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Impacts of ecological water conveyance on groundwater dynamics and vegetation recovery in the lower reaches of the Tarim River in northwest China

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Abstract The ecological water conveyance project (EWCP) in the lower reaches of the Tarim River provided a valuable opportunity to study hydro-ecological processes of desert riparian vegetation. Ecological effects of the EWCP were assessed at large spatial and temporal scales based on 13 years of monitoring data. This study analyzed the trends in hydrological processes and the ecological effects of the EWCP. The EWCP resulted in increased groundwater storage—expressed as a general rise in the groundwater table—and improved soil moisture conditions. The change of water conditions also directly affected vegetative cover and the phenology of herbs, trees, and shrubs. Vegetative cover of herbs was most closely correlated to groundwater depth at the last year-end ($R=0.81$), and trees and shrubs were most closely correlated to annual average groundwater depth ($R=0.79$ and 0.66, respectively). The Normalized Difference Vegetation Index (NDVI) responded to groundwater depth on a 1-year time lag. Although the EWCP improved the NDVI, the study area is still sparsely vegetated. The main limitation of the EWCP is that it can only preserve the survival of existing vegetation, but it does not effectively promote the reproduction and regeneration of natural vegetation.

Keywords Groundwater depth · Vegetative cover · NDVI · Inland river · Arid region

Introduction

In the arid regions of northwest China, precipitation is generally <100 mm. Under such conditions, the survival of natural vegetation highly depends on renewable groundwater instead of precipitation (Hao et al. 2010; Li and Zhang 2003). Groundwater table frequently fluctuates under natural and anthropogenic influences (Chen et al. 2007, 2011). The dynamic changes of groundwater table often determine the types of plant communities (Guo and Liu 2005). So, the response mechanism of desert riparian vegetation to groundwater dynamics has been a focus of hydrology, ecology, and soil science. Ecological problems caused by groundwater dynamics are particularly prominent in the lower reaches of the Tarim River because the river has been dry for 30 years. Thus, the ecological water conveyance project (EWCP) in this area provides a valuable opportunity to reveal the mechanism of hydro-ecological processes.

The Tarim River, the longest inland river in China with a length of 1,321 km, is located in the arid zone of northwestern China and surrounded by the Taklimakan and Kuluke Deserts. During the last 40 years, the natural ecosystem of the Tarim River Basin has undergone major changes caused by excessive exploitation of water resources. The lower reaches of the Tarim River (320 km) and the tail lakes were dried up, and groundwater levels dropped sharply, which resulted in

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degradation of desert riparian vegetation that was dominated by *Populus euphratica* (Chen et al. 2003b; Hao et al. 2009). In order to save the "Green Corridor"—a historically heavily vegetated area in the middle and lower segments of the lower reaches of the Tarim River, between the Taklimakan and Kuruke Deserts—the EWCP has been implemented in this area since 2000. After 13 years of EWCP implementation (from 2000 to 2012), groundwater levels have increased significantly (Chen et al. 2010; Xu et al. 2003; Hou et al. 2007) and degraded vegetation has been effectively restored (Ye et al. 2009; Liu and Chen 2007).

Many studies have been conducted since the implementation of the EWCP to understand the complicated relationships between hydrological and ecological processes. These studies were generally concerned about the appropriate groundwater depth for vegetation, ecological water demand of natural vegetation, and water use strategies of individual plants. The optimum groundwater depth was primarily studied by analyzing the physiological and biochemical responses at an individual plant level (Chen et al. 2003a, 2004) and the ecological responses including diversity, ecological niche, distribution pattern, and community succession at the population and community scale (Hao et al. 2009; Liu et al. 2004; Chen et al. 2003b, 2006b; Guo and Liu 2005) under various water stresses. Studies on ecological water demand of natural vegetation were focused on minimum and optimum ecological water demands based on the assessment of evapotranspiration (Ye et al. 2010, 2012; Chen et al. 2013). Researches related to water use strategy of individual plant were mostly focused on the changing character of water potential, the xylem hydraulic conductivity, and the photosynthetic response of leaves or assimilating branches under different soil water conditions (Chen et al. 2006a; Ayup et al. 2012; Fu et al. 2006). Besides these, the hydraulic redistribution of roots was also considered (Hao et al. 2012). However, these studies have concentrated more at the individual plant scale.

An integrated assessment of the benefits and limitations of the EWCP is necessary to understand the hydrological and ecological responses of natural vegetation to water conveyance. Two crucial questions need to be answered: (1) How did the EWCP affect the ecological processes at the large temporal and spatial scales (such as community, landscape, or regional scale)? (2) How can the EWCP be improved to solve the fundamentally ecological problems in the lower reaches of the Tarim River? The objectives of this study were to assess the ecological effects of the EWCP, analyze its problems, and propose suggestions to advance ecological restoration practices. This study used the Normalized Difference Vegetation Index (NDVI) time series data to reveal the effects of ecological water conveyance and groundwater depth dynamics on vegetative cover and the phenological characteristics of typical communities.

Materials and methods

Study area

The study area, located in the lower reaches of the Tarim River, is surrounded by the Taklimakan and Kuruke Deserts. The climatic condition is extremely arid in this region, with an annual precipitation of 35 mm and an average annual temperature of 11.5 °C. The vegetation structure is generally simple, with only a few plant species, but several halophytic species are growing along the riverbank in the lower reaches of the Tarim River.

In the past 40 years, the natural vegetation, such as *P. euphratica* Oliv. and *Tamarix* spp. communities, and herbaceous plants (*Phragmites communis* Trin., *Apocynum venetum* L., *Alhagi sparsifolia* Shap.) have been severely degraded due to declines in groundwater levels. Consequently, the wind erosion and desertification have intensified (Liu and Chen 2007).

We constructed nine monitoring transects along the river course (Fig. 1) where the effects of the EWCP were assessed. We also installed six groundwater wells in each section at intervals of 100–300 m. A total of 44 monitoring wells are operating normally, while several other wells were damaged so we had to monitor intermittently. A total of 44 vegetation plots, corresponding to the location of the wells, were also established in the lower reaches of the Tarim River.

Data collection

NDVI image data

NDVI time series data (MOD13Q1 level data, from February 2000 to December 2012) were downloaded from the Web site of the National Aeronautics and Space Administration (http://modis.gsfc.nasa.gov/). The temporal and spatial resolutions of the data are 16 days

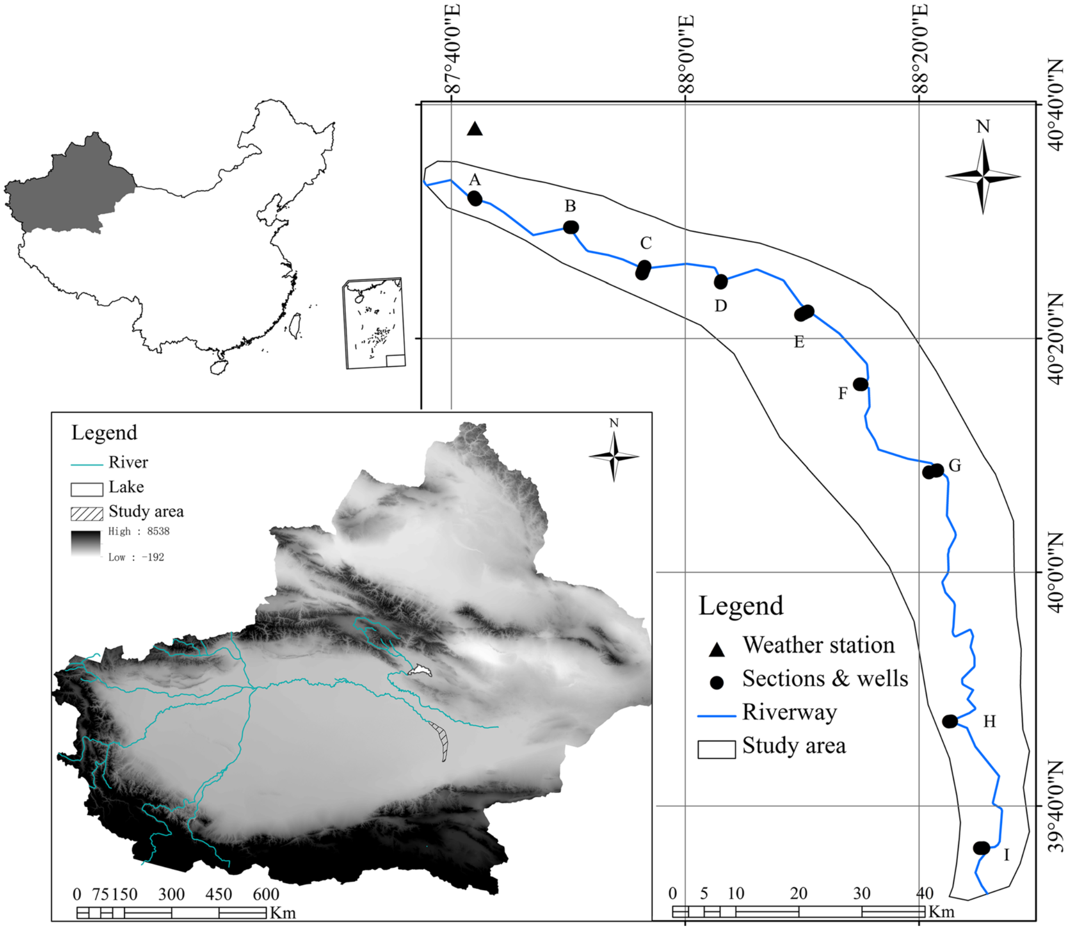

Fig. 1 The location of the study area and the layout information of the 9 transects and 44 groundwater monitoring wells

and 250 m×250 m, respectively. MODIS data were processed using the MODIS Reprojection Tool to generate a Tagged Image File Format in the WGS84 coordinate system. All data were further analyzed by using ArcGIS 9.3 software (ESRI, Redlands, CA, USA). The NDVI was calculated for the end of July (27 July) each year as an indicator of annual vegetation cover.

Hydrological and vegetation data

Water flow and groundwater depth data of the EWCP in the lower reaches of the Tarim River were collected from 2000 to 2012. The basic data of the EWCP, such as water flow and duration, were obtained from the hydrological station. A total of nine transects named A, B, C, D, E, F, G, H, and I were established along one side of the river to monitor groundwater depth. The six upstream transects were spaced approximately 20 km apart and the remaining three transects were spaced approximately 45 km apart. All transects were perpendicular to the main channel. Six groundwater monitoring wells (from 8 to 17 m deep) were installed along the center line of each transect. The wells were at distances of 50, 150, 300, 500, 750, and 1,050 m from the center line. We measured groundwater depth monthly in 44 wells.

The natural vegetation was examined at 44 plant sampling sites, around each well, in July of each year (2000 and 2012). The size of each site was 50 m×50 m, and each site was further divided into four tree and shrub sampling plots of 25 m×25 m. Vegetative cover, number of each species (trees and shrubs), and plant height were recorded. Alternatively, each plot was divided into four herbaceous sampling subplots of 5 m×5 m to collect data on the number of plants, vegetative cover, plant height, and frequency. All sampling sites were located by GPS. In this study, we confirm the herb, shrub, and tree (*P. euphratica*) communities based on the dominant species and the importance value index of each site (50 m×50 m).

Meteorological data

We collected temperature and precipitation data monthly from 2000 to 2012 from a weather station located in the lower reaches of the Tarim River and used for analyzing the effects of meteorological factors on vegetation.

Analysis methods

Vegetation coverage

In this study, we calculated vegetative cover based on the NDVI using Eq. (1):

$$f_c = (\mathrm{NDVI}{-}\mathrm{NDVI}_{\min})/(\mathrm{NDVI}_{\max}{-}\mathrm{NDVI}_{\min}) \qquad (1)$$

where NDVI is the Normalized Difference Vegetation Index and $\mathrm{NDVI}_{\max}$ and $\mathrm{NDVI}_{\min}$ are the maximum and minimum values of the NDVI in the study area, respectively. Disturbances from soil type and surface conditions were excluded by setting $\mathrm{NDVI}_{\max}=0.85$ and $\mathrm{NDVI}_{\min}=0.05$ based on image data and a vegetation map (1:100,000) of the study area. When calculations resulted in a pixel having a negative value, of no practical significance, we assigned a value of zero to the pixel.

Hydrological and vegetation data analysis

We calculated the annual mean, maximum, minimum, and annual fluctuations of groundwater depth and the groundwater depths at the end of each year. Each vegetation site corresponded to a groundwater well; therefore, we extracted the NDVI of each site using ArcGIS software and constructed a data series comparing the NDVI and groundwater depth.

Phenological information analysis

Tree, shrub, and herb communities were confirmed based on the dominant species and the importance value of each site (50 m×50 m). The 44 sites comprised 16, 17, and 11 tree, shrub, and herb sites, respectively. Phenological information of the different vegetation types (tree, shrub, and herb) was analyzed using Timesat (V3.1) software based on the NDVI (Eklundha and Jönssonb 2012; Jönsson and Eklundh 2002, 2004).

Results

Groundwater depth and species richness under ecological water conveyance

The water conveyance significantly changed the groundwater depth. The correlation analysis (Fig. 2a) showed that with the increase of the (longitudinal) distance between wells and the water source of the EWCP, the groundwater table experienced a decrease trend. A similar trend in the groundwater table was observed in the transverse distance (the vertical distance between wells and the river course). The runoff loss per kilometer and the volume of water conveyance were another two factors affecting the groundwater depth; however, these two factors all negatively correlated with groundwater depth. Simulation showed that the distance factor and runoff loss per kilometer were two key elements that affected groundwater depth under water conveyances, although many other factors also can influence the groundwater depth including topography and soil texture.

The EWCP influenced groundwater depth, which affected the species richness in the lower reaches. As can be seen from Fig. 3a, the individual number of trees (*P. euphratica*) showed a slight increase in sections C and G while showing a slight decrease in sections E and H. The average individual number of trees in C, E, G, and H transects remained nearly constant under the EWCP. Shrub and herb numbers increased over time, especially the individual number of herbs (Fig. 3b, c). The number of species fluctuated over time in all transects (Fig. 3d), and there were no clear increase or decrease except in section I (where herbs were the dominant plant type). Based on the above data, the EWCP leads to an increase in the individual number of herbs and shrubs but does not affect the individual number of trees or the total species number in the lower reaches.

Phenological response to ecological water conveyance

Dynamics of groundwater depth also changed vegetation phenological characteristics (Table 1) in the lower

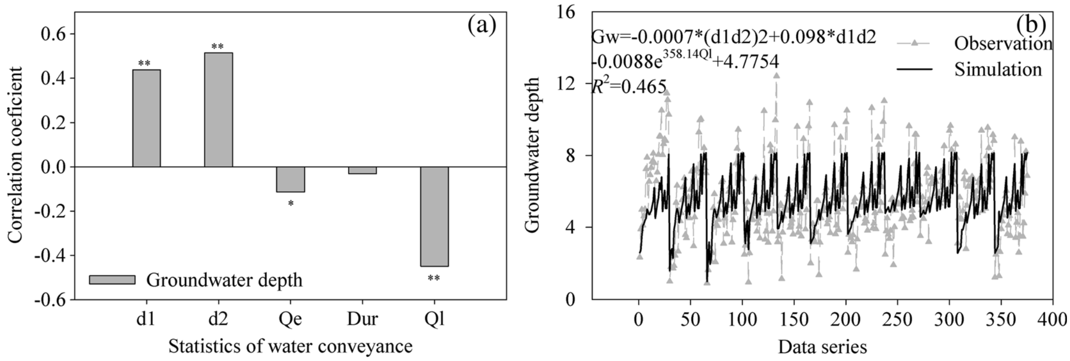

Fig. 2 Response of groundwater depth under the EWCP. **a** Pearson correlation analysis between groundwater depth and the EWCP. **b** The fitting curve of groundwater depth based on the parameters in Fig. 2a. In panel **a**, *d1* is the transverse distance between wells and the river course, *d2* is the longitudinal distance between wells and the reservoir (the water source of the EWCP) along the river, *Qe* is the annual volume of water conveyance, *Dur* is the duration (in days) of water conveyance in a year, and *Ql* is the runoff loss per kilometer along the river on different monitoring transects and is calculated based on the Qe. *Two asterisks* indicates correlation that is significant at 0.01 level, and *one asterisk* indicates correlation that is significant at 0.05 level

reaches of the Tarim River. Water delivery volume determined the start time of the growing season and the appearance time of the NDVI peak value for herbs. The annual average groundwater depth not only determined the start time of the herb growing season but also affected the length of the growing season. Water delivery volume did not significantly affect the phenological characteristics of trees; however, the annual average groundwater depth determined the start and end time of the growing season. In general, a lower groundwater table usually leads to a delay in the start and end time of the growing season and the appearance time of the NDVI peak value. The annual average groundwater depth significantly affected the appearance time of the NDVI peak value of shrub sites. Aside from the EWCP, meteorological factors can also affect phenological

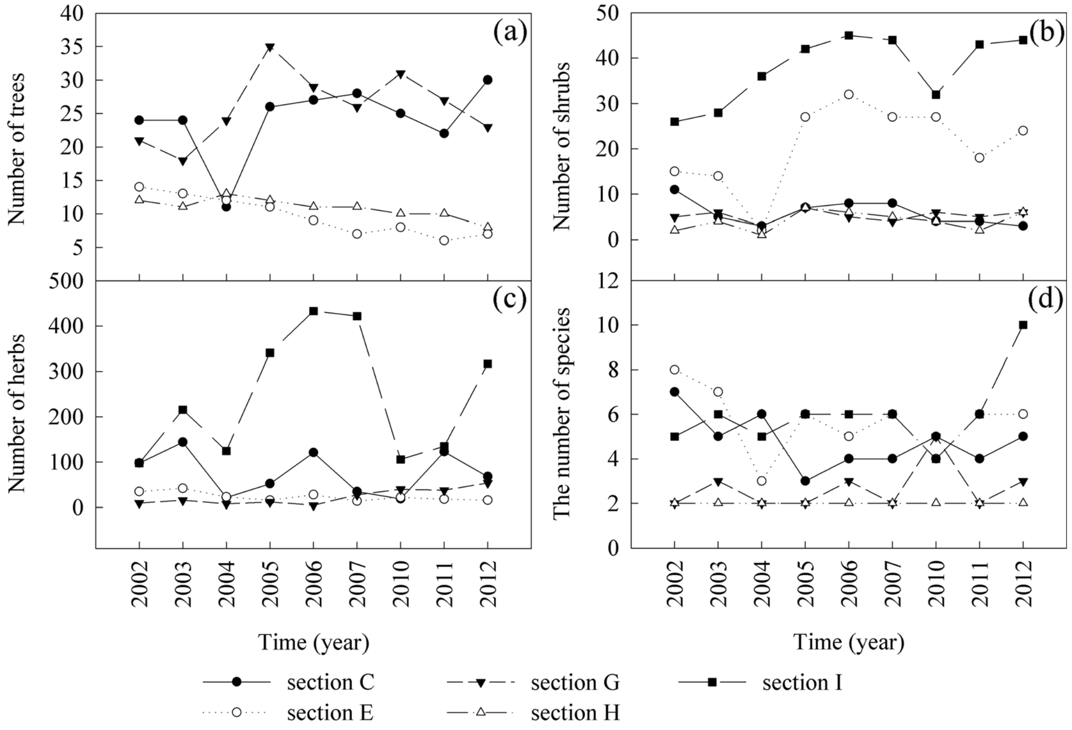

Fig. 3 The individual number of trees (**a**), shrubs (**b**), and herbs (**c**) and the number of species in sections C, E, G, H, and I. All of the statistical data were calculated from the plots that were 100 m away from the river in the above transects

Table 1 Correlation analysis between the phenological index and environmental factors

		Start *t*	End *t*	Season length	Peak *t*
Herbs	Volume of EWC	−0.499*	0.315	0.451	−0.513*
	Groundwater depth	−0.652*	−0.469	−0.612*	0.307
	Annual precipitation	0.218	−0.252	−0.241	−0.296
	Accumulated temperature ≥10 °C	−0.147	0.092	0.133	−0.088
Populus forest	Volume of EWC	−0.221	−0.467	−0.381	−0.276
	Groundwater depth	0.641*	0.655*	0.129	0.570*
	Annual precipitation	0.444	0.468	0.109	−0.191
	Accumulated temperature ≥10 °C	0.075	0.315	0.348	0.357
Shrubs	Volume of EWC	0.224	−0.028	−0.283	−0.491
	Groundwater depth	−0.056	−0.349	−0.393	0.824**
	Annual precipitation	0.610*	0.375	−0.184	0.06
	Accumulated temperature ≥10 °C	−0.377	−0.424	−0.138	−0.406

Start *t* and End *t* is the time (Julian day) of the start and end of the growing season, respectively. Peak *t* is the time (Julian day) the NDVI reaches the peak value during the growing season. Season length is the duration of the growing season (from the start to the end of the season)

characteristics. The results (Table 1) showed that meteorological factors can only affect the phenological characteristic of shrubs, and the annual precipitation is positively correlated with the start time of the NDVI peak value.

Responses of vegetation cover to ecological water conveyance

The vegetative cover in the lower reaches of the Tarim River has been significantly improved since 2000 (Fig. 4). Vegetative cover gradually increased and reached a peak value in 2005, but it decreased from 2006 to 2008 due to the sharp drop of recharged water volume. Since 2008, vegetative cover gradually increased again with the increase of the recharged water volume. Overall, total vegetative cover was 5.76 times greater in 2012 compared to that in 2000. During the same period, areas with <10 and 10–20 % vegetative cover increased 4.72 and 44.11 times, respectively, while area with vegetative cover exceeding 20 % increased to 38.9 from 0 km^2. Areas with <10 % vegetative cover accounted for 80 % of the total vegetation area, so sparse vegetation still dominated the study area. The influence of the EWCP on herbs is most significant, followed by the trees (*P. euphratica*) and shrubs. The multiyear average coverage of herbs, trees, and shrubs was 21.25, 6.94, and 5.41 %, respectively, and the difference between maximum and minimum coverage of herbs, trees, and shrubs was 23.23, 4.96, and 4.45 %, respectively.

Figure 4 presents the response of vegetation to water delivery, which showed an obvious time lag. During the study period, the area of vegetative cover and water delivery volume were not consistent. For example, vegetative cover was at a minimum (during 2010) while volume of water delivery was at a minimum in 2007 and 2009.

Relation between groundwater and the NDVI

This study extracted the NDVI for 44 vegetation plots and analyzed the relationship between the NDVI and groundwater depth. The statistical indices of groundwater depth included annual maximum (Dmax), minimum (Dmin), and mean (Dave) groundwater depth; fluctuation of groundwater depth (Dflu); and groundwater depth in the last year-end (Dlast). Figure 5 shows that the NDVI of herbs and trees was correlated to all of the statistical indicators of groundwater depth. The NDVI of shrubs was also correlated to these indicators except for the annual fluctuation of groundwater depth. Correlation analysis showed that herbs were most strongly correlated to groundwater depth in the last year-end (R=0.81), and the response of the NDVI to groundwater depth in the last year-end exhibited a 1-

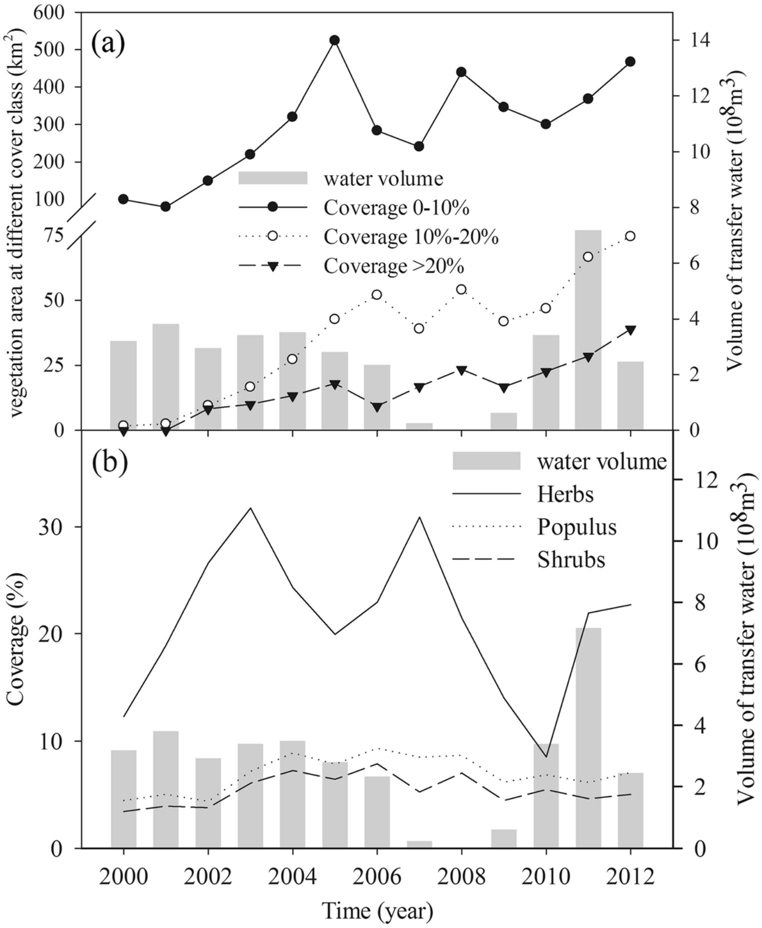

Fig. 4 Trend in vegetation area with different coverage classes (**a**) and the coverage of different vegetation types (**b**) under the EWCP from 2000 to 2012. Vegetative cover was calculated from the NDVI at the end of July (27 July) of each year

year time lag (Fig. 5a). Trees and shrubs were primarily related by the annual average groundwater depth (R^2=0.79 and 0.66, respectively), and the response of the NDVI also exhibited a time lag of 1 year (Fig. 5b, c). The correlation analysis also showed that groundwater depth most strongly correlated to the NDVI of herbs, followed by trees and shrubs.

The NDVI and groundwater depth exhibited an exponential relationship (Fig. 5d–f). Usually, herbs were distributed in the area where groundwater depth ranged from 0 to 6 m, and the corresponding NDVI was 0.17 to 0.41. Trees were mainly distributed in the area where groundwater depth ranged from 2 to 10 m, and the corresponding NDVI was 0.07 to 0.15. Shrubs were mainly distributed in the area where groundwater depth ranged from 3 to 10 m, and the corresponding NDVI was 0.07 to 0.11. The NDVI of herbs was the highest, followed by those of trees and shrubs. Although the EWCP increased the NDVI, the region still had sparse vegetative cover and the NDVI remained low.

Discussion

Effects of ecological water conveyance

One of the most significant results of the EWCP was the rise of the groundwater table. However, the rise of the groundwater table exhibited obvious spatial variation. Our study indicates that the location of wells was closely related to groundwater depth (Fig. 2). In addition, the groundwater table was shallow in the upper segments of the river and near the water course compared to the lower segments and farther away from the water course (Huang and Pang 2010; Hou et al. 2007). Besides the well locations, the diversion water volume also influenced groundwater depth (Xu et al. 2013). However, the correlation coefficient between groundwater depth and volume of water diversion is very small. This may be due to an increase in river seepage after water diversion and stability of river seepage as water diversion volume continues to increase (Wan 2008). Therefore, larger

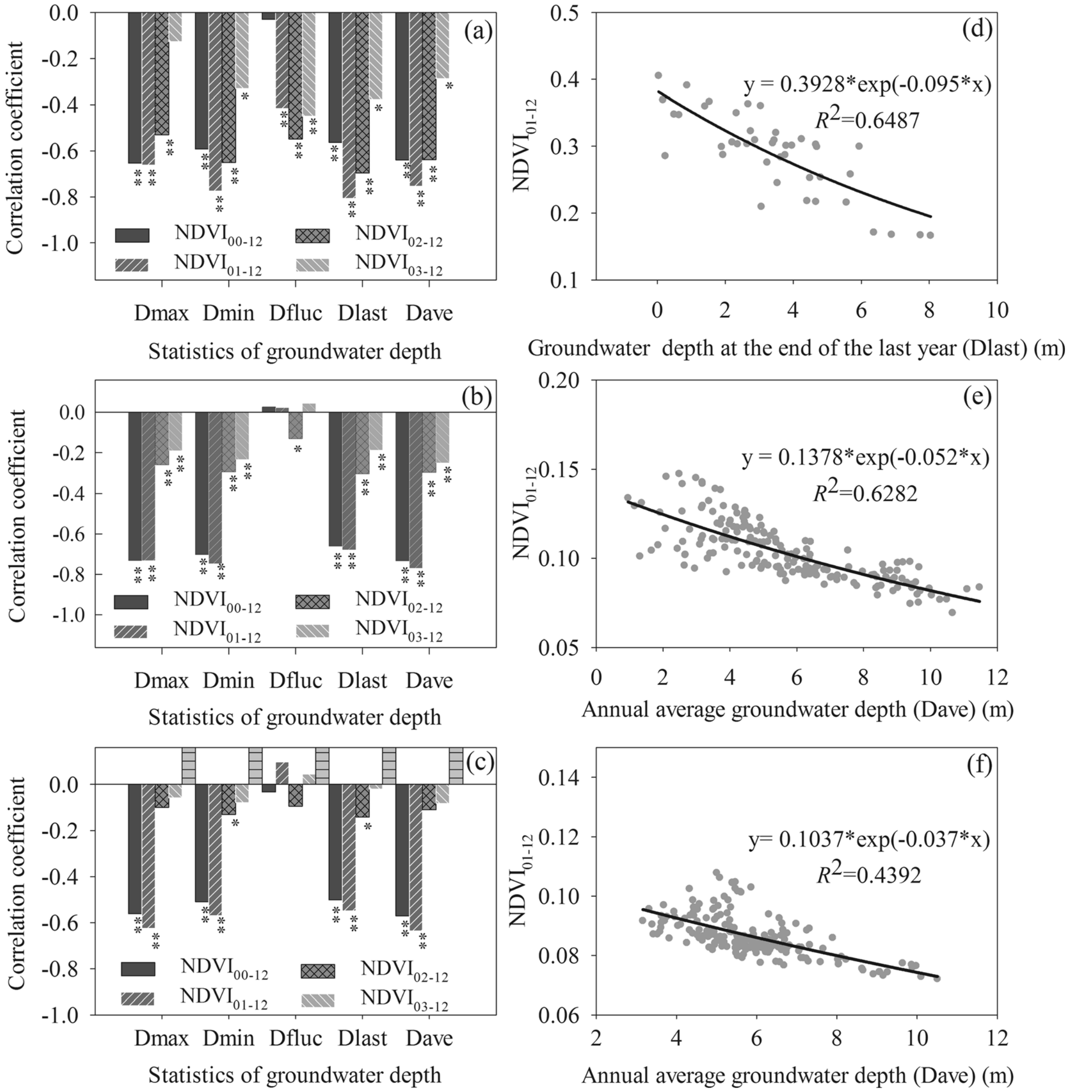

Fig. 5 Relationship between the NDVI of desert riparian vegetation and groundwater depth. The *left panel* shows the correlation analyses between the NDVI of herb (**a**), tree (**b**), and shrub (**c**) communities and the statistical index of groundwater depth. The *right panel* shows the relationships between herb (**d**), tree (**e**), and shrub (**f**) communities and the statistical index of groundwater depth. $NDVI_{00-12}$, $NDVI_{01-12}$, $NDVI_{02-12}$, and $NDVI_{03-12}$ respectively represent the NDVI without a time lag and with 1-, 2-, and 3-year time lags corresponding to groundwater index from 2000 to 2012

amount of water conveyance does not, necessarily, result in higher groundwater recharge rates. Figure 2 indicates that the runoff loss per kilometer more strongly correlated with groundwater depth ($R=-0.45$, $P=0.00$) than water diversion volume($R=-0.12$, $P=0.02$).

Changes in groundwater depth also lead to a corresponding change of groundwater quality and soil moisture. Research showed that groundwater salinity will decrease when the groundwater table rises; however, that may not be observed at great distances from the river course (Li et al. 2010). Soil moisture has an explicit relationship with groundwater depth and can be represented by an exponential curve (Fig. 6). Soil moisture was not obviously affected by groundwater depth when depth was >4 m, but when groundwater depth was <4 m, it clearly affected the soil moisture, especially in the lower and middle soil layers (100–200- and 200–300-cm soil layers). This implies that the EWCP can improve the soil water condition, which is beneficial for restoring degraded herbs and subshrubs (i.e., shrubs with shallower root systems). However, the soil water conditions only have limited effect on big trees (e.g.,

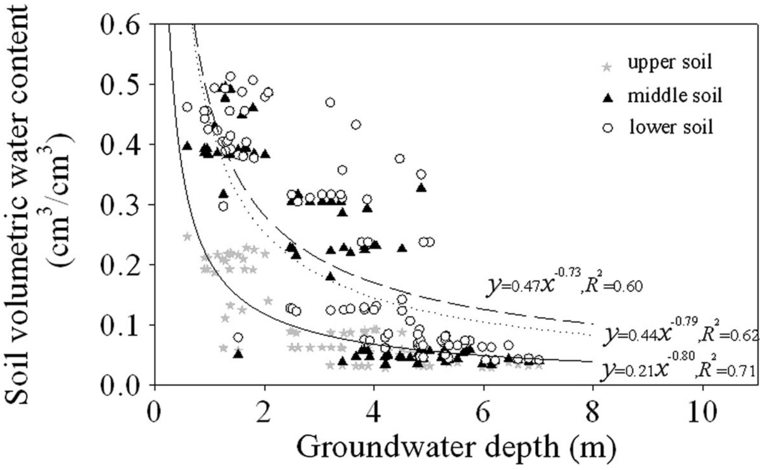

Fig. 6 Fitting curve between soil volumetric water content and groundwater depth. Data were collected from 2002 to 2006 from monitoring wells that were 50 and 150 m away from the river course in transects C and H, respectively

Populus) and shrubs (e.g., *Tamarix*) because their growth highly depends on the groundwater (Zhu et al. 2009; Zhao et al. 2008).

Degraded natural vegetation was restored because of the rise of the groundwater table. Coverage, biomass, and species diversity of natural vegetation also increased with the rise in groundwater level (Ye et al. 2009, 2010; Hao et al. 2009). Our results showed that the high-cover vegetation (coverage >10 %) mainly was herbs while the sparse vegetation (coverage <10 %) mainly was trees and shrubs. Areas with vegetative cover of <10 and 10–20 % increased by 4.7 and 44.1 times, respectively, since 2000. Areas with vegetative cover of >20 % increased to 39 from 0 km^2 during the same period. Individual numbers of herbs and shrubs also increased after the EWCP, which is also related to the original vegetation distribution pattern and the water environmental conditions. In general, there was only sparse *P. euphratica* where groundwater depth was >8 m. Dense vegetation was found in regions where groundwater depth was <8 m, but the dense understory vegetation (herbs) only appeared in regions where groundwater depth was <3 m (Thevis 2009). Herbs were usually distributed near the river course and in the upper segments of the water conveyance river channel where water conditions were favorable and overflow also occurs. The trees and shrubs (e.g., *Tamarix*) were often distributed far from the rivers and in the middle and lower segments of the water conveyance channel where the groundwater table is lower and overflow is limited. We conclude that the low vegetative cover (trees and shrubs) is due to lack of reproduction and regeneration ability despite water being delivered 12 times. This study also showed that the EWCP and groundwater depth can change the phenological characteristics of natural vegetation. Based on the results, it can be deduced that herbs and trees were more easily influenced by the EWCP, and shrubs were not very sensitive to the EWCP. Considering the changes of phenological characteristics, coverage, and richness under the EWCP, we can further infer that herbs were most restricted by water condition, and their drought resistance was minimal; shrubs were not affected by water condition, and their drought resistance was relatively high; and drought resistance of *P. euphratica* was moderate, but more similar to the shrubs.

The limitation of ecological water conveyance

The EWCP has positive impacts on ecosystems, but according to our research, the effects are not nearly as significant as previously reported (Chen et al. 2013; Liu and Chen 2007). Areas with <10 % vegetative cover remained predominant in the study area and areas with >20 % vegetative cover only accounted for 6.7 % of the study area, although water was delivered 12 times and the annual maximum volume of water delivery reached 7.16×10^8 m^3. Hence, the EWCP did not significantly change the basic pattern of vegetative cover in the lower reaches of the Tarim River. Correlation analyses of the NDVI and groundwater depth (Fig. 5) indicate that the highest NDVI values of herbs, trees, and shrubs were approximately 0.4, 0.15, and 0.11, respectively. This result implies that the NDVI or natural vegetative cover seemed to have reached its limit, although 35×10^8 m^3 of water was transported into the study area. This may be due to (1) maximum lateral influence of the EWCP based on the original river course being <1,000 m on both sides of the river (Xu et al. 2003; Hou et al. 2007). Hence, the influence of linear water delivery along the original river course was limited and improvements in vegetative cover were also limited. (2) Although the EWCP raised the groundwater level and supplied enough water to plants, such artificial water delivery changed the natural flow process of the river, particularly when the river no longer overflowed during floods. This condition disrupted the basis and rhythm of seed propagation and made self-renewal of natural vegetation difficult. From this point of view, the EWCP can only preserve the survival of existing plants but cannot promote effective regeneration of plant populations, especially trees. Studies have shown that *P. euphratica* can reproduce by sprouting (Petzold et al. 2013), but sprouting has a lower success rate because of dry upper soil that results from scarce rainfall and the cessation of river overflow. Studies have demonstrated that lateral roots of *P. euphratica*, which have the potential to sprout, are distributed in 0–100-cm soil layers within 50 m from the river after water delivery (Zhao et al. 2009). Hence, the primary limitation of the EWCP is that it can only preserve the survival of vegetation but cannot promote the reproduction of natural vegetation without artificial interventions.

It is well known that water scarcity is unavoidable in the Tarim River Basin (Thevs 2011). The water of the EWCP mainly comes from the water saving of irrigation and excess water during high-flow years. The fundamental purpose of the EWCP is to restore the degraded vegetation and to save the Green Corridor, so we should maximize the ecological effects of limited water resources. However, managers of the EWCP tend to prioritize transfers of water into the terminal lake—Taitema Lake. During the last 14 years, the surface area of the terminal lake changed from 6 to 300 km^2. Evaporation is very high in extreme arid regions, such as in Bosten Lake (located in the middle reaches of the Tarim River) where the annual water surface evaporation is about 10×10^8 m^3 on a 1,646-km^2 water area. Based on this quantitative relationship, we estimated that the daily average water surface evaporation of Taitema Lake is about $1.0–50.0\times10^4$ m^3 (on a 6–300-km^2 water area). Such loss of water is not recommended in a water scarce region, but instead, higher groundwater recharge rates may allow us to store some of the excess water below ground. With increased groundwater recharge, the groundwater table may rise and improve soil moisture conditions by increasing seepage into the soil zone. This approach for managing excess water in a water scarce region may help to restore degraded natural vegetation and save the Green Corridor.

Improving the ecological effects of water conveyance

It is critical to maximize ecological benefits of the EWCP. According to our results and those of previous studies, we are aware that a higher NDVI value appears on both sides of the river. Hence, the most direct measure to maximize ecological benefits of the EWCP is to abandon water conveyance along a single river course. By contrast, water should be conveyed along multiple waterways, which will increase seepage. Aside from increasing vegetative cover, regenerating plant populations is also important. For example, *P. euphratica* can reproduce by sprouting; thus, the success rate of sprouting should be improved by artificial measures, such as promoting lateral root suckering by excavating a 100-cm-deep narrow ditch and cutting off lateral roots in the woodland. The growth of seedling sprouts should be promoted as soon as possible through irrigation measures. Another effective measure is constructing a water gate on the water transfer canal and conducting artificial river overflow to activate the soil seed bank. We can also improve riparian vegetation seed germination and growth opportunities through seed flotation during river overflow.

Conclusions

The EWCP significantly raised the groundwater table, which may improve soil moisture conditions and be beneficial to vegetation growth.

After 12 years of water conveyance management with the EWCP, vegetative cover and species richness have increased rapidly. The EWCP also resulted in changes in phenological characteristic of natural vegetation, especially for herbs. However, locations with sparse vegetative cover are still present in the study area. Artificial water conveyance may not promote the reproduction and regeneration of trees (e.g., *P. euphratica*), which is the ultimate goal of the EWCP. Therefore, the current mode of water conveyance must be modified to increase the ecological benefits of the EWCP.

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