Environ Earth Sci (2016) 75:782
DOI 10.1007/s12665-016-5573-x

THEMATIC ISSUE

Characteristics of soil infiltration in the Tarim River floodplain

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Received: 25 August 2015 / Accepted: 19 March 2016

Abstract The ecology in the Tarim River Basin is influenced by inundation of its floodplain. To date, however, there is limited information about the infiltration properties of floodplain soils that are inundated by this river. The aim of this study was to investigate steady-infiltration rates of these soils under four different hydraulic heads (5, 10, 20, and 30 cm). Results showed that the mean infiltration rates were generally high and ranged from 3.17 to 3.50 cm h^{-1} when the hydraulic head was between 5 and 30 cm. The steady infiltration increased slightly as the hydraulic head increased. The relationship between the hydraulic head and the infiltration rate can be described by the equation $y = 0.0122x + 3.072$, ($R^2 = 0.739$), where y is the steady-infiltration rate and x is the hydraulic head. There was no significant difference between the infiltration rates for the four different hydraulic heads. The infiltration rate was highest for loamy sand, followed by sandy loam, and was lowest for silt soils. Infiltration was influenced by soil texture and crust, and was low (<1 cm h^{-1}, hydraulic head of 5 cm) for soils with thick crusts, and high for soils without surface crusts (mean of 6.09 cm h^{-1}, hydraulic head of 5 cm). The steady-infiltration rate was not influenced by soil organic matter. These results indicate that flood water can percolate into the floodplain soils and give an improved understanding of the factors that influence the ecological processes on the Tarim River floodplains.

Keywords Infiltration rate · River flooding · Topsoil · Tarim River · Hydraulic head

Introduction

Floods are important sources of recharge water in several arid lands worldwide (Morin et al. 2009). With suitable management practices, floods can benefit the ecology in arid and semi-arid areas (Kowsar 1992). Flood spreading is a flood management and water-harvesting method that increases groundwater recharge, improves soil fertility, and provides soil nutrition (Dhruva Narayana et al. 1990; Unger et al. 2009). Global warming increases the water-holding capacity of the atmosphere and accelerates the water redistribution in the atmosphere (Whitfield 2012). Global warming is also associated with increased flooding (Kundzewicz and Schellnhuber 2004). Therefore, flooding is expected to exert serious impacts on water cycle and ecology in the future.

The Tarim River is the largest continental river in China. In recent years, climate change has increased the temperature and precipitation (Xu et al. 2008; Chen and Xu 2005; Chen et al. 2007, 2013) in the region, and the increase in temperature has accelerated glacier melting (Li et al. 2010). Glacier melting is anticipated to dramatically increase in the next 50 years, which may increase the frequency of flooding (Li et al. 2010). Therefore, flooding may become a serious concern along the Tarim River in the future.

This article is part of a Topical Collection in Environmental Earth Sciences on ‘‘Water in Central Asia’’, guest edited by Daniel Karthe, Iskandar Abdullaev, Bazartseren Boldgiv, Dietrich Borchardt, Sergey Chalov, Jerker Jarsjö, Lanhai Li and Jeff Nittrouer.

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Severe natural flooding events have recently occurred in the region. The Tarim River floodplain covers an area of approximately 3000–5000 km^2. Shen et al. (2006) reported that the Tarim River floods 1.74 times annually from 1951 to 2000. Flood peaks >800 m^3/s occurred almost annually from 2000 to 2006, and flood peaks >1000 m^3/s occurred in 6 of these 7 years (Chen et al. 2011).

Planned or controlled flooding is indispensible to rehabilitate rivers and reverse ecosystem degradation (Wuetrich 1996). But the new embankment project was built and reduced the natural river flooding. To recover the degenerated natural vegetation, ecological water consumption has been artificially regulated by an ecological gate (Chen et al. 2007). The purpose of the ecological gate (Fig. 1) was that it provides river water (like natural flood before) to plants in the Tarim River. Ecological gates controlled the river flooding of the Tarim River. Artificial planned flooding have been used in many regulated streams and rivers to flush fine sediments, increase sediment porosity, improve morphological integrity, and enhance ecological conditions for the development of plant communities (Gabrielie et al. 2005; Jansson et al. 2005). Regulated flooding could supply water for seed germination (Xu et al. 2009) and vegetation recovery along the Tarim River. However, the volume of water infiltration or the rate of infiltration under various flood water depths in the Tarim River Basin is unknown. For planned flooding, the regulated flow of ecological gates, the appropriate amount of water to be released during flooding, and the depth of flood water that greatly increases soil moisture must be determined. Low infiltration rate and flood depth only slightly contribute to increase in soil moisture and groundwater because of the strong potential evaporation (>2000 mm) in the Tarim River basin. Moreover, the amount and infiltration direction of runoff are important determinants of vegetation patterns (Arnau-Rosalén et al. 2008; van Schaik 2009). Vegetation patterns also affect the amount and spatial distribution of infiltration. Dahan et al. (2008) reported that the management of water resources in arid environments relies on quantifying flood water infiltration that recharges the shallow alluvial aquifers.

Fig. 1 A ecological gate in the low reach of Tarim River

Previous studies (Xu et al. 2009; Yu et al. 2012) investigated the effect of flooding in Tarim Basin on the ecological characteristics of riparian vegetation. Results show that flooding affects flow (Sun et al. 2012), eco-hydrological processes (Liu et al. 2012; Yu et al. 2012; Hao et al. 2010; Chen et al. 2004; Chen et al. 2006), soil properties (Zhou and Li 2011; Zhou et al. 2010), water quality (Xu et al. 2012; Huang and Pang 2012), and land cover (Zhao et al. 2013; Xu et al. 2009). However, the mechanism by which water infiltrates into soil in the region remains unknown. Therefore, determining the infiltration characteristics in the river floodplain of the Tarim River is critical to assess the contribution of natural or artificial planned flooding to soil water replenishment. This study aimed (1) to determine the steady-infiltration rate and (2) to measure the steady-infiltration rate under various levels of flood hydraulic head in the laboratory.

Materials and methods

This study was conducted at the upper and middle reaches of the Tarim River, which is located in the inland arid region of Northwest China. The Tarim River Basin is located near the Taklimakan Desert, the largest desert in China with a total land area of 1.02×10^6 km^2. The average annual surface runoff at the confluence of three headstreams (Aksu, Yarkand, and Hotan Rivers) is 45×10^8 m^3. Runoff is mainly composed of snowmelt from and precipitation in mountain areas. Our study area is located between the Alaer and Yingbazha transects in the upper and middle reaches of the Tarim River (Fig. 2). The Tarim River Basin has an extreme arid desert climate with an average annual temperature ranging from 10.6 to 11.5 °C and a monthly mean temperature ranging from 20 to 30 °C in July and −10 to −20 °C in January. The annual precipitation varies from 20 to 50 mm, but the annual potential evaporation can reach 2500–3000 mm. The most dominant species in the area include *Populus euphratica*, *Tamarix* spp., *Lycium ruthenicum*, *Karelinia caspica*, *Phragmites communis*, *Alhagi sparsifolia*, and *Glycyrrhiza inflata.*

Undisturbed soil infiltration rates were measured under varying hydraulic gradients in the laboratory using an infiltration instrument. The laboratory method of determining soil infiltration and hydraulic conductivity is used

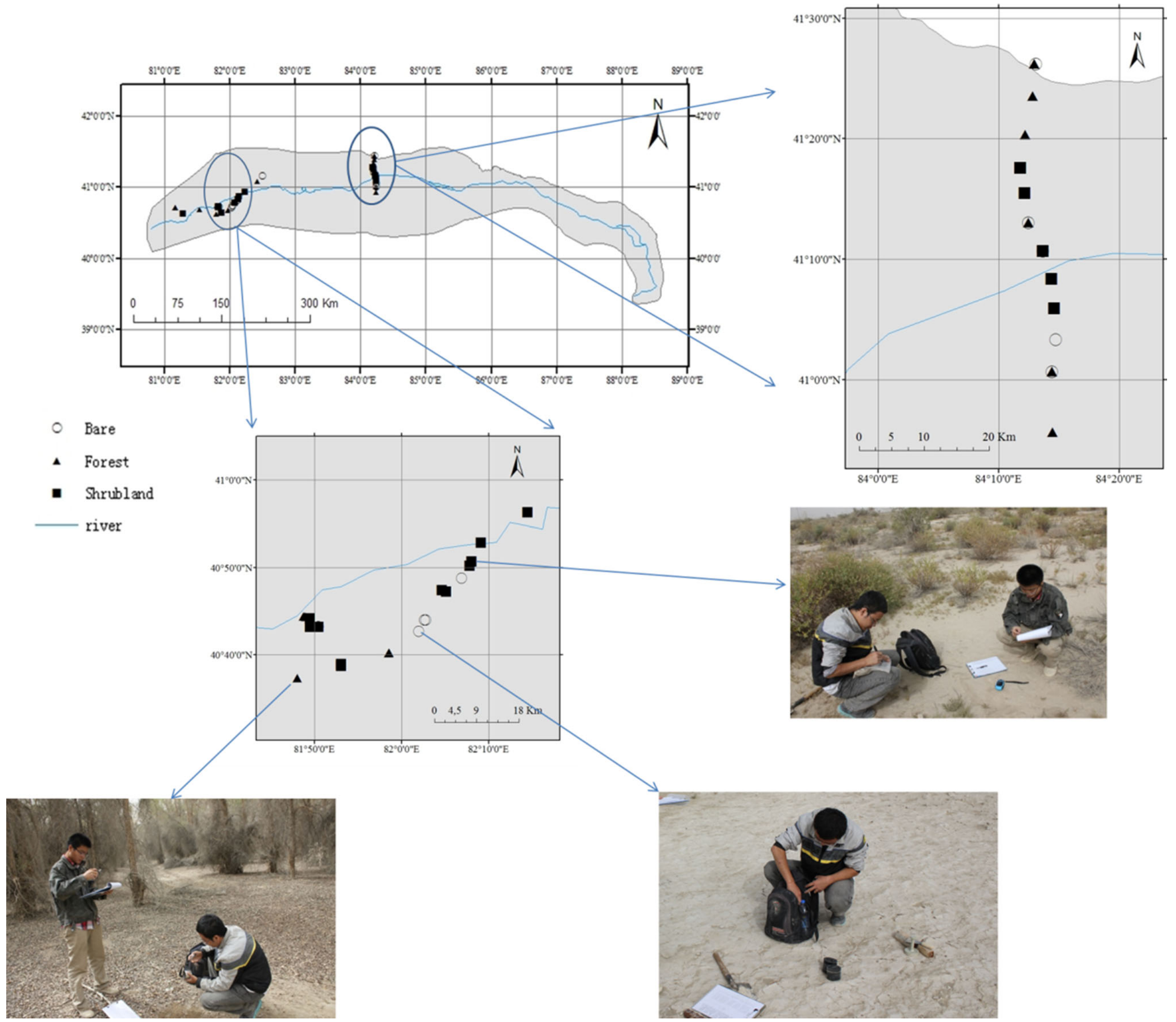

Fig. 2 Location of soil sampling sites in the river floodplain of the Tarim River

by many scientists because of its reliability (Klute and Dirksen 1986; Bruckler et al. 2002). The instrument comprises a soil cylinder, a water supply tube, and a Mariotte bottle. The soil cylinder was 5.2 cm in length and 7.0 cm in diameter. Amoozegar and Wilson (1999) suggested that the samples collected or prepared by the above techniques are usually 5–10 cm in diameter. A constant water depth is usually used in infiltration experiments (Chowdary et al. 2006; Angulo-Jaramillo et al. 2000). In the present study, the water level was controlled at 5, 10, 20, and 30 cm during the respective measurements. Soil samples were collected using short cylindrical iron rings, 5.2 cm in length and 7.0 cm in diameter. Fifty-one undisturbed topsoil samples (0.0–5.2 cm depth) were collected (Fig. 2). The steady-state infiltration rate was measured for each soil sample.

Soil particle size was analyzed using a Malvern Mastersizer S laser diffractometer (Malvern Instrument, Malvern, England), which measures the volume percent of particles in 100 size classes from 0.02 to 2000 μm in diameter. Soil texture was determined by the percentage of clay (<2 μm), silt (2–50 μm), and sand (50–2000 μm) in accordance with the taxonomy developed by the US Department of Agriculture. Soil organic matter content was determined using the potassium dichromate method. These properties were measured using other samples collected in the field. The measured soil samples were collected at the same time and place.

The thickness of the soil crust was measured as follows. A cross section of the soil was first exposed by vertically slicing through the soil profile with a knife and then inserting the knife horizontally. The knife was gently lifted to expose the cross section of the crust, which was then gently tilted on one side to measure the thickness with a ruler.

A nonparametric statistical test was conducted to compare the mean infiltration rates ($p < 0.05$) in various treatments. The differences between individual means were evaluated using the Mann–Whitney *U* test. Our null hypothesis (H_0) was that no significant difference in infiltration rate exists between two treatments, whereas our alternative hypothesis (H1) was that a significant difference exists between two treatments. If $p < 0.05$, we rejected H_0 and accepted H1. Statistical analysis was conducted using SPSS 19.0 for Windows (Field 2000).

Results and discussion

The steady-state infiltration rates significantly differed in floodplain of the Tarim River in the entire research region. The steady-state infiltration rates ranged from 0.09 to 14.45 cm h^{-1} (mean 3.17 cm h^{-1}) at the 5 cm hydraulic head, 0.07 to 11.82 cm h^{-1} (mean 3.20 cm h^{-1}) at the 10 cm hydraulic head, 0.11 to 11.82 cm h^{-1} (mean 3.25 cm h^{-1}) at the 20 cm hydraulic head, and 0.07 to 14.70 cm h^{-1} (mean 3.50 cm h^{-1}) at the 30 cm hydraulic head. At the 5–30 cm hydraulic head treatment, the mean infiltration rate ranged from 3.17 to 3.50 cm h^{-1}.

The infiltration rate only slightly increased with increasing hydraulic head. These data suggest that a relationship exists between hydraulic head and infiltration rate ($y = 0.0122x + 3.072$, $R^2 = 0.739$, y was steady-infiltration rate, x was hydraulic head). The results of the nonparametric test showed that the infiltration rates at the four hydraulic heads were not significantly different from one another.

The steady-infiltration rate of the 51 soil samples greatly varied. Soil texture significantly influences infiltration rate (Saxton et al. 1986; Abu-Hamdah et al. 2006; Liu et al. 2003). Table 1 shows that soil texture was different among these samplers. Loamy sand had high infiltration rate (mean 8.98 cm h^{-1} at 5 cm column), followed by sandy loam (mean 5.23 cm h^{-1} at 5 cm column), the silt soils had the lowest infiltration rate (mean 1.60 cm h^{-1} at 5 cm column) (Fig. 3). Soils with similar textures, particularly bare soils, differed in infiltration rate, indicating that other factors aside from soil texture contribute to low infiltration. The physical crust might be the other reasons causing low infiltration rates. Previous laboratory or field experiments and numerical simulations revealed that physical soil crust reduces hydraulic conductivities and infiltration rates (Romkens et al. 1990; Singer and Bissonnais 1998). Lu and Yang (2004) reported that crust removal reduces the hydraulic conductivities of soil by ten times that of soil with a crust layer in arid deserts. Our measurements also indicated that soil crusts significantly hindered infiltration. In addition, thick crusts were found in all soils with low infiltration rates (<1 cm h^{-1} at 5 cm hydraulic head, mean value was 0.93 cm h^{-1}) (Table 1), particularly in most bare soils (90 %) that exhibit a thick (>5 mm) and solid crust. The soils without surface crust had high infiltration rate, and the mean value was 6.09 cm h^{-1} at 5 cm hydraulic head.

Previous researchers (Martens and Frankenverger 1992; Osuji et al. 2010) suggested a positive relationship between soil organic material and infiltration rate. Organic material increases the macroporosity of the soil, thereby improving water infiltration (Martens and Frankenverger 1992). However, this relationship was not observed in our research. The thick crust soils contained a high content of soil organic material (10.4 g kg^{-1}), but still had low infiltration rates. This result indicates that soil organic material is not an important factor affecting infiltration in the river floodplain of the Tarim River.

Numerous scientists (Philip 1958; Wu et al. 1997; Abbasi et al. 2003; Warrick et al. 2005; Feng et al. 2001; Chowdary et al. 2006; Fox et al. 1998) found a close relationship between hydraulic head and infiltration rate. In the present study, the infiltration rates increased with increase in depth of the hydraulic head. Philip (1958) reported that increasing hydraulic head also increases the infiltration rate and the cumulative infiltration by approximately 2 %/cm of hydraulic head. Our results were slightly higher than those of Philip (1958) because of the different soil textures employed. Philip (1958) studied Yolo light clay, whereas we investigated silt loam and sandy loam. In the study by Wu et al. (1997), the falling head infiltration rates decreased by 30 % when the ponded head was reduced from 5 to 1 cm in the sandy clay loam. Our results were inconsistent with those of Wu et al. (1997) because of the different hydraulic heads employed. Wu et al. (1997) studied the ponded head from 1 to 5 cm, whereas we applied the head range from 5 to 30 cm. Tian (2011) developed a relation ($y = 0.0184x + 1.078$, $R^2 = 0.988$, y is the steady-infiltration rate, x is the hydraulic head) between the depth of ponding water and the infiltration rate by numerical simulation; it was similar to our results. Guo et al. (2010) reported that hydraulic conductivities decrease with increasing hydraulic head. They attributed this observation to soil compression, which reduces soil porosity and increases soil bulk density at a high water pressure head (60 cm). The present results differed from those reported by Guo et al. (2010) because

Table 1 Soil texture and surface characteristics at 51 soil sample sites

No	Vegetation type	Texture	Crust	Infiltration rate (cm h^{-1})[a]	No	Vegetation type	Texture	Crust	Infiltration rate (cm h^{-1})
01	Forest	Sandy loam	Very thin	8.19	27	Shrubland	Sandy loam	Very thin	4.58
02	Forest	Sandy loam	No	5.04	28	Shrubland	Sandy loam	No	2.16
03	Forest	Silt loam	Very thin	1.12	29	Shrubland	Sandy loam	No	6.93
04	Forest	Silt loam	Thin	1.59	30	Bare	Silt loam	Thick	0.40
05	Forest	Silt loam	Thin	1.995	31	Bare	Silt	Thick	1.20
06	Bare	Silt loam	Thick	0.84	32	Shrubland	Silt	Thin	1.80
07	Shrubland	Silt loam	Thick	0.84	33	Shrubland	Silt loam	Thin	7.68
08	Shrubland	Loamy sand	No	10.75	34	Shrubland	Silt loam	Thin	3.34
09	Shrubland	Silt loam	Thin	1.38	35	Shrubland	Silt	Thin	2.62
10	Shrubland	Sandy loam	No	2.88	36	Forest	Silt	Thin	4.19
11	Shrubland	Silt loam	Thick	0.96	37	Forest	Silt loam	Thin	1.20
12	Shrubland	Silt loam	No	6.93	38	Forest	Silt loam	Thick	1.00
13	Shrubland	Silt loam	Very thin	3.0975	39	Forest	Loamy sand	No	5.32
14	Bare	Silt	Thick	0.80	40	Forest	Silt loam	No	1.02
15	Shrubland	Silt loam	Thin	1.176	41	Forest	Silt loam	Thin	1.20
16	Shrubland	Silt loam	Thick	2.01	42	Forest	Sandy loam	Very thin	6.89
17	Bare	Silt	Thick	1.06	43	Forest	Silt	Thick	1.90
18	Bare	Silt loam	Thin	1.26	44	Forest	Silt loam	Thin	2.40
19	Forest	Silt loam	Thin	1.29	45	Bare	Silt	Thick	0.09
20	Shrubland	Silt loam	Thin	3.67	46	Bare	Silt	Thick	0.77
21	Shrubland	Silt loam	Thin	1.60	47	Bare	Silt loam	Thick	0.40
22	Forest	Silt loam	Thin	11.9	48	Bare	Silt loam	Thick	0.50
23	Shrubland	Loamy sand	No	5.40	49	Forest	Silt loam	Thin	1.80
24	Bare	Silt loam	Thick	1.20	50	Forest	Silt loam	Thin	2.95
25	Shrubland	Loamy sand	No	14.45	51	Forest	Silt loam	Thin	1.34
26	Forest	Silt loam	Thin	6.90					

[a] Infiltration rate was steady-infiltration rate at 5 cm hydraulic head

of two possible reasons. First, the soils we measured were undisturbed soils, whereas Guo et al. (2010) took measurements on disturbed soils, which can be easily compressed. Another possible reason is the lower hydraulic head (5–30 cm) in the present research compared with the study conducted by Guo et al. (2010) (10–60 cm). Philip (1958) reported that infiltration rate was reduced by approximately 1 % as the hydraulic head was 200 cm. Therefore, future research should focus on understanding the effect of high hydraulic heads on infiltration. The depth of flood could reach 120 cm in low-lying areas during our investigation.

Xu et al. (2009) and Yu et al. (2012) observed that river flood influences riparian vegetation along the Tarim River by increasing the amount of available water. However, the effect of flood water on soil moisture has not yet been determined. The present results showed that soils exhibited high infiltration rates, indicating that flood water could efficiently percolate into soils. This finding could explain the ecological process in the Tarim River. The stream beds of ephemeral rivers are largely composed of permeable, coarse alluvial sediments that promote relatively rapid infiltration of floodwater that recharges the local alluvial aquifers in arid environments (Izbicki 2002; Izbicki et al. 2000).

A positive relationship was found between hydraulic head and infiltration rate, but no significant difference was observed among the four hydraulic heads. In addition, the infiltration rate only slightly increased with increasing hydraulic head. Therefore, high flood depths may not be efficient in rehabilitating the Tarim River Basin, although the effects of flood frequency and duration may be considered for ecological gate irrigation.

Our research also measured the surface infiltration rates of topsoils. Topsoil replacement in reclaimed mine lands is vital to improve infiltration and enhance nutrient cycling; topsoil is also an important plant rooting medium and a potential source of plant propagules to increase plant community diversity (Bowen et al. 2005). Percolation through the subsoil, however, may control surface

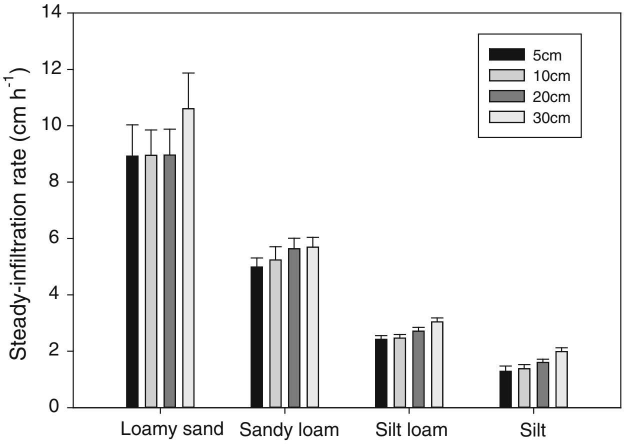

Fig. 3 Steady-infiltration rate of soil samples with different soil texture taken from the river floodplain of the Tarim River, measured at four hydraulic heads

infiltration. The less permeable layer governs the infiltration process regardless of whether or not this layer lies above or below the more permeable layers (Colman and Bodman 1945); therefore, the less permeable layer mainly controls the entire infiltration process (Damodhara-Rao et al. 2006). Future studies will focus on water infiltration in the entire soil profile (e.g., subsoil) in the river floodplain of the Tarim River.

Conclusion

Fifty-one soil samples were taken from the upper 5.2 cm layer of the soil profile in the flooding area of the Tarim River. Measurement of infiltration rate on those soils indicated that there was no significant difference among the four hydraulic heads of 5, 10, 20 and 30. Soil texture and crust considerably influenced infiltration. Our results explained some of the positive ecological effects of flooding in the Tarim River Basin. The present results also suggest that the effects of flood frequency and duration may be considered for ecological gate irrigation.

Acknowledgments This research was supported by the National Natural Science Foundation of China (Grant No. 41201040, 41571035 and 41371011), the National 973 project (No. 2013CB429905) of China, and the Foundation of Chinese Academy of Sciences (Grant No. XBBS201207).

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