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Monitoring the hydrological and ecological response to water diversion in the lower reaches of the Tarim River, Northwest China

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ABSTRACT

During the past twelve years, the assessment of hydro-ecological response of degraded floodplain ecosystems to the emergent water diversion practices in the lower reaches of the Tarim River has become a key research topic. This paper presents the current ecological conditions and analyzes what the water diversion has achieved. The limitations of this floodplain restoration program are discussed, based on the review of literature and long term field work data (groundwater data, eco-morphological parameters of riparian forests, Quick Bird remote sensing data) collected from three transects (Yingsu, Karday, Arghan). The results show that annual average groundwater depth responded to a certain degree after water diversion since May 2000. After a second water diversion, groundwater depth within 300 m distance from the river channel recovered significantly from 9.4 m in 1997 to 4.28 m in 2001 at Yingsu. With the exception of relatively favorable groundwater depth for floodplain forests within 150 m distance from the riverbed, groundwater depth at larger distances remained far below 5 m, and most forest plants excluding *Tamarix* sp. will suffer from water scarcity. The average crown loss (CL) and crown diameter (CD) of *Populus euphratica* trees in different distances from the riverbed have shown various degrees of responses. The effects of recovery were notable within 200 m distance to the riverbed. Distribution patterns of young seedlings, new shoots and root suckers of *P. euphratica* generated by water diversion also demonstrated that most were distributed close to the riverbed and reduced sharply with increasing distance. Twelve water diverting actions in the lower reaches of the Tarim River have made significant achievements in forest recovery near the riverbed, but had limited positive effects on more distant floodplain sites.

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1. Introduction

Rivers all over the world support natural environments, provide habitat for flora and fauna, contribute to preservation of biodiversity and offer space for human activities (Hughes and Rood, 2003; Rood et al., 2003, 2005; Kasahara et al., 2009). In arid and semi-arid regions, socio-economic activities are highly dependent on water resources provided by rivers (Feng and Endo, 2001; Cui and Shao, 2005; Jiang et al., 2005; Shafroth et al., 2010), and these watercourses play a significant role in sustaining normal cycles of socio-economic systems as well as fragile floodplain ecosystems. Over the past decades, however, floodplain ecosystems have often been disconnected from their river as a result of population increase, economic growth, large-scale agricultural development, and mismanagement of river oases. Hence, natural vegetation along both sides of the river has been severely degraded (Woolsey et al., 2007; Wang et al., 2008; Chen et al., 2011; Thevs, 2011; Tuck-Fatt and Doell, 2012).

The Tarim River is one of the largest inland rivers in the world, along with the Volga, Syr Darya, Amu Darya, and the Ural (Hai et al., 2006). It is mainly supplied by glacial and snow melt-water, and precipitation from Tianshan Mountains. Over the past 50 years, due to climate change and rapid socio-economic development, many tributaries had been disconnected from the Tarim River. At present, only the Aksu River, Yarkand River and Hotan River remain connected to the Tarim. The Aksu River is the primary water source, as it conveys 73% of total runoff of its main stream of the Tarim (Halik et al., 2006; Chen et al., 2011).

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Floodplain forests distributed along the river are extremely important natural barriers supporting the ecological stability of these areas. *Populus euphratica* Oliv., found in the extremely dry areas of Central Asia, is the dominant tree. More than 90% of existing floodplain forests along the Tarim is this species (Song et al., 2000; Huang, 2002). These forests, as a safeguard for the cycle of all economic activities, provide a wide range of ecosystem services (ESS) and functions (ESF) such as protecting biodiversity, reducing the impact of sandstorms, moderating desertification, regulating oasis climate, fertilizing forest soils and maintaining ecosystem balance (Huang et al., 2010). Therefore, the protection of the floodplain forests is of crucial importance for the long term social and economic development of the Tarim River Basin (Song et al., 2000; Ye, 2005; Wu and Tang, 2009).

Due to these unique natural conditions, all human activities and natural floodplain ecosystems directly or indirectly depend on the Tarim River as their key water supplier. Irrigation for crop production (mainly cotton) is the largest water consumer in the entire basin. Climate conditions in this region are likely to be more conducive to increased river runoff during the recent years, but simultaneously agricultural areas with high water demand have been increasing rapidly (Song et al., 2000; Xu et al., 2008; Sun et al., 2011; Thevs, 2011). Consequently, water scarcity in the downstream of the Tarim River has been exacerbated due to growing water demand for irrigation along the upper and middle reaches. Thus, the natural flood regime at the main stream has been completely altered, resulting in uneven distribution of river runoff, desiccation of rivers and lakes, groundwater level decline, vegetation deterioration and ecosystem degradation (Xu et al., 2008; Chen et al., 2010; Halik et al., 2011). The eco-hydrological processes in the lower reaches have been affected to a high degree as a consequence of the human changes in spatial and temporal patterns of natural water resources at the upper and middle reaches. The last 320 km of the main river channel and lakes have dried up, groundwater levels declined, riparian vegetation decayed, and desertification increased (Halik et al., 2009; Zhuang et al., 2010; Chen et al., 2011; Zhang et al., 2012).

Since 2000, in order to restore and reconstruct these highly degraded floodplain ecosystem, Chinese government invested 10.7 billion RMB (approx. 1.8 billion US dollars) to implement the Ecological Water Diversion Program (EWDP) for the lower reaches of the Tarim River. The implementation of this project has produced positive effects on the eco-environment. It was accompanied by extensive research conducted from different perspectives (Chen et al., 2004, 2006, 2008, 2010, 2011; Xu et al., 2007, 2008, 2009; Zhou et al., 2008a,b; Halik et al., 2009, 2011; Duan et al., 2010; Liu et al., 2012) in order to evaluate the effectiveness of this project. These researches mainly focused on the restoration of hydrological process integrity (Wu and Tang, 2009; Chen et al., 2010), groundwater level recharge (Hou et al., 2007a,b; Ye et al., 2009a,b,c) and eco-physiological response of floodplain forests (Chen et al., 2004, 2006, 2008; Xu et al., 2008, 2009; Halik et al., 2009, 2011). Theses researches also revealed controversial issues regarding ecological water diversion practices. For example, how to achieve maximum positive recovery of degraded floodplain ecosystem by using the limited water resources rationally?

The aim of this paper is to address current ecological problems along the lower Tarim River related to water diversion, to analyze the spatial and temporal dynamics of groundwater depth and floodplain forests recovery associated with water diversion and evaluate the possibilities and limitations of twelve water transfers. The results provide a scientific basis for the potential recovery of the "Green Corridor" and for the optimization of future water diversion schemes.

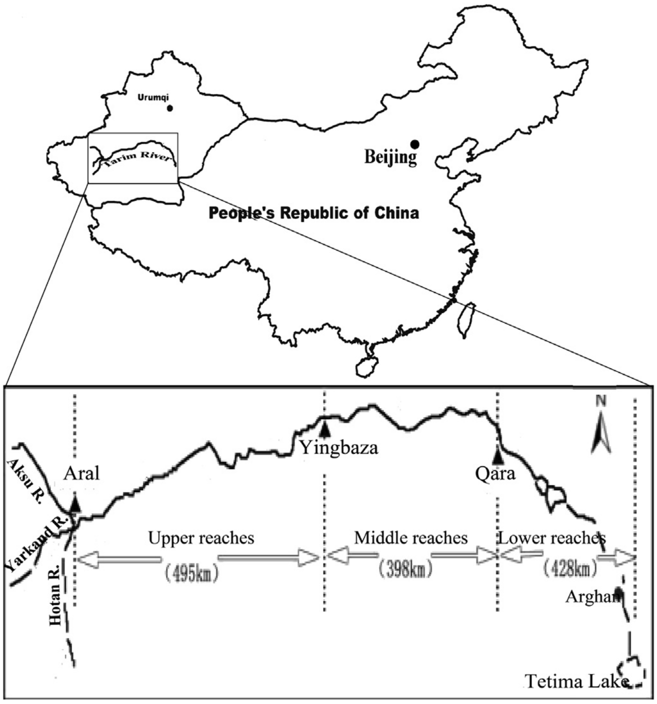

Fig. 1. Location of the Tarim River in Northwest China and its three main reaches (R. = River).

2. Material and methods

2.1. Study area description

The Tarim River is located in Xinjiang Uyghur Autonomous Region (XUAR), northwest China. The river basin (39°24′08″-41°03′40″N; 86°37′23″-88°30′00″E) is known for its rich natural resources and vulnerable ecosystems. This area is characterized by an extremely arid continental climate, with an annual precipitation of about 20–50 mm; and a potential annual evaporation of about 2500–3000 mm (Song et al., 2000; Chen et al., 2004; Halik et al., 2006; Xu et al., 2007). The main stream of the river, measured from the confluence of the Aksu, Yarkand, and Hotan rivers to terminal Lake Tetima (syn. *Taitema Hu*) is about 1321 km (Fig. 1) (Chen et al., 2010; Lam et al., 2011).

The Tarim (Figs. 1 and 2) is fringed with floodplain forest of Euphrates poplar. Along the lower reaches these forests form a so-called "Green Corridor" between the two deserts of Taklimakan and Kuruk Tag (Fig. 2). As a natural barrier protecting communication lines and road traffic, it is of critical importance to prevent the two deserts from merging (Chen et al., 2011).

The structure of the riparian communities here is relatively simple. Main trees are *P. euphratica* Oliv., *Elaeagnus angustifolia* L., main shrubs are *Tamarix ramosissima* Ledeb., *Tamarix hispida* Willd., *Tamarix elongata* Ledeb., *Lycium ruthenicum* Murr., *Halimodendron halodendron* (Pall.) Voss., *Halostachys caspica* (M.B.) C.A. Mey., *Poacynum hendersonii* (Hook. F.) Woodson., *Alhagi sparsifolia* (B. Keller et Shap.) Shap., *Glycyrrhiza inflate* Bat., *Karelinia caspica* (Pall.) Less., *Inula salsoloides* (Turcz.) Ostrnf., *Hexinia polydichotoma* (Ostent.) H.L. Yang (Zhang et al., 2005; Halik et al., 2009; Thevs, 2011). This natural vegetation had been heavily degraded and natural river flows had been extremely reduced due to the massive water extraction for irrigated agriculture along the river course since 1950, which resulted in the desiccation of the lower reaches and the terminal lakes, salinization of soils and waters, degradation

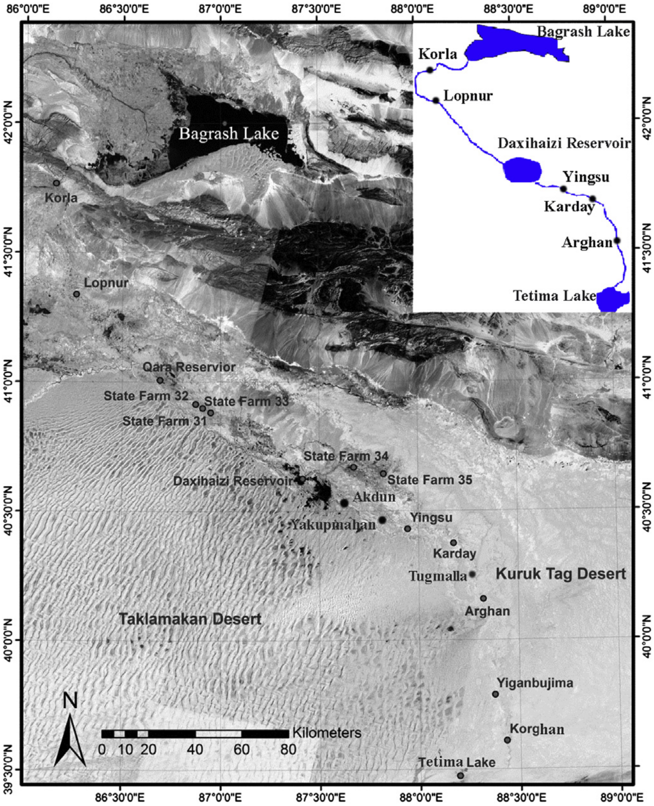

Fig. 2. The lower reaches of the Tarim River with water diversion route from the Bagrash Lake to the Daxihaizi Reservoir and to the Tetima Lake (Map based on Landsat TM/ETM + data 2011).

of floodplain vegetation, and intensification of wind erosion. To a large extent, these effects can be attributed to the fast change of land use pattern along the entire river basin, mismanagement of limited water resources, and changes of the natural river flow pattern (Feng and Endo, 2001; Hughes and Rood, 2003; Rood et al., 2003, 2005; Cui and Shao, 2005; Tuck-Fatt and Doell, 2012).

2.2. Data acquisition and processing

Hydrological data, terrestrial vegetation data and Quick Bird high resolution satellite image are used in this paper. Data for volume and time of 12 water diversion events and groundwater dynamics after initiation of the project have been supplied by Tarim River Basin Administration Bureau (TRAB). They are collected at long term groundwater monitoring wells at 9 transects, at 90° to the main water flowing channel between Daxihaizi Reservoir and Tetima Lake (Fig. 2). TRAB has established these 9 monitoring transects at Akdun (A), Yakupmahan (B), Yingsu (C), Abdal (D), Karday (E), Tugmalla (F), Arghan (G), Yiganbujima (H) and Korghan (I). Specifically, groundwater depth data used for Yingsu, Karday and Arghan before the start of the water diversion were taken from Song et al. (2000).

This paper considers data from the three transects of Yingsu/C (60 km to the Daxihaizi Reservoir), Karday/E (110 km) and Arghan/G (190 km). For each of these three transects, groundwater data from different wells at 50 m, 150 m, 300 m, 500 m, 750 m, 1050 m distance to the main river channel were provided. Due to unavailability of the latest groundwater data, only those from 2003 to 2009 were used for this paper. Groundwater variation analysis before and after water diversion events was done using Origin pro 8.5 software. Vegetation data were collected from a total area of 100 hm^2 long term ecological monitoring plots (100 square plots with 100 × 100 m size) established in Arghan transect, where coverage of natural vegetation is relatively high because of its location at the confluence of the two major water ways of Qiwenkol River and old Tarim River (Fig. 2). A total of 4500 *Populus euphratica* trees within these plots are monitored individually by extensive terrestrial investigations in combination with high resolution (60 cm) Quick Bird satellite image. Before the establishment of this monitoring base, mean or low resolution satellite images (TM/ETM+, SPOT and CBERS) had been used for monitoring the dynamics of riparian vegetation.

Major parameters such as vegetation coverage, canopy density, tree height (TH), diameter at breast height (DBH), crown diameter (CD), crown loss (CL), number of new shoots, root suckers, geographical coordinates, and digital photos of each tree were observed during the vegetation season within the permanent observation plots. Average CD and CL data were taken from Halik et al. (2006, 2009, 2011). Number of young seedlings, new shoots and root suckers of *P. euphratica* trees at different distances from the river channel were collected during the field work from May to October annually from 2004 to 2010 along the Arghan transect. Microsoft Excel 2010 software was used for analyzing the distribution of these trees. Analysis of spatial distribution pattern for young seedlings in different DBH was done by using ArcGIS 10.0 software based on a GIS database which was established by integrating Quick Bird data with terrestrial field survey data.

2.3. Overview of the water diversion project

Water diversion to the lower reaches is one of several large scale ecological engineering projects in China's Northwest (e.g., Integrated Management of the Tarim River Basin and the Heihe River Basin). The main object of this project is to recharge groundwater tables up to certain levels where natural vegetation can revitalize, and severely damaged floodplain ecosystems under long term water stress can be rehabilitated (Xu et al., 2008; Chen et al., 2011). Water is mainly diverted from Bagrash Lake to Daxihazi reservoir, and continually delivered into Tetima Lake. The entire water flowing course is 320 km long (Fig. 2). Until November 2011, water was diverted twelve times in irregular frequencies throughout 1289 days in eleven years with a total volume of 27.98 × 10^8 m^3 (Table 1). On seven occasions, water diversions reached Tetima Lake. Thus, almost 30 years of its desiccation since 1973 finally came to an end (Halik et al., 2006).

Table 1
Twelve events of ecological water diversion to the lower reaches of the Tarim River (2000–2011)

Diversion	Starting time (day/month/year)	Ending time (day/month/year)	Duration (day)	Water volume ($\times 10^8$ m^3)	Reached transect
1st	14/05/2000	13/07/2000	61	0.99	Karday
2nd	03/11/2000	14/02/2001	104	2.27	Arghan
3rd (1st period)	01/04/2001	06/07/2001	97	1.84	Arghan
3rd (2nd period)	12/09/2001	17/11/2001	67	1.98	Tetima
4th	20/07/2002	10/11/2002	114	2.93	Tetima
5th (1st period)	03/03/2003	11/07/2003	131	2.50	Tetima
5th (2nd period)	12/09/2003	07/11/2003	56	0.90	Tetima
6th (1st period)	22/04/2004	25/06/2004	64	1.02	Tetima
6th (2nd period)	01/08/2004	15/09/2004	46	2.30	Tetima
7th (1st period)	18/04/2005	07/06/2005	32	0.52	Arghan
7th (2nd period)	30/08/2005	02/11/2005	65	2.30	Tetima
8th	25/09/2006	30/11/2006	66	2.33	Korghan
9th	15/10/2007	21/11/2007	38	0.50	Karday
10th	12/05/2009	20/06/2009	39	0.60	Karday
11th	25/06/2010	11/11/2011	139	3.64	Tetima
12th (1st period)	07/01/2011	25/01/2011	19	NA	Tetima
12th (2nd period)	25/06/2011	23/11/2011	151	1.36	Tetima

Source: Tarim River Basin Administration Bureau (TRAB).

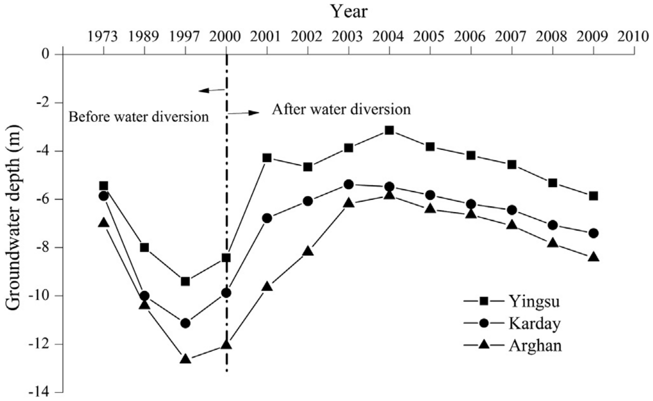

Fig. 3. Groundwater depth before and after water diversion (annual average groundwater depth within 300 m distance to river channel). Source: 1973–1997 data (Song et al., 2000), after water diversion on May 2000 (TRAB).

3. Groundwater variation and the response of floodplain forests

3.1. Groundwater variation before and after water diversion

Groundwater plays an important role in water supply for natural vegetation and the sustainable development of arid regions. The lower reaches of the Tarim are extremely susceptible to water conflicts. Groundwater is not only the main source of floodplain agriculture, but also maintains the regeneration of natural vegetation (Cui and Shao, 2005; Chen et al., 2010; Cao et al., 2012). The water course downstream of Daxihaizi Reservoir was desiccated before the implementation of the water diversion project in 2000, and correspondingly, the groundwater of this region had not received any recharge from river surface water for nearly 30 years. As a result, groundwater table dropped and natural vegetation degraded correspondingly. Groundwater water depth at Yingsu, Karday and Arghan declined to a minimum depth of 9–12 m, thus inhibiting any normal development of floodplain forests. Since the water diversion in 2000, the groundwater depth near to the riverbed started to rise again (Fig. 3). After a second water diversion in 2001, groundwater depth has recovered significantly from 9.4 m in 1997 to 4.28 m in 2001 at Yingsu. Karday and Arghan also have shown remarkable responses to water diversion practices (Fig. 3).

3.2. Effects of water diversion on floodplain forests

With the continuation of water diversion, the floodplain ecosystem has positively responded to different degrees and recovered significantly (Chen et al., 2006, 2010; Xu et al., 2007; Halik et al., 2009). Extensive research has been conducted from different perspectives on the effects of water diversion. It confirms the great potential to restore highly degraded floodplain forests and to sustain the "Green Corridor". The existing research has mainly focused on the response of groundwater and eco-physiological parameters of floodplain forests to the man-made water flow. Ye et al. (2009a,b,c) have analyzed groundwater fluctuations induced by ecological water diversions in the lower reaches. They studied the relation between the transmission loss per unit river length, the change in groundwater depth and the distance from the main river course by using data from 40 monitoring wells across the nine transects mentioned above. They concluded that the volume for recharging the groundwater was 7.82×10^8 m^3 after eight water diversions and the area affected by water diversion had certain differences in the scope of each transect. Hou et al. (2007a,b) have studied the response of groundwater to water diversion and interpreted water table dynamics. They have concluded that this water diversion had great impact on raising water table levels. However, the highest impacts of the restoration strategy were restricted to the area within a certain distance from the riverbed. Chen et al. (2004, 2006), Xu et al. (2007, 2009) and Wang et al. (2007), in their extensive studies on eco-physiological response of floodplain forests to the change of groundwater level, studied the relationship between groundwater table, salt concentration in groundwater and the contents of proline, soluble sugars, plant endogenous hormone (abscisic acid, ABA and cytokinin, CTK), and anatomy in *P. euphratica* leaves before and after water diversion. They found that following water diversion, a rising groundwater table reduced physiological stress of *P. euphratica*. They also examined the relationship between plant species diversity and groundwater level and concluded that species diversity indices (Shannon–Weiner Index and Simpson Index) were closely related to groundwater level. Thus, the response of groundwater and floodplain forests to water diversion is conspicuous. However, close to the desert margin, groundwater quantity and quality showed almost no sign of response, which means that forest stands close to desert margins are still suffering water stress and have a tendency to further deterioration.

The results of these research projects mainly applying methods of physiology concluded that the given diversion water was not sufficient in volume to assure a full restoration of the floodplain

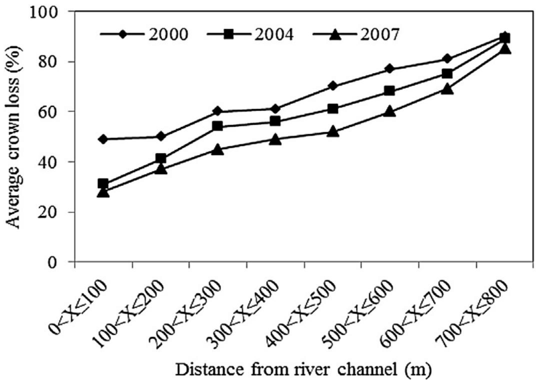

Fig. 4. Dynamics of average crown loss (CL) of *P. euphratica* at Arghan.

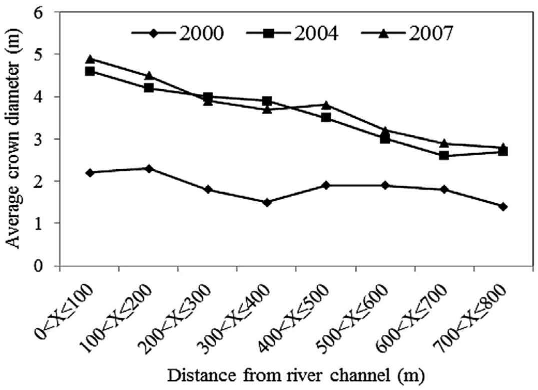

Fig. 5. Dynamics of average crown diameter (CD) of *P. euphratica* at Arghan.

forest. Forest morphological research, as developed in connection with the evaluation of acid rain and similar environmental impacts on forest ecosystems in Europe, may provide further insight into the reproductive capacity of individual trees as well as their population dynamics. The annual forest condition survey (Waldzustandserhebung) was developed in Germany since the 1980s in order to evaluate the environmental impact on different forest stands on local, regional and national levels. This method basically consists of the combined use of remote sensing information and on-site data collection.

Focus considered other important ecological indicators of *P. euphratica*, such as the changes of crown diameter (CD) and crown loss (CL). They can reflect the overall response of floodplain forests to water diversion (Halik et al., 2009, 2011). Generally, higher frequencies of water diversion and water volume have positive effects on forest growth. Fig. 4 and Fig. 5 show the average CL had decreased significantly after water diversion. Average CD within the range of 100 m near the river had increased from 2.25 m (in 2000) to 4.50 m (in 2004) and 4.99 m (in 2007). At 800 m distance from the river, the average CD still responded (from 1.6 m in 2000 increased to 3 m in 2007). Thus, the CD of *P. euphratica* has increased significantly during the restoration process. Comparative analyses of CD changes in relation to water diversion indicate that significant changes of CD mainly took place close to the river, whereas with increasing distance, the variation of CD declined correspondingly. This result fully illustrated the response of floodplain forests to water diversions in the transverse direction from the main river course.

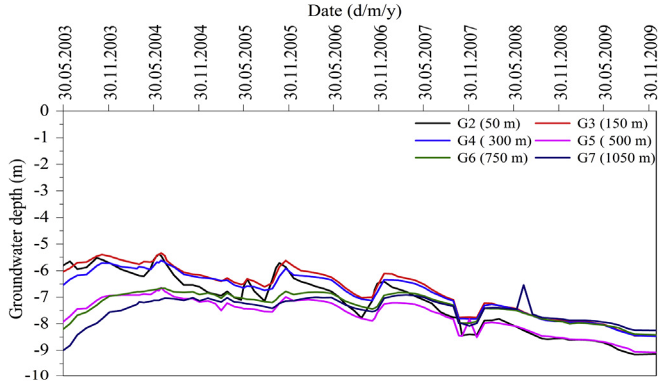

Fig. 7. Variation of groundwater depth at different distance to river channel at Karday (Source: TRAB).

4. Limitations of water diversion practices

4.1. Unfavorable groundwater depths for normal growth of floodplain forests

Since 2000, when the first water diversion for floodplain restoration had been implemented, groundwater levels have responded with different degrees of recovery (Hou et al., 2007b). Groundwater variation analyses from 2003 to 2009 at the transect Yingsu, Karday and Arghan showed that there were significant differences between impact intensity of water diversion on groundwater recharge. Groundwater variation for Yingsu showed that average groundwater depth at the monitoring well at 50 m from the river reached 0.58 m during the fifth water diversion (Fig. 6). Groundwater changes at different distances from the river showed various responses. Groundwater depth at monitoring well 150 m from the river has risen 3.3 m after six (first period; Table 1) water diversions had been completed. During the sixth (water volume: 3.32×10^8 m^3; flooding time: 110 days) water diversion, groundwater depth at all wells at 50 m, 150 m, 300 m, 500 m, 750 m and 1050 m distance from the river-flow channel had risen to its highest level. This might be a result of extended releasing duration and water volume. At Karday transect (Fig. 7), although the groundwater table also experienced increase at various degrees during each water diversion period, it was less significant compared to Yingsu transect. This might be related to the distance of each transect from the Daxihaizi Reservoir, because transects close to Daxihaizi Reservoir receive longer river runoff and a higher water volume. Groundwater depth at well (E1) at 50 m from the river fluctuated from 3.5 m to 5 m until the seventh water diversion. After the seventh water diversion, there was a declining trend in groundwater table at all wells at 50 m, 150 m, 300 m, 500 m, 750 m, and 1050 m from the river. At Arghan transect (Fig. 8), groundwater response to the water diversion was almost identical with Karday transect. From Fig. 8, groundwater depth at the nearest well to the river is below 5 m, a depth considered as a threshold for regeneration of floodplain forests (Table 2). Although there was a rise of the water-table at the nearest well (50 m) from river channel of each transect. Along Yingsu transect, the groundwater depth at Karday and Arghan is well below 5 m. These are levels unlikely to support normal growth of floodplain forests (Table 2). Floodplain forests growing farthest from the river course might be still suffering from water stress.

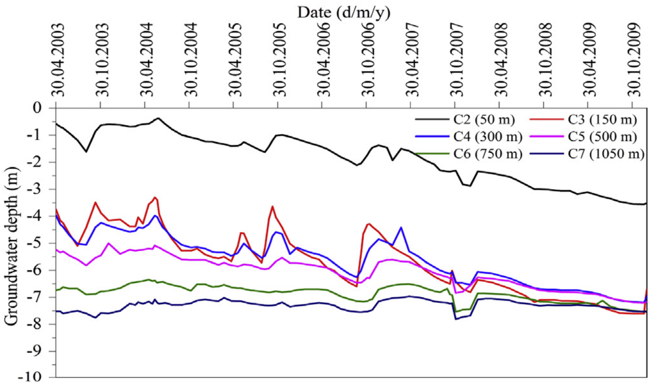

Fig. 6. Variation of groundwater depth at different distance to river channel at Yingsu (source: TRAB).

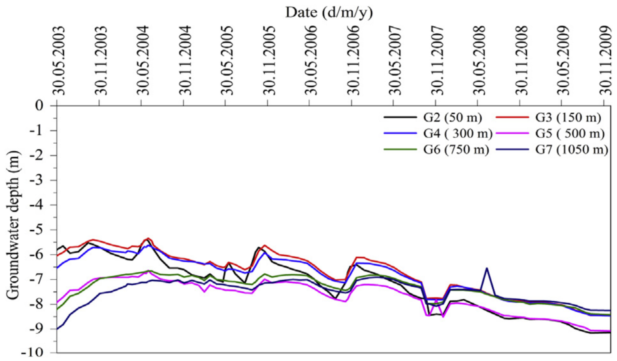

Fig. 8. Variation of groundwater depth at different distance to river channel at Arghan (Source: TRAB).

Table 2
Plant species with their corresponding groundwater depth measured at the lower reaches of the Tarim River.

Plant species	Depth of main root (m)	Groundwater depth favorable to growth (m)	Groundwater depth causing insufficient growth (m)	Groundwater depth resulting in partial or total desiccation (m)
Populus euphratica	<7.0	1.0–4.0	5.0–6.0	Generally > 8.0
Tamarix sp.	<5.0	1.0–6.0	>7.0	>10.0
Phragmites australis	0.5–1.0	1.0–3.0	>3.0	>3.5
Glycyrrhiza inflate	1.0–2.0	1.0–3.0	>3.0	>4.0
Alhagi sparsifolia	>4.0	1.0–4.0	>4.0	>5.0
Halostachys caspica	<1.6	1.0–2.5	>3.0	>3.5
Halimodendron halodendron	1.0–3.0	2.0–4.0	>4.0	>5.0
Apocynum venetum	2.0–3.0	1.5–4.0	>4.0	>5.0
Karelinia caspica	>3.0	1.0–3.0	>4.0	>5.0
Elaegnus angustifolia	0.5–2.5	1.0–4.0	>5.0	>6.0
Halocnemum strobilaceum	1.02–2.0	1.0–2.5	>3.0	>4.0

Source: Song et al. (2000).

4.2. Limitations of water diversion on floodplain forest regeneration

As explained by Takenaka (1997), vegetation shoots have several functions, including exploiting available space, capturing light for photosynthesis, bearing flowers and fruit for reproduction and supporting other shoots. In addition, developments of shoots contribute to the overall structure of tree crowns. Thus, crown size and crown diameter (CD) of trees are closely related to extension of new shoots. Therefore, the number of frequency of trees with new shoots is a major indicator that exhibits the contribution of water diversion to the morphological development of *P. euphratica*. From Fig. 9, a large number of trees ($n = 596$) with various numbers of new shoots are mainly distributed within 20 m distance from the river. With the increased distance, new shoots of *P. euphratica* showed declining frequency. Above 500 m distance from the river channel, trees with new shoots become extremely rare due to unfavorable groundwater supply. *P. euphratica* is the dominant tree species in the floodplain ecosystems of arid Central Asia (Thevs, 2011), and large scale recruitment of new seedlings of floodplain forests is essential to their long term sustainable development (Hughes and Rood, 2003; Rood et al., 2003, 2005). It also as a key parameter to assess the output and success of water diversion in the lower reaches of the Tarim River.

Previous studies found that *P. euphratica* has the ability to regenerate by both seeds/seedlings and root suckers (Hukin et al., 2005; Wiehle et al., 2009). An attempt was made to examine the contribution of water diversion to the development of root suckering of *P. euphratica* trees (Fig. 9). Numbers of root suckers were significantly decreasing with increasing distance from the river course. Young and middle age trees which have shorter roots than adult trees, and have very strong tendency to produce root suckers if habitat conditions are suitable (mainly soil moisture). Extensive surveys of the permanent monitoring plots in Arghan forestry station has been conducted since 2005, in order to interpret the response of seedlings ($0 \leq \mathrm{DBH} \leq 2$) and saplings ($2 < \mathrm{DBH} \leq 4$) of *P. euphratica* more accurately to the environmental alternations. Frequency of young seedlings is a sensitive ecological parameter as it is closely related to soil water content, soil salt content, and groundwater depth, mainly influenced by water diversion (Ma et al., 2011). Figs. 10 and 11 show the number of young *P. euphratica* seedlings of different DBH and their spatial distribution at different distances to river channel. Within 20 m distance from the river course, the frequency of young tree seedlings in DBH ≤ 4 cm was relatively high. As the distance from the main river course increased, the number of young tree seedlings decreased dramatically. Large numbers of young seedlings are mainly distributed within 200 m of the main river channel. Farther than 200 m from the river, distribution of seedlings of different diameters is simpler and sparser. More than 400 m from the river, no seedlings formed. As soil moisture is a key factor for the establishment of *P. euphratica* seedlings and their survival (Cao et al., 2012), high density of *P. euphratica* seedlings along the Arghan transect can only occur in the vicinity of flooding zone affected by water diversion. However, the zone far away from the river is unable to provide favorable habitat requirements for seedling recruitment, and subsequently the remaining few successful seedlings also would not be able to maintain contact with adequate soil moisture due to their shallow root system.

P. euphratica stands have limitations to renew their forest structure by seeds in large areas under current conditions. All on-site investigations confirmed that high densities of seedlings occur near the riverbank every year, and they are likely to germinate rapidly if they land on suitable moist site conditions.

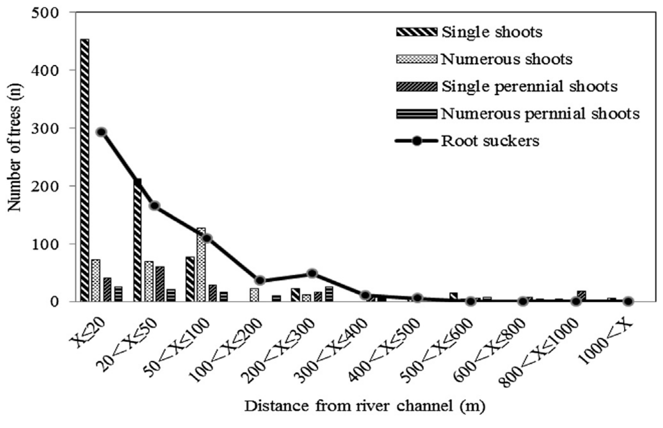

Fig. 9. Effect of water diversion on root suckers and shoots development of *P. euphratica* at Arghan.

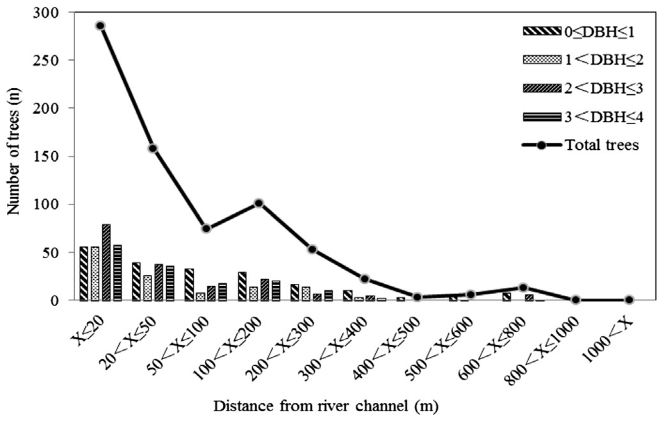

Fig. 10. Effect of water diversion on seedlings and young saplings of *P. euphratica* at Arghan.

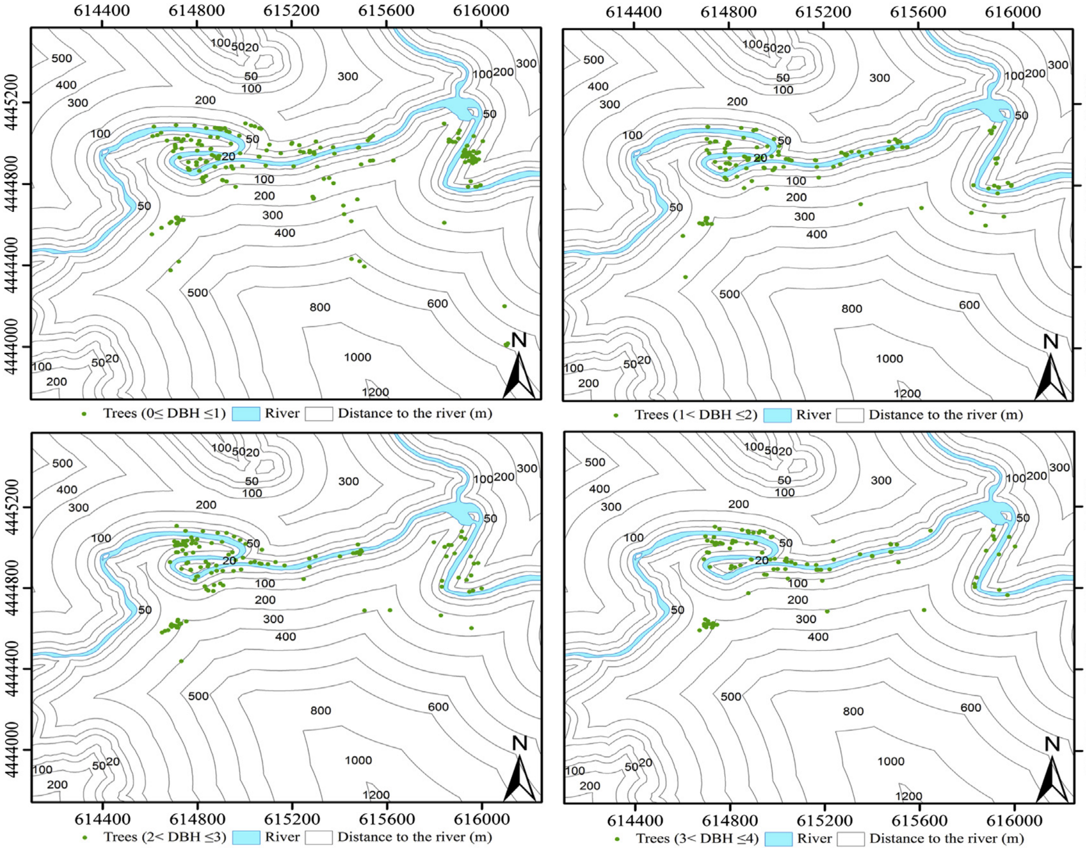

Fig. 11. Spatial distribution patterns of *P. euphratica* trees with different diameters (DBH) at Arghan.

However, many will not survive due to drought stress. Therefore, additional research should be conducted to determine the flow regime that affects soil moisture content and seedling success, and to develop a model identifying suitable site conditions for the establishment of *P. euphratica* seedlings successfully, and for further evaluating the contribution of water diversion to forest recovery and maintenance.

5. Conclusions

Research findings indicate that the 12 water diversion events in the lower reaches of the Tarim River have played a significant role in raising groundwater tables near the main river course and in recovering floodplain forests to a certain degree. However, the impact of groundwater table rise shrinks with increasing distance from the river. The responses of ecological indices (average crown diameter, average crown loss) of trees within short distance from the river were striking. The contributions of water diversions to the recovery of vegetation growing relatively far from the main riverbed were not obvious. Young seedlings, new shoots, and root suckers of *P. euphratica* mainly appeared close to the river. The distribution of floodplain forests is also influenced by topographic conditions, soil moisture and soil salinity. All these factors need to be further investigated. Current water diversion practices have preliminarily made site conditions favorable for forest recovery restricted within 200 m distance of the main river. To date, such expensive efforts fall short of fully restoring the hundreds of kilometers of highly degraded floodplain ecosystem in the near future. Intensified and excessive upstream exploitation of water resources should be effectively controlled to allocate regular and sufficient water for the successful restoration of the degraded floodplain ecosystem in the lower reaches. The volume and time of water diversion practices should be closely coordinated with physical and biological processes as well as the phenological characteristics for the purpose of generating juvenile floodplain forests.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2013.08.006.

References

Cao, D.C., Li, J.W., Huang, Z.Y., Baskin, C.C., Baskin, J.M., Hao, P., Zhou, W.L., Li, J.Q., 2012. Reproductive characteristics of a Populus euphratica population and prospects for its restoration in China. PLoS ONE 7 (7), e39121.

Chen, Y.N., Wang, Q., Ruan, X., Li, W.H., Chen, Y.P., 2004. Physiological response of Populus euphratica to artificial water-recharge of the lower reaches of Tarim River. Journal of Integrative Plant Biology 46, 1393–1401.

Chen, Y.N., Zilliacus, H., Li, W.H., Zhang, H.F., Chen, Y.P., 2006. Ground-water level affects plant species diversity along the lower reaches of the Tarim River, Western China. Journal of Arid Environments 66, 231–246.

Chen, Y.N., Pang, Z., Chen, Y., Li, W., Xu, C.C., Hao, X.M., Huang, X., Huang, T.M., Ye, Z.X., 2008. Response of riparian vegetation to water-table changes in the lower reaches of Tarim River, Xinjiang Uygur, China. Hydrogeology Journal 16 (7), 1371–1379.

Chen, Y.N., Chen, Y.P., Xu, C.C., 2010. Effects of ecological water conveyance on groundwater dynamics and riparian vegetation in the lower reaches of Tarim River, China. Hydrological Process 24, 170–177.

Chen, Y.N., Ye, Z.X., Shen, Y.J., 2011. Desiccation of the Tarim River, Xinjiang, China, and mitigation strategy. Quaternary International 244 (2), 264–271.

Cui, Y.L., Shao, J.L., 2005. The role of ground water in arid/semiarid ecosystems, Northwest China. Ground Water 43 (4), 471–477.

Duan, H.M., Kurban, A., Halik, Ü., Wang, S.S., Ablekim, A., Barat, M., 2010. Vegetation change based on temporal trajectory analysis with multi-temporal CBERS/CCD data in the lower reaches of Tarim River. Arid Land Geography 33 (2), 263–271 (in Chinese).

Feng, Q., Endo, K.N., 2001. Towards sustainable development of the environmentally degraded arid rivers of China – a case study from Tarim River. Environmental Geology 41, 229–238.

Hai, Y., Wai, L., Hoppe, T., Thevs, N., 2006. Half a century of environmental change in the Tarim River Valley – an outline of cause and remedies. In: Hoppe, T., Kleinschmit, B., Roberts, B., Thevs, N., Halik, Ü. (Eds.), Watershed and Floodplain Management Along the Tarim River in China's Arid Northwest. Shaker Press, Aachen, pp. 39–76.

Halik, Ü., Kurban, A., Mijit, M., Schulz, J., Parroth, F., Coenradie, B., 2006. The potential influence of enbankment engineering and ecological water transfer on the riparian vegetation along the middle and lower reaches of the Tarim River. In: Hoppe, T., Kleinschmit, B., Roberts, B., Thevs, N., Halik, Ü. (Eds.), Watershed and Floodplain Management Along the Tarim River in China's Arid Northwest. Shaker Press, Aachen, pp. 221–236.

Halik, Ü., Chai, Z., Kurban, A., Cyffka, B., 2009. The positive response of some ecological indices of Populus euphratica to the emergency water transfer in the lower reaches of the Tarim River. Resources Science 31 (8), 1309–1314 (in Chinese).

Halik, Ü., Tayierjiang, A., Kurban, A., Cyffka, B., OPP, C., 2011. Response of crown diameter of Populus euphratica to ecological water transfer in the lower reaches of Tarim River. Journal of Northeast Forestry University 39 (9), 82–84 (in Chinese).

Hou, P., Beeton, R.J.S., Carter, R.W., Dong, X.G., Li, X., 2007a. Response to environmental flows in the lower Tarim River, Xinjiang, China: ground water. Journal of Environmental Management 83 (4), 371–382.

Hou, P., Beeton, R.J.S., Carter, R.W., Dong, X.G., Li, X., 2007b. Response to environmental flows in the lower Tarim River, Xinjiang, China: an ecological interpretation of water-table dynamics. Journal of Environmental Management 83 (4), 383–391.

Huang, P., 2002. Irrigation-free Vegetation and It's Recovery in Arid Region. Science Press, Beijing, pp. 15–50 (in Chinese).

Huang, X., Chen, Y.N., Ma, J.X., Chen, Y.P., 2010. Study on change in value of ecosystem service function of Tarim River. Acta Ecologica Sinica 30 (2), 67–75.

Hughes, F.M.R., Rood, S.B., 2003. Allocation of river flows for restoration of floodplain forest ecosystems: a review of approaches and their applicability in Europe. Environmental Management 32 (1), 12–33.

Hukin, D., Cochard, H., Dreyer, E., Thiec, D.L., Bogeat-Triboulot, M.B., 2005. Cavitation vulnerability in roots and shoots: does Populus euphratica Oliv., a poplar from arid areas of Central Asia, differ from other poplar species? Journal of Experimental Botany 56, 2003–2010.

Jiang, L.W., Tong, Y.F., Zhao, Z.j., Li, T.H., Liao, J.H., 2005. Water resources, land exploration and population dynamics in arid areas - the case of the Tarim River basin in Xinjiang of China. Population and Environment 26, 471–503.

Kasahara, T., Datry, T., Mutz, M., Boulton, A.J., 2009. Treating causes not symptoms: restoration of surface–groundwater interactions in rivers. Marine and Freshwater Research 60 (9), 976–981.

Lam, T.Y., Kleinn, C., Coenradie, B., 2011. Double sampling for stratification for the monitoring of sparse tree populations: the example of Populus euphratica Oliv. forests at the lower reaches of Tarim River, Southern Xinjiang, China. Environmental Monitoring and Assessment 175 (4), 45–61.

Liu, G.L., Kurban, A., Halik, U., Duan, H.M., Gartner, P., Kleinschmit, B., Ablekim, A., Niu, T., 2012. Analysis of vegetation landscape pattern dynamics based on trajectory change detection: a case study of ecological water transportation in the lower reaches of Tarim River. Journal of Desert Research 32 (5), 1472–1478 (in Chinese).

Ma, X.D., Chen, Y.N., Zhu, C.G., Li, W.H., 2011. The variation in soil moisture and the appropriate groundwater table for desert riparian forest along the Lower Tarim River. Journal of Geographical Science 21 (1), 150–162.

Rood, S.B., Gourley, C.R., Ammon, E.M., Heki, L.G., Klotz, J.R., Morrison, M.L., Mosley, D., Scoppettone, G.G., Swanson, S., Wagner, P.L., 2003. Flows for floodplain forests: a successful riparian restoration. BioScience 53, 647–656.

Rood, S.B., Samuelson, G.M., Braatne, J.H., Gourley, C.R., Hughes, F.M., Mahoney, J.M., 2005. Managing river flows to restore floodplain forests. Frontiers in Ecology and the Environment 3 (4), 193–201.

Shafroth, P.B., Wilcox, A.C., Lytle, D. a., Hickey, J.T., Andersen, D.C., Beauchamp, V.B., Hautzinger, A., McMULLEN, L.E., Warner, A., 2010. Ecosystem effects of environmental flows: modelling and experimental floods in a dryland river. Freshwater Biology 55, 68–85.

Song, Y.D., Fan, Z.L., Lei, Z.D., 2000. Research on Water Resources and Ecology of the Tarim River, China. Xinjiang Peoples Press, Urumqi (in Chinese).

Sun, Z.D., Chang, N.B., Opp, C., Hennig, T., 2011. Evaluation of ecological restoration through vegetation patterns in the lower Tarim River, China with MODIS NDVI data. Ecological Informatics 6 (2), 156–163.

Takenaka, A., 1997. Structural variation in current-year shoots of broad-leaved evergreen tree saplings under forest canopies in warm temperate Japan. Tree Physiology 17, 205–210.

Thevs, N., 2011. Water scarcity and allocation in the Tarim basin: decision structures and adaptations on the local level. Journal of Current Chinese Affairs 3, 113–137.

Tuck-Fatt, S., Doell, P., 2012. Transdisciplinary research for supporting the integration of ecosystem services into land and water management in the Tarim River Basin, Xinjinag, China. Journal of Arid Land 4 (2), 196–210.

Wang, Q., Ruan, X., Chen, Y.N., Li, W.H., 2007. Eco-physiological response of Populus euphratica Oliv. to water release of the lower reaches of the Tarim River, China. Environmental Geology 53, 349–357.

Wang, J.S., Halik, Ü., Cyffka, B., Osman, K., Peng, S.H., 2008. Study on DBH-structure of Populus euphratica and their spatial distribution in the lower reaches of the Tarim River. Chinese Bulltein of Botany 25 (6), 728–733 (in Chinese).

Woolsey, S., Capelli, F., Gonser, T., Hoehn, E., Hostmann, M., Junker, B., Paetzold, A., Roulier, C., Schweizer, S., Tiegs, S.D., Tockner, K., Weber, C., Peter, A., 2007. A strategy to assess river restoration success. Freshwater Biology 52, 752–769.

Wu, J., Tang, D., 2009. The influence of water conveyances on restoration of vegetation to the lower reaches of Tarim River. Environmental Earth Sciences 59 (5), 967–975.

Wiehle, M., Eusemann, P., Thevs, N., Schnittler, M., 2009. Root suckering patterns in Populus euphratica (Euphrates poplar, Salicaceae). Trees 23 (5), 991–1001.

Xu, H.L., Ye, M., LI, J.M., 2007. Changes in groundwater levels and the response of natural vegetation to transfer of water to the lower reaches of the Tarim River. Journal of Environmental Sciences 19, 1199–1207.

Xu, H.L., Ye, M., Li, J.M., 2008. The water transfer effects on agricultural development in the lower Tarim River, Xinjiang of China. Agricultural Water Management 95 (1), 59–68.

Xu, H.L., Ye, M., Li, J.M., 2009. The ecological characteristics of the riparian vegetation affected by river overflowing disturbance in the lower Tarim River. Environmental Geology 58, 1749–1755.

Ye, M., 2005. Eco-water conveyances applied to control desertification at the lower reaches of the Tarim River. Journal of Geographical Sciences 15 (3), 360–366.

Ye, Z.X., Chen, Y.N., Li, W.H., Yan, Y., 2009a. Effect of the ecological water conveyance project on environment in the lower Tarim River, Xinjiang, China. Environmental Monitoring and Assessment 149 (1–4), 9–17.

Ye, Z.X., Chen, Y.N., LI, W.H., 2009b. Ecological water demand of natural vegetation in the lower Tarim River. Journal of Geographical Sciences 19, 1–13.

Ye, Z.X., Chen, Y.N., Li, W.H., Yan, Y., Wan, J.H., 2009c. Groundwater fluctuations induced by ecological water conveyance in the lower Tarim River, Xinjiang, China. Journal of Arid Environments 73 (8), 726–732.

Zhang, Y.M., Chen, Y.N., Pan, B.R., 2005. Distribution and floristics of desert plant communities in the lower reaches of Tarim River, southern Xinjiang, People's Republic of China. Journal of Arid Environments 63, 772–784.

Zhang, X.H., Yang, D.G., Xiang, X.Y., Huang, X., 2012. Impact of agricultural development on variation in surface runoff in arid regions: a case of the Aksu River Basin. Journal of Arid Lands 4, 399–410.

Zhou, Q.M., Li, B.L., Kurban, A., 2008a. Trajectory analysis of land cover change in arid environment of China. International Journal of Remote Sensing 29, 1093–1107.

Zhou, Q.M., Li, B.L., Kurban, A., 2008b. Spatial pattern analysis of land cover change trajectories in Tarim Basin, northwest China. International Journal of Remote Sensing 29, 5495–5509.

Zhuang, L., Dong, Y.S., Yin, F.H., Chen, Y.N., 2010. Historical evolution and the effects of ecological management in Tarim Basin, China. Chinese Science Bulletin 55, 4097–4103.