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Response to environmental flows in the lower Tarim River, Xinjiang, China: Ground water

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Abstract

In China's west since the 1950s large-scale ecosystem degeneration has occurred through water diversions for agricultural purposes. Since 2000, $1038 \times 10^6\,m^3$ of water have been released into the Tarim River with the result that water reached the terminal Taitema Lake for the first time in 30 years. This environmental flow raised water-table levels along 350 km of the river. To assess the response of the water-table, a comparison "pristine" site is compared with downstream monitored sites. The results show huge changes in water-table levels. The study verifies that the water-table is extremely responsive to environmental flows, that strong internal similarities exist along the length of the river, and that the effect on the water-table and hence likely riparian vegetation recovery can be tentatively predicted. The actual impacts of the restoration strategy are less than those originally expected politically, socially and within the scientific community. We make recommendations on more effective release strategies.

Keywords: Water-table manipulation; Ecosystem degradation; Restoration

1. Introduction

River systems sourced in higher rainfall areas are vital components in arid landscapes (Thoms, 2002). They dominate the pattern of surface and underground water flows, and hence the distribution of vegetation communities and the location of farmland (Toyne, 1996; Howell and Benson, 2000). Ecologically, the variability of flow, timing and duration (McMahon et al., 1992; Puckridge et al., 1998, 2000; Sear1 et al., 1999; Pettit, 2001) determines and sustains biota in arid landscapes through its influence on ground water systems. Unsurprisingly, biotic diversity is concentrated in riparian areas (Davies et al., 1994; Walker et al., 1995).

When river flow is regulated for water-resource based development in the upper reaches of such rivers, severe hydrological and consequential ecological impacts result down stream (Crean et al., 2002; Lyons et al., 1992; Davies et al., 1994; Kingsford, 1995, 1998; Stevens et al., 1995; Song and Fan, 2000; Maddock et al., 2001). In water-scarce northern China, human requirements have overridden the ecosystem's needs for water (Dudgeon, 1999). Recently, this 50-year trend has reversed and now the paradigm for managing river health is towards restoration and rehabilitation (Boon, 1998). In this context, understanding the environmental flows necessary for restoring and maintaining ecological integrity, without compromising economic development, is a national objective.

The Tarim River, China's longest internal river had an estimated natural flow of $800–900 \times 10^6\,m^3$ per annum from snow and glacial fed sources. After 50 years of water extraction for agriculture, the river system has been degraded, with no water flowing to its historical terminus, Taitema Lake (Fig. 1). To restore the river and the riparian vegetation, the Chinese Government in 2000 initiated the largest environmental restoration project in western China with water diversions from the glacial and snowmelt-fed Borstem Lake to Daxihaizhi reservoir with subsequent releases to the lower reaches of the River (Fig. 1). From 2000 to 2002 there were four releases. Each flow progressed further down the dry riverbed until the final release reached

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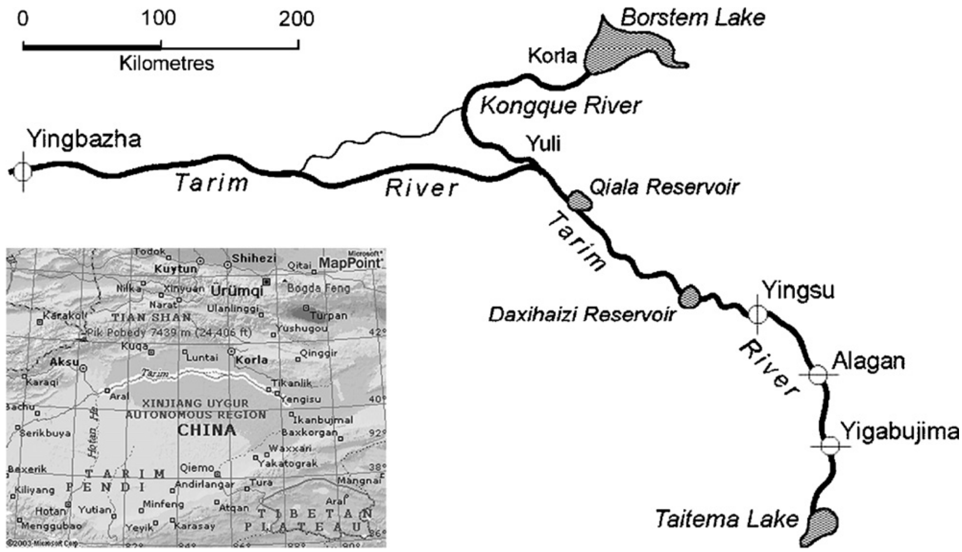

Fig. 1. Study area in the lower reaches of the Tarim River.

Taitema Lake. This was the first water to enter the lake in 30 years. The future of this program depends on identifying the response of the river system to environmental flows. As yet, no targets for the extent of restoration have been set, although there are expectations that the river can be restored to pre-water removal levels. This study, in part, explores this possibility. The location of the three principal study sites (Yingsu, Alagan and Yigabujima), the comparison site (Yingbazha), the source Lake Borstem and the terminal Lake Taitema are shown.

Given that the water-table is the most responsive and immediate indicator of environmental change and vegetation recovery potential, its recharge could be expected to arrest the process of desertification. This opportunistic study of water-table response to environmental flows is important for its spatial scale, covering 300 km of river; the volumes of water released, $1038 \times 10^6\,m^3$ released over 3 years; its temporal dimensions and ground-water response after 30 years of no surface flows. In addition, the receiving environment has been degraded by the absence of water flows. The study will inform riparian restoration ecology efforts in many parts of the arid world.

2. The Tarim River study area

The study area is in the east of the Tarim Basin (Lat. 41°03′40″—39°24′08″N; Long. 86°37′23″—88°30′00″E), Xinjiang Autonomous Region, in western China. This site is typically hyper-arid with a continental climate. Mean annual solar radiation is 3118.7 h (at Yuli, Fig. 1). The mean annual air temperature is about 10.5 °C. The coldest and warmest mean monthly temperatures are 8.5–9.4 °C in January, and 26.3–27.4 °C in July. The average annual precipitation is about 17.4–33.6 mm, with most occurring between June and August. The mean annual pan-evaporation is between 2671.4 and 2902.3 mm; exceeding precipitation by 80–166 times. Annually, there are 15.7–36.9 days of high wind and 8.9–19.2 days of sand storms, when wind speed can reach 70–140 km/h.

Geologically, the area is a continental basin of mainly Quaternary aeolian sand to a depth of 400 m. The sands are composed of surface powder sand (0–0.76 m), then coarser sand to an effective impermeable clay layer at about 80 m. Near Lake Taitema this reduces to between 20 and 40 m.

The Tarim River is 1321 km long (Song and Fan, 2000). The lower reaches extend from Qiala to Taitema Lake, a length of 458 km (Fig. 1). The Bureau of Tarim River Management (1999) divides the river into three parts: the upper-part (from Qiala to Daxihaizi Reservoir, 108 km), the middle part (from Daxihaizi to Alagan, 188 km), and the lower part (from Alagan to Taitema Lake, 162 km). The average altitude is 800–860 m above sea level with a slight eastward gradient (1:4500–1:7900). The average depth of the river is 2–4 m from the bank to the lowest part of the riverbed.

The lower reaches around Lake Taitema are still referred to locally as the 'Green Corridor'; a reference to the vegetation communities that once were 5–10 km wide and included wetlands connected by a series of channels. Between 1950 and 1990, farmland around the upper parts of the river more than doubled, from 35.12×10^5 ha in 1949–77.66×10^5 ha in 1993. The consequential removal of water from the river resulted in the cessation of flows in the lower reaches (Table 1). Downstream communities, who had depended on the river, migrated upstream as water became unavailable.

Without water flows, the area progressively degraded, with significant vegetation loss and wind erosion of the land surface (Feng et al., 2001). This was especially the case in the lower reaches. Annuals and shallow rooted perennials effectively disappeared by 1980, and the remaining vegetation declined with periods of prolonged stress being evident in the deep-rooted perennial vegetation (Song and Fan, 2000) (see Figs. 2 and 3).

Table 1
Water-flows ($10^6\,m^3$/yr) at three locations on the Tarim River

Period	Locations		
	Qiala	Daxihaizhi	Alagan
1957–1960	1170	800–900	Permanent flow
1961–1970	1087	288	Seasonal flow
1971–1980	617	47	Nil
1981–1990	252	36	Nil
1991–2000	236	13	Nil

Fig. 2. Degraded riparian forest near Yingsu.

Fig. 3. Tarim River with encroaching sand, Yingsu.

3. Methodology

Norris and Thoms (1999) have argued that a priori comparison sites are essential for the precise understanding of geomorphologic processes, changes in river health, and other responses to restoration projects. The ideal comparison is between a pristine site (a control) and the altered sites. Alternatively, longitudinal data that includes measures when the study site was believed to be 'healthy' can be used. Each provides reference conditions enabling comparison of like with like (Davis and Simon, 1995; Reynoldson and Baily, 1995; Wright, 1995; Parsons and Norris, 1996; Reynoldson et al., 1997; Norris and Thoms, 1999). For this study, no a priori data are available, hence the 'ecologically nearest' possible comparison site was chosen for the study, at Yingbazha (Fig. 1), at the start of the middle reaches of the river. It has similar meteorological characteristics, a historically uninterrupted river flow, and geomorphology and underlaying geology are similar to the lower reaches of the river. The riparian community structure and plant species are also similar to that recorded down-stream. The associated groundwater aquifer is intact, and the government has collected surface flow and underground water data at this site over many years. It is the only site available for comparison in a vast area.

Three hydrological transacts were established as part of an extensive ecological hydrological survey of the area (Feng et al., 2001) with monitoring wells at right angles to the riverbed at Yingsu, Alagan and Yigabujima. The distribution and type of wells at the three study sites mirrored those at the Yingbazha comparison site. This allowed observed site changes in the water-table to be related to the release of water.

4. Water releases post-2000

There have been five water releases from Borstem Lake since 2000 for the targeted restoration areas downstream of Daxihaizhi Reservoir (Fig. 1). The first of $204\times10^6\,m^3$ commenced on 14 May 2000 (60 days), with $98\times10^6\,m^3$ reaching Daxihaizhi Reservoir, and subsequently 102 km below this reservoir. The second release of $225\times10^6\,m^3$ commenced on 3 November 2000 (95 days), and flowed for an additional 113 km. The third release was divided into two stages because of upstream agricultural demand for irrigation water. The first of these was between 1 April and 6 July 2001 (97 days), the second between 12 September and 18 November 2001 (68 days), with a total of $382\times10^6\,m^3$ being released. This release reached the dry Taitema Lake to form a 10 km^2 lake. A fourth release of $3.31\times10^6\,m^3$ from 20 July to 10 November 2002 (144 days), created three wetlands of 22.35 km^2 along the river at Yingsu. It also increased the surface area of water in Taitema Lake to 16.7 km^2.

Of the $1038\times10^6\,m^3$ (Table 2) released from Daxihaizhi Reservoir, 80.3% is distributed in the middle part of the lower reaches ($834\times10^6\,m^3$), from Daxihaizhi to Alagan. About $181\times10^6\,m^3$ (17.6%) is available to the lower part of the lower reaches, from Alagan to Taitema Lake, with only a small amount ($22\times10^6\,m^3$ or 2.1%) reaching Taitema Lake. These data suggest that, with each release, water-table recharge occurs progressively; enabling surface flows to increase further downstream. For the volumes of water released, most ground water replenishment occurs in the middle part of the lower reaches.

Table 2
Distribution of released water ($10^6\,m^3$) between Daxihaizhi Reservoir and Taitema Lake

	Daxihaizhi reservoir to Yingsu	Yingsu to Alagan	Alagan to Yiganbujima	Yigabujima to Taitema lake	Taitema lake	Daxihaizhi reservoir to Taitema lake (Total)
1. First release	82.759	15.072				97.831
2. Second release	130.192	90.437	5.923			226.552
3(1) Third release—Stage 1	84.078	79.636	12.296	8.327		184.337
3(2) Third release—Stage 2	53.202	71.276	37.345	28.607	7.478	197.908
4. Fourth release	77.534	149.826	56.204	33.553	14.176	331.293
Total	427.765	406.247	111.768	70.487	21.654	1037.921

Table 3
Volume of water lost, time taken to reach monitoring sites during environmental flows in the Tarim River between Daxihaizhi Reservoir to Taitema Lake

	Daxihaizhi to Yingsu		Yingsu to Alagan		Alagan to Yiganbujima		Yigabujima to Taitema Lake	
	Volume loss ($10^6\,m^3$)	Days	Volume loss ($10^6\,m^3$)	Days	Volume loss ($10^6\,m^3$)	Days	Volume loss ($10^6\,m^3$)	Days
1. First release	42.448	24						
2. Second release	12.960	6	155.210	67				
3(1) Third release—Stage 1	10.038	4	43.628	16	116.960	38		
3(2) Third release—Stage 2	7.603	4	41.299	16	78.451	28	170.916	56
4. Fourth release	10.830	5	39.089	19	132.515	56	206.876	77

Table 4
Flow loss (m^3/s) between Daxihaizhi Reservoir and Taitema Lake

	Daxihaizhi Reservoir to Yingsu	Yingsu to Alagan	Alagan to Yiganbujima	Yigabujima to Taitema Lake	Daxihaizhi Reservoir to Taitema Lake (Total)
1. First release	15.20				
2. Second release	15.53	11.38			
3(1) Third release—Stage 1	9.93	9.70			
3(2) Third release—Stage 2	8.92	11.62	6.75	6.25	33.54
4. Fourth release	7.30	14.57	6.20	5.71	33.77

After the first release, while water loss from the river gradually decreases at the upper sites with each release (Table 3), the time taken for the water to reach the monitoring sites stabilized; particularly so between Yingsu and Alagan, where rate of loss stabilizes suggesting that the water-table rapidly reaches maximum recharge capacity. However, this does not mean that the ground water has been fully restored. In addition, the rate of recharge further downstream did not stabilize with each watering event and ground water restoration is even more unlikely. The unusual nature of the river around Alagan is illustrated by the pattern of water loss during stages 1 and 2 of the third release and the fourth release, when the riverbed was saturated and the whole river was flowing, water loss between Daxihaizhi to Yingsu and Yingsu to Alagan stabilized while water loss from Alagan to Yigabujima and Yigabujima to Taitema Lake continued to increase. Flow loss on the other had remained high between Yingsu and Alagan (Table 4).

For practical engineering purposes, an estimate of the release rate at Daxihaizhi Reservoir is required if maximum efficiency is to be obtained for environmental flows. The most efficient system could be postulated as one where the Tarim River flows throughout its length but no excess water accumulates in Taitema Lake. This will occur when the volume entering the system matches loss over the length. Although total aquifer recharge is identified as variable, a minimum flow rate from Daxihaizhi Reservoir can be estimated. When the river below Yiganbujima is flowing, the aggregate change in flow rate is about 33–34 m^3/s between Daxihaizhi Reservoir and Taitema Lake (Table 4). This represents the minimum flow from Daxihaizhi Reservoir for water to just reach the terminal Taitema Lake. However, it does not represent, necessarily, the most effective parameter for maximizing the remedial effect of the environmental flow, because of water loss variation and water-table dynamics.

5. Dynamics of the water-table at the comparison site

The monthly profile of the water-table at Yingbazha (comparison site) is relatively constant (Fig. 4). A plot of the monthly water-table depth (Fig. 5) suggests that the closer a well is to the river, the more it responds to short-term river level changes. Stabilization occurs around 800 m from the river, with almost no change in water-table depth beyond 950 m. This indicates that seasonal effects on the water-table extend between 0 and 950 m. This confirms that the water-table at Yingbazha is 'pristine' and an appropriate comparison site.

To explain lateral water-table dynamics, we applied water-table slope computations (Bureau of Tarim River Management 1999), using the standard measure of the water-table gradient increment (WTGI), a surrogate measure of ground water volume. WTGI is the vertical increment of water-table per meter (cm/m). The WTGI is calculated by dividing the difference in water-table depth between the well nearest the river and that further away by the distance between the wells. If the depth of water-table is increasing with distance, the result will be positive, otherwise it will be negative. A plot of WTGI values by month and between wells (Fig. 6) reveals that all WTGI values are positive and confirms that water-table depth gradually increases with distance from the river, throughout the year. However, there are two WTGI peaks: between 150–400 m and 801–950 m from the river. Consequently, the water-table from the bank of the river to 7500 m can be divided into three zones, i.e. 0–400 m, 401–950 m and 951–7500 m. Around 950 m, water-table depth dips sharply from about −3 m at 800 m to about −5 m at 950 m, and then to over −6 m at 3500 m.

The water-table stress level for grasses on saline meadow around the Tarim River is −3.5 m, for *Populus* sp. it is −4.5 m, and for *Tamarix* spp. it is −5 m (Song and Fan, 2000). These depths indicate ecologically transition zones,

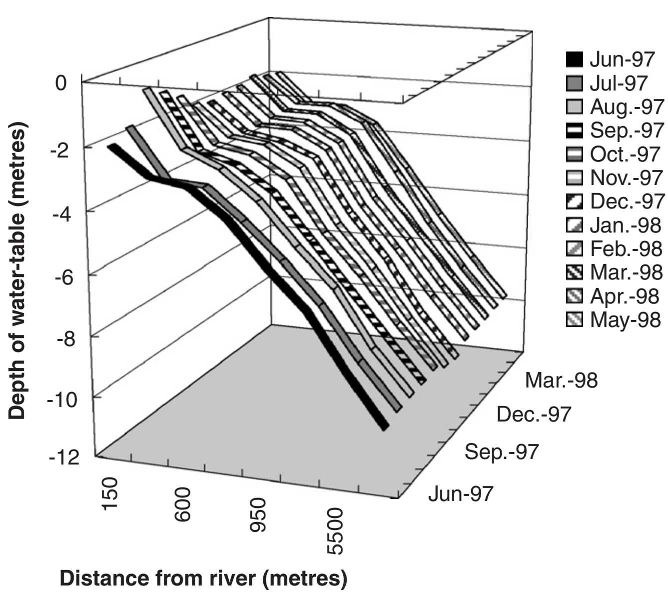

Fig. 4. Monthly water-table depth at Yingbazha, June 1997–May 1998.

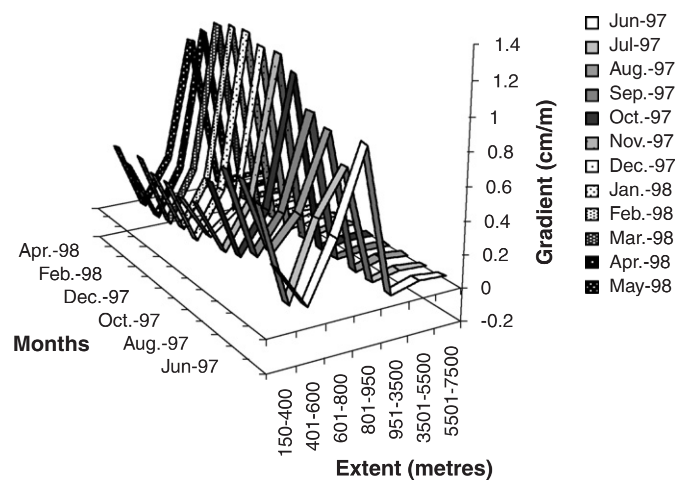

Fig. 6. Water-table gradients at Yingbazha.

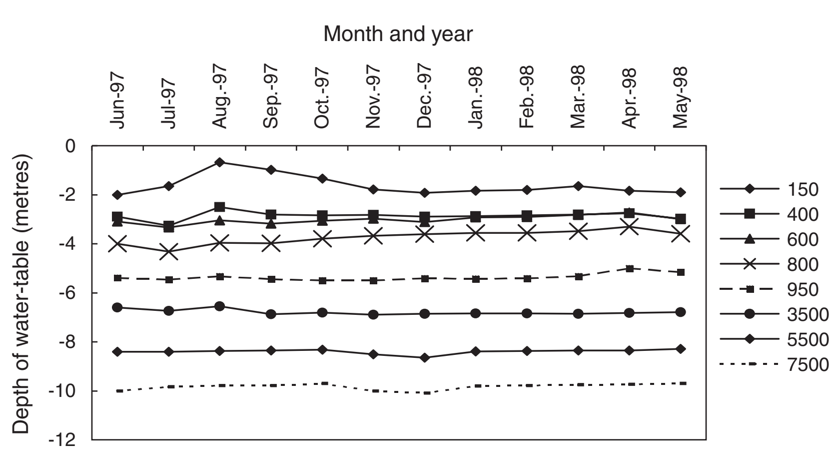

Fig. 5. Monthly water-table depth by distance from the river at Yingbazha, June 1997–May 1998.

where any increase in water-table depth will result in vegetation changes and 'environmental degradation'. Equally, the process of vegetation restoration will first appear in these areas when water-table depth reaches these thresholds. On this basis, the likely extent of vegetation will be to 950 m from the river bank.

Although the water-table has three steps, laterally, there are significant differences between all paired wells (T-test, $p < 5\%$). River flow volume dominates the dynamics of the water-table close to the river. The closer the wells are to the river, the more significant is this difference. The correlation coefficients between the flow volume and WTGI are 0.91 between 150 and 400 m, 0.83 between 401 and 600 m, 0.64 between 601 and 800 m, −0.51 between 801 and 950 m, −0.54 between 951 and 3500 m, 0.27 between 3801–5500 m, and 0.20 between 5501 and 7500 m. This indicates that 800 m is the approximate extent of immediate influence of water additions to the Tarim River at Yingbazha. Beyond this point, the water-table status is most likely the consequence of the long-term condition of the river and underground water flows.

Table 5
Coefficients of the Cubic model at Yingbazha

Months	Cubic					
	b_0	b_1	b_2	b_3	r^2	F
Jun 1997	1.7219	0.0034	-7×10^{-7}	5.4×10^{-11}	0.97	37.42**
Jul 1997	1.6202	0.0039	-9×10^{-7}	6.5×10^{-11}	0.96	33.56**
Aug 1997	0.6726	0.0048	-1×10^{-6}	8.2×10^{-11}	0.95	27.27**
Sep 1997	0.8984	0.0047	-1×10^{-6}	8.0×10^{-11}	0.96	33.76**
Oct 1997	1.1500	0.0042	-9×10^{-7}	7.0×10^{-11}	0.96	32.34**
Nov 1997	1.4351	0.0037	-8×10^{-7}	5.7×10^{-11}	0.97	36.78**
Dec 1997	1.6396	0.0034	-7×10^{-7}	4.8×10^{-11}	0.97	39.67**
Jan 1998	1.4898	0.0036	-7×10^{-7}	5.3×10^{-11}	0.96	35.44**
Feb 1998	1.4462	0.0036	-7×10^{-7}	5.4×10^{-11}	0.96	35.44**
Mar 1998	1.3090	0.0037	-8×10^{-7}	5.6×10^{-11}	0.97	38.32**
Apr 1998	1.4488	0.0032	-6×10^{-7}	4.3×10^{-11}	0.97	49.50**
May 1998	1.6230	0.0033	-7×10^{-7}	4.7×10^{-11}	0.97	49.34**

* = p<.05; ** = p<.01

There is a high correlation between monthly water-table levels for the wells, irrespective of distance from the river. However, there are still differences in water-table dynamics between some months with significant differences mainly occuring in winter and spring. December has the lowest water-table level when there is less water in the river. From January to March, the water-table is rising, but falls, probably in response to water consumption for agricultural production, spring vegetation growth and higher evaporation levels. The lowest water-table level occurs in June (mid summer). With the arrival of snow and glacial-melt, there is increasing availability of water to replenish the water-table and it again rises through to October. Water-table levels are at their highest in August.

6. The dynamics of the water-table at the comparison site

Eleven correlations (linear, quadratic, cubic, power, compound, S, logistic, growth, exponential, logarithmic, and inverse) were used to model monthly trends in water-table levels at Yingbazha. The cubic model ($y = b_0 + b_1x + b_2x^2 + b_3x^3$) where y is depth of the water-table and x is the distance from the river was a better predictor of measured values and was used for further modelling purposes (Table 5).

A dichotomy exists in measured (and modelled) values around the −5 m water-table depth in all months. To improve predictive precision, the data were divided around the −5 m depth (950 m from the river), i.e. from point −1 to −5 m and from −5 to −9. The re-worked data provide models with parameter, r^2, and F values as listed in Tables 6 and 7, with much improved r^2 values (almost all rounding up to 1) and hence effectively a perfect match between the paired observed data and predicted values.

7. The spatial response of the water-table to the environmental flows

Water-table levels at well sites at Yinsu, Alagan and Yigabujima were monitored for all releases (Tables 8–10).

Table 6
Parameters for cubic model from well 1 to well 5 (150–950 m) at Yingbazha

	B_0	b_1	b_2	b_3	r^2	F (one tail)
Jun 1997	0.5879084	1.27315×10^{-2}	-2.447×10^{-5}	1.7278×10^{-5}	0.999	425.29*
Jul 1997	−0.530672	1.91601×10^{-2}	-3.308×10^{-5}	2.0636×10^{-5}	0.992	42.63
Aug 1997	−1.6639312	1.99913×10^{-2}	-3.19×10^{-5}	1.9591×10^{-5}	1.000	2176.36*
Sep 1997	−1.6323137	2.28079×10^{-2}	-3.896×10^{-5}	2.3999×10^{-5}	1.000	1919.14*
Oct 1997	−1.1997	2.26388×10^{-2}	-4.216×10^{-5}	2.7104×10^{-5}	1.000	18443.3**
Nov 1997	−0.27592	1.88592×10^{-2}	-3.797×10^{-5}	2.5782×10^{-5}	1.000	760.05*
Dec 1997	−0.1566624	1.90145×10^{-2}	-3.843×10^{-5}	2.5845×10^{-5}	0.996	85.08
Jan 1998	−0.4300002	2.08896×10^{-2}	-4.292×10^{-5}	2.8849×10^{-5}	0.999	568.92*
Feb 1998	−0.4332368	2.0524×10^{-2}	-4.202×10^{-5}	2.8305×10^{-5}	0.999	634.92*
Mar 1998	−0.7145474	2.16608×10^{-2}	-4.376×10^{-5}	2.9098×10^{-5}	1.000	3841.39*
Apr 1998	−0.2427185	1.91804×10^{-2}	-3.99×10^{-5}	2.6868×10^{-5}	1.000	1359.54*
May 1998	−0.2089105	0.0193411	-3.859×10^{-5}	2.5443×10^{-5}	1.000	255493**

* = p<.05; ** = p<.01

Generally, the water-tables were around −8 to −10 m at Yingsu, −10 m at Alagan, and −8 m at Yiganbujima before the first water release. Initially, environment flows failed to raise the water-table to what would be expected from the Yingbazha data. However, with subsequent releases, wells near the river progressively approach these values. For example, at Yingsu the well 150 m from the river, after the second stage of the third water release, has a level 2 cm higher than that expected. With each water release, beyond Yingsu, wells closest to the river were more responsive to the environmental flows. By the fourth release, for example, there has been a 2–3 m increment with a 700 m lateral effect at Yingsu, a 1–2 m increment and over 550 m lateral effect at Alagan, and 0.78–1.47 m increment and over 550 m lateral effect at Yiganbujima. Notwithstanding this, the remaining difference between expected and observed levels clearly indicates that the system has not been replenished at least to a theoretical maximum. While raising the water-table may be temporary during the releases, the increment may be lost by water-table lateral flow, probably over considerable distances in the depleted sand basin, through surface and subsurface evaporation

Table 7
Parameters of cubic model from well 5 to well 9 (950–750 m) at Yingbazha

	b_0	b_1	b_2	b_3	r^2
Jun 1997	5.600039	-4.6×10^{-4}	2.76×10^{-7}	-1.8×10^{-11}	1
Jul 1997	5.514632	-2.6×10^{-4}	2.3×10^{-7}	-1.6×10^{-11}	1
Aug 1997	5.589779	-5.5×10^{-4}	3.15×10^{-7}	-2.2×10^{-11}	1
Sep 1997	5.160133	1.98×10^{-4}	1.08×10^{-7}	-7.0×10^{-11}	1
Oct 1997	5.400908	-0.43×10^{-4}	1.65×10^{-7}	-1.1×10^{-11}	1
Nov 1997	5.345452	0.0764×10^{-4}	1.62×10^{-7}	-1.1×10^{-11}	1
Dec 1997	5.427236	-2.4×10^{-4}	2.45×10^{-7}	-1.7×10^{-11}	1
Jan 1998	5.23289	0.806×10^{-4}	1.43×10^{-7}	-0.96×10^{-11}	1
Feb 1998	5.22638	0.753×10^{-4}	1.45×10^{-7}	-0.98×10^{-11}	1
Mar 1998	4.963859	2.92×10^{-4}	0.933×10^{-7}	-0.63×10^{-11}	1
Apr 1998	4.462241	5.25×10^{-4}	0.59×10^{-7}	-0.47×10^{-11}	1
May 1998	4.714095	3.91×10^{-4}	0.763×10^{-7}	-0.53×10^{-11}	1

Table 8
Monitored water-table depths at Yingsu

	Monitoring date	Depth to water-table (m) 1000 for wells to 700 m from the river				
		150 m	250 m	350 m	450 m	700 m
Before release 1	25.05.2000	−8.34				
After release 1	12.08.2000	−5.98				
Change		2.4				
Before release 2	11.11.2000	−8.50	−8.17	−8.09	−8.17	
After release 2	14.02.2001	−3.03	−4.86	−5.85	−6.83	
Change		5.47	3.31	2.24	1.34	
Before release 3(1)	03.04.2001	−5.38	−5.35	−5.81	−6.42	
After release 3(1)	19.06.2001	−4.44	−4.40	−4.96	−5.77	
Change		0.94	0.95	0.85	0.65	
Before release 3(2)	16.11.2001	−5.49	−5.24	−5.43	−5.86	−8.35
After release 3(2)	18.08.2001	−1.77	−3.57	−4.58	−5.42	−6.8
Change		3.72	1.67	0.85	0.44	1.55
Before release 4	19.11.2002	−6.01	−5.79	−5.60	−5.84	−6.65
After release 4	23.07.2002	−3.54	−3.45	−3.97	−4.69	−6.30
Change		2.47	2.34	1.63	1.15	0.35

Table 9
Monitored water-table depths at Alagan

	Monitoring date	Depth to water-table for wells to 1000m from the river			
		50 m	200 m	550 m	1000 m
Before release 2	10.01.2001	−11.51			
After release 2	04.02.2001	−9.55	−10.67		
Change		1.96			
Before release 3(1)	18.04.2001	−10.1	−10.28		
After release 3(1)	19.06.2001	−8.34	−9.41		
Change		1.76	0.87		
Before release 3(2)	25.08.2001	−9.34	−9.46		
After release 3(2)	16.11.2001	−7.92	−8.98		
Change		1.42	0.48		
Before release 4	31.07.2002	−8.86	−8.72	−7.26	−9.55
After release 4	19.11.2002	−6.16	−7.20	−8.90	−9.40
Change		2.7	1.5	−1.64	0.2

Table 10
Monitored water-table depths at Yigabujima

	Monitoring date	Depth to water-table for wells to 550 m from the river		
		50 m	200 m	550 m
Before release 3(1)	11.05.2001	−8.31	−8.52	−8.71
After release 3(1)	19.06.2001	−6.78	−7.55	−8.27
Change		1.53	0.97	0.44
Before release 3(2)	18.08.2001	−7.29	−7.68	−8.45
After release 3(2)	16.11.2001	−5.82	−7.27	−8.08
Change		1.47	0.41	0.37
Before release 4	20.08.2002	−6.84	−7.29	−7.93
After release 4	13.11.2002	−4.16	−5.32	−7.50
Change		2.7	2.0	0.4

and transpiration from stimulated plant growth. However, short-term elevation of the water-table is an important ecological stimulus for the degraded system that has not received water for 30 years (Hou et al., 2006).

The dynamics of the water-table after each release is important in terms of the environmental benefits being sought. The question of whether the water-table effects are persistent and sufficient is important in this context. Our data show that there is a cumulative effect on the water-table at each monitoring site with successive releases and the underground water level does not return to the pre-release level in the interval between releases at any site (Tables 8, 9 and 10). For example, between the second stage of the third release and the fourth (nearly 8 months), the water-table remained steady at each site, except for the points closest to the river. This was possibly a response to evapo-transpiration associated with plant growth and return drainage into the drying river. However, cumulative effects on the water-table decrease at all transacts with time. This suggests a strong internal balancing system exists where underground water spreads laterally once an environmental maximum water-table level is reached. The water flow creates gradients during watering; and then the gradients are balanced during the intervening time. Both the water flow and intervening stabilization phases are probably important for system functioning and restoration. The former can stimulate plant recovery by flows that transfer seeds to the lower parts of the river and short-term increases in the water-table, which promotes root growth and ultimately canopy biomass. The latter then sustains the degraded system and recruited plant growth, sustainably increasing biodiversity and vegetation cover.

There is an additional aspect of the water-table dynamics that is common to all locations. At all sites, monitored and expected values from the river initially converge and then stabilize in parallel. This suggests that there are inherent similarities between the downstream transects and the comparison site. It also suggests that very large amounts of water may be required to fully restore and maintain the aquifers associated with downstream area to bring it to the status of the comparison site. There are significant changes in water-table depth at each monitored site and with each water release. The average differences are 2.72–3.59 m at Yingsu, 3.99–8.39 m at Alagan, and 5.2–5.91 m at Yiganbujima. It is clear that the underground water and soil water situation is far from an optimal state to support full restoration of all ecological community components to Song and Fan's (2000) thresholds for grasses on saline meadow (−3.5 m) for *Populus* sp. (−4.5 m), and for *Tamarix* spp. (−5 m).

Gradients can be found on both lateral and longitudinal axes. For example, at Yingsu the water-table at 150 m from river is −3.54 m, which is equal to the water-table at 755.4 m from the river at the comparison site (Yingbazha), a difference of 605.4 m. At 250 m the difference between actual and expected lateral extent is 482.1 m; at 350 m the difference is 471.88 m; at 450 m it is 433 m; and at 700 m the difference is 1714.89 m. The distance between the observed and expected water-table levels becomes extremely large at 700 m from the river. This indicates that the lateral effect of the water release ceases 700 m from the river at Yingsu. This is 250 m short of the expected extent of flooded river influence derived from the Yingbazha model.

The situation is more extreme at Alagan and Yiganbujima where there was less water available for water-table replenishment. The water-table 50 m from the river at Alagan corresponds with 2161.7 m as predicted by the model; 200 m corresponds with 3872.67 m.

An unexpected result was that the water-table at Yiganbujima is higher than that at Alagan. The possible reason is that Yiganbujima is located close to the terminus at Lake Taitema where past natural flows slowed, with deposition of silts and clays. Consequently, it is expected that clay layers at Yiganbujima create impermeable barriers, effectively reducing the volume of water needed to raise the water-table.

Because the expected ground water condition and the actual response to the water releases is so great, it can be postulated that the five flows have only given the degraded system an initial stimulus towards recovery. Because the lateral and longitudinal effects are uneven and sharp water-table gradients exist along the entire river from Yingsu to the river terminus, it is probable that a steady state may not be reached for some time. While some plants are stimulated by the temporary elevation of the water level, restoration claims on hydrological data will require more careful ecological analysis (see Hou et al., 2006).

8. Trend analysis

The environmental response to water release requires an understanding of the extent of lateral and lineal influence of the altered water-table compared to the comparison site (Yingbazha). The shape of the water-table curve is an important characteristic of the system. The distance between the surveyed site cross-sections and the comparison site represents the difference between the systems, especially in extreme dry-land areas because of the dominant function of the ground water system.

The lateral dimensions of the water-table at Yingbazha (Fig. 7) in November were chosen as the standard curve. Curves for Yingsu, Alagan and Yiganbujima are also shown. The Yingbazha curve has very different characteristics to the others (Fig. 7). From the water-table depth of −1 m to −5 m, the curve is S-shaped; thereafter, the depth of the water-table varies proportionally with the distance from the river. Around −5 m (a water-table depth of 5.49 m), the water-table depth is beyond the stress threshold for *Tamarix* sp. (the most water stressed plant in the area; Song and Fan, 2000). Song and Fan (2000) claim −6 m is the water-table level for desertification. That is, if the water-table is permanently below −6 m, the landscape will be devoid of plant growth. Thus, only where the water-table is above −5 m will there be ecological security in terms of available water for plant growth. At comparison site Yingbazha, the −5 m water-table depth occurs around 900 m from the river, according to the predicted model. In addition, there will be an eco-sensitive zone between −5 and −6 m, or between 900 m and 1890 m from river. While the lateral extent of riparian vegetation is around 900 m, the water-table zone between 900 and 1890 m constitutes a buffer to water-table variation and hence has an important function in maintaining the riparian area of seasonal rivers. When water is in the stream, and available to replenish the water-table, the water-table in this zone rises, but not sufficiently to support riparian vegetation. When the stream is dry and the water-table retracts laterally and vertically, the zone buffers the riparian vegetation by replenishing the riparian area (to 900 m) with water temporarily held in the zone. That is, this zone, and its ability to store underground water when the river flows, significantly contributes to the resilience (and once re-established, the resistance (see Holling et al., 1995; Berkes and Folke, 1998)) of the riparian area when the river is dry and vegetation is under stress.

In contrast, if a stream is permanent, the buffer zone is redundant in the functioning of the system, because the water-table retracts minimally in dry conditions. That is, for non-desert areas, the buffer zone concept is functionally insignificant because the zone is extremely narrow. However, for desert systems, we consider this water-table zone to be highly significant conceptually and in terms of ensuring the maximum restoration potential of any water release. Thus, this zone requires special protection consideration as well on-going monitoring.

At all monitored sites, the water-table level drops with distance from the river (Fig. 7A). However, the superficial difference in shape at different monitoring sites is partially a scale effect and differences disappear if the scale is changed (Fig. 7B). If the cubic model is applied to these data, r^2 correlation coefficients of 0.9996, 0.9969, 1.0000 and 1.0000 are returned for Yingbazha, Yingsu, Yigabujima and Alagan, respectively. This means that the cubic model derived from the Yingbazha is useful for comparison purposes.

If the curves are extrapolated back to the river level point at Yingbazha (−1.4 m intercept value for November, Table 6), then the Yingbazha curve is repeated for each site. However, its sigmoidal component is compressed. The extent of lateral influence of the released water on the system decreases at Alagan and expands at Yigabujima; that is, it has an hour-glass shape with a pinch at Alagan. In other words, the influence of released water expressed as distance from the river where riparian growth is possible (water-table depth above −6 m) is minimal at Alagan, but reaches to 400 m at Yigabujima and 700 m at Yingsu. The shape of the downstream curves, with their compressed sigmoidal part, means that these areas have greatly diminished buffer zones to support the establishment and maintenance of the riparian vegetation.

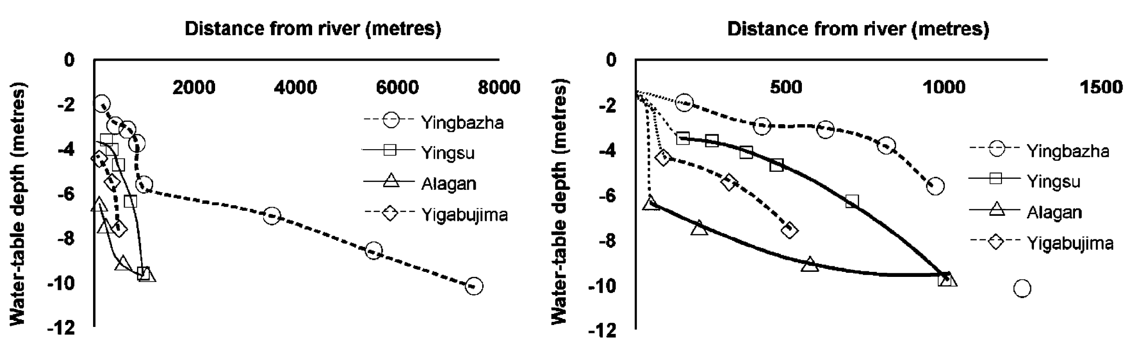

Fig. 7. Water-table curves at the three monitored transects: (A) water-table depth to 8000 m from river and (B) water-table depth to 1000 m from river.

If the objective is to 'restore' the riparian system, the most important part of the water-table to monitor is where the *S* part of the curve occurs laterally (currently from 0 to 150 m depending on the site). In each case, the critical point is where the water-table reaches −6 m. Under the current water release regime, at Yingsu, the water-table has been raised to the extent of being equivalent to the part of the Yingbazha curve beyond 800 m. That is, it will take little additional water to expand the sigmoidal component so vital to restoration of a wide riparian area (an increase in the level of the water-table from −3.54 to −2.82 will create a riparian distance of around 600 m). In contrast, an equivalent increase in the level of the water-table at Yigabujima (from −5.32 to −4.60) would require a significant increase in water flows and, while increasing the water-table level, would have limited effect on the width of the affected riparian zone. At Alagan, it will be extremely difficult to change the water-table depth, let alone establish conditions for riparian area restoration, other than on the river banks.

These data have significant implications. The Alagan area of the Tarim River appears to be a sink point where little effect will be obtained even from prolonged increases in river level. This is undoubtedly an effect of unexpected local geomorphology. The implication is that rapid river flow past this point will be more effective than prolonged releases of less water.

9. A possible strategy for water release

Given the continuing demand for water from upstream agricultural areas, it will be impossible to restore the whole lower reaches of the Tarim River to its pre-human intervention state, i.e. there is insufficient water to keep permanent flows in the river. However, on-going seasonal flows may be possible with $350 \times 10^6\,m^3$ proposed to be released to Daxihaizhi Reservoir annually, starting in 2005. This is more than that released in the 1960s ($288 \times 10^6\,m^3$ per annum), but far less than the natural flow of the 1950s ($800–900 \times 10^6\,m^3$ per annum). However, the average annual water consumption is $5.80 \times 10^6\,m^3$/yr/km in the middle reaches, while it is only $1.00 \times 10^6\,m^3$/yr/km in the lower reaches. Since the middle reaches are a major 'sink' for any water released, maintaining flow volumes to the lower reaches using an intermittent or slow release strategy will be ineffective.

There are two possible water release peaks in a year: in spring when the snow on the lower mountains melts and in summer when glaciers in the deep and high mountains are melting. Using a seasonal flow strategy, there are three possible approaches to water release. One approach is to release sufficient water to keep the river in full flow during a single release. This would recharge the water-table in the whole system but for a short time. It would stimulate plant regeneration throughout the system, but the affected area would be uneven and the water-table would drop rapidly during the long interval between releases. Based on the discussion above, the shape of the affected area would be broad in the upper middle reaches, be rapidly diminished at Alagan and then would expand again towards Lake Taitema.

An alternative is to divide water releases into 3 or 4 large pulses. These might not maintain water flows throughout the system but would reduce the effect of the Alagan sink and increase the effective area subject to restoration below and above it. Also the effectiveness of the release on plant growth would probably be enhanced and progressively increase the water-table level further downstream with less loss to evaporation and the Alagan sink.

Another release strategy could be a variation of the intermitted release strategy above. Initially, a relatively large amount of water could be released and flows directed to targeted areas using earth works and old streambeds within the braided channel. This could be done while avoiding known sinks and ensuring that no water enters Taitema Lake. This strategy could target pre-determined places of potential biodiversity value that have relatively large remnant patches of vegetation beside the river.

Of these possibilities, we believe the first strategy, the 'linear-shaped release', is suitable for the initial stage of a long-term restoration process. It would invigorate plant life along the river, rapidly change the background water-table profile, and probably immediately check the current degradation process (but to an increasingly limited extent further downstream). The second strategy is probably suitable as a process for continuing the 'repair' of the ecosystem. It would support both 'fine restoration' and ecosystem level restoration. The third strategy is a targeted one that could be developed once greater experience with system dynamics is obtained. It can be used to restore special places that are important components of the ecosystem or small reaches.

This study suggests that given the expected availability of water for environmental flows and the −5 m water-table depth limitation, only a narrow restoration zone is possible at Alagan, a 900 m restored area is possible to be sustained at Yingbazha, and around 450 m at Yingsu. This would be associated with limited restoration of the riparian areas further down stream and no continuous flow along the entire river to Lake Taitema. The study very clearly demonstrates that ecological restoration will require an adaptive approach if limited water resources are to be effectively used to the best ecological effect.

10. Conclusion

In dry-land areas, the water-table is the most important and sensitive indicator of ecosystem response to environmental flows, for it is the constraining factor for riparian community restoration. All other ecological responses, such as soil water, plant growth and vegetation recovery, and any increase in biodiversity, will be based on the dynamics of the water-table. To understand the resilience of the water-table is to understand the potential dynamics of the riparian ecosystem. So assessing the changes of underground water becomes a vital issue for restoration strategies in degraded riparian systems.

This study shows an effective way to identify the differences in the spatial patterns of the water-table, using at least one comparison site as the crucial first step. It involves verifying the inherent similarity between the intact site and sites being evaluated as the basis for modelling trends in water-table dynamics for quantitative assessment.

Although in this study there are huge volumes of water being released with resultant significant impact on the water-table, there are still large differences downstream from the comparison site. The degraded ecosystem is only beginning to be affected by the initial release, with apparently no inherent change having occurred, other than in the upper reaches. The temporary raising of the water-table during and after water release has a significant role in stimulating plant regeneration: a strong signal that there is functional recovery of the ecosystem, but this is not sustained (Hou et al., 2006). In addition, the response of the water-table is uneven. In the study area, the water-table is recharged to the −5 m key depth in only about half of the waterway area, with sharp gradients occurring both laterally and longitudinally.

While the effect of water release varies with distance downstream, there is consistency and similarity in the gradients of the water-table. This permits prediction of the effect of water releases on the water-table and consequently the affected riparian area. In turn, this informs the water release strategy. The study highlights the importance of a buffer area that exists in the water-table beyond the extent of the replenished zone, temporarily or permanently. We believe that in arid areas, protection of this buffer from disturbance (e.g. extraction wells) is vital to sustaining the restoration process and hence should be considered as part of the system and its ecological functioning.

At present, the buffer belt in the lower reaches of the Tarim River is highly circumscribed. Thus, the existing water release program has not had the effect of restoring the system, yet. The results suggest that it will be a long-term continuous process to restore the lower reaches of the Tarim River. Even the best-case scenario will not result in complete or evenly spread restoration. In addition, our data supports the proposition that the fundamental progenitors to restoration (in this case, available water to plants from elevated water-tables) will take significant time to be restored, and progress will require the setting of short and long-term objectives that meet social needs and ecosystem restoration. We believe that restoration of the Tarim River ecosystem will be limited and confined because of the seasonal flow and water resource availability. The probable outcome is that there is sufficient water available only to replenish the water-table adequately to restore vegetation in a belt of about 450 m on either side of the river. However, this can only be achieved for about half of the lower reaches. Even this will require multiple community negotiations at different levels, and new policies for the project, the reorganization of social groups, and a series of supporting projects (McMahon and Finlayson, 1995; Hillman et al., 2003).

This study has demonstrated that a restoration project at this scale depends upon significant organization of scientific effort and analyses that allow the building of realistic and adaptive management scenarios. This constitutes the first level of such projects and on-going monitoring of water-table dynamics is essential to provide better information to inform the management of water release for the achievement of desired outcomes. However, even with this limited data set, it is clear that decision makers will probably have to accept a scale of restoration that is less than the original extent of the system in question and even that targeted at the inception of the water release program. Hou et al. (2006) explore the companion question of whether the vegetation above the restored water-table can be reasonably expected to return to ecological functionality.

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