

# Dynamics of willow tree (*Salix matsudana*) water use and its response to environmental factors in the semi-arid Hailiutu River catchment, Northwest China

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**Abstract** Sap flow (SF) of a willow tree, meteorological variables, soil water content, and water table depth were measured during the growing period from mid-April to October, 2011 in the semi-arid Hailiutu River catchment, Northwest China. The measurements of SF showed diurnal fluctuations in sunny days and seasonal changes from 1.65 l/h in mid-April to 33 l/h in July. At hourly scale, SF is significantly correlated with net radiation, followed by air temperature, relative humidity, and wind speed. At daily scale, air temperature affects the dynamics of SF significantly. Daily SF correlates positively with net radiation and negatively with relative humidity. There is no correlation observed between daily SF and wind speed. The measurements of SF do not indicate water stress although the experimental period is dry. Correlation analysis shows that SF is strongly correlated with soil moisture and water

table depth, indicating the willow tree uses both soil water and groundwater for transpiration.

**Keywords** Sap flow · Willow tree · *Salix matsudana* · Meteorological factors · Water use

## Introduction

Reforestation is carried out to alleviate land degradation in many semi-arid regions in the world (Lamb et al. 2005) and is one of the Chinese policies (Yang et al. 2012). However, one of the major concerns is the high rate of water use of forest plantations (Jackson et al. 2005; Qu et al. 2007; Cao and Wang 2010), particularly in semi-arid regions where water resources are scarce. Since the 1970s, large-scale ecological restoration programs have been carried out in Northwest China (Cao 2011). Consequently, water yields have dropped by 30 to 50 % in the semi-arid Loess Plateau due to water consumption by plants (Sun et al. 2006). Proper tree species selection might lower water use rates to acceptable levels (Kunert et al. 2010), but understanding of species-specific water use of trees and the response to environmental variables in semi-arid environments are very limited.

Different methods can be used to quantify tree water use, including Eddy covariance methods (Saugier et al. 1997; Sun et al. 2008; Ding et al. 2010), Bowen ratio energy balance systems (Malek and Bingham 1993; Zhang et al. 2007; Zeggaf et al. 2008), and various sap flow (SF) methods. SF measurements have been increasingly used since 1990s as the instruments are nowadays quite reliable and can be easily installed, and are less expensive than the use of lysimeters (Hall et al. 1998; Green et al. 2003; Pereira et al. 2007; Yue et al. 2008; Kume et al. 2011;

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Jonard et al. 2011; Ma et al. 2012; Mollema et al. 2013). SF can be measured by the heat-pulse (Alarcon et al. 2005), the heat-balance (Kjelgaard et al. 1997), and the thermal dissipation techniques (Guan et al. 2011; Jonard et al. 2011).

SF in semi-arid regions is very dynamic due to the variation of growing periods and meteorological factors (Oguntunde 2005; Liu et al. 2011). However, very few studies cover the entire growing season of trees in semi-arid regions but cover short periods of a few days to weeks (O'Brien et al. 2004; Oguntunde 2005). In arid regions of China, a few studies have been carried out to establish the relation between SF and environmental variables (Yue et al. 2008; Xia et al. 2008; Liu et al. 2011), and the interactions between SF and environmental variables are not well understood (O'Brien et al. 2004; Qu et al. 2007; Liu et al. 2011). In addition, SF and its response to the variation of environmental factors may vary strongly among species or locations in arid environments (Qu et al. 2007). However, to the best of the authors' knowledge, no study was done on the water use of *Salix matsudana* (willow) and its relation to environmental factors in terrestrial environments.

The objectives of this study are to analyze the response of SF to meteorological variables, soil water content and water table depth and to establish the relationship among them. The study will contribute to a better understanding of the dynamics of tree water use under seasonally changing environmental conditions in arid regions.

## Field measurements

### Site description

The study was conducted at an ecological experimental site in the Hailiutu River catchment in NW China (Fig. 1). The surface elevation is 1,250 m above sea level and the climate semi-arid. Based on the meteorological data for a 50-year period (1957–2007) from a meteorological station ~40 km northwest of the study site, the long-term average annual air temperature is 8.1 °C, and the lowest and highest monthly average air temperature is –8.6 °C in January and 23.9 °C in July. The average annual precipitation is 340 mm and about 70 % occurs between July and September. The average annual potential evaporation is estimated to be 2,180 mm. The lowest monthly average wind speed is about 1.5 m/s in December and January and the highest is about 3.2 m/s in April. Soils are characterized by eolian and lucustrine sands, and have a thickness of ~50 m, and are highly susceptible to wind erosion due to the coarse texture and low cohesion. The depth to water

table was around 1.5 m and the range of variation during the experimental period was 52 cm. The landscape includes fixed, semi-fixed sand dunes, and farmland. The dominant plants are willow trees (*S. matsudana*) and bushes. Willow trees were planted in the 1970s in the study area for the three North Shelterbelts Forest project. Planting density is about 16 trees per 100 m<sup>2</sup>. One representative healthy willow tree was selected for this study. The height of the willow tree was 2.6 m, the stem circumference at a height of 1.3 m was 70 cm, and the crown-to-stem diameter was 1.8 m.

### Measurement of meteorological variables

Meteorological parameters were measured by a meteorological station about 200 m away from the experimental site. Wind speed (m/s) was measured with a 05130-5 RM Yong wind monitor (R.M. Young Co., Michigan, USA) at 5.3 m above the ground, about 2 m above the top of the willow tree. Air temperature (°C) and relative humidity (%) were measured with a thermo-hygrometer (HMP45C, Vaisala Co., Helsinki, Finland) at 4.3 m. Net radiation (W/m<sup>2</sup>) was measured using a NR-LITE sensor (Kipp & Zonen, Delft, The Netherlands). Precipitation rate (mm/h) was recorded using a rain gauge (type 52203 RM Young rain gauge, R.M. Young Co., Michigan, USA). All these variables were sampled every 60 s, and recorded as 1-hour means with an automatic data logger (CR3000, Campbell Scientific Inc., Utah, USA). The meteorological variables were measured from April to November, 2011. Air temperature and relative humidity were used to calculate water vapor pressure deficit (VPD, kPa):

$$S = \exp\left(\frac{17.27T}{237.3 + T}\right), \quad (1)$$

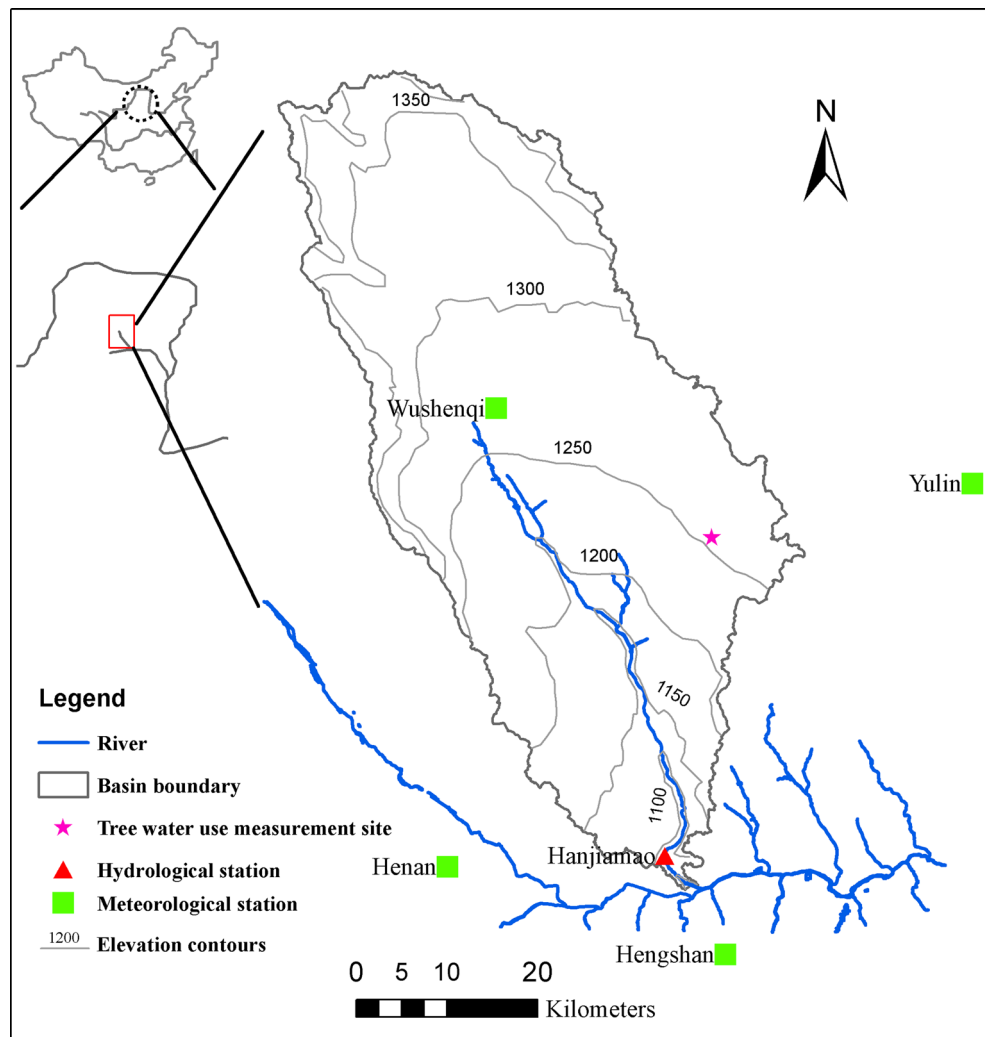
$$\text{VPD} = S - S \times \text{RH}/100$$

where  $S$  is the saturation air pressure (kPa), RH is the relative air humidity (%), and  $T$  is the air temperature (°C).

### Measurement of soil moisture and water table depth

Soil water content was monitored using a Time Domain Reflectometry System (miniTrase, Soilmoisture equipment Corp., Santa Barbara, CA, USA) from May to November. Five probes were installed at the depth of 10, 20, 40, 70, and 100 cm. The water table depth is shallow (around 1.5 m), and the capillary rise is around 47 cm. In a nearby location, the measured soil water content at 130 cm depth is constantly saturated. Therefore, we placed five sensors at shallow depths. Soil water content was recorded every 4 h. Groundwater levels were measured hourly using a MiniDiver (Eijkelpamp Agrisearch Equipment, Giesbeek,

**Fig. 1** Location of the study site



The Netherlands) installed in a borehole next to the willow tree. Barometric effects were removed from the observed groundwater levels using the air pressure measured by a BaroDiver (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) at the same site. Groundwater levels were reported as the height of water column above the MiniDiver.

Measurement of SF of willow trees

The thermal dissipation method (Granier 1985) was used to measure the SF velocity from 20 April to 7 November 2011, covering the entire growing season. Five sensors (FLGS-TDP XM1000, Dynamax Inc., Houston, TX, USA) were installed at different orientation at a height of 1.3 m. Each sensor has two metal probes with a diameter of 2 mm and a length of 20 mm. The heated probe is equipped with a heating element and the reference probe has no heating element. The sensors were installed following strictly the

manufacturer’s instructions. A plastic protection and an aluminum shield were used to protect the sensors from rain and solar heating. The data were recorded every 10 s and stored as 1 h averages using a data logger powered by a 12-V battery (CR1000, Campbell Scientific, Logan, UT, USA). SF velocity was calculated using the empirical equation (Granier 1985):

$$SF = 3600 \times 0.0119 \times \left( \frac{\Delta T_m - \Delta T}{\Delta T} \right), \tag{2}$$

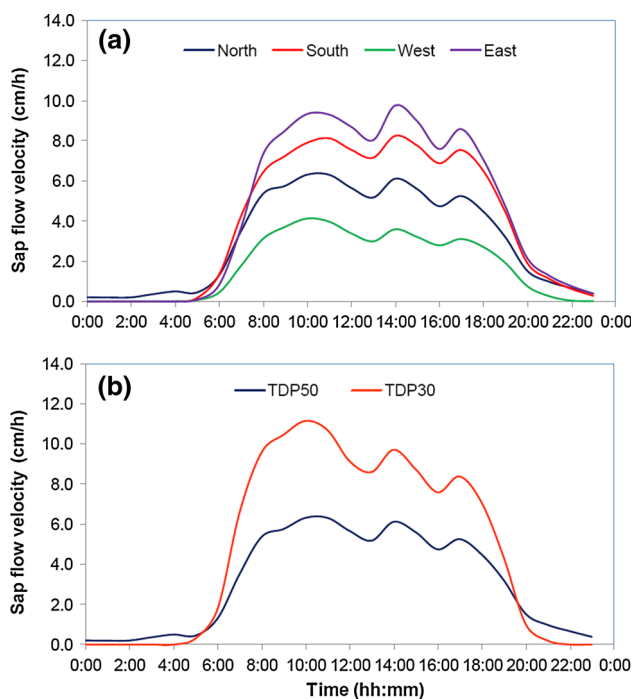
where SF is the sap flow velocity (cm/h),  $\Delta T$  is the temperature difference (°C), and  $\Delta T_m$  is the maximum temperature difference with zero SF (°C).

In order to calculate the sapwood area, the willow tree was cut down after the experiment and a tree disc was immersed into a blue dye solution overnight and was photographed afterwards. The sapwood area of the willow tree was determined to be 274.6 cm<sup>2</sup>.

## Results

### Sap flow

SF velocity shows circumferential heterogeneity as well as radial heterogeneity (Fig. 2). SF velocity is highest in the eastward direction, followed by south, north, and west (Fig. 2a). In northward direction, SF velocity in a shorter distance (TDP30, 30 mm) is higher than that with the longer distance (TDP50, 50 mm) (Fig. 2b). Although the magnitudes of SF velocity are different, diurnal fluctuation patterns are almost the same. The correlation coefficients of SF velocity of the five sensors are very high ranging from 0.95 to 0.99. The differences in aspects and radial distance are caused by heterogeneity of the sapwood, while diurnal and seasonal variations are caused by meteorological and water sources factors. Therefore, mean SF velocity was used in the analysis of SF variations in relation to environmental factors. The hourly mean SF velocity during a sunny day around the 20th of each month is shown in Fig. 3 and shows clearly diurnal fluctuations. The shape of the SF curves versus time in May, June, and July was similar, but the magnitude of SF was higher in July. SF started to increase around 6:00 in the morning, reached peak values during midday, and went back to minimum values around 20:00 in the evening. In August and September, SF started at around 9:00, reached peak values between 13:00 and 15:00, and showed minimum values around 20:00. In October, the values of SF were close to zero.



**Fig. 2** Measurements of sap flow velocity on June 10 in different aspects (a) and in different radial distance in North direction (b)

SF was obtained by multiplying mean SF velocity with the sapwood area (Fig. 4). SF increased significantly from 1.7 l/d in mid-April to 22.0 l/d in mid-May, reached the highest value of about 33.0 l/d in July, and decreased gradually to 16.5 l/d at the end of September. SF dropped to about 2.8 l/d in October. In the entire growing period, about 3.2 m<sup>3</sup> of water was consumed by the tree.

Wullschleger et al. (1998) listed water use of 93 plants ranging from 10 to 1,180 l/d. The average SF of the willow tree is about 13 l/d; therefore, willow trees seem to be suitable for reforestation purposes. Previous studies show that some bushes consume less water and can be used for preventing land desertification in arid regions. For example, SF was about 3.4 l/d for *Caragana korshinskii* (peashrub) over the growing season (Yue et al. 2008), about 4.2 l/d for *Tamarix elongate Ledeb* (salt cedar) (Qu et al. 2007), and about 0.2 l/d for *Artemisia ordosica* (mugwort) (Huang et al. 2010).

### Meteorological variables

The meteorological variables also show clear diurnal variations (Fig. 5). Net radiation reached its highest values at 12:00 and became negative during the night. Air temperature reached its highest values around 15:00, 3 h later than the peak of net radiation. Relative humidity was low during daytime and high during night, and the minimum relative humidity occurred at 15:00. Wind speed was high during the day and low during the night in general, but there were more complex fluctuations.

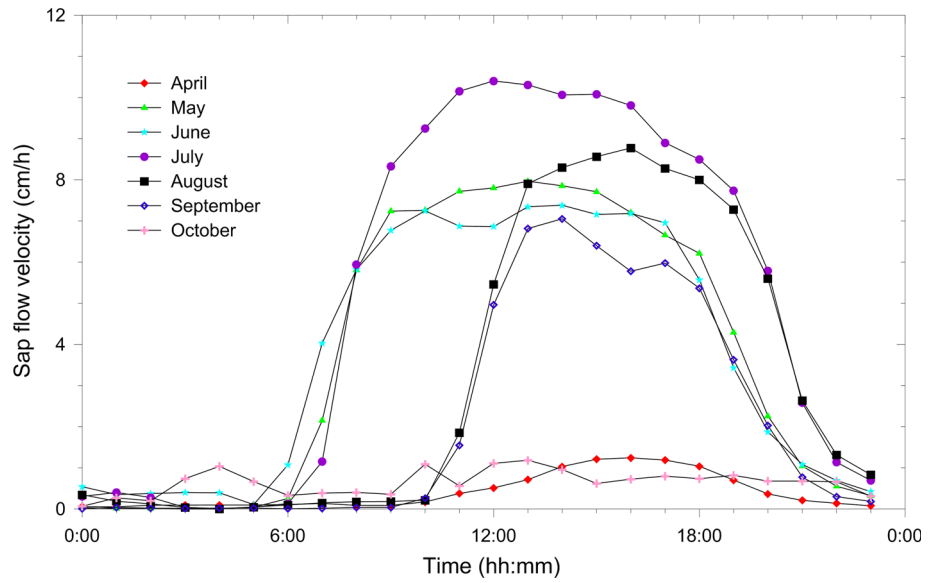
Daily meteorological data are shown in Fig. 6. Net radiation increased from April onwards, reached the highest values of over 200 W/m<sup>2</sup> in July, and then decreased from September until the end of the study period. Air temperature has a similar seasonal pattern as net radiation. Relative humidity was 33 % on average before June and then increased. Wind speed was higher before June and the average wind speed was 2.15 m/s.

In the study period, rainfall occurred in 55 days. About 80 % of daily rainfall is <5 mm, and heavy rainfall (>20 mm/d) only occurred two times. The cumulative rainfall is 189.6 mm and occurred mainly in May (68 mm) and July (53 mm). The growing season in 2011 is relatively dry, and the cumulative precipitation is only 62 % of the long-term average rainfall. The pattern of rainfall is similar to that in other arid regions (Loik et al. 2004; Zhao and Liu 2010).

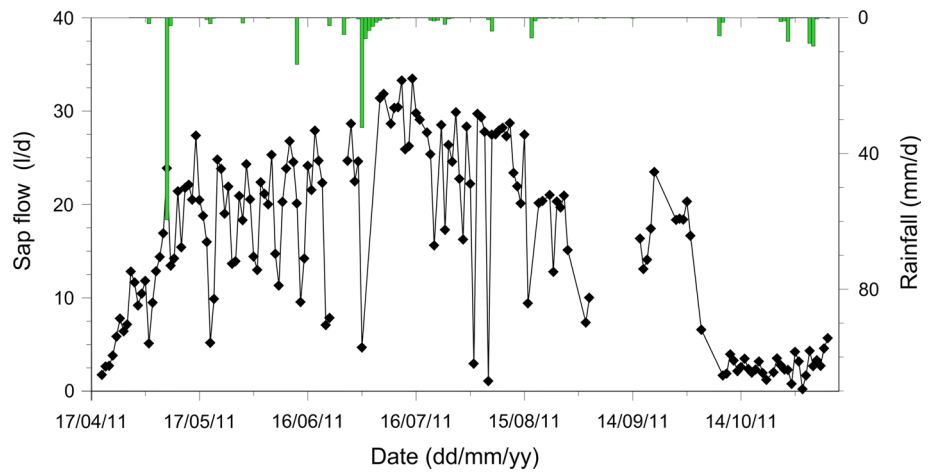
### Relation between SF and meteorological variables

Correlation coefficients between hourly SF velocities and meteorological variables were calculated and are shown in Table 1. From May to September, hourly SF velocity is

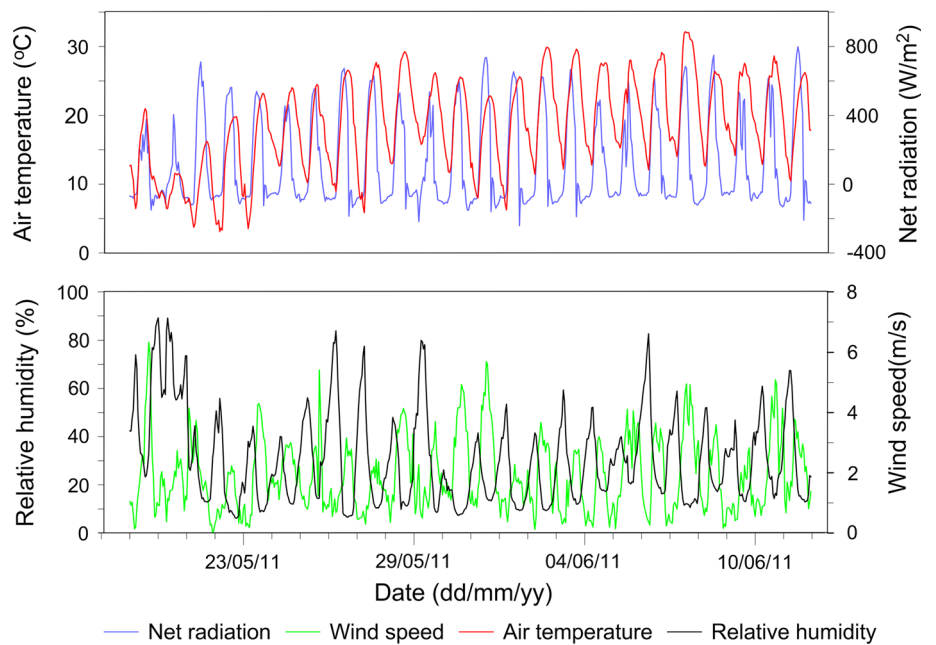
**Fig. 3** Diurnal variations of sap flow of the willow tree in different months



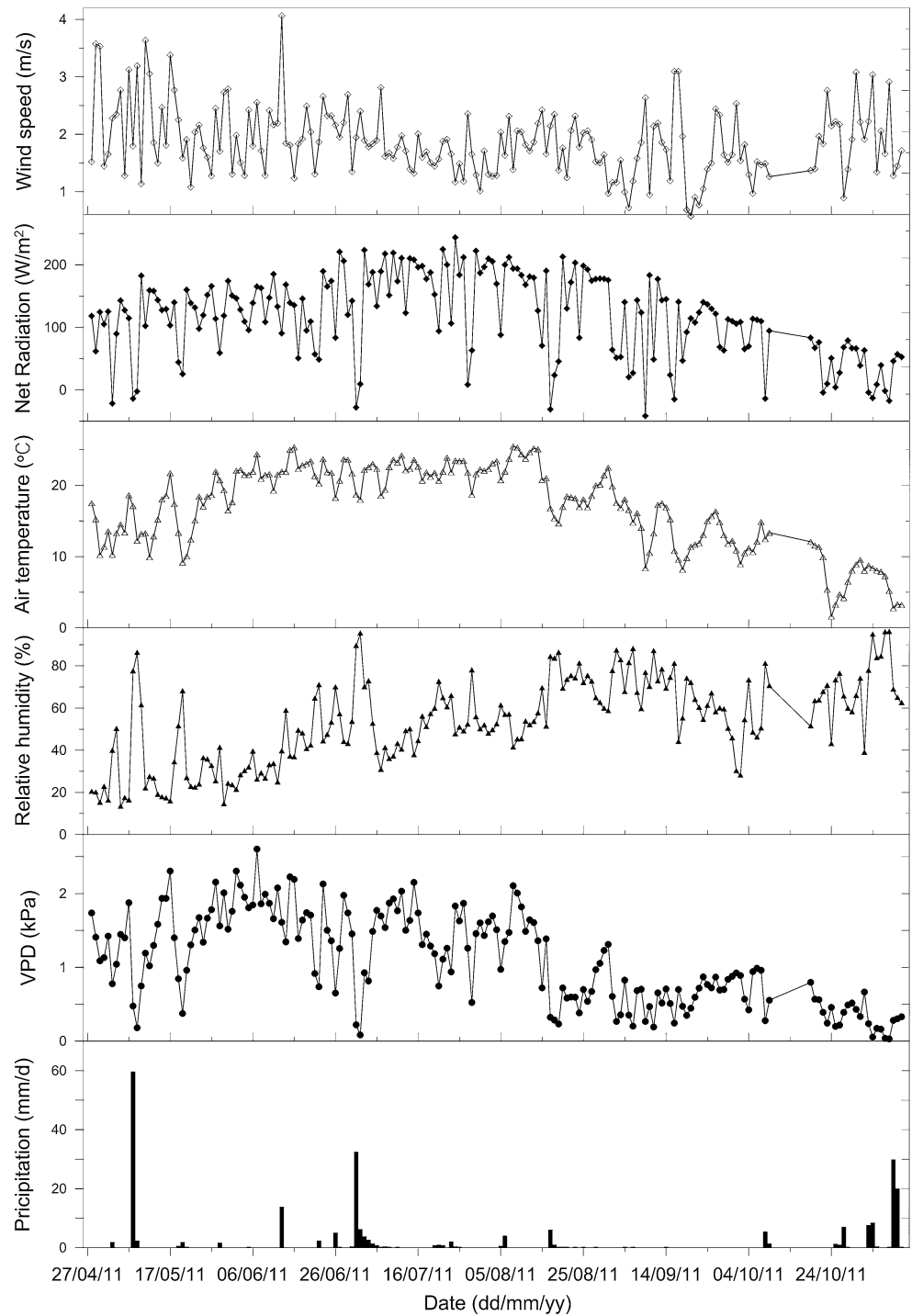
**Fig. 4** Daily variation of sap flow of the willow tree



**Fig. 5** Diurnal fluctuations of meteorological variables



**Fig. 6** Daily variations of meteorological variables



significantly correlated with net radiation, VPD, and air temperature, with an average correlation coefficient of  $R = 0.75$ ,  $0.63$  and  $0.62$ , respectively. It is also correlated with relative humidity and wind speed, with an average correlation coefficient of  $R = -0.44$  and  $0.41$ , respectively. Correlation coefficients of daily SF with daily meteorological variables were calculated and are shown in Table 2. The correlation coefficients between SF and net

radiation and relative humidity are  $0.1$  smaller than the hourly data. The correlation coefficient between SF and air temperature is highest ( $0.72$ ); therefore, air temperature has more influence on SF than net radiation in daily scale, while wind speed has less influence on SF.

Correlation coefficients between hourly SF velocities of an adjacent willow tree and meteorological variables measured from May to September 2012 indicate that

**Table 1** Correlation coefficients between hourly sap flow velocity and meteorological variables

	Net radiation (W/m <sup>2</sup> )	VPD (kPa)	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)
Total	0.75**	0.63**	0.62**	−0.44**	0.41**
May	0.76**	0.58**	0.65**	−0.39**	0.53**
June	0.78**	0.54**	0.58**	−0.46**	0.56**
July	0.86**	0.81**	0.83**	−0.75**	0.42**
August	0.68**	0.71**	0.71**	−0.70**	0.51**
September	0.57**	0.58**	0.39**	−0.52**	0.32**

\*\* Indicates  $P < 0.01$

**Table 2** Correlation coefficients between daily sap flow velocity and meteorological variables

	Net radiation (W/m <sup>2</sup> )	VPD (kPa)	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)
Total	0.65**	0.65**	0.72**	−0.34**	−0.09
May	0.26	0.50**	0.57**	−0.32	0.10
June	0.32	0.25	0.19	−0.20	0.17
July	0.78**	0.89**	0.58**	−0.88**	0.03
August	0.19	0.37*	0.36*	−0.28	−0.20
September	0.30	0.23	0.45*	−0.30	−0.09

\* Indicates  $P < 0.05$  and \*\* indicates  $P < 0.01$

**Table 3** Regression coefficients for different months

	$b_0$	$b_1$	$b_2$	$b_3$	$b_4$	$R^2$
Total	−0.55	0.0062	0.15	−0.0092	0.22	0.68
May	−0.73	0.0053	0.15	−0.0030	0.19	0.72
June	−0.30	0.0068	0.10	−0.0011	0.37	0.70
July	−1.49	0.0067	0.24	−0.0027	0.29	0.89
August	−0.68	0.0043	0.18	−0.0026	0.69	0.68
September	2.43	0.0043	0.09	−0.0029	0.17	0.41

hourly SF velocity is significantly correlated with net radiation, VPD, and air temperature, with an average correlation coefficient of  $R = 0.83, 0.66,$  and  $0.65,$  respectively. It is also correlated with relative humidity and wind speed, with an average correlation coefficient of  $R = −0.56$  and  $0.39,$  respectively. It means that net radiation affects the dynamics of SF significantly in hourly scale, which is consistent with the correlation analysis for data collected in 2011.

The multiple linear regressions of hourly SF and net radiation, air temperature, relative humidity, and wind speed were performed with the following regression equation:

$$SF = b_0 + b_1R_n + b_2T + b_3RH + b_4U, \tag{3}$$

where SF is sap flow velocity (cm/h),  $R_n$  is net radiation (W/m<sup>2</sup>),  $T$  is air temperature (°C), RH is relative humidity (%), and  $U$  is wind speed (m/s). The regression coefficients ( $b_0$  to  $b_4$ ) were estimated and listed in Table 3. The coefficient of determination ( $R^2$ ) is higher than 0.7 for May, June, July, and August, but it is as low as 0.41 for September.

### Correlation between SF and water sources

Soil water content at different depths and groundwater levels in the observation well from May 19 to June 11 are plotted in Fig. 7. Soil moisture decreased by 2 % and groundwater levels decreased by 14 cm during this dry period. Table 4 shows the correlation matrix among soil water content at different depths, groundwater level, and the cumulative SF. It can be seen that the cumulative SF is strongly negatively correlated to soil water content at all depths and groundwater level. The correlation coefficients range from −0.92 to −1.00. It can be concluded that the transpiration of the tree causes the continuous decline of soil water content and groundwater level. Groundwater provides an important water source to the willow tree during the long dry period.

## Discussion

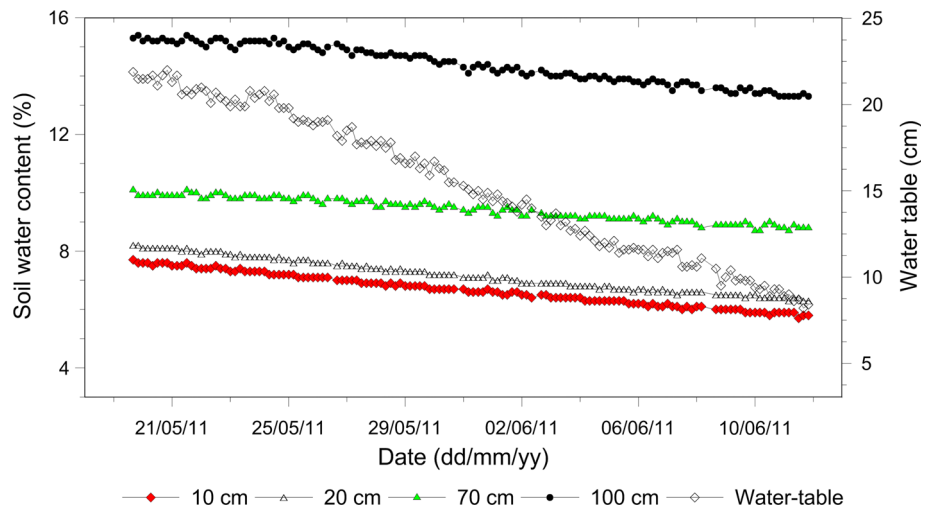
### Sap flow variations

The starting time of SF at different seasons is consistent with previous studies in arid regions of Northwest China (Xia et al. 2008; Huang et al. 2010; Guan et al. 2011). The seasonal variation of the starting time is due to the seasonal change of sunrise time. Based on the time of sunrise at the study site (<http://www.sunrisesunsetmap.com>), the time of sunrise is around 5:30 in May, June, and July and changes to 6:30 in September.

SF was measured also during the night as shown in Fig. 3, indicating that roots can take up water during the night (Si et al. 2004; Zhang et al. 2004; Bai et al. 2005). Commonly stomata are closed at night and open in the morning in response to sunrise. However, the stomata of some plants remain open during the night and transpiration may occur in favorable conditions, such as elevated VPD or strong wind (Green et al. 1989; Chu et al. 2009).

A rapid increase of SF from mid-April to early May might be due to the increase of leaf area index as observed by Guan et al. (2011) and Huang et al. (2010). During this period, the leaf area of plants increases quickly in similar areas (Du et al. 2001). A sharp decrease of SF in early October is due to low air temperature. After a small rain in early October, temperature dropped to nearly 0° during

**Fig. 7** Decreases of soil water content and groundwater level during a long dry period from May 19 to June 13

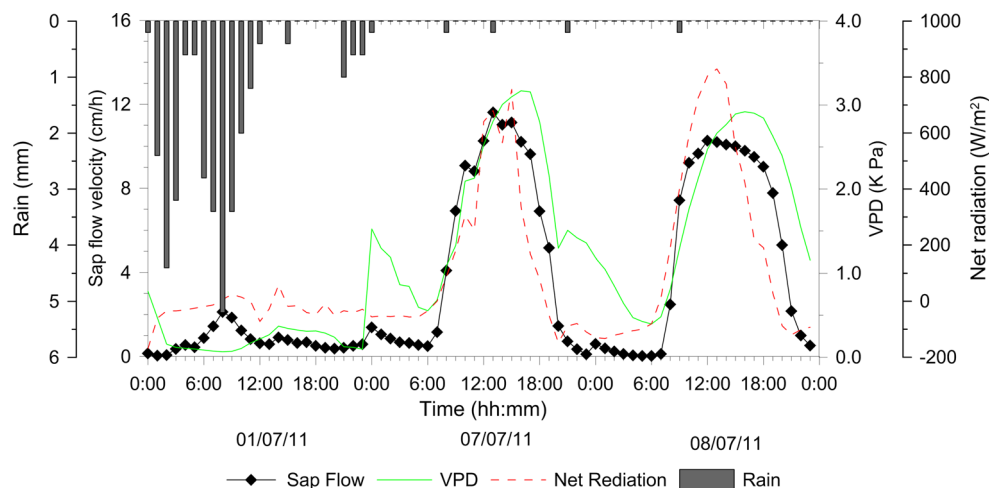


**Table 4** Correlation matrix of the cumulative sap flow with water sources during a long dry period from May 19 to June 11, 2011

	10 cm	20 cm	40 cm	70 cm	100 cm	Groundwater level	Cumulative SF
10 cm	1.00						
20 cm	0.97**	1.00					
40 cm	0.94**	0.99**	1.00				
70 cm	0.93**	0.98**	0.99**	1.00			
100 cm	0.95**	0.98**	0.99**	0.99**	1.00		
Groundwater level	0.96**	0.99**	0.99**	0.98**	0.99**	1.00	
Cumulative SF	-0.92**	-0.98**	-1.00**	-0.99**	-0.99**	-0.98**	1.00

\*\* Indicates  $P < 0.01$

**Fig. 8** Relation between sap flow and rainfall in early July, 2011



night. Low temperature slows down metabolism and modifies membrane lipids.

Effects of meteorological variables on SF variations

The decline of SF during rainy days has been widely reported (Qu et al. 2007; Xia et al. 2008; Zhao and Liu 2010). When rainfall is larger than 1 mm/d, SF on the

following day is usually dramatically lower than on the previous one (Fig. 4). However, an exception is the SF of the 8th of May when a heavy rainfall event (59.6 mm) occurred. SF increased dramatically and was about 1.5 times larger than on the previous sunny days (Fig. 4). The phenomena may be caused by stem refilling as it experienced a long-term dry period before May 8 (Fig. 4). Peak values of SF increased after heavy rainfall (larger than



10 mm/d) as soil moisture increased. The peak value of SF was 6 cm/h before the rainfall during early July and was 8 cm/h after the rainfall.

Previous studies showed good correlations between SF of different plants and radiation in arid regions (Oguntunde 2005; Kume et al. 2011). As shown in Fig. 8, SF followed the variation of net radiation. SF is also affected by air temperature and relative humidity that are often combined into VPD indicating atmospheric water demand. Figure 6 shows that VPD gradually declined after the middle of August, and SF followed a similar trend (Fig. 4).

However, the effect of wind speed on SF is less obvious in the study area. At hourly scale, wind speed is positively correlated with SF (Table 1). At a daily scale, wind speed is not correlated to SF (Table 2). In the hourly data set, wind speed has the similar diurnal fluctuation as SF; therefore, a weak positive correlation exists. However, in daily data, diurnal patterns of both wind speed and SF were averaged out, and daily average wind speed is not correlated to daily SF. In arid environments, humidity is very low, transpired water can be absorbed by dry air, and wind is not required to blow the air moisture away. Therefore, in general, correlation between SF and wind speed is lowest comparing with other meteorological factors.

## Conclusions

SF of the willow tree shows diurnal and seasonal variations. The diurnal fluctuation is found to be driven mainly by net radiation. Air temperature is the main controlling factor for the seasonal variation of SF. However, wind speed has no impact on daily SF.

The major water consumption of the willow tree occurs in May, June, July, August, and September. Multiple regression equations between the hourly SF and net radiation, temperature, relative humidity, and wind speed were established for the months of growth. The growing season of 2011 is relatively dry, and the total precipitation is only 62 % of the long-term average precipitation in the same period. However, SF does not show water stress of the willow tree. The willow tree was found to have access to groundwater.

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