Chinese with English abstract).

Wu, B.F., Yan, N.N., Xiong, J., Bastiaanssen, W., Zhu, W.W., Stein, A., 2012. Validation of ETWatch using field measurements at diverse landscapes: a case study in Hai Basin of China. J. Hydrol. 436, 67–80.
Wu, C., 1999. The impact of river changes on soil and soil salinization in the North China Plain. Geogr. Territ. Res. 15 (4), 70–75.
Xu, Q.H., Wu, C., Zhu, X.Q., Yang, X.L., 1996. Palaeochannels on the North China Plain: stage division and palaeoenvironments. Geomorphology 18 (1), 15–25.
Yang, L., Qu, W., Liu, C., 2013. Research on the groundwater resource – function decline and sustainable exploitation. J. Arid Land Resour. Environ. 27 (7), 8–16 (in Chinese with English abstract).
Yang, Y., Yang, Y., Moiwo, J.P., Hu, Y., 2010. Estimation of irrigation requirement for sustainable water resources reallocation in North China. Agric. Water Manage. 97 (11), 1711–1721.
Yuan, Z., Shen, Y., 2013. Estimation of agricultural water consumption from meteorological and yield data: a case study of Hebei, North China. PLoS ONE 8 (3), e58685.
Zhang, G., Fei, Y., Liu, K., 2004. Evolution of and Countermeasure for the Groundwater in the Haihe Plain. Science Press, Beijing (in Chinese).
Zheng, C., Liu, J., Cao, G., Kendy, E., Wang, H., Jia, Y., 2010. Can China cope with its water crisis? – perspectives from the North China Plain. Ground Water 48 (3), 350–354.