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Effects of ecological water conveyance on groundwater dynamics and riparian vegetation in the lower reaches of Tarim River, China

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Abstract:

On the basis of the field measurements of changes in groundwater level and plant species abundance along nine transects crossing the Tarim River in Xinjiang, China, we examined the responses of groundwater and plant communities to a government-controlled 7-year recharge regime to the lower reaches of the river. Our results showed that the water recharges considerably lifted the groundwater table on both sides of the river course. The 6–8-m groundwater depths before the water recharges rose to 2–4 m after the recharges. In the transverse direction, the response of the groundwater table could be observed at as far as 850 m from the river course, and the affected *Populus euphratica* could be observed at 700 m. However, we did not observe significant influence of the water recharges on herbaceous plants. We infer that the plant communities will be benefited more from the combination of overbank flows and stream aquifer recharge than from sole stream aquifer recharge. Such a combination may maximize the ecological benefits of water conveyance and accelerate the restoration of the damaged arid ecosystems in this area. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS ecological restoration; water conveyance; groundwater recharge; riparian vegetation; the Tarim River

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INTRODUCTION

Ecological restoration of degraded arid inland river ecosystems has received much attention worldwide because of the rapid decrease in biodiversity and human-induced water resource scarcity in such areas. This type of restoration is challenging due to the limited knowledge on the processes and mechanisms underlying the serious landscape fragmentation caused by dams and driven by hydrological, geochemical, and biological variables, as well as their complicated relationships (Zhang *et al*., 2002; Si *et al*., 2005).

The Tarim River, the longest inland river in China with a length of 1321 km, is located in the arid zone of northwestern China. This is a region that is featured by abundant natural resources and meanwhile considerable ecological vulnerability, particularly, a serious water deficiency (Feng *et al*., 2005). During the last 50 years, the natural ecosystem processes of the Tarim River basin have undergone major changes caused by the influence of intensive economic and social activities. The conflicts between ecological protection and economic development have increasingly manifested in the use of water resources, especially in the lower reaches of the Tarim River. The ecosystem and eco-processes have been severely affected when the patterns of water resource utilization were changed by anthropogenic activities. Rivers were intercepted, lakes dried up, and groundwater levels dropped sharply, resulting in significant reduction in the desert vegetation communities dominated by *Populus euphratica* (Chen *et al*., 2003a). In addition, catastrophic climatic events, such as floating dust and sand storms, have increased (Chen *et al*., 2003a). The lower reaches of the river are most seriously impacted, which has led to calls for saving the 'Green Corridor'†. A number of scientific studies have been conducted on analysing the variation in water processes, investigating the relationship between economy and ecology under the water exploitation, exploring measures for eco-protection, analysing physiological and ecological characteristics (including photosynthesis, biochemical reactions, water potential, plant water consumption) of plant under drought and salt stress, as well as groundwater movement during water

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† The middle and lower sections of the lower reaches of Tarim River are located in a zone between the Taklamakan and the Kuruk Deserts, where previously vegetation thrived. Hence, it was called the 'Green Corridor'. The National Highway No. 218 runs through the 'Green Corridor', and the Xinjiang–Qinghai Railway currently planned will also pass here.

conveyance in lower reaches of Tarim River (Chen *et al.*, 2003c, 2004, 2006; Fu *et al.*, 2006; Li *et al.* unpublished; Xie *et al.* unpublished; Hao *et al.* unpublished). In the government aspect, the central government has listed the integrated management of Tarim River Basin from 2001 to 2005 in its 'Tenth 5-Year Plan'; the Chinese Academy of Sciences brought the recovery of the eco-environment of Tarim River into its 'Western Action Plan'; and the local government has urgently carried out a water conveyance project since 2000.

On the basis of continuous field investigation and measurements, the present paper presents our examination of the effects of the intermittent water conveyance on the shallow groundwater and the surface natural vegetation. Through this examination, we intend to explore approaches to vegetation restoration and ecosystem repair in inland river basins. We aim to provide detailed suggestions for water conveyance and ecological restoration, which may ultimately lead to the formation of scientific guidelines for saving the 'Green Corridor' in the lower reaches of Tarim River.

STUDY AREA AND DATA

Study area

The Tarim River basin is composed of 114 rivers of 9 water systems including the Aksu, Hotan, Yarkant, Qarqan, Keriya, Dina, Kaxgar, Kaidu-konqi, and Weigan Rivers, with an area of $1{\cdot}02 \times 10^6$ km^2. Hydrologically, the Tarim River basin is a closed catchment and is a unique freshwater ecosystem, located near the Taklimakan Desert, the largest desert in China. The Tarim River is a typical meandering river. The average annual surface runoff at the confluence of three headstreams is $45{\cdot}5 \times 10^8$ m^3. Runoff is mainly made of ice–snow melt water from high mountainous area and precipitation at middle mountains. During the past 50 years, many tributaries have lost the surface hydraulic relationship with the main stream due to the large-scale water exploitation. At present, only three headstreams, the Aksu River, the Yarkant River, and the Hotan River, supply water to the Tarim River (Figure 1). Among the three rivers, the Aksu River system is the largest one and contributes 73·2% of the total replenishment, while the Hotan and Yarkant Rivers supply 23·2 and 3·6% respectively. The Hotan River supplies water only during the flood period of each year (July through September). Yarkant River did not have a flow at all from 1986 to 2002, with only an exception in the flood period of 1994 (Chen *et al.* 2003a, 2007a, b).

Our study area is located between Daxihaizi Reservoir and Taitema Lake in the lower reaches of Tarim River (Figure 1). The riverbank stretches from east to south on alluvial fans along the Taklamakan Desert and the Kuluke Desert. The region is within the extremely arid warm temperate zone, with an annual precipitation from 17·4 to 42·0 mm and a total annual potential evaporation of approximately 2500–3000 mm. A strong wind is a frequent phenomenon in the region.

Vegetation is sparse in the area and largely follows the rivers to form green belts. In the study area, the arbor is mainly formed by *Populus euphratica*; the shrub mainly includes *Tamarix* spp, *Lycium ruthenicum, Halimodendron halodendron, Nitraria sibirica*; and herbs mainly include *Phragmites communis, Poacynum hendersonii,*

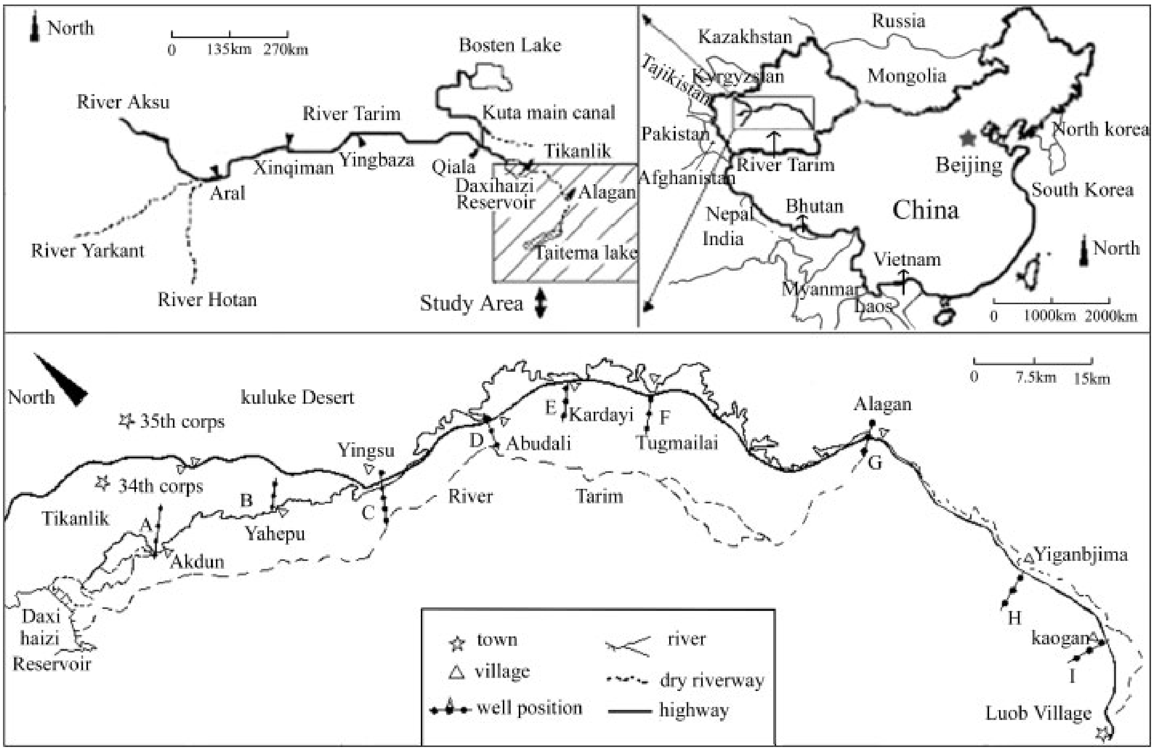

Figure 1. Sketch map of the study area

Alhagi sparsifolia, Karelinia caspica, Glyzyrrhiza inflate. As the rainfall in the study area cannot meet the requirement of the natural vegetation, the survival of the vegetation depends mainly on the groundwater (soil water).

The construction of the Daxihaizi Reservoir in 1972 reduced the water flow into Tarim River and dried up its lower reaches of a length of 321 km. With little precipitation and no surface runoff in the study area, the groundwater table fell greatly to 8–12 m at Yingsu and in the area downstream. The vegetation communities that depend on groundwater, including populations of the herbaceous plants *Phragmites communis, Apocynum venetum*, and *Alhagi sparsifolia*, and non-herbaceous plants *Tamarix* sp. and *Populus euphratica*, decreased extensively following the drop in the water table. Another consequence of dropping water table was the intensification of land desertification.

A government-run water-conveyance project in the lower reaches of the Tarim River commenced in May 2000 (Table I). Its purpose is to recharge the groundwater and lift the shallow groundwater table to benefit the natural vegetation, aiming to regenerate the seriously degraded natural vegetation and ecosystems in the lower reaches of Tarim River. The project transported water from Bosten Lake to the Tarim River (Figure 1). Bosten Lake, the largest inland freshwater lake in China, is the end of Kaidu River. The average annual water level of Bosten lake is 1048·75 m with a corresponding surface area of 1002·40 km. The lake's volume is 88×10^8 m^3 and the average annual water volume is 34×10^8 m^3. The length of transporting way from Bosten Lake to the study area is about 500 km (Zuo *et al.*, 2003). During the period from 1999 to 2005, the stream flow from Kaidu River was much more than usual, and the Bosten Lake was in a high-flow period. The water transportation generally has two stages: the water is first transported to the Daxihaizi Reservoir, and then to the lower reaches of the Qiwenkur River, a large tributary of the Tarim River.

Materials and methods

Aiming to determine the possible ecological effects of water conveyance, we established nine monitoring transects in the lower reaches of Tarim River, where the water conveyance occurred **(Figure 1)**. Starting from the Daxihaizi Reservoir, these transects included Akdun (A), Yahepu (B), Yingsu (C), Abudali (D), Kardayi (E), Tugmailai (F), Alagan (G), Yiganbjima (H), and Kaokan (I). The interval between two neighboring transects of the first six is 20 km, and that of the last three transects is 45 km. Owing to the different geographical settings of the transects, their lengths are variable, with the maximum of 1050 m at transect C. Along the nine transects, we drilled a total of 40 water-level-monitoring wells, with depths of 8–17 m, for monitoring changes in groundwater table and water salinity. The numbers of wells on the transects, from A to I, were 5, 4, 8, 3, 5, 3, 6, 3, and 3, respectively. The distance between adjacent monitoring wells was 50, 100, or 200 m. We measured the groundwater table using the conductance method and we generally took measurements every 1 or 2 months, but every 10 days during the water conveyance. In order to analyse the effect of water conveyance on the groundwater, the data of groundwater depth were obtained at nine transects during each water conveyance from 2000 to 2005. We also established 18 plant sample plots (1–3 for each transect) and 56 quadrates to monitor species distribution in order to investigate the response process of the natural vegetation to the water conveyance. The plots sizes varied across different plant communities: 5×5 m for herbage communities and 50×50 m for mixed communities of arbor, shrubs, and herbage. The latter was further divided into four 25×25 m quadrates. One vegetation sample was located near each monitoring well. At these sampling locations, we measured plant species composition and abundance, vegetation cover, plant height, and diameter at breast height of trees in early July. The variables used to assess the conditions of vegetation communities are shown in Table I.

ANALYSIS AND DISCUSSION

Effect of water recharge on shallow groundwater depth

The present water-conveyance program is a linear watering process along the natural river course. Our observations show that, temporarily, the rise in the groundwater table was closely related to the watering process and the water volume. Figure 2 is a graph of the groundwater depth at Yingsu transect, which is located at the middle part of the lower reaches of Tarim River. In Figure 2, I–VII indicate the beginning times of the seven water conveyances, respectively. The groundwater table kept rising along with the watering time. With the seven watering processes, the shallow groundwater depth

Table I. The variables used to assess the condition of vegetation communities

Variables	Equation	Description
Density (Den)	$\text{Den} = N/A$	Where N is number of plants and A is the area of the plot (50×50 m in this study)
Species richness index (D)	$D = (S - 1)/\ln N$ (Margalef, 1958)	Where S is the number of species and N is number of plants
Summed dominance ratio (SDR)	$\text{SDR} = (Cr + Hr + Dr)/3^{*}\ 100\%$ (Li, 2000)	Where $Cr = C_i/C_{\max}$, $Hr = H_i/H_{\max}$, $Dr = D_i/D_{\max}$; C_i, H_i, D_i is the cover, height and density of species i, respectively, $C_{\max}$, $H_{\max}$, $D_{\max}$ is the maximum of cover, height, and density of species on a spot where species i is found.

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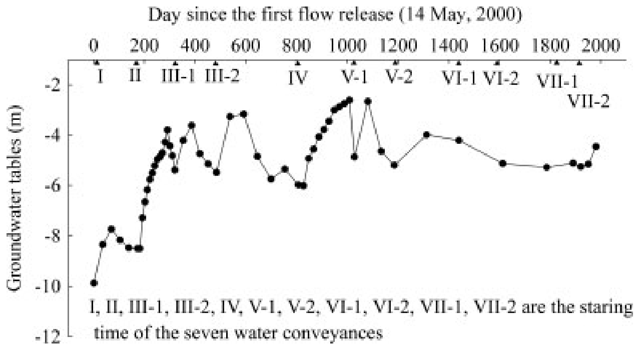

Figure 2. Water conveyance and groundwater table dynamics at the Yingsu transect

changed from −9·87 m before water conveyance (May 8, 2000) to −7·74, −3·79, −3·61, −3·16, −2·66, −4·63, −3·98, −5·12, −5·11, and −4·45 m (the last one was measured 20 days after the water conveyance), and the corresponding amplitude increases were 21·6, 66·4, 34, 42·3, 55·4, 4·7, 23·3, 1·3, 3·0, and 15·2%, respectively (Table II). The amplitude increases were largest at the second and fifth water conveyances, which reveals the effects of different water conveyance strategies. First, when the water amounts of conveyances are similar, it seems that a longer watering duration is more effective in lifting the water table. The second, fourth, and the second phase of the seventh conveyances all have water amounts larger than 2×10^8 m^3, but the amplitude increases of the first two are several times that of the last. It turned out that both watering durations of the second and fourth conveyances were over 100 days, while the duration of the second phase of the seventh conveyance was only 61 days. Second, it seems that amplitude is also influenced by the watering season. The watering volume and duration of the second conveyance were both less than those of the fourth one, but the rise in the groundwater table associated with the second one was greater, and we believe it was mainly because the second conveyance occurred in winter (from November 3, 2001 to February 14, 2002) when the temperature was below zero, and there was little evaporation from the river surface. In contrast, the fourth conveyance occurred in ???

The greatest rise in shallow groundwater as a response to the water conveyance occurred near the Daxihaizi Reservoir, where the water was from. This rise gradually decreased from upstream to downstream. The first of the nine transects at Akdun (transect A), which is 20 km from the Daxihaizi Reservoir, saw an amplitude increase as high as 84% after the seven water conveyances; whereas at the ninth transect at ??? (transect I), this percentage was only six due to the long distance from the water source, with the last five water conveyances having the largest impact **(Figure 3)**.

In the transverse direction, the range of the responding area was increasing as the water conveyance project carried on. After the first conveyance, the rise in the ground water table could be observed at 450 m from

Table II. Relationships between water conveyance and groundwater table

Times of water conveyance	First	Second	Third		Fourth	Fifth		Sixth		Seventh	
			First phase	Second phase		First phase	Second phase	First phase	Second phase	First phase	Second phase
Lifting amount of groundwater table(m)	2·31 ± 0·43	4·71 ± 0·22	1·77 ± 0·11	2·32 ± 0·28	3·45 ± 0·24	0·23 ± 0·08	1·21 ± 0·21	0·07 ± 0·04	/	0·16 ± 0·08	0·80 ± 0·15
Lifting percentage of groundwater table(%)	21·6 ± 3·5	66·4 ± 4·8	34 ± 3·7	42·3 ± 4·5	55·4 ± 4·2	4·7 ± 0·9	23·3 ± 4·5	1·3 ± 0·6	/	3·0 ± 1·1	15·2 ± 1·2
Starting time of water conveyance (d/m/y)	14/05/2000	03/11/2000	01/04/2001	12/09/2001	20/07/2002	03/03/2003	12/09/2003	22/04/2004	01/08/2004	07/05/2005	30/08/2005
Duration of water conveyance (day)	61	104	97	67	110	131	56	62	90	30	61
Daily mean water conveyance volume($\times 10^4 m^3$)	162·02	211·54	189·68	294·03	266·37	190·84	160·71	193·55	255·56	173·33	373·77
Water volume of delivery($\times 10^4 m^3$)	9883·2	22 000	18 400	19 700	29 300	25 000	9000	12 000	23 000	5200	22 800

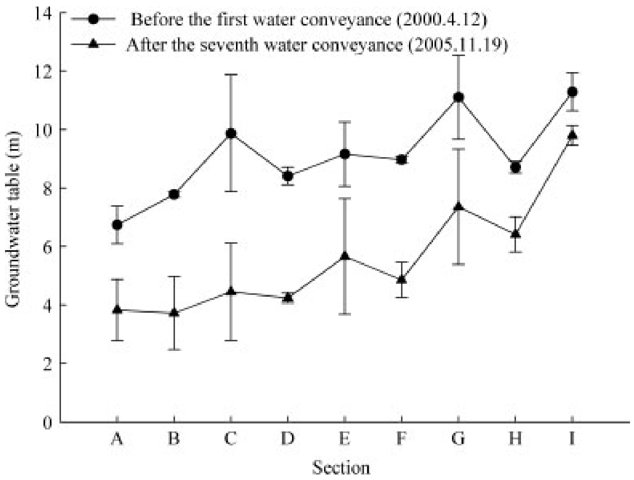

Figure 3. Groundwater table changes along the river before and after the water conveyance

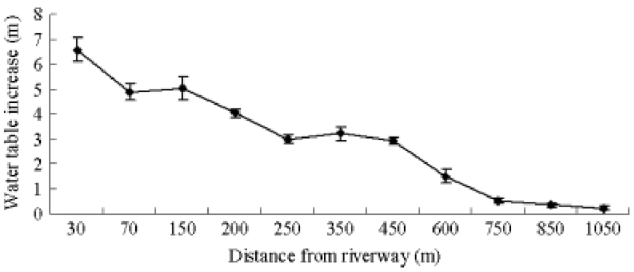

Figure 4. Transverse variation in the groundwater table in the lower reaches of Tarim River

the river channel; and, after the fourth conveyance, this distance became 850 m **(Figure 4)**. The amplitude of groundwater table rise decreased as the distance from the river channel increased. Within 150 m from the river, the increase was over 5 m; between 150 and 450m, the rise in the groundwater table were still obvious for the second, third and fourth conveyances, but seemed to be less sensitive to individual conveyances. Beyond 850 m, the change in the groundwater table was hardly observable.

Water conveyance and regeneration of natural vegetation

In the lower reaches of Tarim River, the natural vegetation, which is dominated by desert riparian forests, primarily depends on groundwater. During the past 50 years, the vegetation communities in this area died or severely degraded because of the drawdown of the water table, until the water conveyance project started. After the conveyances, vegetation communities regenerated rapidly within 300 m of the riverbank, apparently due to the rise in the groundwater table (Ruan *et al*., 2005). The growth condition of vegetation was closely related to the change in groundwater table **(Table III)**. A general pattern is that, as the lateral distance from the river channel increased, the number of plant species reduced and plant species composition became simpler. Most of the vegetation was distributed within 500 m of the river channel, with some shallow rooted plants disappearing as the distance from the channel increased. Between 800 and 1000 m, only *Populus eupratica, Tamarix* sp., *Lycium ruthenicum*, and *Alhagi Pseudalhagi* occurred. In a longitudinal direction, from the Akdun to Yiganbujima transects, as the groundwater table decreased, the ecosystem increasingly degenerated as well, indicated by the reduced coverage, density, and richness of vegetation, decreased species diversity index, and simpler community composition (Figure 5). These observations align with the understanding that natural vegetation relies on groundwater and soil water, and that species diversity and ecosystems are strongly affected by water stress in arid zones.

The natural vegetation responded actively to the water-conveyance project. Some herbaceous plants, such as *G.uralensis* sp., *Alhagi. pseudalhagi, Apocynum venetum, Phragmites communis, Salsola* spp., *Hexinia polydichotoma*, and *Karelinia caspica*, regrew along the river

Table III. Floristic inventory at the Yingsu transect in 2001 and in 2005 after the seven water conveyances

Plant names	Distance from riverway											
	0–100 m		100–200 m		200–300 m		300–500 m		500–800 m		800–1000 m	
	01	05	01	05	01	05	01	05	01	05	01	05
Populus euphratica	+	+	+	+	+	+	+	+	+	+	+	+
Tamarix sp.	+	+	+	+	+	+	+	+	+	+	+	+
Alhagi sparsifolia	+	+	+	+	+	+	+	+	+	+		+
Halostachys caspica	+	+	+	+	+	+	+	+	+	+		+
Lycium ruthenicum	+	+	+	+	+	+	+	+	+	+		
Glycyrrhiza inflata	+	+	+	+	+	+	+	+		+		
Apocynum venetum	+	+	+	+	+	+	+	+		+		
Halimodendron halodendron		+	+	+	+	+	+	+		+		
Phragmites communis	+	+	+	+	+	+						
Karelinia caspica	+	+		+						+		
Elaeagnus angustifolia		+				+						
Hexinia polydichotoma		+								+		
Inula salsoloides		+										
Aeluropus pungens		+										
Taraxacum sp.		+										

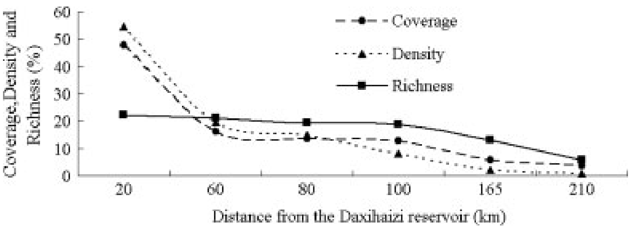

Figure 5. Variation in plant coverage, density, and richness in the lower reaches of Tarim River in 2005

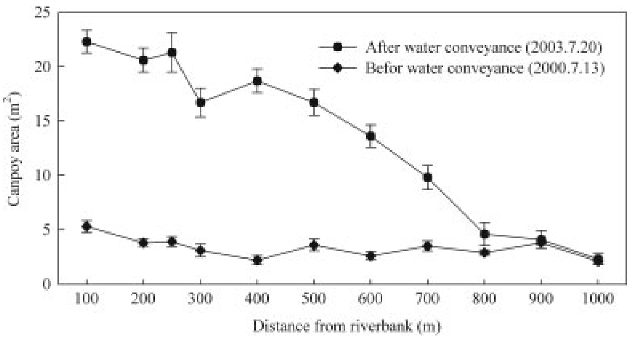

Figure 6. Response of *Popular euphratica* to the change in the groundwater level in the lower reaches of Tarim River before and after the seven water conveyances

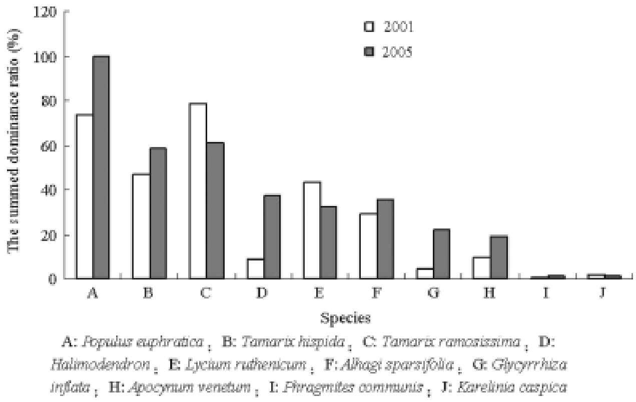

Figure 7. Comparison between the summed dominance ratio of main species in 2001 and that in 2005

channel. Some drought-resistant tress and shrubs also grew again. For example, the continuous increases in canopy area and density of *Populus euphratica*, the most abundant species in the lower reaches of the Tarim River, were obvious within 400 m from the channel, and were detectable at as far as 700 m (**Figure 6**). These results suggested that the roots of *Populus euphratica* are deep and their drought-resistant capabilities are strong.

Our observations suggest that the responses and endurances of plant species to water stress variy due to their different demands for groundwater. Among herbaceous plants, the leaf characteristics of *Phragmites communis* are most sensitive to the change in groundwater levels, and the observations in our sample plots indicate that these responses were strongest between 150 and 250 m from the river. The index tests of *Populus euphratica*, including relative water content, mean leaf weight, leaf length, and mean length of small branches of the same year showed that changes to the aquifer due to the water conveyance effected plants 700 m from the channel (Li *et al*., 2004).

Effect of water conveyance on dominance of plant species and community composition

In this study, we used the summed dominance ratio (SDR) to assess the relative role of plant species in a plant community. In plant communities, the effect of dominant species on the structures and environment of plant communities is significant (Dong *et al*., 1996). Analysing the dominant position of different species among the vegetation communities during the course of water conveyance is very useful to understand the plant restoration condition, the change of structure types, and the ecological functions of plants. Vegetation regenerations are different at the nine transects during the water conveyances, which can be attributed to the differences in groundwater depths and the types and structures of the plant communities (**Figure 7**). In terms of type of community, the largest increase of SDR occurred in the herbaceous communities, followed by that of shrubs, and then of trees. Geographically, we observed considerable increase in the SDR for *Phragmites communis* and *Glycyrrhiza* spp. along the Yingsu and Abudali transects that are in the upper part of our study area, and the SDR increase reached its peak with *Alhagi maurorum* along the Kardayi transect that is in the middle part of our study area. The SDR of trees along all the transects increased slightly. The SDR of herbs, especially *Phragmites communis* and *Glycyrrhiza inflate*, along the Yingsu transect increased from 5·49 to 15·19% and from 2·09 to 17·18%, respectively. The summed dominance ratio of the plant species along all the transects increased universally. Although the dominant and hypo-dominant species in the plant communities along the Yingsu transect in the upper part of lower reaches did not change, the summed dominance ratios of *Phragmites communis* and *Glycyrrhiza* spp. in herbaceous plant communities distinctly increased. The difference between the species with the highest and lowest SDR decreased from 78·20% at the early stage of the water conveyance to 71·27% after the conveyance; the response of summed dominance ratios of species in the plant communities at Kardayi transect in the middle of the study reaches is also obvious. For example, the difference between the highest SDR (for *Tamarix hispida*) and the lowest SDR (for *Glycyrrhiza* spp.) decreased from 73·24% at the beginning of the water conveyance to 68·69% after the conveyance. The increase in SDR for *Alhagi maurorum* is 5·26%, the highest among all the species. There were fewer plant species along the Yiganbjima transect that were in the lowest part of our study area. Along this transect, only *Populus euphratica* and *Tamarix ramosissiama* grew in the sample plots, and the changes in their SDR were less distinctive than those in the upper and middle parts.

We also observed a remarkable increase in plant species during the water conveyance. Along the Yingsu transect, for example, the species composition changed from 18 species, belonging to 15 genera before the water conveyance (2000), to 20 species, belonging to 19 genera in 2005. After the conveyance, a number of new species appeared in the communities, including *Inula salsoloides* and *Aeluropus. pungens* var. *pungens*. However, we did not find new tree species after the conveyance.

RESULT AND SUGGESTION

The water conveyance to the lower reaches of the Tarim River considerably lifted the water table, making it accessible to the natural vegetation on both sides of the river. In the upper and middle parts of the study area, the water table near the riverbank was lifted by 2–4 m, which meets the needs of *Populus euphratica* and *Tamarix* sp., the dominant species of the river ecosystems in the lower reaches of Tarim River. However, in the area 250 m beyond the riverbank, the groundwater table is still low and the vegetation still suffers from water stress (Chen *et al.*, 2003b).

When there is water in the river, its level is higher than that of the groundwater, so the river recharges the groundwater, and as a result the groundwater table rises. As the distance from the riverbank increases, the amplitude of the water table change decreases. The magnitude of the groundwater table change was affected by the following factors: the river water level, the permeability and saturation of riverbed materials, and the flow duration. When the water conveyance was stopped, the water table dropped, indicating that the water table was unstable. Therefore, a long-term water conveyance should be carried out in order to maintain a groundwater table that can meet the need of growth of natural vegetation and ecological restoration in the lower reaches of the Tarim River.

The present water conveyance in the lower reaches of the Tarim River aimed to regenerate the 'green corridor' along the river. However, it is difficult to achieve a long-term renewal of desert plants, such as *Populus euphratica* and *Tamarix* sp., although conveyance flow did increase the water table near the riverbank and thus saved the severely degenerated natural vegetation at an early stage. The process of vegetation regeneration was slow and only occurred in a narrow belt along both riversides. Although some large trees could be regenerated and rejuvenated, the production of herbaceous plants could not be apparently improved. The activation of mobile sand dunes in the forests, especially in the lower reaches, has not yet been controlled. Longitudinally, downstream the effect of water conveyance on the water table declined and the vegetation regeneration became poorer. Transversely, the response of the groundwater table to the water conveyance was limited within 850 m from the riverbank, and the intensity declined as distance increased. Beyond 850 m, there was almost no effect of water conveyance on the groundwater table. Therefore, submerging or overflowing on the surface should be carried out at transects one by one to increase the effect of water conveyance and accelerate the regeneration of natural vegetation. The period from August to September of each year is the optimal time to conduct the water conveyance because this is the period when most seeds mature, and water conveyance will assist them in spreading and germinating. Also, the river water is high during this period (i.e. high-water period), so overflowing water can activate the seed bank in the soil and expand the surface coverage and accelerate the regeneration of natural vegetation.

Water is the key factor in restoring the lower reaches of the Tarim River. The first four water conveyances all used water from neighbouring Bosten Lake, which was in high flow and could offer sufficient water for the conveyances. However, when the water level of Bosten Lake is low and there is only limited water available, an integrated management of the water resources in the Tarim River basin itself is crucial in solving the ecological problems presented. An integrated water resource management includes (1) implementing a unified water management to achieve a reasonable water resource allocation (e.g. the total water volume supplied from the three major headstreams, the Aksu River, the Yarkant River, and the Hotan River, should not be less than 45×10^8 m^3) and (2) reinforcing the mainstream management, particularly blocking the water slots and stopping random water interceptions completely, in order to ensure $2 \sim 3 \times 10^8$m^3 ecological water to be delivered to the lower reaches of the Tarim River each year.

More detailed studies are needed to fully understand the economic and ecological impacts of water utilization in the Tarim River. Comprehensively considering the social, economic, and ecological factors of water use and evaluating water use efficiency and security should be a priority of the future development in the region. Sustainable water utilization requires balances between urban and rural areas, upper and lower reaches, and ecological safety and socioeconomic development.

In arid regions, the supply of water is critical to both ecological processes and socioeconomic development. Sustainable development of the local economy requires unified efforts by all stakeholders in managing water resources so that water production and utilization consider both ecology and economy. To maintain the integrity of ecological processes, policies that ensure the equal rights of sustainable development among the upper, middle, and lower reaches should be implemented. Management should maintain the communal advantages of all nationalities and establish ecological compensation mechanisms needed to guarantee sufficient water flows into the main stream of the Tarim River. Additionally, regulation mechanisms are needed so that the water market can be controlled by introducing new means of moderating access to water. Allocation of water should favour high economic efficiency and highly active industries and regions. Expansion of water-saving agriculture and removal of irrational water utilization practices are strongly called for in the Tarim River basin to ensure sufficient water supply to the lower reaches for ecological purposes.

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