Journal of Arid Environments 73 (2009) 726–732

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Groundwater fluctuations induced by ecological water conveyance in the lower Tarim River, Xinjiang, China

Z.X. Ye [a,b], Y.N. Chen [a,b,*], W.H. Li [a,b], Y. Yan [c], J.H. Wan [a,b]

[a] Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, PR China
[b] Key Laboratory of Oasis Ecology and Desert Environment, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, PR China
[c] College of Resources and Environmental Science, Xinjiang University, Urumqi 830046, PR China

ARTICLE INFO

Article history:
Received 24 March 2008
Received in revised form
6 January 2009
Accepted 26 January 2009
Available online 26 February 2009

Keywords:
Continental river
Groundwater depth
Recharge volume
Transmission loss per unit river length

ABSTRACT

Data from 40 monitoring wells across 9 sections of the lower Tarim River from 2000 to 2006 were analyzed to investigate the relationship between the transmission loss per unit river length and the change in groundwater depth. The relationship between the rise of the groundwater table (y) and the distance from the main river reach (x) was then assessed through regression analysis. We concluded that the maximum affected area was 1933 m away from the main river reach in the Alagan section, and the minimum affected area was 576 m away in the Kaogan section. In addition, after 8 water deliveries, the volume for recharging the groundwater was 78 248.7 $\times$ 10^4 m^3. Using the Yingsu section as an example, we found that the volume for recharging the groundwater decreased with additional periods of delivery except after the second and sixth water delivery The results revealed that the beneficial effect of an ecological water conveyance project on the ecosystem in the lower Tarim River is a long-term process. These findings may be useful for guiding studies on instream flow requirements and provide a scientific basis for implementing similar ecological projects in other areas.

1. Introduction

Water is the foundation for arid oasis formation and development. It also influences the opposing and conflicting processes of environmental evolution, such as oasis transformation and desertification (Chen et al., 2003a; Deng and He, 1993; Li et al., 1998). The ecosystem services of natural oasis in northwest China depend strongly on the groundwater depth. Two primary factors, moisture and salinity, which are closely relate to the groundwater table, influence the growth of vegetation. Change in groundwater depth can affect the growth of vegetation (Chen et al., 2003a). Some researchers (Song et al., 2000) have shown that if the water table approaches too close to the ground surface, salts dissolved in the water will rise up through capillaries and accumulate on the surface of the ground with evaporation and the soil will be salinized. On the other hand, if the water table is too deep, the soil will dry out and desertification may occur. In view of secondary salinization (a kind of soil degeneration phenomenon), a low water table is favorable to reduce the salinity in soil by irrigation or rain; but for prevention of desertification, a low water table cannot guarantee the soil moisture that the vegetation needs. When there is no irrigation, mass vegetation will die off and desertification will be accelerated. The primary causes of secondary salinization include the clearing of natural vegetation for dry-land farming and irrigation in arid regions, both of which increase the salinity of aquifers and interrupt the hydrologic cycle by reducing evapotranspiration and causing saline water tables to rise (Barica, 1972; Dyson, 1983; Ghassemi et al., 1995). Thus, an appropriate water table depth is the key to the protection and development of vegetation in arid areas.

Tarim River, located in the hinterland of the Taklimakan Desert, is an extremely arid continental river where the ecological environment is vulnerable. The unbridled development and utilization of water resources, especially the exploitation of water resources over the last half century, have led to observable changes in the natural and ecological process of the Tarim River (Feng et al., 2005; Zu et al., 2003). As a result, groundwater depth has increased excessively and resulted in loss of natural vegetation which has affected the ecosystem stability in northwest China and restricted local economic sustainable development. All aspects indicated that the lower Tarim River have become an issue of ecological and environmental concern in western China. In order to retrieve the ecosystem of the lower reaches of Tarim River, a series of environmental measures have been implemented. An ecological water conveyance project (EWCP) was one of them. Some scholars have

* Corresponding author. Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, PR China. Tel.: +869917885432; fax: +869917885320.
E-mail address: chenyn@ms.xjb.ac.cn (Y.N. Chen).

0140-1963/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jaridenv.2009.01.016

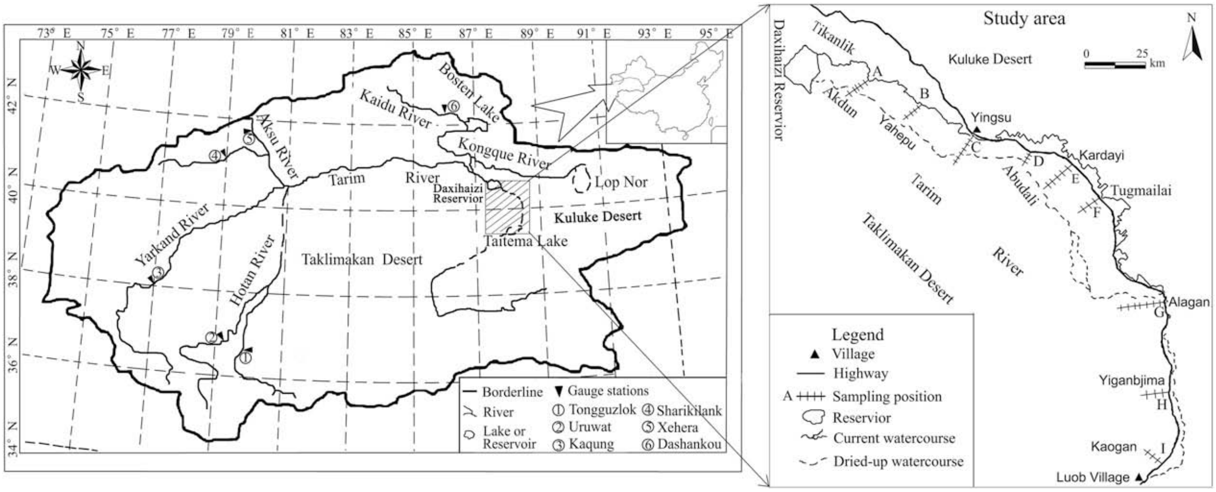

Fig. 1. Location of the Tarim River in Western China.

observed and investigated many aspects of this project, including groundwater depth (Chen et al., 2003a; Xu et al., 2003a; Zhen et al., 2004a,b), changes of water quality (Zhang et al., 2003), response of vegetation (Chen et al., 2004a; Yang and Guo, 2004) and physiological variety of vegetation (Chen et al., 2004c; Xu et al., 2003b). The results have shown that the ecological water conveyance project has achieved some success. Extensive artificial water transfer has also taken place in other countries (Mampiti and Rashid, 2005; Munoz-Reinoso, 2001). However, the direct relationship between groundwater depth and water conveyance has not been studied. This paper attempts to analyze the influence of 7 years of EWCP, including change in groundwater depth, the relationship between the change of groundwater depth and the bulk watering, and the volume for recharging the groundwater. On the one hand, this study can verify the phased achievement of EWCP. On the other hand, it can be a good means to adjust and control the groundwater for vegetation re-growth by regulating EWCP. Therefore, it can provide the scientific information for restoring and protecting the degraded ecosystem in the Tarim River.

2. Materials and methods

2.1. Description of the study area

The study area is located between Daxihaizi Reservoir and Taitema Lake in the lower Tarim River (Fig. 1). The channel bed stretches from west to east on alluvial fans along the Taklimakan Desert and the Kuluke Desert. Over the past 30 years, the extraction of groundwater for large-scale agricultural cultivation without surface water supply has resulted in a severe reduction of stream-flow of the Tarim River. Construction of the Daxihaizi Reservoir in 1972 disrupted much of the stream-flow in the Tarim River, which resulted in the absence of surface water for a stretch of 321 km and increased groundwater depth in the lower reaches. Two lakes at the terminal of the Tarim River, the Lop Nur and the Taitema Lake, dried-up in 1970 and 1972, respectively. The groundwater depth has increased from 3 and 5 m to 8 and 12 m beneath the ground surface over the past three decades (Chen et al., 2003a,b,c).

The region is one of the extremely arid zones of China, with annual average precipitation less than 50 mm, but potential annual evaporation in a range between 2500 and 3000 mm. The strong evaporation makes precipitation insignificant in groundwater supply. The source of groundwater is the surface water. The groundwater flow of the lower Tarim River can be divided into two types: longitudinal direction and transverse direction (Li et al., 2002). In the longitudinal direction, the groundwater flow is controlled by the terrain, and the flow direction of the groundwater is the same as that of the surface water (from upstream to downstream). Because of the lower hydraulic gradient and permeability, the flow velocity is slow or even stationary. In the transverse direction, groundwater flow is controlled by the river level. If the river level is higher than the groundwater level, transverse flow will be formed with increasing distance away from the mid-point of the channel. In the lower Tarim River, during the process of water conveyance, the river level is higher than the groundwater level, so the supply direction is from the mid-point of the channel to the two banks.

Table 1
Water delivery duration and volume from the Daxihaizi Reservoir.

Time/Phase		Period (d/m/y)	Duration (d)	Volume ($\times 10^8$ m^3)	Arriving section	Distance (km)
1st		14/05/2000–13/07/2000	61	0.99	Kardayi	106
2nd		03/11/2000–14/02/2001	104	2.2	Alagan	146
3rd	1	01/04/2001–06/07/2001	97	1.84	Alagan	160
	2	12/09/2001–17/11/2001	67	1.97	Taitema Lake	358
4th		20/07/2002–10/11/2002	114	2.93	Taitema Lake	358
5th	1	03/03/2003–11/07/2003	131	2.5	Taitema Lake	358
	2	12/09/2003–07/11/2003	56	0.9	Taitema Lake	358
6th	1	22/04/2004–25/06/2004	64	1.2	Taitema Lake	358
	2	01/08/2004–15/09/2004	46	2.3	Taitema Lake	358
7th	1	07/05/2005–07/06/2005	32	0.52	Taitema Lake	358
	2	30/08/2005–02/11/2005	65	2.3	Taitema Lake	358
8th		25/9/2006–30/11/2006	66	2.33	Kaogan	324

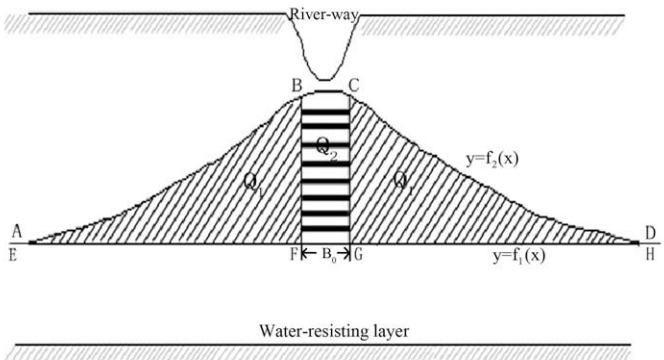

Fig. 2. Sketch map of groundwater recharge in riverbed and river banks.

2.2. Ecological water conveyance project

EWCP is part of a larger conservation plan, "Integrated management of the Tarim River Basin", implemented by the Tarim River Management Bureau. In 2000, about 2 billion dollars were allocated by the central government to the Tarim River project in order to rescue the riparian forest of the lower Tarim River and to conserve water resources for the entire river basin. Recent wet and mild years in the Kaidu River region provided an opportunity to divert water from the Bosten Lake to the lower Tarim River. The distance between Bosten Lake and Taitema Lake (the terminus of the Tarim River) is 927.59 km. Since 2000, 8 water deliveries had been implemented and the total volume discharged was 22.98×10^8 m^3 (Table 1). Water was first delivered on May 14, 2000, and continued flowing for 61 days; However, the water only flowed 106 km downstream of the Daxihaizi Reservoir because of infiltration along the dry riverbed. With the third delivery, which lasted for 164 days, water finally reached Taitema Lake and formed a lake with 10 km^2 water surface. Additional deliveries in 2002, 2003, 2004 and 2005 expanded Taitema Lake. At the lower reach the water conveyance was carried out using two rivers: Qiwenkuer River and original Tarim River. The Qiwenkuer River is a parallel one nearby the lower Tarim River. The course of original lower Tarim River was filled up with sand because of water shortage for years, which results in difficulties for carrying out ecological water conveyance project. So water was delivered through Qiwenkuer River course from Yingsu section to Alagan section of the lower reaches. Since the fifth delivery, in order to improve efficiency, double river-ways water conveyance was carried out. These two river-ways were merged into one way at the Alagan section. The deliveries have had a beneficial effect on the area.

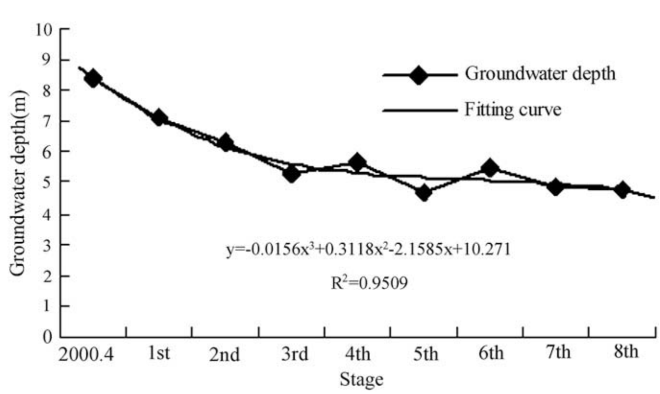

Fig. 3. Variation of groundwater depth during water conveyance in the lower Tarim River.

2.3. Origin of data

Nine study sites were chosen for monitoring groundwater depth between the Daxihaizi Reservoir and the Taitema Lake. Starting from the Daxihaizi Reservoir the sections were Akdun (A), Yahepu (B), Yingsu (C), Abudali (D), Kardayi (E), Tugmailai (F), Alagan (G), Yiganbjima (H), and Kaogan (I) (Fig. 1). The distance interval between two neighboring sections for the first six sections was 20 km, and 45 km for the last three sections. In each section, monitoring wells (varying between 8 and 17 m in depth) were set up with a distance interval of 100–200 m, in order to monitor the dynamic change of groundwater depth. In total, 40 monitoring wells were drilled.

In fact, before the first water delivery, there were only 25 wells in six sections (Akdun, Yahepu, Yingsu, Kardayi, Tugmailai and Yiganbjima), and other wells were built completely in two years after the first water delivery. In order to improve the comparability of the groundwater level before the first water delivery and after the eighth water delivery, we chose the data from 25 wells in six sections to analyze the relationship between groundwater depth and water delivery from the first to the eighth water discharge. Data to calculate the recharge of groundwater were obtained from investigations before the first water delivery and after the eighth water delivery in those six sections. The data for the spatial analysis were obtained from investigations before and after the second phase of the seventh water delivery in five sections, which were the Yingsu, Kardayi, Alagan, Yiganbjima and Kaogan sections at regular intervals of about 50 km along the lower Tarim River. There were six wells located in every section which were drilled by the Tarim River Management Bureau. The vertical distances from the mid-point of the channel were 50 m, 150 m, 300 m, 500 m, 700 m and 1050 m, respectively.

2.4. Methods

Calculation of volume for recharging the groundwater is built on the basis of three assumptions. The first is that the surface water was translated into groundwater directly by infiltration and lateral seepage (accord with hydrogeological characteristics of the study area). The second is that the scope of supply is the same on the two sides of the river. The third is that the groundwater depth is horizontal when EWCP was not carried out, due to the relatively deep groundwater level and the gentle hydraulic gradient (less than 0.2‰), of the study area.

In the process of water delivery, surface water continuously replenishes groundwater, accompanied by phreatic water evaporation and soil sorption. If the distributions of groundwater depth before and after water conveyance are monitored (Fig. 2), the volume for recharging the groundwater can be calculated in three parts between the line ABCD (groundwater depth after water delivery) and that of EFGH (groundwater depth before water delivery). The formulae are as follows:

$$Q = 2Q_1 + Q_2 \tag{1}$$

$$Q_1 = \mu \times \int_0^x [f_1(x) - f_2(x)]\mathrm{d}x \tag{2}$$

$$Q_2 = \mu \times [f_1(0) - f_2(0)] \times B_0 \tag{3}$$

where $f_1(x)$ and $f_2(x)$ are the curves of groundwater depth before and after water delivery, respectively; x is the maximum transverse affected area; μ is the saturation deficiency of the soil after water delivery (Song et al., 2000; Yang et al., 2005); B_0 is the average

Table 2
Change in groundwater depth during watering in the Yingsu section.

Time /phase		Transmission loss per unit river length (10^4 m^3/km)	Change in groundwater depth in different distances from river-way (m)						
			50	150	300	400	500	700	1050
1st		139.60	2.36	2.13	/	0.91	/	/	/
2nd		216.99	/	3.66	3.05	2.39	1.71	/	/
3rd	1	140.13	/	2.8	2.6	1.7	1.1	/	/
	2	88.67	/	1.98	1.82	0.78	0.39	0.25	/
4th		129.22	3.8	2.56	3	2.06	1	0.57	/
5th	2	34.92	/	0.2*	0.27*	0.03*	0.13*	0.2*	0.18
6th	1	21.87	/	0.35**	0.26**	0.21**	0.08**	0.04**	0**
7th	1	40.64	/	1.03**	0.46**	0.15**	0.04**	−0.06**	−0.05**
	2	88.62	0.61	0.68**	0.95**	0.59**	0.41**	0.01**	0.1**

Note: Data signed by * was quoted from Quwei et al's research; Data signed by ** was quoted from the Tarim River Management Bureau; Positive number indicated that the groundwater depth was decreased after water delivery, negative number indicated that the groundwater depth was increased after water delivery.

width of the channel, equal to 30 m. The volume for recharging the groundwater between two sections is

$$W = L \times (Q_{up} + Q_{down})/2 \quad (4)$$

where Q_{up} and Q_{down} are the unit water recharges of the upper and lower sections of the lower reaches, respectively; L is the length between the two sections.

3. Results and analysis

3.1. Relationship between groundwater depth and water delivery

The average groundwater depth showed a polynomial variation from April 2000 to the end of the eighth water delivery (Fig. 3). It could be seen that except for the fourth and sixth delivery, the groundwater depth at the other times kept decreasing and with the watering times increasing, the groundwater reaches a relatively stable level. This indicates that keeping surface water of a definite magnitude is important for groundwater balance.

The average groundwater depth in all monitoring sections was 8.36 m before the water delivery and reached 4.74 m after the eighth delivery. The 6-year ecological water conveyance significantly influenced the change in groundwater depth in most sections. Except for Kardayi, Alagan, Yiganbjima and Kaogan sections, the grounder water depth was less than 4.5 m in the other sections, and reached a level sufficient for healthy growth of vegetation (Chen et al., 2006; Ye et al., 2007). In a word, the EWCP can recharge groundwater, promote shallow groundwater depth and regenerate the seriously degenerated natural vegetation and ecosystems in the lower Tarim River. But how much water should be delivered is an urgent question which needs to be resolved at present time.

Research by Qu et al. (2005) revealed that the transmission loss per unit river length (closely related to the quantity of water delivery) and the change in groundwater depth showed a logarithmic relationship. The transmission loss per unit river length is the water loss due to infiltration and evaporation from the channel between observation points. The total water consumption of the length (from Daxihaizi reservoir to Yingsu section) could be calculated according to the different runoff in different sections. In order to eliminate the influence of the river length, the total transmission loss was converted into transmission loss per unit river length (Table 2). By plotting the data in Fig. 4 and fitting the curve, the functions could be obtained (Fig. 4).

Fig. 4 proved the same relationship as that shown in Qu et al. (2005) at different distances from the mid-point of the channel. Keeping the transmission loss per unit river length stable, the

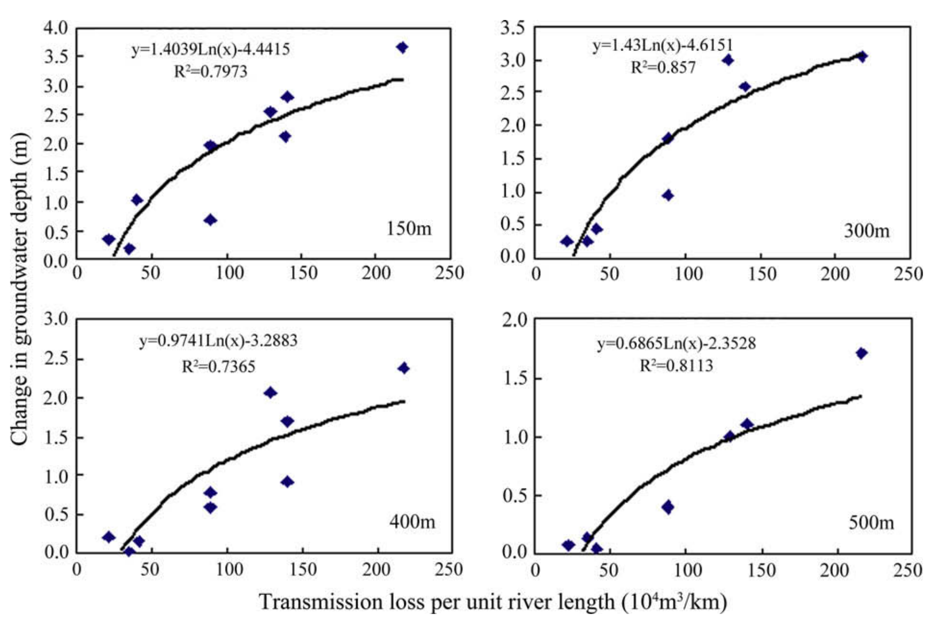

Fig. 4. The relationship between transmission loss per unit river length and change in groundwater depth.

Table 3
Relationship between the rise of groundwater table (y) and distance from the main river reach (x).

Sections	Simulation equation	R^2
Yingsu	$y = -0.0008x + 0.8088$	0.6253*
Kardayi	$y = -0.6575Ln(x) + 4.5074$	0.9534**
Alagan	$y = -0.3983Ln(x) + 3.0138$	0.9914**
Yiganbjima	$y = -0.7092Ln(x) + 4.606$	0.9012**
Kaogan	$y = -0.5227Ln(x) + 3.3224$	0.6895*

* Significant correlation ($p < 0.05$); ** Utmost significant correlation ($p < 0.01$).

Table 4
Estimating the affected areas in different sections on one side of river (m).

Section	Yingsu	Kardayi	Alagan	Yiganbjima	Kaogan
Affected areas	1011	949	1933	662	576

change in groundwater depth decreased with the increasing distance from the mid-point of the channel. For example, given the transmission loss per unit river length as 100×10^4 m^3, the decrease in groundwater depths at distances of 150 m, 300 m, 400 m and 500 m from the mid-point of the channel are 2.024 m, 1.97 m, 1.2 m and 0.81 m, respectively. Similarly, by requiring the same groundwater depth, the transmission loss per unit river length would increase with increasing distance from the mid-point of the channel. This means that unique transmission loss per unit river length can be calculated if only given the groundwater depth and specific scope at the same time. So this is a good basis for developing an ecological water conveyance project.

3.2. Spatial variation of groundwater depth

One important guideline in evaluating the influences of the environment is the level of the water table in transverse orientation along the direction of river, and this is also an important factor in estimating the regeneration of natural vegetation (Xu et al., 2003a).

According to the data obtained from Yingsu, Kardayi, Alagan, Yiganbjima and Kaogan sections, it was found that the decrease in groundwater depth in four sections continued to descend with increasing distance from the mid-point of the channel except for Yingsu section. Due to the different descending rates in different sections, this study simulated the relationship between the rise of groundwater table and distance from the main river reach by regression analysis, in five sections (Table 3). Except for Yingsu section, the others showed the same relationship and coefficients of determination were significant. The groundwater depth in Yingsu section was relatively steady because it was closed to the upper section of the lower reaches and gained more water than the other sections. According to the models in Table 3, assuming that $y = 0$, we can calculate the value of x, which represents the maximum affected area (Table 4).

It was clear that the maximum affected areas of watering were in the Alagan section, the second in the Yingsu section, and the minimum affected areas were in the Kaogan section which was near the end of the river. In fact, the quantity of water in Alagan section was maximum in the second phase of the seventh water delivery because two rivers of conveyance merged into one way in the Alagan section. There was another investigation (Li et al., 2003) which showed that the changes in groundwater depth was related to two factors: the quantity and duration of watering. Therefore, ecological water delivery is a long-term and arduous task.

3.3. Recharge volume of groundwater

The relationship between groundwater depth and the distance from the mid-point of the channel can be simulated by a quadratic polynomial (coefficients of determination are greater than 0.9) (Fig. 5(a–f)). According to Equations (1)–(4), the recharge volume can be calculated in different reaches. It can be seen from Tables 5 and 6 that the net volume for recharging the groundwater was $78\,248.7 \times 10^4$ m^3, accounting for 35.63% of the total discharge from Daxihaizi reservoir. This showed that the water conveyance project was significant for decreasing groundwater depth. In order to extend the influence of water conveyance, a double river-ways delivery project has been put in practice since the fifth water

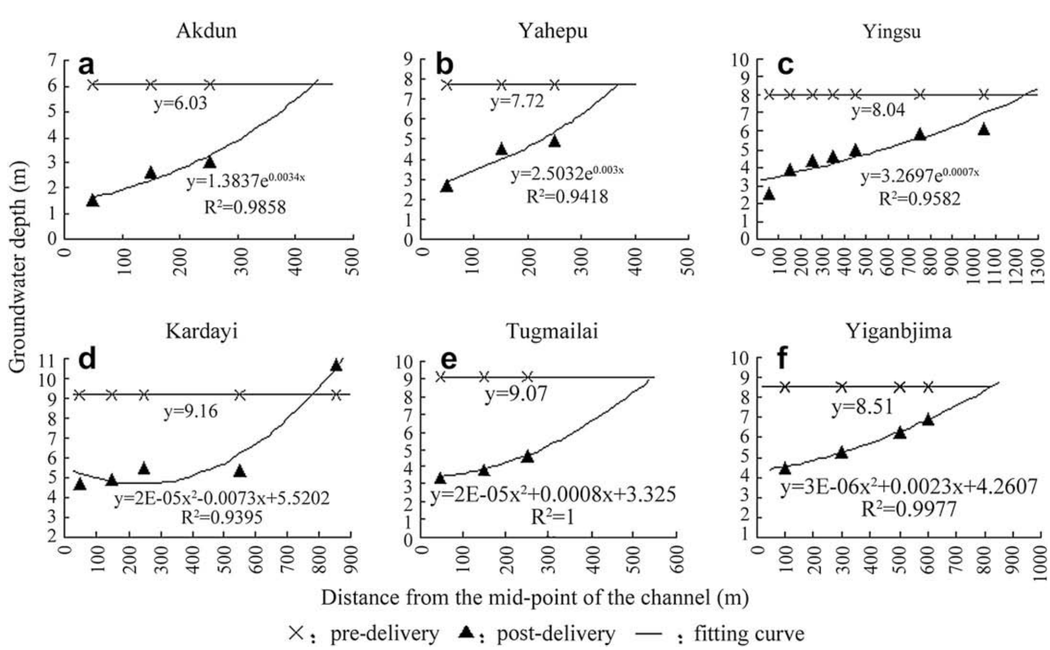

Fig. 5. The groundwater depth before the first water delivery and after the second phase of the seventh water delivery in typical sections.

Table 5
The volume for recharging the groundwater in Qiwenkuer River after the water delivery.

Reach	Daxihaizi Reservior–C	C–D	D–E	E–G	G–H	H–I	Riverbed
Recharge volume per unit river length (10^4 m^3/km)	180	177.5	141.8	200	200	80.7	3.3
Length of reach (km)	40	25	32	86	95	50	328
Recharge volume of reach (10^4 m^3)	7200	4437.5	4537.6	17 200	19 000	4035	1079.1
Total recharge volume (10^4 m^3)	57 489.2						

Note: Capital C–I represent the sections as the paper in Section 2.3.

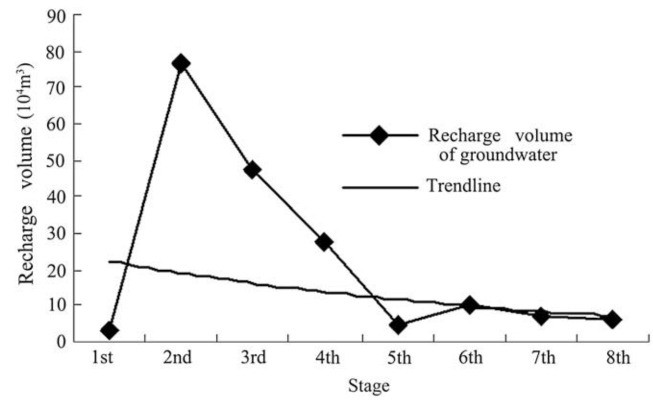

Fig. 6. The volume for recharging the groundwater in Yingsu Section in each times of watering.

delivery. Meanwhile, the government built many barrages to encourage flooding and enlarge the area of vegetation affected. In the process of delivery, 64.37% of the total discharge volume was lost. The loss included surface water evaporation, phreatic water evaporation and infiltration. Phreatic water evaporation accounted for the majority of the loss. Research by Ye et al. (2007) revealed that phreatic water evaporation was 3.2×10^8 m^3 per year in the lower Tarim River. At the same time, double river-ways delivery and overflowing augmented the surface water evaporation. Therefore, the percentage of volume for recharging was not great.

Taking Yingsu section as an example, the volume for recharging the groundwater of eight water deliveries can be calculated according to the method outlined above (Fig. 6). It can be seen that the volume for recharging the groundwater decreased with the ecological water conveyance project carried out continuously, except for the second and sixth discharges. In the second water delivery, the duration was 104 days, and the quantity was 2.20×10^8 m^3, which was larger than that in the first delivery. In the sixth water delivery, enlargement of the affected areas in the transverse orientation led to an increase in the volume for recharging the groundwater although the quantity was 0.1×10^8 m^3 more than that in the fifth water delivery. When the groundwater depth decreased continuously and approached or was less than the critical phreatic water depth, phreatic evaporation would markedly strengthen and the volume for recharging the groundwater would decrease. It can also be seen that the volume for recharging the groundwater would decrease gradually and tend to homeostasis with increasing implementation times of ecological water conveyance. By then, the groundwater depth is in homeostasis and the vegetation is growing healthily.

4. Discussion and conclusions

(1) The relationship between the transmission loss per unit river length and the change in groundwater depth can be the basis of studies on instream flow requirement. Instream flow requirement is one of the important issues in water resources management and it is also the main aspect of eco-hydrology. Based on the analyses of monitoring data of groundwater depth during the watering, the extensive artificial watering introduces a positive function to raise the groundwater depth along two sides of the river. However, these favorable changes appeared only on a small scale. In the lengthways orientation from upper to lower sections of the lower river, the influence progressively weakens with the increase in delivering distance from Daxihaizi. In the transverse orientation, the change in groundwater table is remarkable within 300 m away from the mid-point of the channel. This is similar to the research of Chen et al. (2004b), whose study suggested that within 250 m from the river, the groundwater depth was very sensitive to water recharge. Within 250–450 m from the river, the groundwater depth was less sensitive but rose considerably, and the response of groundwater depth was comparatively weak at a distance greater than 750 m. The maximum affected area on one side was 1933 m in the Alagan section, where the quantity of watering was greatest. Thus, it can be concluded that the affected area was closely related to the quantity of watering in the lower Tarim River.

(2) In this paper, the volume for recharging the groundwater was calculated using correlation analysis and the water balance principle. This method makes use of groundwater depths pre- and post-discharge, avoiding analyzing unsteady fluid flow of groundwater movement and spatial variability of parameters due to lack of basic data. However, there are only a few studies on water loss of river, especially in water delivery for the dried-up river-way of the Tarim River. Further detailed studies are expected.

(3) A mathematical model of groundwater flow (e.g. MODFLOW) might provide a higher precision, but these models are often too complex and difficult to be applied due to the large numbers of parameters needed, such as borderline condition, waterpower gradient. The method I chose in this paper can be applied more easily because it needs fewer parameters (e.g. groundwater table depth, soil water content, saturated water content and width), and these parameters can be obtained easily. Additionally, coefficients of determination of the simulating models were significant. The method is suitable for arid area lack of monitoring data. Certainly, mathematical models of groundwater flow will be applied when the more data are obtained and further studies are carried out in the Tarim River.

(4) In general, the groundwater depth decreased in a short period after water conveyance. This result was directly related to the

Table 6
The volume for recharging the groundwater in the original river after the water delivery.

Reach	Daxihaizi reservoir–Original Yingsu	Original Yingsu–Bozikule	Bozikule–Alagan	Riverbed
Recharge volume per unit river length (10^4 m^3/km)	98	103	200	2.7
Length of reach (km)	58	28	59	145
Recharge volume of reach (10^4 m^3)	5684	2884	11 800	391.5
Total recharge volume (10^4 m^3)	20 759.5			

quantity and duration of delivery, delivery times and interval. However, widening affected areas is limited because of the single conveyance route, multiple routes need to be put into effect. In order to further exert the benefits of EWCP and achieve the goal of restoring and protecting the degraded natural vegetation on a large-scale, some suggestions and counter measures are put forward for the conservation, restoration and rehabilitation of the ecosystem in the lower Tarim River, such as continually carrying out the EWCP, developing ecological forests and implementing man-made flooding.

(5) Ecological water conveyance aims to promote a groundwater depth suitable for the growth of natural vegetation, protecting the "Green Corridor" in the lower Tarim River, and rehabilitating and reconstructing the degraded ecosystems of the lower Tarim River. Thus, an accurate estimate of groundwater depth in water conveyance in arid land is significant for analysis of the ecological response and water resources management. The next task should focus on establishing a forecast model to predict groundwater depth under the conditions of water conveyance.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (Grant No. 90502004 and 40671014), the Knowledge Innovation Project from the Chinese Academy of Sciences (KZCX2-YW-127 and KZCX2-YW-Q10-3-4) and the National Science and Technology support plan (2006BAC01A03).

References

Barica, J., 1972. Salinization of groundwater in arid zones. Water Research 6, 925–933.

Chen, Y.N., Chen, Y.P., Li, W.H., Zhang, H.F., 2003a. Response of the accumulation of proline in the bodies of *Populus euphratica* to the change of groundwater level at the lower reaches of Tarim River. Chinese Science Bulletin 48, 958–961.

Chen, Y.N., Cui, W.C., Li, W.H., Zhang, Y.M., 2003b. Utilization of water resources and ecological protection in the Tarim River. Acta Geography Sinica 58, 215–222.

Chen, Y.N., Li, W.H., Xu, H.L., Liu, J.Z., Zhang, H.F., Chen, Y.P., 2003c. The influence of groundwater on vegetation in the lower reaches of Tarim River, China. Acta Geographica Sinica 58, 542–549.

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., Li, W.H., Chen, Y.P., Wang, Q., 2004a. Response of Tamarix spp. and *Phragmites communis* to ecological water conveyance in the lower reaches of the Tarim River, Xinjiang. Journal of Glaciology and Geocryology 26, 596–602.

Chen, Y.N., Zhang, X.L., Zhu, X.M., Li, W.H., Zhang, Y.M., Xu, H.L., Zhang, H.F., Chen, Y.P., 2004b. Ecological responses to the artificial water recharge into the downstream reaches of Tarim River in Xinjiang. Science in China Series D-Earth Sciences 34, 475–482.

Chen, Y.P., Chen, Y.N., Li, W.H., Zhang, H.F., 2004c. Effect of ecological water input on MDA of *Populus euphratica* oliv leaf in the lower reaches of the Tarim River. Chinese Journal of Applied and Environmental Biology 10, 408–411.

Deng, W., He, Y., 1993. Discussion of groundwater effect to surface ecology. Scientia Geographica Sinica 13, 161–168.

Dyson, P.R., 1983. Dryland salting and groundwater discharge in the Victorian uplands. Proceedings of the Royal Society of Victoria 95, 113–116.

Feng, Q., Liu, W., Si, J.H., Su, Y.H., Zhang, Y.W., Cang, Z.Q., Xi, H.Y., 2005. Environmental effects of water resource development and use in the Tarim River basin of northwestern China. Environmental Geology 48, 202–210.

Ghassemi, F., Jakeman, A.J., Nix, H.A., 1995. Salinisation of Land and Water Resources: Human Causes, Extent, Management & Case Studies. University of New SouthWales Press Ltd., Sydney, Australia.

Li, W.H., Xu, H.L., Nayoupu, A.H.M.T., 2003. Preliminary report of water transportation and ecological restoration in the lower reaches of Tarim River. Arid Land Geography 26, 122–128.

Li, X., Zhou, H.F., Fan, Z.L., 1998. Water resources utilization of Tarim River and land desertification effect analysis. Journal of Desert Research 18, 46–54.

Li, X.Y., Zhang, Y.S., Wang, L.X., Zhang, H.Q., Zhang, P.T., 2002. Analysis of the groundwater characteristics at the lower reaches of Tarim River. Journal of Arid Land Resources and Environment 16 (2), 27–31.

Mampiti, M., Rashid, H., 2005. An ecological economics framework for assessing environmental flows: the case of inter-basin water transfers in Lesotho. Global and Planetary Change 47, 193–200.

Munoz-Reinoso, J.C., 2001. Vegetation changes and groundwater abstraction in SW Donana, Spain. Journal of Hydrology 242 (3–4), 197–209.

Qu, W., Tang, D.S., Huang, Y., Lu, H.S., 2005. Making use of dynamic programming in the water allocation at the lower reaches of the Talimu River. Rural Water Conservancy and Hydropower (7), 21–24.

Song, Y.D., Fan, Z.L., Lei, Z.D., Zhang, F.W., 2000. Research on Water Resources and Ecology of Tarim River, China. Xinjinag People's Press, Urumqi.

Xu, H.L., Chen, Y.N., Li, W.H., 2003a. Study on response of groundwater after ecological water transport at the lower reaches of the Tarim River. Research of Environmental Sciences 16 (2), 19–23.

Xu, H.L., Song, Y.D., Wang, Q., 2003b. Response of physiological indexes of *Populus euphratica* to ecological water transport in the lower reaches of the Tarim River. Research of Environmental Sciences 16 (4), 24–27.

Yang, G., Guo, Y.P., 2004. The change and prospect of vegetation in the end of the lower reaches of Tarim River after ecological water delivering. Journal of Desert Research 24 (2), 167–172.

Yang, P.N., Dong, X.G., Omerjan, 2005. Calculation of groundwater recharge volume after the fifth emergency water transfer to the lower reaches of the Tarim River, Xinjiang. Journal of Natural Resources 20 (1), 1–6.

Ye, Z.X., Chen, Y.N., Li, W.H., 2007. Ecological water demand of vegetation based on eco-hydrological processes in the lower reaches of Tarim River. Acta Geographica Sinica 62 (5), 451–461.

Zhang, H.F., Li, W.H., Ge, H.T., Chen, Y.P., 2003. Compositor analysis on correlation between groundwater level and water chemical contents in lower reaches of Tarim River. Arid Land Geography 26 (3), 260–263.

Zhen, D., Chen, Y.N., Xue, Y., 2004a. Analysis on the influence of the stream water transporting on the groundwater level in the lower reaches of Tarim River, Xinjiang. Arid Land Geography 27 (2), 216–220.

Zhen, D., Li, W.H., Dong, T.Z., Zhang, H.F., 2004b. Impact of embankment on groundwater depth in middle reaches of Tarim River. Journal of Desert Research 24 (6), 745–750.

Zu, R.P., Gao, Q.Z., Qu, J.J., Qiang, M.R., 2003. Environmental changes of oasis at southern margin of Tarim Basin, China. Environmental Geology 44 (6), 639–644.