# The contribution of groundwater to soil moisture in *Populus euphratica* root zone layer

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**Abstract** *Populus euphratica* is the predominant tree species forming natural woodlands in the Ejina basin of northwest China. Changes in *P. euphratica* woodlands represent significant changes in the basin's ecology. The growth and development of these woodlands relies on groundwater recharged by flows in the middle reaches of the Heihe River. In recent years reduced flow in the Ejina basin, because of increase of water consumption, has endangered woodland ecology, environmental quality and social development. In order to maintain ecological stability and ecological restoration in the Ejina basin, a certain volume of water should be transported downstream, at the same time *P. euphratica* should be artificially cultivated. Therefore determining the contribution of the current groundwater to the soil moisture in the root zone of *P. euphratica* is required for making ecological restoration plans in the Ejina basin. A HYDRUS-1D model is used to determine the required groundwater and soil moisture conditions during the growing period from 1 May to 31 October for *P. euphratica* woodlands. The results of this study suggest the contribution of groundwater to root-zone soil moisture is 442 mm.

**Key words** arid region; contribution of groundwater to soil moisture; HYDRUS-1D

## INTRODUCTION

The Ejina basin is a sub-catchment of the Heihe River Basin, China's second largest inland river basin. This is an extremely arid region of northwest China, because of low rainfall, and as a consequence plant growth relies on groundwater recharged by the flow from the middle reaches of Heihe River. *Populus euphratica* is the only natural forest tree species in the catchment and is a key indicator of ecological changes within the Ejina basin. In recent years, large areas of *P. euphratica* have withered, resulting in ecological degradation. The Ejina basin is connected to the Badanjilin Desert in the southeast and the Jigedecha Gobi in the west, therefore the stability of the Ejina Oasis plays a protective role in further desertification of the larger region. Disappearance of the Ejin Oasis would result in the Badanjilin Desert connecting with the Jigedecha Gobi and collectively they would form an important source for sand-storms that would directly impact on the middle reaches of Heihe River. This would have significant implications on Beijing and other regions in northwest and north China.

In the 1950s, there were $5 \times 10^4$ ha of *P. euphratica* woodland, but recent studies show only $2.26 \times 10^4$ ha of woodland (Bai *et al.*, 2008). Withering of the Ejina Oasis has led to an increase in the frequency of sandstorms in the northwest and north of China and also has impacted on the middle reaches of the Heihe River (Du *et al.*, 2005). Therefore, improving and restoring the ecological environment, safeguarding ecological security, is required.

*Populus euphratica* woodlands rely heavily on groundwater. Average annual precipitation in the region is only 38.24 mm (Zhu, 2002). Therefore, estimating the contribution of groundwater to the soil moisture in the *P. euphratica* roots zone is imperative to the ecological restoration of *P. euphratica* woodlands. Many studies have studied the contribution of groundwater to soil moisture in plant roots zones (e.g. Soppe & Ayars, 2003), but most are limited to crops (e.g. Kahlown *et al.*, 2005) and grasses (e.g. Soppe & Ayars, 2003). Research in this area on natural trees in arid desert regions is limited. According to Babajimopoulos *et al.* (2007), previous research has been conducted by weighing and drainage lysimeters. Although accurate, it has serious limitations because of costs of construction, operation and maintenance of the lysimeters. Estimation of the contribution of groundwater to soil moisture can occur by the use of mathematical models (Babajimopoulos *et al.*, 1995).

In this study, the contribution of groundwater to soil moisture in the *P. euphratica* root-zone is estimated by a HYDRUS-1D model. Here, the HYDRUS-1D model was used to simulate the soil moisture in the root-zone layer and the simulated data was compared with measured data in order to verify whether the HYDRUS-1D model is feasible. This model was then used to estimate the soil moisture distribution in *P. euphratica* root-zone under the lower boundary condition of variable pressure head and free drainage. Finally the contribution was calculated by the difference of soil water storage under different lower boundary conditions.

## MATERIALS AND METHODS

### Description of research site

The modelling used in this study is based on data gathered at a Chinese Academy of Sciences eco-hydrological research site located in the extremely arid natural woodlands of the Ejina basin (41º57′N, 101º20′E, 940.5 m above sea level). This area is at the northwestern edge of the Badanjilin Desert, in the lower reaches of the Heihe River basin (Fig. 1). Mean annual precipitation is 38.24 mm, mean annual free water surface evaporation is 3632 mm, and average temperature is 8°C. The *P. euphratica* woodlands studied comprises *P. euphratica* that is 10 years old, which is not been significantly affected by human activities and has been fenced off from anthropogenic disturbances. The study site is a riparian woodland, 4 km southwest of the Ejina City, 450 m from the river with a sampling area of 1430 $m^2$. In the sampled woodland, the average density is 1 tree per 15 $m^2$. The groundwater depth is 2–3 m below the surface. The water table was observed at an average depth of 2.64 m below soil surface. Tree roots are distributed through

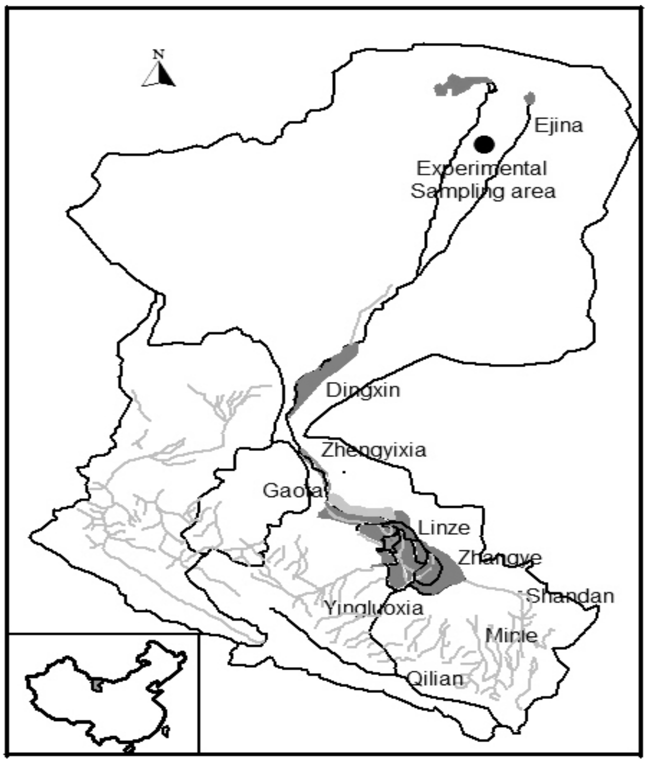


**Fig. 1** The experimental site.

the soil profile from 0 to 200 cm depth, though predominantly in the 60–100 cm soil layers. The average crown is 185 × 140 cm; average height is 265 cm, and the maximum vegetation coverage was 55% in 2000.

## METHODS

### Experimental data collection

The study area was divided into 5 subplots for sampling. In each subplot, one tree with average height and tree crown characteristics was chosen to measure growth. The branch length was measured once every 15 days. At the same time, leaf area index (LAI) was measured with a LAI-2000 Plant Canopy Analyzer (LI-COR, USA).

In each of the 5 subplots, a site was chosen for measurement of soil moisture. Sites were selected having soil characteristics representative of the subplot. The measurements were continued for 6 months in 2000, beginning 1 May and ending 31 October of every year. A soil sample was taken once every 5 days with a soil drill. The total depth of the soil sample profile was 200 cm. Within this, the 11 sampled soil layers were 0–10 cm, 10–20, 20–40, 40–60, 60–80, 80–100, 100–120, 120–140, 140–160, 160–180, and 180–200 cm. Three replicate samples were taken at the vertical midpoint of each layer. Soil samples were weighed as collected, then dried at 105°C and re-weighed to determine soil moisture.

The measurement of effective root length in every soil layer was taken on 15 August 2000. For the study area, one tree was selected. Within a soil column 3.5 m in diameter and 2.5 m deep around each tree trunk, every 20 cm soil layer was excavated, and its root content quantified. Root diameters and lengths were measured, and all roots with diameter less than 10 cm were scored as effective roots, active in absorbing moisture from the soil (Zhu & Wu, 2003).

In the study area the soil type was treated as fine sand. Other data needed for calculating potential evapotranspiration, such as air density $\rho_a$ and the saturation vapour pressure $e_s$, were obtained from the Ejina County Weather Station.

Water table was observed from the observation wells.

### Calculation method of the contribution of groundwater to the *P. euphratica* root zone soil moisture

Initially, the HYDRUS-1D model is used to estimate soil moisture with a variable pressure head as the lower boundary condition. Second, the feasibility of the model is verified; third, the soil moisture profile is determined in different bottom boundary of variable pressure head and free drainage. Finally, the contribution of groundwater to the *P. euphratica* root zone soil moisture is determined by the difference of soil moisture storage from the soil moisture profile calculated.

The HYDRUS-1D model includes a master equation which sets the boundary conditions, and in this study the Richards equation was used with the sink term estimated by equation (1) (van Genuchten, 1987; Skaggs *et al.*, 2006):

$$s(z,t) = T_p \cdot R(z) \cdot \alpha[h(z,t)] \tag{1}$$

$T_p$ (cm) is the potential transpiration rate, $R(z)$ is the relative distribution function of roots in soils, $\alpha[h(z)]$ is the dimension uptake reduction function related to water pressure head, estimated by equation (2):

$$\alpha(h) = \frac{1}{1 + (h/h_{50})^p} \tag{2}$$

where $h$ is the soil water pressure head, $h_{50}$ represents the water pressure head at which transpiration is halved; $p$ is a constant, which determines the steepness of the transition from potential to reduced uptake rates as $h$ decreases.

Potential transpiration rate $T_p$ is calculated by equation (3):

$$T_p = ET_P - E_p \tag{3}$$

where $ET_p$ is the potential evapotranspiration; $E_p$ is potential evaporation of the soil surface.

Potential evapotranspiration, $ET_p$, was calculated by the method of Liu *et al.* (2005). This method uses the surface resistance $r_s$, calculated for trees according to formulae given by Rey (1999) and Kelliher *et al.* (1993); the aerodynamic resistance for heat and vapour transfer $r_a$, were calculated according to the method of Thom (1972) using the plant height and branch growth data.

Potential evaporation of soil surface $E_p$ is calculated using equation (4) as follows:

$$E_p = veg_{\max} \cdot ET_p \cdot \exp(-0.623LAI) + ET_p \cdot (1 - veg_{\max}) \tag{4}$$

where $veg_{\max}$ (<1) is the maximum fraction of *P. euphratica* cover and *LAI* is the leaf area index. Equation (4) is a modification of an expression given by AL-Khafaf *et al.* (1978), formulated to account for the fact that the *P. euphratica* surface coverage was less than 100%. Values for $veg_{max}$ and *LAI* were determined from the field measurements described above.

**Boundary conditions and initial conditions**: The boundary conditions are the atmospheric boundary condition with a surface layer while the lower boundary is the variable pressure head as the contribution of groundwater is considered. In the scenario where free drainage is considered the contribution of groundwater is ignored. The initial condition in our study was given in terms of measured soil moisture.

$$\theta(z,t) = \theta_i(z) \qquad t = 0$$

### Determination of parameters

**The soil hydraulic properties**. The soil material in experimental site was 91.2% sand, 4.8% silt, and 4% clay, and the bulk density is 1.4 g cm$^{-3}$ (Feng & Chen, 1999). The soil heterogeneity was not considered. These data were used as input into the Rosetta pedotransfer function model (Skaggs *et al.*, 2006) to obtain estimates for the van Genuchten–Mualem parameters: $K_s$ = 522.01 cm day$^{-1}$, $\theta_r$ = 0.0517 cm$^{-3}$ cm$^{-3}$, $\theta_s$ = 0.4194 cm$^{-3}$ cm$^{-3}$, $\alpha_{vg}$ = 0.035 cm$^{-1}$, $n$ = 2.6787, and $l$ = 0.5.

**Root distribution**. In this study, *P. euphratica* roots were approximated as being distributed at 10% of the root length located in the top 60 cm soil layer of the root zone; 60% of the root length located in the soil layer of 60–100 cm; 25% of that in the soil layer of 100–180 cm and 5% of that in the soil layer of 180–200 cm. Consistent with these data, we modelled the root distribution with the following normalized function:

$$R(z) = \begin{cases} 9/L_R & 0 \le z \le 60 \text{ cm} \\ 81/L_R & 60 < z \le 100 \text{ cm} \\ 16.875/L_R & 100 < z \le 180 \text{ cm} \\ 13.5/L_R & 180 < z \le 200 \text{ cm} \end{cases} \tag{5}$$

where $z$ = 0 cm is the soil surface, $z$ = 200 cm is the maximum rooting depth, and $L_R$ = 5400 cm is the measured total length of roots.

**Determination of $h_{50}$ and *p*** The range of the value for $h_{50}$ can be determined by the van Genuchten-Mualem formulas. According to Dudley & Shani (2003), Homaee *et al.* (2002), usually $p$ is equal to 1.5 to 3. In the paper, when HYDRUS-1D model is used to calculate the soil moisture content, $p$ is finally determined as 3 and $h_{50}$ is finally estimated to be –950 cm after many times of simulation.

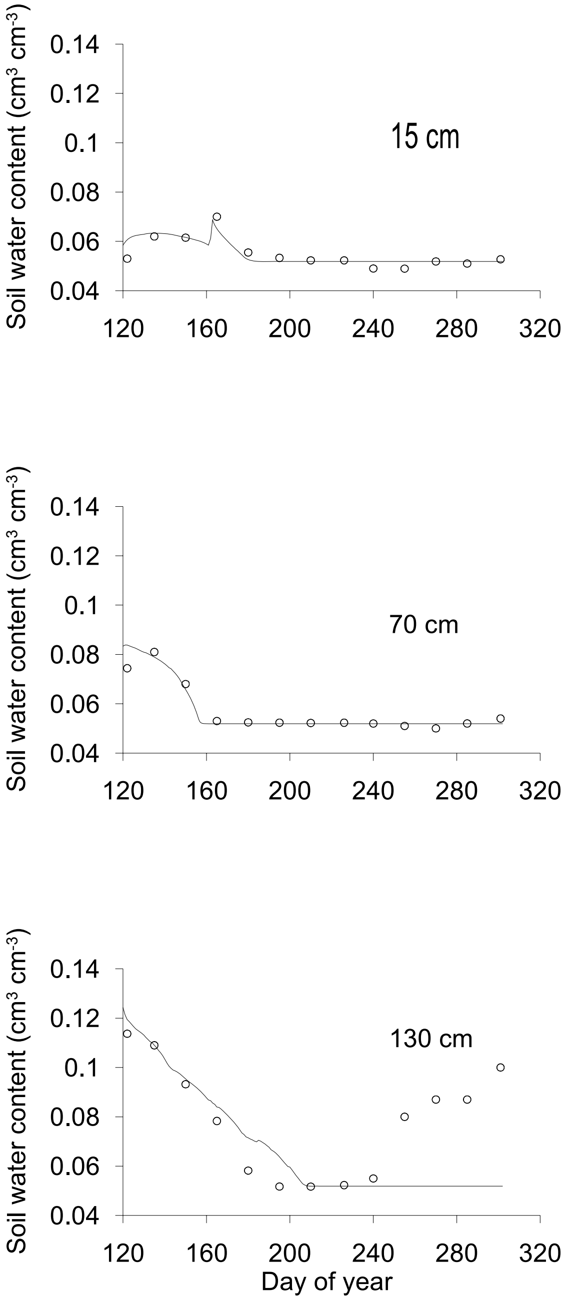


**Fig. 2** The comparison of simulated and measured soil moisture content at the depth of 15 cm, 70 cm and 130 cm during the growth period (1 May–31 October).

## RESULTS

### Feasibility of simulating the soil moisture of *P. euphratica* root zone with HYDRUS-1D

The HYDRUS-1D model did simulate the soil moisture of *P. euphratica* root zone (Fig. 2 and Table 1). Figure 2 shows the comparison of simulated and measured moisture content at three different soil depths in the *P. euphratica* root zones during the growth period (May–October). For the near-surface depth (15 cm) and the middle depth (70 cm) the time-course of the simulated water content agrees very well with the data. For the deeper depth (130 cm) , before about DOY 235, the simulated water content agrees very well with the data, but after DOY 235, the observed data shows a trend of increasing and having the same trend as that in simulated bottom flux (seen in Fig. 3) while the simulated data is constant. This may be caused by the capillary action from the silty layer between 1.0 m and 1.2 m. Table 1 gives the root mean square error (r.m.s) and the relative mean error (r.m.e) for the simulations and data presented in Fig. 2. Table 1 further indicates that the simulated values agree very well with the measured data for the first two layers, and also agree well with the measured date for the third layer.

**Table 1** The errors of the simulated and measured values at different depth of soil root zone

| Depth of soil | 15 cm | 70 cm | 130 cm |
|---|---|---|---|
| Root mean square error($cm^3cm^{-3}$) | 0.0026 | 0.0021 | 0.0204 |
| The average relative error | –0.0058 | –0.003 | 0.0792 |

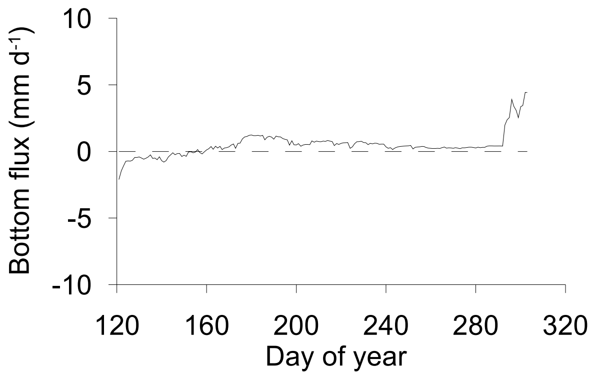


**Fig. 3** The daily flux across the bottom of the soil profile in *P. euphratica* root zone.

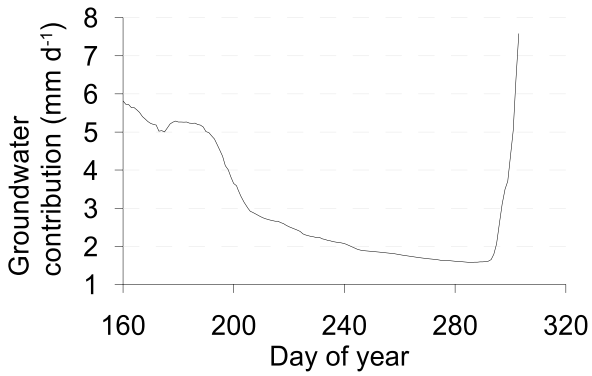


**Fig. 4** The daily change of groundwater contribution to the soil moisture in *P. euphratica* root zone.

## The contribution of groundwater to soil moisture in *P. euphratica* root zone

By using the HYDRUS-1D model, from day 160, the flux started flowing into the root-zone of *P. euphratica.* Then, the daily change of contribution of groundwater to the soil moisture in *P. euphratica* root zone from day 160 to day 302 (seen in Fig. 4) was determined by the difference of soil water storage in root zone under the lower boundary condition as variable pressure head and free drainage, respectively.

The contribution varies between 1.59 mm day$^{-1}$ to 7.58 mm day$^{-1}$ with an average value of 3.09 mm. This adds up to about 442 mm.

It is apparent in the Ejina basin that groundwater is very important for *P. euphratica* growth. The accurate estimation of groundwater contribution will lead to a much better management of ecological restoration of *P. euphratica* woodlands in the future.

## CONCLUSION

In this paper, a 10-year-old *P. euphratica* woodland in the Chinese northwest arid region is taken as an example. HYDRUS-1D model is used to simulate the soil moisture and calculate the contribution of groundwater to root-zone soil moisture during the growth period (1 May–31 October). The conclusions result as follows:

- It is feasible to use HYDRUS-1D model to simulate the natural plant soil moisture in arid areas of northwest China by the comparison of the measured and simulated soil moisture values at the typical depth with low errors.
- The daily change of groundwater contribution to the root-zone soil moisture is calculated during the growth period by the difference of soil water storage under different lower boundary conditions. The whole contribution of groundwater to soil moisture is 442 mm.
- There are many factors affecting the contribution of groundwater to soil moisture of natural plants in arid regions, such as soil texture, soil heterogeneity, temperature, the variation of roots growth, the variation of water table, the depth of soil layer, etc. In this paper, the variation of water table, the total depth of plant roots and soil texture are considered, but temperature, the variation of roots growth and soil heterogeneity are not considered. In future studies, these factors need to be considered.
- In shallow groundwater areas, irrigation district and riparian zones, the contribution of groundwater to plant root zone layer needs to be estimated in order to make scientific decisions on choice of plant variety, determination of irrigation time and volume, and provide scientific guidance for making agriculture ecological restoration planning and practice. In the future, the HYDRUS-1D model can be used to study the contribution of groundwater to soil water in other areas of shallow groundwater.

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