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ORIGINAL ARTICLE

Climatic and human drivers of recent lake-level change in East Juyan Lake, China

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Abstract Drying of an inland river's terminal lake in arid regions is an important signal of environmental degradation in downstream regions. A long-term, high-resolution understanding of the lake's retreat and expansion and the driving mechanisms will inform future adaptive water management strategies, ecosystem restoration, and government decision-making in the context of a growing water scarcity in the inland river basin. The shrubs that grow along the shore of a lake often provide evidence of lake retreat or expansion. The chronological results showed that the earliest germination dates of the lakeshore shrubs, tamarisk, were in 1901, 1943, 1966, 2009, and 1990 from the higher terrace to the lower terrace of East Juyan Lake, a terminal lake of China's Heihe River. Coupled with river and lake hydrological data, six obvious lake's fluctuations were identified: shrinkage from 1900 to 1940s and during the early 1990s, expansion and retreat in the late 1950s and early 1970s, continued expansion from 2002 to 2008, and stabilization at a water area of around 40 km^2 from 2009 to the present. The water elevation in the 1900s was below 905 m a.s.l., resulting in a water area <80 km^2, but decreased to 40 km^2 after 1960 and dried up completely by the 1990s. By analysing climatic and hydrological records since 1950, tree-ring climate proxy data, river runoff outside the observation period, and water resource consumption in the middle and lower reaches of the Heihe River, we found that the periodic expansion and retreat of East Juyan Lake was influenced by both climate change and human activities, but especially by human activities. The lake's recent recovery and stability was achieved by government policy designed to provide environmental flows to the lake.

Keywords Dendrochronology · Lake drying · Juyan Lake · Heihe River Basin · *Tamarix ramosissima*

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Introduction

Changes in lake water area result from changes in the water balance of the surrounding watershed and respond with high sensitivity to climate change and human influences (Ding et al. 2006). The arid regions of central Asia contain many inland lakes. Since 1960, the total area of these lakes has decreased by 30–50 % (Ding et al. 2006; Bai et al. 2011), especially in arid north-western China; prominent examples include Lop Nur in the Xinjiang Autonomous Region and Juyan Lake in Inner Mongolia (Feng et al. 2001; Cheng 2009; Xiao et al. 2011).

Drying of the terminal lake is an important signal of ecological and environmental degradation in the watershed of inland rivers in arid regions. The drying degrades the aquatic environment, the soil, and the vegetation community, resulting in soil erosion, desertification, and salinization that create sources of sand and salt dusts (Hu et al. 2005; Wang et al. 2007; Yang et al. 2008). This process also reduces biological diversity and productivity and gradually reduces or even eliminates the ecosystem services provided by lakes and wetlands, including climatic and hydrological regulation; the provision of water, food, fuel, and minerals; habitat provision; soil formation and nutrient cycling; and cultural values such as recreation, education, aesthetics, and scientific research (Millennium Ecosystem Assessment 2005; Ren et al. 2012). The drying of lake basins and associated ecological degradation have raised public concerns around the world, and in China, the central government implemented the Inland Watershed Water Division Plan for the Tarim, Shiyang, and Heihe River Basins in 2000 to address the problem (Xiao et al. 2011, 2014; Zhang et al. 2011).

Fluctuations of water levels in Juyan Lake, the terminal lake of the Heihe River, have been inferred over long periods using analyses of lake sediment cores, but these results have relatively low temporal resolution and reveal high variability (Zhang et al. 1998; Jin et al. 2005). In contrast, direct monitoring of lake levels provides higher resolution, but the documented changes are poorly understood. Moreover, the instrumental data cover only a short time period, as gauging stations were only fully implemented in East Juyan Lake in 2003. Thus, it is necessary to find ways to obtain a long-term, high-resolution understanding of the lake's retreat and expansion and the driving mechanisms, since this information will inform future adaptive water management strategies, ecosystem restoration, and government decision-making in the context of a growing water scarcity in this inland river basin.

Tree-ring data offer a possible way to infer water-level changes outside the period when instrumental data were available. Trees not only provide precise chronological data (due to the annual resolution of their growth rings), but also provide proxy information about the climate and environment when each growth ring formed. Using dendrochronological methods, precise chronological data have been used around the world to reconstruct historical lake-level fluctuations (Begin and Payette 1988; Begin and Filion 1995; Winchester and Harrison 2000; Xiao et al. 2005), saltwater intrusion (Benson et al. 2001), swamp drainage (Schweingruber 1996; Florentine and Westbrooke 2005), river channel changes (Scott et al. 1996; Downs and Simon 2001), glacier activity (Xu et al. 2012; Wiles et al. 1999), and other geomorphic processes (Bollati et al. 2012; Ballesteros-Cánovas et al. 2013).

The trees or shrubs that grow along the shore of a lake often provide evidence of lake retreat or expansion (Begin and Payette 1988; Begin and Filion 1995). To provide information that would support ecosystem and water management in the Heihe River Basin, we hypothesized that (1) changes in the shrub community age structure in lake terraces would be closely related to lake retreat or expansion; (2) the earliest date of shrub establishment would represent a time when the terrace was not inundated for a long period; and (3) dates when many shrubs died would represent periods with a higher lake-level and long-term inundation.

To test these hypotheses, we combined modern monitoring data with tree-ring data to invert the historical retreats and expansions of East Juyan Lake. Based on this knowledge, we inferred the magnitudes of the driving mechanisms (climate change and human activity) since 1900.

Study area

The Heihe River Basin lies between 96°20′E and 104°05′E and between 37°41′N and 42°42′N (Fig. 1). The Heihe River originates in the Qilian Mountains, flows west along the middle part of the Hexi Corridor, then turns north-east and enters the Ejin Banner of the Inner Mongolia Autonomous Region. The meandering of the river's channel, particularly in the lower reaches, has resulted in the formation of several terminal lakes and bodies of water along the eastern and north-eastern edges of the alluvial fan from the mountains: East Juyan Lake, West Juyan Lake, Juyanze Lake, the Guaizihu wetland, and the Gurinai wetland (Fig. 1). The hydrological stations in Yingluoxia (YLX; 1944–2012) and in Langxinshan (LXS; 1960–2012) divide the watershed into upper, middle, and lower reaches of the river, which are the mountain area, an agricultural oasis, and a desert riparian forest oasis, respectively. At Langxinshan, the river divides into two main branches, the East and West branches of the river, and flows mainly into East and West Juyan Lake, respectively.

The study area is an extremely arid region of China. Based on data from a local meteorological station at Ejin, the mean annual temperature (1950–2012) was about 8.8 °C, with the monthly mean temperature ranging from a minimum of −12.2 °C in January to a maximum of 26.3 °C in July. The annual precipitation totals 37 mm in Ejin, of which 84 % occurs during the growing season (May to September). The measured pan evaporation is >3000 mm (Xiao et al. 2014).

Materials and methods

Study sites and sampling

The East Juyan Lake basin is a shallow, roughly circular structure, and the wetland landscapes of the lake's shore exhibit clear plant zonation associated with long-term water-level fluctuations. From the water's edge to the highest terraces, the landscape evolves from tall and dense reed (*Phragmites australis*) beds, low reeds growing with dense tamarisk (*Tamarix ramosissima*) shrubs, tamarisk shrub dunes up to 1.0 m tall, and dense tamarisk shrub

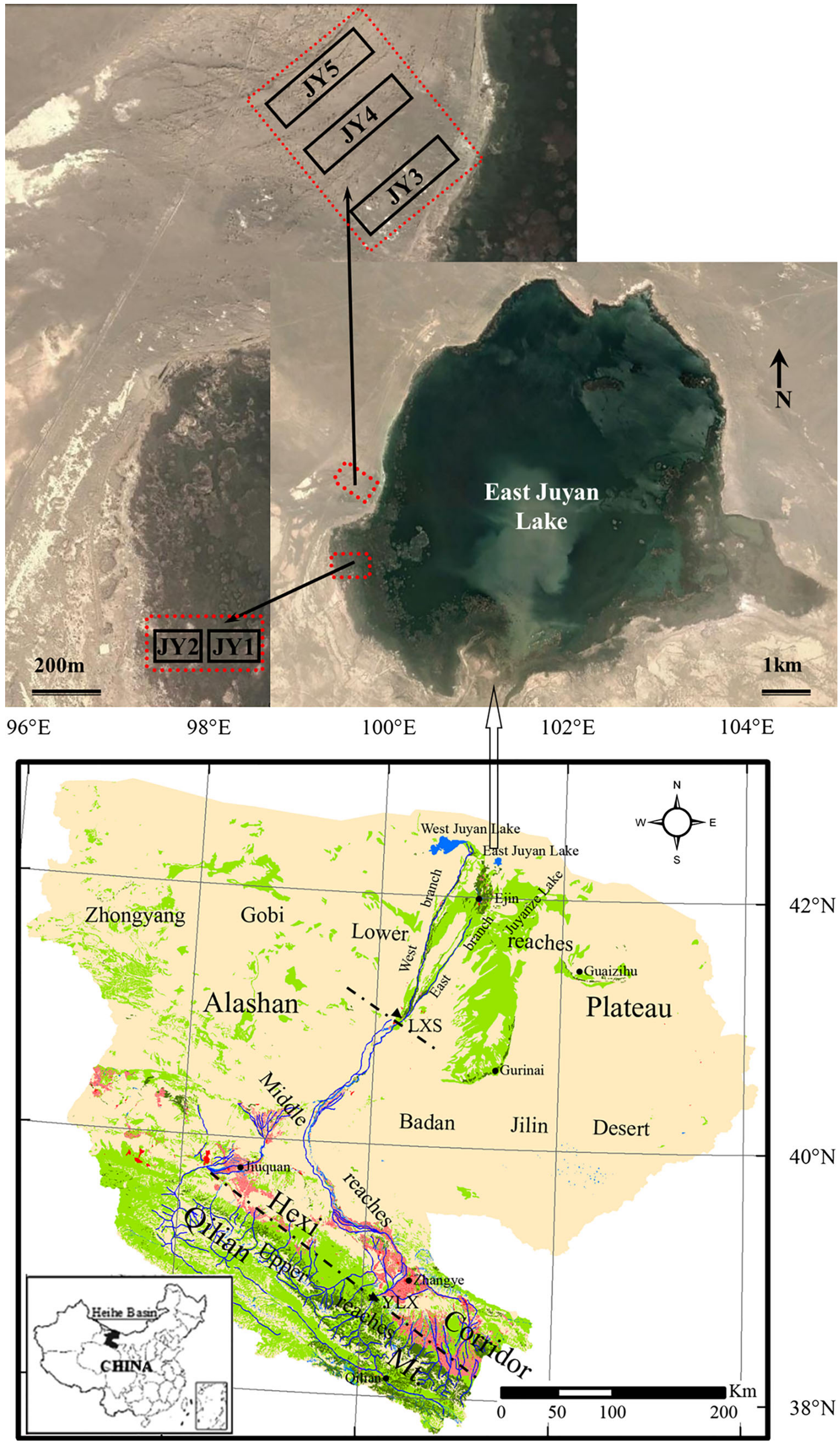

Fig. 1 Location of the study area and of the sampling sites (JY1–JY5). See Table 1 for details of each site. Yingluoxia and Langxinshan hydrological stations were abbreviated by YLX and LXS, respectively. The basin was divided into the *upper*, *middle*, and *lower* reaches by the *dotted line* in the two hydrological stations

Table 1 Characteristics of the shrub communities and landscapes at the sampling sites

Sampling sites	Position/elevation (a.s.l.)/sample size (living/dead)	Characteristics of the shrubs and geomorphology	Landscape images (photos by Xiao, July 2012)	Chronological characteristics (date of Shrub germination or death)
JY1(JY1-1)	101°13′08.7″E, 42°16′01.5″N 896.6 ± 1.0 m (44/16)	Lower terrace with a gentle gradient; mostly dead or weakly growing tamarisk shrubs up to 100 cm tall; 20-cm soil depth below root collar were washed off by lake waves		1990–1995 (Germination) 2007–2011 (Death)
JY2	101°12′55.2″E, 42°15′58.5″N 897.6 ± 0.5 m (38/0)	Lower terrace with a gentle gradient; shrubs up to 50 cm tall		2009–2011 (Germination)
JY3	101°12′24.0″E, 42°17′28.9″N 898.9 ± 1.0 m (29/0)	Middle terrace with alternating dunes and interdune areas; most tamarisk have a distinct main stem and a few with a height taller than 100 cm have formed shrub dunes		1966–1979 (Germination)
JY4	101°12′26.7″E, 42°17′37.3″N 900.2 ± 2.0 m (48/0)	Higher terrace; shrub dunes ranging in height from 100 to 200 cm; few of the tamarisk growing in the interdune lowlands have a distinct main stem		1943–1973 (Germination)
JY5	101°12′13.5″E, 42°17′57.0″N 905.0 ± 2 m (25/0)	Higher terrace; chains of shrub dunes ranging in height from 200 to 500 cm		1902–1939 (Germination)

Locations of the sites are shown in Fig. 1

dunes between 2.0 and 5.0 m tall. Due to the range of slope directions and range of terrace widths, the widths of the plant zones vary along the lake's shore.

Five sampling plots (JY1–JY5) were established to account for the geomorphological characteristics of the land and the growth status of the tamarisk, with the plots oriented perpendicular to the topographic contours (Fig. 1; Table 1). At each sampling plot, a minimum of 20 large-diameter shrubs were selected and transverse sections were collected at the root collar. For the shrubs growing on higher terraces, where the shrub dunes formed, the transverse sections were collected as near as possible to the lower edge of the dune.

Sample processing and ascertaining the germination and death dates

In the laboratory, sample discs were air-dried, planed, and sanded with progressively finer sandpaper to enhance the visibility of the boundaries between growth rings. Some discs required additional planing to ensure that the cross sections were perpendicular to the stem. Tree rings on each disc were cross-dated visually along two or three radii. False or missing rings were identified by comparing the two to three radii used in each cross section (Xiao et al. 2005, 2007, 2012). After performing this quality control, the calendar year of each ring in every sample was ascertained. For discs that contained a pith layer, the germination year can be calculated directly by counting the number of rings. For discs that lack a pith (e.g. due to heart rot), the number of rings was extrapolated to account for the missing portion and correct the shrub's germination year (Table 2). To perform the extrapolation, we first used the radius of the innermost rings to determine the pith's position, and then estimated the dates for the missing rings by dividing the missing portion of the radius by the mean width of the innermost five rings (Xu et al. 2012; Rozas 2003). All of the sample discs from the JY5 site were obtained at a level above the root collar and represented branches rather than the main stem. Because these branches grew at an angle to the vertical, their discs could not be corrected accurately one by one. We assumed that the large area of dead shrubs at the JY1 site resulted from a lake expansion event that drowned the shrubs, so we separated the germination and death dates for these individuals (as JY1-1) from the sample discs obtained from living trees at this site.

Table 2 Corrected germination dates for sample discs that lacked a pith or inner rings due to rot

Code	Adjustment/date	Code	Adjustment/date	Code	Adjustment/date
JY101	+4/1994	JY308	+7/1981	JY403	+3/1964
JY108	+2/1992	JY313	+3/1975	JY404	+1/1965
JY109	+3/1993	JY326	+1/1968	JY432	+3/1931
JY128	+3/1993	JY330	+2/1981	JY439	+3/1939
JY143	+2/1992				

JY followed by a three-digit number refers to the sites described in Table 1 (the first digit) followed by two digits that represent the shrub number at that site. The adjustment number refers to the number of years added to the age of a specific disc, followed by the corrected (estimated) germination date

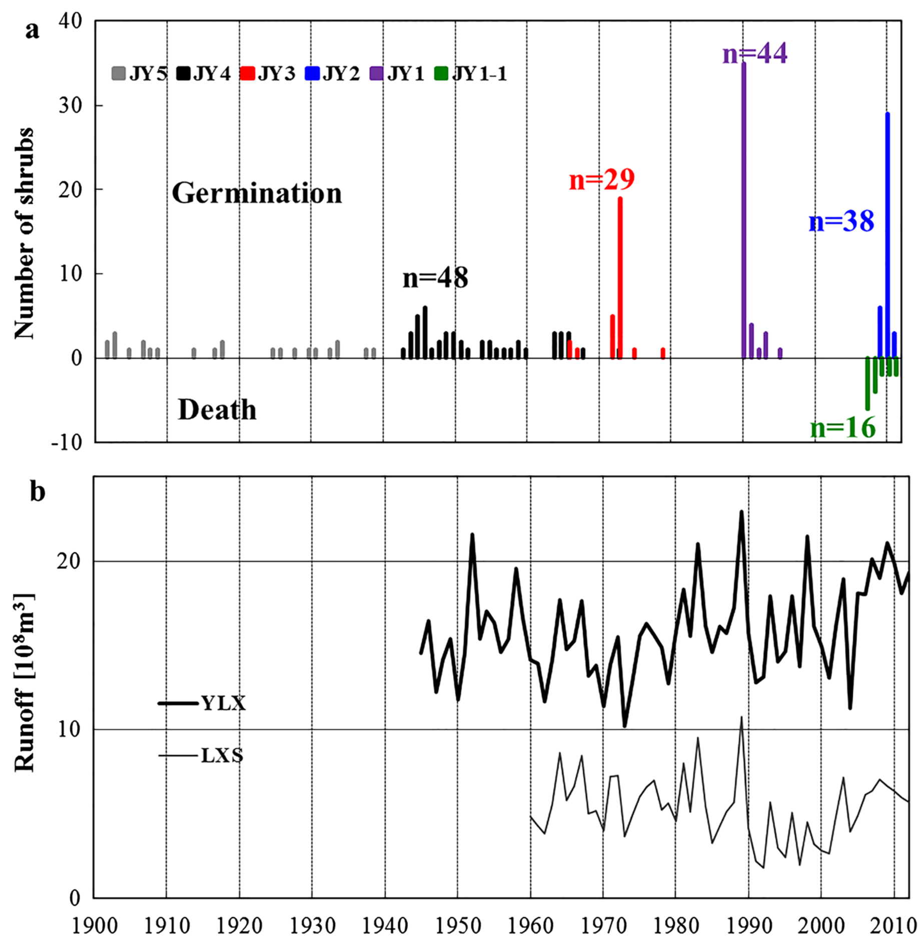

Fig. 2 **a** Shrub germination and death dates at the five lakeshore terraces above East Juyan Lake. See Table 1 for the positions, elevation and characteristics of each site. **b** Runoff based on the instrumental records from two hydrological stations on the Heihe River. Yingluoxia and Langxinshan hydrological stations were abbreviated by YLX and LXS, respectively

Meteorological and hydrological gauge data

Annual total river runoff data were obtained from 1943 to 2012 at the Yingluoxia hydrological gauge station and from 1960 to 2012 at the Langxinshan station. Meteorological data (the mean monthly temperature and total monthly precipitation from 1960 to 2012) were obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). The lake area data were obtained from the Heihe River Authority (http://www.yellowriver.gov.cn/trsweb/heihe/index.htm).

Results and discussion

Germination and death dates for shrubs in the lakeshore terraces

Figure 2a shows the germination and death dates of shrubs in the five sampling plots. Moving from the lower terrace sites (JY1 and JY2) to the higher terrace sites (JY4 and JY5), the oldest tamarisk germination dates were 1990 for JY1, 2009 for JY2, 1966 for JY3, 1943 for JY4, and 1901 for JY5, and the death dates at site JY1-1 ranged from 2007 to 2011. In the JY1 and JY2 plots, the germination dates were concentrated within a range of 3–5 years and the peak shrub germination dates occurred in 1990 and 2010, respectively. The germination dates in the JY3 plot occurred from 1966 to 1979 and peaked in 1973. The germination dates in the JY4 and JY5 plots showed a dispersed distribution with smaller or missing peaks and spanned the periods from 1943 to 1973 and 1901 to 1938, respectively.

Except in the JY2 plot, the germination dates gradually became later moving from the higher terrace to the lower terrace, which results from a primary succession process in which the shrubs colonized newly exposed lakeshore as the lake retreated (Table 1). In contrast, the germination dates in the JY2 plot represent the most recent lake expansion. Therefore, the germination and death dates of the lakeshore shrubs can provide a basic estimate for the timing of lake retreat or expansion. Figure 2b presents the annual runoff.

Lakeward expansion of the shrubs and associated hydrological processes

Lake water area changes and shrub germination and death dates in the lower lakeshore terraces since 2003

The lake's water area changed repeatedly as the lake retreated or expanded. From 2003 to the present, the lake's water area ranged from 31 to 43 km^2, with the minimum area in 2003 and the maximum in late 2011 (Fig. 3). Overall, the lake's water area increased during this period, apart from a decrease in mid-2011. The continued lake expansion during this period resulted in submergence of the shrubs in the lower lakeshore terrace JY1 plot for long enough to cause considerable shrub death, starting in 2007 (Fig. 2a). The maximum water area occurred in the winter and early spring, after which the area decreased to its minimum value during the summer. As the lake water recedes, the land–water interface provides suitable soil moisture and bare land for the germination of tamarisk seeds. The decrease in lake levels from 2010 to 2011 would therefore have promoted seedling survival. In contrast, the rising water level from 2009 to 2010 and from 2011 to 2012 would decrease seedling survival. Therefore, the peak for tamarisk establishment in the JY2 plot occurred in 2010 (Fig. 2a).

Hydrological processes, instrumental runoff, and shrub establishment in the lower lakeshore terraces

The terminal lake's expansion or retreat was closely related to river runoff. Since 1945, the annual runoff in the Heihe River at the Yingluoxia station averaged $15.87 \times 10^8 \pm 2.74 \times 10^8$ m^3 (mean ± SD), with periods of lower runoff in the late 1940s and from the late 1960s to the early 1970s (Fig. 2b). The annual runoff at the Langxinshan station averaged $5.32 \times 10^8 \pm 1.88 \times 10^8$ m^3, which represented the total surface water resources flowing into the Ejin Oasis from the eastern and western branches of the Heihe River. From 1968 to 1974, the runoff fluctuated, decreasing from 5.00×10^8 m^3 to 3.98×10^8 m^3 from 1968 to 1970, increasing to 7.26×10^8 m^3 from 1971 to 1972, and then decreasing to 3.67×10^8 m^3 and 4.93×10^8 m^3 in 1973 and 1974, respectively. In response to these changes in river runoff, the lake's water area increased from 36 km^2 in 1966 to 61 km^2 in 1972, and then decreased to 38 km^2 in 1975. The sharp decrease in river runoff from 10.75×10^8 m^3 in 1989 to 1.80×10^8 m^3 in 1992 resulted in complete drying of the lake in 1992, which continued until 2001 (Fig. 2b).

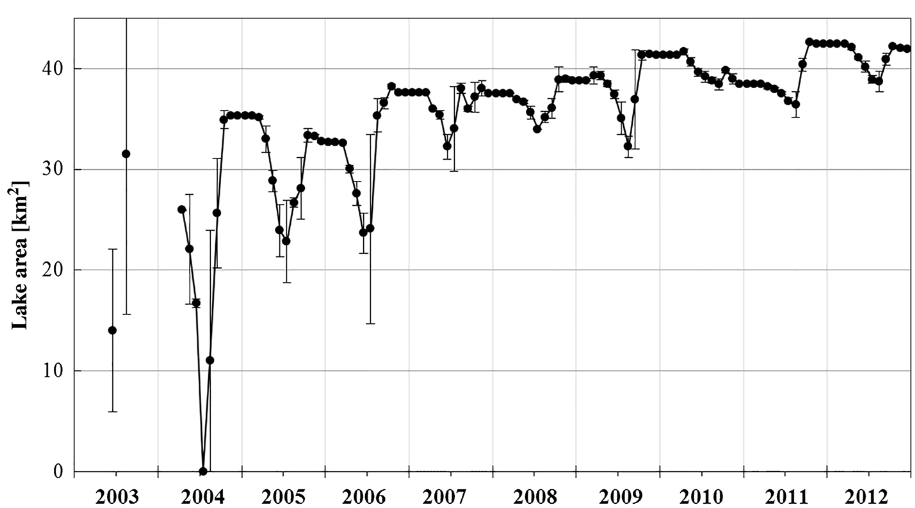

Fig. 3 Monthly water area changes of East Juyan Lake in 2003–2012

Based on these hydrological processes, it appears that the tamarisk establishment that occurred in the JY3 and JY1 plots (in the middle and lower lakeshore terraces, respectively) resulted from two periods of lake retreat, which started in 1968 and 1989, respectively.

Hydrological processes based on historical documents, river runoff proxies, and shrub establishment dates in the higher lakeshore terraces

The local chronicles of Ejin Banner recorded the construction of dams near the Langxinshan gauging station, where the Heihe River divides into its eastern and western branches, in 1941 and 1952 (Gao and Li 1991). These dams decreased river runoff in the eastern branch from 1941 to 1951, with flows increasing again in 1952, and this affected flows into East Juyan Lake (Gao and Li 1991). In addition, two reservoirs were constructed in Jinta County in 1944–1950, which sited in the middle reaches of the western main branch of the Heihe River. This stopped all flows of water into the lower reaches of this branch. The annual runoff decreased to about 1.5×10^8 m^3, which amounts to roughly one-third of the previous total annual runoff in the lower reaches. This decreased runoff from 1960 to 1963 caused the lake to shrink continuously. In response to the increasing river runoff from 1964 to 1967 (Fig. 2b), the lake's water area expanded slightly and then stabilized. The decreasing river runoff in the lower reaches and the highly variable river runoff in the eastern branch led to a trend of decreasing water area. The continuous seedling establishment in the JY4 plot from the 1940s to the late 1960s is likely to be related to the simultaneous changes in hydrological processes in the basin from 1943 to 1973. Based on the elevation of the JY4 plot, the lake area did not exceed 65 km^2 from the 1940s to the 1950s.

The runoff in the upper reaches of the inland Heihe River represents the total water resources available to supply the lake. The tree-ring records in the mountains in the upper reaches of Heihe River serve as proxies for these flows and reveal a period with high runoff from the 1890s to the early 1900s and a period with lower runoff from the 1920s to the 1930s (Kang et al. 2002; Liu et al. 2010; Zhang et al. 2012; Sun and Liu 2013). Based on the position of the JY5 plot, the lake area did not exceed 80 km^2 in the early 1900s. From 1927 to 1932, the highest measured water level in East Juyan Lake was 4.12 m (Gao and Li 1991), and the resulting water area would have been about 60 km^2. The lake retreat that occurred from the 1900s to the 1930s suggests that seedlings should have gradually become established in the JY5 plot in parallel with decreasing water levels, which agrees with our data (Fig. 2a).

Uncertainty of the tamarisk establishment dates

Tamarisk shrubs form the desert riparian forest and grow along the middle and lower reaches of inland rivers and at the edge of lake basins in arid north-western China. The tamarisk seedling stage is strongly associated with surface water levels, and wet but not flooded landscapes are required for their establishment (Huang and Gao 2004; Huang and Yao 1991). From the river to the lower terrace and to higher terraces, there is a progression from sapling forest to immature forest, then to mature and old or senescent forest, as soil moisture conditions change from wet to dry. This spatial sequence of tree ages reflects the temporal succession pattern of the tamarisk community in response to hydrological processes (Liu 1995). Consistent with this phenomenon, and based on the first 13 years of plant colonization along the shoreline of Lake Mead in the Mojave Desert, Engel et al. (2014) showed that the abundance of the tamarisk decreased with increasing age of the newly exposed lakeshore.

The establishment and death of tamarisk seedlings depend both on their position along the water-level gradient (and the resulting soil moisture gradients) and on the length of time since the water retreated (Wilcox and Nichols 2008). In addition, water-level fluctuations will structure the wetland vegetation community that develops along lakeshores (Chapin and Paige 2013). In north-west China, Tamarisk flowers twice per year, between May and September, and seed maturation takes 20–25 days. The mature seeds can germinate immediately, and the germination percentage decreases during the subsequent weeks. Riparian forest becomes established in exposed areas with stable moisture levels and an absence of interference from other vegetation after germination (Scott et al. 1996). If the water recedes rapidly, the exposed soil surface dries quickly, decreasing seed germination and seedling survival (Walker et al. 2006; Engel et al. 2014). Only when water levels are stable or decline slowly can tamarisk seedlings become established near the water's edge and form even-aged populations, which typically run along contour lines. A previous study in the Boulder Basin of Lake Mead, in the American Mojave Desert, showed that tamarisk dominated the vegetation within 200 m of the water's edge, but declined sharply at greater distances and was absent at distances beyond 250 m (Walker et al. 2006).

A study based on satellite images showed that in 1989, the water area of East Juyan Lake changed from 0 km^2 in May to 38.6 km^2 in July, 48.5 km^2 in September, and 41.0 km^2 in November, then decreased to 29.1 km^2 in the fall of 1990 (Guo et al. 2003). This decline agreed well with the establishment date of the tamarisk in the JY1 plot. In 1998, a year with high runoff, the high fall rainfall caused the water area of East Juyan Lake to increase from

0 km^2 in June to 6.5 km^2 in September and 22.9 km^2 in December, followed by drying out in the next spring (Guo et al. 2003). Some tamarisk seeds would germinate during this change in the lake level, but would not survive and become established because the seedlings could not live through the winter. The instrumental lake area data since 2003 (Fig. 3) showed that the lake dries quickly due to the high summer evaporation (0.6 × 10^8 m^3 to 0.8 × 10^8 m^3) when the water area is <35.0 km^2 and there is no inflow feed, and the resulting higher salt concentration and dry soil surface will restrain germination of the seeds and seedling establishment. Thus, we found no tamarisk individuals in the JY1 plot that became established in 1998 and 1999 (Fig. 2a). The tamarisk growing in the lower terraces would subsequently die due to the prolonged inundation duration when the lake expanded and most would die in the current year, as is shown by the pattern (a tight grouping of germination dates) for the JY1-1 plot (Fig. 2a).

Geomorphic diversity can cause the age structure of a riparian forest to differ within the same terrace (Scott et al. 1996, 2013). In desert areas, sand deposition occurs around the shrubs and shrub dunes develop, accompanied by erosion in the interdune areas. When the lake bottom is exposed, the individuals in the low land that is subject to greater erosion will die first, whereas growth of the shrubs in dunes will improve, and the increasing area of newly exposed land at the water–land interface will be suitable for the recruitment of seedlings. Thus, shrub establishment dates will vary spatially and the higher the lakeshore terrace, the higher the spatial diversity. Thus, the JY4 and JY5 plots have plants with a larger span of ages, a more complex age structure, and a decentralized pattern of ages, unlike the patterns in plots in lower terraces (Fig. 2a).

Impacts of climate change and human activities on retreat and expansion of the lake

Influences of regional climate change and the related changes in river runoff

The water sources of terminal lakes in arid regions include river flows, groundwater flows, and precipitation. Our study area is located in an extremely arid region, and the low annual precipitation (37 mm) is a weak source for the lake's water supply. The groundwater is also fed mainly by seepage from the river. Because of evaporative losses in the upper reaches of the river and interference with the flow by dams and reservoirs, the terminal lake's water resources are mostly provided by flows in the lower reaches of the Heihe River. Water consumption from the terminal lake includes evaporation from the water surface, evapotranspiration by vegetation, and evaporation from and leakage into the soil, of which the first two parts can account for more than 98 % of the total (Zhang and Shi 2002).

Climate change affects both runoffs from the upper reaches of the river, which represents the total water resources available within the inland river's basin, but also water consumption by the agricultural oasis that has been established in the middle reaches and the desert riparian forest oasis and terminal lakes in the lower reaches. These forms of consumption lead to overlapping and interacting demands on the water resources. During dry periods, river runoff decreases, and water consumption by the oasis and the terminal lake increases, especially due to withdrawals from the river by the agricultural oasis, thereby decreasing the terminal lake's inflow and accelerating the retreat of the lake. Conversely, during wet periods, the increased water resources and lower water consumption within the river basin will lead to expansion of the terminal lake. The meteorological record since 1960 for the Ejin Basin showed a trend of increasing mean annual temperature and decreasing annual precipitation (Fig. 4). This drier and warmer climate would accelerate the terminal lake's retreat by increasing water consumption.

Influences of water resource allocations at a basin scale caused by human activities

The drying of the terminal lakes and deterioration of the desert riparian forest oasis in this inland river basin was caused by changes in water resource allocations between the middle and lower reaches of the river (Xiao et al. 2011). With a growing population and expansion of cultivated land in the middle reaches of the Heihe River, the proportion of the river runoff intercepted by reservoirs and

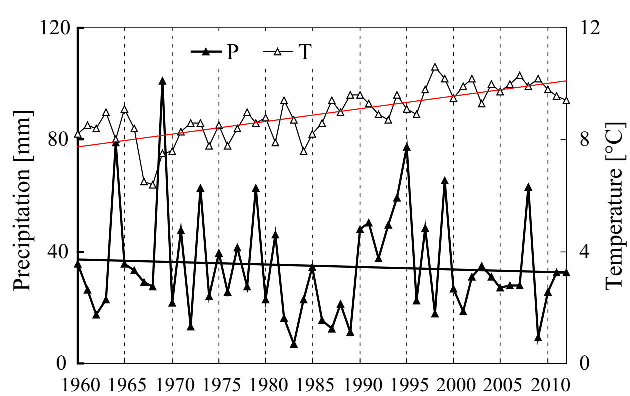

Fig. 4 Meteorological record (*T* mean annual temperature; *P* total precipitation) since 1960 in the Ejin Basin. The *trend line* represents the variation trend for the mean annual temperature and total precipitation, respectively

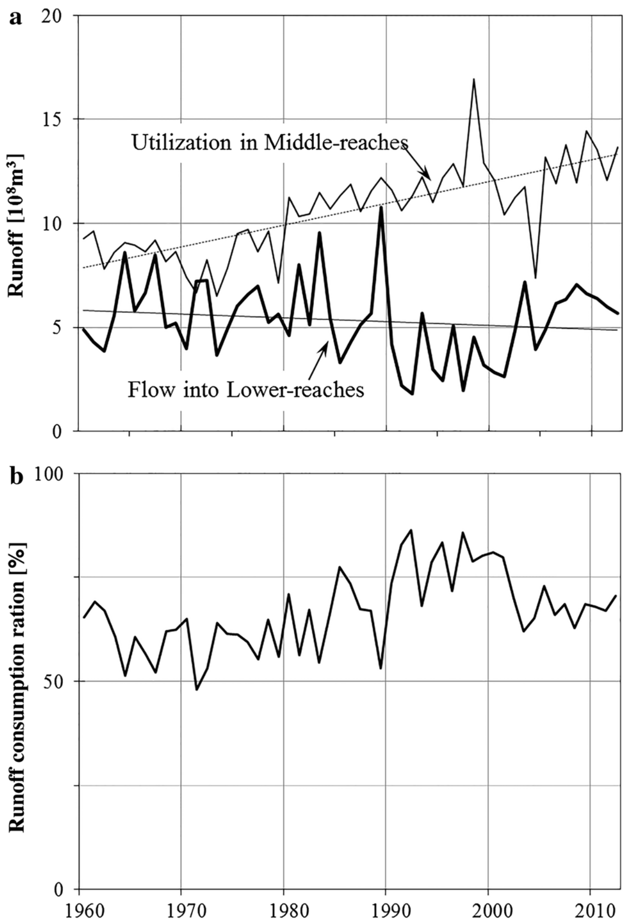

Fig. 5 **a** Changes in annual runoff consumption (*curves*) and its tendency (*straight lines*) in the middle and lower reaches of the Heihe River. **b** The water consumption ratio of the middle reaches in the total runoff of Heihe River since 1960

diverted to support irrigation of farmland has continued to increase. Figure 5a shows steadily increasing withdrawals of water in the middle reaches of the Heihe River (which is divided from the lower reaches at the LXS gauge station), accompanied by decreasing utilization in the lower reaches. In order to more clearly to present the water consumption between the middle and lower reaches, the water consumption ratio of the middle reaches in the total runoffs of Heihe River was calculated and presented in Fig. 5b. The result showed that the water consumption in the middle reaches accounted for approximately 60 % of the total river runoff from the upper reaches before the middle of the 1980s, leaving only 40 % of the water resources to flow into the lower reaches. The proportion of total water usage in the middle reaches increased to an average of 79 % from 1990 to 2001 and reached the peaks of 86 % in 1992 and 1997 (Fig. 5b). Since 2002, the proportion has decreased to an average of 67 %. These changes clearly show the large amounts of water that were intercepted in the middle reaches since the 1980s, resulting in drastically decreasing river runoff in the lower reaches. As a result of these withdrawals, East Juyan Lake received no inflows and dried up entirely for more than 10 years, from 1992 to 2002. To prevent further degradation of the ecosystem, the Heihe River treatment project was implemented in 2000 and a dedicated water channel was constructed from Langxinshan to East Juyan Lake to guarantee flows of a certain volume of water into the lake. Therefore, the lake has retained at least 30 km^2 of water area throughout the year since 2004 (Fig. 3).

Temporal heterogeneity of the factors that influence retreat and expansion of the lake

The lake's retreat and expansion represent the results of complex interactions among hydrological processes that result from the combined effects of climate change and human activities. A previous study on such changes in lakes in western China showed that the changes corresponded well to changes in precipitation in this arid region since 1960 (Ding et al. 2006). Although that study found a clear effect of temperature variations, the effects of precipitation changes were stronger. A study of the sediments of East Juyan Lake based on particle size and elemental analysis showed relationships between changes in the lake's level and climate changes during the past 1500 years, that is, during warmer periods, there was more precipitation and the lake expanded, whereas colder periods had less precipitation and the lake retreated (Jin et al. 2005). Another study in the same area showed that changes in the environment surrounding East Juyan Lake resulted in patterns of a cold–wet climate or a warm–dry climate on a century scale during the past 2600 years, which was consistent with climate changes in adjacent high-elevation areas such as the northern Tibetan Plateau (Zhang et al. 1998). The influences of human activities take the form of periodic changes that result from changes in national policy, population pressure, and policy orientation, which have become especially significant in modern times and sufficiently strong to conceal the impacts of climate change (Xiao and Xiao 2008). Although the Heihe River had lower runoff from 1960 to the 1970s, East Juyan Lake, nonetheless, retained a certain water area because the overall withdrawals were small enough to allow at least some water to reach the lake. In contrast, runoff was much higher from 1980 to the 2000s, but East Juyan Lake gradually evolved into a seasonal lake and even dried up completely for more than 10 years because withdrawals of water by human activities left no water to flow into the lake. Since 2000, the central government's new policy has guaranteed flows of water into East Juyan Lake and the water area has stabilized at more than 40 km^2.

Conclusions

The spatial age sequences reflect the temporal succession pattern of the tamarisk community in response to hydrological processes of the lake. It can be concluded that the sequence, which from JY5 and JY4 plots in the higher terrace to JY3 plot in the middle terrace and JY1 plot in the lower terrace with the occurring period of 1901–1938, 1943–1973, 1966–1979, and 1990–2010, respectively, represented a lakeward expansion process of the shrub community. The death date in JY1 plot (labelled by JY1-1) and germination date in JY2 plot with the occurring period of 2007–2011 and 2009–2011 represented a landward retreat process.

This long-term distribution pattern was influenced in the same time or not by the inner-factor of tamarisk and outer-factors of the environmental situation. Therefore, the peak time of the tamarisk communities' age structure would concentrate in the lower terrace more than the higher terrace on the lakeshore. These dates will present more accurate information for the lake retreat and expansion, whatever the germination or death of the shrub.

The lakeward expansion of the tamarisk forest generally reflected the retreat of East Juyan Lake since 1900. The lake level was not higher than 905 m a.s.l. during the 1900s, and the corresponding water area was <80 km^2. During the second half of the twentieth century, the lake's water area fluctuated, but overall represented a retreating trend until government policy stabilized the water area at around 40 km^2 after 2004. The lake exhibited several stages since 1900, with a continuous retreating trend from 1900 to the 1940s, short expansion and retreat stages in the late 1950s and early 1970s, retreating and drying during the early 1990s, and an expansion stage since 2002. The periodic expansion and retreat of East Juyan Lake has been influenced by both climate changes and human activities, and the lake's recovery and stabilization since 2002 have been achieved by changes in government policy.

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