Desert riparian vegetation and groundwater in the lower reaches of the Tarim River basin

Yaning Chen · Weihong Li · Changchun Xu ·
Zhaoxia Ye · Yapeng Chen

Abstract The Green Corridor in the lower reaches of Tarim River in northwestern China has an extreme hot and dry climate. Vegetation here, consisting of arbor, shrub and grass, relies on groundwater exceedingly. However, the increasing anthropogenic activities of large-scale agricultural reclamation and unreasonable water utilization in the upper and middle reaches caused the 321-km riverway in the lower reaches to dry up completely in 1972 and resulted in the sharp decline of groundwater, followed by the ruin of desert riparian vegetation on a large scale. The Green Corridor is on the verge of shrinking. Water has a key role in maintaining ecological balance and socioeconomic development. This paper, focused on the relationship between vegetation and groundwater, discusses (1) the change of groundwater table caused by the ecological water delivery carried out in the lower reaches of Tarim River; (2) the appropriate groundwater depth meeting the vegetation's survival; (3) the minimum ecological flux and ecological water requirement for the growth of natural vegetation. It was shown that (1) based on the analysis of the monitoring data from the groundwater level of ten times water delivery, such an extensive artificial watering takes positive effect on raising the groundwater level along the two sides of the river; (2) a groundwater table depth of 2–4 m is probably the appropriate ecological water table level for the lower reaches of the Tarim River, and 6 m is the threshold for the local vegetation; (3) at the lower Tarim River, 1.157×10^8 m^3 of water flow is needed for itself. The longer the duration of water releases, the greater would be the groundwater rise and the larger the range of vegetation influenced. It was found that the duration and volume of water delivery was closely related to restoration of vegetation in the lower reaches of the Tarim River. The goal of this paper is to offer scientific evidences for water delivery in the rigorous areas to maintain an ecological balance.

Keywords Desert riparian vegetation · Groundwater · Ecological water requirement · The Tarim River basin · Arid region

Y. Chen (✉) · W. Li · Z. Ye · Y. Chen
State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, 818 South Beijing Road, Urumqi 830011, Xinjiang, People's Republic of China
e-mail: chenyn@ms.xjb.ac.cn

C. Xu
Key Laboratory of Oasis Ecology, School of Resources and Environmental Science, Xinjiang University, Urumqi 830046, China

Introduction

Natural vegetation in arid region plays an important role in biodiversity conservation and desertification reduction. However, biological activities in this area are limited and ecosystems are simple and unstable. Change in groundwater table can influence the development and composition of vegetation, which in turn affects the fragile ecosystem (Lammerts et al. 2001; Chen et al. 2006; Doble et al. 2006). Some researches (Chen et al. 2004a) have indicated that the soil moisture that influences plant growth and recovery are related to the groundwater depth. The incidence of vegetation coverage is similar to that of groundwater depth. The change in vegetation coverage is explained by the change in groundwater depth (Sultan et al. 2004). Assuming that other ecological factors do not constrain the growth of plant, there is an optimal groundwater level, called

appropriate groundwater depth (AGD). Above AGD vegetation can develop fully, but below it plants will be significantly limited in growth and may even die if such conditions last for a period of time (Rey Benayas et al. 1990; Stromberg et al. 1996; Munoz-Reinoso 2001). Nevertheless, the relationship between groundwater table change and vegetation status is complicated, representing a dynamic equilibrium between groundwater, soil, and vegetation. This relationship has become a key issue in the worldwide study of water resources in arid regions (Kite and Webster 1989; Caldow and Racey 2000; Rey Benayas et al. 1990; Ross et al. 1994; Stromberg et al. 1996; Munoz-Reinoso 2001; Chen et al. 2003a, b; Naumburg et al. 2005; Eamus et al. 2006). Suggestions have also been made to re-establish hydro-geomorphic regimes by restoring appropriate surface water flow so that groundwater is well sustained (Rood et al. 2005; Stromberg et al. 2007). To achieve these goals, it is necessary to improve the understanding of the vegetation's response to a changing groundwater table, e.g., riverway water delivery. The extremely arid region in western China is a good test site for this purpose. Chen Yaning's research group have worked there for more than 10 years and produced multiple papers about these issues, such as the changes in vegetation and groundwater tables induced by water deliveries (Chen et al. 2004a, b), response of vegetation and soil moisture to water conveyances (Ye et al. 2009; Hao et al. 2009) and dynamic variations of groundwater tables during water conveyances (Di et al. 2011; Wan et al. 2009). This paper, as a case study based on the long-term research work in the lower reaches of Tarim River, reveals the interactive relationship between vegetation and groundwater, presents an appropriate groundwater table for the regular growth of natural vegetation, and provides scientific evidences for the ecological restoration in arid and semi-arid regions (Tables 1, 2, 3 and 4).

Study area and monitoring

Study area

The study area is located between Daxihaizi Reservoir and Taitema Nor in the lower reaches of Tarim River (39°38′41°45′N, 85°42′89°17′E), northwestern China (Fig. 1). The channel stretches to the southeast on alluvial fans between Taklimakan and Kuluk deserts. The ground surface is remarkably flat, with a descending elevation from north to south. Water seeps from streams into the alluvial fans to recharge the phreatic aquifer. The region is an extremely arid zone. The annual precipitation varies in the range 17–42 mm, and the total annual potential evaporation is 2,500–3,000 mm. Strong winds blow frequently in the region. The riverbank vegetation, known as the Green Corridor, provides a natural defense against wind by obstructing sand movement and plays an important role in keeping the National Highway No. 218 free of obstructions.

The vegetation of this region consists of 14 families, 24 genera, and about 40 species of vascular plants. The major plant species include *Populus euphratica oliv.*, *Tamarix ramosissima*, *T. hispida*, *Lycium ruthenicum*, *Phragmites communis*, *Alhagi sparsifolia*, *Apocynum venetum*, *Karelinia caspica*, and *Glycyrrhiza inflata*. The shrub–grass vegetation is dominated by *T. chinensis*, *Halimodendron halodendron*, *Phragmites communis*, and *Apocynum venetum*. The forest is dominated by *Populus euphratica*. Both shrub–grass and forest relying on groundwater for survival and growth have been seriously degenerated due to the aggravated climatic environment. Sand dunes between forests have become unstable. Even worse, the construction of the Daxihaizi Reservoir in 1972 dried up the 321-km riverway in the lower reaches. The groundwater table had sharply dropped to 8–12 m due to the lack of surface water

Table 1 Average soil moisture change in the lower reaches of Tarim River

Section	Qiala–Tikanlik	Tikanlik–Yinsu	Yinsu–Kaogan	Kaogan–Taitema Nor
Soil texture				
<0.005 mm	9.76	8.34	5.52	4.05
0.005–1.0 mm	90.24	91.66	94.48	95.95

Table 2 Characteristics of vegetation related to the groundwater depth at each monitoring section before water delivery in the lower reaches of Tarim River

Section	Vegetation coverage (%)	Vegetation density (individuals/m^2)	Vegetation abundance (Margalef index)	Species number (per plot 50 × 50 m)	Mean groundwater depth (m)
A	80.86	0.34	1.48	11	5.5
C	27.62	0.12	1.40	9	8.34
D	23.18	0.09	1.29	8	8.41
E	21.86	0.05	1.24	8	9.16
G	9.72	0.01	0.87	4	11.1

Table 3 Transpiration estimation of woods, shrubs, and herbs in the main stream of Tarim River

	Range of groundwater depth (m)	Average groundwater depth for calculation (m)	Phreatic water evaporation (m^3/hm^2)
Woods			
Young and half-mature forest, coverage >0.4	1.0–3.0	2.0	3,741.5
Near-mature and mature forest, coverage >0.2	2.0–4.5	2.5	2,343.8
Over-mature forest, coverage >0.2	3.0–6.0	4.0	497.3
Declining and dead forest, coverage <0.1	4.0–8.0	4.5	392.1
Shrubs			
Shrub, coverage >0.3	1.0–4.0	2.5	2,343.8
Sparse shrub, coverage >0.1	2.5–6.0	4.0	497.3
Sparse and declining shrub, coverage <0.1	4.0–10.3	4.5	392.1
Herbs			
Everglade, coverage >0.6	<1.0	1.0	10,738.0
Meadow grassland, coverage >0.3	1–3.5	2.5	2,343.8
Shrub grassland, coverage >0.2	3.0–4.0	3.5	867.3
Sparse and degraded grassland, coverage <0.1	>4.0	4.5	392.1

Table 4 The minimum ecological water requirement (EWR) in the main stream of Tarim River

Vegetation type	Area (10^4 hm^2)				Water consumption (10^4 m^3)				Actual EWR
	Upper	Middle	Lower	Sum	Upper	Middle	Lower	Sum	
Forests	17.77	20.4	3.37	41.53	30,860.6	35,420.83	5,856.01	72,137.39	90,171.75
Shrubs	10.19	6.84	0.25	17.28	11,629.3	7,791.35	278.94	19,699.54	24,624.43
Herbs	18.85	53.9	10.54	83.25	35,846.1	102,238.6	19,985.03	158,069.7	197,587.125
Sum	46.81	81.1	14.16	142.1	78,335.9	145,450.8	26,119.98	249,906.7	31,238.375

recharge for nearly 30 years (Chen et al. 2003c). The soil texture of the lower Tarim River was coarse grained from the upper to the lower section because of gradually increasing degree of desertification (Table 1) (Zhang et al. 2004). Since 2000, diversion of water from the Bosten Lake to the lower reaches of Tarim River has been implemented and 12 times intermittent water deliveries had been realized by the end of 2011. The groundwater table was raised significantly and riparian vegetation improved.

Monitoring

Nine monitoring sections had been established along the riverway from the Daxihaizi Reservoir to the Taitema Nor (Fig. 1). They are Akdun (A), Yahopumarhan (B), Yinsu(C), Abudali (D), Kardayi (E), Tugmailai (F), Alagan (G), Yiganbjima (H), and Kaogan (I). The interval distance between two neighboring sections for the first six sections is about 20 km, and that for the last three sections about 45 km.

At each section, monitoring wells of 8–17 m in depth were dug with intervals of 100–200 m away from the riverway to investigate the change in groundwater depth. In total, 40 monitoring wells were established. Measurements were carried out three times a month during the water delivery period and once a month during the water delivery intervals.

Plant sample plots were set 50 × 50 m at each section. Within each plot, four 25 × 25-m sub-plots were set to record the characteristics of vegetation, such as the number of species, coverage, diameter at breast height, basic diameter, height and width of canopy, etc. Four herbaceous surveys were also undertaken in each plot to investigate the number of species, coverage, height, and frequency in July of each year when there was maximum biomass. The elevation, latitude, and longitude of each survey plot were recorded using GPS.

Results and analysis

Response of groundwater depth to water delivery

Transverse orientation

The increment of groundwater table at six distances, 50, 150, 300, 500,700 and 1,050 m, away from the riverway was monitored at five sections (Fig. 2). The increments of groundwater table at the sections except Yinsu always
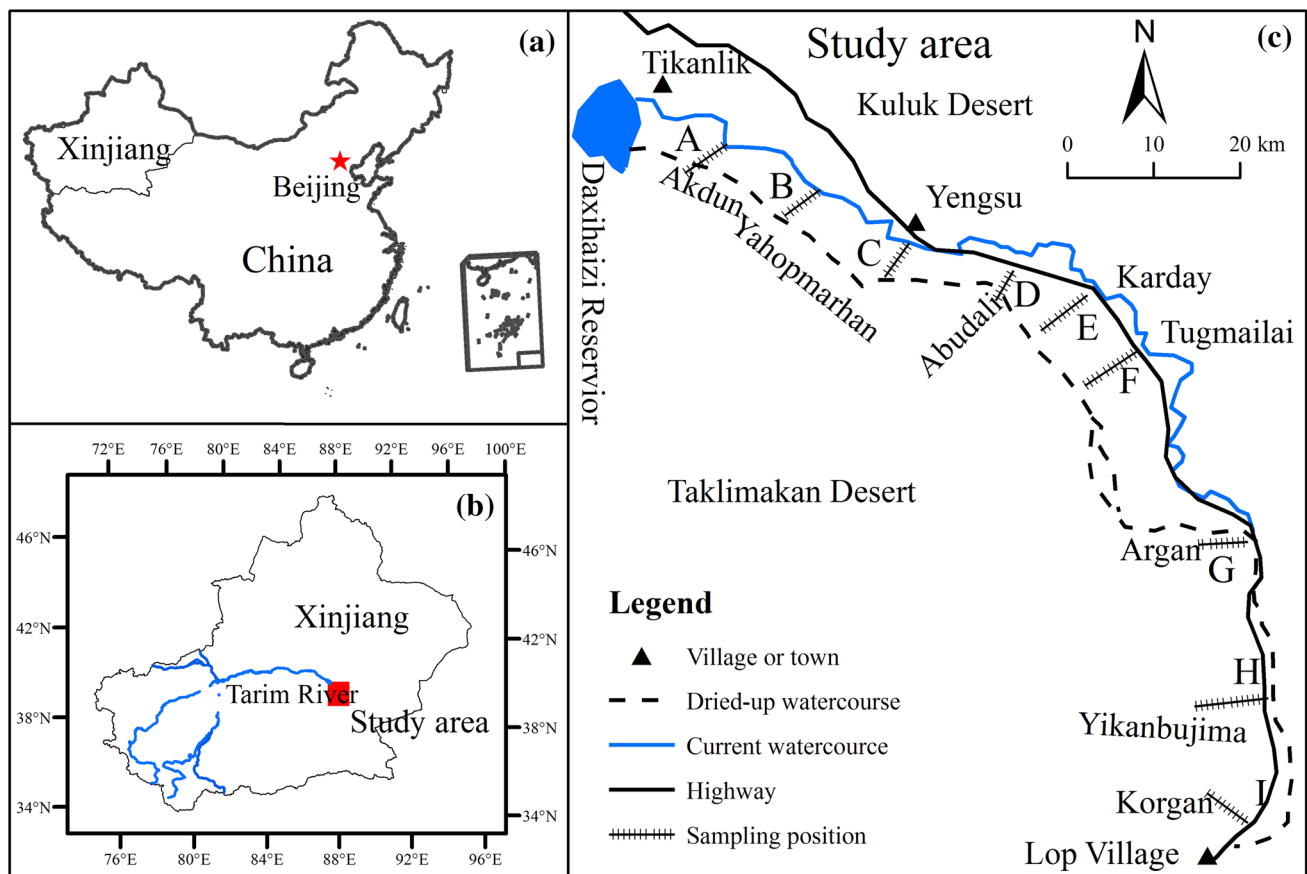
Fig. 1 Sketch map of the study area (**a** and **b** location of the study area in Xinjiang Uygur region, China. **c** Monitoring sections *A–I* in the study area)

decreased as the distance increased. The largest increment 2.12 m occurred at the Yiganbjima section, 50-m distance away from the riverway. The larger the distance, the less was the change in decreasing rate. From the slope of curves, the turning point lay 300 m away from the river-way. Beyond this point, the slopes of curves became gentle, ranging from 0.03 to 0.55 m. Most evidences showed that the water delivery influence was remarkable within 300 m, though the result at the Yinsu section was different due to the weakening seeping capacity of the multiple water deliveries. Xie and Yuan (2010)'s research on groundwater table of the lower Tarim River showed that the rise in the water table due to water conveyance varied 1–5 m in a region that was <1 km from the riverbank. The rapidly decreasing trend for the water table rise suggested that the effects of water conveyance on the groundwater level were limited to a small region along the river.

The influence range of water delivery was closely related to the watering volumes (Fig. 3). It kept extending with the increase in watering times, from 570 m after the first time to 4,022 m after 12 times. In fact, the amplitude of incidence showed different characteristics during
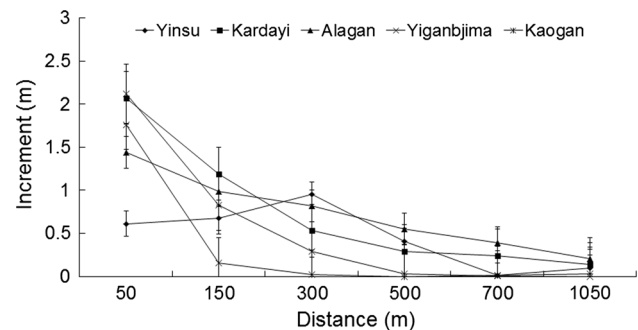
Fig. 2 Increment in the groundwater level in transverse orientation

various times. For example, the incidence range of the second time was the most, broadening 1,100 m more than that of the first time. The incidence range of the sixth time was 990 m more than that of the fifth time. Because the watering volumes of the fourth time were less than that of the third time, the incidence range of the fourth time decreased by 674 m. For the same reason, that of the seventh time had diminution of 350 m. The watering duration of the third times and the fifth times were over

Fig. 3 Incidence of one side and the watering volumes
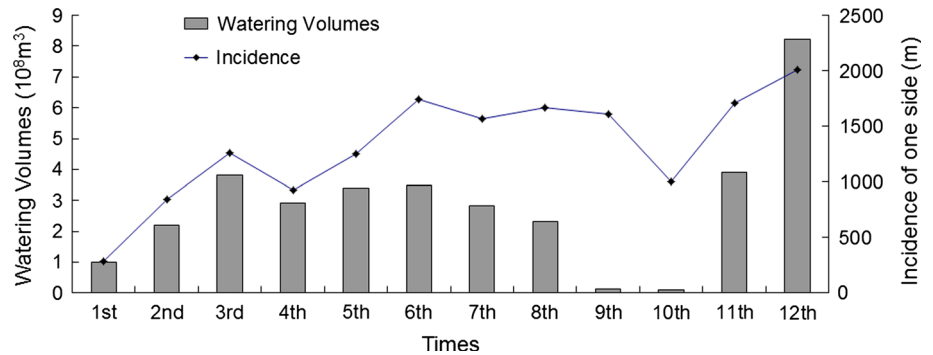
150 days, and both the watering volumes were more than 3×10^8 m^3, so the incidence range increased between 848 and 642 m, respectively. The incidence range of the ninth time increased to 212 m because of the small amount of watering volume. After 2 years, the tenth time conveyance was carried out by the end of 2009. The watering duration was only 36 days and the watering volumes were only 0.11×10^8 m^3; so the incidence range is very limited, only 2,000 m. With the increasing volume of origins, the 11th and 12th conveyance were carried out in 2010 and 2011. The watering volume is the maximum, 4.2×10^8 m^3 and 8.23×10^8 m^3, respectively, so incidence range is also the maximum, 3,416 and 4,022 m, respectively.

Lengthwise orientation

From Yinsu to Kaogan, in lengthwise orientation, the increment of groundwater level almost decreased along the riverway beyond 50 m, but the fluctuant range was not evident. It showed that the increment in groundwater level and the lengthwise distance were not very close at a larger distance away from the riverway. Moreover, at the same section, the increment in groundwater level decreases with the distance away from the riverway except at the Alagan section. The reason is that the Alagan section is the confluent point of double river courses. All evidences show that the relationship between the watering volumes and the increment in groundwater level tends to steady when the watering volumes are sufficient. Another investigation (Li et al. 2003) shows that the increment in groundwater level involves two factors, the bulk and the duration of watering. Therefore, ecological water delivery is a long-term and arduous task.

Response of vegetation to the change in groundwater depth

Relationship between vegetation and groundwater depth before water delivery

Characteristics such as composition, distribution, and growth of riparian vegetation are closely related to the condition of groundwater. Before the water deliveries, with increasing groundwater depth from the Yinsu section (C) to Taitema Nor, plant communities changed from three layers (tree, shrub, and herb) to only one layer (shrub). In sections C and D, as well as the western part of section E, trees (*Populus euphratica*), shrubs (*T. ramosissima*, *T. hispida*, *Nitraria sibirica*, *H. halodendron*) and herbs (*G. inflata*, *Poacynum hendersonii*, *Alhagi sparsifolia*, *Phragmites communis*) occurred in the communities, among which *Populus euphratica* and *Tamarix* spp. were the dominant species. In the eastern part of sections E, F, G and H, plant communities consisted of trees (*Phragmites communis*) and shrubs (*Tamarix* spp., *N. sibirica*) with a few herbaceous species (*Alhagi sparsifolia*). In the lower part of section I, the plant community only consisted of shrubs with very poor growth. Some species with a high drought-tolerance capacity existed when the depth of groundwater was greater. The coverage, density, and abundance of the plant communities decreased with the increase in groundwater depth (Table 2). The areas of decreased vegetation coverage and density were larger than that of reduced species abundance. Species diversity decreased with increased drying time and also with groundwater depth. From section C to section H, the Simpson diversity index decreased from 0.70 to 0.26, the McIntosh index from 0.48 to 0.17, and the Margalef index from 1.40 to 0.87. It is clear that there is a close relationship between natural vegetation and groundwater depth in the study area.

Response of vegetation to the groundwater table change after water delivery

Natural vegetation in the study area mainly comprised *Populus euphratica* and *Tamarix* spp., whose survival depends on groundwater and soil water. Therefore, the change in depth of shallow groundwater has a direct influence on the development of natural vegetation. After water deliveries, the change of natural vegetation was closely related to the rising groundwater table along the lengthwise and transverse directions. Some plants, such as *G. inflata*, *Alhagi sparsifolia*, *Apocynum venetum*, *Phragmites communis*, *Salosola sp.*, *Scorzonera sp.*, and *K. caspica*,

appeared again in profusion in the study area. Some drought-tolerant trees and shrubs were restored together, when the groundwater table reached its common optimal depth (4–6 m).

Since different plants require different optimal groundwater levels, the sensitivities of plants to the change in groundwater depth are different. Among some herbaceous plants, it was found that the leaf characteristics of *Phragmites communis* were highly sensitive to groundwater change. In the transverse direction, the weight, length, and width of the leaves of *Phragmites communis* at the first sample location, 50 m from river, are the biggest and become smaller as the distance from the river channel increases. This shows that the response is most sensitive at 100–150 m from the river and the growth indices of *Phragmites communis* fall significantly beyond this range.

Relationship between species diversity and groundwater status

We used the average of species diversity indices from all plots to represent vegetation diversity at each groundwater depth class. The Alatalo index (Alatalo 1981) is used to represent the evenness of species. The Shannon–Wiener index (Shannon and Weiner 1949) using the information formula is used to represent diversity. The modified Simpson index reflects the comprehensive species richness and evenness (Romme 1982). Hill index (Hill 1973) can also be used to help explain the ecological significance of the scale of vegetation diversity. The indices are calculated using the following equations:

Alatalo evenness index:

$$E = \left(1 \middle/ \sum_{i=1}^{S} \left(\frac{Ni}{N} \right)^2 - 1 \right) \middle/ \left(\exp\left(-\sum_{i=1}^{S} \frac{Ni}{N} \ln \frac{Ni}{N} \right) - 1 \right) \tag{1}$$

Shannon–Wiener index:

$$H = -\sum_{i=1}^{S} (Pi \ln Pi) \tag{2}$$

Modified Simpson index:

$$D = -\ln\left[\sum_{i=1}^{S} \left(\frac{Ni}{N} \right)^2 \right] \tag{3}$$

Hill's diversity index containing variant:

$$N_\alpha = \left(\sum_{i=1}^{S} Pi^\alpha \right)^{1/1-\alpha} \tag{4}$$

where Pi is the richness ratio for species i; Ni is the individual number of species i; N is the total number of individuals in each sampling plot; S is the number of species in the sampling plot. In Eq. (4), when $\alpha = 1$, $N_\alpha = e^H$ and H is the Shannon–Wiener information index; when $\alpha = 0$, $N_\alpha = S$; when $\alpha = 2$, $N_\alpha = \frac{1}{D}$ and D is the Simpson diversity index.

Data analysis revealed that all the values increased gradually, reached the maximum value at the 2- to 4-m groundwater depth, and then began to decrease as the groundwater level decreased. Simpson, Shannon–Wiener, and Alatalo index values were higher for groundwater depth of 4–6 m than of 0–2 m. The Shannon–Wiener index had the most significant fluctuation in a range of 0.21–1.47 in response to decline of the groundwater level. The Alatalo index changed between 0.49 and 0.78 as the most stable parameter. This trend of different indices reflects that plant species diversity, richness, and evenness have all undergone trends of decline in response to the drop in groundwater table in the lower reaches of Tarim River.

Hill diversity index analysis revealed that the species diversity showed a decreasing order corresponding to the groundwater depths of 2–4, 4–6, 0–2, 6–8, 8–10, and >10 m. Changes in the Hill diversity index were positively correlated with all other indices tested. Hill diversity index analysis also indicated that the changed trends of diversity can be separated into three phases. The first phase is at the groundwater table depth of 0–6 m. Within this range, all slopes of the Hill index appeared similarly for the three classes of groundwater table depth (0–2, 2–4, and 4–6 m). The Hill index changed significantly with the modifying factor α, which causes a sensitive response from the slopes. The second phase is represented by groundwater table depth between 6 and 10 m. The diversity slope basically leveled off and became insensitive because the diversity index could not respond to the modifying factor α. The third phase includes the groundwater table depth below 10 m. At this stage, the vegetation degenerated, consisting solely of the *Tamarix L.* population. Because of serious water shortage, *T. ramosissima* was the dominating species and spread together with *T. hispida*. The diversity slope became almost linear. The correlation between groundwater depth and plant diversity clearly indicates that species diversity will significantly degenerate when the groundwater depth drops below 6 m in the lower reaches of the Tarim River. As the groundwater level becomes deeper than a suitable water table level for herbaceous plants, these species will die out, leading to a sharp decrease in the species composition of the vegetation.

Effect of groundwater table depth on species ecological niche

The results of the analysis revealed that herbaceous plants appeared mostly in the sampling plots with a 0- to 6-m

groundwater table depth and that the trees were distributed in a much wider range. Generally, the species ecological niche expanded at lower groundwater levels. The widest ecological niche was realized at groundwater depth between 4 and 6 m and then narrowed as the water table got deeper. Among the 19 plant species identified in the lower reaches of the Tarim River, the total ecological niche breadths were the highest at 27.67, 19.21, and 18.83 for *T. ramosissima*, *P. euphratica*, and *T. hispida*, respectively.

This study compared 11 major species for their niche overlap. The highest values of niche overlap index were reached at water tables between 0 and 2 m. The overlap index became smaller at groundwater table depth between 4–6 and 6–8 m, which indicated that each species had sufficient resources and that different species established a coordinated and balanced relationship by mutual adaption. The vegetation structure maintains a relatively stable state. At this stage, many species have an ecological niche overlap index at 0, indicative of no sharing of natural resources. However, when the groundwater table depth dropped to 8–10 m, competition among species became intense again, an effect that manifests mainly in some herbaceous plants and shrubs. The ecological niche overlap index between *G. inflata* and *A. venetum* reached 0.981.

Corresponding to groundwater table depth of 0–2, 2–4, 4–6, 6–8, and 8–10 m, the percentages of species with ecological niche overlap index higher than 0.5 were 57.1, 11.1, 1.8, 0, and 10.7 %, respectively. The respective percentages were 81, 40, 21.8, 28.6, and 28.6 % for those with an ecological niche overlap index of 0.3. However, when the groundwater depth dropped below 10 m, the vegetation degenerated into single species *Tamarix L.*, and the ecological niche overlap index for *T. ramosissima* and *T. hispida* was 0.046. We can definitively conclude that, as the groundwater table drops, the degree of species ecological niche overlap will be significantly reduced initially and then slightly increased. That is, the separation scale of ecological niches among different species basically decreases first and then increases slightly as the groundwater table depth becomes lower.

Indicating appropriate groundwater depth

Simpson, Shannon–Wiener, Margalef, Alatalo, and Hill diversity index analyses all indicate that species diversity reached the highest level when the groundwater table depth was at 2–4 m, followed by 4–6 m, and then 0–2 m. The Hill diversity index also indicates that, by using the 6- and 10-m groundwater table depth as the cutoff thresholds, one can distinguish species diversity into three changing phases. Plant species diversity decreased sharply and then leveled off below the 6-m groundwater table depth. Therefore, the 6-m groundwater table depth can be considered the threshold for determining species diversity in the lower reaches of the Tarim River. The 2- to 4-m level is the most appropriate groundwater table depth for species diversity. Plant species ecological niche in the lower reaches of the Tarim River expanded gradually as the groundwater table level became lower, and the widest place appeared at the 4- to 6-m groundwater table depth and then started to narrow. Ecological niche overlap was obvious under the high groundwater table depth (0–4 m), suggesting that competition can be strong among the herbaceous species and among grass, shrubs, and trees. Ecological niche overlap was not pronounced at the deep water table (6–10 m). However, when the groundwater table depth was lower than 10 m, only the Tamarix trees survived. At groundwater table depths between 4 and 6 m, the ecological niche overlap among various species became the least obvious, indicating that interspecies competition also becomes less intense, and different species can accommodate each other. After comparing the comprehensive ecological breadth and ecological niche overlap, we speculate that 4- to 6-m depth of groundwater plays an essential role for these two parameters. Its ecological significance is that this groundwater table depth is the threshold determining plant species' ecological niche in the lower reaches of the Tarim River. On the basis of the findings from our study, we recommend that the groundwater table depth be maintained at 6 m and above to ensure the restoration of the vegetation in this area.

Ecological water requirement estimation

Precipitation of plain area in the Tarim River basin is sparse (<30 mm), which cannot form runoff and also has no ecological sense. The natural vegetation in this area mainly consists of azonal vegetation of mesophyte or xerophyte which relies on groundwater. Therefore the ecological water requirement for the natural vegetation could be approximatively estimated by the phreatic water evaporation. In a large-scale space, when the soil evaporation is steady, the surface evaporation intensity and the soil moisture are steady too, i.e., the phreatic water evaporation intensity, soil water flux, and the soil evaporation are the same.

The ecological water consumption can be calculated as follows.

$$E_{\mathrm{w}} = S_{\mathrm{p}} \times E \tag{5}$$

In which E_{w} is the ecological water consumption for maintaining a certain area of vegetation; S_{p} is the area of vegetation that should be maintained; E is the phreatic water evaporation intensity. Evapotranspiration per unit can be estimated using the following formula which is modified by the Averyanov formula (Chen et al. 2008).

$$E = \frac{1}{4} \sum_{i=1}^{4} f(E_{20}, H) \quad (6)$$

In which $i = 1,2,3,4$ indicates this experience formula; E_{20} is the surface evaporation; H is the groundwater depth. Evaporation per unit of arbor, shrub and grass are from 392 to 10,738 m^3/hm^2 (Table 3).

The goal of estimating ecological water consumption is to offer theoretic evidence and referential modes for the reasonable estimation of ecological water requirement. Based on the features of climate, terrain, landform, hydrology, and soil in the Tarim River basin and combined with the current conditions of the hydraulic project, the water consumption of natural vegetation is not the actual water requirement which is larger than the estimated one. Thus, water use efficiency should be considered. According to theory, research and practical experiences, the extra 25–30 % water should be added to the estimated value and then the minimum water demand maintaining vegetation survival could just be guaranteed. For the goals of ecological protection in the main stream of Tarim River, the area of the natural forests that should be protected currently is 142×10^4 hm^2, so the present ecological water requirement is estimated to be $249,906.65 \times (25 \% + 1) = 31.24 \times 10^8$ m^3 (Table 4). It is 9.79×10^8, 18.18×10^8, and 3.26×10^8 m^3, respectively, for the upper, middle, and lower reaches of Tarim River.

Minimum ecological flux

The Tennant method (Tennant 1976) is adopted to calculate the minimum ecological flux. This is a standard non-field measurement method. The recommended flux can be based on the predefined percentage of annual average flux. For example, 10 % of annual average flux is considered necessary to maintain a viable river ecosystem, 30 % of annual average flux is considered the minimum threshold to maintain a healthy river ecosystem, and 60–100 % of annual average flux is considered the natural level of a thriving river ecosystem.

After the Daxihaizi Reservoir was built in the early 1970s on the Tarim River, the 321 km of river downstream of the reservoir started to desiccate. In the 1990s, the point of zero flow moved upstream to the Qiala section on the lower reach of the Tarim River. The desiccation river length increased from 321 km in the 1970s to 428 km (Chen et al. 2011). There were no historical data on the annual average flux. The annual average flux for the lower reaches was calculated indirectly by hydraulic data obtained from the Qiala Hydrologic Station, located 150 km from the Daxihaizi Reservoir. For the Tennant method, continuous annual average flux over 10 years and minimal human activity are required. Hao et al. (2006)'s

studies showed that the main stream runoff was not influenced by human activities until Peacock River water was imported into the Tarim River in 1970. Therefore, using the annual average fluxes from 1957 to 1970, the multi-year average runoff volume was 11.57×10^8 m^3. This means that the stream flow requirement should be 1.157×10^8 m^3 at Qiala Hydrologic Station. Assuming the volume had symmetrical distribution, the multi-year average flux and minimum ecological flux could be 36.7 and 3.67 m^3/s, respectively. With the water consumption along the river-way, the minimum ecological flux of different sections of the lower reaches would be changed.

Discussion and conclusions

In the lower reaches of the Tarim River, riparian vegetation strongly depends on groundwater. Reduction in stream water induced a falling groundwater table, which had led to degraded riparian vegetation and decreased biodiversity. The water deliveries to the lower reaches of the Tarim River have resulted in a significant rise in the groundwater table, which has led to good growth of some drought-tolerant trees and shrubs. It means that water delivery has played an important role in restoration of riparian vegetation in this area.

Groundwater table and EWD

The third, fifth, sixth, and seventh water delivery is divided into two phases. If we take different phases as one-time watering, the second phase of seventh watering will be the tenth watering. It has a 3-year interval and five times watering between the fifth (Xu et al. 2007) and tenth (the second phase of seventh watering). Whatever the groundwater level is, the vegetation has changed a lot. If the predictions were based on previous law, a large error would be made. So, such a research is important to the present condition.

Based on the analysis of the monitoring data from the groundwater level of ten times water delivery, such an extensive artificial watering has a positive effect in raising the groundwater level along the two sides of the river. However, these favorable changes appeared only at a small scale. In lengthwise orientation (from upside to downside), the influence weakens with the increment of watering distance. In transverse orientation, the increment in groundwater table is remarkable within 300 m away from midstream. It is similar to the research of Chen et al. (2004a), whose study suggests that the groundwater level within 250 m from the river is very sensitive to water recharge. The groundwater level within 250–450 m grew less sensitive, but rose considerably, and the groundwater response was weaker at a distance >750 m.

In general, the groundwater improved shortly after water delivery. This result is directly related to the bulk and duration of water delivery and watering times and interval. To further exert the benefits of EWD and achieve the goal of restoring and protecting the degraded natural vegetation at a large scale, some suggestions and strategies are put forward for the conservation, restoration, and rehabilitation of the ecosystem in the lower reaches of the Tarim River, such as keeping on the EWD, developing the ecological forests, and making man-made flood. Multiple river course and regional water delivery are feasible means.

It is significant to calculate the water needed for recovery of damaged ecosystem of the lower Tarim River. We simulated the relationship between the discharges from Daxihaizi Reservoir and the maximal incidence on one side of the river based on available data and found the relationship to be close ($p < 0.05$; $R^2 = 0.7315$). Thus, it can be concluded that the incidence is close to the watering volume in the lower Tarim River. If we intend to have certain influence on groundwater, water demand could be estimated. For example, 1,000-m incidence of one side needs 2.48×10^8 m^3 of watering volumes. Certainly, with the ongoing ecological water transmission, the same incidence needs less watering volumes because of the cumulative effect of water delivery.

Response of vegetation to the change in groundwater table

The decline in species diversity in the lower reaches of the Tarim River is mainly caused by the disappearance of herbaceous plants and serious degeneration of semi-shrubs and shrubs (Liu et al. 2005). In our study, the maximum value of diversity index appeared at a groundwater depth of 2–4 m, followed by 4–6 m. Vegetation had the lowest species diversity index when the groundwater depth was lower than 6 m. These results suggest that to increase the species diversity, the groundwater depth needs to be maintained at a threshold level, probably higher than 6 m for this area. All these indices, including the Margale index, Alatalo index, Shannon–Wiener index, and modified Simpson index, have fixed values. When values and samples are collected from defined areas, one index can be calculated for each sampling plot. However, the ecological relationship is relatively more complex in the natural habitat; none of these fixed-value parameters can represent the characteristics of species diversity (Patil and Tailie 1982). Therefore, Hill index was used as a measure of diversity ordering to determine species diversity at different spatial dimensions and under the influence of environmental changes. Hill diversity index analysis concluded that species diversity can be divided into three phases, using 6 and 10 m as the cutoff threshold end point values

for the groundwater table depth. When the groundwater table depth was below 6 m, species diversity decreased significantly, as shown by the slope of the Hill index eventually leveling off. By then, the groundwater had little effect on species diversity. Six meters could be used as the threshold for this area. Therefore, the groundwater depth needs to be raised to above 6 m to maintain the growth of tree, shrub, and herbaceous vegetation in this region. The environmental water requirement of plants can be a complex function of several attributes of the groundwater systems (including attributes related to the quantity and quality of groundwater). Each species may have a physiological limit to the depth and rate of groundwater extraction (Zencich et al. 2002) or a maximum salinity level above which groundwater cannot be used (Lamontagne et al. 2005). Relevant studies on degeneration process, stress plant physiology, and the water quality requirement of the vegetation in the same area (Chen et al. 2004c, 2007; Zhuang and Chen 2006; Ruan et al. 2007) also indicate that a 6-m groundwater table depth is the cutoff criterion for plants to start experiencing stresses.

In the study area, the ecological niche overlap was phenomenal at high groundwater table depth (0–4 m), especially between 0 and 2 m, which indicated that the trees, shrub, and grass, as well as different herbaceous species, compete furiously. This finding also indicated that the competitive repelling relationship was intense among herbaceous plants and among grass, trees, and shrubs. As the groundwater table depth got deeper (6–10 m), ecological overlap became less obvious. When the water table dropped to >10 m, only *Tamarix L.* could grow because of lack of water resources. With the water table at 4–6 m, ecological overlap among various species was moderate, competition among species was not so intense, and they were able to accommodate each other. On the basis of these findings that when the groundwater depth is 4–6 m in the lower reaches of the Tarim River, plant species ecological niches separate obviously, different species occupy their own spaces of resources, and no obvious overlap exists. Furthermore, in addition to ecological separation in resource usage, coexistence of different species can be regulated by the life forms and their phenology (Lusk and Smith 1998). Therefore, even if most of the species appear in the 4- to 6-m groundwater class, these species can still adapt to and synchronize with each other because of the difference in life forms and the phenology of each species.

Species diversity reached the highest at the 2- to 4-m groundwater table depth, whereas the ecological niche breadth was the largest at 4–6 m. As the groundwater gets deeper (4–6 m), some species cannot survive the water stress and begin to die. As fewer species are present in the vegetation, the diversity of the vegetation decreases. On the other hand, the surviving species should have strong ability

to use limited water resources; and with less ecological niche overlap and interspecies competition, it is easily understandable that these species would have larger ecological niche breadth. This assertion should be postulated as an adaptive trait for the plant species to survive the harsh conditions in arid areas. The ecological significance is that a groundwater table depth of 2–4 m is probably the appropriate ecological water table level for the lower reaches of the Tarim River, which is in accordance with Fan et al. (2004)'s research, and 6 m is the threshold for the local vegetation.

The relationship between ecological niche overlap and interspecies competition is still a controversial issue. Some studies (Colwell and Futuyma 1971; Silvertown and Law 1987; Mahdi et al. 1989) indicate that ecological niche overlap does not necessarily lead to interspecies competition, whereas the findings of other analyses (Pianka 1974; Abrams 1980; Chesson 1991) do not support this notion. Wu and Tang (2010)'s research showed that in the area of low groundwater depth the vegetation grows luxuriantly, while in the area of high groundwater depth it grows sparsely. A third hypothesis is postulated based on the results from this study, i.e., whether the ecological niche reflecting interspecies competition depends on the supply of resources. Clearly, the vegetation degeneration in the lower reaches of the Tarim River is caused by discontinuous water flow and dropping of the groundwater table. Currently, the groundwater table has been raised by the artificial water transportation system. However, water resources for the plants are still limited; therefore, the ecological niche overlap can indicate the interspecies competition under such circumstances.

In the 8- to 10-m class of groundwater table depth, herbaceous species, including *G. inflata* and *A. venetum* and others, can still grow. There is extraordinarily significant ecological niche overlap among these species, partly because of the ecological characteristics of these two species. *A. venetum* is a perennial root herbaceous plant. The root can grow up to 2–3 m in depth. G. inflata has a large root system; it can still grow when the groundwater drops below 6 m. Another plausible factor is the "hydro-lift" effect of the dry desert plant community. The hydro-lift effect means that the deep plant root absorbs water from deep soil (including groundwater) and transfers it to the upper-level soil through the root system. Horton and Hart (1998) suggested that this effect can supply water to nearby plants and thus promote their growth. This process will eventually change the composition and distribution of the species in the vegetation. Consequently, the hydro-lift effect should also be considered when studying the effect of groundwater on vegetation in dry areas. When analyzing groundwater, one should also include the effect of soil moisture on the ecological processes of the vegetation.

Ecological water requirement

Riverway infiltration to recharge groundwater and flooding overflow for surface irrigation are the two main forms of ecological water consumption in the main stream of the Tarim River. Riverway infiltration generates a trapezoid groundwater area in the cross sections on both sides of the riverway, which enables the roots of natural vegetation to absorb water efficiently. Flooding overflow for surface irrigation enables vegetation to self-renew as well as meets the requirements of young forests breeding and herb growth. The ecological water requirement in the main stream of Tarim River includes two types: one is water for the existing natural vegetation to survive and the other is for restoring the degenerated ecosystems.

The growth status of natural vegetation in the main stream of the Tarim River varies depending on water supply. The upper reaches of the main stream is covered, first, with forests, and, second, shrubs and herbs. Thus, the ecological water consumption is dominated by, first, the surface irrigation of flooding overflow and, second, the riverway infiltration. In the middle reaches, arbor, shrubs, and herbs are approximately equal. They are degenerated and restrained by groundwater which decreases with the distance away from the riverway, so the infiltration in riverway and cross streams recharging groundwater forms the main ecological water consumption. In 2002 when the embankment was built from Yingbaza to Qiala in the middle reaches, the ecological water delivery of peripheral embankment was carried out through ecological brakes on the embankment. In the lower reaches, the 321-km riverway from the Daxihaizi Reservoir to the downward part cut off completely in 1972. The groundwater table dropped to 8–11 m, resulting in the degeneration and death on a large scale of natural vegetation. Thus, the ecological water consumption delivers water to the riverway to raise the groundwater table. At present, the groundwater table in the lower reaches has been raised obviously by the EWDP (Ecological Water Delivery Project). In a way, the desert riparian forests have been renewed (Chen et al. 2004a).

The longer the duration of water releases, the greater would the groundwater rise and the larger would be the range of vegetation influenced. It was found that the duration and volume of water delivery were closely related to restoration of vegetation in the lower reaches of the Tarim River. Differences in the response distances of *Populus euphratica* and *Phragmites communis* indicate that the optimal groundwater level for these two plants are different, as well as for other plants. More water releases are needed in the future to improve the ecological benefits. Seeding time and other factors may be considered in future operations to accelerate plant generation.

Minimum ecological flux

The essential function of the minimum flux of the river is to maintain a river's original conformation and ensure its continuity. The minimum flux is the basement to calculate in-stream flow requirements of rivers. In-stream flow requirement of a river is the amount of water needed for hydrophytic life forms to survive, for the aquatic ecosystem to maintain stability, and for the river to preserve its original conformation (Ji et al. 2006). Flow requirement and ecological water demand outside the river constitute regional ecological water requirement.

Minimum ecological flux can maintain the continuity and geometric shape of a river and assist hydrophytic life forms adapt to adverse environments during low-water seasons. Once flux is under minimum requirements, a riverway will face the risk of desiccation and will be unable to adjust. At the lower Tarim River, 1.157×10^8 m^3 of water flow is needed for itself.

In this study, responses of groundwater table and vegetation on water deliveries are analyzed, without considering the response of soil moisture, and the appropriate groundwater depth needs further study and validation by considering the factor of soil moisture. In recent years, more and more researchers pay attention to the relationship between soil moisture and vegetation (Fu et al. 2012) and the variation of groundwater chemistry before and after intermittent water delivery (Xu et al. 2012). Those studies will give more evidences to improve the studies on appropriate groundwater depth.

References

Abrams P (1980) Some comments on measuring niche overlap. Ecology 61:44–49

Alatalo RU (1981) Problems in the measurement of evenness in ecology. Oikos 37:199–204

Caldow RG, Racey PA (2000) Large-scale processes in ecology and hydrology. J Appl Ecol 37:6–12

Chen YN, Chen YP, Li WH, Zhang HF (2003a) Response of the accumulation of praline in the bodies of Populus euphratica to the change of ground water level at the lower reaches of Tarim River. Chin Sci Bull 48(18):1995–1999

Chen YN, Cui WC, Li WH (2003b) Utilization of water resources and ecological protection in the Tarim River. Acta Geogr Sin 58(2):177–215

Chen YN, Li WH, Xu HL, Liu JZ, Zhang HF, Chen YP (2003c) The influence of groundwater on vegetation in the lower reaches of Tarim River, China. Acta Geographica Sinica 58(4):542–549 (in Chinese)

Chen YN, Zhang XL, Zhu XM, Li WH, Zhang YM, Xu HL, Zhang HF, Chen YP (2004a) Analysis on the ecological benefits of the stream water conveyance to the dried-up river of the lower reaches of Tarim River, China. Sci China (Series D) 47(11):1053–1064

Chen YN, Zhang XL, Zhu XM, Li WH, Zhang YM, Xu HL, Zhang HF, Chen YP (2004b) Ecological responses to the artificial water recharge into the downstream reaches of Tarim River in Xinjiang. Sci China (Series D) 34(5):475–482 (in Chinese)

Chen YN, Li WH, Chen YP, Zhang HF, Zhuang L (2004c) Physiological response of natural plants to the change of groundwater level in the lower reaches of Tarim River, Xinjiang. Prog Nat Sci 14:975–982

Chen YN, Zilliacus H, Li WH, Zhang HF, Chen YP (2006) Groundwater level affects plant species diversity along the lower reaches of the Tarim River. J Arid Environ 66:231–246

Chen YJ, Zhou KF, Chen YN, Li WH, Liu JZ, Wang T (2007) Response of groundwater chemistry to water deliveries in the lower reaches of Tarim River, Northwest China. Environ Geol 53:1365–1373

Chen YN, Hao XM, Li WH, Chen YP, Ye ZX, Zhao RF (2008) An analysis of the ecological security and ecological water requirements in the inland river of arid region. Adv Earth Sci 23(7):732–738

Chen YN, Ye ZX, Shen YJ (2011) Desiccation of the Tarim River, Xinjiang, China, and mitigation strategy. Quatern Int 244:264–271

Chesson P (1991) A need for niches? Trends Ecol Evol 6:26–28

Colwell RK, Futuyma DJ (1971) On the measurement of niche breadth and overlap. Ecology 52:567–576

Di ZH, Xie ZH, Yuan X, Tian XJ, Luo ZD, Chen YN (2011) Prediction of water table depths under soil water–ground water interaction and stream water conveyance. Sci China (Earth Sci) 54(3):420–430

Doble R, Simmons C, Jolly I, Walker G (2006) Spatial relationships between vegetation cover and irrigation-induced groundwater discharge on a semi-arid floodplain, Australia. J Hydrol 329:75–97

Eamus D, Murray B, Froend R (2006) A functional methodology for determining the groundwater regime needed to maintain health of groundwater dependent ecosystems. Aust J Bot 54:114–197

Fan ZL, Ma YJ, Zhang H, Wang RH, Zhao Yuan J, Zhou HF (2004) Research of eco-water table and rational depth of groundwater of Tarim River drainage basin. Arid and geography 27(1):8–13

Fu AH, Li WH, Chen YN (2012) The threshold of soil moisture and salinity influencing the growth of Populus euphratica and Tamarix ramosissima in the extremely arid region. Environ Earth Sci 66:2519–2529

Hao XM, Chen YN, Li WH (2006) The driving forces of environmental change during the last 50 years in the Tarim River Basin. Acta Geographica Sinica 61(3):262–272 (in Chinese)

Hao XM, Chen YN, Li WH (2009) Indicating appropriate groundwater tables for desert river-bank forest at the Tarim River, Xinjiang, China. Environ Monit Assess 152(1–4):167–177

Hill MO (1973) Reciprocal averaging, an eigenvector method of ordination. J Ecol 61:237–249

Horton JL, Hart SC (1998) Hydraulic lift: a potentially important ecosystem process. Trends Ecol Evol 13:232–235

Ji LN, Liu SX, Lv HX, Men BH (2006) Theoretical study of minimum instream flow requirement using the wetted perimeter method. J Northwest Sci-Tech Univ Agric For (Nat Sci Ed) 34(2):124–130 (in Chinese)

Kite J, Webster K (1989) Management of groundwater resources for protection of native vegetation. J R Soc West Aust 71(4):100–102

Lammerts EJ, Maas C, Grootjans AP (2001) Groundwater variables and vegetation in dune slacks. Ecol Eng 17(1):33–47

Lamontagne S, Cook PG, O'Grady A, Eamus D (2005) Groundwater use by vegetation in a tropical savanna riparian zone (Daly River, Australia). J Hydrol 310:280–293

Li WH, Xu HL, Nayoupu AHMT (2003) Preliminary report of water transportation and ecological restoration in the lower reaches of Tarim River. Arid Land Geogr 26:122–128

Liu JZ, Chen YN, Chen YJ, Zhang N, Li WH (2005) Degradation of Populus euphratica community in the lower reaches of the Tarim River, Xinjiang, China. J Environ Sci 17(5):740–747

Lusk CH, Smith B (1998) Life history difference and species coexistence in an old-growth New Zealand rain forest. Ecology 79:795–806

Mahdi A, Law R, Willis AJ (1989) Large niche overlaps among coexisting plant species in a limestone grassland community. J Ecol 77:386–400

Munoz-Reinoso JC (2001) Vegetation changes and groundwater abstraction in SW Donana, Spain. J hydrol 242(3/4):197–209

Naumburg E, Mata-Gonzalez R, Hunter RG (2005) Phreatophytic vegetation and groundwater fluctuations: a review of current research and application of ecosystem response modeling with an emphasis on great basin vegetation. Environ Manag 35(6):726–740

Patil GP, Tailie C (1982) Diversity as a concept and its measurement. J Am Stat Assoc 77:548–567

Pianka ER (1974) Niche overlap and diffuse competition. Proc Natl Acad Sci 71:2141–2145

Rey Benayas JM, Bernáldez FG, Levassor C, Peco B (1990) Vegetation of groundwater discharge sites in the Douro Basin, central Spain. J Veg Sci 1(4):461–466

Romme WH (1982) Fire and landscape diversity in subalpine forests of Yellowstone National Park. Ecol Monogr 52:199–211

Rood SB, Samuelson GM, Braatne JH, Gourley CR, Hughes FMR, Mahoney JM (2005) Managing river flows to restore floodplain forests. Front Ecol Environ 3(4):193–201

Ross MS, Jones RD, O'Brien JJ, Flynn LJ (1994) Nitrogen and phosphorus in the Florida Keys: groundwater-vegetation relationship. Bull Mar Sci 54(3):1082–1083

Ruan X, Wang Q, Chen YN, Li WH (2007) Physiological response of riparian plants to watering in hyper-arid areas of Tarim River, China. Frontiers Biol China 2:54–61

Shannon CE, Weiner W (1949) The mathematical theory of communication. Unknown Distance Function, Urbana. Illinois Press, Champaign

Silvertown J, Law R (1987) Do plants need niches? Some recent developments on plant community ecology. Trends Ecol Evol 2(1):24–26

Stromberg JC, Tiller R, Richter B (1996) Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro, Arizona. Ecol Appl 6(1):113–131

Stromberg JC, Beauchamp VB, Dixon MD, Lite SJ, Paradzick C (2007) Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid southwestern United States. Freshw Biol 52:651–679

Sultan D, Song YD, Marina J (2004) Influence of groundwater level change on vegetation coverage and their spatial variation in arid regions. J Geog Sci 14(3):323–329

Tennant DL (1976) Instream flow regimens for fish, wildlife, recreation and related environmental resources. In: Orsborn JF, Allman CH (eds) Proceedings of symposium and specialty conference on instream flow needs II. American Fisheries Society, Maryland

Wan JH, Chen YN, Li WH, Yang PN, Ye ZX, Fu AH (2009) Study on net groundwater recharge after ecological water conveyance in the lower reaches of Tarim River. J Desert Res 29(2):376–382

Wu J, Tang DS (2010) The influence of water conveyances on restoration of vegetation to the lower reaches of Tarim River. Environ Earth Sci 59:967–975

Xie ZH, Yuan X (2010) Prediction of water table under stream–aquifer interactions over an arid region. Hydrol Process 24:160–169

Xu HL, Ye M, Song YD, Chen YN (2007) The natural vegetation responses to the groundwater change resulting from ecological water conveyances to the lower Tarim River. Environ Monit Assess 131:37–48

Xu JH, Chen YN, Li WH, Zhang LJ, Hong YL, Bi XL, Yang Y (2012) Statistical analysis of groundwater chemistry of the Tarim River lower reaches, Northwest China. Environ Earth Sci 65:1807–1820

Ye ZX, Chen YN, Li WH, Yan Y (2009) Effect of the ecological water conveyance project on environment in the Lower Tarim River, Xinjiang, China. Environ Monit Assess 149(1–4):9–17

Zencich SJ, Froend RH, Turner JV, Gailitis V (2002) Influence of groundwater depth on the seasonal sources of water accessed by Banksia tree species on a shallow, sandy coastal aquifer. Oecologia 131:8–19

Zhang YS, Wang LX, Zhang HQ, Li XY (2004) Desertified soil characteristics and fractal feature in lower reaches of Tarim River. Resour Sci 26(5):11–17

Zhuang L, Chen YN (2006) Physiological responses of three contrasting plant species to groundwater level changes in an arid environment. J Integr Plant Biol 48:520–526