Water consumption of *Populus euphratica* woodlands in an arid region of China

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Abstract The Ejina basin is a sub-watershed in the lower reaches of the Heihe River basin, which is situated in an exceedingly arid region of China. In recent years, the reduction of flow into the Ejina basin has endangered its ecological and environmental quality and the social development. *P. euphratica* is the predominant tree species forming natural woodlands in the Ejina basin, and changes of the *P. euphratica* woodlands symbolize changes in the Ejina basin's ecology. Understanding the quantity and pattern of water consumption of *P. euphratica* woodlands in the Ejina basin will provide a scientific basis for maintaining its present ecological environment and can help prevent deterioration. In this paper, ecological water consumption of *P. euphratica* is determined using an improved Penman-Montieth method, soil moisture content and effective root distribution density, and the pattern of water consumption of *P. euphratica* is analysed. The minimum ecological water requirement of *P. euphratica* woodland is found to be 1.45×10^8 m^3 $year^{-1}$.

Key words arid desert region; Ejina basin; *P. euphratica* woodland; water consumption

INTRODUCTION

Of the soil moisture taken up by plant root systems during vertical soil moisture transfers in the soil–plant–atmosphere continuum, only 1% participates in photosynthesis; the rest is transpired in order to adjust the plant's temperature and carry nutrients for the plant. Accordingly, the majority of water consumption in terrestrial plant systems is represented by plant evapotranspiration. There have been many studies of evapotranspiration, but most are limited to agricultural crops, industrial crops, or planted forest in various climate regions (e.g. Noilhan & Planton, 1989; Droogers, 2000; Poulovassilis *et al.*, 2001). There appear to be no such studies of natural woodlands in arid desert regions. There have been numerous studies of *P. euphratica* dealing with its plant physiology, ecology or genetics (e.g. Chen *et al.*, 2002; Su *et al.*, 2003), but there have not been any studies on *P. euphratica* concerning its eco-hydrology. Currently, in the Ejina basin there are 390.28 km^2 of natural woodlands, of which the *P. euphratica* woods occupy 52.7%, or 205.68 km^2 (Wu, 2000). Determination of the evapotranspiration characteristics, water consumption and minimum ecological water requirement of *P. euphratica* woodlands will thus provide a scientific basis for environmental protection and ecological restoration of the Ejina basin.

Aggregate evapotranspiration of the whole woodland area in the basin is assumed to represent the water consumption of *P. euphratica* in the Ejina basin. Actual evapotranspiration of the whole woodland area is commonly determined by multiplying potential evapotranspiration by a reduction factor.

Potential evapotranspiration is determined by an improved Penman-Montieth method (Stockle *et al.*, 1992). The reduction factor is related to the percentage soil moisture content (Ragab, 1995). Because different soil layers have differing soil moisture contents, a reduction factor is calculated for every soil layer present. Potential evapotranspiration in each soil layer is calculated as the ratio of the effective root length in each layer to the total effective root length in all soil layers, multiplied by the total potential evapotranspiration (Zhu &Wu, 2003). With this method, climatic, edaphic and vegetation factors influencing evapotranspiration are all considered.

The minimum ecological water requirement of *P. euphratica* woodland in Ejina basin includes two parts: one is actual evapotranspiration of whole woodlands, the other is the water consumed by channel infiltration and evaporation during the process of water flowing into the woodland from the middle reaches of the Heihe River basins.

MATERIALS AND METHODS

Description of research site

Our modelling 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 (41°57′N, 101°20′E; 940.5 m a.s.l). The Ejina basin is located at the northeastern edge of the Badanjilin Desert, in the lower reaches of the Heihe River basin. It is the second largest inland river basin in the arid region of northwest China. Mean annual precipitation is 38 mm, mean annual free water surface evaporation is 3632 mm, and average temperature is 8°C. *P. euphratica* woods have not been significantly affected by human activities in this area. The experimental sampling area is located in a river-side woodland, 150 m away from the river, 4 km southwest of Ejina City. The sampling area comprises 2430 m^2. In the sampled woodlands, 67 % of the trees (*P. euphratica*) are old (≥50 years) and 33% of the trees are either young (≤15 years) or middle-aged. The average density is one tree per 15 m^2. The groundwater depth is 2–3 m below the surface. Tree roots are distributed through the soil profile from 0 to 200 cm depth, though predominantly in the 60–120 cm soil layers.

Methods

Experimental data collection The study area was divided into five subplots for sampling. In each of the five 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 three years (2001–2003), beginning 1 May and ending 31 October of every year. A soil sample was taken once every five days with a soil drill. The total depth of the soil sample profile was 200 cm. Within this, the 11 sampled soil layers were 0–0.1, 0.1–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, 0.8–1.0, 1.0–1.2, 1.2–1.4, 1.4–1.6, 1.6–1.8, and 1.8–2.0 m. 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 2003. For the study area, one tree was selected in each age class. Within soil columns (each 2 m deep with a diameter of 3.5 m) surrounding each tree trunk, every 20 cm soil layer was excavated, and its root content quantified. Root diameters and lengths were measured. All roots with diameter less than 10 cm were scored as effective roots, i.e. being active in absorbing moisture from the soil (Zhu &Wu, 2003).

In the study area, the soil type was characterized as fine sand with 31.7% soil moisture content at field capacity and 0.73% at wilting point (Feng & Chen, 1999). Other data needed for calculating potential evapotranspiration (equation 4) during three years (2001–2003) such as air density (ρ), vapour pressure (e_a), the saturation vapour pressure at mean air temperature (e_d), net radiation (R_n) and wind speed for calculating r_a were obtained from the Ejina County Weather Station.

Actual evapotranspiration calculation Actual evapotranspiration (*ET*) was calculated by multiplying potential evapotranspiration (*PET*) by a reduction factor. The experimental soil profile was divided into 11 layers vertically, as described above. In equation (1) i expresses the day of measurement (from May 1 to October 31), j is the soil layer ($1 \le j \le 11$), and *SI* expresses the reduction factor. Evapotranspiration is assumed to be at its potential level as long as the actual available water is equal to the maximum available water. This is defined as the difference between the soil moisture at field capacity and the soil moisture at wilting point. The actual available soil water is calculated as a difference between the actual soil moisture content and the wilting point as follows:

$$SI(i,j) = \frac{\theta(i,j) - \theta_{wilting\ po\mathrm{int}}(j)}{\theta_{field\ capacity}(j) - \theta_{wilting\ po\mathrm{int}}(j)} \tag{1}$$

Note that the reduction factor is 0 if actual soil moisture content is less than or equal to soil moisture at wilting point (evapotranspiration is nonexistent), and the reduction factor is 1 if actual soil moisture content is greater than soil moisture at field capacity (actual evapotranspiration is assumed to be at its potential level).

The actual evapotranspiration *ET* is calculated as

$$ET(i,j) = SI(i,j)PET(i,j) \tag{2}$$

$$PET(i,j) = PET(i)\frac{lr(i,j)}{lr(i)} \tag{3}$$

where $lr(i,j)$ is the effective root length of day i and layer j, and $lr(i)$ is the total effective root length of day i.

Potential evapotranspiration, *PET*, is calculated by the method of Stockle *et al.* (1992):

$$PET(i = \frac{\Delta(i)\left[R_n(i) - G(i)\right] + 86.7\rho(i)[e_d(i) - e_a(i)]/r_a(i)}{\lambda(i)[\Delta(i) + \gamma]} \tag{4}$$

where Δ is the slope of the saturation vapour pressure curve in kPa°C^{-1}, R_n is the net radiation in MJ m^{-2}, G is the soil heat flux in MJ m^{-2}, ρ is the air density in g m^{-3}, e_d is the saturation vapour pressure at mean air temperature in kPa, e_a is the vapor pressure at mean air temperature in kPa, r_a is the aerodynamic resistance for heat and vapour transfer in s m^{-1}, after Thom & Momentum (1972), with the plant height equal to that on 1 May plus the addition of the new shoot length of the chosen branch in the calculation period, γ is a psychrometer constant in kPa °C^{-1}, and λ is the latent heat of vaporization in MJ kg^{-1}.

Monthly actual evapotranspiration during the growth period of *P. euphratica* woodlands was determined in four steps. First, monthly potential evapotranspiration during the growth period was determined using data from field measurements. Second, the reduction factors for the various soil layers were determined from actual soil moisture contents, soil moisture at field capacity and soil moisture at wilting point (equation 1). Third, potential evapotranspiration extracted for each soil layer was calculated by multiplying the total potential evapotranspiration (equation 4) and the ratio of the effective root length in each layer to the total effective root length in all soil layers (equation 3). Fourth, monthly actual evapotranspiration in *P. euphratica* woodlands was calculated using equation (2).

Minimum ecological water requirement calculation Minimum ecological water requirement is calculated using the actual evapotranspiration from equation (5):

$$RW_{eco} = S\,\frac{ET}{1000}(1+\alpha) \qquad (5)$$

where, RW_{eco} is the minimum ecological water requirement (m^3); S is the total area of *P. euphratica* woodland (m^2); ET is the actual evapotranspiration (mm) calculated from equation (2) and α is a reduction coefficient expressing channel loss ($\alpha = 0.25$) (Wang *et al*., 2001).

RESULTS AND DISCUSSIONS

Results of the calculation process described above are presented in Tables 1 to 2 below. Both monthly potential evapotranspiration and monthly actual evapotranspiration of *P. euphratica* woodlands during the May–October growing period are shown in Table 1. The reduction factors for the various soil layers are shown in Table 2.

Water consumption patterns in *P. euphratica* woodlands

Amount of evapotranspiration of the whole woodlands During the May–October growing period of *P. euphratica* woodlands, the amount of actual evapotranspiration is greatest in July, and only slightly lower in June and August (Fig. 1).

Over the whole growth period, monthly actual evapotranspiration of *P. euphratica* woodlands is considerably smaller than monthly potential evapotranspiration, but far greater than monthly precipitation. Monthly actual evapotranspiration is only 15.7–40.2% of the monthly potential evapotranspiration, and monthly precipitation is only 3.8–8.7% of the monthly actual evapotranspiration, showing that in natural *P. euphratica* woodlands of this arid desert region water consumption does not come mainly from precipitation. Furthermore, moisture for evapotranspiration in depths 0–2 m is chronically deficient during the growing season (Table 3).

Table 1 Monthly potential evapotranspiration (mm) in *P. euphratica* woodlands during the growing period.

	May	Jun.	Jul.	Aug.	Sep.	Oct.	Growing period
Potential evapotranspiration	240.87	280.08	378.11	326.28	217.14	126.39	1568.87
Actual evapotranspiration	65.41	113.10	148.90	139.46	76.02	20.35	563.24

Table 2 Reduction factors in various soil layers of *P. euphratica* woodlands during the growing period.

	May	Jun.	Jul.	Aug.	Sep.	Oct.
0-10cm	0	0	0	0.0255	0	0
10-20cm	0.1034	0.1093	0.1790	0.2218	0	0
20-40cm	0.1021	0.1027	0.2780	0.1572	0.0146	0.0213
40-60cm	0.0711	0.0806	0.2767	0.2533	0.09768	0.0648
60-80cm	0.0916	0.0969	0.1120	0.1908	0.1070	0.1152
80-100cm	0.6874	0.8594	0.4301	0.4866	0.1824	0.0819
100-120cm	0.2135	0.2735	0.9409	0.8954	0.0403	0.0986
120-140cm	0.2116	0.3408	1	0.8731	0.1941	0.3597
140-160cm	0.2231	0.3415	1	1	0.2011	0.3612
160-180cm	0.4517	0.3629	1	1	0.3190	0.4107
180-200cm	1	1	1	1	1	1

Table 3 Proportional monthly actual evapotranspiration, potential evapotranspiration and precipitation in the growing period of *P. euphratica* woodlands.

	May	Jun.	Jul.	Aug.	Sep.	Oct.
Actual evapotranspiration/potential evapotranspiration (%)	33.00	34.80	39.00	38.00	40.20	15.70
Precipitation/actual evapotranspiration (%)	4.20	7.00	8.80	5.30	3.80	8.70

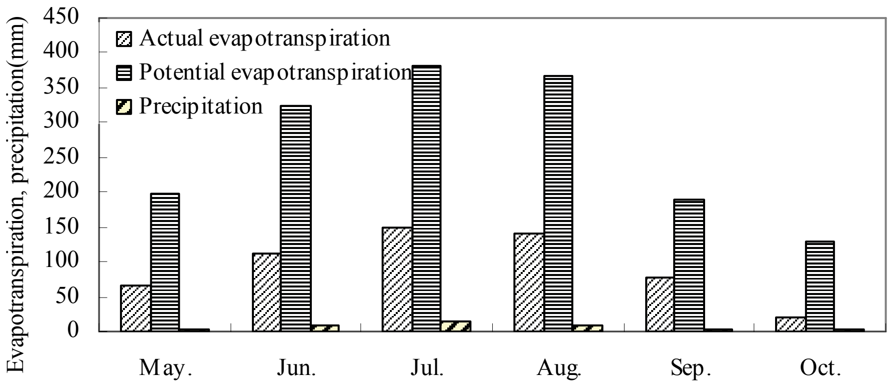

Fig. 1 Monthly actual and potential evapotranspiration and precipitation during the growing period of *P. euphratica* woodlands.

Source of water consumption in *P. euphratica* woodlands Ignoring lateral runoff (annual precipitation is very small), the water-balance equation of *P. euphratica* woodlands is:

$$P + E_g + W_{beginning} - W_{end} - ET = 0 \quad (6)$$

where P is the accumulated precipitation during a certain period (mm), E_g is the phreatic water supply during the period (mm), $W_{begining}$ and W_{end} are the soil moisture storage at the beginning of the period (mm) and that at the end of the period (mm), and ET is the evapotranspiration during the period (mm).

During the summer growing season, when $ET > P$, the water consumption of *P. euphratica* woodlands in the Ejina basin comes mainly from phreatic water supply and soil moisture storage.

Minimum ecological water requirement

According to Table 2 and equation (5), the minimum ecological water requirement of *P. euphratica* woodlands in the Ejina basin is calculated as 1.45×10^8 m^3 $year^{-1}$.

CONCLUSIONS

The water consumed by natural riverbank *P. euphratica* woodlands during the May–October growing season comes mainly from phreatic water and soil moisture storage, which makes it less dependent on precipitation. However, studies should be continued to find out the particular relationships between the amount of water consumption and the available phreatic water and soil moisture storage.

The minimum annual water requirement for natural *P. euphratica* woodlands in the Ejina basin is 1.45×10^8 m^3 $year^{-1}$. This means that in order to maintain the current extension and condition of *P. euphratica* woodlands, a minimum of almost 145 million cubic metres of water per year must reach the Ejina basin in the lower Heihe River. Impoundment and diversion of water in the upper Heihe River for agriculture and industry make this far from certain. It will be up to the managers of water resources to make allocation decisions that will support both economic development and the existence of natural woodlands.

In the paper, the spatial heterogeneity of *P. euphratica* woodlands in space is not considered. Studies should be continued to find methods to accurately represent *P. euphratica* woodlands in distributed hydrological modelling.

Acknowledgement This research is supported by the National Key Basic Research Program of China (2006CB400502).

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