A Species-Specific and spatially-Explicit Model for Estimating Vegetation Water Requirements in Desert Riparian Forest Zones

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Abstract Balancing human demands for water with environmental requirements to maintain functioning ecosystems requires the quantification of ecological water requirements. In arid regions, high spatial variability of vegetation cover and different water consumption of plant species make it different to estimate reasonable ecological water requirements. We developed a simple and practical approach that estimates the vegetation water requirements (VWRs) of desert riparian ecosystems. This model is species-specific and spatially-explicit; it considers the water consumption characteristics required by different species and highlights the impacts that high vegetation cover spatial variability has in arid regions on evapotranspiration. The model was parameterized based on the observation of the water consumption of two typical desert riparian species, *Populus euphratica* and *Tamarix* spp., in the lower basin of the Tarim River in northwestern China. Comparisons between the modeling results and measured data for two mature *Populus* and *Tamarix* stands indicate that the model is reasonable predictive. A case study in the lower basin of the Tarim River demonstrated the model's practicality and transferability. This model could run based on near real-time or forest weather data and spatial vegetation patterns, and provides a continuous estimation of the temporal and spatial variations of the VWR. Particularly, this model forecasts VWRs under different vegetation spatial distribution and coverage scenarios, and evaluates the impacts and consequences of different management actions. This model can serve as a useful tool for management agencies interested in improving their decisions to allocate river water between human activities and natural ecosystems in arid regions.

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1 Introduction

In arid northwestern China and central Asia, there are many endorheic rivers, which usually originate from high mountain glaciers, and rush from the mountains to cultivate oases in alluvial plains before crossing deserts or gobis, finally forming a terminal lake or disappearing in a great desert (Zheng and Yin 2010). In the lower reaches of these rivers, narrow desert riparian forest zones are often formed along the river banks. The riparian ecosystems fostered by these endorheic rivers are often vital to the control of desertification and ecosystem restoration in these areas. However, desert riparian ecosystems along endorheic rivers are highly vulnerable to sudden changes in river water supply and threats from frequent wind and sand erosion (Rumbaer et al. 2015). As human activities such as irrigation farming in the oases along the middle reaches of these rivers becomes increasingly intense, the water supply to the lower reaches has decreased and in some cases has dried up altogether (Feng and Cheng 1998). Reduced stream flow has given rise to obvious damage in these lower reaches riparian ecosystems (Chen 2003; Feng et al. 2005). In recent years, water diversion projects have occurred on the longest endorheic rivers in China, the Tarim River (Tao et al. 2008; Xu et al. 2007) and the Heihe River (Zhang et al. 2011), necessitating river and ecosystem restoration in the lower reaches. One of the primary goals of these projects was to supply water to the lower reaches in a planned way; however, water shortages in the middle-reach oases, where most people in arid regions live, challenge this goal. Balancing human demands for water with environmental requirements to maintain functioning ecosystems is crucial to the development of successful water resources management options for rivers in arid regions (Merritt and Bateman 2012). To efficiently and sustainably manage river water resources, it is important and necessary to reasonably estimate the ecological or environmental water requirements along these rivers in these arid regions (Rumbaer et al. 2015; Wang et al. 2012).

Basic ecological water requirements (EWR) are often defined as the minimum amount of water necessary to meet the basic needs of natural ecosystems (Gleick 1998). Generally, ecosystem evapotranspiration (ET) under non-water-stressed conditions is regarded as the essential measurement of a vegetated ecosystem's water requirements (Hu et al. 2009; Liu et al. 2010). Thus an EWR estimate is also an estimate of ecosystem ET under non-water-stressed conditions. Methods to estimate ET differ widely, from simple empirical models based on pan evaporation or potential evaporation (Izadifar and Elshorbagy 2010; Sumner and Jacobs 2005), to comprehensive methods using process-based simulations (Daly et al. 2004; Sellers et al. 1997; Wang 2008). Different types of models, including ecological models, hydrological models and land surface models, can also simulate and calculate surface ET. Of the different methods used to estimate ET, physically-based methods are thought to have advantages over empirical approaches (Fernandes et al. 2007). However, most physically-based models generally require complicated input data and parameters that focus on the interactions between different land surface processes; and these models are often developed to explore processes' controlling mechanisms without considering their feasibility and applicability in practical managements situations (Wang and Dickinson 2012).

The ultimate aim of developing an EWR estimation model is to improve sustainable water resources and ecosystems management; and management agencies often prefer simple, efficient

estimation methods. A simple and practical method for estimating EWR should employ fewer variables and parameters while producing reasonable EWR estimation results. To address the regulation of water resource allocations in river reaches, a simple EWR estimation method should be able to predict temporal and spatial variations in EWR and evaluate those variations to forecast the impacts and consequences of different management options and projects on water availability. In recent years, many weather networks have provided reference ET figures to estimate agricultural crop water requirements, following FAO56 methods (Allen et al. 1998). Methods to estimate the EWR of natural ecosystems derived from the FAO56 method have also been developed for near real-time and forecast management (Irmak et al. 2013; Spano et al. 2009). However, these methods cannot be directly applied in desert and arid riparian ecosystems because of the highly spatial variability of desert riparian vegetation cover. In FAO56 method, the crop coefficients, K_c , usually simplify the impacts of vegetation cover spatial variability. In hyper-arid regions, surface ET is almost entirely the result of plant transpiration (Yuan et al. 2014). This phenomenon indicates that regional ET amount in hyper-arid regions is largely controlled by vegetation cover (Yuan et al. 2015). Given the high spatial variability of vegetation cover in arid environments (Li et al. 2013; Xu et al. 2007), it is necessary to develop simple ET model to consider the effect of variable vegetation cover in hyper-arid regions.

Methods to estimate the EWR of desert riparian ecosystems in different endorheic rivers of China have been developed previously (Ling et al. 2014; Liu et al. 2010; Ye et al. 2010; Zhao et al. 2007). However, these methods generated approximate results that did not consider the unique characteristics of surface ET processes in desert riparian communities, and the models were not calibrated or validated. Consequently, the estimates provided by these models do not meet the needs of endorheic river water resources and ecosystems management teams. Furthermore, because these methods generally were not developed based on real-time weather data or spatial vegetation patterns, they do not provide temporally or spatially variable EWR figures. Considering the difference in water requirements between species and the spatial change of vegetation cover in an EWR estimation model can improve the model's accuracy, which is important for water resources and ecosystem management of endorheic rivers in arid regions and can lead to EWR forecasts under different spatial distributions and plant species coverage scenarios, as well as the evaluation of the impacts and consequences of different management actions.

In this paper, we relied on our understanding of the surface ET processes through a four-year observation of desert riparian forests in the lower reach of the Tarim River of China (Yuan et al. 2015; Yuan et al. 2014) to develop a simple, practical model to estimate riparian forest water requirements in the lower reaches of the endorheic rivers in arid regions. The model can run on near real-time or forecast weather data and, thus, can provide a continuous estimation of vegetation water requirements. It is a species-specific and spatially-explicit model, and it highlights different species' water requirements and the impacts of spatial changes in vegetation cover on those requirements. This model can serve as a valuable tool for water resources and ecosystems management agencies in arid regions because it is a practical and transferable way to estimate EWR.

2 Model Description

2.1 Definition, Assumptions and Model Descriptions

In this study, the essential water requirements of desert riparian forests are defined as the regional ET of desert riparian forests without water stress, in other words, the regional

maximum ET (ET_m) under local climate and actual vegetation cover conditions. This definition represents vegetation water requirements (VWR) rather than total ecological or environmental water requirements (EWR). EWR includes different all water requirements necessary for the maintenance of an ecosystem, including water for vegetation, the river channel, and a terminal lake (Acreman et al. 2014; Meijer et al. 2012). EWR estimates are important to water resources management agencies; However, VWR is an important foundation for the estimation of EWR and so is the focus of this paper.

Due to scarce precipitation, desert riparian forests in arid regions are often typical terrestrial groundwater-dependent ecosystems (Bertrand et al. 2012; Orellana et al. 2012). Soil evaporation is often very weak due to nearly completely dry soil surfaces; as a result, its contribution to surface ET is miniscule (Yuan et al. 2014). According to a three-year observation of surface ET over desert riparian forests in the lower Tarim River basin of China, the spatial pattern of surface ET is mainly controlled by the vegetation leaf area index (LAI), and seasonal ET is controlled by plant phenology in the hyper-arid climate (Yuan et al. 2015). In the lower reaches of endorheic rivers in China, vegetation coverage is often highly spatially variable, which results in significant spatial variations in surface ET. Therefore, a modified crop coefficient approach highlighting the spatial changes of regional ET_m was drawn from the FAO56 method and employed to develop an empirical model that estimates desert riparian forest VWR.

In the model presented here, the VWR of desert riparian forests without water stress, or the ET_m , is determined by atmospheric and biotic factors. The model was developed to estimate the spatial and temporal patterns in daily ET_m over desert riparian forests:

$$ET_m = f(\text{structural}) \cdot f(\text{physiological}) \cdot ET_0 \quad (1)$$

where, ET_0 is the reference ET, $f(\text{physiological})$ is a function of vegetation physiological activities, and $f(\text{structural})$ is a function of vegetation structural characteristics and dynamics, which highlights the role of vegetation coverage in regional ET.

ET_0 is the daily reference ET (mm d^{-1}) described using the FAO56 method. It can be calculated by the FAO56 Penman-Monteith equation based on weather data (Allen et al. 1998):

$$ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 D}{\Delta + \gamma (1 + 0.34 u_2)} \quad (2)$$

where, R_n is net radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), G is the soil heat flux density ($\text{MJ m}^{-2} \text{d}^{-1}$), T is the mean daily air temperature ($^{\circ}\text{C}$), u_2 is the wind speed at 2 m height (m s^{-1}), D is the saturation vapor pressure (kPa), Δ is the slope vapor pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$), and γ is a psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

Because LAI determines the spatial pattern of desert riparian forest ET (Yuan et al. 2014), the function of the vegetation's structural characteristics and dynamics, $f(\text{structural})$, can be described as:

$$f(\text{structural}) = \alpha_p \cdot \text{LAI} \quad (3)$$

where, LAI is the leaf area index, and α_p is a species-specific parameter describing the impact of the structural traits of specific species on ET_m . In a desert riparian forest community along a low reach of an endorheic river in China, there is often one dominant species, and species richness is usually low (Tao et al. 2008; Zhu et al. 2012). Therefore, the parameter α_p can also be seen as a community-specific parameter.

In this model, a simple linear relationship is used to describe the impact of plant physiological activities on daily ET (Spano et al. 2009):

$$f(\text{physiological}) = K_b \quad (4)$$

where, K_b is a species-specific parameter expressing the impact of species physiological activities on ET_m under non-water stress conditions. Combining Eqs. (1), (2) and (3), a simple equation to calculate the VWR of desert riparian forests in arid regions, namely, daily ET_m can be written as:

$$ET_m = \alpha_p \cdot LAI \cdot K_b \cdot ET_0 \quad (5)$$

In this model, parameters α_p and K_b represent the effects of different plant species on ET_m . LAI reflects the spatial changes of VWR, and ET_0 expresses the effects of atmospheric factors on ET_m . LAI should be seasonally variable, and α_p and K_b should be parameterized for different plant phenological stages. After obtaining the parameters α_p and K_b for all types of plant species in a given region, the regional VWR of desert riparian forests and their temporal and spatial patterns can be obtained easily and quickly based on remotely sensed regional LAI and observed weather data.

2.2 Parameterization Method of Model

2.2.1 Seasonal Variation of LAI Values

A process to determine the seasonal LAI must be developed in this model because the direct measurement of LAI is laborious. Actually, for desert riparian forests with low species richness, seasonal change in the LAI can be simplified into a trapezoid process (Foley et al. 1996). The growing season of desert riparian forests can generally be divided into three phenological stages: the greening period (GP), the maturity period (MP), which includes the vegetative, blooming and fruit ripening phases; and the senescence period (SP). For each phenological stage, the change in LAI can be simplified. In GP, the LAI value increases linearly from 0 to the maximum LAI (LAI_m). In MP, the LAI does not vary, remaining at LAI_m . In SP, the LAI value decreases linearly from LAI_m to 0. During the non-growing season, the LAI is 0. By simplifying seasonal changes in LAI, an LAI value can be obtained for each day based on LAI_m and the plant's phenological date. For a single observation plot, LAI_m can be measured in MP. For an entire region, remotely sensed data can be used to obtain the spatial pattern of LAI_m . Regional plant phenological dates can be determined from phenology observation data.

2.2.2 α_p and K_b Values

Determining the values of α_p and K_b separately in the model is unnecessary as water requirements can be calculated by obtaining the product of α_p and K_b . The value of $\alpha_p \cdot K_b$ can be obtained by converting the Eq. (5) as follows:

$$\alpha_p \cdot K_b = \frac{ET_m/ET_0}{LAI} \quad (6)$$

By fitting measured ET_m/ET_0 and LAI linearly for the three different phenological stages, $\alpha_p \cdot K_b$ for GP, MP and SP can be obtained.

Equation (6) suggests that, in this model, the relationship between surface ET without water stress and ET_0 should be linearly significant during the MP because the LAI remains unchanged; and the ratio of ET_m to ET_0 should be related linearly to the LAI during the GP and SP periods. The effectiveness of fitting the data between measured ET_m/ET_0 and LAI can also verify the feasibility of the model presented here.

3 Materials and Methods

Field observations were conducted to parameterize and test the model. A case study in the lower Tarim River basin of China was executed to evaluate the practicality of the model for water resources management agencies.

3.1 Site Descriptions

The lower reach of the Tarim River was chosen for field observations. The Tarim River is the longest endorheic river in China. The lower reach of the Tarim River is located between the Taklimagan Desert and the Kuluk Desert and runs from the Daxihaizi reservoir to the terminal Taitmar Lake. The lower river is approximately 300 km long (Fig. 1). The Tarim basin is a relatively flat desert region with a mean annual precipitation of less than 50 mm and an annual potential evaporation as high as 2000 mm. Under this hyper-arid desert climate, desert riparian vegetation dominates. The narrow riparian forest zone in the lower reach of the Tarim River

Fig. 1 Locations of the case study area, the lower basin of the Tarim River in China

has a width of approximately 3 km or less and forms a “green corridor” that protects the ancient silk road and a current national road along the river.

The plant communities in this area are generally classified into two categories: *Populus* (*Populus euphratica*) woodland and *Tamarix* (*Tamarix* spp.) thicket. The *Populus* woodland belongs to the arboreal forest ecosystem and the *Tamarix* thicket belongs to the shrub ecosystem. Species richness in these plant communities is low. A small number of other shrubs and herbs, such as *Lycium ruthenicum*, *Halimodendron halodendron*, *Phragmites australis*, *Apocynum venetum*, *Alhagi sparsifolia*, *Karelinia caspica*, *Glycyrrhiza inflata*, grow in the two communities. The coverage of plant communities in this area is also low due to scarce precipitation. The highest observed vegetation coverage was 0.65 in the riparian forests. Vegetation coverage in most of the region is less than 0.2, and the spatial change between these densities is obvious.

Two typical, mature riparian vegetation stands were chosen to measure surface ET using the eddy covariance (EC) method. One stand was dominated by *Populus euphratica* and the other by *Tamarix* spp. According to our analysis, the two mature riparian vegetation communities were not under water stress (Yuan et al. 2015). Thus, measured surface ET over the two riparian stands can be regarded as the maximum ET under non-water-stressed conditions and can be used to parameterize the model and evaluate its performance.

The *Tamarix* stand chosen for observation covers an area of approximately 300 m × 300 m. This area is flat and is located at 87°54'E, 40°27'N, with the altitude 846 m. The vegetation coverage index was 0.65. The average vegetation height was approximately 2 m and the leaf area index (LAI_m), which was measured using an LAI-2250 canopy analyzer (Li-cor, Nebraska USA) during the MP, was 1.15. The dominant species in the stand are *Tamarix ramosissima*, *Tamarix hispida* and *Tamarix elongat*. A small number of herbs (mainly *Alhagi sparsifolia* and *Glycyrrhiza infata*) grow under the shrubs. The Simpson diversity index for the stand was 0.71. The groundwater depth fluctuates between 5.6 m and 6.4 m, and the soil is a silt loam with an approximately 20 cm dry sand surface layer.

The *Populus* stand chosen for observation is located at 88°1'E, 40°26'N, with an altitude of 844 m. The stand covers an area of approximately 1.5 km × 2 km. The average vegetation height was approximately 10 m, coverage was 0.47 and the leaf area index (LAI_m) during the MP was 0.57. Excluding individual reeds spread along the river bank, *Populus euphratica* was the only species observed in the stand. The soil texture in the root layer is slightly complex, and the soil is a silt loam at a depth of 0 to 3 m, while the soil is sandy below 3 m. The groundwater depth fluctuates approximately 3.8 m.

3.2 ET Measurements and Data Processing

Two flux towers were established to measure surface ET and other relevant factors over the two riparian forest stands, respectively. The EC technique was used to measure the energy and CO₂/H₂O fluxes on a continuous basis. Matching EC systems were installed on the flux towers in the *Tamarix* stand and the *Populus* stand, respectively. The *Tamarix* stand system was installed at a height of 1.8 m above the *Tamarix* canopy, and the *Populus* stand system was installed at a height of 5 m above the *Populus* canopy. Continuous measurements over the *Tamarix* stand were taken from June 8th, 2011, and continuous measurements over the *Populus* stand were taken from June 18th, 2013.

Surface evapotranspiration was obtained from the flux data sets. Detailed data processing for the EC data was introduced in our other articles (Yuan et al. 2015; Yuan et al. 2014).

3.3 Other Data

Meteorological data were collected from the Tikanlik Weather Station (WMO number 51,765), a national weather observation stations in China located in the lower reach of the Tarim River. The station's distance from the two observation sites is approximately 30–40 km. The meteorological data were used primarily to calculate daily ET_0 .

The leaf area indices over the *Tamarix* stand and the *Populus* stand were measured using a LI-2250 canopy analyzer (Li-cor, Nebraska USA) in July 2013. These values represent the LAI_m values for the observation stands.

The phenology of desert riparian forests was divided into three stages: GP, MP and SP. The start and end dates for the three stages within *Tamarix* thickets and *Populus* woodlands in the lower Tarim River basin were determined from previous observational results (Abdurahman et al. 2008; Bai 1998). For *Tamarix* thickets, the GP runs from April 27 to June 3, the MP from June 4 to September 17, and the SP from September 18 to October 18. For *Populus* woodlands, the GP runs from March 29 to June 4, the MP from June 5 to September 25, and the SP from September 26 to November 12.

3.4 Model Evaluation Method

We obtained the $\alpha_p \cdot K_b$ value for a *Tamarix* thicket using the data observed during the 2012 growing season and the $\alpha_p \cdot K_b$ value for a *Populus* woodland using data observed during the 2013 MP and SP stages and the 2015 GP stage. We compared model predictions with measured ET over the observed *Tamarix* stand from the 2011 and 2013 growing seasons and measured ET over the observed *Populus* stand from the 2014 growing season. The comparisons were assessed using the root mean square deviation (RMSD). The RMSE is computed as

$$RMSD = \left[\frac{1}{n} \sum_{i=1}^n (ET_{mi} - ET_i)^2 \right]^{1/2} \quad (7)$$

Where, ET_i is the measured ET (mm d^{-1}) over the desert riparian forests during day i , and ET_{mi} is the predicted ET under non-water stress conditions (mm d^{-1}) as defined by Eq. (5).

In addition to $RMSD$, the Nash–Sutcliffe model efficiency coefficient (NSE) was used to assess the predictive power of the Eq. (5) approach in estimating the water requirements of different species:

$$NSE = 1 - \frac{\sum_{i=1}^n (ET_i - ET_{mi})^2}{\sum_{i=1}^n (ET_i - \bar{ET})^2} \quad (8)$$

The NSE values can range from $-\infty$ to 1, where an efficiency of 1 ($NSE = 1$) indicates a perfect match of the modeled ET_m to the observed ET. An efficiency of 0 ($NSE = 0$) indicates that the model predictions are as accurate as the mean of the observed data, whereas a negative efficiency ($NSE < 0$) occurs when the observed mean is a better predictor than the model or when the residual variance (numerator) is larger than the data variance (denominator).

4 Model Verification

4.1 Parameter $\alpha_p \cdot K_b$ Values

In GP and LP of both the *Tamarix* thicket and the *Populus* woodland, the linear relationships between LAI and the ratio of daily ET to daily ET_0 were significant. The correlation coefficients, R^2 , ranged between 0.65 and 0.84 (Fig. 2). These significant linear relationships verified the rationality of the Eq. (5) in the GP and LP of plants. Based on this, the $\alpha_p \cdot K_b$ values during the GP and LP of both the *Tamarix* thicket and the *Populus* woodland could be obtained using the Eq. (6) (Table 1).

During the MP, the LAI values were not supposed to change with time. According to Eq. (5), the linear relationships between ET and ET_0 should be significant during the MP for desert riparian vegetation. Figure 3 shows the relationships between ET and ET_0 at hourly and daily scales. The linear relationships at the hourly scale were significant for both the *Tamarix* thicket and the *Populus* woodland (Fig. 3a, c); however, they were not significant between daily ET and daily ET_0 (Fig. 3b, d). The poor correlations between daily ET and daily ET_0 may be due to the narrow fluctuation ranges of daily ET during the MP. Although the correlations between daily ET and daily ET_0 were poor, the $\alpha_p \cdot K_b$ values obtained during the MP based on the relationships between daily ET and daily ET_0 using Eq. (6) were nearly equal to those for hourly ET and hourly ET_0 (Fig. 3). Here, we used the fitted slope values of the daily ET and ET_0 relationships to calculate the $\alpha_p \cdot K_b$ values for the MP based on Eq. (6). Table 1 lists the $\alpha_p \cdot K_b$ values that can be used in the model for different phenological stages of *Tamarix* thickets and *Populus* woodlands.

Fig. 2 Linear relationships between leaf area index (LAI) and the ratio of surface evapotranspiration (ET) versus corresponding reference evapotranspiration (ET_0) in (a) greening period and (b) senescence period of the observed *Tamarix* stand, and in (c) greening period and (d) senescence period of the observed *Populus* stand. $P < 0.0001$

Table 1 Values of $\alpha_p \cdot K_b$ suitable for use in the model at different phenological stages of *Tamarix* thickets and *Populus* woodlands

Phenological stages	<i>Tamarix</i> thickets	<i>Populus</i> woodlands
GP	0.457	0.872
MP	0.635	0.964
SP	0.773	0.889

4.2 Model Test

The comparisons between the modeled ET_m and the measured ET for the non-water-stressed *Tamarix* and *Populus* stands are shown in Fig. 4. Gaps in the measured ET data occurred because of a malfunctioning instrument. Nevertheless, the results indicate that seasonal variations and daily fluctuations in ET over the non-water-stressed *Tamarix* and *Populus* stands could be reproduced using Eq. (5). *NSE* values were 0.79, 0.78 and 0.59 for the 2011 and 2013 *Tamarix* growing seasons (Fig. 4 a, b) and the 2014 *Populus* growing season (Fig. 4 c), respectively, indicating that the modeled ET_m values were close to the observed ET values. The corresponding *RMSD* values were 0.74, 0.68 and 0.63 mm d⁻¹, indicating that the agreements of the trends between the modeled ET_m and the observed ET were good.

A small number of large, intermittent differences between the modeled ET_m and the observed ET were found. Particularly from June 20th to 22th, 2011 (Fig. 4 a), the mean ET was 5.09 mm, but the mean ET_m was 3.48 mm. Two rare heavy precipitation events preceded those days, one on June 16th (20.8 mm) and one on June 19th (15.7 mm), which resulted in increased soil evaporation in the hyper-arid region. The additional contribution of soil evaporation after heavy precipitation could increase the total surface ET over desert riparian forests

Fig. 3 Linear relationships between evapotranspiration (ET) and corresponding reference evapotranspiration (ET_0) in mature period of the observed *Tamarix* stand (a and b) and the observed *Populus* stand (c and d). Units are hourly in a and c and daily in b and d. $P < 0.0001$

Fig. 4 Comparisons between the modeled maximum evapotranspiration (ET_m) and the measured evapotranspiration (ET, Marked by red O) in (a) 2011 growing season of the *Tamarix* stand, (b) 2013 growing season of the *Tamarix* stand and (c) 2014 growing season of the *Populus* stand

under similar weather conditions. This result indicates that the model parameters may only be suitable for arid environment with little precipitation.

5 Model Application: a Case Study in the Lower Tarim River Basin

5.1 Data Processing

5.1.1 Calculation Process

The above model can provide continuous, near real-time estimations of the spatial and temporal variations of VWR based on three types of input data: satellite remote sensing data, meteorological data and vegetation phenological data (Fig. 5). Satellite remote sensing data provides the spatial distribution of different vegetation types and the inverse of their spatial LAI_m values. Because this model is a species-specific model, different species or communication types must be spatially discerned by remote sensing methods; therefore, high spatial resolution remote sensing data are necessary for the model's application. At the catchment scale, Landsat TM data with

Fig. 5 Data preparation and calculation process of the model

30 m $\times$ 30 m resolution are appropriate. Phenological data are used to estimate daily LAI processes for different vegetation types using the simplified method described in Section 2.2.1, as well as to determine $\alpha_p \cdot K_b$ values at different phenological stages. Meteorological data are used to calculate the daily ET_0 values.

One of critical difficulties faced in the regional application of this model is the discernment of vegetation (species) types and the inverse of their LAI_m values at the catchment scale using remote sensing data. Fortunately, because there are few species types and the vegetation structure of desert riparian forests is relatively simple, vegetation types and their spatial distribution can be discerned from remote sensing data using the simple artificial supervised classification method. Furthermore, an empirical LAI inversion model is enough to obtain the LAI values from simple desert riparian forests.

The spatial calculation of ET_m should be performed on each pixel; however, meteorological data are not usually available at the pixel scale. Consequently, up-scaling the meteorological data is necessary to calculate spatial variations in ET_m . In the lower reach of the Tarim River, the land is flat and the climate is hyper-arid. The spatial variability of meteorological factors in this region is low. Hence, in this study we used the meteorological data observed by the Tieganklik weather station, which is located in the study area, to calculate the spatial ET_m .

5.1.2 Remote Sensing Classification of Vegetation and their LAI Inversion

Because the desert riparian forests in the study area can generally be classified into *Populus* woodlands and *Tamarix* thickets, the land cover types discerned by remote sensing data in the study area were divided into six categories: *Populus* woodland, *Tamarix* thicket, *Phragmites* grassland, farmland, water body and sandy land (bare soil). The water requirements of the *Phragmites* grassland, farmland and water body were not considered in the estimation of water requirements of desert riparian forests. Particularly, we ignored the water requirements of the *Phragmites* grassland in this area during our calculation of the VWR of desert riparian forests. The herbaceous vegetation here usually depends directly on the presence of river or rain water rather than groundwater, and it only survives beside the river channel or around the terminal lake. The growth of these herbaceous plants is controlled by surface or rain water, which differs from typical desert riparian species; therefore the water consumption characteristics of these plants do not satisfy the assumptions of our model. Given that the grassland is not important in maintaining the stability of desert riparian ecosystems in the lower Tarim River basin, and its area is relatively small, the water requirements of herbaceous vegetation were not included in the VWR of desert riparian forests.

Relevant Landsat 8 OLI remote sensing data from July 20th, 2013, which were downloaded from the website <http://glovis.usgs.gov/>, were used to classify the vegetation and identify the LAI inversion values in the study area. The pre-processing of the remote sensing data, including geometric and atmospheric corrections, was conducted prior to analysis.

A supervised classification method was used to classify the vegetation types based on the Landsat 8 OLI remote sensing data. A total of 1024 training samples were chosen from many field surveys across the lower reach of the Tarim River. The classification results are shown in Fig. 6a. Based on this result, the areas of *Populus* woodlands and *Tamarix* thickets in the lower reach of the Tarim River were approximately 3.364×10^4 ha and 4.053×10^4 ha, respectively.

Fig. 6 Spatial distribution of the (a) vegetation categories and (b) leaf area index of the *Tamarix* thickets and the *Populus* woodlands in the lower basin of the Tarim River in China inverted by the Landsat 8 OLI remote sensed data

An empirical LAI inversion model was developed using the optimum vegetation index for *Populus* woodlands and *Tamarix* thickets in the study area. Detailed field measurements and an analysis are described in a previously published paper (Zhu et al. 2014). The LAI values of the *Tamarix* thickets were inverted based on the remotely sensed NDVI (Normalized Difference Vegetation Index). The empirical relationship ($R^2 = 0.69$) between the LAI of the *Tamarix* thickets (LAI_T) and the NDVI is:

$$LAI_T = -0.216(NDVI)^2 + 5.744NDVI - 0.356 \quad (8)$$

The LAI values of the *Populus* woodlands were inverted based on remotely sensed ARVI (Atmospherically Resistant Vegetation Index). The empirical relationship ($R^2 = 0.82$) between the LAI of the *Populus* woodlands (LAI_P) and the ARVI is:

$$LAI_P = 8.119(ARVI)^2 + 2.036ARVI + 0.095 \quad (9)$$

Based on the empirical inversion models, the LAI_m spatial distributions of the *Populus* woodlands and *Tamarix* thickets in the lower reach of the Tarim River were obtained from the Landsat 8 OLI data for July 20th, 2013 (Fig. 6b). The results showed the LAI_m values were generally low. The largest LAI_m value for the *Populus* woodland was 1.85, and that for the *Tamarix* thicket was 1.65. Mean LAI_m values for both the *Populus* woodlands and the *Tamarix* thickets were 0.25, indicating that the vegetation cover was very sparse in the study area, which is consistent with field observations (Chen et al. 2004).

5.2 Water Requirements under Current Vegetation Cover

We estimated the VWR of the desert riparian forests in the lower reach of the Tarim River based on the remotely sensed spatial distributions of desert riparian vegetation and their LAI, meteorological data from the 2013 growing season, and fitted $\alpha_p \cdot K_b$ values (Table 1). The model is able to calculate daily VWR values, which provides more detailed temporal process information for desert riparian forest VWR vital to water resources management. The daily cumulative curve of total regional ET_m shows seasonal variations in VWR (Fig. 7). The VWRs during the GP and LP were small, accounting for approximately 20 % of total VWR during the growing season. During the MP, the slope of the cumulative curve did not vary, indicating that the mean daily VWR during the MP remained relatively stable at approximately $8.0 \times 10^4 \text{ m}^3$ per day during the 2013 growing season.

The model is also able to provide VWRs of different vegetation types. Table 2 identifies the VWRs for different phenological stages of the *Populus* woodlands and *Tamarix* thickets in the 2013 growing season. The data demonstrate the differences in VWRs for the two types of desert riparian forests in the study area, providing valuable information for desert and water resources management teams.

The spatial distribution of desert riparian forest VWRs throughout the study area is another important result of the model (Fig. 8a). Further analysis of this spatial distribution can reveal spatial patterns in VWRs (Fig. 9). During the 2013 growing season, the VWR for the largest area was only 76.5 mm m^{-2} , while the area with a VWR of just under 400 mm m^{-2} comprised 97.4 % of the total desert riparian forest area. Mean VWR in the 2013 growing season was only 134.6 mm m^{-2} , reflecting the low water needs of desert riparian forests with sparse vegetation cover in hyper-arid regions.

Fig. 7 Cumulative curve of total daily vegetation water requirements (VWR) of the desert riparian forests in the lower basin of the Tarim River in China under current vegetation cover condition (Existing) and for three different vegetation cover scenarios (S1, S2 and S3)

Table 2 Vegetation water requirements (VWR) of two main desert riparian vegetation species at different phenological stages in the lower basin of the Tarim River, China

Phenological stages	<i>Tamarix</i> thickets		<i>Populus</i> woodlands		Total VWR (10^6 m^3)
	VWR (10^6 m^3)	Proportion (%)	VWR (10^6 m^3)	Proportion (%)	
GP	5.197	4.4	14.230	12.0	19.427
MP	41.313	35.0	50.282	42.6	91.595
SP	3.483	2.9	3.643	3.1	7.126
Total VWR	49.993	42.3	68.155	57.7	118.148

5.3 Water Requirements under Different Vegetation Cover Scenarios

Because this model is both species-specific and spatially-explicit, setting different vegetation types and spatial patterns for the lower reaches of endorheic rivers allows the model to predict VWRs under different vegetation cover scenarios. Here, we set three scenarios of vegetation cover: scenario 1 (S1) represents deforestation, in which vegetated areas decreases by 2 % and mean LAI decreases by 23 % of existing vegetation cover; scenario 2 (S2) represents a single vegetation restoration scene, in which vegetated areas increase 26 % while mean LAI increases 6 % from the existing vegetation cover; and scenario 3 (S3) represents a second vegetation restoration scene, in which vegetated areas increase 42 % while mean LAI increases by 13 % of the existing vegetation cover (Table 3). The three scenarios were obtained using a simple algorithm. In this algorithm, we assumed that the desert riparian forest vegetation cover changes in the study area were related to the water supply rather than artificial control; thus, the spatial changes in the forests were primarily influenced by existing vegetation cover and the drought-tolerance of vegetation. According our field observations of riparian forests in hyper-arid regions, if the water conditions become worse at the decadal scale, the decrease in vegetation LAI is more obvious than the decrease in the distribution area of vegetation. However, if water conditions improve, the increase in the distribution area of vegetation is more obvious than that for vegetation LAI. Based on this reasoning, a simple algorithm was designed to obtain different LAI_m values for each pixel. In the vegetation restoration scenarios, we assumed that when water conditions improved, vegetation cover with an LAI value greater than 0.7 changed little because the vegetation with an LAI value greater than 0.7 were usually not water-stressed, while the

Fig. 8 Spatial distribution of vegetation water requirements in the lower basin of the Tarim River in China under different vegetation cover conditions: **a** current vegetation cover, **b** scenario 1, **c** scenario 2, and **d** scenario 3

Fig. 9 Covering area of the different vegetation water requirements (ET_m) in the lower basin of the Tarim River in China

vegetation with LAI value of less than 0.7 changed significantly because they were usually more sensitive to water conditions. However, in the deforestation process, when water conditions became worse, vegetation with LAI values greater than 0.7 were more sensitive to water conditions than those with values less than 0.7.

Based on the 2013 weather data, we estimated the VWRs for desert riparian forests under the three vegetation cover scenarios (Table 3). The spatial distributions (Fig. 8b–d) and the temporal patterns (Fig. 7) of the VWRs under the three vegetation cover scenarios can also be displayed visually.

6 Concluding Remarks

The model presented here included an LAI variable in order to highlight the effect of the spatial variation of desert riparian vegetation cover on regional ET, making the model more

Table 3 Areas of vegetation cover, their mean LAI and the total vegetation water requirements (VWR) in the lower basin of the Tarim River under current vegetation cover condition and for three different vegetation cover scenarios

Scenarios	Area of vegetation (10^3 ha)	Mean LAI	Total VWR (10^6 m ³)
Existing	74.2	0.25	118.148
S1	72.7	0.19	88.822
S2	93.2	0.27	157.542
S3	105.4	0.29	188.831

suitable in hyper-arid regions. Moreover, the model is species-specific, and can consequently be used to estimate the VWRs of different desert riparian vegetation species, assuming the appropriate $\alpha_p \cdot K_b$ values for different desert riparian vegetation species at different growth stages can be obtained. The test results indicated that the model provide a feasible estimate of the VWRs for desert riparian forests. Because the model used two dominant desert riparian species in arid northwestern China, *Tamarix* thicket and *Populus* woodland, the positive model test result also indicate that the model may be applied effectively in desert riparian ecosystems along other endorheic rivers in arid northwestern China.

The model also exhibited its practical applications for water resources management of rivers in arid regions. First, this model is simple, easy to operate, and only requires a few input data items and parameters. When the $\alpha_p \cdot K_b$ values have been obtained, and the algorithms to discern vegetation categories and the inverse of the LAI values from remotely sensed data have been established, running the model in a single region only requires meteorological data. Second, this model not only provides continuous historical, near real-time and forecasted VWR estimations of desert riparian forests based on historical, real-time observational and forecasted meteorological data, but also shows the spatial patterns of VWRs in certain areas based on the remote sensing data. Estimates of temporal fluctuations and spatial distributions of VWRs can provide more abundant information to improve the efficiency of water use. Third, this model can predict VWRs under different vegetation spatial distributions and covers, which can provide a valuable reference point for how to balance the conflict between ecological restoration and water use, thus informing the sustainable management of water resources and desert riparian ecosystems in arid regions.

Nevertheless, this model has its limitations. The VWR in this model was defined as the regional ET under non-water-stressed conditions. However, this definition does not consider the impacts of other environmental factors such as salinization, desertification, etc., on desert riparian ecosystem health and functionality, which would directly affect the VWR. Additionally, this model estimates VWR rather than EWR and, thus, cannot provide immediate guidance on water resources allocation. Nevertheless, this model can serve as a foundation for determining EWR along rivers in arid regions.

Briefly, the model to estimate the water requirements of desert riparian forests in arid regions presented here is novel because the model is spatially explicit and highlights the effect of vegetation cover's spatial variability on surface ET amount in arid regions, and is also species specific, reflecting the different water needs of different desert riparian plants. The model is also feasible for desert riparian ecosystems in hyper-arid regions and has practical application for water resources management because it is easy to operate and can provide abundant information related to the spatiotemporal patterns of vegetation water requirements under different vegetation cover scenarios. This model can serve as a useful tool for water resources management agencies to improve their decisions related to river water allocation between irrigation farming and natural ecosystems in arid regions.

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