Evapotranspiration and its main controlling mechanism over the desert riparian forests in the lower Tarim River Basin

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Evapotranspiration (ET) and its controlling mechanism over the desert riparian forests in arid regions are the important scientific basis for the water resources managements of the lower reaches of the inland rivers of China. Nearly three years of continuous measurements of surface ET, soil water content at different depths and groundwater table over a typical *Tamarix* spp. stand and a typical *Populus euphratica* stand were conducted in the lower reach of the Tarim River. The ET seasonal trends in the growing season were controlled by plant phenology, and ET in non-growing season was weak. The diurnal variations of ET resulting from the comprehensive effects of all atmospheric factors were significantly related with reference ET. The spatial pattern of ET was determined by vegetation LAI, more vegetation coverage, more ET amount. Groundwater is the water source of surface ET, and the soil water in shallow layers hardly took part in the water exchange in the groundwater-soil-plant-air system. The temporal processes of ET over the *Tamarix* stand and the *Populus* stand were similar, but the water consumption of the well-grown *Populus euphratica* was higher than that of the well-grown *Tamarix* spp. Further analysis indicates that plant transpiration accounts for most of the surface ET, with soil evaporation weak and negligible; groundwater table is a crucial factor influencing ET over the desert riparian forests, groundwater influences the processes and amounts of ET by controlling the growth and spatial distribution of desert riparian forests; quantifying the water stress of desert riparian forests using groundwater table is more appropriate, rather than soil water content. Based on the understanding of ET and water movements in the groundwater-soil-plant-air system, a generalized framework expressing the water cycling and its key controlling mechanism in the lower reaches of the inland rivers of China is described, and a simple model to estimate water requirements of the desert riparian forests is presented.

lower reaches of the Tarim River, water cycling, evapotranspiration, desert riparian forests, *Tamarix* spp., *Populus euphratica*

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The inland rivers are the main source of water resources in arid northwestern China. Revealing the water cycling processes of these inland rivers and their controlling mechanism is an important scientific basis for managing water resources in the arid northwestern China. The attention of

the relevant researches generally focused on the upper and middle reaches of these inland rivers because the upper reaches are the areas of producing water resource, and the middle reaches are the main water consuming area for human beings. However, less attention has been given to the researches on the water cycling in the lower reaches of these inland rivers, including the exchanges between river water and groundwater, the water movements in the groundwa-

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ter-soil-plant-air system and the surface evapotranspiration (ET) processes. In the lower reaches of these inland rivers, the long and narrow riparian forests along the rivers usually develop, and it is important for managing the environment and controlling the desertification in the lower reaches (Shi, 2004). In the lower reaches of the Tarim River, which is the longest inland river of China, the desert riparian forests zone is also called “Green Corridors” (Fang, 2001), which ensures the transportation between the northern and southern areas of the Tarim Basin. The understanding of the water cycling processes and its influencing factors of the lower reaches of the inland rivers, especially of the desert riparian forests, can help quantify the water consumptions and water requirements of the desert riparian forests, understand the maintaining mechanisms of the desert riparian forests, improve the water resource management of these inland rivers, and enhance the ability of controlling desertification in arid region of China.

The previous relevant researches on hydrology and water resources in the lower reaches of the inland rivers of China were mainly conducted at two aspects. One was interested in the hydrological controls of the desert riparian forests, mainly exploring the relationships between groundwater and vegetations, from leaf scale to communities level (Chen et al., 2003, 2006; Hao et al., 2008, 2010; Zhang et al., 2011; Zhu et al., 2012; Wang et al., 2014; Li et al., 2008, 2013). The other attempted to estimate ecological water requirements of the desert riparian forests for the water resource management (Wang et al., 2002, 2005; Liu, 2004; Ye et al., 2007; Chen et al., 2007; Chen et al., 2008a). Most researches focused on the ecophysiological and ecohydrological processes, but the hydrological processes, particularly the water movements and ET over the desert riparian forest zone, have received little study.

All of the lower reaches of the inland rivers in China are located in hyper-arid regions with scarce precipitation. The water cycling process in the lower reaches can be simply characterized as a process of the water movement from the river water to groundwater, and then to the surface ET, in which the water movement in the groundwater-soil-plant-air system is one of the critical processes controlling the water cycling in the lower reaches. In addition, the desert riparian forests are one of the most valuable landscapes in the lower reaches. ET over the desert riparian forests is the main form of water resources consumptions in these regions. Therefore, revealing the characteristic of water movements and ET in the groundwater-soil-plant-air system can help understand the water cycling processes and their critical controlling mechanisms in the lower reaches of the inland rivers of China.

In this study, we selected a well-grown *Tamarix* spp. stand and a well-grown *Populus euphratica* stand in the lower reach of the Tarim River to conduct our field observations. Based on the eddy covariance (EC) method, the carbon and vapor fluxes, energy balance, radiation balance,

soil water content at different depths and groundwater table were measured concurrently in the last three years. In this paper, we focus mainly on the water movement in the groundwater-soil-plant-air system and ET over the *Tamarix* stand and the *Populus* stand. Our objective is to reveal ET temporal and spatial processes and their controlling mechanisms. These results will improve our understanding of water cycling processes in the lower reaches of the inland rivers of China, and provide new scientific ideas for managing water resources and desertification control in these regions.

1 Materials and methods

1.1 Site descriptions

The lower reach of the Tarim River are located between the Taklamagan Desert and Kuluk Desert, from the Daxihaizi reservoir to the terminal Taitmar Lake with a length of approximately 250 km (Chen et al., 2004). This region is located in the typical continental temperate hyper-arid climate zone. According to the meteorological records of the Tieganklik Weather Station, located in the lower Tarim River Basin, the average annual temperature is 10.7°C, annual accumulated temperature is 4167.7°C, annual total solar radiation is 6180 MJ m⁻², annual sunshine number is about 3118.7 h, with 220 frost-free days. The mean annual precipitation was 33.7 mm from 1957 to 2012; however, the annual potential evapotranspiration can reach more than 2000 mm (Chen et al., 2006). The plant communities in this area can mainly be classified into two categories: *Populus* (*Populus euphratica*) forest and *Tamarix* (*Tamarix* spp.) forest. *Populus* forest belongs to arbor forest and *Tamarix* forest belongs to shrub forest. The species richness in the plant communities is low. The coverage of community in this area is also low due to poor water condition (Chen, 2010).

Two typical and well-grown riparian forests were chosen to conduct our field observation (Figure 1). The *Populus* forest is located at 40°25′59″N, 88°01′34″E, with an altitude of 844 m, and the *Tamarix* stand located at 40°25′59″N, 88°01′34″E, with an altitude of 846 m.

The *Tamarix* stand chosen for observation covers an area of approximately 300 m × 300 m. The dominant species in the stand are *Tamarix ramosissima*, *Tamarix hispida* and *Tamarix elongata*. Small amounts of other shrubs and herbs, such as *Lycium ruthenicum*, *Halimodendron halodendron*, *Phragmites australis*, *Apocynum venetum*, *Alhagi sparsifolia*, *Karelinia caspica*, *Glycyrrhiza inflata*, grow in the communities. The Simpson diversity index of the observation site is 0.71, the vegetation cover is 0.65, and the leaf area index (LAI) measured by LAI-2250 (Li-cor, Nebraska USA) is 1.15. The soil of the observation site is predominately silt loam with approximately 20 cm of a dry sand surface layer. The average soil bulk density is approximately 1.3 g cm⁻³. The depth of the water table (DWT) fluctuates around 6 m.

Figure 1 Locations of the observation stands in the lower reach of the Tarim River.

The *Populus* stand chosen to observe stretches along the river for about 1.5 km, with a width of about 500 m. The canopy height here is about 10 m. Besides some pieces of reed spreading along the river bank, the *Populus euphratica* is the only species in the observation area. The forest is well grown, with 0.49 coverage rate. The leaf area index observed by LAI-2250 canopy analyzer is 0.57. The soil texture in root layer is slightly complex, and at depths of 0–3 m, soil is silt loam, while below 3 m, soil is sandy. The DWT fluctuates around 3.8 m.

1.2 Observation and data processing

1.2.1 Flux measurements and data processing

Two EC observation towers were used to measure fluxes of momentum, sensible heat (H) and latent heat (LE) in *Populus* stand and *Tamarix* stand, respectively. The core flux instrumentation consists of a high-frequency (10 Hz sampling with a 30-min integration period) sonic anemometer (CSAT3, Campbell Scientific, USA), and an open-path infrared H_2O/CO_2 gas analyzer (EC150, Campbell Scientific, USA) to measure momentum, heat, vapor and CO_2 flux. Both wind speed and gas concentration measurements and their fluctuations were obtained at a frequency of 10 Hz. Down- and up-welling long- and short-wave radiation were measured using a CNR4 net radiometer (Kipp & Zonen,

Delft, Netherlands). Two heat flux plates (HFP01-L, Campbell Scientific, USA) were buried 0.08 m below the surface to measure the soil heat flux. Four thermocouple temperature sensors (109, Campbell Scientific, USA) were buried in the upper 0.02 m and 0.06 m. A datalogger (CR3000, Campbell Scientific, USA) was used for raw data collection and online flux data preliminary processing. The sonic anemometer and the gas analyzer were set at 1.8 m above the canopy for *Tamarix* stand and 5 m for *Populus* stand. The CNR4 net radiometer was set at 1.5 m above the canopy for *Tamarix* stand and 3.5 m for *Populus* stand.

The EdiRe software (School of Geosciences, University of Edinburgh) was used for the post-processing of the EC data, including spectral correction, coordinate rotation density correction and gap filling. The half-hourly turbulent fluxes and meteorological variables were again screened to remove spurious data points caused by sensor malfunction, rain events, and sensor maintenance. The energy balance was forced to close according to the Bowen ratio (Wohlfahrt et al., 2009) to obtain the sensible heat flux and latent heat flux data.

1.2.2 Other measurements

Air temperature and relative humidity were measured at 3.5 m (HMP155A-L, Vaisala, Helsinki Finland) above the ground for *Tamarix* stand, and 15 m for *Populus* stand. An

automatic rain gauge (52203, RM Young Inc., USA) was placed at an empty plot in the south of the flux tower in the *Tamarix* stand to record precipitations.

Proximal to the flux tower in *Tamarix* stand at depths of 0.3, 0.6, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, and 5.0 m, soil volumetric water content (SWC) was measured every 30 min using 9 frequency domain capacity (FDC) sensors (FDS100, Unism, Beijing, China). The FDC sensors were calibrated at the field in this research.

A 20-m-deep observation well was drilled, 30 m from the flux tower, and an automatic groundwater table logger (CTD-Diver, Eijkelcamp, EMGiesbeek Netherlands) was placed to record the DWT and water temperature. The DWT was corrected by air pressure measured by the EC system.

All of these factors were measured every 30 min and recorded by the CR3000 datalogger except that the depth of the water table was recorded by the sensor itself.

1.2.3 Statistic method

Statistical analysis of data and the calculation of statistics were conducted using the SigmaPlot v12.3 software (Systat Software Inc. Illinois, USA).

1.3 Calculations

1.3.1 Calculations of ET and reference ET

Hourly ET was calculated based on the observed hourly *LE* value. The quality of the EC data in the night is poor because of the weak turbulence, and ET is weak in the night. To reduce the impact of poor quality observation data in the night on the results, the daily ET was the sum of the hourly ET at daytime ($\text{PAR} > 1 \text{ W m}^{-2}$). The ET was compared with the reference ET (ET_0). The ET_0 was calculated from Penman-Monteith equation corrected by FAO (Allen et al., 1998) at daily and hourly scales. The daily weather data used to calculate the daily ET_0 were from the Tieganlik Weather Station, and the data used to calculate the hourly ET_0 were from the observation at our flux tower.

1.3.2 Calculation of groundwater evapotranspiration

Hourly or even higher frequent measurements of the groundwater table are able to reveal the diurnal fluctuation of the groundwater table. Based on the principle of water balance, White et al. (1932) presented a method to estimate the daily groundwater evapotranspiration (ETg) based on the groundwater table diurnal variation, as the following equation:

$$\text{ETg} = S_y (24r \pm s), \quad (1)$$

where ETg is daily groundwater evapotranspiration (mm d^{-1}), S_y is specific yield (dimensionless), r is the groundwater recharge rate (mm h^{-1}), and s is the groundwater storage change, which equals the rise or fall of the groundwater table after 24 h (downward is positive, mm d^{-1}). Variables r and s are both determined by the 24 h water table fluctua-

tion curve.

S_y is of crucial importance because errors in S_y estimation directly translate to the ETg estimates. In this study, a readily available S_y (Loheide et al., 2005) was selected. The readily available S_y value was determined solely from the soil texture at the depth of the groundwater table. The S_y value used in this study was finely determined based on the soil textures at the depth of the groundwater table in the *Tamarix* stand using the method presented by Loheide et al. (2005). The S_y value was 0.065. r value was obtained as the slope of the groundwater hydrography during 3–7 a.m. (Beijing time), when the plant root water uptake ceased. The value s is the net fall or rise of the water table in the 24 h period. In this study, s values were determined from the difference between the two water levels at 0 a.m. today and the subsequent day.

2 Results

2.1 Temporal processes and the control factors of ET

2.1.1 Seasonal variation

Figure 2 shows the seasonal variations of daily ET in 2013 over the *Tamarix* stand and the *Populus* stand, and the comparison between the daily ET and corresponding ET_0 . The day to day variations of ET over the *Tamarix* stand were consistent with those over the *Populus* stand in the most time period, and generally consistent with ET_0 too. This phenomenon was particularly obvious in the vibrant growing season (VGS), including the vegetative phase, blooming, and fruit ripening stage. In VGS, the correlation between ET and ET_0 was high in both the *Tamarix* stand ($R^2 = 0.66$) and the *Populus* stand ($R^2 = 0.53$) (Figure 3), indicating that integrated weather conditions controlled the daily fluctuations of ET in VGS. However, the seasonal trend of ET change was not consistent with that of ET_0 (Figure 2). In the *Tamarix* stand, the first obvious difference occurred in the germination and leaf expansion period (GLE) (Bai, 1998). During GLE, ET increased gradually with time, but ET_0 have fluctuated at a high level in the whole year (Figure 2), suggesting that the influence of the biotic factors on ET was obvious during this period. The second obvious difference occurred in the leaf senescence period (LSP) (Bai, 1998), in which the decreasing rate of ET was bigger than that of ET_0 . The same phenomenon was also observed in 2011 and 2013 growing season over the *Tamarix* stand. The different trends of ET and ET_0 between different plant phenological stages indicated that ET seasonal variations over the riparian *Tamarix* stand were significantly affected by the plant phenology. The observation over the *Populus* stand only covered the VGS and LSP stages. According to available data, the seasonal change trend of ET over the *Populus* stand showed the same pattern as those over the *Tamarix* stand (Figure 2). In LSP of the *Populus* (Figure 2), ET decreased more quickly than ET_0 , just like that over the *Tamarix*

Figure 2 Seasonal variations of daily ET over the *Tamarix* stand and the *Populus* stand, and their comparisons with plant phenology and reference evapotranspiration (ET_0). DOR refers to the dormancy period of plant, GLE refers to the germination and leaf expansion period, VGS refers to the vibrant growing season, and LSP refers to the leaf senescence period.

stand. However, the beginning time of rapid decline of ET over the *Populus* stand was later than that over the *Tamarix* stand (Figure 2), which might be due to the delay of the beginning time of the LSP stage of the *Populus* stage (Abdurahman et al., 2008). The different responses of ET to the LSP stage between the two communicates of *Tamarix* and *Populus* further verified the influence of plant phenology on the seasonal variation of ET over the desert riparian forests.

In the non-growing season, namely in the plant dormancy period (DOR), ET was weak, even in March and April, in which ET_0 had been high. Obvious ET could be observed only in growing season.

The differences of change trends of ET between different phenological stages and weak ET in DOR indicated that ET over the desert riparian forests was controlled by plant phenology, suggesting that the desert riparian forests play a key role in controlling the water cycling in the lower reaches of the Tarim River. The vegetation coverage of the two

observed stands was 0.65 and 0.49, respectively. Low plant coverage usually means that the soil evaporation would have more contributions to the total surface ET. But the strong correlation between the seasonal variations of ET over the sparse riparian stand and plant phenology suggested the influence of soil evaporation on ET was not obvious, consequently, the contribution of soil evaporation to the total surface ET was weak.

2.1.2 Diurnal process

Ten mean days averaging data of hourly ET from July 10 to 19, 2013 expressed 24-h diurnal variations of ET over the riparian forests in VGS (Figure 4). The diurnal processes of hourly ET both over the *Populus* stand and the *Tamarix* stand showed a unimodal variation, weak at night, rapidly increased with the sun rising, increased and decrease slowly at a level for most of the daytime (11:00 a.m.-06:00 p.m. Beijing time, 09:00 a.m.-16:00 p.m. local time), and then decreased rapidly after 06:00 p.m. Beijing time (16:00 p.m. local time). However, the shape of the unimodal variation of hourly ET was different between over the *Tamarix* and *Populus* stand. The shape of diurnal variation of ET over the *Tamarix* stand was near triangle, consistent with the solar radiation and air temperature, while the shape over the *Populus* stand was near trapezoid, suggesting that photosynthesis restraint at noon could exist for *Populus euphratica*, consequently reducing plant transpiration.

The mean daily ET was 4.52 mm over the *Populus* stand, and 5.07 mm over the *Tamarix* stand. Considering the vegetation cover and LAI in the *Populus* stand were significantly less than those in the *Tamarix* stand, the difference of daily ET amount over between the *Populus* and *Tamarix* stand did not indicate that the water consumption of *Tamarix* spp. was larger than that of *Populus euphratica*. Instead, if the linear relationship between LAI and ET (see section 3.2) was supposed, the daily ET over a *Tamarix* stand with the same LAI value of the observed *Populus* stand

Figure 3 Linear relationships between daily ET and daily ET_0 in the vibrant growing seasons over the *Tamarix* stand and the *Populus* stand ($P < 0.0001$).

Figure 4 Diurnal processes of hourly ET in the vibrant growing seasons over the *Tamarix* stand and the *Populus* stand. The data is obtained by averaging the observation data from 10 to 19 July, 2013. The error bar is the standard error.

would be 2.58 mm, indicating that the water consumption of *Populus euphratica* was higher than that of *Tamarix* spp. under the same weather conditions and the same LAI values.

Correlation analysis of main meteorological factors (temperature, humidity, wind speed) and diurnal ET processes showed that diurnal processes were not significantly correlated with any one factor, but significantly correlated with ET_0 . The correlation coefficient was mostly above 0.9 in the randomly selected days in GLE, VGS and LSP over the *Tamarix* stand, and the same correlations existed over the *Populus* stand (Figure 5).

This indicated that the diurnal process of ET was not controlled by any single atmospheric factor, but influenced by integrated atmospheric conditions. This was different with the results observed in the semiarid steppe, where the vapor pressure deficit influenced the diurnal processes of ET significantly (Hao et al., 2007).

2.2 Key control factors on the spatial variations of ET

The plant coverage is usually low in the desert riparian forest zone in arid Northwest China, and shows a large spatial variation with the distance from river channel (Chen et al., 2004; Tao et al., 2008; Li et al., 2013). Since the surface ET was obviously under control of the vegetation, the ET values observed over one site could not represent ET characteristics over the whole riparian forest zone due to the large spatial variation of plant coverage. Although the surface ET cannot be measured under all different plant coverages, the control factors of ET spatial variations in the lower reaches of Tarim River under the hyper-arid climate could be assessed according to the observation results.

As mentioned in section 2.1.1, the proportion of the soil evaporation over the desert riparian forests in the total ET is little. This conclusion can be more supported by the comparison of the surface ET before the growing season and the

Figure 5 Linear relationships between hourly ET and hourly ET_0 in three different phenological stages over the *Tamarix* stand and the *Populus* stand. The data in GLE was from May 17, 2013; the data in VGS was from July 19, 2013; the data in LSP was from October 12, 2013. $P < 0.0001$.

corresponding atmospheric conditions. Every spring, under a rapid rise in temperature, ET_0 began to increase rapidly, while the observed daily ET remained less than 0.1 mm until *Tamarix* began to sprout at the end of April (Figure 2). The high atmospheric evaporation demand (ET_0) did not lead to the increase in soil evaporation until plant germination. On the other hand, due to the hyper-arid climate, a dry sand layer without liquid water covers the soil surface, which produces great resistance to the soil evaporation from the soil layer below (Vervoort, et al., 2009). This is the physical explanation of the weak soil evaporation in hyper-arid area.

Since the proportion of soil evaporation in the surface ET is little under hyper-arid climate, the spatial variation of ET of desert riparian forest would be controlled by vegetation LAI. The larger LAI, the higher ET. The same pattern was observed in arid regions of southwest USA (Sala et al., 1996). We analyzed the relationship of LAI and ET/ET_0 in GLE and LSP for both *Tamarix* stand and *Populus* stand. According to the approximate method commonly used, the daily LAI values were set to be linearly increased with time in GLE, and linearly declined with time in LSP (Foley et al., 1996). The results showed that ET/ET_0 was significantly linearly correlated with LAI (Figure 6). ET gradually increased with the increasing of LAI in the early period of growing season, and decreased gradually with the decreasing

Figure 6 Linear relationships between leaf area index and ET/ET_0 in GLE of *Tamarix* spp. (a), LSP of *Tamarix* spp. (b), and LSP of *Populus euphratica* (c). $P < 0.0001$.

of LAI in the late period of growing season. The linear correlation was more significant in GLE than in LSP. In LSP, physiological activity of leaves usually decreased with time, and also impacted the water consumption of plants other than the LAI. The significant linear relationships between ET/ET_0 and LAI in the early and late of growing season of the desert riparian forests could strongly supported our conclusions that the spatial variation of ET over the desert riparian forest zone was controlled by the vegetation LAI.

2.3 Variations of the DWT and SWC and their roles

Figure 7 shows 3-year temporal processes of DWT and SWC at depths of 3.0 and 5.0 m in the *Tamarix* stand. The gray area in Figure 7 represents the growing seasons during the observation periods. The DWT and the SWC at a depth of 5.0 m exhibited obviously seasonal variations, but the SWC at a depth of 3.0 m changed little. The DWT would drop after the onset of the growing seasons, and exhibits obviously diurnal fluctuation, which suggested groundwater consumption by plant water uptake; however, after mid-August, the DWT would arise, which indicated that the plant water consumption was less than the lateral seepage. This result was not caused by the decrease in plant water

consumption (Figure 2) but by the increase in lateral seepage that resulted from the artificial water conveyance at this time every year. The SWC at a depth of 5.0 m would decline in growing seasons and revert to a maximum of 51% when the DWT rose to a certain height or at the end of growing season under the dual control of capillary rise and root water uptake of the phreatophytic *Tamarisk* spp. As the representative of the temporal process at a depth of 3.0 m, the SWC in the soil profile 1 m above the groundwater table did not exhibit clear temporal variations, which was in contrast to the SWC in deeper layers and the DWT, which suggested that the soil water in shallow layers hardly took part in the water exchange in the groundwater-soil-plant-air system, or the water movement from groundwater to surface ET in the groundwater-soil-plant-air system was in a steady state. Based on our observation results, under the deep groundwater depth, the contribution of the soil water in shallow layers to the surface ET was weak, and the main water source of ET was groundwater and the soil water in deeper layers.

The groundwater evaporation (ET_g) in the growing season of 2012 was calculated using White's method, and compared with the corresponding ET. The comparison revealed that the seasonal variations in the estimated ET_g and

Figure 7 Variations of groundwater table and SWC at depths of 3.0 and 5.0 m. The inset shows the diurnal fluctuation of groundwater table from July 11 to 13, 2012. The gray area refers to the growing seasons.

the observed ET coincided (Figure 8). Only after obvious precipitation events, was the estimated ETg usually significantly less than the observed ET (Figure 8). This was due to the rainfall contribution to the surface ET other than the groundwater contribution. The ETg was 474.3 mm while the surface ET was 509.1 mm in the growing season of 2012. If subtracting the rainfall amount of 27.9 mm in this period, the amounts of ETg and ET were almost equal. The same phenomenon about the comparison between ETg and ET can be found in the growing season of 2013 in the *Tamarix* stand. The consistent seasonal variation and adjacent total amount between ETg and ET further indicated that the water source of ET was groundwater rather than soil water.

Because groundwater was the direct water source of plant water uptake, the ET process should be controlled by groundwater table changes. During our observation period, the groundwater table decline occurred in the earlier stages of the growing seasons, but the decline did not influence the ET processes. In the growing season of 2012, approximately 0.5 m of the groundwater table decline did not lead to the ET decreasing trend (Figure 9). This result indicated that the

Figure 8 Comparison of seasonal courses between surface ET and groundwater ET (ETg) in the 2012 growing season of *Tamarix* spp. The large difference between ET and ETg appeared in June after two high precipitations occurred.

Figure 9 Effect of the groundwater table decline on surface ET over the *Tamarix* stand during the growing season of 2012. The groundwater table is the groundwater depth. The groundwater depth is the daily averaged data from the observed data.

groundwater table decline must exceed a threshold value to produce effects on the surface ET, and also suggested that the observed *Tamarix* spp. community was not under water stress condition.

The DWT and SWC temporal processes indicated that it was the groundwater table rather than the soil water content that influenced the plant water uptake. The groundwater table is the crucial indicator to quantify the water stress of desert riparian forests, contrary to the mechanism on plant water stress in wet, semi-wet, and semiarid regions, in which soil water content is the critical factor influencing plant water stress. This role of groundwater table implies that quantifying the response of ET to the groundwater table change and its threshold is a critical requirement of the water resource management of the lower reaches of the inland rivers of China, which can improve our understanding of the hydrological threshold of desert riparian forests, and provide valuable scientific knowledge for effectively managing water resources of the inland rivers.

3 Discussions

3.1 Key controlling mechanism on water cycling in lower reaches of inland rivers

Anthropogenic oases have been developed along the middle reaches of the inland rivers of China. Irrigations in these oases causes the decreasing of channel incoming water to the lower reaches, even stream drying in many years (Shi, 2004; Liu et al., 2013). Consequently, flood is scarce in the lower reaches, and the water supplied for the soil water and plant water consumption is usually from groundwater rather than flood. Therefore, the water cycling in the lower reaches of the inland rivers of China is characterized as the process from the channel incoming water to groundwater, and ending in the form of surface ET. Because the environment in other lower reaches of the inland rivers of China is similar with that in the lower Tarim Basin with hyper-arid climate, sparse, narrow and long desert riparian forests that mainly consist of *Tamarix* spp. and *Populus euphratica* communities, based on our understanding of the water movements and ET processes in the lower Tarim Basin, we present a framework for describing the critical controlling mechanism on the water cycling in the lower reaches of the inland rivers of China (Figure 10).

Because of scarce precipitation, the incoming of water in the water cycling in the lower reaches is determined by runoff out of the middle reaches, which is controlled by climate change and anthropogenic activities in the upper and middle reaches of the inland rivers. Although influenced by the change of the internal climatic system, the ET amount in the lower reaches is mainly determined by the vegetation cover. According to the previous study, the vegetation cover was mainly influenced by the amount of channel incoming water (Tao et al., 2008; Li et al., 2013),

Figure 10 Generalized framework of water cycling process and its controlling mechanism in the lower reaches of the inland rivers in arid North-west China.

and the change of the channel incoming water, controlled by the anthropogenic activities, is more intensive than the climate change. Therefore, the impacts of the anthropogenic activities on the water cycling in the lower reaches are much more than those of internal climatic system variation. In addition, climate change can significantly influence the runoff from the upper reaches of the inland rivers, and thus influences the amount of the incoming water to the lower reaches (Chen et al., 2008b). This is the main way by which climate change influences the water cycling in the lower reaches. On the other hand, the controls of anthropogenic activities on the channel incoming water are more and more intensive due to farming irrigation and population increase. For the most of the inland rivers of China, the amounts of incoming water to the lower reaches are generally controlled by the anthropogenic activities. In a sense, the water cycling in the lower reaches is a human-controlled water cycling, and the influences of climate change are increasingly weak as anthropogenic activities are becoming wider and deeper.

If the lower reaches of the inland rivers can be seen as a close system, after the incoming water enters the system, each process of water cycling in the system is rarely disturbed by anthropogenic activities. Groundwater is the key factor in the processes of the water cycling; it influences the soil water dynamics (Ridolfi et al., 2008; Laio et al., 2009), plant water uptake, and consequently the surface ET process. According to our results, the impacts of groundwater table to surface ET process consist of two aspects (Figure 10): (1) the differences of groundwater depths determine the spatial pattern and vegetation coverage (Zhu et al., 2012; Li et al., 2013) of desert riparian plants, in consequence, influence the amount of ET; and (2) the changes of groundwater table impact the ET processes by influencing plant growth and physiological activities. Because of little contribution of soil evaporation, the ET amounts in the lower reaches depend on water consumption characteristics and the coverage of plant species. The species and their water consumption characteristics are the results of evolution and adaptability of the plants to specific environment, therefore, the ET amounts are mainly determined by the coverage of

plant species, which is further determined by the spatial pattern and changes of the groundwater table (Hou et al., 2007).

Revealing the relationship between the groundwater table and growth and spatial pattern of the desert riparian forests is vital for understanding the water cycling and its controlling mechanism in the lower reaches of the inland rivers. Although the relationships between groundwater depth and spatial pattern of desert riparian forests have been explored and revealed (Tao et al., 2008; Zhu et al., 2012), it is lack of the understanding of the impacts of groundwater dynamics on the surface ET processes. Through quantifying these impacts of groundwater dynamics, we can obtain valuable tools to adjust groundwater table through properly water resources allocations in the lower reaches. However, it is difficult to achieve this aim because there is little field environment to satisfy the related field observation and experiment. It will be a feasible way to resolve this problem using the numerical analysis based on processing mechanical models.

3.2 A new method to estimate water requirements of desert riparian forests

Reasonable estimation of the water requirements of the desert riparian forests is necessary for the water resources management of the inland rivers. Existing methods that have been proposed for estimating ecological water requirements or vegetation water requirements of the inland rivers (Hu et al., 2008) could not answer the two questions in water resources management of the inland rivers: (1) the spatial and temporal processes of the water requirements of the desert riparian forests; and (2) the trend of water requirements under different human's intervention. Additionally, water resource management agencies usually hope to know real-time water requirements and to predict water requirements in the future based on the real-time and forecasted weather data. The previously proposed methods of estimating water requirements cannot satisfy the practical demand of the water resources management agencies. Based on our understanding of the characteristics of water consumption and the controlling mechanisms of *Tamarix* and *Populus* forests in the lower Tarim River Basin, it is possible to develop a simple and practicable model of estimating water requirements of desert riparian forests in the lower reaches of the inland rivers for water resources management, which can use weather data, and can answer the above-mentioned two questions.

The water requirements of desert riparian forests are defined to be the regional ET of desert riparian forests without water stress, namely, the regional potential ET (ET_p) under local climate and actual vegetation cover condition. Because of weak soil evaporation, under appropriate groundwater depth, the ET over desert riparian forests is determined by atmospheric conditions and vegetation status. The vegeta-

tion status can also be divided into spatial distribution and plant physiological activities that could influence the amount and the process of ET, respectively. According to our results, ET is linearly related with ET_0 (Figure 3), and LAI is linearly related with ET/ET_0 (Figure 6). Further considering the influence of plant physiological factors to ET, this model can be expressed as

$$ET_p = \alpha_p \cdot LAI \cdot K_b \cdot ET_0, \quad (2)$$

where LAI is the leaf area index; α_p is a population-specific parameter, describing the structural trait of certain population; K_b is a species-specific parameter expressing the impact of species physiological activities on ET.

This model is a species-specific and spatially-explicit model, and it highlights the impact of spatial variations of vegetation cover (LAI). The model can be parameterized through the measurement of ET for different desert riparian forests under appropriate groundwater depth. The model runs through weather data, and can estimate the spatial difference of water requirements of desert riparian forest zone based on the LAI spatial distribution data. The model can also predict the water requirements under different vegetation restoration scenarios through setting different areas of species and their coverage. Therefore, this model can provide more practicable and wider references for water resources management of the inland rivers of China.

Because the water consumption characteristics of desert riparian forests of the inland rivers in the northwest of China are similar, the model presented here can be used to estimate water requirements of desert riparian forests in other inland rivers of China after parameterization of different desert riparian vegetation types through field measurement data.

4 Conclusions

In the lower reaches of the Tarim River under hyper-arid climate, ET over the desert riparian forests zone was weak in the non-growing season, and its seasonal variation in the growing season was consistent with plant phenology. The ET processes were influenced by atmospheric condition as well as plant phenology. Plant transpiration accounted for most of the surface ET, with soil evaporation weak and negligible. The spatial pattern of ET was determined by vegetation LAI. The more vegetation coverage, the higher LAI and ET amount, and *vice versa*. Groundwater table and its dynamics are crucial factors influencing ET over the desert riparian forests. Groundwater influenced the processes and amounts of ET by controlling the growth and spatial distribution of desert riparian forests. Contrary to the obviously seasonal variations of groundwater table, the soil water content in shallow layers did not exhibit temporal variations. Quantifying the water stress of desert riparian forests using groundwater table is more appropriate, rather than soil

water content. Quantifying the response of ET to the groundwater table change and its threshold is a critical requirement of the water resource management of the lower reaches of the inland rivers of China.

The processes of ET over the observed *Tamarix* stand and the observed *Populus* stand were similar, but the water consumption of the well-grown *Populus euphratica* was higher than that of the well-grown *Tamarix* spp. Under the same LAI (LAI = 0.57), ET over the well-grown *Populus* stand was 4.52 mm, while that over the well-grown *Tamarix* stand was 2.58 mm.

These understandings of ET processes and their controlling mechanisms over the *Populus* stand and the *Tamarix* stand indicate that it is feasible to develop a simple and practicable model to estimate water requirements of desert riparian forests in arid regions by considering the vegetation coverage, plant growth and meteorological condition. This model can not only reveal and predict the temporal and spatial variations of water requirements of desert riparian forests using real-time or forecasting weather data, but also assess and direct the water resources managements by predicting the water requirements under different vegetation distributions and coverages. This model is proposed based on our understanding of ET processes over the observed desert riparian forests; its feasibility needs to be tested using more data.

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