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Evolution of the human–water relationships in Heihe River basin in the past 2000 years

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Abstract

This paper quantitatively analyzed the evolution of human–water relationships in the Heihe River basin of northern China over the past 2000 years by reconstructing the catchment water balance partitioning precipitation into evapotranspiration and runoff. The reconstruction results provided the basis for investigating the impacts of human societies on hydrological systems. Based on transition theory the evolutionary processes of human–water relationships can be divided into four stages: predevelopment (206 BC–AD 1368), take-off (AD 1368–1949), acceleration (AD 1949–2000), and rebalancing (after AD 2000). The evolutionary process analysis revealed that there were large differences in the rate and scale of change and the period over which they occurred, and transition of the human–water relationship had no fixed pattern. This understanding of the dynamics of the human–water relationship will assist policy makers to identify management practices that require improvement by understanding how today's problems were created in the past, for more sustainable catchment in the future.

1 Introduction

The development of land and water resources within catchments over thousands of years has led to spectacular growth in agricultural production along with increased human consumption of water, significant modification of catchment vegetation, and serious degradation of ecosystems, worldwide (Carpenter et al., 2011; Falkenmark and Lannerstad, 2005; Röckstrom et al., 2009; Vörösmarty et al., 2010). The future of human wellbeing may be seriously compromised if we pass a critical threshold that tips catchment ecosystems into irreversible degradation.

Understanding the connections and feedback mechanisms between changes in human activities and hydrological systems in the long term, and uncovering the mechanism governing the human–water feedback loop, can help understand how today's conditions and problems were created in the past, and have important implications for future management (Sivapalan et al., 2012; Liu et al., 2013; Montanari et al., 2013; Savenije et al., 2013). However, there is at present limited understanding of the major modes of interactions between the human and hydrologic systems over long time scales, although social-hydrology as a new discipline emerged in 2012 (Savenije et al., 2013).

Historical analysis is a key method of socio-hydrology in which hydrological analysis over a long timeframe is a key component. Accurate historical data for hydrology, climate, land use, ecology and geomorphology are often unavailable, but hydrological reconstruction that aims to generate long-term datasets, could provide a basis for the identification, description and parameterization of feedback mechanisms between human activities and water (Thompson et al., 2013). Empirical reconstructions of changes in single hydrological elements at specific locations have been reported, such as precipitation, streamflow, water salt content and lake levels (Turner et al., 2008; Lowry and Morrill, 2011). Whilst these studies are empirically informative, few of them have been conducted on water balance in basins that are facing significant threats e.g. water over-abstraction, sea level rise, or land use change, and that experience transitions in different ways (Vörösmarty et al., 2010).

In the social science literature transition is a well-established concept. It is: "a non-linear process of social change in which the structure of a societal system (energy sector, water management and agriculture) transforms" (Rotmans, 2005). Although there is a considerable number of empirical studies focusing on the dynamics of transition, and in particular on the different stages and processes of transition, they are criticized for empiricism: good at description but weak at explanation (Wimmer, 2006). There have already been several early attempts at exploring the co-evolution of human and water systems. For example, Xiao and Xiao (2004) divided the evolutionary processes of the human–land relationships affected by the water resources in the Ejin region, downstream of the Heihe River basin, into four periods. Geels (2005) studied the trajectories of the co-evolution of water technology and society in present-day Netherlands. Kallis (2010) studied the co-evolution of water resource development in ancient

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Athens. Pataki et al. (2011) provided an outline of the interplay of sociological and ecological processes in urban water management. Unfortunately, most of them adopted "thick descriptive" approaches that have poor explanatory and predictive ability.

The Hexi Corridor, located in western Gansu Province, is an important part of the ancient Silk Road established in the Han Dynasty (206 BC–AD 220), a trade route between China and western countries that facilitated cultural and economic exchange for approximately 1500 years. It is an arid area supported by oases ecosystems where water dominates the dynamics of human society and natural systems, and therefore the interactions and feedbacks between humans and water are very prominent. The region has a rich written history of over 2000 years. Over-development of land and water resources over thousands of years has significantly modified the catchment vegetation conditions and desertification is a continuing process causing environmental degradation in the region.

The overarching goal of this paper is to reveal the evolutionary processes of human–water relationships in the Heihe River basin, an important part of the Hexi Corridor over a period spanning approximately 2000 years, in which hydrologic, social and environmental systems were connected. The specific objectives are to reconstruct the water balance at the basin scale over the past 2000 years and to determine the development stages of evolutionary processes of the human–water relationships. It is expected to gain important understanding of the human–water relationships and provide guidance for the region's sustainable development.

2 Methods

2.1 Study area

We selected the Heihe River basin (HRB) in northwest inland China, an important part of the ancient Silk Road, and one of the most arid regions in the world, as our case study area. The HRB, covering approximately 130 000 km^2, is located at the climatic intersection between the Westerlies and the East Asian summer monsoon (Fig. 1). Many civilizations and cultures were found there, such as the Siba culture, and Juyan Wooden Slips and Literature of Heishui city in the HRB (Cheng et al., 2011; Shi, 2007). The rise and fall of civilizations in the HRB is closely linked with water: when there is water there are oases and flourishing societies, when there is no water, there is desert and diminished human activities.

The Qilian Mountains are the principal water source areas of the Heihe River and have an elevation varying between 2000 and 5500 m and mean annual precipitation varying from 250 to 500 mm. The midstream oases area is a part of the Hexi Corridor with elevations between 1000 and 2000 m and mean annual precipitation ranges from 100 to 250 mm. The lower reaches are located on the arid Alaxa Plateau where the mean annual precipitation is less than 50 mm (Qin et al., 2010). The Heihe River is the second largest inland river in China with a length of 821 km. Starting from the upstream Yingluoxia Hydrological Station (YLX), the Heihe River flows northward into its midstream area, and finally flows out of the midstream area, that is measured at the Zhengyixia Hydrological Station (ZYX), and flows into the terminal lakes in downstream areas. Its upstream flow provides water supplies for agricultural production and ecosystem stabilization in the middle and lower reaches of the HRB.

The HRB is an important area for grain production in China and is a highly developed irrigation district with an unremittingly agricultural history dating back nearly 2000 years. The intensive and non-sustainable utilization of water resources in the middle reaches of the basin has led to a sharp decrease of water supply in the lower reaches during the last 50 years (Zhou and Yang, 2006). As a consequence the ecosystem in the lower reaches has been degraded with land desertification, more frequent sandstorms, and the drying out of terminal lakes. Therefore the HRB is a compelling case study area for an analysis on the co-evolution of the human–water systems at basin scale.

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2.2 Study period

We selected the past 2000 years as our study period. This time scale represents a period in which dramatic changes in climate, land uses, runoff, management policy, population, societal development and catchment ecological conditions have occurred. These are major variables affecting the river basin water cycles. It is also a time of significant civilisation development in China. There is a wealth of documentary evidence available (Holmes et al., 2009; Zheng and Wang, 2005). Due to the limitations of land use information, several periods were selected in the past 2000 years according to the results of Shi (2010), Wang et al. (2013) and Xie et al. (2013) (Table 1). We reconstructed the co-evolutionary processes of societal development and hydrological system based on seven Dynastic periods.

2.3 Reconstructing the evolutionary processes of catchment water balance

We used annual water balance partitioning, which is widely used as a signature of hydrologic regimes when catchments experience changes in precipitation regimes, temperature and land use change (Budyko and Miller, 1974; Sivapalan et al., 2003), to provide insights into the evolutionary processes of human–water relationships at basin scale. For this study, the water balance equation can be written as:

$$P + R_{in} = E + R_{out} \tag{1}$$

where P and E are precipitation and evapotranspiration in the mid- and down-stream areas of HRB, respectively, R_{in} is the streamflow in the upstream part of HRB flowing into the midstream area, and R_{out} is the amount of water flowing into the terminal lakes of the downstream areas. In arid regions soil water content is very small and the groundwater levels were stable over historical periods, so changes of soil water content and groundwater are negligible and not included in Eq. (1).

Due to lack of measured data in historical periods the reconstruction of P, R_{in} and E, and validation of the derived R_{out} from Eq. (1) are important steps for developing

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catchment water balance over the long-term timeframe necessary for understanding the co-evolutionary process of human–water relationships.

2.3.1 Reconstructing precipitation (*P*) in the mid- and down-stream areas

We estimated precipitation (*P*) in historical periods based on instrumental data in the most recent period and changes in paleoclimatic conditions. Ren et al. (2010) reconstructed the mean precipitation sequence of the whole HRB in the past 2000 years using historical drought and flood sequences, based on the good correlation between drought and flood disasters and precipitation in the 40 years from 1956 to 1995 ($R^2 = -0.892$). We reconstructed the distributed precipitation (*P*) in the mid- and downstream areas in historical periods by multiplying the instrumental data from 1956 to 1995, when there were continuous records at ten meteorological stations, by the proportion of the precipitation in each historical period reconstructed by Ren et al. (2010) to that in the measured period. The instrumental precipitation data in the recent period were obtained from the China Administration of Meteorology.

2.3.2 Reconstructing streamflow flowing into midstream R_{in}

Dendrochronological-based hydrological reconstructions have been widely used to extend existing instrumental streamflow records as streamflow variations correlate well with tree ring-width series (Woodhouse et al., 2006; Saito et al., 2008). There are many studies on the streamflow reconstruction in Qilian Mountains based on tree ring analyses. The longest streamflow record in this region is about 1400 years obtained by Yang et al. (2012), then 1300 years by Kang et al. (2002) and 1000 years by Qin et al. (2010). None of these streamflow reconstructions spanned 2000 years or more.

In order to reconstruct the historical streamflow in the upstream area of HRB (R_{in}) in the past 2000 years, we firstly analyzed the consistency of the historical streamflow reconstructions by Yang et al. (2012), Kang et al. (2002) and Qin et al. (2010), and selected the more reasonable two reconstructions based on the humidity change of cli-

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mate in this region reflected by other proxy indices, e.g. lake sediments and ice cores; then among the two selected streamflow reconstructions, the shorter one was used to extend the historical series and the longer one was used to validate the extension in the gap period between the shorter and the longer. We then extended the selected reconstructed streamflow up to 2000 years by using the reconstructed precipitation based on the established relationship between the selected streamflow and existing precipitation reconstructions in the upstream area. As all the streamflow reconstructions focused on mountainous region of the mainstream of the Heihe River (Fig. 1), in order to obtain the streamflow flowing into the midstream area (R_{in}), we multiplied the streamflow at YLX by a proportion of the total streamflow of the upstream area of the HRB to the one at YLX, based on the instrumental data in the recent 50 year period. In addition to the meteorological data mentioned in Sect. 2.3.1, the instrumental streamflow in the recent period was obtained from the Hydrographic Service of Gansu province.

2.3.3 Estimating E based on the reconstruction of land use

E in Eq. (1) was calculated by the top-down method of the Budyko hypothesis. We used the equations developed by Fu (1981) fFor details, see Fu, 1981 and Zhang et al., 2004) which are expressed as:

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P}\right)^w\right]^{1/w} \tag{2}$$

$$\frac{E}{E_0} = 1 + \frac{P}{E_0} - \left[1 + \left(\frac{P}{E_0}\right)^w\right]^{1/w} \tag{3}$$

where E_0 is potential evapotranspiration. E_0 on a daily timescale was estimated using the Penman–Monteith equation, which was acknowledged as the best method for this region (Zhao and Ji, 2010). It is known that air temperature is one of most key factors that influences the PET. As the oscillating range of the temperature change was not more than 2 °C in the past 2000 years (Zheng et al., 2010), the E_0 in the historical period was considered the same as in modern instrumented times. w is a model parameter determining the E ratio (E/P) for a given E_0/P. It is a catchment parameter and the value of w for HRB was set at 3.5 according to Yang et al. (2007). The sources of water supply for E include precipitation, groundwater, and irrigation water in this region, so P in Eqs. (2) and (3) can be replaced as follows:

$$\text{for cultivated oases: } P_{\text{crop},i} = P_i + I$$
$$\text{for natural oases: } P_{\text{veg},i} = P_i + G_{\text{veg}} \quad (4)$$

where $P_{\text{crop},i}$ and $P_{\text{veg},i}$ are the precipitation equivalent in the period i for crop and natural oases respectively; P_i is actual precipitation in period i; I is irrigation; G_{veg} is the consumed groundwater by natural oases. According to Xiao and Xiao (2008) flood irrigation was the main irrigation method in northern China from the Han dynasty to the early modern period, and the value of I in historical period was set at 500 mm. G_{veg} was set at 225 mm for natural oases according to Wang et al. (2005). So the total ET of the basin is:

$$E_{\text{total}} = \sum_{l=1}^{3} E_l \times S_l \quad (5)$$

where E_{total} is the total evapotranspiration of the basin; l is the number of the land use types: cultivated oases, natural oases, and unused land. E_l is the evapotranspiration from land use type l, and S_l is the area of land use type l.

The maps of cultivated oases in historical periods were downloaded from the Heihe Plan Science Data Center: www.heihedata.org/heihe (Xie, 2013). As a historical reconstruction of natural oases in this region was not found in the literature we used the land use scenario in 1975 as the final land use pattern in order to reconstruct the distribution of natural oases because it is known that the expansion of the farmland was at the expense of the desert after 1975. We made the following two assumptions about the reclamation of cultivated oases based on the previous results (Li, 1998; Wu, 2000;

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Xie et al., 2009): (1) people selected the regions with natural oases (grassland and forest) rather than desert for reclamation in the historical period because the former has better water and soil conditions in arid regions, and (2) once the reclaimed farmland were abandoned and without the vegetation cover, they were subsequently desertified because of wind-driven sand and dune coverage. The hundreds of ruins of towns along the Silk Road in the vast deserts of northwest China are clear evidence of this change of oases systems. Therefore, we considered the total area of oases from the first period to the period of 1975 as the largest area of the oases in historical period, which included cultivated oases and natural oases. In each period the area of cultivated oases had reconstructed data (Xie, 2013), then the area of natural oases was obtained by deducting the area cultivated oases in this period and area of cultivated oases abandoned in the past periods from the total oases area, and the remainder was considered unused land.

Based on the land use reconstructions, precipitation reconstructions and estimated PET, the E in Eq. (1) was obtained according to Eqs. (2) and (3). The data sources used for calculations of E and reconstruction of land use included: land use data obtained for three periods by remote sensing (1975 Landsat MSS, 2000 and 2010 satellite TM and ETM+ data), the historical atlas of China (Tan, 1996), and meteorological data from the China Administration of Meteorology, including daily mean, maximum and minimum air temperatures, wind speed, and relative humidity.

2.3.4 Validating the derived R_{out} with the reconstructed evolution of the terminal lakes

The input volumes of water to terminal lakes R_{out} were derived from the reconstructed precipitation, E based on the reconstructed land use, and reconstructed streamflow R_{in} using Eq. (1). We validated the derived R_{out} with the lake evolution reconstructed by previous research on the lithology, geochemistry and mineralogy of lacustrine sediment depth profile sequences.

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As sediment profiles of lakes in arid zones sensitively reflect changes in climate changes and human activities they are regarded as excellent resources for palaeoclimate research (Jin et al., 2004). Lacustrine sediment sequences have been widely used for deducing the mass balance between the inflow water volume and evaporation from terminal lakes, climate change and human activity (Jin et al., 2004, 2005). For example, grain size distributions of lacustrine sediments directly reflect water dynamics, and soluble salt content reflects the chemical characteristics of lake water, which is affected by climate and inflow water (Jin et al., 2004).

Due to the unavailability of systematic and consistent studies on lake evolution in the HRB, we validated the derived R_{out} values based on the changes of input volumes of water to the terminal lakes in downstream areas as they reflect changes of the hydrologic cycle involving precipitation, land use, evaporation and runoff in the upper and middle reaches. R_{out} directly influences the processes of expansion and shrink, deposit and salinization of the terminal lakes. When the input volume of water to the terminal lakes is relatively abundant, lake area extends, lake water level rise, lake water has smaller salt concentrations, and the deposition environment is relatively stable, and vice versa.

The data and information sources used for reconstruction of the evolution of the terminal lakes include all collected research achievements on the palaeoenviroment evolution in the downstream area of the HRB from Lakes Sogo Nur, Gaxun Nur and Juyanze. The evolution of the terminal lakes in the Heihe River experienced three periods: Juyanze from Warring States Period to Yuan dynasty, Juyanze-Gaxun Nur from Yuan dynasty to Ming dynasty and Gaxun Nur-Sogo Nur from Ming dynasty to AD 1961 (Chen, 1996). The data include granularity, soluble salt, sedimentary pigment, organic carbon content and groundwater level (Jin et al., 2004, 2005; Qu et al., 2000; Zhang et al., 1998).

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2.4 Determining the development stages of evolutionary processes of human–water relationships

River basins are co-evolved social-ecological systems in which water management decisions affect environmental outcomes that are subject to sociological conditions. We interpreted and determined the key states of the evolutionary processes of the human–water relationships in the HRB based on the transition theory of social science. Transition theory is one of the most relevant approaches to understand societal evolution and support the management of societal adaptation to sustainability (Tàbara and Ilhan, 2008). In general terms a transition can be understood as the process of change of a system from one stage of dynamic equilibrium to another. According to Rotmans (2005) a set of typological phases can be identified in a transition: (1) predevelopment, (2) take-off, (3) acceleration, and (4) stabilisation. Transitions can fail at any stage.

A transition can be measured and assessed by indicators which could be variables with actual physical meanings or their surrogates. In this study we used human water consumption and natural oases area as the indicators to understand the evolutionary processes of the human–water relationships in the HRB over the past 2000 years. Human water consumption, the difference between evapotranspiration and precipitation in cultivated land, reflects the consequence of human societal development on water cycles. The natural oases area reflects water supporting the environment. We used the change trend and rate of these two indicators over time to divide the human–water relationship into different development stages. Both the natural oases area and human water consumption were obtained using the methods above.

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3 Results

3.1 Reconstructed precipitation (P) in mid- and down-stream reaches

The proportions of the precipitation of the whole HRB, derived using drought and flood sequence information and data, to that in the most recent period in the seven selected historical dynastic periods over the past 2000 years, were 0.7, 0.95, 1, 0.9, 1, 0.98 and 0.96, respectively. The precipitation in mid- and down-stream areas in the historical periods obtained by multiplying the mean instrument-measured precipitation from 1966 to 1995 at ten meteorological stations by these proportions is shown in Fig. 2. The precipitation in historical periods decreased from the midstream to downstream reaches, and it was least in the Han Dynasty, was similar to the present level in the Tang and Ming Dynasties.

3.2 Reconstructed streamflow flowing into midstream reaches (R_{in})

The streamflow reconstruction of Qin et al. (2010) was used to extend the streamflow reconstruction, and the streamflow reconstruction of Yang et al. (2012) was used to validate it. It was found that the streamflow record reconstructions obtained by Yang et al. (2012), Qin et al. (2010), and Kang et al. (2002) for the period AD 1000–2000 are generally consistent, however, discrepancies occurred around the years of 1290, 1530, 1690, 1840 and 1910. Based on the results from the paleoclimate established in this region with tree rings from living trees or archaeological woods in Qilian Mountain and the Tibetan Plateau (Yang et al., 2014; Sheppard et al., 2004; Shao et al., 2010), lake sediments in Qinghai Lake (Shen et al., 2001) and ice cores in Dunde (Liu et al., 1998), the reconstructions by Yang et al. (2012) and Qin et al. (2010) were more consistent with the changes of regional humidity and were considered to be the more reasonable.

It is known that the annual streamflow at YLX and mean precipitation in the Qilian Mountains region changed consistently in the past 50 years. It was found that precipitation reconstructions of Yang et al. (2014) (Fig. 3a) and streamflow reconstructions of Qin et al. (2010) (Fig. 3b) changed consistently in the last 1000 years. We derived the linear relation between them as follows: $R_{\text{Qin et al. (2010)}} = 0.2771 \cdot P_{\text{Yang et al. (2014)}} + 80.632$. We used this relationship to extend the streamflow reconstruction from AD 0 to 1000 at YLX (Fig. 3c). The extended streamflow reconstruction is consistent with the streamflow reconstruction of Yang et al. (2012) for the period from AD 575 to 1000. From historical periods to now the reconstructed streamflow into midstream areas (R_{in}) were between about 2.6 and 4.0 billion m^3. It peaked in recent years due to abundant precipitation together with glacier and snow melt in the upstream areas due to rises in temperature.

3.3 Reconstructed historical land use and land cover

The reconstructions of land use in the seven historical periods and three land use maps for 1975, 2000 and 2010 in modern New China (since 1949) obtained by image interpretation are shown in Fig. 4. The cultivated oases areas changed significantly in historical periods. It had a large size in the Han Dynasty, and then decreased in area until Yuan Dynasty. From the Ming Dynasty it increased gradually, and finally reached a peak in the period of New China. The cultivated areas were mainly distributed in the downstream area of the basin in the first period, and then moved toward the upstream area, and finally focused on the middle reaches. It can be seen that when the streamflow was more abundant (Fig. 3), the cultivated oases area was larger. This could reflect that land reclamation was directly affected by the available water resources.

3.4 Validation of derived R_{out} with the reconstructed evolution of the terminal lakes

The volume of water that entered the terminal lakes (R_{out}) in the historical periods is shown in Table 2. The data were obtained from Eq. (1) based on the reconstructed precipitation, streamflow and E related to land use. The lake evolution reconstruction

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based on lithological, geochemical and mineral data from the lacustrine sediment profile sequences in terminal lakes is also described in Table 2.

There are relatively good relationships between the input volumes of water to the terminal lakes (R_{out}) and evolution of the terminal lakes in historical periods. The input of water to terminal lakes was not only determined by the streamflow from upstream, but also affected by land use in the mid- and down-stream areas of the basin. When the streamflow from the upstream area was high and the cultivation activity in the middle stream was not intense, the input of water to terminal lakes was high, such as in the Tang and Ming Dynasties, and vice versa. This was reflected by the pigmentation and organic carbon content of the sediments of the terminal lakes (Qu et al., 2000; Zhang et al., 1998). After the turn of this century R_{out} became negative which meant that there was a deficit in groundwater recharge because of over-extraction of water for irrigation to meet the need of food (Wei, 2013).

3.5 Reconstructed catchment water balance in the past 2000 years

We reconstructed the catchment water cycles at the HRB in the past 2000 years from the precipitation reconstruction (P) in mid- and down-stream areas, the streamflow reconstruction (R_{in}), land use reconstruction, evapotranspiration reconstruction (E) and the derived streamflow reconstruction into terminal lakes (R_{out}). Through validation with the lake sediment evolution reconstruction, the reconstructed water cycles reasonably reflected the reality of water balance partitioning at HRB in the past 2000 years.

Figure 5 shows the evolution of catchment water balance elements in the HRB in the past 2000 years. Human water consumption changed clearly, especially after the founding of modern China, when streamflows from upstream areas were approximately unchanged. The main factor for this was rapid expansion of the cultivated area around oases, reflecting the increasing population which was a primary driver for this. The cultivated oases areas shrank from the Han to the Yuan Dynasty but thereafter expanded until now, the natural oases areas were continually shrinking until 2000, and the areas of desertified land increased as cultivated land was abandoned due to war, disasters or other causes. The volumes of streamflow into terminal lakes remained about 1 billion m^3, even more in historical periods, but it decreased sharply after 1975, and even became negative which meant the groundwater was overexploited so that there was a negative mass balance. After a water reallocation scheme was implemented in 2000 the ecological and environment deterioration was halted and the lakes were restored. At the same time, the cultivated oases areas, population and human water consumption increased. This was at the expense of groundwater in midstream areas and the benefits of a wet period of about ten years.

3.6 Determination of the development stages of evolutionary processes of human–water relationships

The human water consumption and natural oases areas changed with different rates in different periods (Fig. 5). Based on their change rates with time we divided the evolutionary processes of the human–water relationships in HRB in the past 2000 years into four phases (Fig. 6): (1) predevelopment (206 BC–AD 1368), (2) take-off (AD 1368–1949), (3) acceleration (AD 1949–2000), and (4) starting to rebalance between the human and water relationships (after AD 2000).

The predevelopment phase started after the Han Dynasty. In the Han Dynasty an unprecedented expansion of manmade cultivated areas based on oases occurred. This happened because of defence needs, immigration and settling of farms, which changed the production mode from nomadic herding into farming. It also corresponded with the warm and humid climate in the early Western Han Dynasty (Ren et al., 2010; Xie et al., 2009). However, in the late eastern Han Dynasty, agricultural production levels declined due to population loss and damage to water conservancy facilities after long-term warfare. During the Southern and Northern Dynasties (420–581) to the Yuan Dynasty (1271–1368), the people led nomadic lifestyles and the Hexi corridor was in the state of frequent wars and dynastic changes, and the HRB was primarily pastoral land as most agricultural oases were abandoned (Li, 1998; Xie et al., 2013). In this predevelopment stage of about 1500 years, the population did not increase, and recla-

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mation was small and focused on downstream areas, so humans had little impacts on the water system and the natural oases area did not change significantly.

Since the Ming Dynasty, in which agricultural civilization revived, the evolutionary processes of the human–water relationships in HRB entered the take-off stage. During this phase oases reclamation activities were promoted and moved up to the midstream area (Wu, 2000). In the middle of the Qing Dynasty, the Hexi corridor was politically stable and free of wars and innovative farming and engineering methods were introduced, such as better seeds, new crops, and the steel farm implements. Therefore the population increased quickly (Shi, 2010). It was also during this period that water disputes arose (Cheng et al., 2011; Shen and He, 2004). This phase was short, lasting about 580 years. During this phase, human water consumption increased at a rate of 1.09 million $m^3\,yr^{-1}$ on average, and the natural oases area decreased at an average rate of 1.38 $km^2\,yr^{-1}$. The human intervention of the water system was gradually increasing.

After New China was founded the social development in the HRB stepped into the acceleration stage. During this stage the population, cultivated land and human water consumption increased sharply especially after the world-wide green revolution in the 1960s, and China's reform and opening-up in 1978. In addition, food self-sufficiency has dominated Chinese agricultural and water resources development policy. Many wells, reservoirs and channels were built during this stage. This stage was the shortest, only 60 years long, but the human water consumption increased at an alarming rate of 35.1 million $m^3\,yr^{-1}$, and the natural oases area decreased at an average rate of 58 $km^2\,yr^{-1}$. The influence of human activities on water resources reached its peak and the environment was seriously degraded as natural wetlands, rivers, and lakes dwindled rapidly (Xiao et al., 2004).

In order to prevent continuing environmental degradation a series of actions and measures were carried out, such as the Natural Forest Protection Project after 2001 and project of turning the cultivated land into forests or grasslands from 2002 to 2004, and Zhangye city in the midstream area was selected as the first construction experi-

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mental site by the Water Saving and Conservation Society (WSCS) of China in 2002. This was supported by a water reallocation scheme in 2000 by which the midstream area should discharge 950 million m^3 of water in normal years as measured at the ZYX to downstream areas when the upstream YLX discharges 1580 million m^3 of water. The Central Government's No.1 Water Document in 2011, which limits total water diversion, promotes water use efficiency and reduces water pollution signaled a big step in the relationship between humans and water. All of these actions have resulted in some improvements to downstream ecosystems, such as halting ecological and environment deterioration and restoring the lake. The natural oases area increased at an average rate of 28 $km^2 yr^{-1}$ from 2000 to 2010. A new equilibrium stage between the human and water emerged since 2000.

4 Discussions and conclusions

This paper represents an attempt to reveal the evolutionary processes of the human–water relationships in the HRB over the past 2000 years. We quantitatively analyzed the dynamics of coupled human and hydrological system as well as the associated climatic and ecological changes in the past more than 2000 years within HRB by reconstructing the catchment water balance. Based on transition theory we divided the evolutionary processes of human–water relationships into four stages including predevelopment (206 BC–AD 1368), take-off (AD 1368–1949), acceleration (AD 1949–2000), and rebalancing (after AD 2000). This study for the first time provided new understandings of how societal drivers and societal responses over time interact and feedback with catchment water cycles over a timescale of 2000 years. This evolutionary process was not at a uniform pace. The predevelopment stage experienced 1500 years, take-off was shorter at only 580 years, and after that only 60 years' acceleration when the population increased up to 1.9 million, cultivated oases areas expanded by 3649 km^2, which was about two times that in the beginning of this stage, and human water consumption increased by 1.9 billion m^3, which was more than two times of that in the beginning of this

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stage. This resulted in volumes of water from midstream areas being discharged into terminal lakes decreasing from more than 1 billion m^3 to 0. This situation became the trigger for sustainability transition in HRB in 2000 when a water reallocation scheme was implemented, which meant the evolutionary processes of human–water relationships in the basin started a new stage: rebalancing. This understanding of the dynamics of transitions will assist policy makers to identify management practices that require improvement by understanding how today's conditions and problems were created in the past. It could also help integrate management of land and water use to allow for more sustainable catchment management against desertification in this region.

This paper, through reconstruction, incorporated metrics of human–water interaction into fundamental understanding of complex human–water systems. The quantitative historical analysis not only improved our understanding of past human–water relationships but also facilitated improved predictions of its possible future dynamics. It has added a valuable case study for comparative socio-hydrologic studies across different human–water systems around the world. This paper has suggested some guidelines toward an analytical approach to water related societal transitions that should be, on one hand, strongly attached to social science theory, and on the other hand, firmly based on formal hydrological modeling. It can be seen from the four stages of evolutionary processes of human–water relationships in the HRB that transitions have no fixed pattern. The stabilization, a typological phase in the standard transition theory, did not appear. In addition, there were large differences in the rates and scales of changes and the period of time over which they occurred. This happened because during a process of change, humans are able to adapt to, learn from and anticipate new situations (Chen, 2005).

This paper reconstructed catchment water balance by using a range of data sources, including paleo-climates and paleo-environments reflected by dendrochronology, ice cores, lake sediments and historical drought and flood sequences, a historical atlas of China, remote sensing images and instrumented streamflow and climate data, which explained the evolutionary-process of human–water relationship in HRB in the past

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2000 years with relatively good agreement. The reconstruction provided the basis for generating baseline data against which to evaluate recent changes, investigating the impact of human societies on hydrological systems in historical contexts and generating datasets for improving models of hydrological systems over timescales that exceed the length of the instrumented record (Savenije et al., 2013). However, there were some discrepancies among the reconstruction methods. They might come from: (1) inconsistency between the data extracted from the different proxy materials, for example, the streamflow reconstructions by Yang et al. (2012), Qin et al. (2010), and Kang et al. (2002) using tree rings were not completely consistent, (2) limitations of the data's representativeness of locations, for example the data from tree rings only focused in the upstream of the mainstream areas of the Heihe River and the samples of lake sediment mainly focused in the terminal lake Sogo Nur; and (3) non-representativeness of data in time periods and different resolutions of data, for example, the land use maps only covered several recent periods, the tree ring can be specific to the annual scale, and the information from ice cores and lake sediment profiles was at the century scale. In future, we should improve the consistency, length and quality of historical datasets by advancing data analysis techniques.

Author contributions. Z. Lu made substantial contributions to model simulations, data collection and analysis, and drafting and revising the article; Y. Wei, H. Xiao and S. Zou suggested/designed the research theme and methods; Y. Wei and A. Western helped to revise the manuscript; J. Xie and J. Ren made substantial contributions to the acquisition and interpretation of data.

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Table 1. Seven periods selected in the past 2000 years.

Periods	Selected time
Han Dynasty	The beginning of the 1st century AD
Wei-Jin Era	The end of the third century AD
Tang Dynasty	The mid-8th century AD
Yuan Dynasty	The end of the 13th century AD
Ming Dynasty	The mid-16th century AD
Qing Dynasty	The mid-18th century AD
New China	The 1950s

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Table 2. The input volumes of water to the terminal lakes (R_{out}) and evolution of the terminal lakes in historical periods.

Periods	R_{out} /10^8 m^3	Evolution of terminal lakes
Han Dynasty	7.5	The lake was shrinking (Qu et al., 2000), and fine magnetic minerals peaked in the sediment profile (Qu et al., 2000; Zhang et al., 1998). This might be affected by low R_{out} and intense reclamation in the downstream areas around the terminal lake.
Wei-Jin Era	9.2	The lake was still shrinking (Qu et al., 2000), and the primary productivity of the lake was low, such as Osc, Myx and CD (Qu et al., 2000; Zhang et al., 1998). This may be because of low R_{out} and weakening reclamation due to war and other factors.
Tang Dynasty	18.1	There were stable water dynamics, a large lake area and deep water reflected by the sediments with higher contents of silt and clay, and relatively low contents of coarse grains (Jin et al., 2005, 2004). This indicated a large R_{out} during this period.
Yuan Dynasty	14.9	Same as the Tang dynasty.
Ming Dynasty	18.9	The salinity of lake water decreased and the lake extended (Zhang et al., 1998). This was indicated by a large R_{out}.
Qing Dynasty	11.8	Same as the Ming dynasty.
New China in 1949	15.4	The lake kept a relatively large area (Zhang et al., 1998; Xiao et al., 2004). This was indicated by a large R_{out}.
1975	2.0	Terminal lake Gaxun nur dried up, Sogo nur came and went (Xiao et al., 2004). This is because of intense reclamation in the midstream area and the streamflow decreased and was unstable.
2000	−2.8	The lakes dried out, and the groundwater depth decreased (Xiao et al., 2004). This is because of intense reclamation in the midstream area and overexploitation of the groundwater in the basin.
2010	−0.5	Lake restoration.

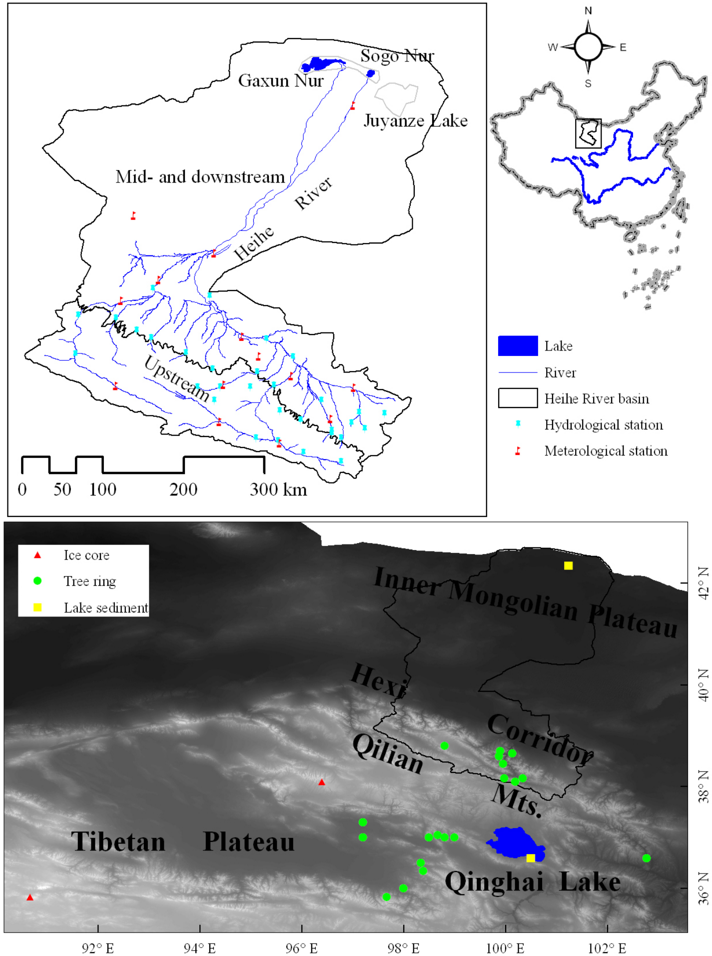

Figure 1. Location of the Heihe River basin and locations of data of ice core, tree ring and lake sediment.

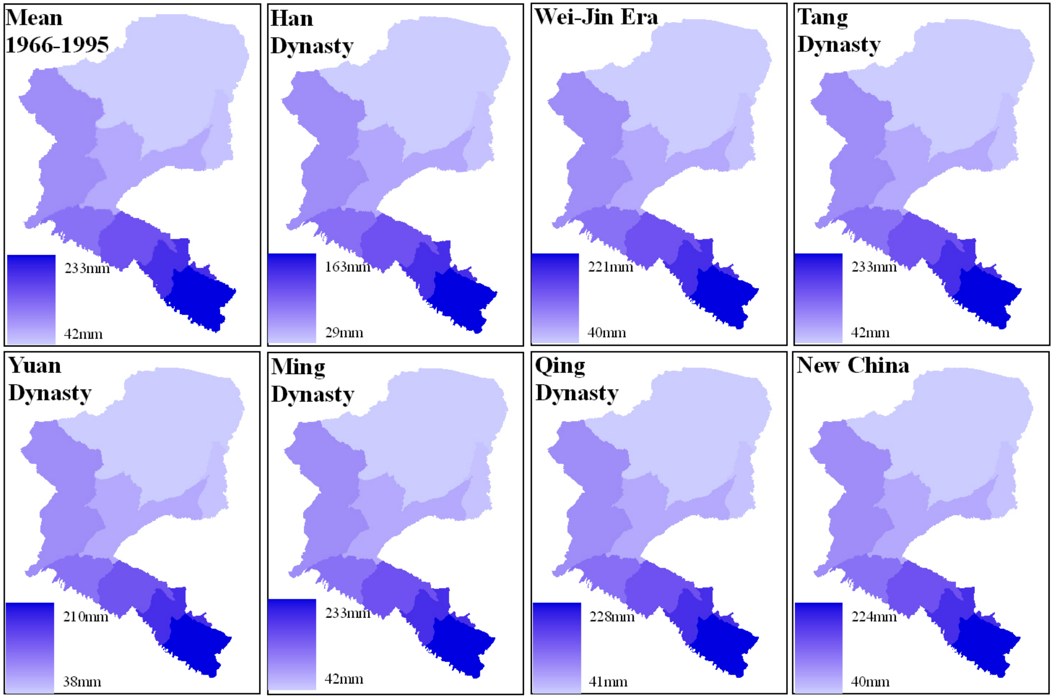

Figure 2. The reconstructed precipitation in historical periods in mid- and down-stream areas of the HRB.

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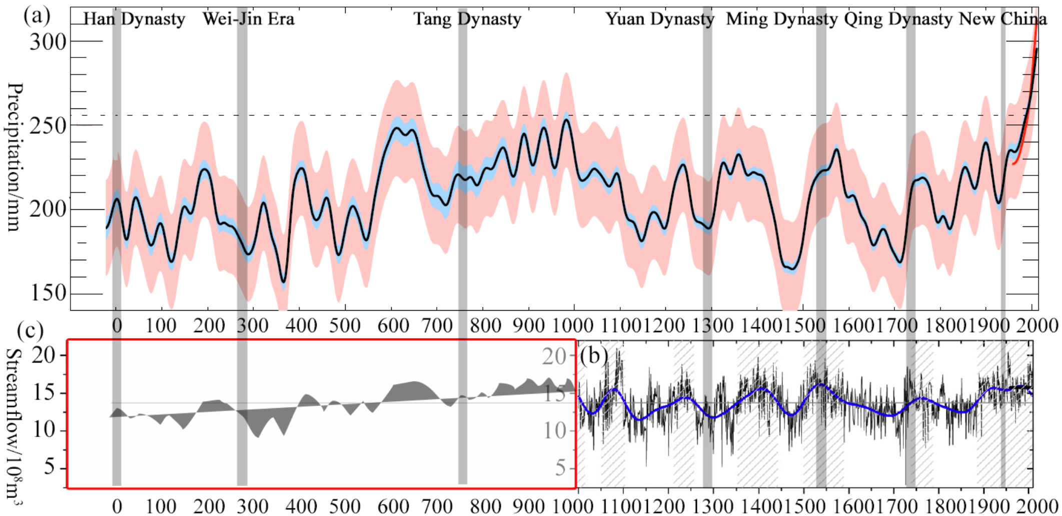

Figure 3. (a) Yang et al. (2014) annual precipitation reconstruction with 50 year smoothing in Qilian Mountains region over the last 2000 years. **(b)** Qin et al. (2010) annual streamflow reconstruction spanning the last millennium with 50 year smoothing at YLX. **(c)** The extension of the streamflow from AD 0 to 1000 by comparing and analyzing the Yang et al. (2014) precipitation reconstruction and Qin et al. (2010) streamflow reconstruction.

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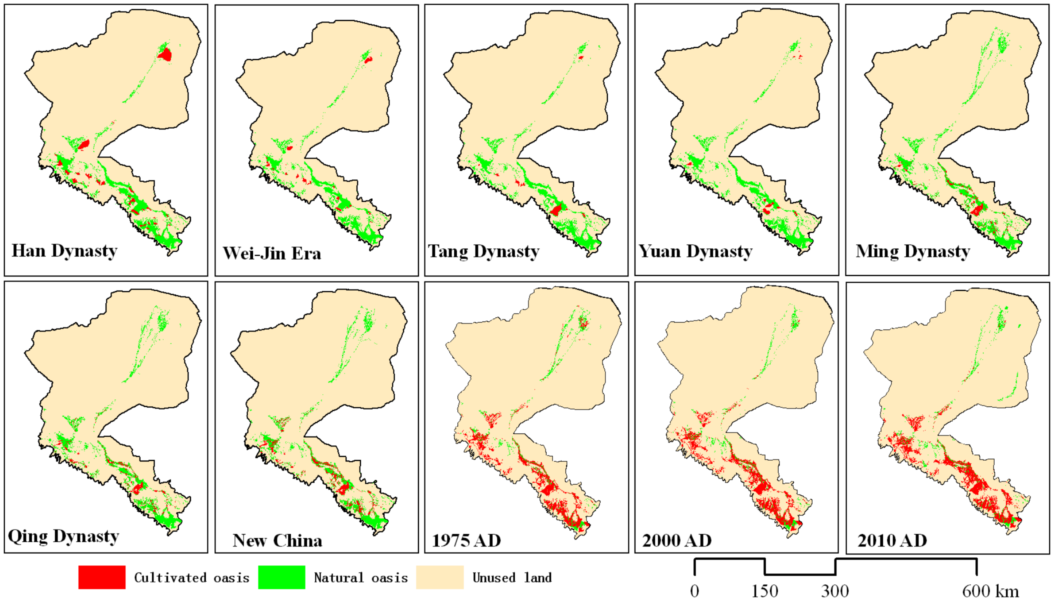

Figure 4. Land use reconstructions in historical periods and land use through image interpretation in recent periods in mid- and down-stream areas of HRB. (It should be noted that the grassland, forest and water or wet land were combined into the natural oases, and the farmland and built-up land were combined into cultivated oases in the land use in 1975, 2000 and 2010.)

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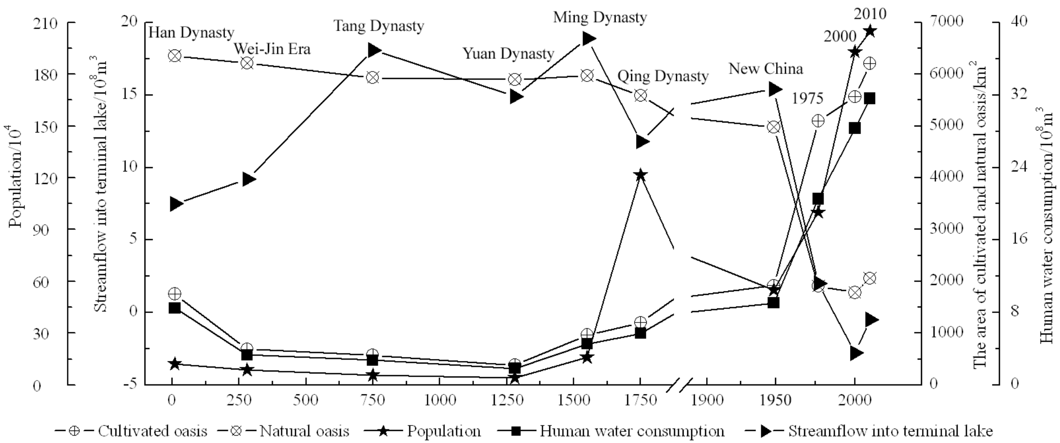

Figure 5. Changes of reconstructed catchment water balance elements in the past 2000 years in the mid- and downstream area.

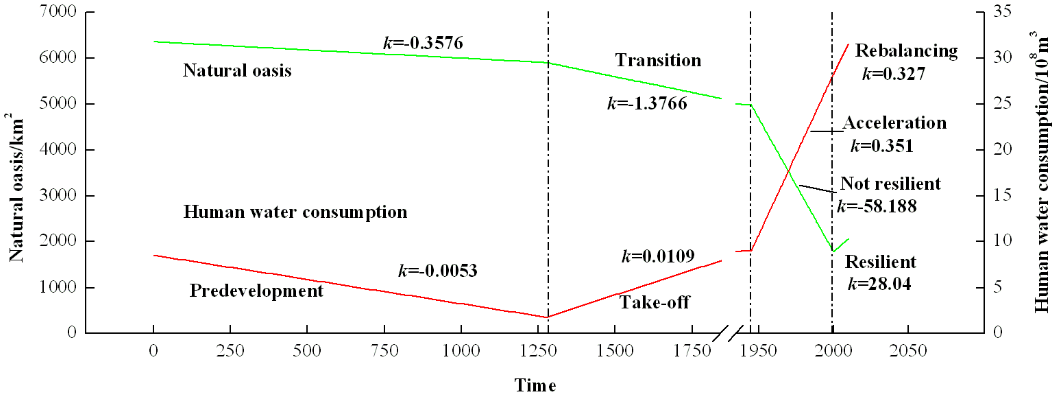

Figure 6. The development stages of evolutionary processes of human–water relationships.

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