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Determining the ecological water allocation in a hyper-arid catchment with increasing competition for water resources

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ABSTRACT

Meeting ecological water requirement adequately plays a significant role in guaranteeing the stability of river basin ecosystems in arid lands. The amounts of water leaked through the riverbed and drawn by ecological brakes in Tarim River were ascertained. Based on data related to soil, hydrology, and vegetation of the river basin, the aims of this paper are to 1) analyse the variation in the size of soil particles and in hydraulic conductivity of four sections of the river; 2) calculate the amount of water that leaked from the riverbed and the percentage of ecological water requirement that can be guaranteed at different frequencies of water inflow; and 3) recommend – using a combination of particle size analysis, Darcy's Law, and GIS – the amount of water to be drawn from ecological brakes along both banks of the river for meeting ecological water requirement adequately. The results showed that 1) the size of soil particles in the riverbed ranged from 1.6 μm to 98.9 μm; 2) hydraulic conductivity followed the normal distribution from year to year but varied in spatial terms, that is across different section of the river; 3) riverbed leakage varied with water frequencies, being 11.36×10^8 m^3, 10.62×10^8 m^3, 9.84×10^8 m^3, 9.32×10^8 m^3, and 8.87×10^8 m^3 at the frequencies of 10%, 25%, 50%, 75%, and 90%, respectively; 4) the distance over which the leakage contributed to meeting ecological water requirement in the south bank was greater than or equal to the distance in the north bank; and 5) water drawn from ecological brakes on the north bank exceeded that drawn from the brakes on the south bank by 10.89×10^8 m^3–11.28×10^8 m^3. Ecological water requirement of the desert riparian vegetation was met mainly from riverbed leakage in the south and by drawing from ecological brakes in the north. The present research not only offers a scientific method that could be used for developing suitable schemes for meeting ecological water requirement but also provides a technical guide on running ecological brakes and achieving the optimal allocation of water resources in Tarim River Basin.

1. Introduction

Water is one of the key environmental factors that guarantee the structural integrity and stability of river basin ecosystems (Colloff et al., 2015; Bennetsen et al., 2016; Boithias et al., 2016; Campitelli et al., 2016). In such ecosystems in arid lands, the ecological processes are particularly affected by hydrological processes (Ludwig et al., 2005; Ling et al., 2014; Zhou et al., 2014; Daessle et al., 2016; Gu et al., 2016). Desert riparian vegetation, as the main component of river basin ecosystems in arid lands, is sustained mainly by groundwater, which is recharged by water leakage from the riverbed (Yuan et al., 2014; Viola et al., 2014; Garssen et al., 2015; Hamdan and Stromberg, 2016). This leakage that not only recharges the groundwater but also supports the renewal, population succession, and distribution pattern of vegetation (Wang et al., 2010; Chen et al., 2013; Agapiou et al., 2016). However, with the increasing requirement for water by human settlements in the inland river basins, water for the desert riparian vegetation is becoming increasingly scarce (Zhao et al., 2013; Ye et al., 2014a; Wang et al., 2015). Therefore, judicious allocation of water for ecological purposes based on the characteristics and distribution of the desert riparian vegetation has become a hot topic among many scholars (Davies et al., 1992; Yang et al., 2007; Zhao et al., 2007; Ling et al., 2014; Si et al., 2015; Villeneuve et al., 2015).

Ecological water requirement of desert riparian vegetation in an inland river basin refers to the amount of surface water and groundwater that can guarantee normal growth of such vegetation and restrict further deterioration of the ecosystem (Zhao et al., 2007; Ling et al., 2014; Si et al., 2015). Previous studies provide many references for the calculation and allocation of ecological water (Table 1). Concretely, some scholars present several strategies on the calculation of ecological water requirements (Davies et al., 1992; Yang et al., 2007; Villeneuve et al., 2015), some propose a number of approaches on how to allocate ecological water and solve conflicts while making water allocation

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Table 1
Summary of relevant studies on the calculation and allocation of the ecological water.

Order	Study	Location	Methods	Relevant key results
1	Davies et al. (1992)	Africa, Australia and USA	Propose a world-wide research strategy—IBTs (inter-basin water transfers)	One of the main reasons for inter-basin water transfers is need for ecological ethic.
2	Doupé and Pettit (2002)	Old River, Western Australia	Compared the water requirements of irrigation and ecology in dry seasons	Agriculture water demand is more essential than ecological water demand in dry seasons.
3	Thoms and Sheldon (2002)	Condamine–Balonne River, Australia	Develop an ecosystem approach	Water allocation should obey the hierarchy of ecosystem.
4	Schlüter et al. (2005)	Amudarya delta region, Aral Sea Basin	EPIC (Environmental Policies and Institutions for Central Asia) model	Surface water plays a significant role in long-term modeling of water allocation.
5	Messner et al. (2006)	Spree River, German	Presents an integrated methodological approach (IMA)	This approach could resolve water allocation conflict.
6	Chen (2007)	Yellow River, China	Established an early warning mechanism on flooding or low inflow	Minimum, suitable and maximum ecological flows are essential in ecological water allocation.
7	Yang et al. (2007)	Yellow River, China	Holistic approach in a basin scale to calculate ecological water requirement	(1) 45% of the total surface water resources allocated to ecological system. (2) The ecological water requirements of inside river systems and outside river systems were respectively 261.0×10^8 m^3 and 3.65×10^8 m^3.
8	Bangash et al. (2012)	Catalonia, northeastern Spain	DHI's MIKE BASIN model	Conjunctive use of surface water and groundwater is efficient in water allocation.
9	Villeneuve et al. (2015)	Woodforde River, central Australia,	Field monitoring	(1) 25% of this water recharges the deep aquifer. (2) 75% is used by the riparian vegetation or evaporated directly from the soil.
10	This paper	Tarim River, western China	Particles analysis, water balance and spatial analysis of GIS	(1) Ecological water requirements are supplied mainly by riverbed leakage and water drawn from ecological brakes. (2) Spatial analysis of GIS can be used for spatial distribution of vegetation ecological water requirement. (3) The amount of riverbed leakage and water drown could determine the range of vegetation preserve through under different water frequencies.

plans (Thoms and Sheldon, 2002; Doupé and Pettit, 2002; Messner et al., 2006; Chen, 2007), and the others develop models to determine the water amount of surface and ground water in ecological water allocation (Schlüter et al., 2005; Bangash et al., 2012). But few of them put forward a specific plan on how to meet ecological water requirement by utilizing the surface water and leakage water conjunctively. In Tarim River, the requirement is mainly influenced by water leaked through riverbeds and drawn from ecological brakes (Ling et al., 2014; Chen et al., 2015). Riverbed leakage and water drawn from ecological brakes are the two main sources of ecological water requirement of vegetation. Therefore, if riverbed leakage cannot meet the requirement, the water drawn from ecological brakes should be taken into consideration. Therefore, it is particularly important to conduct research on hydraulic conductivity and transformation of the river-groundwater connection

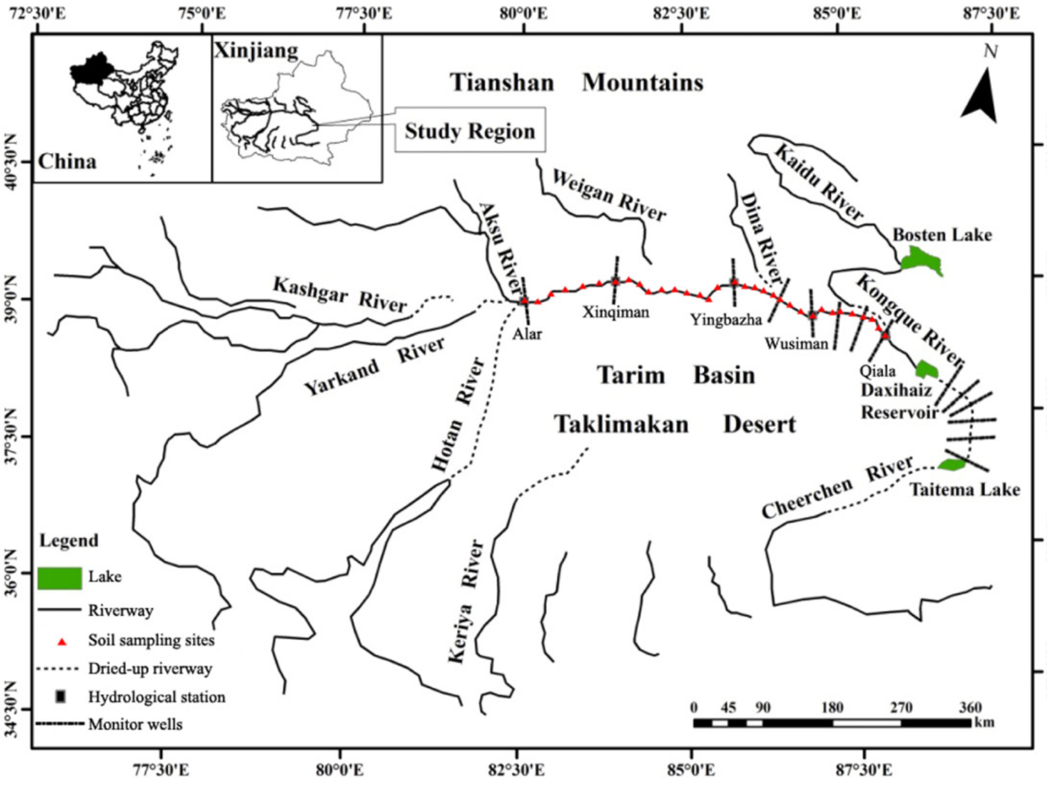

Fig. 1. Sketch map and soil sampling sites in Tarim River Basin.

Table 2
Formula selections of coefficients C and $\phi(n)$ in the process of calculating hydraulic conductivity.

Method	Function of porosity ($\phi(n)$)	Effective grain diameter (d_e, mm)	Value of coefficient (C)	Domain of applicability (mm)
Hazen	$1 + 10(n - 0.26)$	d_5	6×10^{-4}	0.1 mm $< d_e <$ 3 mm, $\eta < 5$
Slichter	$n^{3.278}$	d_{10}	6.1×10^{-3}	0.01 mm $< d_e <$ 5 mm
Tezaghi	$(\frac{n-0.13}{\sqrt[3]{1-n}})^2$	d_{10}	$6 \times 10^{-4}\log(500 / \eta)$	Coarse sand (0.5 mm $< d_e <$ 2 mm)
Beyer	1	d_{10}	3.75×10^{-3}	0.06 mm $< d_e <$ 0.6 mm; $1 < \eta < 20$
Sauerbrai	$n^3/(1-n^2)$	d_{17}	6×10^{-4}	$d_e <$ 0.5 mm
Kozeny	$n^3/(1-n^2)$	d_{10}	8.3×10^{-4}	Coarse sand (0.5 mm $< d_e <$ 2 mm)
USBR	1	d_{20}	$4.8 \times 10^{-4} d_{20}^{0.3}$	Medium sand (0.25 mm $< d_e <$ 0.5 mm), $\eta < 5$

for safeguarding the ecosystem of this river basin. However, such research has been mainly focused in the lower reaches (Song et al., 2000; Hu, 2007), and scant in the upper and middle reaches, making it difficult to calculate accurately the amount of water – in the form of riverbed leakage – needed for recharging the groundwater to support desert riparian vegetation. To meet ecological water requirement in Tarim River basin, the riverbed leakage and water diversion from ecological brakes have to be quantified, taking into account the spatial distribution of the requirements.

In addition, many scholars have studied the hydraulic conductivity of riverbed by using different methods, e.g., the particle-size analysis (Vukovic and Soro, 1992; Alayamani and Sen, 1993; Song et al., 2009; Giuffrida and Consoli, 2016), the in situ standpipe method (Hvorslev, 1951; Chen, 2000; Kennedy et al., 2008; Jiang et al., 2015), the slug test (Springer et al., 1999; Landon et al., 2001; Woodward et al., 2016), etc. However, the particle-size analysis is not restricted by field conditions, and the results, obtained by using sophisticated equipment, can be determined more accurately by the particle size than by any the other methods (Vukovic and Soro, 1992).

Against this background, the aims of this study are to analyse the hydraulic conductivity based on the size of soil particles in four sections of the river, calculate the amount of leakage by using data on the hydrology, soil properties, and ecological water requirement of the area and the vegetation, and put forward a suitable water diversion scheme of ecological brakes. The present research not only offers a scientific method that could be used for developing similar schemes for meeting ecological water requirement, but also provides a technical guide on achieving suitable distribution of ecological brakes and optimal water resource allocation in Tarim River Basin.

2. Regional setting

Tarim River Basin (34.20°–43.39° N, 71.39°–93.45° E) lies in southern Xinjiang, China, and abuts Taklamakan Desert, surrounded by nine great rivers, namely Aksu, Yarkant, Kaxgar, Hetian, Keriya, Weigan, Kuqa-Dina, Kaidu-Kongque, and Qarqan (Chen et al., 2013; Zhao et al., 2013) (Fig. 1). The annual runoff of Tarim River Basin is 39.8 billion m^3, , and its total water resources amount to 42.9 billion m^3. The area of this river basin is 1.02 million km^2 and covers five prefectures, forty-two counties, and fifty-five regiments of the Construction and Production Corps of Xinjiang, with a population of 9.84 million in 2010 year.

Tarim River is the longest inland river in China, with a total length of 1321 km. Average annual precipitation in the river is only 25–30 mm/year, whereas annual potential evaporation is 2500–3000 mm/year during the 1960–2010 year (Ling et al., 2014). Far away from any ocean and located in the hinterland of Eurasia, Tarim River Basin falls in the continental arid desert climate zone (Chen et al., 2013; Ling et al., 2014). Tarim River produces no runoff but depends on its tributaries and is a dissipative-type inland river (Hao et al., 2008). Since the 19th century, six of the nine rivers mentioned above have been cut off from Tarim River because of climate change and human activities, and only three, namely Aksu, Hetian, and Yarkant feed into it, contributing 73.2%, 23.2%, and 3.6% respectively to its total runoff (Hao et al., 2008; Chen et al., 2013). The desert riparian vegetation in Tarim River Basin is dominated by *Populus euphratica* and *Tamarix* among the trees and by *Phragmites australis*, *Alhagi sparsifolia*, and *Karelinia caspica* among the herbaceous plants.

In Tarim River, the lower reaches is the most prominent ecologically degraded area in China, and perhaps even in the world (Xu et al., 2007; Ling et al., 2014; Zhang et al., 2016). To bridge the wide gap between the supply of and the demand for water in Tarim River Basin and thus to protect the ecology and environment of the region, Chinese government has invested 10.7 billion yuan in the Ecological Water Conveyance Project (EWCP) since 2001. So far, 350 million m^3 of water has flowed into the lower reaches of Tarim River every year (transferred from Kongque River to areas downstream of Tarim River). As a result, the ecology and environment in the lower reaches of Tarim River have improved markedly, making what was once the most ecologically degraded area in the world into a shining example of ecological restoration achieved through human intervention (Ling et al., 2015; Chen et al., 2015).

3. Data resources

3.1. Data of the riverbed soil

For the present study, the upper and middle reaches of the river were divided into four sections as follows: Section 1, Alar-Xinqiman; Section 2, Xinqiman-Yingbazha; Section 3, Yingbazha-Wusiman, and

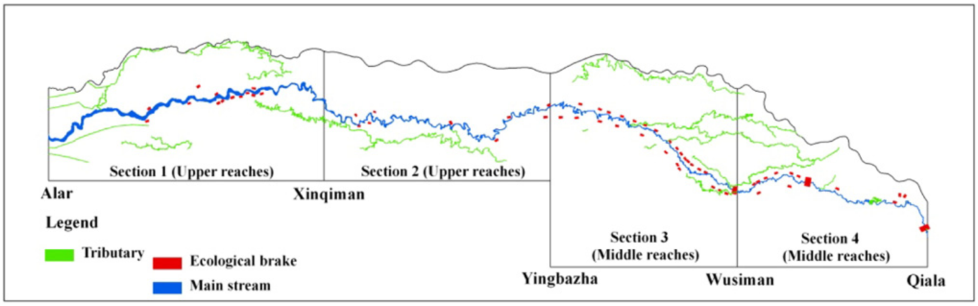

Fig. 2. Distribution map of ecological brakes in Tarim River.

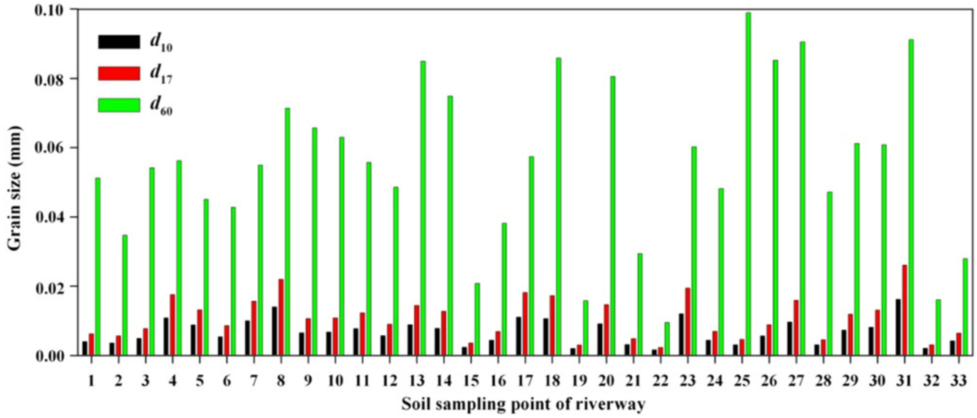

Fig. 3. Grain size of soil sampling point in the riverway of Tarim River from Alar to Qiala.

Section 4, Wusiman-Qiala. Data on the size of particles of the riverbed soil is based on 132 soil samples collected during 2012/13 from 33 sites.

3.2. Hydrological data

The hydrological data comprised monthly volumes of runoff and depths of the water table monitored at the hydrological stations of Alar, Xinqiman, Yingbazha, Wusiman, and Qiala over the period 1960–2013 and monthly groundwater depths from 2010 to 2013 of 86 monitoring wells perpendicular to the flow. Data on ecological water requirement of the desert riparian vegetation was taken from an earlier paper by the author (Ling et al., 2014).

4. Methods

4.1. Variation in the size of soil particles and in hydraulic conductivity

4.1.1. Soil sampling and determination of particle size

The thirty-three sampling sites were along Tarim River at intervals of 20–30 km. To analyse in detail the changes of soil permeability at different depths, we collected the soil samples (50 g each) at four depths, namely 30 cm, 60 cm, 100 cm, and 150 cm, mainly concentrating in the vadose zone. The samples were processed in the laboratory. The processing consisted of edulcoration, desalination, removal of organic matter, and drying (Lei et al., 2006). The samples were treated with a dispersant and cleaned by oscillation for 10 min using an ultrasonic cleaner (SB-4200DTDS, China) before measuring the particle size using a particle size analyser (Mastersizer 2000, Malvern Instruments, Malvern, UK).

4.1.2. Calculation of riverbed hydraulic conductivity

As suggested by previous studies (Vukovic and Soro, 1992; Song et al., 2009), the hydraulic conductivity of soil was calculated using the following equation:

$$K = \left(\frac{g}{v}\right) \cdot C \cdot \varphi(n) \cdot d_e^2 \qquad (1)$$

where K is the hydraulic conductivity (m/day); g is acceleration due to gravity (9.81 m/s^2); v is kinematic viscosity (m^2/s); C is sorting coefficient; $\varphi(n)$ is porosity function, n is porosity, and d_e is the effective particle diameter (mm).

Kinematic viscosity v is determined based on the temperature of water (t, °C) by the following equation:

$$v = 0.01775/\left(1 + 0.0337t + 0.000221t^2\right) \qquad (2)$$

The values of the sorting coefficient C and $\varphi(n)$ in Eq. (1) should be determined by soil texture (Table 2). The equation for calculating the

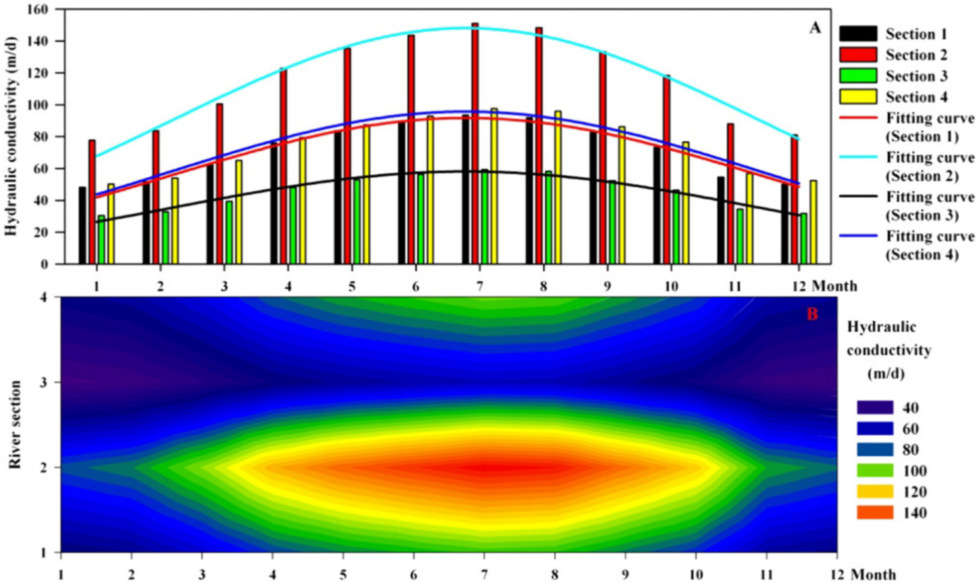

Fig. 4. Spatial-temporal variation of hydraulic conductivity in Tarim River.

Table 3
Amount of available water supply under the different water frequencies in Tarim River.

River section	10% (10^8 m^3)	25% (10^8 m^3)	50% (10^8 m^3)	75% (10^8 m^3)	90% (10^8 m^3)
Section 1	13.64	13.31	13.22	10.10	8.26
Section 2	13.34	13.09	9.57	8.30	7.57
Section 3	17.13	14.75	11.82	8.13	6.61
Section 4	12.67	7.86	6.29	4.04	2.50
Sections 1–4	56.78	49.01	40.90	30.57	24.94

porosity, n, is as follows:

$$n = 0.255(1 + 0.83^{\eta}) \tag{3}$$

$$\eta = d_{60}/d_{10} \tag{4}$$

4.2. Calculation of riverbed leakage conductivity

Darcy's Law, which describes the flow of a fluid through a porous medium, was used for calculating the extent of riverbed leakage in Tarim River from the following equation (Neuman, 1977; Wang, 2007):

$$Q_R = K{\cdot}W{\cdot}L{\cdot}\frac{h_R - h_G}{\Delta L} \tag{5}$$

where Q_R is the riverbed leakage (i.e., leakage from the river to the vadose zone, m^3); K is hydraulic conductivity (m/day); W is the width of the riverway (m); L is the length of the section (m), h_R is river water level (m), h_G is the depth of the groundwater (m), $h_G - h_R$ is the leakage height from the river to the vadose zone and ΔL is the length of the river path that recharges groundwater (m).

The length of the river in different sections was as follows: Section 1, 189 km; Section 2, 258 km; Section 3, 179 km; and Section 4, 219 km. The widths of the sections were calculated based on available prior research, as follows (Song et al., 2000):

$$B_{AL} = 3.6965 Q_{AL}^{0.7992}, \quad R^2 = 0.846 \tag{6}$$

$$B_{XQ} = 0.0305 Q_{XQ}^{1.3439}, \quad R^2 = 0.876 \tag{7}$$

$$B_{YB} = 21.64 \ln Q_{Yb} + 15.88, \text{and } R^2 = 0.952 \tag{8}$$

$$W_1 = (B_{AL} + B_{XQ})/2 \tag{9}$$

$$W_2 = (B_{XQ} + B_{YB})/2 \tag{10}$$

$$W_3 = W_4 = 0.8 B_{YB} \tag{11}$$

where B_{AL}, B_{XQ}, and B_{YB} are widths of the water surface in Alar, Xinqiman, and Yingbazha sections (m), respectively; W_1, W_2, W_3, and W_4 are widths (m) of the water surface in Sections 1 to 4; and Q_{AL}, Q_{XQ}, and Q_{YB} are water velocities (m^3/s) in Alar, Xinqiman, and Yingbazha sections, respectively.

Table 4
Leaking water amounts of different water frequencies in Tarim River.

River section	10% (10^8 m^3)	25% (10^8 m^3)	50% (10^8 m^3)	75% (10^8 m^3)	90% (10^8 m^3)
Section 1	3.21	3.12	2.78	2.56	2.50
Section 2	2.70	2.64	2.49	2.33	2.29
Section 3	2.25	2.02	1.91	1.85	1.72
Section 4	3.20	2.84	2.65	2.57	2.36
Sections 1–4	11.36	10.62	9.84	9.32	8.87

Table 5
Percentage of leaking water to available water supply under the different water frequencies in Tarim River.

River section	10%	25%	50%	75%	90%
Section 1	23.5%	23.4%	21.0%	25.3%	30.3%
Section 2	20.2%	20.2%	26.0%	28.1%	30.2%
Section 3	13.1%	13.7%	16.2%	22.8%	26.0%
Section 4	25.3%	36.1%	42.1%	63.6%	94.4%
Sections 1–4	20.0%	21.7%	24.1%	30.5%	35.6%

4.3. Frequency calculation of water inflow

Earlier estimates of the surface runoff of Tarim River have varied because the volume of flow varies from year to year (Hao et al., 2008). To arrive at reasonable allocations of ecological water in Tarim River, we estimated the runoff in each section at five frequencies of water inflow: −10% is an extremely high-flow year, 25% is a high-flow year, 50% is a normal-flow year, 75% is a low-flow year, and 90% is an extremely low-flow year (Ling et al., 2014; Ye et al., 2014b). The frequencies were calculated based on Pearson-III curve and monthly runoff data from the hydrological stations in Alar, Xinqiman, Yingbazha, Wusiman, and Qiala from 1960 to 2013 (Singh, 1987; Ye et al., 2014b).

4.4. Calculation of water amount to be drawn from ecological brakes

In Tarim River, the ecological water requirement of desert riparian vegetation is met mainly through river leakage and by diversions of the flow achieved by 77 ecological brakes distributed along the course of the river (Fig. 2).

Amount of water to be drawn from ecological brakes was calculated from the following equation,

$$\text{WEB} = \text{EWR} - \text{WBL} \tag{12}$$

where, WBL and WEB are the amounts (10^8 m3) of water leaked through the riverbed and drawn by ecological brakes, respectively, and EWR is ecological water requirement (10^8 m^3).

The ecological water requirement was calculated as follows: we acquired a distribution map of the desert riparian vegetation by digitization, based on Landsat™ images of Tarim River in 2010 and the spatial distribution data on ecological water requirement by using the Field Calculation Module in ArcGIS ver. 10.0 combined with a distribution map of groundwater depth and modelled values of phreatic evaporation. The ecological water requirement of desert riparian vegetation was calculated at intervals of 1 km for stretches perpendicular to the river bank, based on the Buffer Analysis Module in ArcGIS ver. 10.0. The specific research methods are described elsewhere (Ling et al., 2014).

5. Results and analysis

5.1. Variation in the size of soil particles and in hydraulic conductivity

The contribution of soil particles of different diameters to the weight of the soil is shown in Fig. 3. Of the total weight of the soil, 10% was contributed by soil particles with an average diameter of 6.8 μm (group 1, range 1.6–16.2 μm), 17% was contributed by the particles from group 1 together with those with an average diameter of 10.8 μm (group 2, range 2.3–26.0 μm), and 60% by particles of groups 1 and 2 together with those with an average diameter of 55.4 μm (group 3, range 9.5–98.9 μm). The average particle size in the riverbed was thus between 1.6 μm and 98.9 μm. In addition, the variation coefficients (CVs) for the soil particles of d_{10}, d_{17} and d_{60} are respective 0.540, 0.553 and 0.424, thus the d_{60} has the minimum rangeability. Based on the Pearson correlation test, the correlation degrees for the soil particles of the d_{10} to

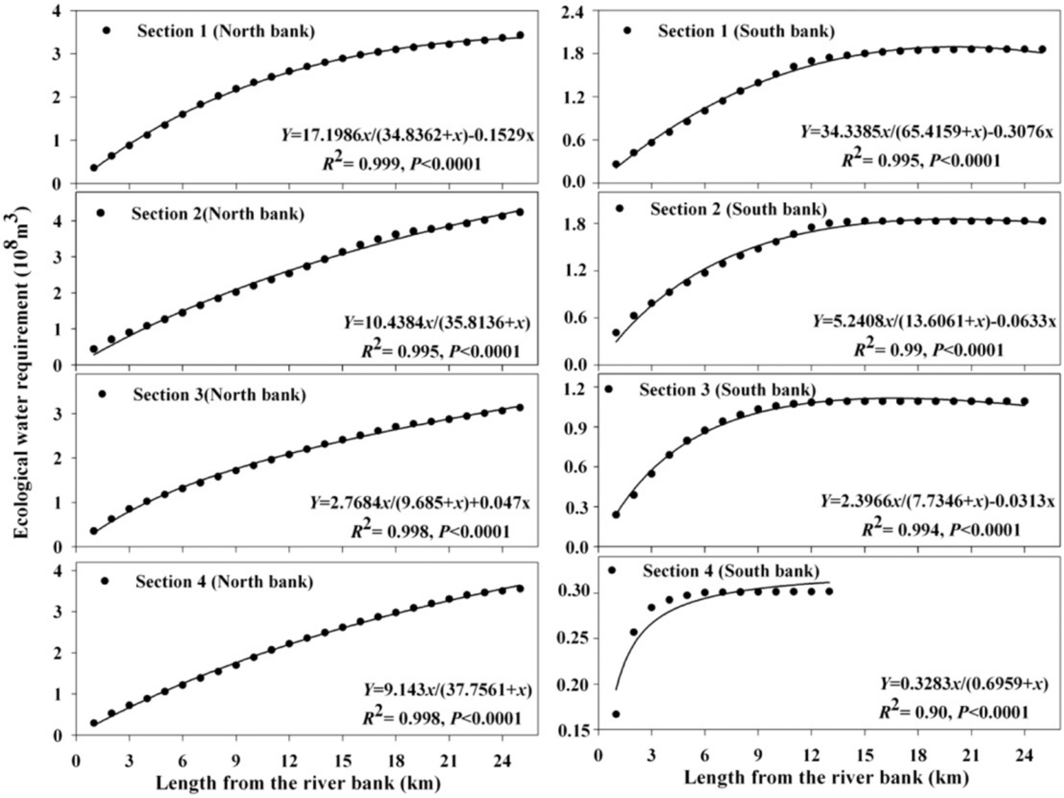

Fig. 5. Ecological water requirements of different distances away from the river channel in Tarim River.

d_{17} and the d_{17} to d_{60} are extreme significant ($P < 0.01$), while it is not so significant for the d_{10} to d_{60} ($P > 0.05$).

Combined with Table 2, the hydraulic conductivity of Tarim riverbed was calculated by the formula proposed by Sauerbrai (Fig. 4) (Song et al., 2009).

Fig. 4A shows that the hydraulic conductivity of all the four sections followed a normal distribution from January to December. The function of the normal distribution was calculated as follows: $f(x) = a * \exp(-\frac{(x-\mu)^2}{2\sigma^2})$, where $\mu = 6.7816, \sigma = 4.6261$, values of a are 91.6822, 148.0488, 58.084, 96.654 for Sections 1 to 4 in that order; $R^2 = 0.97$, $F = 124.3$ and $P < 0.0001$. The hydraulic conductivity was high during April to October, peaking in July (100.327 m/day), and at its lowest in January (51.718 m/day). Section 2 recorded the highest value (115.313 m/day), followed, in that order by Sections 4, 1, and 3.

5.2. Amount of leakage from different river sections

Different frequencies of flow resulted in different percentages of available water supply (Table 3). For example, in high-flow years (water frequencies of 10% and 25%), about 30% of the total supply is available in Section 3 of the river; in normal-flow years (water frequencies of 50%) and low-flow years (water frequencies of 75% and 90%), the available water supplies occupy the rates of 29% and 27%, respectively. Therefore, as the flow decreased, the proportion of the available water supply declined gradually.

As can be seen in Table 4, riverbed leakages in the upper and middle reaches of Tarim River are 11.36×10^8 m^3, 10.62×10^8 m^3, 9.84×10^8 m^3, 9.32×10^8 m^3 and 8.87×10^8 m^3 respectively, and gradually declines, under the water frequencies of 10%, 25%, 50%, 75% and 90%. Section 1 and Section 4 show relative high rate, their combined values being 56.4%, 56.1%, 55.2%, 55.0%, and 54.8% under the five water frequencies, respectively; Section 3 shows minimal leakage, the corresponding values being 19.8%, 19.0%, 19.4%, 19.9%, and 19.4%.

Using the data in Table 3, we calculated, for each section, the proportions of leaked water in the total and available water supply (Table 5), which ranged from 20.0% to 35.6%, increasing gradually as the inflow of water decreased in Tarim River. Especially, Section 4 held the maximum proportion, the corresponding values being 25.3%, 36.1%, 42.1%, 63.6%, and 94.4% under the water frequencies of 10%, 25%, 50%, 75% and 90%.

5.3. Water diversion scheme for allocation of ecological water

According to Fig. 5, the ecological water requirement was significantly and positively correlated to the distance from the river ($R^2 \geq 0.9$, $P < 0.0001$) on both the banks. Therefore, it is possible to calculate accurately the range (distances from the river) over which ecological water requirement of the desert riparian vegetation can be met - a figure particularly significant for developing a regime that can maintain the stability of the desert riparian vegetation ecosystem by ensuring a minimum level of ecological water supply.

Using the data from Table 4 and plotting the amounts of leakage onto the graph shown in Fig. 5, we calculated the range over which water leakage can meet the ecological water requirement in every section at different water frequencies (Fig. 6).

From the Fig.6, the farthest point thus calculated was 10.0 km away from river in Section 1, 8.1 km in Section 2, 4.9 km in Section 3, and 5.0 km Section 4 (Bai et al., 2013). Therefore, the ecological water requirement of the desert riparian vegetation can be met over the stretch between 4.9 km and 10.0 km from the river. Therefore, we defined the range over which water leakage can meet the ecological water requirement by buffer analysis using ArcGIS ver. 10.0 (Fig. 6 and Table 6). Overall, such influence of the leaked water extended farther in the south

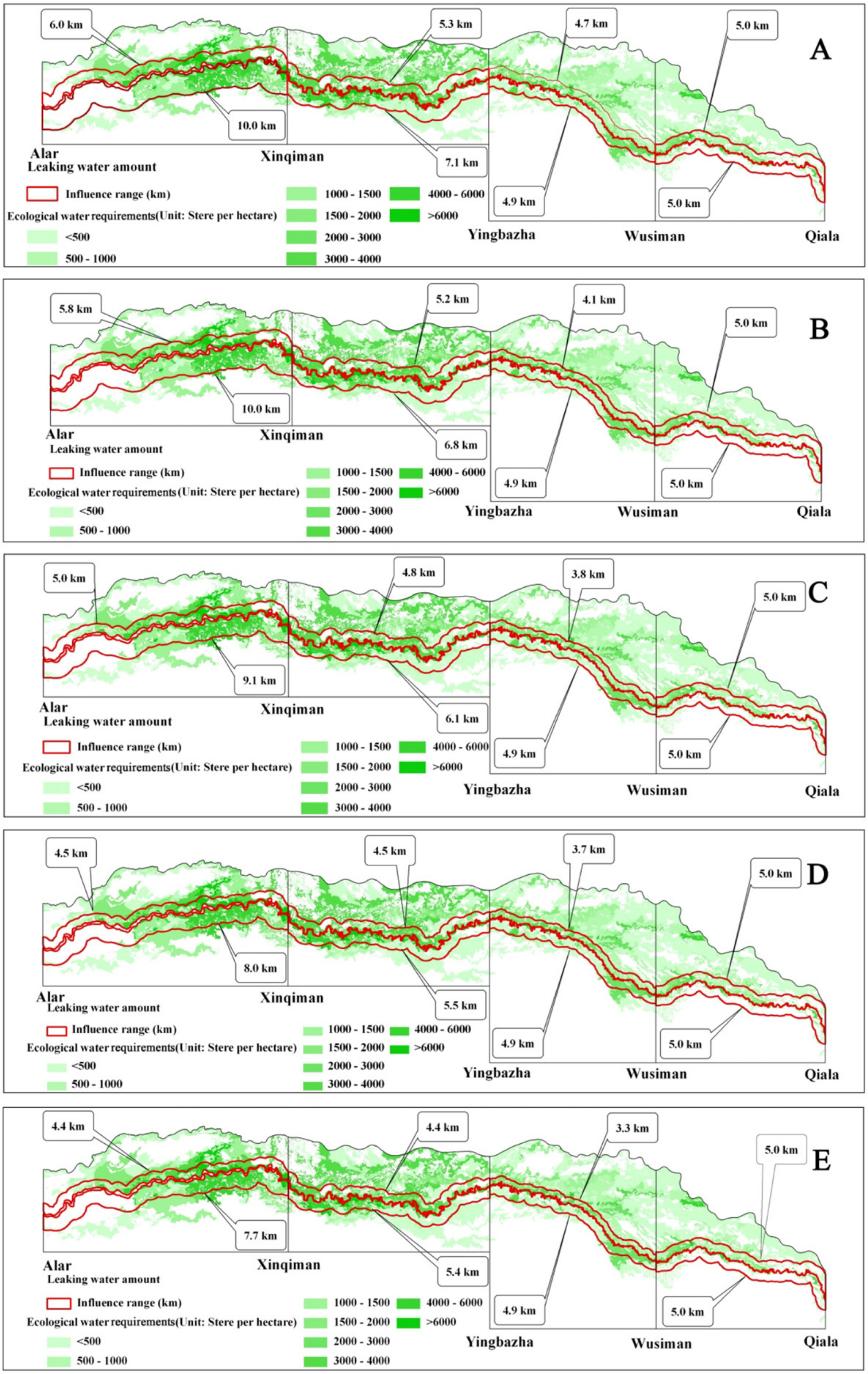

Fig. 6. Influence range of leaking water amount for ecological water requirement under the different water frequencies (A. 10%, B. 25%, C. 50%, D. 75% and E. 90%) in Tarim River.

Table 6
Influence range of leaking water amount under the different water frequencies in Tarim River.

River section	River bank	Ecological water requirement (10^8 m^3)	Influencing range of leaking water amount (km)				
			10%	25%	50%	75%	90%
Section 1	North	3.84	6.0	5.8	5.0	4.5	4.4
	South	1.86	10.0	10.0	9.1	8.0	7.7
Section 2	North	5.75	5.3	5.2	4.8	4.5	4.4
	South	1.83	7.1	6.8	6.1	5.5	5.4
Section 3	North	3.83	4.7	4.1	3.8	3.7	3.3
	South	1.09	4.9	4.9	4.9	4.9	4.9
Section 4	North	3.80	5.0	5.0	5.0	5.0	5.0
	South	0.30	5.0	5.0	5.0	5.0	5.0

bank in Sections 1 to 3 and for about the same distance as in the north bank in Section 4.

We also estimated the amount of water drawn by the ecological brakes (Table 7), based on ecological water requirement and riverbed leakage (Table 4 and Table 6).

From the Table 7, the amounts of drawn water are 13.27 × 10^8 m^3, 13.49 × 10^8 m^3, 13.95 × 10^8 m^3,14.36 × 10^8 m^3 and 14.52 × 10^8 m^3 under the five water frequencies, respectively; more specifically, the values ranged from 0.02 × 10^8 m^3 in Section 4 to 4.61 × 10^8 m^3 in Section 2, with the north bank drawing more than the south bank by 10.89 × 10^8 m^3, 11.04 × 10^8 m^3, 11.18 × 10^8 m^3, 11.21 × 10^8 m^3, and 11.28 × 10^8 m^3.

Lastly we estimated the amount of water drawn and lost by leakage as percentage of ecological water requirement (Fig. 7).

As shown in Fig. 7, percentages of drawn water to ecological water requirement in Section 1 to 4 are 58.2%–67.5%, 76.5%–80.1%, 70.8%–77.6% and 71.8%, respectively; in the south bank of the four sections, the corresponding values are 20.4%–32.5%, 26.2%–37.5%, 29.1% and 5.0%. Overall, the ecological water requirement in the north bank is met mainly by the ecological brakes whereas those in the south bank are met mainly through leakage from the riverbed.

6. Discussion

6.1. Reasons for variations in hydraulic conductivity and amount of leakage

The calculated values of hydraulic conductivity were within a reasonable range for a given set of soil conditions, which means that the empirical formulae adopted in the present study are suitable for the area studied, and that the results are reasonable (Zheng and Bennett, 2009). In Tarim River, hydraulic conductivity is high from April to October, because the mean water temperature during this period is 16.6 °C higher than that during the period from November to March. Hydraulic conductivity also varied with the section, being the highest in Section 2 and the lowest in Section 3. Because the difference in water temperature among the four sections is not significant ($F = 0.052$, $P = 0.984 > 0.05$), the differences in conductivity must be due to the size of the soil particles (Table 8).

Table 7
Drawing water amount by using the ecological brake under the different water frequencies in Tarim River.

River section	River bank	Drawing water by using the ecological brake (10^8 m^3)				
		10%	25%	50%	75%	90%
Section 1	North	2.24	2.28	2.45	2.56	2.59
	South	0.38	0.38	0.46	0.57	0.61
Section 2	North	4.40	4.44	4.51	4.59	4.61
	South	0.48	0.51	0.59	0.67	0.69
Section 3	North	2.71	2.82	2.88	2.91	2.97
	South	0.32	0.32	0.32	0.32	0.32
Section 4	North	2.73	2.73	2.73	2.73	2.73
	South	0.02	0.02	0.02	0.02	0.02

Table 8
Analysis of change processes on hydraulic conductivities in the different river section.

River section	η (d_{60} / d_{10})	n	d_{17} (mm)	$\varphi(n)$	$\varphi(n) * (d_{17})$^2
Section 1	8.7848	0.3046	0.0100	0.0312	3.1348E − 06
Section 2	6.1797	0.3356	0.0154	0.0426	1.0070E − 05
Section 3	9.7591	0.2964	0.0101	0.0285	2.8951E − 06
Section 4	9.5146	0.2983	0.0112	0.0291	3.6852E − 06

Eq. (1) shows that the key factors that determine the hydraulic conductivity are $\varphi(n)$ (a function of d_{10} and d_{60}) and d_{17}. The maximum value of $\varphi(n)$ was recorded in Section 2, followed, in that order, by Sections 1, 4, and 3, and the maximum value of d_{17} was recorded in Section 2, whereas the value of $\varphi(n) * (d_{17})$^2 corresponded with hydraulic conductivity in all the four sections. There was a close and positive relationship between the extent of leakage and water frequencies: the amount of leakage declined with the decrease in frequency (Table 8).

6.2. Ecological water allocation in Tarim River

At the five frequencies of inflow (10%, 25%, 50%, 75%, and 90%), river leakage can meet roughly 35%–40% of the ecological water requirement of the desert riparian vegetation in Tarim River. Therefore, it is inappropriate for some researchers who only study the normal inflowing level for ecological water allocation (Millot et al., 1992; Bangash et al., 2012). The reason is that the satisfaction degree of ecological water requirement of desert riparian vegetation may be even worse under low inflow periods (Ling et al., 2014), while much precious water will be wasted under high inflow periods (Song et al., 2000; Gupta et al., 2015; Rai et al., 2015). In this study area, the vegetation is mainly distributed on both banks within 3.3–10.0 km from the river (Bai et al., 2013; Ling et al., 2014); forests of *Populus euphratica* and grassland are the great natural green barriers that protect the stability of the ecosystem; they offer adequate cover (degree of coverage > 30%), grow well, spread over wide areas, and grow when groundwater depth is 4–5 m. Besides, the desert riparian vegetation beyond 10.0 km is distributed in the form of a belt, with low coverage (degree of coverage < 30%), and grows where groundwater depth is >5 m, supplied mainly by drawing water using ecological brakes (Ling et al., 2014). In drawing water through ecological brakes, priority is given to areas where water table is low and vegetation is sparse. Therefore, the ecological water allocation should be in terms of the natural distribution of vegetation (Zacharias et al., 2005). In addition, ecological water allocation in other places merely focus on the riverbed leakage (Zhao et al., 2007; Wang et al., 2010; Narres et al., 2012), whereas, our research not only calculates the extent to which water leakage meets ecological water requirement, but also puts forward the amount of water drawn by the ecological brakes and this is a new step forward in study of ecological water allocation.

Our data (Table 4 and Table 6) shows that such water should be drawn as guided by the data in Table 7 and extra water supplied through flooding once or twice a year when the supply exceeds the ecological water requirement of the desert riparian vegetation (Fu et al., 2014). However, in low-flow years, when demand outstrips supply (as in Section 4 at 90% frequency, for example), drawn water should be concentrated to the period from June to September, because all the three important phases or periods, namely the period in which the inflow is relatively abundant, that during which the ecological water requirement peaks, and that during which the plants renew and reproduce, coincide with the above four months (Ye et al., 2012; Ling et al., 2014). The purposes of ecological water allocation are to protect the desert riparian vegetation and accomplish effective utilization of ecological water (Xu et al., 2007; Ling et al., 2014). Therefore, ecological water should been supplied according to the growth and breeding characteristics of the

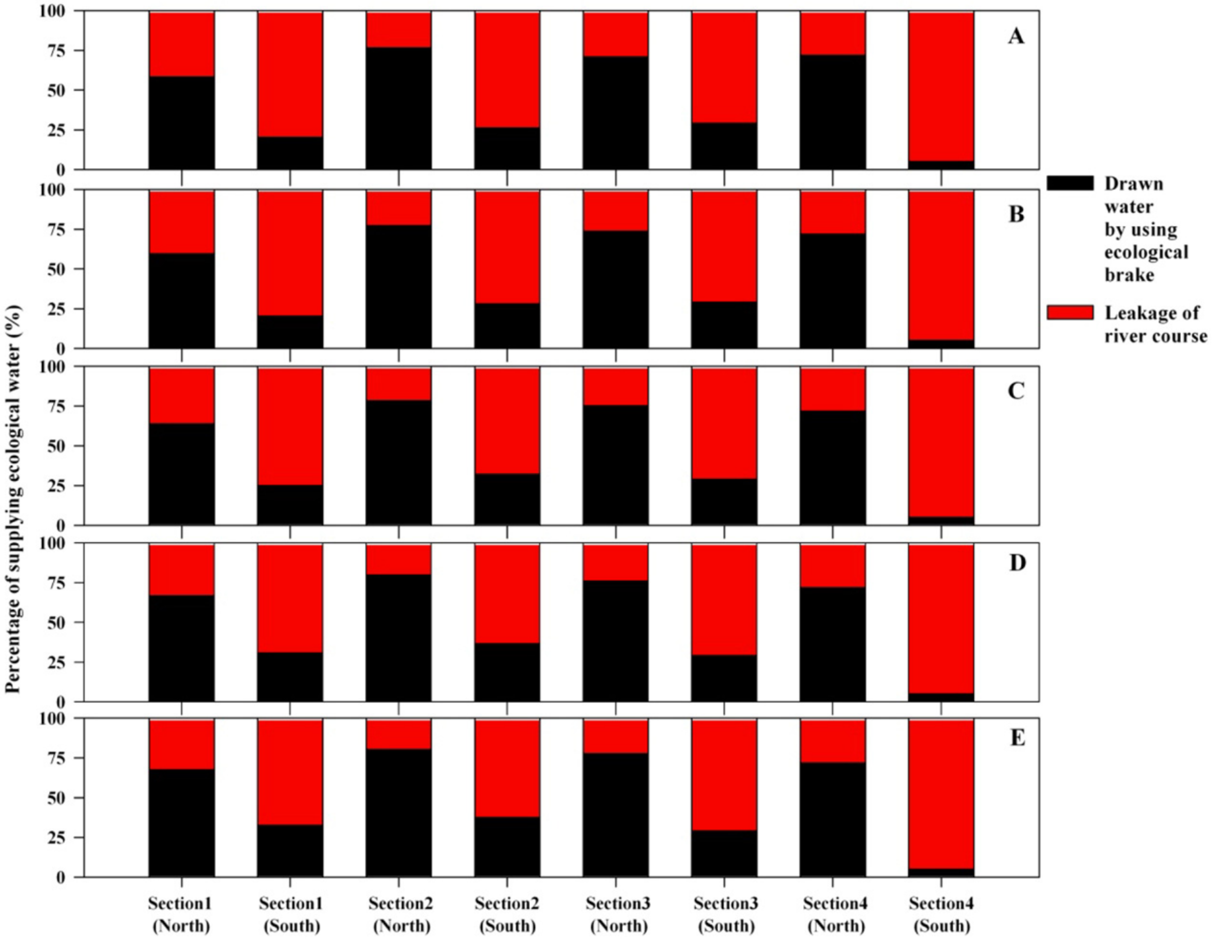

Fig. 7. Percentages of drawing water and leakage to ecological water requirement under the different water frequencies (A. 10%, B. 25%, C. 50%, D. 75% and E. 90%) in Tarim River.

vegetation (Xu et al., 2007; Ye et al., 2012). However, less of other studies have mentioned it when making the plan of ecological water allocation. In addition, earlier research suggests (Ling et al., 2014) that water supply should meet at least 55% of the ecological water requirement of the desert riparian vegetation in this river basin.

7. Conclusions

According to our research, the size of soil particles in the riverbed of Tarim River ranges from 1.6 μm to 98.9 μm, thus the hydraulic conductivity should be calculated based on the Sauerbrai formula. The monthly variation in hydraulic conductivity follows the normal distribution. The results establish a theory foundation for the further calculation of riverbed leakage. According to calculation, as the water inflow declined, the proportion of leaked water in the available water supply increased gradually. Therefore, the ecological water should been reasonably allocated in accordance with water inflow.

Ecological water requirement of the desert riparian vegetation is supplied mainly by leakage from the riverbed in the south and by the water drawn from ecological brakes in the north. The extent of drawn water as a percentage of the ecological water requirement from Section 1 to Section 4 is 58.2%–67.5%, 76.5%–80.1%, 70.8%–77.6%, and 71.8% in the north bank; the corresponding figures for the south bank are 20.4%–32.5%, 26.2%–37.5%, 29.1%, and 5.0%. The results can offer a scientific guide on efficiently running the ecological brakes and achieving the optimal allocation of the ecological water in Tarim River Basin.

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