Global and Planetary Change 122 (2014) 292–304

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Configuration of water resources for a typical river basin in an arid region of China based on the ecological water requirements (EWRs) of desert riparian vegetation

Hongbo Ling [a,b], Bin Guo [c], Hailiang Xu [a,*], Jinyi Fu [a]

[a] State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (CAS), Urumqi 830011, China
[b] Sino-German Joint Research Center for the Management of Ecosystems and Environmental Change in Arid Lands, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (CAS), Urumqi 830011, China
[c] College of Geomatics, Shandong University of Science and Technology, Qingdao 266510, China

ARTICLE INFO

Article history:
Received 8 July 2013
Received in revised form 7 June 2014
Accepted 25 September 2014
Available online 5 October 2014

Keywords:
Water resources
Ecological water requirement (EWR)
Desert riparian vegetation
Inland river basin
Tarim River

ABSTRACT

Desert riparian vegetation is a natural cover promoting the stability and development of inland river ecosystems in arid regions. Calculating the ecological water requirements (EWRs) of desert riparian vegetation is an important step in achieving reasonable water utilization. Therefore, this study examined the Tarim River, located in an extremely arid region of China, and collected relevant data on hydrology, weather and vegetation using remote sensing. Subsequently, we analyzed the spatial distribution of the desert riparian vegetation in four sections of the Tarim River and calculated the EWR of the desert riparian vegetation using the phreatic evaporation model; additionally, we determined the required runoffs at five hydrologic stations based on the water balance principle. Ultimately, the necessary protection ranges and goals for desert riparian vegetation were established according to the water resource variations in the Tarim River. Our research showed that the total area of desert riparian vegetation along the Tarim River is 16,285.3 km^2; this distribution area gradually decreased as the distance from the river increased, and areas varied in the different river sections. The EWRs of desert riparian vegetation from Sections 1 to 5 are 5.698 $\times 10^8$, 7.585 $\times 10^8$, 4.900 $\times 10^8$, 4.101 $\times 10^8$ m^3 and 1.078 $\times 10^8$ m^3, respectively. Therefore, the total EWR of the study region is 23.362 $\times 10^8$ m^3. In terms of the transpiration law of the "unimodal type", the peak value of EWR of natural vegetation occurs in July, and the decreasing trend appears in the other months. Based on the water balance principle, the required runoffs in Alar, Xinquman, Yingbaza, Wusiman and Qiala were determined to be 47.105 $\times 10^8$, 35.174 $\times 10^8$, 22.734 $\times 10^8$, 15.775 $\times 10^8$ and 7.707 $\times 10^8$ m^3, respectively. According to the water resource frequency and the EWR of the desert riparian vegetation along the Tarim River, we divided the region into three protection ranges: key protection (8.9–11.8 km from the river), basic protection (15.8–21.8 km from the river) and influence protection (43.0 km from the river). This research not only provides a reasonable calculation method for EWR on the scale of a river basin but also supports the healthy development of the desert riparian vegetation ecosystem and helps to achieve the optimal water allocation for this river.

1. Introduction

The ecological conservation and sustainable economic development of inland river basins in arid regions have attracted worldwide interest (Abellan et al., 2006; Vass et al., 2009; Naidoo et al., 2011; Zhang et al., 2012). As the main element of inland river basins in arid regions and the top-level community in the natural succession of temperate desert climates, desert riparian vegetation is crucial in maintaining ecological balance, biodiversity and agricultural production (Elosegi et al., 2010; Merritt and Bateman, 2012). The occurrence and succession of desert riparian vegetation relate closely to the natural features and hydrologic processes of the environment (Xu et al., 2009; Cao et al., 2012; Merritt and Bateman, 2012). However, due to the excessive utilization and general scarcity of water resources in arid regions, increasingly serious conflicts among the water needs of production, daily life and the ecological environment have unbalanced portions of the ecosystem and even threatened human survival (Cai and Rosegrant, 2004; Ye et al., 2010). Therefore, the regulation of limited water resources to achieve the harmonious development of ecology and the economy in arid and semiarid regions is of great importance (Lioubimtseva and Henebry, 2009; Howard and Merrifield, 2010). To guarantee sustainable ecosystem stabilization and development, the water requirements of natural vegetation growth, namely, the ecological water requirements (EWRs) of desert riparian vegetation in the inland rivers of arid regions, must be considered. Recently, a number of studies (Song et al., 2002; Cai and Rosegrant, 2004; Zhao et al., 2007; Wang and Lu, 2009; Ye et al., 2010;

* Corresponding author at: Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, Xinjiang 830011, China.
E-mail address: linghongbo0929@163.com (H. Xu).

http://dx.doi.org/10.1016/j.gloplacha.2014.09.008
0921-8181/

Jin et al., 2011; Sun et al., 2012; Yan et al., 2012) have calculated the regional EWR of arid regions using the area quota, water balance, phreatic evaporation, biomass and remote sensing methods. However, relatively few studies have calculated EWR at the river basin scale based on the spatial distributions of desert riparian vegetation and groundwater depth by using the software of ArcGIS. In addition, the area quota method is most accurately applied to calculate the EWR of artificial vegetation, such as artificial oases and farmlands. The phreatic evaporation method is more suitable for the EWR of vegetation in arid regions. The water balance method is limited, as it does not consider the structure and function of ecosystems and their water demands. The biomass and remote sensing methods have low calculation accuracy due to the difficulty of obtaining the biomasses of tall trees and underground vegetation. Moreover, the remote sensing method still suffers from inadequate image resolution (Hu and Zhao, 2008). As a result, remote sensing should be combined with abundant field investigations to enhance the accuracy of remote sensing interpretation. According to the above analysis, we combined the phreatic evaporation method with remote sensing technology, supported by numerous field surveys, to calculate the EWR of desert riparian vegetation in the Tarim River Basin.

The Tarim River Basin is one of China's most water-stressed regions and may be one of the most fragile ecological environments in the world (Xu et al., 2011). The desert riparian vegetation in this region provides the vital ecological service of developing and supporting oases (Leng et al., 2011). However, decades of unreasonable land and water resource utilization have resulted in spatiotemporal changes in the water distribution pattern of the Tarim River Basin, including zero-flow areas in its lower reach, dried-up lakes, the degradation of natural vegetation and the aggravation of desertification (Cai and Rosegrant, 2004; Feng et al., 2005; Pang et al., 2010; Ye et al., 2010; Chen et al., 2011a; Lam et al., 2011; Leng et al., 2011). Therefore, determining the EWR of desert riparian vegetation is a vital step in the optimal allocation of regional water resources and the protection of ecosystem stability in the river basin.

Especially detrimental to the ecology of the region was the establishment, in 1976, of the Daxihaizi Reservoir in the lower reach of Tarim River. Although the reservoir restored the water supply for the irrigation of the lower reach, it allowed water to flow into Taitema Lake only during the flood period. Today, the lower reach has become the most seriously ecologically degenerated region in China (Leng et al., 2011). In 2000, the Chinese government invested RMB 10.7 billion yuan to restore the natural desert riparian vegetation and ecological conditions of the Tarim River Basin. Management measures included the implementation of ecological water conveyance (a water transfer of 4.5×10^8 m^3 per year from the Kongqi River, flowing through the Qiala hydrologic station into the lower reach) to revitalize the riverway of the lower reach, which has been cut off for 30 years.

Therefore, to guarantee the sustainable ecological watering of the lower reach and control the ecosystem deterioration of the Tarim River Basin, this study collected the Landsat™ images from 2010 along with data for the region's vegetation, hydrology, weather and social economy, and thus calculated the EWR of desert riparian vegetation and the required runoffs of different hydrologic stations. The aims of this paper are (1) to present a reasonable model for the calculation of EWR on the river basin scale, offering a scientific reference for the ecological protection of the Tarim River and similar river basins, and (2) to provide technical support for the optimal management and sustainable utilization of water resources in the Tarim River Basin.

2. Data resources

Data collected in this study are as follows: (1) water requirement of desert riparian vegetation includes daily transpiration quantities of *Populus euphratica* (the major constructive species), *Tamarix spp*. (the dominant species of shrub layer) and *Phragmites australis* (the dominant species of herb layer) during 2003–2009 in the mainstream of Tarim River. (2) Landsat™ images of the Tarim River were chosen from August to September in 2010, which has less cloud cover (<5%) and is the high-flow period with high vegetation coverage. The monthly weather data is the evaporation collected from Alar, Kuche, Luntai, Korla and Tieganlik during 1991–2010. Hydrologic data includes the monthly runoff from Alar during 1957–2010, the available groundwater quantity of the study region in 2010, and the groundwater tables of 86 monitoring wells during 2000–2010. Data of socioeconomic water requirement (industrial, agricultural, animal husbandry and life water requirements) in 2010 were provided by the Management Bureau of Tarim River Watershed.

3. Study region

Tarim River (34.20°–43.39°N, 71.39°–93.45°E) is located in the Southern Xinjiang and is the longest inland river of China with the overall length of 1321 km (Chen et al., 2006) (Fig. 1). Flowing through the Taklimakan Desert, the basin contains 144 rivers of nine river systems including the Aksu, Kashgar Yarkand, Hotan, Kongqi, Dina, Weigan-Kuche, Keriya and Qarqan rivers, with a total area of 102×10^4 km^2. Hydrologically, Tarim River Basin is a closed catchment. The main runoff in this river basin is recharged by precipitation and glacial melt water in mountain headstreams. However, the mainstream of the Tarim River is a typical pure-dissipation inland river that does not yield water resources on its own, and is only supplied by runoff from the headstreams. Therefore, the hydrological processes of the river basin are more typical than those of other regions in the middle and high latitudes of the Northern Hemisphere. Historically, nine water systems flew water to Tarim River. However, because of the human activities and climate change, Keriya River and Dina River were separated from Tarim River successively in the early 20 centuries. Moreover, Kashgar River, Kaidu River-Kongqi River, and Weigan River also lost connection with Tarim River after 1940s (Hao et al., 2008). Presently, there are only three headstreams, Hotan River, Yarkand River, and Aksu River flowing into Tarim River, occupying 23.2%, 3.6%, and 73.2% of the total inflow, respectively.

Owning to the particular geographical conditions (located in hinderland and adjoining desert), the regional climate is the typical continental climate of arid region. The average precipitation of many years is 25 mm, while the annual average evaporation is up to 2500–3000 mm (Xu et al., 2011; Ling et al., 2013).

For the ecosystem of desert riparian vegetation in the river basin, *P. euphratica Oliv*. and *Tamarix spp*. are the main constructive species. The major herb species includes *P. australis*, *Karelinia caspica* and *Glycyrrhiza glabra* (Xu et al., 2011; Ling et al., 2013).

4. Methods

4.1. Data acquisition of natural vegetation

The data for land use/cover along the mainstream of the Tarim River was obtained by the digitization of Landsat™ images from 2010. Moreover, we tested and corrected the image data through numerous field investigations to ensure the accuracy of the distribution data for the desert riparian vegetation in the study region.

4.4.1. Remote sensing data processing

For image processing, the relief maps of 41 amplitudes (with the ratio of 1:100,000) for the research region were first scanned and registered by ArcGIS 10 (error precision below 0.5 pixels), and the digital raster graphic (DRG) was created. Subsequently, the 2010 Landsat images were registered into the digital raster graphic (DRG). Thirty interpretation symbols, such as the cross points of roads and canal systems and residential centers, were chosen evenly over the whole image plane. In addition, the images were corrected based on the field survey and sampling results.

Visual interpretation is utilized to rely not on the spectral and spatial characteristics of images, various non-remote sensing information and the laws of biogeography alone, but to draw additional support from the thought processes of discrimination, comprehensive analysis, and

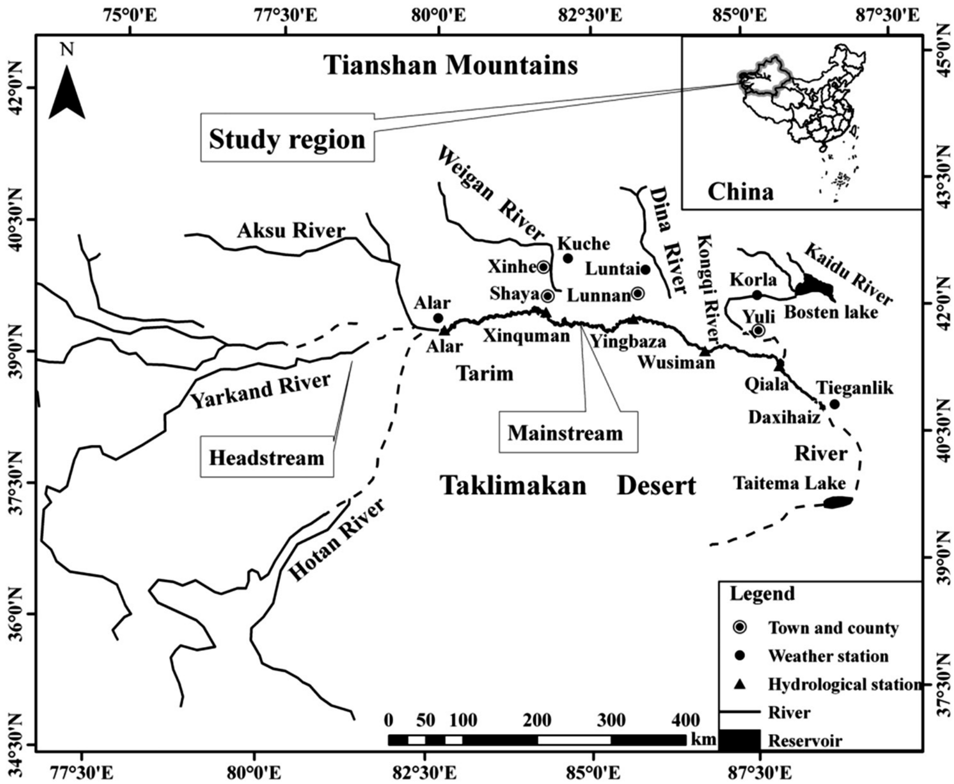

Fig. 1. Sketch map of Tarim River watershed.

logical reasoning (VanderMeer, 1997). According to the spectral characteristics of each band for the Landsat, these images were fused using the bands 4, 3, and 2. Therefore, the vegetation, water, desert and saline land were presented as red, blue or black, light brown or yellow and clear white, respectively. Subsequently, the interpretation keys for the classifications of land use/cover were established based on the spectral, radiation and geometric characteristics (i.e., the shape, size, hue, brightness, saturation, structure, location, texture etc.) of the surface features inflected by the remote sensing images. Furthermore, the classification accuracy of the remote sensing data was assessed by the Kappa coefficient (Congalton and Green, 1999). According to the classification precision evaluation for the land cover/use of the Tarim River Basin, the Kappa coefficient (classification precision evaluation index) (Congalton and Green, 1999) is 92.3%, indicating that the images accurately reflect the situation of land use in the study region.

4.1.2. Simple plot survey

In the Tarim River, we established 49 transects (25 transects on the south bank and 24 transects on the north bank), staggered in the vertical direction of the river, with lengths of 20–50 km and widths of 1–2 km. According to the distribution range of the natural vegetation, three quadrats of trees and shrubs of 25 × 25 m were established at every other 1 km. Two herb samples of 1 × 1 m or 5 × 5 m were established within each quadrat. A total of 1831 vegetation samples were selected.

The following measurements were taken: the coverage proportions of *P. euphratica Oliv*., *Tamarix spp*., herbaceous plants and bare land within each quadrat; the diameter at breast height (DBH) of *P. euphratica* (0–5, 5–10, 10–30 and >30 cm); the number, DBH, height, canopy density and crown width of the trees and shrubs within each quadrat; and the species type, number, coverage degree, height and frequency of the herbs within each sample.

According to the remote sensing images (as corrected based on the simple plot survey), the natural desert riparian vegetation was divided into four categories: forest land, sparse woodlot, high cover grassland and low cover grassland. As outlined by a previous study (Wang et al., 2001), sparse woodlot includes various sparse trees and shrubs with coverage of 5%–30% and a groundwater depth below 4.5 m; forest land includes the denser forests of *P. euphratica* and *Tamarix spp*. with coverage exceeding 30% and a groundwater depth above 4.5 m; high cover grassland consists of natural grassland with coverage exceeding 20% and a groundwater depth above 3.5 m, where growth is relatively denser due to desirable water conditions; low cover grassland consists of natural grassland with coverage of 5–20% and a groundwater depth below 3.5 m, where growth is sparse due to poor water conditions and is insufficient for animal husbandry (Fig. 2). In Fig. 2, we divided the Tarim River into five river sections as follows: Alar–Xinquman (Section 1) and Xinquman–Yingbaza (Section 2) in the upper reach, Yingbaza–Wusiman (Section 3) and Wusiman–Qiala (Section 4) in the middle reach, and Qiala–Taitema Lake (Section 5) in the lower reach. The land use types are classified based on the national criteria in the book "Current Land Use Classification (GB/T 21010–2007) (2007) which was published by the Chinese government.

4.2. Calculation model for EWR in the Tarim River

The phreatic evaporation method is applicable for the vegetation of arid regions and is mainly related to groundwater. The mainstream of the Tarim River experiences sparse rainfall, and the desert riparian vegetation along the river is dominated by nonzonal mesophytes and xerophytes, the growth of which relies on the supply of groundwater. The actual evapotranspiration of the desert riparian vegetation is supplied by soil water (generated by upward phreatic water), and the soil water condition is thus determined by the evaporation of phreatic water (Chen et al., 2008). On a larger spatial scale, when the soil has a stable evaporation rate, the surface evaporation intensity is stable, and the soil water content also remains unchanged (Chen et al., 2008). The phreatic water evaporation intensity, soil water flux and soil evapotranspiration intensity are all equal (Li, 1988). Accordingly, the phreatic

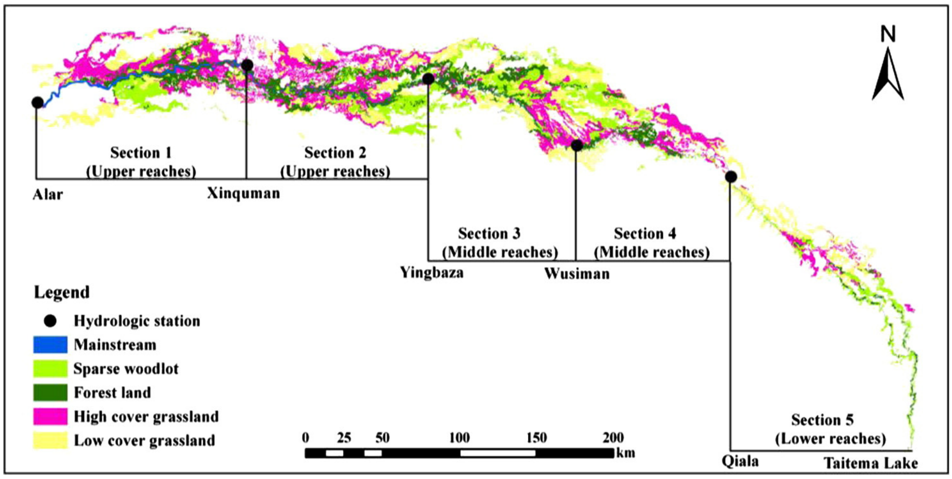

Fig. 2. Distributions of desert riparian vegetation in the Tarim River.

evaporation method is applicable in calculating the EWR of desert riparian vegetation.

The phreatic evaporation method was applied to estimate indirectly the EWR of the desert riparian vegetation, as based on the remote sensing interpretation. EWR is defined as the product of the area of a given vegetation type at a given phreatic water depth and its corresponding phreatic evaporation (Song et al., 2000):

$$W = (1 + 30\%) \cdot \sum 10^3 A_i W_{gi} k_p \tag{1}$$

where W is the EWR of desert riparian vegetation (m^3), A_i is the area of the vegetation type i (km^2), W_{gi} is the phreatic evaporation of the vegetation type i at a given groundwater depth, 30% is the water use coefficient (Chen et al., 2008), and k_p is the influence coefficient of desert riparian vegetation. As established in previous work (Song et al., 2000; Hu, 2007), the k_p of the Tarim River Basin is defined in Table 1.

The areas of different vegetation types were determined using remote sensing interpretation. Phreatic evaporation (W_{gi}) is critical in calculating the EWR through the phreatic evaporation method, and Aviriyanover's Empirical Formula is usually utilized to determine this value (Ye et al., 2010).

$$W_{gi} = a(1 - h_i/h_{max})^b E_{\varphi 20} \tag{2}$$

where a and b are the empirical coefficients, h_i is the groundwater depth of the vegetation type i (m), h_{max} is the critical phreatic water depth (m), and $E_{\varphi 20}$ is the evaporation of a 20 cm general weather evaporation dish (mm). Many researchers have determined the value of extreme phreatic evaporation (h_{max}) in the Tarim River as 5 m, the value of a as 0.62 and the value of b as 2.8 (Song et al., 2000; Ye et al., 2010). In addition, the spatial distribution of h_i (Fig. 3) was calculated by the spatial analyst tools in ArcGIS 10 based on the monitoring or calculating data of 8301 from 86 monitoring wells and groundwater model (Hu, 2007).

$$\lambda = 0.5537 \exp(-0.2403H) \tag{3}$$

where λ is the soil moisture content (%), and it is acquired by using the soil moisture content measurement instrument; H is the groundwater depth (m). According to the measured data of soil moisture content, the groundwater depths evenly distributed on both sides of the Tarim River were calculated.

4.3. Water requirement quantities of different river sections

4.3.1. Water requirement model in the inland river

According to the principle of water balance, water requirement model of each river section is as follows,

$$W_S = W_{SE} + W_O + W_N + W_R \tag{4}$$

where W_S is the water supply quantity including surface runoff and available groundwater ($10^8\ m^3$), and precipitation is unavailable in a extreme arid region (Chen et al., 2011b); W_{SE} is the socioeconomic water requirement (i.e., industry, agriculture, the lives of residents and livestock, etc.) ($10^8\ m^3$), W_N is the EWR of the desert riparian vegetation ($10^8\ m^3$), W_O is the water requirements of the other land use types (i.e., water area, bare land and intertidal zone) ($10^8\ m^3$), and W_R is the water requirements of the riverway ($10^8\ m^3$).

In addition, water requirements of bare land and intertidal zone can been calculated by using the Eq. (2). Based on the measured data, the average groundwater tables (h_i) are 4 and 1 m, respectively.

4.3.2. Calculation of water area evaporation

In the Tarim River Basin, water area evaporation is calculated based on the area quota, and precipitation should have been also considered for the water area (Hu, 2007).

$$W_{WE} = A \cdot \left(E_\phi \cdot k - P\right) \cdot 10^{-5} \tag{5}$$

Therefore, the equation of water area evaporation in the riverway is,

$$W_{WER} = B \cdot L \cdot \left(E_\phi \cdot k - P\right) \cdot 10^{-8} \tag{6}$$

where, both W_{WE} and W_{WER} are the water area evaporation ($10^8\ m^3$); A is the water area (km^2), B is the riverway width (m), L is the riverway length (m), $E_{\varphi 20}$ is the evaporation of 20 cm general weather evaporation dish (mm), P is the precipitation (mm) and k is the conversion coefficient of water area.

Table 1
Influence coefficient of vegetation in different groundwater depths.

Groundwater depth (m)	<1.25	1.25–1.75	1.75–2.25	2.25–2.75	2.75–3.25	3.25–4	>4
Influence coefficient (k_p)	1.98	1.63	1.56	1.45	1.38	1.29	1.00

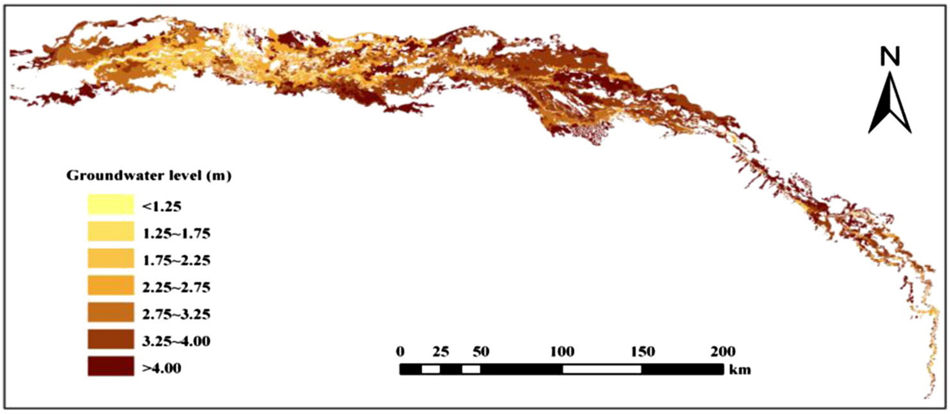

Fig. 3. Spatial distribution map of groundwater depth in Tarim River Basin.

4.3.3. Water consumption in the riverway (W_R)

Based on the previous studies (Song et al., 2000; Hu, 2007), calculation formulas of water area widths of riverway are acquired in the different hydrological stations of the Tarim River.

$$B_{AL} = 15.582 Q_{AL}^{0.4985} R^2 = 0.846 \quad (7)$$

$$B_{XQ} = 24.476 Q_{XQ}^{0.3809} R^2 = 0.876 \quad (8)$$

$$B_{YB} = 47.909 Q_{YB}^{0.1776} R^2 = 0.952 \quad (9)$$

where B_{AL}, B_{XQ} and B_{YB} are the water area widths of Alar, Xinquman and Yingbaza (m), respectively, and Q_{AL}, Q_{XQ} and Q_{YB} are the surface runoffs of three hydrological stations (10^8 m^3). Therefore, water consumptions of four river sections are calculated as follows.

(1) Water consumption between Alar and Xinquman (i.e., Section 1)
According to formula (6) and data of the evaporation and precipitation during the 1991–2010, water area consumption (W_{WES1}) of Section 1 in the riverway is calculated,

$$W_{WES1} = \frac{B_{AL} + B_{XQ}}{2} \cdot L_{S1} \cdot \left(E_{\phi S1} \cdot k_{S1} - P_{S1}\right) \cdot 10^{-8} \quad (10)$$

where L_{S1} is 189 km, $E_{\phi S1}$ is 1965.3 mm, k_{S1} is 0.67 (Zhou, 1999) and P_{S1} is 68.15 mm. Formulas (7) and (8) are put into formula (10), and thus water area (A_{WS1}) in the riverway is

$$A_{WS1} = 1.4724499 Q_{AL}^{0.4985} + 2.312982 Q_{XQ}^{0.3809}. \quad (11)$$

Therefore, water area consumption (W_{WES1}) in Section 1 is,

$$W_{WES1} = 0.018386 Q_{AL}^{0.4985} + 0.02888 Q_{XQ}^{0.3809}. \quad (12)$$

Subsequently, the area (A_{IS1}) of intertidal zone in the riverway is calculated,

$$A_{IS1} = A_{RS1} - A_{WS1} = 223.56 - \left(1.472499 Q_{AL}^{0.4985} + 2.312415 Q_{XQ}^{0.3809}\right). \quad (13)$$

Based on the phreatic evaporation method (formula (2)), the water consumption (W_{IES1}) of intertidal zone is

$$W_{IES1} = 6.52 \times 10^{-3} A_{IS1}. \quad (14)$$

(2) Water consumption between Xinquman and Yingbaza (i.e., Section 2)
For Section 2 in the Tarim River, water area consumption (WWES2) in the riverway is calculated as,

$$W_{WES2} = \frac{B_{XQ} + B_{YB}}{2} \cdot L_{S2} \cdot \left(E_{\phi S2} \cdot k_{S2} - P_{S2}\right) \cdot 10^{-8} \quad (15)$$

where, L_{S2} is 258 km, $E_{\phi S2}$ is 2053.05 mm, k_{S2} is 0.72 (Zhou, 1999) and P_{S2} is 66.34 mm. Therefore, the water area(A_{ws2}) of riverway is,

$$A_{WS2} = 6.180261 Q_{YB}^{0.1776} + 3.157404 Q_{XQ}^{03809} \quad (16)$$

Then, water area consumption (W_{WES2}) is

$$W_{WES2} = 0.087256 Q_{YB}^{0.1776} + 0.044578 Q_{XQ}^{0.3809} \quad (17)$$

Meanwhile, area (A_{IS2}) of intertidal zone in the riverway is

$$A_{IS2} = A_{RS2} - A_{WS2} = 73.63 - \left(6.180261 Q_{YB}^{0.1776} + 3.157404 Q_{XQ}^{0.3809}\right) \quad (18)$$

Water consumption (W_{IES2}) of intertidal zone is calculated by

$$W_{IES2} = 6.81 \times 10^{-3} A_{IS2} \quad (19)$$

(3) Water consumption between Yingbaza and Wusiman (i.e., Section 3)
Based on the related study (Hu, 2007), water area consumption (W_{WES3}) in the riverway of Section 3 is defined as,

$$W_{WES3} = 0.8 B_{YB} \cdot L_{S3} \cdot \left(E_{\phi S3} \cdot k_{S3} - P_{S3}\right) \quad (20)$$

where L_{S3} is 204 km, $E_{\phi S3}$ is 2345.55 mm, k_{S3} is 0.65 (Zhou, 1999), and P_{S3} is 54.5 mm. Formula (9) is put into formula (20), thus the water area (A_{WS3}) of riverway in Section 3 is

$$A_{WS3} = 7.818749 Q_{YB}^{0.1776} \quad (21)$$

Subsequently, water area consumption (W_{WES3}) of riverway is

$$W_{WES3} = 0.114944 Q_{YB}^{0.1776} \quad (22)$$

In addition, the area (A_{IS3}) of intertidal zone of riverway is

$$A_{IS3} = A_{RS3} - A_{WS3} = 26.41 - 7.818749 Q_{YB}^{0.1776} \quad (23)$$

Finally, the water consumption (W_{IES3}) of intertidal zone is calculated as,

$$W_{IES3} = 7.79 \times 10^{-3} A_{IS3} \quad (24)$$

(4) Water consumption between Wusiman and Qiala (i.e., Section 4) According to the study (Hu, 2007), calculation formula (20) of water area consumption in Section 3 can be used in Section 4. In Section 4, L_{S4} is 194 km, $E_{\phi S4}$ is 2600.35 mm, k_{S4} is 0.57 (Zhou, 1999), and P_{S4} is 42.98 mm. According to formal (20), the water area (A_{WS4}) of riverway in Section 4 is

$$A_{WS4} = 7.435477 Q_{YB}^{0.1776} \quad (25)$$

Therefore, the water area consumption (W_{WES4}) of riverway is

$$W_{WES4} = 0.107013 Q_{YB}^{0.1776} \quad (26)$$

Additionally, the area (A_{IS4}) of intertidal zone of riverway is calculated as,

$$A_{IS4} = A_{RS4} - A_{WS4} = 14.83 - 7.435477 Q_{YB}^{0.1776} \quad (27)$$

Finally, the water consumption (W_{IES4}) of intertidal zone of riverway is

$$W_{IES4} = 8.63 \times 10^{-3} A_{IS4} \quad (28)$$

where A_{RS1}, A_{RS2}, A_{RS3} and A_{RS4} are the riverway areas of Sections 1, 2, 3, and 4 in the Tarim River, which are acquired by the remote sensing images. In addition, for the water consumption of riverway in the inland river of arid region, riverway leakage water is mainly utilized to maintain the vegetation growth of desert riparian vegetation by virtue of recharging groundwater (Xi et al., 2012). Therefore, riverway leakage water can be regarded as a part of EWR of desert riparian vegetation in the Tarim River, and it should not be calculated in order to avoid double-count of EWR.

5. Results and analysis

5.1. Distribution of desert riparian vegetation in the Tarim River Basin

In the Tarim River Basin, desert riparian vegetation is the main component of the ecosystem outside of the riverway and represents the major object of protection. The distribution of desert riparian vegetation varies with the spatiotemporal changes of water resources, and analyzing its distribution is therefore vital to calculating the EWR of desert riparian vegetation in the Tarim River Basin. With the support of the spatial analyst tools in ArcGIS 10, the area of the desert riparian vegetation was determined for every 1 km interval from the river bank, and the distribution curves were drawn (Figs. 4 and 5). Due to distribution within the 2 km for the desert riparian vegetation in Section 5, it is not suitable to use the spatial analyst tools in this study.

The distribution area of the desert riparian vegetation along the Tarim River decreased with increased distance from the river bank (Fig. 4). The desert riparian vegetation of Sections 1 and 2 is distributed within 35 km from the river bank. Compared to those of Sections 1 and 2, the distribution ranges of Sections 3 and 4 are greater, at 43 and 37 km, respectively. In addition, the total area of desert riparian vegetation in the five river sections is 16,285.3 km^2, and the areas of Sections 1 to 5 compose 24.2%, 28.5%, 23.3%, 14.8% and 9.2% of the total, respectively.

We summed up the area percentage of riparian forest at every 1 km to attain the area percentages at different distances from the river bank, which were designated as the protection rates of the desert riparian vegetation of the Tarim River. The distances from the river bank representing different protection rates (Table 2) were calculated by the fitting equations in Fig. 5. According to Table 2 and Fig. 5, Section 1 has the most concentrated desert riparian vegetation. Ranges of 8.9 and 15.8 km from the river bank, with areas of 1965.8 and 2948.7 km^2, protected 50% and 75% of the desert riparian vegetation in Section 1, respectively. Therefore, the remaining 25% of the desert riparian vegetation in Section 1 is located at 15.8–35 km from the river bank; this represents a distance of 19.2 km, which exceeds the range containing 75% of the vegetation by 3.4 km. For Sections 2, 3 and 4, 50% of the desert riparian vegetation is distributed within 10.8, 11.4 and 11.8 km from the river bank, respectively. However, these distances are shorter than those

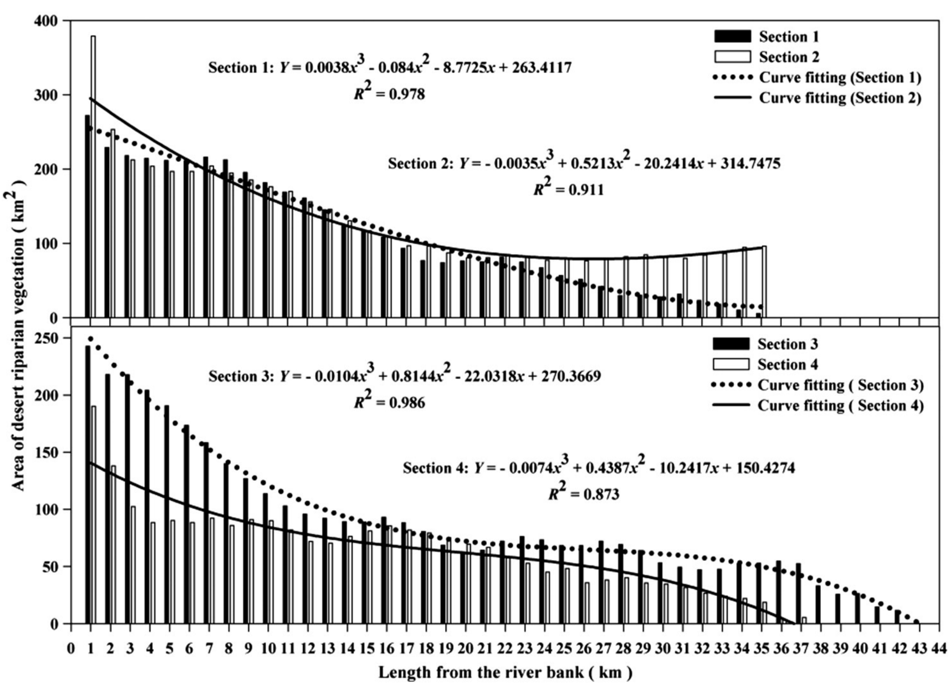

Fig. 4. Distributions of desert riparian vegetation under the different distances from the river bank in different sections of Tarim River.

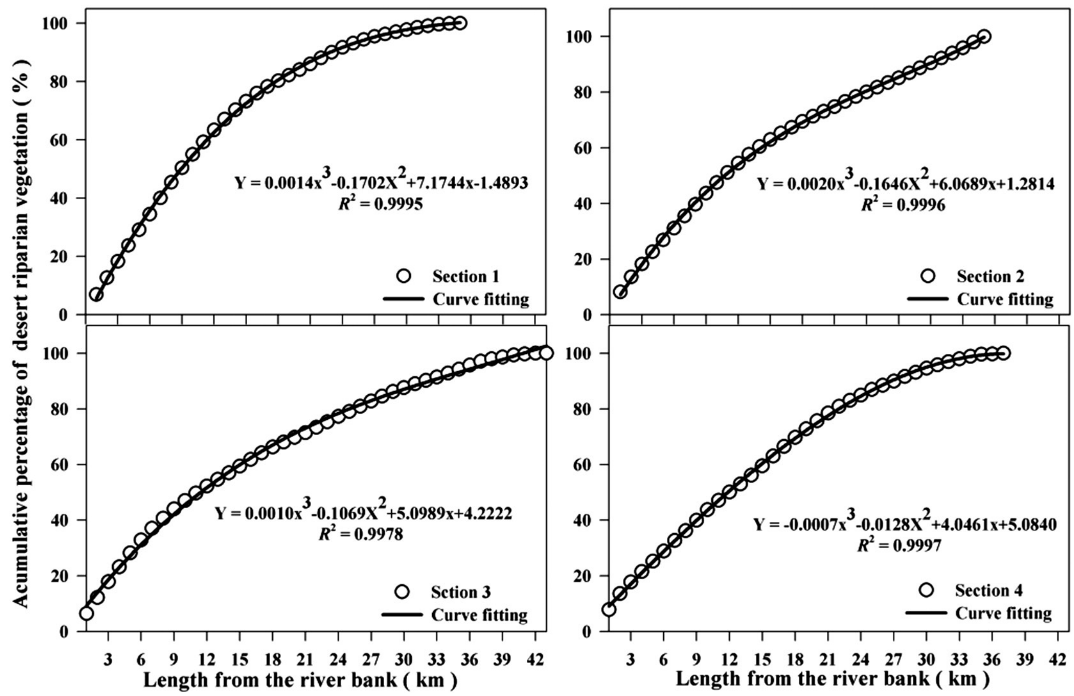

Fig. 5. Accumulative distribution rates of desert riparian vegetation under the different distances from the river bank in different sections.

containing the remaining 50% of the vegetation by 13.4, 22.2 and 13.4 km, respectively. Moreover, the widths representing a protection rate of 75% in these three sections are less than those protecting the remaining 25% of vegetation by 7.4, 0.6 and 2.8 km, respectively. Therefore, the distribution of the desert riparian vegetation along the Tarim River is mainly concentrated near both sides of the riverway.

5.2. EWR of desert riparian vegetation along the Tarim River

Based on the evaporation data from the Tarim River Basin during 1991–2010, the evaporation values of Section 1 through Section 5 are 1965.3, 2053.05, 2345.55, 2600.35 and 2707.4 mm, respectively. A combination of the phreatic evaporation model, relevant monitoring data, and the spatial analyst tools and field calculator in ArcGIS 10 were used to generate the spatial distribution map for the EWR of the desert riparian vegetation (Fig. 6).

In Figs. 6 and 2, the EWR of the five sections is highest in the high-cover vegetation types (forest land and high-cover grassland) close to the course of the Tarim River. The regions with poorer water conditions are dominated by sparse vegetation (sparse forest and low-cover grassland), so EWR values in these regions are low. The EWRs at different distances from the river bank and under areas with different protection rates were calculated through the buffer analysis of every 1 km in AcrGIS 10 (Fig. 7), and the EWRs of the desert riparian vegetation in areas containing 50%, 75% and 100% of the total are displayed (Table 3). In the lower reach of Tarim River, the desert riparian forest deteriorated seriously, therefore, EWRs of the river section should have been completely met under different inflows of mainstream to achieve conservation and restoration of natural vegetation.

In Fig. 7 and Table 3, the total EWRs of the desert riparian vegetation from Sections 1 to 4 covered under 50%, 75% and 100% protection and lower reach in the Tarim River Basin are 14.553×10^8, 19.692×10^8 and 23.362×10^8 m^3, respectively. Under the scenario where the entirety of the desert riparian vegetation is protected (100% protection rate), the values of EWR in Sections 1 and 2 are the greatest, reaching 7.585×10^8 and 5.698×10^8 m^3, respectively. Sections 3 and 4 have a wider distribution of desert riparian vegetation than the upper reach (Sections 1 and 2) (Fig. 4), but their values of EWR are smaller, with values of 4.900×10^8 and 4.101×10^8 m^3, respectively. The smallest value of EWR in Section 5 is 1.078×10^8 m^3. The area of high-cover desert riparian vegetation is greater in the upper reach (Sections 1 and 2) than in the middle reach (Sections 3 and 4) and the lower reach (Section 5) by 2235.4 and 4645.1 km^2, respectively; Section 2 has the largest area of this vegetation of all five sections, with a value of 2825.2 km^2. In addition, the area of high-cover desert riparian vegetation is smallest in Section 5, at 396.4 km^2, leading to the lowest EWR observed in the five sections.

5.3. Time allocation (annual process) of EWR of desert riparian vegetation in the Tarim River

In the Tarim River, calculating the transpiration of single plant is the basis for analyzing the water requirement process of desert riparian vegetation. Fig. 8 reflects the monthly transpiration processes of three typical vegetations, including *P. euphratica* (the dominant species of tree layer), *Tamarix spp*. (the dominant species of shrub layer) and *P. australis* (the dominant species of herb layer). The monthly transpiration changes of *P. euphratica* in the growth periods are as follows. The monthly transpiration of *P. euphratica* increases gradually from January to July, and thus decreases gradually from July to December. The

Table 2
Protection rate of desert riparian vegetation in different distances from the river bank.

Protection rate of desert riparian vegetation	Section 1		Section 2		Section 3		Section 4	
	Range (km)	Area (km^2)	Range (km)	Area (km^2)	Range (km)	Area (km^2)	Range (km)	Area (km^2)
50%	8.9	1965.8	10.8	2322.2	11.4	1898.2	11.8	1208.6
75%	15.8	2948.7	21.2	3483.3	21.8	2847.3	19.9	1812.9

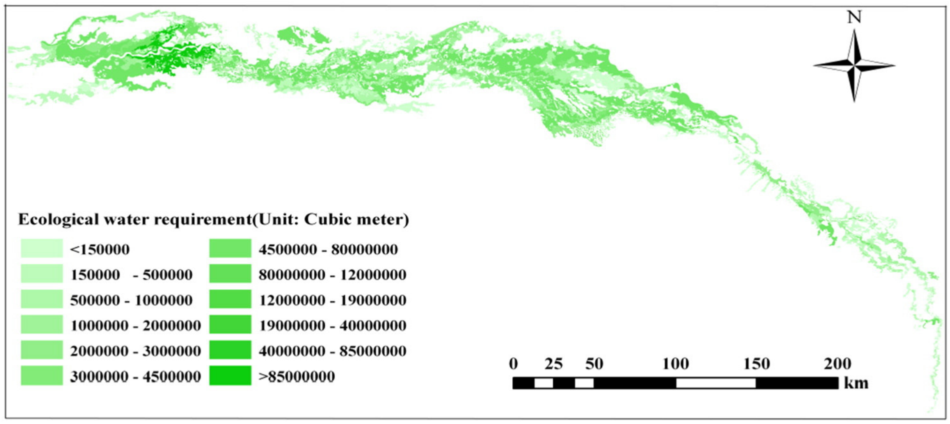

Fig. 6. Spatial distributions of EWR in the Tarim River.

maximum is in July (201.31 mm) and the minimum is in January (12.52 mm). Different from *P. euphratica*, the monthly transpiration of *Tamarix spp.* increases gradually from January to June and the other months decrease. The maximum is in September (87.33 mm); the decreasing trend appears in following September to December, and the minimum is in December (5.0 mm). The monthly transpiration of *P. australis* presents a fluctuant uptrend from January to July and reaches the maximum (131.67 mm) in July. The decreasing trend occurs from July to December, and the minimum is in December (9.0 mm). For three plants, the annual transpiration of *P. euphratica* is the largest (1150.53 mm), followed by *Tamarix spp.* (750.92 mm) and *P. australis* (483.65 mm). Additionally, the monthly transpirations of three plants were summed, and the percentages of monthly transpirations in the annual total transpiration were calculated. Accordingly, the monthly transpirations of three plants are all the largest in July, occupying 16.5% of the annual transpiration. The transpiration from April to September occupies 77.2% of the total, so these months are the main water requirement period of desert riparian vegetation in the Tarim River Basin.

Based on the proportions of monthly transpiration in yearly transpiration, the total EWR of desert riparian vegetation (Table 3) was divided into the twelve months, and thus the time allocation of EWR was acquired (Table 4). In Table 4, the EWR of desert riparian vegetation presents a unimodal trend and appears the maximum in July (3.247×10^8 m^3); especially, in Section 2, the EWR reaches to 1.252×10^8 m^3, which is the maximum of different river sections in this month. The minimum of EWR is in December, and it is only 0.28×10^8 m^3; especially, Section 5 has the minimum (i.e., 0.013×10^8 m^3) of different sections in this month.

5.4. Water consumption of the social economy and other land use types

To determine the water requirements of each section of the Tarim River, the socioeconomic water consumption was obtained. According to previous study (Liu et al., 2012) and our present work, the total water requirement was 7.717×10^8 m^3 in the lower reach of the Tarim River in 2010. Therefore, the water consumption of the social economy was calculated mainly in the middle and upper reaches.

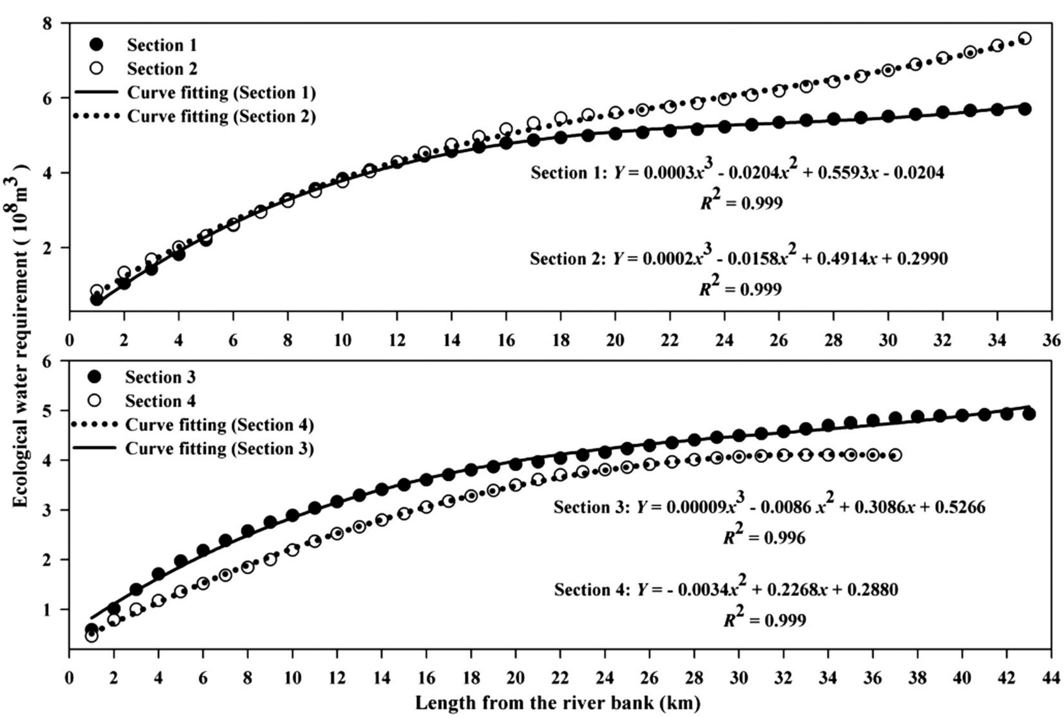

Fig. 7. EWRs under the different distances from the river bank in different sections.

Table 3
EWRs of different protection rates in five river sections of Tarim River Basin.

Water resource item	Protection rate of desert riparian vegetation	Section 1	Section 2	Section 3	Section 4	Section 5	Sum
Ecological water requirement (10^8 m^3)	50%	3.909	4.015	3.06	2.491	1.078	14.553
	75%	5.539	5.521	4.099	3.455		19.692
	100%	5.698	7.585	4.9	4.101		23.362

According to the "Report on Comprehensive Planning for Tarim River Basin of Xinjiang in 2010", the amounts of water consumed by the social economy in 2010 for Sections 1 to 4 were 2.878×10^8, 3.502×10^8, 1.475×10^8 and 2.899×10^8 m^3, respectively. Based on Eqs. (2) and (5) and the related data from 2010, the total water consumption of bare land, water area and the intertidal zone outside of the riverway for Sections 1 to 4 are 1.4233×10^8, 0.7416×10^8, 0.568×10^8 and 1.5614×10^8 m^3, respectively (Table 5). Therefore, in the middle and upper reaches of the Tarim River Basin, the water consumption of the social economy and of the other land use types represents 48.2% and 19.2% of the EWR, respectively.

5.5. Water requirements of each section of the Tarim River

For water managers, controlling the water supplies of different river sections is very important for the sustainable utilization of water resources. Accordingly, this study examined the reasonable annual runoff for different hydrologic stations, including Alar, Xinquman, Yingbaza, Wusiman and Qiala. In the lower reach of Tarim River, the total water requirement was 7.717×10^8 m^3, and the available groundwater was 0.01×10^8 m^3; therefore, the surface runoff requirement in Qiala (i.e., the lower reach) was 7.707×10^8 m^3.

Based on Eq. (4) and the water consumption amounts of the social economy and the other land use types, the surface runoff (Q_{WS}) of Wusiman can be calculated from the data for Section 4 of the Tarim River.

$$Q_{WS} + 0.723(\text{Available groundwater}) = 7.707(\text{Runoff in the Qiala}) + 4.4604(\text{Total water consumption of the social economy and the other land use types}) + W_{WES4} + W_{IES4} + W_{NS4} \quad (29)$$

Based on Eqs. (26), (27) and (28), Eq. (29) can been converted into the following:

$$\begin{aligned} Q_{WS} &= 11.4444 + W_{WES4} + W_{IES4} + W_{NES4} \\ &= 11.5724 + 0.042845 + W_{NS4}. \end{aligned} \quad (30)$$

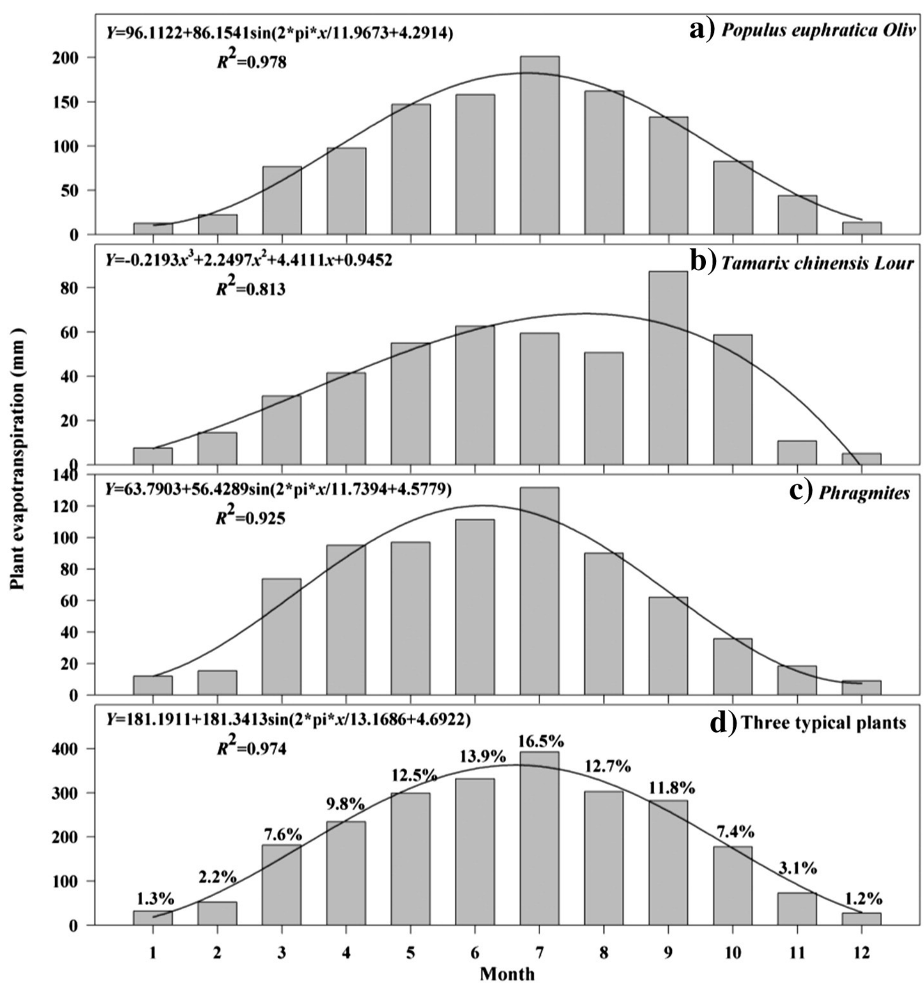

Fig. 8. Time allocation of transpiration quantities of plants in the mainstream of Tarim River.

Table 4
Time allocation of EWR of desert riparian vegetation in the Tarim River Basin (10^8 m^3).

Month	Section 1	Section 2	Section 3	Section 4	Section 5	Sections 1–5
January	0.074	0.099	0.064	0.053	0.014	0.304
February	0.125	0.167	0.108	0.090	0.024	0.514
March	0.433	0.576	0.372	0.312	0.082	1.776
April	0.558	0.743	0.480	0.402	0.106	2.289
May	0.712	0.948	0.613	0.513	0.135	2.920
June	0.792	1.054	0.681	0.570	0.150	3.247
July	0.940	1.252	0.809	0.677	0.178	3.855
August	0.724	0.963	0.622	0.521	0.137	2.967
September	0.672	0.895	0.578	0.484	0.127	2.757
October	0.422	0.561	0.363	0.303	0.080	1.729
November	0.177	0.235	0.152	0.127	0.033	0.724
December	0.068	0.091	0.059	0.049	0.013	0.280

In addition, the available groundwater quantities for Sections 1, 2, and 3 are 0.283×10^8, 0.011×10^8 and 0.058×10^8 m^3, respectively. Using Eqs. (4) and (7)–(25) and the above study results, the surface runoffs of Yingbaza ($Q_{YB,}$), Xinquman (Q_{XQ}) and Alar (Q_{AL}) can be determined:

$$Q_{YB} = 13.5381 + 0.096881Q_{YB}^{0.1776} + W_{NS3} + W_{NS4} \quad (31)$$

$$Q_{XQ} = 18.2251 + 0.142051Q_{YB}^{0.1776} + 0.023076Q_{XQ}^{0.3809} + W_{NS2} + W_{NS3} + W_{NS4} \quad (32)$$

$$Q_{AL} = 24.001 + 0.142051Q_{YB}^{0.1776} + 0.036879Q_{XQ}^{0.3809} + 0.008785Q_{AL}^{0.4985} + W_{NS1} + W_{NS2} + W_{NS3} + W_{NS4} \quad (33)$$

where W_{NS1}, W_{NS2}, W_{NS3} and W_{NS4} are the EWRs of each river section under the different protection rates of desert riparian vegetation (Fig. 7) in the Tarim River Basin.

According to Eqs. (30), (31), (32) and (33), the surface runoff requirements were calculated for five river sections (i.e., Alar, Xinquman, Yingbaza, Wusiman and Qiala) under three protection rates of desert riparian vegetation (Tables 6 and 7). In Table 6, the water demands of the riverway under protection rates of 50%, 75% and 100% are shown to be 3.1097×10^8, 3.1647×10^8 and 3.2317×10^8 m^3, respectively. Therefore, based on the supply and demand balance principle (i.e., Eq. (4)) of the water resources in the river basin, the annual runoffs of Alar under the above three protection rates are 38.174×10^8, 43.368×10^8 and 47.105×10^8 m^3, respectively (Table 7). Overall, in the middle and upper reaches of the Tarim River, the W_N (water requirement of vegetation), W_{SE} (socioeconomic water requirement), W_O (the other water requirements) and W_R (water requirement of the riverway) represent 55.1%, 26.3%, 10.6% and 8.0%, respectively, of the total water requirement necessary to protect the entirety of the desert riparian vegetation.

In addition, according to the model for the calculation of EWR of desert riparian vegetation on the Tarim River (i.e., Eq. (33)), the total water consumption quantity is 39.398×10^8 m^3 between Alar and Qiala (Table 7). Based on the measured data of water consumption from 2005 to 2013 in the same river section, it is 39.58×10^8 m^3, and the deviation between measured data and fitting value is only 0.47%. Therefore, the fitting precision of the calculating model of EWR is very good, and the building model in this river basin is valid and credible.

6. Discussions

6.1. Protection ranges and goals for the desert riparian vegetation of the Tarim River Basin under different water frequencies

Surface runoff rates apparently vary from high to low flow in the Tarim River Basin (Ling et al., 2013). Based on previous study (Peng and Xu, 2010), the surface runoff variation in the Tarim River Basin has been shown to follow a Pearson type III distribution. Therefore, according to the distribution curve (i.e., Pearson type III), the surface runoff amounts for Alar are 50.81×10^8, 47.21×10^8 and 38.04×10^8 m^3 under water frequencies of 30%, 50% and 70%, respectively, during 1957–2010. However, a water resource frequency of 70% cannot meet the EWR of the entirety of the desert riparian vegetation (Tables 6 and 7). Therefore, it is necessary to determine suitable protection ranges and goals for desert riparian vegetation along the Tarim River under the different water frequencies to ensure ecological conservation and ecosystem health.

As indicated by Tables 6 and 7, water resource frequencies of 70% and 50% can essentially meet the EWRs necessary to protect 50% and 100%, respectively, of the desert riparian vegetation along the Tarim River. A water resource frequency of 30% exceeds the 3.705×10^8 m^3 supplied by the surface runoff to the requirement of the total desert riparian vegetation. Moreover, to achieve renewal breeding of the desert riparian vegetation, flooding on top of surface runoff should be ensured in this region (Ye et al., 2012). Therefore, the water resource frequencies of 30%, 50% and 70% can supply the EWRs of 100%, 75% and 50% of the desert riparian vegetation, respectively (Table 8).

In addition, considering the impacts of river flooding on groundwater, the water diversion length of ecological sluices and the water supply of the tributaries of the river system, the goals of desert riparian vegetation protection should vary based on different water frequencies (Table 8). First, the key protection range may be defined as the region of 8.9–11.8 km from the river bank in the four sections under a water frequency of 70%. This region represents the smallest range of desert riparian vegetation that must be protected to ensure the continued existence and development of oases in the Tarim River Basin. Based on relevant previous study (Ye et al., 2010), the natural desert riparian vegetation undergoes a growth period from March to September, and these months also represent the peak period of EWR. Therefore, two or three overtopping flood events are needed (from March to September) every year to guarantee the renewal and germination of desert riparian vegetation along the two river banks (Ye et al., 2010).

Second, the basic protection range covers the area within 15.8–21.8 km of the river bank. The EWR of desert riparian vegetation is primarily supplied by the ecological sluices in this range, and a water resource frequency of 50% is sufficient for the EWR. Due to the river's deviation from its old channel, the local desert riparian vegetation presents a zonal distribution. Additionally, the utilization of

Table 5
Water consumptions of bare land, water area and intertidal zone (outer riverway) in the mainstream of Tarim River.

River section	Land use type (km^2)			Water consumption quantity (10^8 m^3)			
	Water area (outer riverway)	Bare land	Intertidal zone (outer riverway)	Water area (outer river)	Bare land	Intertidal zone (outer riverway)	Total
Section 1	96.15	17.48	33.73	1.201	0.0023	0.22	1.4233
Section 2	44.53	4.08	16.43	0.629	0.0006	0.112	0.7416
Section 3	35.94	0.16	5.10	0.528	0.00002	0.040	0.5680
Section 4	80.7	1.99	46.33	1.161	0.0004	0.400	1.5614
Section 1 Section 4	257.32	23.71	101.59	3.519	0.0033	0.772	4.2943

Table 6
Water demand in the riverway of Tarim River.

Water resource item	Protection rate of natural vegetation	Section 1	Section 2	Section 3	Section 4	Sum
Water demand in the riverway (10^8 m^3)	50%	2.2237	0.6134	0.072	0.2006	3.1097
	75%	2.2707	0.6194	0.073	0.2016	3.1647
	100%	2.3057	0.6224	0.074	0.2296	3.2317

ecological sluices should consider the local desert riparian vegetation and water conditions. The utilization of ecological sluices can be reasonably reduced in those regions with shallow groundwater and better water conditions, while regions with deep groundwater and poor vegetation growth should be considered first for ecological sluices. To achieve the ecological restoration of desert riparian vegetation in this range, overtopping floods should be ensured in the renewal period of the vegetation using ecological sluices and control of the river system.

Finally, the influence protection range for the desert riparian vegetation includes the region up to 43 km from the riverway. The EWR of this range can barely be supplied by the lateral seepage of channels and ecological sluices. Therefore, the EWR can only be met by the abundant overtopping flooding of branch drainages below the water frequency of 30%.

6.2. Calculation of the EWR of desert riparian vegetation in the arid region

Previous international studies have focused on the minimum EWR inside the river channel that maintains the survival of aquatic organisms and improves the aquatic environment (Franchini et al., 2011; Shokoohi and Hong, 2011; Tran et al., 2011). However, uncontrolled water exploration and cultivation in the headstreams can result in a serious shortage of water resources. Therefore, the groundwater level declines substantially, and the desert riparian vegetation totally deteriorates (Hao et al., 2008; Xu et al., 2009; Ye et al., 2010). The EWR of the desert riparian vegetation (the main producer of the ecosystem) cannot be guaranteed, so the water requirements of aquatic organisms and the self-purification of the Tarim River were not considered in this study. To enable the reasonable allocation and sustainable utilization of water resources in the river basin, this paper focused on the EWR necessary to maintain the structural stability of the desert riparian vegetation along the river bank. Meanwhile, the EWR in the arid region was defined in our study as follows: the total water resources (including surface water and groundwater) necessary to maintain the complete hydrological processes of the river system ensure the structural stability of the desert riparian vegetation and improve the ecological environment over time.

The phreatic evaporation model was utilized in this study, as this method is most suitable for arid regions and has been previously verified in a study of the ecological watering practices for the Lower Tarim River (Ye et al., 2010). Therefore, based on the data of the field survey and the desert riparian vegetation distribution along the Tarim River, the EWR of each landscape patch unit for the desert riparian vegetation was calculated using the phreatic evaporation model and the field calculator in ArcGIS 10. This calculation method reflects the desert riparian vegetation distribution accurately and provides detailed results for the EWR at different distances from the river bank. Importantly, this innovative calculation process for EWR in desert riparian vegetation has not been previously reported (Cai and Rosegrant, 2004; Zhao et al., 2007; Ye et al., 2010; Jin et al., 2011; Yan et al., 2012).

6.3. Explanation for the distribution of desert riparian vegetation

Due to the impact of water resources, the distribution of desert riparian vegetation decreases with the increase of distance from the river bank in the Tarim River Basin (Fig. 4). Different sections of this river basin have different distributions of desert riparian vegetation. As the water for the desert riparian vegetation in this river basin is mainly supplied by channel lateral seepage and water diversion engineering, the vegetation usually grows well and is distributed widely in the regions close to the river bank. Ecological water diversion provides support for desert riparian vegetation at longer distances from the river course, but the stripped watering mode influences a smaller range and less vegetation. The desert riparian vegetation area in the upper reach is larger than that of the middle reach by a ratio of 5.8:4.2, and this result is directly related to the relatively abundant water resources in the upper reach. Section 2 contains the largest area of desert riparian vegetation, resulting from the extensive water systems and relative lack of human disturbances in the region. The desert riparian vegetation area of Section 1 is smaller than that of Section 2 because of rapid agricultural exploitation (Wang et al., 2001; Hu, 2007; Chen et al., 2008; Chen et al., 2011b). As shown by the relevant result (Song et al., 2000) and the remote sensing data for 2010, the arable area of the Alar region in Section 1 increased by 193 km^2 from 1959 to 2010 due to the clearing of a large area of desert riparian vegetation. Sections 3, 4, and 5 are restricted by the lesser water flow from the upper reach and severe human activities (Chen et al., 2011b), so the distribution of desert riparian vegetation in this region is relatively narrow.

7. Conclusions

Based on the relevant data for the four sections of the Tarim River Basin, the EWR of the desert riparian vegetation in the different river sections and the required annual runoff at five hydrologic stations were analyzed. Finally, the protection ranges and goals of desert riparian vegetation were presented.

(1) The distribution widths of desert riparian vegetation in the four sections of the Tarim River Basin range from 35 to 43 km, and the amount of vegetation decreases with the increase of distance from the river bank. The total area of desert riparian vegetation in the four sections is 16,285.3 km^2. Ranges of 8.9–11.8 km and 15.8–21.8 km cover 50% and 75% of the vegetation, respectively.
(2) The EWR of the total desert riparian vegetation under the protection rates of 50%, 75% and 100% are 14.553×10^8, 19.692×10^8 and 23.362×10^8 m^3, respectively. EWR of natural vegetation reaches the maximum in July and presents a unimodal type of decreasing trend before and after July. Combined with the other water requirements, the required annual runoff amounts in the river section of the Alar under the protection rates of 50%, 75% and 100% are 38.174×10^8, 43.368×10^8 and 47.105×10^8 m^3;

Table 7
Surface runoff requirements of five river sections under protection rates of desert riparian vegetation.

Hydrologic station	Protection rate of natural vegetation	Alar	Xinquman	Yingbaza	Wusiman	Qiala
Surface runoff requirement (10^8 m^3)	50%	38.174	28.114	19.253	14.136	7.707
	75%	43.368	31.631	21.258	15.101	
	100%	47.105	35.174	22.734	15.775	

Table 8
Protection ranges, rates, areas and objects under different water frequencies.

Water frequency	Protection range (km)	Protection rate (%)	Protection area (km^2)	Protection object	Water supply ways
70%	8.9–11.8	50%	7394.8	Key protection	Influence range of river course
50%	15.8–21.8	75%	11,092.2	Basic protection	Influence range of ecological water diversion project and channel
30%	<43.0	100%	14,789.6	Influence protection	Overtopping influence range of ecological water diversion project and channel

those in the Xinquman section are 28.114×10^8, 31.631×10^8 and 35.174×10^8 m^3; those in the Yingbaza section are 19.253×10^8, 21.258×10^8 and 22.734×10^8 m^3; those in the Wusiman section are 14.136×10^8, 15.101×10^8 and 15.775×10^8 m^3; and those in the lower reach is 7.707×10^8 m^3, respectively.

(3) The surface runoff in the Tarim River has an apparent high and low flow variation. The water resources under the frequencies of 30%, 50% and 70% are 50.81×10^8 m^3, 47.21×10^8 m^3 and 38.04×10^8 m^3. Based on these changes, we divided the protection range into key protection (8.9–11.8 km from the river), basic protection (15.8–21.8 km from the river) and influence protection (43 km from the river) areas. This division informs the optimal management of water resources and ecological conservation.

(4) After calculating the EWR of the desert riparian vegetation in the four sections of the Tarim River, we conclude that the surface runoffs from the mainstream of the Tarim River and the Kongqi River should be used to provide sufficient ecological watering to the lower reach to restore the degraded ecosystem of desert riparian vegetation. Meanwhile, to reestablish the damaged ecosystem of desert riparian vegetation and guarantee sufficient water in the middle and upper reaches of the river basin, several measures should be implemented. First, socioeconomic water consumption should be reduced by improving the utilization rate of water resources, optimizing water use structure, and controlling irrigated areas and population growth. Second, sufficient water flow in the Tarim River mainstream from the three headstreams should be ensured by intensifying the unified management of water resources in the region.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (41471099, 31370551, and 41171427) and West Light Foundation of The Chinese Academy of Sciences (XBBS-2014-13).

References

Abellan, P., Bilton, D.T., Millan, A., Sanchez-Fernandez, D., Ramsay, P.M., 2006. Can taxonomic distinctness assess anthropogenic impacts in inland waters? A case study from a Mediterranean river basin. Freshw. Biol. 51, 1744–1756.
Cai, X.M., Rosegrant, M.W., 2004. Optional water development strategies for the Yellow River Basin: balancing agricultural and ecological water demands. Water Resour. Res. 40, W08S04.
Cao, D.C., Li, J.W., Huang, Z.Y., Baskin, C.C., Baskin, J.M., Hao, P., Zhou, W.L., Li, J.Q., 2012. Reproductive characteristics of a *Populus euphratica* population and prospects for its restoration in China. PLoS ONE 7, e39121.
Chen, Y.N., Takeuchi, K., Xu, C.C., Chen, Y.P., Xu, Z.X., 2006. Regional climate change and its effects on river runoff in the Tarim Basin. China Hydrol. Process. 20, 2207–2216.
Chen, Y.N., Hao, X.M., Li, W.H., 2008. An analysis of the ecological security and ecological water requirements in the inland river of arid region. Adv. Earth Sci. 7, 732–738 (in Chinese).
Chen, Y.N., Ye, Z.X., Shen, Y.J., 2011a. Desiccation of the Tarim River, Xinjiang, China, and mitigation strategy. Quatern. Int. 244, 264–271.
Chen, Z.S., Chen, Y.N., Li, W.H., Chen, Y.P., 2011b. Changes of runoff consumption and its human influence intensity in the mainstream of Tarim River. Acta Geograph. Sin. 66, 89–98 (in Chinese).
Congalton, R.G., Green, K., 1999. Assessing the Accuracy of Remotely Sensed Data: Principals and Practices. CRC Press, London, pp. 137–145.
Current Land Use Classification (GB/T 21010-2007), 2007. Ministry of Land and Resources Press.
Elosegi, A., Diez, J., Mutz, M., 2010. Effects of hydromorphological integrity on biodiversity and functioning of river ecosystems. Hydrobiologia 657, 199–215.
Feng, Q., Liu, W., Si, J.H., Su, Y.H., Zhang, Y.W., Cang, Z.Q., Xi, H.Y., 2005. Environmental effects of water resource development and use in the Tarim River basin of northwestern China. Environ. Geol. 48, 202–210.
Franchini, M., Ventaglio, E., Bonoli, A., 2011. A procedure for evaluating the compatibility of surface water resources with environmental and human requirements. Water Resour. Manag. 25, 3613–3634.
Hao, X.M., Chen, Y.N., Xu, C.C., Li, W.H., 2008. Impacts of climate change and human activities on the surface runoff in the Tarim River Basin over the last fifty years. Water Resour. Manag. 22, 1159–1171.
Howard, J., Merrifield, M., 2010. Mapping groundwater dependent ecosystems in California. PLoS ONE 5, e11249.
Hu, S.J., 2007. Research on Eco-environmental Water Requirement of Tarim Mainstream Watershed. Northwest A & F University, Yangling, Xi'an, China (in Chinese).
Hu, G.L., Zhao, W.Z., 2008. Reviews on calculating methods of vegetation ecological water requirement in arid and semiarid regions. Acta Ecol. Sin. 28, 6282–6291 (in Chinese).
Jin, X., Yan, D.H., Wang, H., Zhang, C., Tang, Y., Yang, G.Y., Wang, L.H., 2011. Study on integrated calculation of ecological water demand for basin system. Sci. China Technol. Sci. 54, 2638–2648.
Lam, T.Y., Kleinn, C., Coenradie, B., 2011. Double sampling for stratification for the monitoring of sparse tree populations: the example of *Populus euphratica* Oliv. forests at the lower reaches of Tarim River, Southern Xinjiang, China. Environ. Monit. Assess. 175, 45–61.
Leng, C., Chen, Y.N., Li, X.G., Sun, Y.X., 2011. Evaluation of oasis stability in the lower reaches of the Tarim River. J. Arid Land. 3, 123–131.
Li, X.M., 1988. Relations of the vegetation distribution to heat and water in Xinjiang. Arid Zone Res. 5, 41–46 (in Chinese).
Ling, H.B., Xu, H.L., Fu, J.Y., 2013. High- and low-flow variations in annual runoff and their response to climate change in the headstreams of the Tarim River, Xinjiang, China. Hydrol. Process. 27, 975–988.
Lioubimtseva, E., Henebry, G.M., 2009. Climate and environmental change in arid Central Asia: impacts, vulnerability, and adaptations. J. Arid Environ. 73, 963–977.
Liu, X.H., Xu, H.L., Ling, H.B., Bai, Y., Fu, J.Y., Dai, Y., 2012. Study on ecological water requirements along the mainstream channel of the Tarim River. Arid Zone Res. 29, 983–991 (in Chinese).
Merritt, D.M., Bateman, H.L., 2012. Linking stream flow and groundwater to avian habitat in a desert riparian system. Ecol. Appl. 22, 1973–1988.
Naidoo, R., Weaver, L.C., Stuart-Hill, G., Tagg, J., 2011. Effect of biodiversity on economic benefits from communal lands in Namibia. J. Appl. Ecol. 48, 310–316.
Pang, Z.H., Huang, T.M., Chen, Y.N., 2010. Diminished groundwater recharge and circulation relative to degrading riparian vegetation in the middle Tarim River, Xinjiang Uygur, Western China. Hydrol. Process. 24, 147–159.
Peng, D.Z., Xu, Z.X., 2010. Simulating the impact of climate change on streamflow in the Tarim River basin by using a modified semi-distributed monthly water balance model. Hydrol. Process. 24, 209–216.
Shokoohi, A., Hong, Y., 2011. Using hydrologic and hydraulically derived geometric parameters of perennial rivers to determine minimum water requirements of ecological habitats (case study: Mazandaran Sea Basin—Iran). Hydrol. Process. 25, 3490–3498.
Song, Y.D., Fan, Z.L., Lei, Z.D., 2000. Research on Water Resources Ecology of Tarim River. China. Xinjiang People's Publishing House, Xinjiang, China, pp. 123–128 (in Chinese).
Song, Y.D., Wang, R.H., Peng, Y.S., 2002. Water resources and ecological conditions in the Tarim Basin. Sci. China. Ser. D 45, 11–17.
Sun, T., Yang, Z.F., Shen, Z.Y., Zhao, R., 2012. Ecological water requirements for the source region of China's Yangtze River under a range of ecological management objectives. Water Int. 37, 236–252.
Tran, L.D., Schilizzi, S., Chalak, M., Kingwell, R., 2011. Optimizing competitive uses of water for irrigation and fisheries. Agric. Water Manag. 101, 42–51.
VanderMeer, F., 1997. What does multisensor image fusion add in terms of information content for visual interpretation? Int. J. Remote Sens. 18, 445–452.
Vass, K.K., Das, M.K., Srivastava, P.K., Dey, S., 2009. Assessing the impact of climate change on inland fisheries in River Ganga and its plains in India. Aquat. Ecosyst. Health 12, 138–151.
Wang, R.H., Lu, X.M., 2009. Quantitative estimation models and their application of ecological water use at a basin scale. Water Resour. Manag. 23, 1351–1365.
Wang, R.H., Song, Y.D., Fan, Z.L., Ma, Y.J., 2001. Estimation on ecological water demand amount in four sources and one main stream area of Tarim Basin. J. Soil Water Conserv. 15, 19–22 (in Chinese).
Xi, H.Y., Feng, Q., Si, J.H., Chang, Z.Q., Su, Y.H., 2012. A review of river course leakage in the Ejina Delta in the lower reaches of Heihe River. J. Glaciol. Geocryol. 34, 1241–1247 (in Chinese).
Xu, H.L., Ye, M., Li, J.M., 2009. The ecological characteristics of the riparian vegetation affected by river overflowing disturbance in the lower Tarim River. Environ. Geol. 58, 1749–1755.

Xu, H.L., Zhou, B., Song, Y.D., 2011. Impacts of climate change on headstream runoff in the Tarim River Basin. Hydrol. Res. 42, 20–29.

Yan, D.H., Wang, G., Wang, H., Qin, T.L., 2012. Assessing ecological land use and water demand of river systems: a case study in Luanhe River, North China. Hydrol. Earth Syst. Sci. 16, 2469–2483.

Ye, Z.X., Chen, Y.N., Li, W.H., 2010. Ecological water demand of natural vegetation in the lower Tarim River. J. Geogr. Sci. 20, 261–272.

Ye, M., Xu, H.L., Ren, M., 2012. Primary study on the rational time of ecological water conveyance to lower reaches of the Tarim River. Arid Zone Res. 29, 907–912 (in Chinese).

Zhang, Q.B., Li, Z.S., Liu, P.X., Xiao, S.C., 2012. On the vulnerability of oasis forest to changing environmental conditions: perspectives from tree rings. Landscape Ecol. 27, 343–353.

Zhao, W.Z., Chang, X.L., He, Z.B., Zhang, Z.H., 2007. Study on vegetation ecological water requirement in Ejina Oasis. Sci. China. Ser. D 50, 121–129.

Zhou, Y.C., 1999. Hydrology and Water Resources of Rivers in Xinjiang. Xinjiang Technology and Health Publishing House, Xinjiang, China, p. 31 (in Chinese).