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

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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 spatial or temporal 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)
(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 km³/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 km² (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 ~780 mm in the northwest and ~400 mm in the southeast (Fig. S2). Mean annual precipitation decreases from ~780 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 km²), representing ~50% of the NCP. Most (~70%) of 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 km³/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 km² (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 km². 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:

$$R_p = P + I_r - ET_a - \Delta \theta$$

(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 \( P \), \( I_r \) and soil water content, and the formulation of CRAE model can be found in the supplementary material. The \( R_p \) values 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 (\( \theta_r \)), which is calculated internally by the UZF package as the difference between saturated water content (\( \theta_s \)) 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 (\( \theta_s \)) 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.
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 1960s, 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. 59). 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. 58) because of its relatively deep water table depth. Temporal variations 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 percolation (Wu et al., 2012) 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 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

\[ R_p + S_p \Delta h - \Delta U = V_d \]  

(2)

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

\[ R + S_s \Delta h = V_d \]  

(3)

where \( R \) is the recharge; \( \Delta U \) is increase in unsaturated zone water storage in the time interval; \( \Delta h \) 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,
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 \((h_s - h_r)\) (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) than 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 \(\geq 30\) m (Fig. 2b), meaning the recharge can be reduced by up to \(\sim 70\%\). 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).

### Table 1

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

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.

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 becomes zero) (Fig. 3c). Groundwater recharge is also reduced to zero for
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 < -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):

\[
R(t) = \int_0^t R_{0}(t - \tau) \phi(\tau) \, d\tau
\]  

(4)

where \( \tau \) 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 \( t \); \( R_{0} \) 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 \( \tau_i \). 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).

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 \( \tau \) 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 zone 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.

![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 \( \tau_i \) of the transfer function of (O’Reilly, 2004) are labeled.](image_url)
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 \(195 \text{ mm} \) (standard deviation, SD of 55 mm); averages for loam of \(108 \text{ mm} \) (SD of 32 mm). The soil texture effects are analyzed assuming an exponential function modified from Acharya et al. (2012):

\[
R = R_p \exp \left(-x d\right)
\]

where \(R\) is recharge rate, \(R_p\) is percolation calculated by the SWB model, \(d\) is water table depth, and \(x\) 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
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 $S_p$ 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 show 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.

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Appendix A. Supplementary material

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