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Effect of the ecological water conveyance project on environment in the Lower Tarim River, Xinjiang, China

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Abstract The dynamic response of groundwater level is examined in traverse and lengthways directions. Take the Yinsu section for an example, we have simulated groundwater levels before and after water-conveyance every time and calculated the incidence of groundwater on the both sides of the river. It is noted that the effect keeps growing with the water-delivery times increasing, from 570 m after the first times to 3,334 m after the eighth times. In addition, this paper involves the temporal response of the natural vegetation to water conveyance, vegetation coverage, planted-species number, dominant position and species diversity from 2002 to 2006. The findings indicate that the positive influence of ecological water conveyance project (EWCP) on the ecosystem in the Lower Tarim River is a long-term process. In this paper, we try to calculate water required for recovery of damaged ecosystem by using data available. This project is likely the base of research on water demand and the reference of measures for research on ecological water conveyance effect.

Keywords Ecological water conveyance project · Groundwater level · Tarim River · Vegetation

Introduction

Water is the foundation of oasis composition and development on the fringe of the desert as the most important ecological and environmental factor. And it also determines the conflicting processes of environmental change, such as oasis metamorphosis and desertification (Deng and He 1993; Li et al. 1998; Chen et al. 2003a, b, c). The ecosystem of inartificial oasis in northwest China largely depends on the groundwater level. As the two primary factors, moisture and salinity, closely related to the water table, influence the growth of vegetation, so the changes of

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groundwater level can affect the growth of vegetation (Chen et al. 2003c). Some examinations (Song et al. 2000) show that if the water table comes close to ground, salinity dissolved in water will rise through capillary and accumulate on the ground with evaporation and the soil will be salinized. On the contrary, if the water table were too low, it would be difficult for vegetation to absorb moisture on dry soil. As a result, desertification might happen. In the case of secondary salinization, the low water table does not help reduce the salinity in soil by irrigation or rain but for the sake of desertification prevention, the low water table cannot hold moisture that vegetation needs. Once there is no irrigation, mass vegetation will fade and desertification will be accelerated. Thus, the height of water table is the key to vegetation's protection and reversion in arid area.

Located in the hinterland of the Taklamakan Desert, the Tarim River is an extremely arid inland river where the ecological environment is fragile. The unbridled exploitation and utilization of water resources, especially over the half past century, has led to the noticeable changes of the natural and ecological process of the Tarim River (Zu et al. 2003; Feng et al. 2005). As a result, the water table drops and natural vegetation falls, which affects the ecosystem stability in northwest China and curbs local sustainable economic development. All the facts mentioned above indicate that the Lower Tarim River has been at hazard, as an issue of ecological and environmental problem in west China. In order to restore the ecosystem of the Lower Tarim River, a series of environmental measures have been taken, including EWCP. Some scholars have made plenty of observations and investigations from multiple angles at a variety of groundwater levels (Chen et al. 2003a; Xu et al. 2003a; Zhen et al. 2003, 2004), changes of water quality (Zhang et al. 2003), response of vegetation (Chen et al. 2004a; Yang and Guo 2004) and physiological shift of vegetation (Xu et al. 2003b; Chen et al. 2004d). The results showed that ecological water conveyance project has achieved something. Such extensive artificial water-transfer has also occurred in other countries (Munoz and Reinoso 2001; Mampiti and Rashid 2005). This paper tries to estimate the influences of EWCP in two main aspects, changes of groundwater level and vegetation. On one hand, this study can verify the phased achievement of EWCP. On the other hand, it can provide the scientific information for the restoration and protection of the degraded ecosystem in the Tarim River, and meanwhile it can also provide some scientific reference for the similar ecological projects in other areas.

Material and methods

Description of the study area

The area under the project is located between Daxihaizi Reservoir and Taitma Lake in the lower reaches of the Tarim River (39°38′–41°45′ N, 85°42′–89°17′ E). The channel bed stretches from west to east on alluvial fans along the Taklamakan Desert and the Kuluke Desert. It is one of the extremely arid areas of China, with average annual precipitation reaching less than 50 mm but potential annual evaporation between 2,500 and 3,000 mm. In the past 30 years, plentiful groundwater has been used for large-scale agricultural cultivation and little surface-water supply has contributed to severe reduction of stream-flow of the Tarim River. The Construction of the Daxihaizi Reservoir in 1972 disrupted much of the stream-flow in the Tarim River, leaving surface water in absence for a stretch of 321 km and dropping groundwater level in the lower reaches. The two lakes at the terminal of the Tarim River, the Lop Nur and the Taitma Lake, dried up in 1970 and 1972. The groundwater level dropped from 3–5 to 8–12 m below the ground surface over the past three decades (Chen et al. 2003a, b, c). Massive *Populus euphratica* has died and sandlot in woods is activated. Among flora are arbor, shrubs and herbage (Huang 1993). Arbor include *Populus euphratica*; shrubs include *Tamarix* spp., *Nitraria sibirica* and *Halimodendron halodendron* (*Tamarix ramosissima*, *Tamarix hispida* and *Tamarix elongate* are dominant species) and Herbage include *Phragmites communis*, *Poacynum hendersonii*, *Alhagi sparisifolia*, *Glyzyrrhiza inflate* and *Karelinia caspica*, etc (Song et al. 2000).

Ecological water conveyance project

The ecological water conveyance project is a part of a larger conservation plan, "Integrated Management of the Tarim River Valley" implemented by the Tarim River Management Administration. In the year 2000, about two billion dollars were allocated by the central government to the Tarim River Project in order to rescue the riparian forest of the Lower Tarim Basin and to conserve water resources for the entire river basin. Recent wet and mild years for the Kaidu River region provided an opportunity to divert water from the Bosten Lake to the Lower Tarim River. Since 2000, seven-times of water delivery has been practiced, with the total volume of 1.715 billion cubic meters (Table 1). Water was first discharged on May 14th, 2000, lasting for 61 days. However, the water flowed only 106 km downstream out of the Daxihaizi Reservoir because of infiltration along the dry riverbed. With the third discharge, which lasted 68 days, water finally reached the Taitma Lake and formed a 10 km^2 water surface. Additional discharges in the years 2002, 2003, 2004 and 2005 enlarged the Taitma Lake with encouraging results.

Origin of data

Nine observation sites are established for monitoring groundwater level between the Daxihaizi Reservoir and the Taitma Lake. Starting from the Daxihaizi Reservoir are the sections of Akdun(A), Yahepu(B), Yinsu(C), Abudali(D), Kardayi(E), Tugmailai(F), Alagan(G), Yiganbjima(H), and Kaogan(I) (Fig. 1). The distance between the two neighboring sections of the first six sections is about 20 km, and the distance between the last three sections is about 45 km. At each section, monitoring wells (varying from 8 and 17 m in depth) were set up with the distance of 100–200 m in order to monitor the dynamic change of the depth of groundwater, and water and salt content. A total of 40 monitoring wells have been built up.

In this study, the groundwater levels were obtained from investigations before and after the second phase of the seventh water-delivery at the five sections of Yinsu, Kardayi, Alagan, Yiganbjima and Kaogan at a regular interval of about 50 km along the lower Tarim River. There are six wells located at every section. The traversal distances from the midstream are 50, 150, 300, 500, 700, 1,050 m.

The natural vegetation was surveyed around one fixed well (C_3) in the Yinsu section in August per year from 2002 to 2006. The samples (50×50 m) are selected in those sites around the wells, and then each sample of 50×50 m is divided into four equal parts (25×25 m) to estimate xerophytic arbpors and shrubs, and five equal segments (1×1 m) are selected randomly in each part (25×25 m) to estimate herbaceous plants. Plant species composition, abundance, vegetation coverage, density and height were measured.

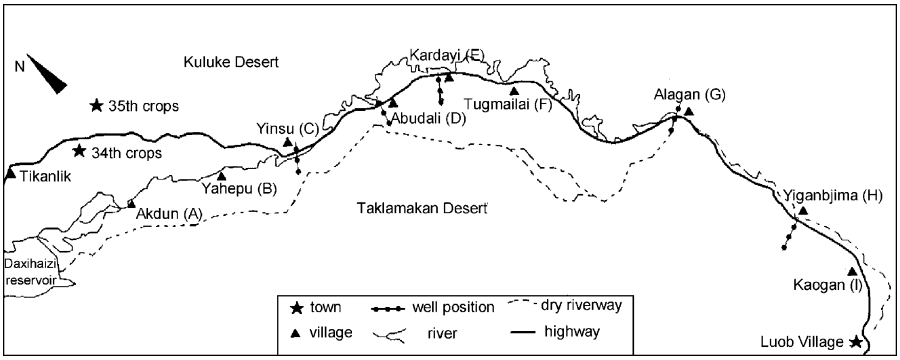
Methods

Plant species diversity can be assessed by measuring the abundance and uniformity of species in plant communities or habitats (Chen et al. 2006). The species abundance refers to the quantity of species in a community or habitat, while the species uniformity refers to the distribution of individuals of all species in a community or habitat. The species diversity index is

Table 1 Water discharge duration and volume from the Daxihaizi Reservoir

Time/phase		Period (day/month/year)	Duration (days)	Volume ($\times 10^8$ m^3)	Arriving Section	Distance (km)
First		14/05/2000–13/07/2000	61	0.99	Kardayi	106
Second		03/11/2000–14/02/2001	104	2.2	Alagan	146
Third	1	01/04/2001–06/07/2001	97	1.84	Alagan	160
	2	12/09/2001–17/11/2001	67	1.97	Taitma Lake	358
Fourth		20/07/2002–10/11/2002	110	2.93	Taitma Lake	358
Fifth	1	03/03/2003–11/07/2003	131	2.5	Taitma Lake	358
	2	12/09/2003–07/11/2003	56	0.9	Taitma Lake	358
Sixth	1	22/04/2004–25/06/2004	64	1.2	Taitma Lake	358
	2	–/08/2004–/11/2004	–	2.3	Taitma Lake	358
Seventh	1	07/05/2005–07/06/2005	32	0.52	Taitma Lake	358
	2	30/08/2005–02/11/2005	65	2.3	Taitma Lake	358
Eighth		25/9/2006–30/11/2006	66	2.33	Kaogan	324

Fig. 1 The distribution of the sections in the lower reaches of Tarim River



a composite index of the abundance and uniformity. We calculated the commonly used species diversity indices (i.e. Simpson index and Shannon–Weiner index), species richness indices (i.e. Margalef index and Menhinick index), and species distribution indices (i.e. Pielou index 1 and Pielou index 2) using the following formulae (Simpson 1949; Margalef 1958; Whittaker 1972; Ludwig and Reynolds 1988, p. 337):

$$\text{Simpson index}: D = 1 - \sum_{i=1}^{s} P_i^2 \tag{1}$$

$$\text{Shannon} - \text{Weiner index}: H = -\sum_{i=1}^{s} P_i LN(P_i) \tag{2}$$

$$\text{Margalef index}: D_{\mathrm{Ma}} = (S-1)/LN(N) \tag{3}$$

$$\text{Menhinick index}: D = S/\mathrm{SQRT}(N) \tag{4}$$

$$\text{Pielou index 1}: \mathrm{JSW} = \left(-\sum_{i=1}^{s} P_i LN(P_i)\right) \Big/ LN(S) \tag{5}$$

$$\text{Pielou index 2}: \mathrm{JSI} = \left(1 - \sum_{i=1}^{s} P_i^2\right) \Big/ (1 - 1/S) \tag{6}$$

Where S is the total number of vascular species, p_i is relative importance value of the species i, equals to N_i/N, N_i is the importance value of species i and N is the sum of the importance values of all species on a plot where species i is found.

Species importance value, N_i, was calculated as

$$N_i = C_{\mathrm{r}} + D_{\mathrm{r}} + H_{\mathrm{r}} \tag{7}$$

Where C_{r} is the relative coverage, D_{r} is the relative density and H_{r} is the relative height of plants.

Results and analysis

The changes of groundwater level during the period of water delivery

Transverse orientation

One important guideline in evaluating influences of environment is the shift of water table in transverse orientation along the river course, and it is also an important key to estimating the natural vegetation's comeback (Xu et al. 2003a; Fig. 2).

It can be seen from Fig. 2 that the most increment of water table is 2.12 m in the distance of 50 m from midstream of Kaogan section. The increment of water table in four sections is decreasing with the distance from midstream increasing except for that in Yinsu

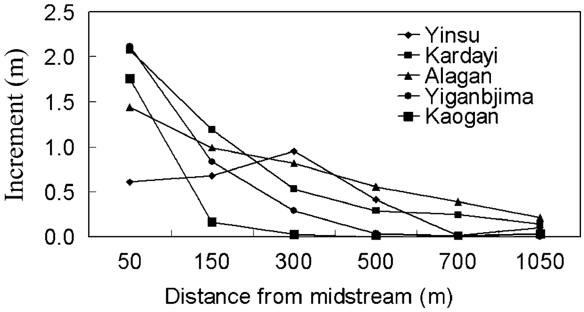


Fig. 2 Increment of the groundwater level in transverse orientation

section, and the distance from midstream is closer, the decreasing rate more obvious. From the slope of curve, the turning point lies at 300 m away from midstream, and the slope of curve becomes gentle outside this point, ranging from 0.03 to 0.55 m. All evidences show the water-delivery influence is remarkable within 300 m, but the result of Yinsu section is contrary because the seeping capacity has become weaken since seven-times of water delivery was made. The curves in Yiganbjima section and Kaogan section have few turning points because they are far away from the Daxihaizi Reservoir.

The incidence of groundwater in transverse orientation

In Yinsu section, the fitting curves of groundwater depth before and after water conveyance can be described in the same coordinate system (abscissa indicates distance from river course, ordinate indicates groundwater depth). Abscissa value corresponding to the point of intersection of two fitting curves is the maximal incidence in transverse orientation of one side of the river. In view of the eco-hydrological process of the Lower Tarim River, the scope of supply is symmetric on two sides of the river during the process of watering. So the maximal incidence in transverse orientation on two sides is twice that on one side of the river (Fig. 3).

It can be seen from Fig. 3 that the incidence keeps extending with the watering times increasing, from 570 m after the first times to 3,334 m after the eighth times. In fact, the amplitude of incidence showed different characteristics during different watering times. For example, the amplitude of incidence of the second times is the most, broadening 1,100 m more than that of the first times. The amplitude of incidence of the sixth times extended 990 m more than that of the fifth times. Because the watering volumes of the fourth times were less than that of the third times, the amplitude of incidence of the fourth times had diminution of 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 150 days, and both the watering volumes were more than 3×10^{8} m^{3}, so the amplitude of incidence increased 848 and 642 m, respectively. After analyzing the incidence of water conveyance, it was found that the amplitude of incidence is closely related to the watering volumes.

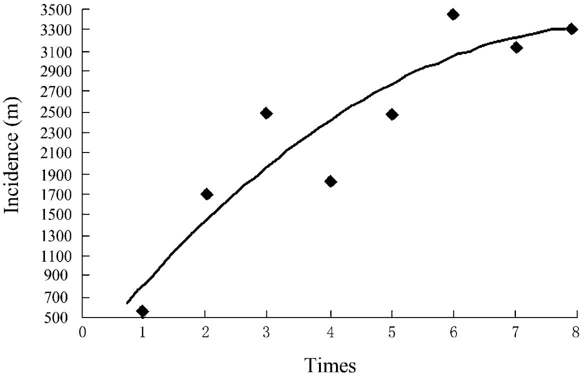


Fig. 3 Variation of transverse incidence of the groundwater in Yinsu section

Lengthways orientation

The paper made the following analysis in order to discuss the relationship between the change of groundwater level and the distance from the Daxihaizi reservoir (Fig. 4).

Firstly, the trend of increment of groundwater level is downwards along the river course outside 50 m, but the fluctuant range is not evident. It shows that the connection between increment of groundwater level and the lengthways distance along the river is not close. Secondly, the fluctuant range becomes weaker when distance becomes farther, and the connection between them is weaker. Thirdly, in the same section, the increment of groundwater level reduces with the distance from midstream especially in Alagan section. The reason is that Alagan section is the confluent point of double river course. All evidences show that the relationship between the watering volumes and the increment of groundwater level tends to steady when the watering volumes is enough. Another investigation

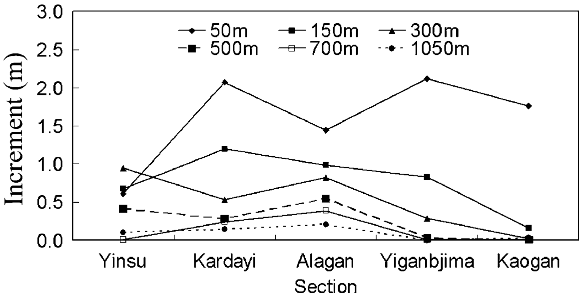


Fig. 4 Increment of the groundwater level in lengthways orientation

(Li et al. 2003b) shows that the increment of groundwater level involves two factors: the bulk and the duration of watering. Therefore, the ecological water delivery is a long-term and arduous task.

The temporal changes of natural vegetation

Coverage and species

Several studies suggest that the composition, distribution, and growth of natural vegetation in the Lower Tarim River Basin are being recovered in response to groundwater restoration (Chen et al., 2004b, 2004c; Deng and He 1993). Herbaceous plants, poplar trees and salt cedar (*Tamarix ramosissima*) have recovered, and the green corridor has been gradually expanded.

Figure 5 shows the changes of total coverage and coverage of *Populus euphratica* from 2002 to 2006. There have been seven times of water-delivery to the lower reaches of Tarim River during the period from 2000 to 2005. Whole ecological water volume is 23.84×10^{8} m^{3}. The vegetation recovers gradually with the continued water delivery. It can be seen from Fig. 5 the coverage of *Populus euphratica* reached the peak value, 34.76%, in 2005, increased rapidly from year 2003 to 2005 and dropped a little in 2006. The total coverage reached the maximum, 43.13%, in 2004, the minimum, 26.31%, in 2003. In general, either total coverage or coverage of *Populus euphratica* has an increasing trend. Some researches (Li et al. 2003a; Wu et al. 2005) showed structure change and growth of *Populus euphratica* community were closely related to soil moisture and salt. Namely, environmental factors were decisive reasons for vegetation recovery and self-renovation was second one. Some of environmental factors, such as volume and the duration of watering, took dominant function.

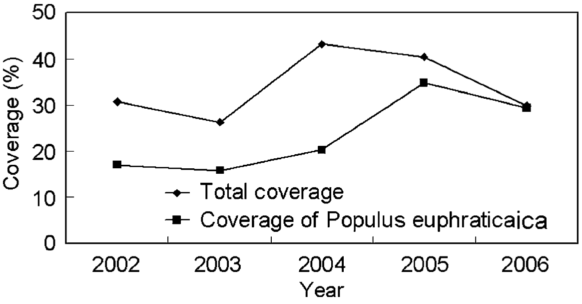


Fig. 5 Coverage variation from 2002 to 2006

Table 2 Plant species number of five sections from 2002 to 2006

Sections	2002	2003	2004	2005	2006
Yinsu	8	8	8	10	10
Kardayi	8	7	4	9	8
Alagan	4	3	4	4	4
Yiganbjima	2	2	2	4	4
Kaogan	–	–	3	7	9

Plants species were also increasing year after year (Table 2), but only at modest growth rate. Yinsu section is in possession of the maximum number of species, two more species from 2002 to 2006. Kaogan section has the maximal increment of species, adding twice from 2004 to 2006.

Flora and dominant position

In the flora, the dominant species govern the formation of community structure and environment (Dong et al. 1996). Study in the dominant position of different species during the period of water conveyance inevitably involves learning condition of vegetation recovery, change of flora structure and zoological characteristics (Chen et al. 2007). In the research of plant ecology, people choose such indices as types, density, dominance, coverage, frequency and so on to figure out the characteristics of community. Curtis and Mcintosh (1951) put forward the concept of importance value. The importance of each strain was calculated by relative density, frequency, and prominence. Because of priority given to other method, it has been extensively applied (Li et al. 2005). In this paper, we accept Mcintosh's view and define the importance values of coverage, density and height before analyzing the dynamic

Table 3 The importance values of the main plants

Species	2002	2003	2004	2005	2006
Populus euphratica	*1.19*	*1.32*	*0.85*	*1.82*	*2.16*
Tamarix ramosissima	0.57	0.47	0.17	0.35	0.27
Tamarix hispida	0.18	–	*1.17*	–	–
Lycium ruthernicum	–	0.35	–	0.10	0.16
Nitraria sibirica	0.45	–	–	–	–
Alhagi sparsifolia	0.61	0.63	0.60	0.57	0.40
Phragmites communis	–	0.23	0.11	0.08	–
Glyzyrrhiza inflata	–	–	0.10	0.08	–

The maximal importance value was indicated in italics changes of species in water-delivery. The importance values of main plants in the Lower Tarim River were showed in Table 3. It can be seen that *Populus euphratica* has been an important species with absolute value except in 2004. Its dominant position was increasing, with value maximized in 2006. *Alhagi sparsifolia* and *Tamarix ramosissima* were ranked the second and third, except in 2004. The importance value of other plants is on decrease except *Populus euphratica* and *Tamarix hispida* because the growth rate of *Populus euphratica* is bigger than others. Although there is great variation of plants, the dominant position of *Populus euphratica* and *Tamarix* is still there.

Plant species diversity

Natural vegetation, as one of the most important component of ecosystem, is significant in curbing desertification and protecting species diversity (Chen et al. 2003c). Species diversity, which is defined by the biodiversity of species and their aggregations, is closely related to the stability of eco-system (Pimm 1984; Tilman and Downing 1994; McNaughton 1997; Tilman 2000). Information on species diversity is of great value to understanding the composition, change and development of flora, as well as to understanding the structural and functional stability of ecosystems.

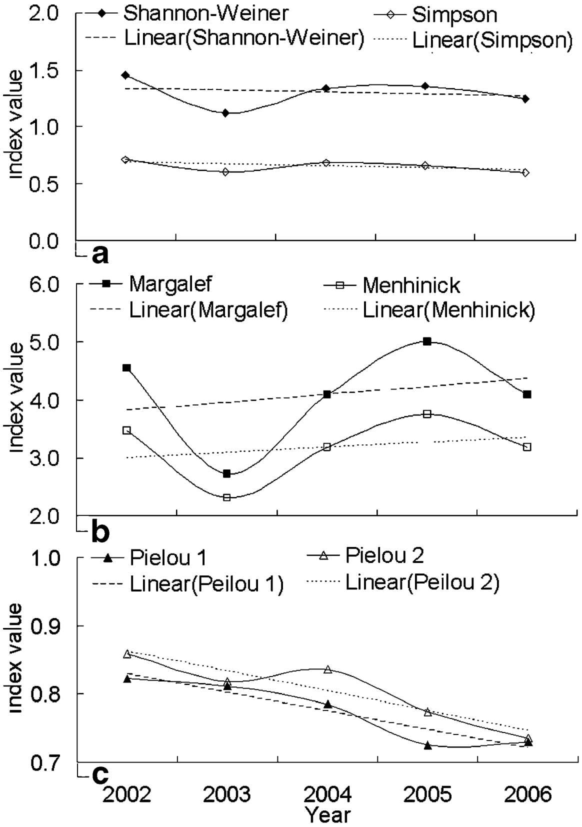


Fig. 6 Plant species diversity variation from 2002 to 2006. **a** Species diversity indices; **b** Species richness indices; **c** Species distribution indices

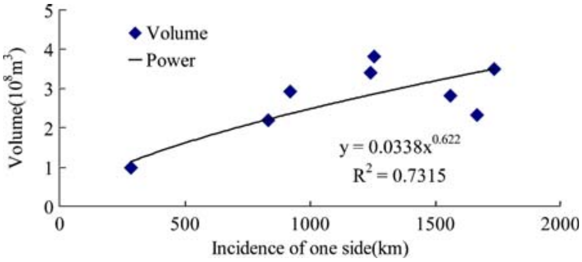


Fig. 7 The relationship between incidence and water volume

Lower levels of plant-species diversity are found by Fig. 6. The Shannon–Weiner index ranges from 1.1172 to 1.4477 and Simpson index ranges 0.5976–0.7096. There are appreciably trends of decreasing values in the above-mentioned indices year after year. Abundance (Margalef index), and Menhinick indices ranges 2.7307–4.5512, 2.3094–3.7528, respectively. There are apparent trends of increasing values in species-richness indices, reaching the minimum in 2003 and the maximum in 2005. For the species-distribution indices, the Pielou index 1 varies from 0.7250 to 0.8223, and the Pielou index 2 varies from 0.7348 to 0.8586. There are no apparent trends in the uniformity because of fewer species, simple community structure and sparse distribution. The research of Ma et al. (1995) suggested that uniformity be independent of species number, and depended on individual number or the spatial distribution of biomass in various species.

Conclusions and discussions

From Table 1, it can be seen the third, fifth, sixth and seventh water delivery is divided into two phases. If we take different phase as one- time watering, the second phase of seventh watering will be the tenth watering. It

Table 4 Water demand for the target incidence on one side of the river

Incidence (m)	500	1,000	1,500	2,000
Water demand (10^8 m^3)	1.613155	2.482657	3.194813	3.820827

has three-year interval and five-time 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 prediction were based on previous law, the great 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-time water delivery, such an extensive artificial watering takes positive effect on raising the groundwater level along the two sides of river. However, these favourable changes appeared only at a small scale. In lengthways orientation (from the upside to downside), the influence is weakening with the increment of watering distance. In transverse orientation, the increment of groundwater table is remarkable within 300 m away from midstream. It is similar to the research of Chen et al. research (2004b), 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 grows less sensitive but rose considerably, and the groundwater response is weaker at a distance greater than 750 m.

Restoring the natural vegetation is a long-term work and their growth is affected by local aboriginality. In this study, we analyse the variation of groundwater depth and vegetation during the ten-times watering, lasting 6 years, including the different phases of watering response. Majority of research is focused on the influences of groundwater depth and vegetation after five-times water conveyance (Deng and He 1993; Li et al. 2004; Xu et al. 2007). And it is concluded from past studies that the first three years of watering (five times) is the period in which groundwater depth increases and vegetation recovers rapidly. Together with this study, it is found that in the late 3 years the groundwater depth has increased moderately and balanced dynamically. The total coverage and the coverage of *Populus euphratica* are increasing year after year except for little fluctuation in some years. For example, in the latest three years, total coverage and coverage of *Populus euphratica* fell back in 2005 and 2004 (Fig. 5); species diversity indices, species rivhness indices, and species distribution indices fell back in 2006, 2006 and 2005 (Fig. 6). So, it should be emphasized that decrease of those indices in some years does not mean deteriorating of vegetation. Although vegetation structure and growth vigour change a lot, the dominant species (*Populus euphratica* and *Tamarix.*) changes never.

In general, the groundwater and vegetation were improved shortly after water conveyance. This result is directly related to the bulk and duration of water delivery and watering times and interval. In order to further exert the benefits of EWCP 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 EWCP, developing the ecological forests and making man-made flood. Multiple river course and regional water conveyance are feasible means.

It is significant to calculate water needed for recovery of damaged ecosystem of the Lower Tarim River. We simulated the relationship between the discharges from Daxihai Reservoir and the maximal incidence on one side of the river based on available data and found the relationship is close ($p<0.05$; $R^2=0.7315$; Fig. 7). 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 (Table 4). Because of limitation of watering times, data is not enough to confirm precision of model. It can be only the reference and needs more practice for future research on water demand.

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