Estimating the contribution of groundwater to rootzone soil moisture

Yonghua Zhu, Liliang Ren, Robert Horton, Haishen Lü, Xi Chen, Yangwen Jia, Zhenlong Wang and E. A. Sudicky

ABSTRACT

In the Huaibei Plain basin, China, soybean is a main crop. During the soybean growth period, rainfall can vary largely and depth to watertable can also vary largely. The amount of water supplied to the soybean rootzone by groundwater affects soybean growth and yield. Accurate simulation of groundwater contributions to soybean rootzone soil moisture (groundwater contribution) can be important for determining irrigation to and drainage from soybean fields. Based on field observations and local weather data of 2005, HYDRUS-1D was validated by comparing simulated and measured rootzone soil water contents. The validated model was used to estimate the daily groundwater contributions for three different soybean hydrological growing seasons, i.e., an average year (1997), a wet year (2005), and a dry year (2004) with soybean growth at its optimal state. The main results were: (1) seasonal groundwater contribution was 157 mm in the experimental field, and the estimated groundwater contributions were 158, 222, and 387 mm in the wet, average, and dry seasons, respectively; (2) the groundwater contribution was about 63% of the total seasonal transpiration in the experimental field, and those were about 142, 80, and 66% of the total seasonal transpiration in dry, average, and wet seasons, respectively.

Key words | groundwater contribution, Huaibei Plain, soybean

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INTRODUCTION

The Huaibei Plain basin of Anhui Province, China, in the transitional zone of northern subtropical and warm temperate climates, has a mean annual rainfall average of 890 mm at the Wudaogou experimental station (Figure 1). Soybean is a main oil and forage crop of the region (Liu *et al.* 2008). During the soybean growth period, rainfall and water table depths (WTD) are variable. There are times when the water table will supply groundwater to the soybean rootzone affecting soybean growth and yield. Accurate simulation of the daily groundwater contributions to soybean rootzone soil moisture (inflow upwards across the bottom of the soil profile) will be important for determining irrigation to and drainage from soybean fields. Based on frequency analysis of annual precipitation at the Wudaogou experimental station (WRRIAH 2008), precipitation greater than 920 mm can be considered as a wet year, precipitation between 760 and 920 mm an average year, and precipitation less than 760 mm a dry year with certain coefficient variation (Cv) and coefficient of skewness (Cs) ($Cv = 0.26$; $Cs/Cv = 2$). Based on precipitation data from 1990 to 2009 (Figure 2), the years 1997, 2004, and 2005 can be selected as representative years of average, dry, and wet conditions, respectively. In this paper, the HYDRUS-1D numerical model will be tested by comparing simulated soybean rootzone soil water contents with soybean rootzone water contents measured at the Wudaogou experimental station

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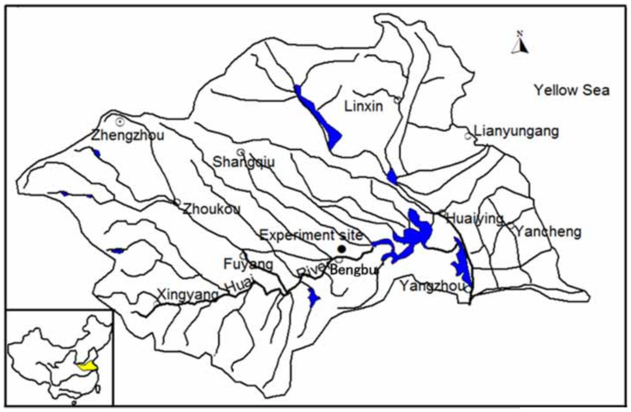

Figure 1 | Location of the experimental site.

in 2005. Once validated, HYDRUS-1D will be used to estimate the daily groundwater contributions to soybean rootzone water contents and transpiration for three different hydrological growing seasons, i.e., wet, average, and dry.

With the range of precipitation occurring during the selected soybean growing seasons representing different hydrological conditions, the importance of groundwater supplying rootzone water in the Huaihe River Basin can be assessed. Understanding and quantifying this type of water flux in soybean fields is crucial for improving soybean growth and yield.

There are four methods to estimate groundwater contributions to plant root soil moisture, i.e., direct measurement by lysimeters (Kowalik 2006), empirical formulas (Doorenbos & Pruitt 1977; Li & Dong 1998), physical mechanism models (Ragab & Amer 1986; Brandyk *et al.* 1992; Prathapar *et al.* 1992; Jorenush & Sepaskhah 2003; Raes & Deproost 2003; Jasper *et al.* 2006; Geerts *et al.* 2008), and part-empirical and part-mechanistic equations (e.g., Liu *et al.* 2006). Physical mechanistic models are often used to estimate groundwater contributions because of the relatively low costs compared to the other methods. Therefore, in this paper, a physical mechanistic model, HYDRUS-1D, was used to estimate the daily contribution of groundwater to soybean rootzone soil moisture during the field experiment of 2005 and during selected simulated years representing wet, average, and dry hydrologic conditions.

Previous research on the contribution of groundwater to crop rootzone soil moisture has been performed for a variety of cropping systems (Ayars & Schoneman 1986; Soppe & Ayars 2003; Kahlown *et al.* 2005; Babajimopoulos *et al.* 2007), but no such studies have been performed with soybean. Research focusing specifically on soybean in China mainly dealt with soybean growth and yield affected by groundwater elevation (Qi *et al.* 1994; Li *et al.* 1999; Zhu *et al.* 2003), and less dealt with the contribution of groundwater to soybean rootzone soil moisture (e.g., Mao *et al.* 2003). The existing studies on the contribution of groundwater to soybean rootzone soil moisture in China mainly focused on direct analysis of experiments and did not examine in detail the physical mechanisms involved in the uptake of groundwater.

In this work, the contribution of groundwater to soybean rootzone soil moisture and root uptake was estimated by using the HYDRUS-1D numerical model (Šimůnek *et al.* 2005). HYDRUS-1D is a well-known mechanistic model capable of simulating variably saturated water flow and root water uptake in soils. First, HYDRUS-1D simulations of rootzone soil moisture were compared with field measurements made in a soybean field in 2005

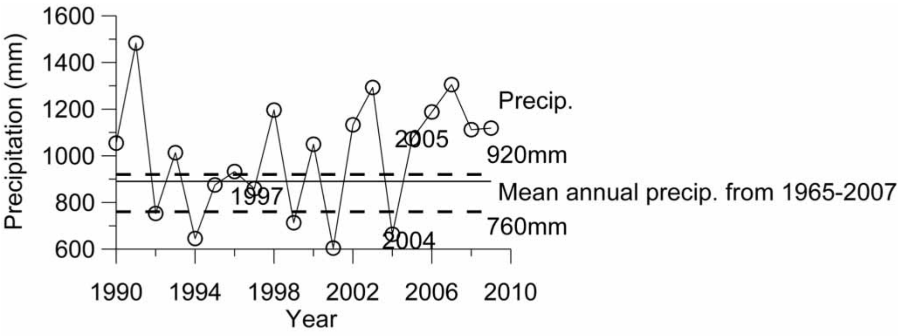

Figure 2 | The annual precipitation from 1990 to 2009.

in order to verify that HYDRUS-1D was suitable for this application. Then, the model was used to estimate the contributions of groundwater to root water uptake for three different hydrological growing seasons representing wet, average, and dry conditions.

MATERIALS AND METHODS

Field site

The work is based on data gathered in 2005 at the Wudaogou Experimentation Research Station of the Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China. The station is located in the northern Huang-Huai-Hai Plain (Bengbu City, Anhui Province, 33°09′ N, 117°21′ E) at an altitude of approximately 20 m (Figure 1).

The study area belongs to the transitional zone of northern subtropical and warm temperate climates. Based on over 40 years of records, annual rainfall averages 890 mm, with nearly 60% or more falling between June and September, most as rainstorms. Therefore, there are periods of drought and of flooding with crop waterlogging. Average annual pan evaporation is 1,000 mm. Mean annual temperature is 14 °C. Mean annual relative humidity is 70%. The annual range of WTD is 0.71–4.19 m, and the annual range of WTD was 0.27–3.80 m in 2005 (wet year), 0.40–4.39 m in 1997 (average year), and 1.00–4.88 m in 2004 (dry year). The ranges of WTD during the soybean growth period (June 10 to September 25) were 0.27–3.40 m with a mean WTD of 1.33 m in 2005, 0.40–4.10 m with a mean WTD of 1.79 m in 1997, and 1.00–4.88 m with a mean WTD of 2.57 m in 2004 (Figure 3).

The sampling area was 1.4 ha, with an average seeding density of 29 seeds per m^2, and a mature soybean population density of 21 plants m^{-2}. In 2005, the average mature soybean height was 63 cm.

Between 1991 and 2009, 2004 was the year with the largest soybean yield, 5,445 kg ha^{-1}. In 2004, plant density was 39 plants m^{-2}, and the average mature plant height was 69 cm. When calculating the daily contributions of groundwater to rootzone soil moisture for the different hydrologic seasons, it was assumed that all of the soybean plants were in a healthy state. The largest leaf area index (LAI) value was set as 7.4 (Setiyono *et al.* 2008), and the actual situation reflected the plant population density at the Research Experiment Station. The root distribution function determined in the 2005 field study was used for the different hydrological years studied.

The soil type was treated as homogeneous clay loam, with a field capacity of 26.6% and wilting point of 15.0%. The soil bulk density was 1.46 g cm^{-3}. The soybean roots were densely distributed in the 0–0.5 m soil layer, extending to a maximum depth of 1.2 m, with an effective depth of 1.0 m, where water absorption by roots occurred.

Field study

Aboveground data

The study area was divided into five equal sections. In each section, a 1 m by 1 m area was sampled for soybean growth measurements. On July 20–21 and 30–31, August 20–23, and September 24–25, 2005, plant density, height, and LAI were measured in the sampling areas. The LAI of the plants in the sampling areas was measured with a LAI-2000 Plant Canopy Analyzer (LI-COR, USA). Measurements were always made near the time of sunset. Data needed for calculating the reference crop evapotranspiration such as air density ρ_a and saturation vapor pressure e_s in 1997, 2004, 2005 and initial soil moisture contents in 1997 and 2004 were obtained from the Bengbu Weather Station.

Subsurface data

Soil moisture was measured near each of the five sampling sites. Measurements were made once every 5–6 days between June 1 and September 30, 2005. At each sampling time, 100-cm soil cores were extracted and sectioned into eight layers: 0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–80, and 80–100 cm. Three replicate samples were taken near the midpoint of each layer. The samples were weighed as collected, dried at 105 °C, and then re-weighed to determine the moisture content. Gravimetric moisture contents were converted to volumetric contents using the soil bulk density.

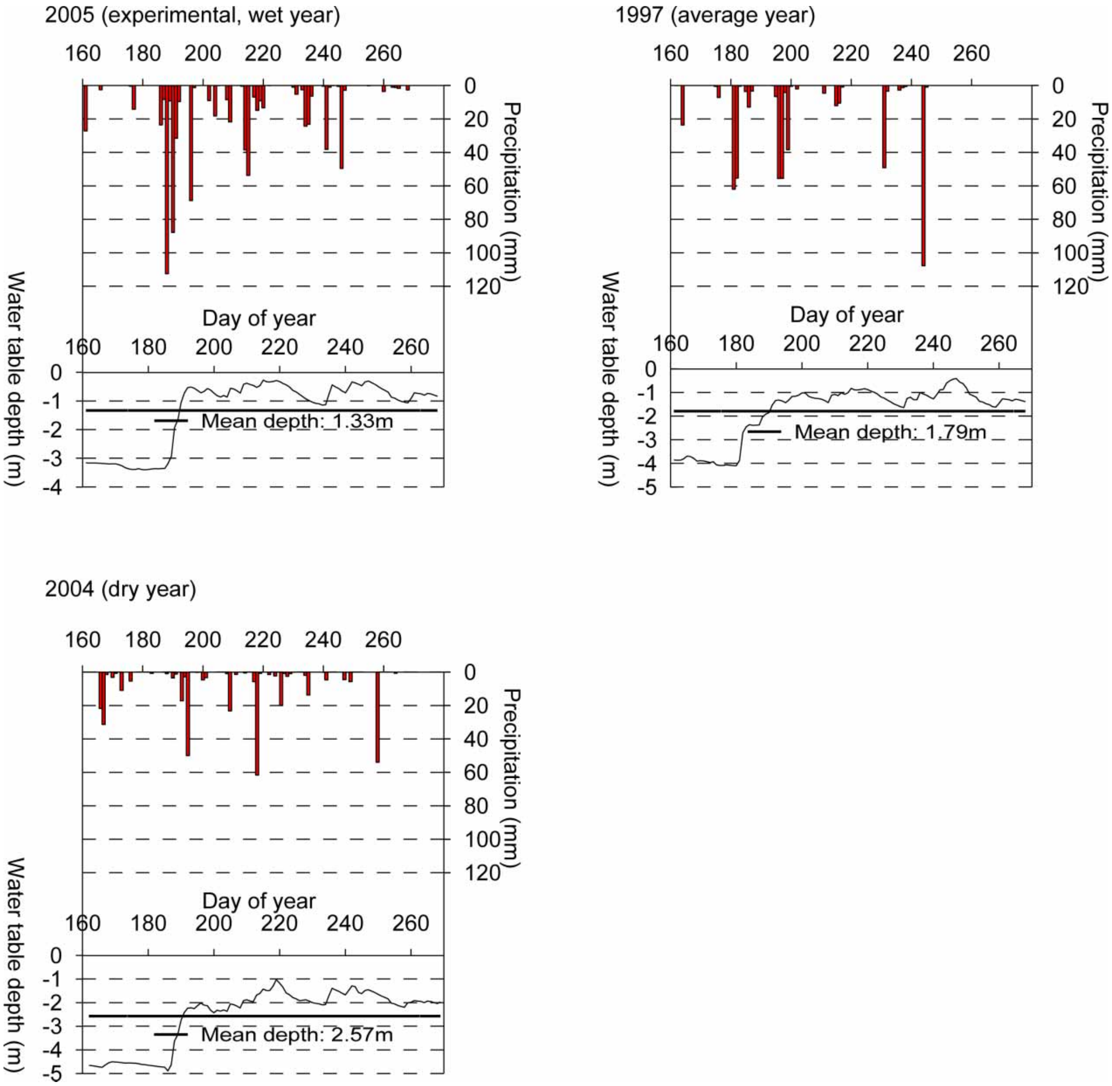

Figure 3 | Time variation of precipitation and water table depth at the experimental site in different hydrological years.

Measurements of the effective root length distribution were taken on August 25, 2005. At each sampling site, a soil column 1.5 m in diameter and 1.2 m deep was excavated in 10-cm layers. The root diameters and lengths in each layer were measured. All roots with diameters less than 0.2 cm were classified as effective roots, active in absorbing soil moisture. Roots were distributed throughout the soil profile to a depth of 120 cm, with the highest concentration of roots being in the 0–15 cm layer. The active root distribution is described in greater detail below.

The soil texture in the study area is clay loam (20.7% sand, 53.0% silt, and 26.3% clay). The water table elevations in 2005 were measured in observation wells, and the water table elevations in 2004 and 1997 were obtained from the Bengbu hydrological yearbook (see Figure 3).

Simulations

HYDRUS-1D (Šimůnek *et al.* 2005) was used to simulate soil water flow and root water uptake. This model simulates one-dimensional flow and uptake processes (in this case, in the vertical direction). In some instances, it is natural to approximate field-average behavior with a one-dimensional model; for example, the case of a grass field where variability in the horizontal plane is minimal. In the study, one-dimensional simulations were used to represent field average behaviors.

In HYDRUS-1D, the governing water flow equation is the Richards equation with a sink term added to simulate the extraction of water by roots (Šimůnek *et al.* 2005):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[k(h)\frac{\partial h}{\partial z} + k(h)\right] - S(z,t) \qquad (1)$$

where θ (cm^3 cm^{-3}) is the volumetric water content, h (cm) is the water pressure head, t (d) is time, z (cm) is the vertical space coordinate (positive downward), k (cm d^{-1}) is the hydraulic conductivity, and S (cm^3 cm^{-3} d^{-1}) is the sink term. The hydraulic conductivity k is represented using the van Genuchten–Mualem model:

$$S_e(h) = \frac{\theta(h)-\theta_r}{\theta_s-\theta_r} = \begin{cases} \left(1+|\alpha_{vg}h|^n\right)^{-m} & h<0 \\ 1 & h \geq 0 \end{cases} \qquad (2)$$

$$k(h) = k_s S_e^l\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \qquad (3)$$

where S_e is the effective saturation, θ_s (cm^3 cm^{-3}) is the saturated water content, θ_r (cm^3 cm^{-3}) is the residual water content, k_s (cm^3 cm^{-3}) is the saturated hydraulic conductivity, and n, m, α_{vg}(cm^{-1}), and l are adjustable parameters where $m = 1\text{–}1/n$.

The sink term is expressed as (Skaggs *et al.* 2006a, b):

$$S(z,t) = T_p R(z)\alpha[h(z,t)] \qquad (4)$$

where T_p (cm^3 cm^{-2} d^{-1}) is the potential transpiration rate, $R(Z)$ cm^{-1}) is the relative root length distribution function, and α is the dimensionless uptake reduction function that accounts for decreases in uptake due to drought stress and is given by (van Genuchten 1980; Skaggs *et al.* 2006b):

$$\alpha(h) = \frac{1}{1+(h/h_{50})^p} \qquad (5)$$

where h_{50} is the pressure head at which transpiration is halved and p is an adjustable constant that determines the steepness of the transition from potential to reduced uptake rates as h decreases.

The parameter h_{50} may be viewed as an effective parameter that lumps together the reduction in uptake due to reduced water potential at the root surface as well reduced flow of water to the root surface (Skaggs *et al.* 2006a). Simulations were performed using a range of values for h_{50} and p as part of an effort to calibrate HYDRUS-1D to 2005 data.

Boundary and initial conditions

The upper boundary was specified as an atmospheric boundary condition (Šimůnek *et al.* 2005). With the atmospheric boundary condition, potential evaporation and transpiration rates were specified on a daily basis. The model then calculated the actual evaporation and transpiration rates based on the simulated soil moisture conditions. In the case of evaporation, water evaporates from the soil surface at the potential rate (a flux boundary condition) whenever the pressure head at the surface is above a threshold value h_{crit}. If the soil surface dries out such that the surface pressure head reaches the threshold value, the boundary switches to a constant pressure head condition ($=h_{\text{crit}}$), generally leading to a computed actual evaporation rate that is well below the potential rate. In the simulations, h_{crit} was assumed to be $-10{,}000$ cm. The actual transpiration rate was determined with Equations (4) and (5).

To specify the potential transpiration (T_p) and evaporation (E_p) rates, potential evapotranspiration (ET_p) was calculated by Equation (6). In Equation (6), the reference crop evapotranspiration ET_0 was calculated by the FAO Penman–Monteith equation (Allen *et al.* 1998), and the crop efficiency coefficient, K_c, was determined by Tang *et al.* (2008).

$$ET_p = K_C ET_0 \qquad (6)$$

$$ET_0 = \frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \qquad (7)$$

where ET_0 is reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), $e_s - e_a$ is saturation vapor pressure deficit (kPa), Δ is slope of the vapor pressure curve (kPa $^\circ C^{-1}$), and γ is psychrometric constant (kPa $^\circ C^{-1}$).

Potential evaporation, E_p was then calculated according to (Al-Khafaf *et al.* 1978):

$$E_p = ET_p \cdot \exp(-0.623LAI) \tag{8}$$

where LAI is the leaf area index. Values of LAI were determined from the field measurements. The potential transpiration rates were determined as:

$$T_p = ET_P - E_p \tag{9}$$

The 2005 daily potential evaporation and transpiration values used in the model surface boundary condition are shown in Figure 4.

The lower boundary was specified as a time-varying pressure head boundary condition representing the time-varying water table conditions. The initial soil moisture profile, $\theta(z, t = 0) = \theta_i(z)$, was specified based on soil moisture data collected at the beginning of the simulation period. The simulated soil profile is 100 cm, and the spatial discretization is 1 cm.

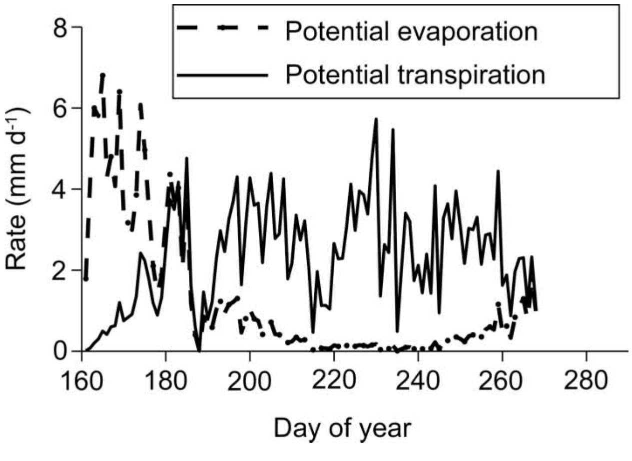

Figure 4 | Potential evaporation and transpiration rates in 2005 (experimental year) used in the model simulations.

Soil hydraulic parameters

Values for the soil hydraulic parameters were estimated by inputting the soil bulk density and texture data into the Rosetta pedotransfer function model (Schaap *et al.* 2001) that is part of the HYDRUS-1D package. The estimated van Genuchten–Mualem parameters were $K_s = 8.22$ cm d^{-1}, $\theta_r = 0.0748$ cm^3 cm^{-3}, $\theta_s = 0.4118$ cm^3 cm^{-3}, $\alpha_{vg} = 0.0071$ cm^{-1}, $n = 1.5597$, and $l = 0.5$.

Root distribution

The data for the soybean root distribution indicated that 58% of the active root length was in the 0–15 cm soil layer, 30% was in the 15–50 cm soil layer, and 12% was in the 50–100 cm soil layer. Consistent with these data, the root distribution was modeled with the following normalized function:

$$R(z) = \begin{cases} 20.88/L_R & 0 \le z \le 15\,\text{cm} \\ 4.63/L_R & 15 \le z \le 50\,\text{cm} \\ 1.30/L_R & 50 \le z \le 100\,\text{cm} \end{cases} \tag{10}$$

where $z = 0$ cm is the soil surface, $z = 100$ cm is the maximum effective rooting depth, and $L_R = 540$ cm is the measured total length of roots.

RESULTS

HYDRUS-1D calibration

Figure 5 and Table 1 show the results of the calibration exercise. The simulated water contents were not very sensitive to the h_{50} and p parameters. The results shown in Figure 5, computed with $h_{50} = -1{,}500$ cm and $p = 3$, changed only slightly when these parameters were varied over the range of values reported in the literature (Skaggs *et al.* 2006a). Figure 5 shows the measured and simulated water contents for a near-surface depth (5 cm), a middle depth where the root density was high (45 cm), and a deeper depth where the root density was lower (90 cm). Table 1 presents the root-mean-square error (r.m.s), the relative mean error (r.m.e), and the Pearson's correlation (R) for the simulations

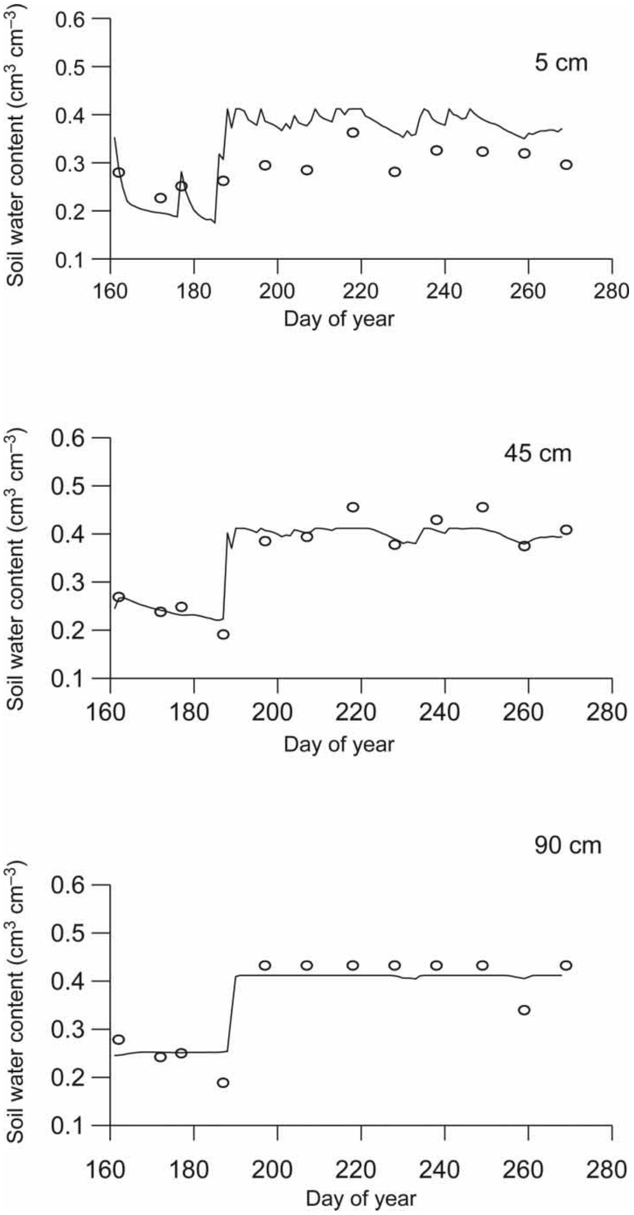

Figure 5 | Comparison of simulated (solid curves) and measured (open circles) soil moisture contents at the 5-cm, 45-cm and 90-cm depths during the soybean growth period (June 10 to September 25) in 2005.

Table 1 | Goodness-of-fit measures for Figure 5

Depth (cm)	Root mean square error (cm^3 cm^{-3})	Average relative error (–)	Pearson's correlation (*R*)
5	0.060	−0.049	0.82
45	0.043	0.023	0.90
90	0.029	−0.003	0.95

and data presented in Figure 5. The simulations were in good agreement with the measured water content data at the near-surface depth, while the simulations were in better agreement with the measured water content data at the middle depth and at the deep depth. For the middle depth and deeper depth, the time-course of the simulated water content agreed very well with the data ($R = 0.90$ for the middle depth and $R = 0.95$ for the deeper depth), while for the near-surface depth, the time-course of the simulated water content agreed well with the data ($R = 0.82$). These goodness-of-fit values in Table 1, as well as a visual inspection of Figure 5, indicates that prediction errors are low and that the simulated values agree well with the data.

Although modeled and measured results were similar, errors did exist between the measured and simulated values in the near-surface layer. There are two possible reasons. The first one is that the soil type was treated as a homogeneous clay loam. In fact, a change of soil properties and texture with depth exists. The near-surface layer is grainy and loose with low clay and high silt and sand, while the deeper layer is tight with high clay and low silt and sand. In the near-surface layer, there is a strong hygroscopic nature and soil surface evaporation, and when dry the soil hardens and cuts off capillary contact preventing groundwater from moving all the way up to the surface. This causes the occurrence of lower measured soil moisture than the simulated soil moisture. The other possible reason for error in the near-surface soil layer was that crop interception of rainfall was not considered. If the crop interception of rainfall is considered, the simulated soil moisture may become smaller because the moisture entering into the soil layer is less.

Groundwater contribution to rootzone soil moisture

According to the WRRIAH (2008), the greatest WTD for phreatic water evaporation is about 1.0 m in an unplanted clay loam field. The greatest depth of the soybean rootzone was 1.2 m, therefore, the greatest WTD for groundwater contributions to soybean rootzone soils would be about 2.2 m according to Mao *et al.* (1999). From Figure 3, it is known, in a wet year and an average year, that after day of year (DOY) 187, the water table is no deeper than 2.2 m. Although in the dry year (2004), after DOY 187, the water table is deeper than 2.2 m on some days, it is the year when the soybean yield was largest. Perhaps root extension was also deepest, enhancing groundwater contributions to rootzone soil moisture by capillary rise. In the calculations, under each scenario, the estimated period for groundwater contributions was from DOY 188 to 268.

Figure 6 shows for each scenario the water flux computed at the bottom of the soil profiles. Groundwater contribution to the soil profile (an upward water flux, positive) occurred initially, although during DOY 161–187, the water table was deeper than 2.2 m. In fact, During DOY 161–187, the roots grew very slowly, and the groundwater contribution to the soil profile was restricted. Any groundwater contributions occurring during DOY 161–187 were due to the initial condition used in each scenario, which included initial soil moisture profile for the actual case (the drier upper soil layer and the wetter lower soil layer) and the soybean root distribution, treated as invariable during the growth period. Therefore, the deep drainage (a downward water flux, negative) and the upward contributions were only calculated from DOY 188 to 268, shown in Table 2.

The deep drainage in Table 2 is drainage (shown as a negative flux) for each scenario, in the experimental year (wet year) of 2005. Not only in the real situation but also in the best growth conditions, the drainage was the same at 137 mm, in the average year, the drainage was 87 mm, and in the dry year, it was 56 mm. In the wet year, because water was not a limiting factor for the soybean growth, the drainage in the real situation was the same as that for the modeled best growth condition. With the total precipitation during the soybean growth period decreasing in different hydrological years, the drainage also decreased correspondingly (see Table 2 and Figure 6) in order to satisfy the water requirement for soybean growth.

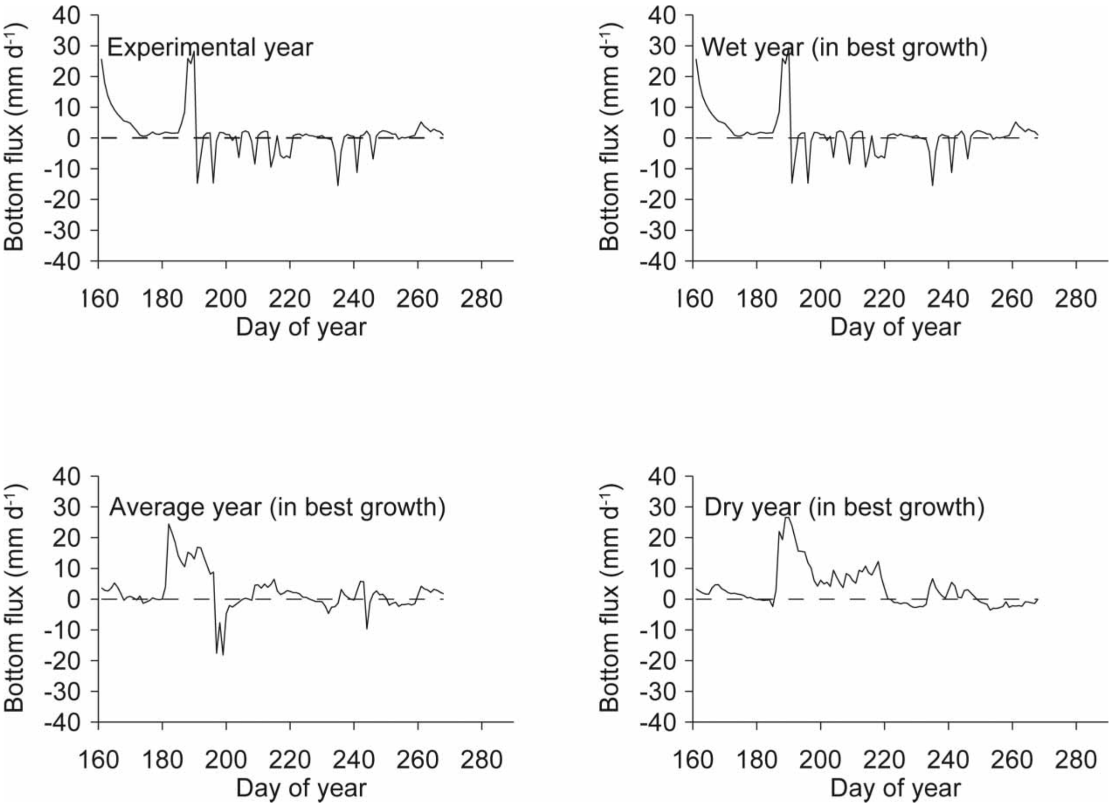

Figure 6 | The simulated water flux at the bottom of the soil profiles for different hydrological years and for experimental year 2005. The bottom flux is the actual flux across the bottom of the soybean rootzone soil profile, negative values indicate deep drainage whereas positive values indicate upward flow, namely, the groundwater contributions to rootzone soil moisture.

Table 2 | Seasonal transpiration and seasonal groundwater contributions to transpiration

Different hydrologic year	Deep drainage (mm)[a]	Transpiration (mm)	Groundwater contribution (mm)[b]	Percentage contribution (%)[c]
Experimental year	136	249	157	63
Average year	87	277	222	80
Dry year	56	272	387	142
Wet year	136	240	158	66

[a] Deep drainage is the flux across the bottom of the soil profile, outflow downwards.
[b] Groundwater contribution is the flux across the bottom of the soil profile, inflow upwards.
[c] Percentage contribution is the ratio of groundwater contribution to transpiration.

Figure 6 indicated an upward (positive) water flux into the soil profile that, as expected, increased as the total precipitation during the soybean growth period decreased in the different hydrological years.

Figure 7 shows the estimated cumulative groundwater contribution to soil moisture in the soybean rootzone layer. The cumulative totals in Figure 7 exclude the first 28 days of the simulation, thereby negating the impact of the initial conditions. Figure 7 permits a quantitative assessment of the seasonal contributions of groundwater to rootzone soil moisture in different hydrological years. In the average year, the mean groundwater depth during the growth period was 1.79 m, and approximately 222 mm of groundwater moved up into the rootzone. In the dry year, the mean groundwater depth was 2.57 m, and the groundwater contribution to the rootzone increased to 387 mm; while in the wet year, a mean WTD of 1.33 m resulted in a groundwater contribution of 158 mm. The field data (2005) had an average WTD of 1.33 m, which indicated a groundwater contribution of 157 mm, similar to that in the wet year when soybean had the best growth conditions. Figure 8 shows the corresponding cumulative transpiration totals for the same time periods. In comparing the totals in Figures 7 and 8, it is again clear that most of the water transpired, especially over the season in the dry year, was obtained from groundwater.

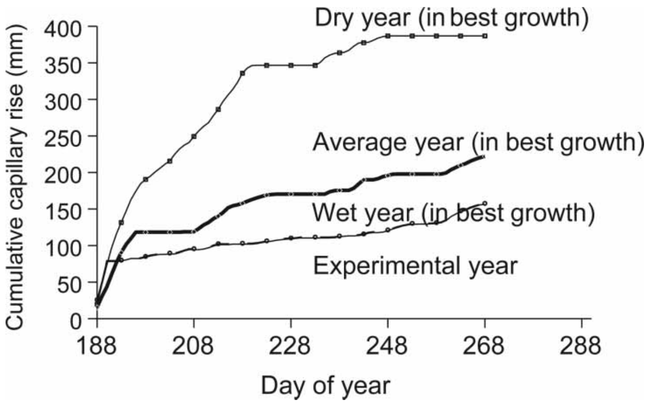

Figure 7 | Cumulative capillary rise at the bottom of the soil profile, which is equal to seasonal contribution of groundwater to soybean transpiration.

The calculations for groundwater contributions to transpiration are summarized in Table 2. In the wet year, whether soybean was growing in the best condition or in the real situation, the groundwater contributions to transpiration are almost the same: 66 and 63%. For different hydrological years, with soybean growing in the best condition, the groundwater contributions to transpiration were 158, 222, and 387 mm in the wet year, average year, and dry year, respectively, or about 66, 80, and 142% of the totals, respectively.

In the study of soybean growth in the Huaibei Plain, deep drainage was large in the different hydrological years, especially in the wet year, which had 137 mm, only slightly smaller than the groundwater contribution of 157 mm (Table 2). This also indicated that because there were strong exchanges of moisture between soil water and groundwater, pesticide and fertilizer in soil water could move down into the groundwater, and salt in the groundwater could move up into soil water. Such contaminant transport should be studied in the future.

SUMMARY AND CONCLUSIONS

Based on field data and weather data from the Bengbu City weather station, the HYDRUS-1D software package

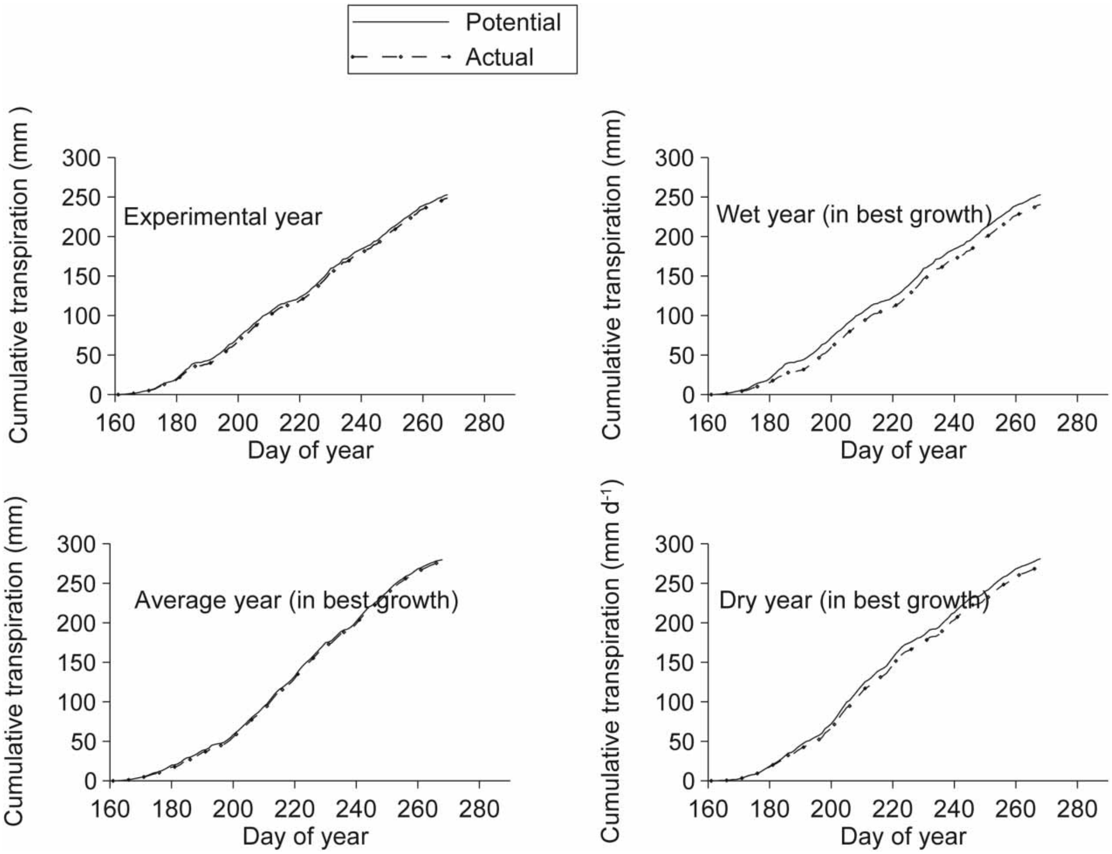

Figure 8 | Simulated cumulative potential and actual transpiration for the experimental year of 2005 and for different hydrological years.

was used to simulate soil moisture and calculate the contribution of groundwater to soybean rootzone soil moisture during the growing season (June 10 to September 25, DOY 161–268). The main conclusions are as follows:

HYDRUS-1D simulated soil moisture values in the soybean rootzone from June to September were similar to measured soil moisture values.

The daily change of groundwater contribution to the soybean rootzone in normal growth in the experimental year and that in the best growth in the different hydrological years was calculated during the growth period from June 10 to September 25. For actual soybeans growing in the field in 2005 (wet year), the contribution of groundwater to soybean transpiration was 63% of the total transpiration. The simulated best growth condition results produced groundwater contributions at 158, 222, and 387 mm in a wet year, an average year, and a dry year, respectively. The contributions of groundwater to soybean transpiration were 142, 80, and 66% of the total transpiration in dry, average, and wet years, respectively.

1. There are many factors affecting the contributions of groundwater to soil moisture in the Huaibei Plain, e.g., soil texture, soil heterogeneity, temperature, variations in root growth, WTD, and the soil depth. In this paper, water table fluctuations, depth of plant roots, and soil texture were considered, but temperature, root growth, and soil heterogeneity were not considered. In future studies, temperature, root growth, and soil heterogeneity need to be further considered.
2. In the Huaibei Plain, because of the large exchange of moisture between soil water and groundwater, the exchange of contaminants (salinity, fertilizer, and pesticide) should be studied in the future.

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