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Socio-hydrologic perspectives of the co-evolution of humans and water in the Tarim River Basin, Western China: the Taiji–Tire Model

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Abstract

This paper presents a historical socio-hydrological analysis of the Tarim Basin, Xinjiang Province, Western China, from the time of the opening of the Silk Road to the present. The analysis is aimed at exploring the historical co-evolution of coupled human–water systems and at identifying common patterns or organizing principles underpinning socio-hydrological systems (SHS). As a self-organized entity, the evolution of the human–water system in the Tarim Basin reached stable states for long periods of time, then punctuated by sudden shifts due to internal or external disturbances. In this study, we discuss three steady periods (i.e. natural, human exploitation, and degradation and recovery) and transitions in between during the past 2000 yr. During the "natural" stage that existed pre-18th century, with small-scale human society and sound environment, evolution of the SHS was mainly driven by natural environmental changes such as river channel migration and climate change. During the human exploitation stage, especially in the 19th and 20th centuries, it experienced rapid population growth, massive land reclamation and fast socio-economic development, and humans became the principal players of system evolution. By the 1970s, the Tarim Basin had evolved into a new regime with a vulnerable eco-hydrological system seemingly populated beyond its carrying capacity, and a human society that began to suffer from serious water shortages, land salinization and desertification. With intensified deterioration of river health and increased recognition of unsustainability of traditional development pattern, human intervention and recovery measures have been adopted. Since then, the basin has shown a reverse regime shift towards some healing of the environmental damage. Spatio-temporal variations of historical socio-hydrological co-evolution are classified into four types: primitive agricultural, traditional agricultural, industrial agricultural and urban SHSs. These co-evolutionary changes have been summarized in terms of the Taiji–Tire Model, a refinement of a special concept in Chinese philosophy, relating to the co-evolution of a system because of interactions among its components.

1 Introduction

Water is the basis of all life, a key factor in production of commodities important to human wellbeing, and is essential for the maintenance of ecosystem health. Many of the great ancient civilizations of Egypt, China, India and Babylon all developed along famous rivers such as the Nile, Yellow, Ganges, Euphrates and Tigris. In the long history of human civilization, people first gathered along river banks, and then gradually expanded away from rivers as they established tribes, villages and cities, accompanied by increasing complexity of social structures. During this evolutionary process natural water conditions posed important constraints on human activities and thus the evolution of society, and in return human activities impacted natural water regimes significantly as well (Ponting, 1992). Recently as well as in the historic past, improper or excessive utilization of water resources and the consequent water related problems (e.g. salinization, pollution, flooding, water scarcity etc.) have hampered sustainable development of human societies (Brink et al., 1990; Ibe and Njemanze, 1999; Klocking et al., 2003; Gordon et al., 2008; Schilling et al., 2008; Ferreira and Ghimire, 2012; Li et al., 2012). In fact, as pointed out by Costanza et al. (2007), human responses to both environmental stress and social change in turn feed climate and ecological systems, which produces a complex web of multi-directional inter-connections in time and space. Understanding such human–water relationships and their evolutionary dynamics is of great importance for sustainable human development, which is the aim of the new emerging discipline of socio-hydrology (Sivapalan et al., 2012).

Historical analysis serves as one of the key methodologies of socio-hydrological study, and basically it involves studying the past (i.e. immediate past or distant past) and reconstructing the associated co-evolutionary processes, through classification into distinct phases and systematic analysis of the social and physical events and mechanisms and their interactions that may have contributed to such history. Although accurate historical data are not always available and the co-evolution processes often tend to be ambiguous, the historical patterns of human-environment interactions

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may still be reconstructed with the support of the relevant "grey" literature and other archeological findings (Costanza et al., 2007; Ponting, 1992).

This paper represents a first attempt at undertaking a historical socio-hydrological study starting from the distant past (more than two millennia before) to the present. The Tarim River Basin in northwestern China is chosen as the study area. The Tarim Basin represents an arid socio-eco-hydrological system (precipitation of just 50–100 mm yr^{-1}) where water dominates the dynamics of the eco-environmental system and the interactions and feedbacks between humans and water are very prominent. In this inland basin, the climate is hyper-arid and the river runoff is principally formed from the thawing of glaciers and mountain snow, as well as orographically generated rainfall in the Kunlun Mountain and Tianshan Mountain surrounding it. In the geological past, the main course of the Tarim River has experienced frequent shifts, which helped to shape a highly mobile and star-studded pattern of oases. In terms of human history, the basin gave birth to a special type of scattered city-state civilization and eventually became the meeting point between the eastern and western worlds with the establishment of the Silk Road in 138 BC. The region has a rich written history of over 2000 yr, with development of human society and socio-economic formation that encompass transitions from the primitive stage to traditional agriculture, then modern agriculture, and finally to the industrial stage at present. The TRB socio-hydrological system displays distinct features in each of its different development stages. Along the way, the human–water relationship also evolved from a nature-dominated regime to a human-dominated regime with the advancement of social productive forces.

Although there have been several studies that focused on more recent decades of the human–water relationship within the TRB (Chen et al., 2005; Hao et al., 2009; Pang et al., 2012; Zhou et al., 2012), the much longer term dynamics of coupled social, hydrological as well as the associated climatic and ecological changes have not been comprehensively analyzed. What is more, there is a considerable lack of an overview of such human–water history, which will be the focus of this paper. The historical analysis of the co-evolution of the socio-hydrological system within TRB could not only improve our understanding of past human–water relationships but also facilitate improved predictions of its possible future dynamics. Also, it has the potential to generate information and insights that will be valuable for comparative socio-hydrologic studies across different human–water systems around the world and could provide insights that might guide more detailed quantitative process studies and modeling in specific places.

The remainder of the paper is organized as follows. Section 2 provides an introduction to the study area, including a historical overview of the co-evolution of humans and water within the TRB. The following three sections describe the salient features of, and the mechanisms behind, the co-evolution of the TRB socio-hydrological system over three distinct stages of development (i.e. natural, exploitation and recovery stages). On the basis of these observations, a general framework is proposed next for analyzing and interpreting the interactions between humans and water. The paper then concludes with a summary of the results and conclusions, and some perspectives on possible future research.

2 Study area

The Tarim River Basin is located within the Xinjiang Uyghur Autonomous Region, northwestern China (see Fig. 1 for its landscape and Fig. 2 for the location and the river system). It is surrounded by Mount Tianshan in the north and Mount Kunlun in the south. This great basin with an area of 1 100 000 km^2 derives its name from the Tarim River, which flows through Taklimakan, China's largest desert. The word "tarim" is used to designate the banks of a river that is not able to be differentiated from the sands of a desert (see Wikipedia website, http://en.wikipedia.org/wiki/Tarim_River). Nowadays, the TRB has a hyper-arid climate with average annual precipitation of just 50–100 mm (and almost zero in the Taklimakan Desert and the Lop Nor Basin). The streamflow in the river mainly comes from the surrounding mountains. The maximum temperature in the TRB is about 40 °C.

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The Tarim River has four tributaries, namely Aksu River, Yarkand River, Hotan River, and Kongqi River. The name Tarim is applied to the river formed by the union of the Aksu River, Yarkand River, and Hotan River, near the Aral City in western Xinjiang, which is deemed as the mainstream of the Tarim River. The mainstream is divided into 3 parts, i.e. the upstream part from Aral to Yenbazar, the middle part from Yenbazar to Karal, and the downstream part from Karal to its terminal lake. The Tarim River empties into its terminal lake (Taitema Lake) intermittently after flowing 1312 km from Aral. Historically the terminus of the Tarim River system was Lop Nor Lake, which is about 160 km northeast of the present Taitema Lake.

Historically, during the past 2000 yr, the climate of TRB experienced significant variations, which can be roughly divided into several phases, i.e. warm-wet, warm-dry, cool-wet, cool-dry, ice age, and several intermission periods (Sun et al., 2005). The variations of temperature and precipitation have strong influences on the melting processes and ice-snow storage in Mt. Tianshan and Mt. Kunlun. The resulting variation of runoff together with the impact of channel sediment deposition and the drifting of the desert caused overflowing and twisting processes, which led to frequent river course migrations, as well as associated degradation and regeneration of oases that humans and plants relied on (Fan and Cheng, 1981; Wang et al., 1996; Shu et al., 2003; Wei, 2008; Xie, 2008).

The history of human activities within TRB goes all the way back to the Stone Age. Since at least 2000 BC, primitive tribes settled in this region despite tough environmental conditions and the enormous distances separating them from ancient civilization centers, e.g. China, Egypt, and the Fertile Crescent (Wang, 1983; Shu et al., 2003). City-states appeared in oases along the river with populations in the hundreds to a few thousands only (Han, 2010). The spatial variability of climatic and eco-hydrologic conditions within the TRB led to diverse development paths and socio-economic formations. In the northern edge of the TRB, influenced by nomadic civilizations further up north, fishing and grazing modes of production lasted for quite a long time. Until the late 18th century, there still lived inhabitants called Lopliks in the Lop Nor region who relied on

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primitive fishing and grazing and could not even digest grains (Han and Lu, 2006). In contrast, irrigation agriculture appeared much earlier along the southern edge and in the source areas of the TRB, especially in the sub-basins of Aksu, Hotan, Niya and Keriya and the ancient Qiemo river (Sun et al., 2005). These are the earliest places which received massive migration of people and introduction of advanced agricultural tools and technologies from Chinese agricultural civilizations in the east (Liao, 2011).

A far-reaching event that occurred during the early development stage of the TRB was the opening up of the famous Silk Road in 138 BC by ZHANG Qian, who was the imperial envoy of the Han Dynasty to the West Regions. West Regions (or Xiyu) was a historical name in Chinese chronicles between the 3rd century BC to the 8th century AD and referred most often to Central Asia but sometimes specifically to the TRB (the eastern-most region of Central Asia) (see Wikipedia website, http://en.wikipedia.org/wiki/Western_Regions). The Silk Road connected East Asia with the Indian sub-continent, central Asia, Asia Minor and Europe, and made the TRB the meeting point between various ancient civilizations. After ZHANG Qian, the West Regions began to be governed by China and to be recorded in Chinese literature as well, which enables us to access the plentiful historical material and data and examine the human–environment relationship in the ancient TRB.

Similar to other parts of the world, the socio-economic formation of the TRB passed through several different stages, i.e. from primitive society (fishing, hunting, picking), agricultural society (grazing, farming), and on to the industrial society that prevails now. Furthermore, the agricultural society that existed can be divided into traditional agricultural mode and modern agricultural mode. In the former mode agricultural production was primarily driven by human and animal power, and in the latter mode, production was driven by machine power that emerged following the industrial revolution. Roughly speaking, traditional agriculture society within TRB reached its peak in the 19th to the 20th century, and modern agriculture started in the 1950s (Tong, 2006). Consistent with the evolution of socio-economic formations, the TRB experienced a paradigm shift in its human–water relationship. In the primitive stage, the human impact on the hydro-

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logical and eco-environmental system was limited to water extraction at local scales. In this case, the human–water relationship was dominated by water availability, which was significantly affected by long-term climate changes and human societies therefore had to adapt to such natural changes of climate, hydrology, geology etc. This situation continued during the era of the traditional agricultural society as well, despite the fact that at some local scales human activities could dominate the evolution of the SHS as more water was able to be extracted for irrigation. However, in the era of the modern agricultural society, as the social productive force was significantly upgraded, large scale agricultural infrastructure (e.g. diversion canals, reservoirs, and groundwater wells) were constructed and the natural hydrological system became greatly disturbed. Humans gradually became the dominant players in the evolution of the SHS. Specifically, since the 1970s the downstream area of the Tarim River suffered from serious water shortages caused by over-exploitation in upstream and source areas. Water shortage and soil salinization enhanced ecological degradation and desertification (Chen et al., 2006; Tong et al., 2006), which in turn seriously restricted socio-economic development. Human society responded to the intensive human–water relationship by undertaking large engineering measures (e.g. emergence of large water transfers since 2000) as well as management measures (e.g. setting up of the Tarim River Basin Authority in 1992), which restored the ecological system to a limited extent (Sun et al., 2004; Chen et al., 2007a, b).

In terms of the human–water relationship, the historical co-evolution of the TRB socio-hydrological system could be divided into three stages, i.e. the natural stage from around the 2nd century BC to the 18th century AD when natural factors dominated socio-hydrological change, the exploitation stage from the 18th century to mid-20th century when the impact of human factors increased gradually to one of total domination, and the degradation and recovery stage since the mid-20th century when human society began to modify its behavior and began to undertake remedial measures to return to balanced development after a period of over-exploitation of water resources and degradation of the eco-environmental system.

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3 Natural stage (up to the 18th century): natural factors dominate socio-hydrological change

3.1 The mathematics of development

Historically, a remarkable feature of the Tarim River is that it experienced frequent and significant changes to its river courses. Recent remote sensing studies (Bai, 1994) show that the Tarim river system had two main courses (i.e. North Tarim river and South Tarim river) about 10 000 yr ago, and had preserved this two-course pattern until at least the 6th century AD, as shown in Fig. 3a and b. Also, historical literature such as the Book of Han (written by BAN Gu in ca. 80 AD) and Shui-Jing-Zhu (literally "Commentary on the Waterways Classic", written by LI Daoyuan in the 6th century AD) say that the ancient Silk Road had two routes (i.e. northern and southern) along rivers in the TRB, which implies that there existed two main rivers during the 5–6th centuries AD. The two books also say that the vegetation cover along the two main streams of the Tarim River was lush and also that there existed many oases. However, the Tarim river system has dramatically changed since then and by the 19th century it had finally evolved into a four-source-one-mainstream pattern that exists presently (see Fig. 3c and Sect. 5.1 for more detail). By comparing the historical patterns of the Tarim river system shown in Fig. 3a–c, an obvious change can be detected in the South Tarim River, which gradually broke up into several smaller isolated river systems with the southern mainstream completely disappearing. Also, the northern mainstream has shrunk significantly and it no longer flows into Lop Nor Lake as it did before.

Another major feature of the Tarim River Basin is that its climate experienced several back and forth swings between cool-dry and warm-wet regimes over the past 2000 yr (as shown in Fig. 4), which are closely linked to the migration of the river courses. The earliest written history of the TRB began from ZHANG Qian's voyage to the West Regions during the Han Dynasty (i.e. 137 BC), during which the climate of the TRB was characterized by warm and moist conditions (Sun et al., 2005). The plentiful precipitation and melt water from Mt. Tianshan and Mt. Kunlun supported a much larger river

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system than exists today, and the large volumes of water flowing from the North and South Tarim Rivers into Lop Nor supported a vast lake surface with abundant vegetation around it. Afterward, however, during the 3rd to 7th centuries AD, the climate of TRB underwent a fluctuating down-trending of both precipitation and temperature (Sun et al., 2005; Han, 2010). Consequently, less water discharged into the main streams of Tarim River and Lop Nor, and more sediment deposited in the river bed, thus helping to intensify the fluvial processes. The changed hydrological situation led to more frequent migrations of river courses and several branches such as the Niya River began to disconnect from the Southern Tarim River system. Meanwhile, the Kongqi River (a source river of the Northern Tarim River, see Fig. 2) lost its connection with the main stream of North Tarim River which moved southward, resulting in a much reduced discharge into Lop Nor (Hu, 1990). In the book of Buddhist Records of the Western World written by Monk Xuanzang in the 7th century during the Tang Dynasty, he describes a degraded picture of the Tarim River, with drying lower reaches, withered vegetation, expanding desert, abandoned farmlands and settlements; this record clearly shows the consequences of the cool-dry climate when compared to the picture described by ZHANG Qian and later in Shui-Jing-Zhu.

After the 7th century AD the climate of TRB returned back to the warm-moist pattern, which lasted for about 300 yr until the 10th century AD (Shu et al., 2003; Sun et al., 2005). During this transition period, floods occurred frequently, which again caused migration of the river courses. However, after the 10th century AD, the fluctuating cool-dry trend dominated climate variability again for another 500 yr, and then a little ice age began from around the 15th century, which reached its peak in the 17th century, and continued for another 100 yr afterward (Sun et al., 2005). During this period of about 800 yr, the dominant feature in the Tarim River was the shrinking of main streams and branches, together with the expansion of the desert, migration of humans, and abandonment of human settlements. The South Tarim River system, as recorded, returned to the disconnected pattern that existed during the 3rd to 7th centuries (i.e. cool-dry period). The whole river system finally broke up into several parts

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and gradually evolved into several smaller separated river systems during the 19th century (as shown in Fig. 3c). Simultaneously, the main stream of North Tarim River moved gradually southward to the route along which the present Tarim River is now flowing.

3.2 Human history and the abandonment of settlements

When we carefully examine China's history before the 19th century, it can be seen that the total human population grew slowly but with periodic fluctuations caused by social shocks such as wars (Durand, 1960). In a similar way, the population of TRB did not increase significantly before the late 18th century. Human population numbers grew from 230 000 in the 2nd century AD (the total population of 36 city-states in West Regions as recorded in the Book of Han), to reach 300 000 in 1760 when the Qing Dynasty re-controlled Xinjiang (Hua, 1998; Shu et al., 2003; Lu and Fan, 2009). Also during this long period, the technology level was low and social organization was week. Therefore, human society had a low level of productive force and limited influences on the environment, including the natural hydrological system.

The ancient human society in the TRB as a whole did not form a unified country and for a long period existed as isolated city-states. All the 36 city-states of the West Regions around 2000 yr ago, as recorded in the Book of Han, which were mainly located within the TRB, had small populations ranging from hundreds to mere thousands each. After the opening-up of the Silk Road the Han Dynasty set up the Authority of West Regions to govern both the West Regions and the business route to the western world. Afterward the city-states within TRB developed fast through communication with both the eastern and western worlds for advanced agricultural and commercial technologies and ideas and thoughts. Also, the Silk Road turned the West Regions into a mixed area, with multiple races and multiple cultures (Yin, 1989), which shaped civilization and social organization that formed as a result. The mixing of agriculture (farming), fishing, grazing and commerce made the TRB human society more stable than the nomadic society in the north or the commercial society in the west, but also more mobile than the traditional agricultural societies in the east. As a result, the city-

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states in TRB became vulnerable to social and environmental stresses and were apt to migrate compared to traditional agricultural societies.

The lower level of productive force and the higher mobility of society were the internal reasons for abandonment of settlements in history, while the external direct drivers were climate variations and the hydrological responses to these variations (which ultimately caused a shift of the river courses). The prosperous period after the Silk Road opened lasted 300–400 yr, mainly during the Han Dynasty, but was interrupted by hundreds of years of cool-dry climate and the resultant river course migrations. Many well-known ancient human settlements were abandoned during this period (see the first peak in Fig. 4b), such as the famous Lolan, Keriya and Niya ruin groups. These states and villages started to decline from the 3rd to 4th centuries AD and finally collapsed around the 7th century AD (Shen et al., 1982; Wang, 1998; Zu et al., 2001). One can note that this timeline is coincident with the cool-dry tendency of climate shown in Fig. 4 (Wang, 1998; Yang et al., 2006).

Another fast growth period of the TRB was during the Tang Dynasty (618–907 AD). The powerful Tang Dynasty effectively re-possessed the West Regions from the mid-7th to early 9th centuries by setting up an administrative agency along with a resident army. A 100 yr long peaceful period that arose helped to recover social production, contributing to prosperity of agriculture, business, and population. The rule of the Tang Dynasty in the TRB, however, was seriously challenged by Arab states in the late 8th century and the Great Battle of Talas between the army of the Tang Dynasty and Arab forces took place in 751 AD. The expeditionary army of the Tang Dynasty stationed in the West Regions and their allies were defeated in Talas (presently in current Kazakhstan) and the Tang Dynasty lost its influence over the West Regions. The wars between these eastern and western empires interrupted the normal development of the TRB socio-economy. As a result, many human settlements were abandoned during the strained years during the mid-8th century despite the beneficial climate (warming and wet, as shown in Fig. 4c). It is worth noting that ruins of these abandoned settle-

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ments were not found until the 10th century AD when the warm-wet climate changed its pattern again (Shu et al., 2007).

After the 10th century, there were two other episodes of abandonment of settlements, according to recent archeological research (Shu et al., 2007). One happened around the 11th century and another around the 13th century (see Fig. 4b), when the climate was in the cool-dry regime. Also, during that time the TRB was controlled by non-agricultural powers such as the Arabs, Huihus and Mongols. The agricultural fields were changed back to grazing, which reduced the capacity of food supply. In fact, a similar phenomenon happened several times before as well. For instance, as early as the 4th century AD (i.e. during the Eastern Jin Dynasty), the lower Tarim River Basin was once controlled by Tubo (which is an ancient name for Tibet in Chinese history), when irrigated agriculture along the south edge of TRB partially retrogressed to grazing or an even more primitive socio-economic formation. With the development in reverse, the size of the SHS was reduced, with a reduced population and a deterioration of system sophistication (Han, 2010).

3.3 Natural dominated socio-hydrological system

During the 2000 yr long history leading up to the 18th century, the societies that developed within the TRB were basically restricted to living within oases, which were isolated from each other. Due to the absence of mutual connection of both economy and politics, each isolated city-state could be regarded as separate SHSs, and the TRB before 19th century could be considered as a set of isolated small SHSs. In the ancient agricultural oasis states within the TRB, farmlands were owned by farmers and a primitive cultivation method called Chuangtian was practiced. In this method, the land is leveled in August and then a hole is dug on the river bank for flood irrigation. The seeds are sowed in the next spring and since that time the farmers had nothing to do until harvest time in July. Abandonment and disuse of the land were very common, and the fallow period could last between 4 to 5 and even up to 10 yr (Han, 2010). Owing to the technological limitation, diversion canals could not be dug too far from the river bank and cultivation was constrained to the riparian area. This way of cultivation and irrigation was quite sensitive to climate fluctuations and river channel changes which therefore led to high vulnerability of society to natural climate variability and hydrological change. When the river course migrated substantially or when the tail section of main river shrunk upstream of a settlement, societies had no capability to adapt to the changed situation and primitive agriculture would thus collapse and settlements would be abandoned (remember Fig. 4b and our discussion on the ruins in Sect. 4.2).

Given the lower level of social productive force, the evolution of Tarim SHS was dominated by natural factors such as climate variability and river course change. When comparing the river system thousands of years ago to the present one shown in Fig. 3a and b, one can see that the ancient South Tarim River broke up into several smaller separated river systems and shrunk far into the desert to its current location. The evidence also comes from archeological research, which showed that the ruins belonging to the 10th century AD and before are mostly located tens to several hundred kilometers into the present desert, while those after the 10th century AD are found several to tens of kilometers into the desert, and the direct reason for their abandonment was river channel shifts and zero-flow conditions (Zu et al., 2001). Another peak of settlement abandonment occurred in the 8th century AD when the climate had just turned into warm and wet. As discussed in the previous section, this abandonment was partly caused by social shocks, i.e. the Battle of Talas and a period of social unrest. However, this is a transitional period from the cool-dry to the warm-wet regimes, and natural factors could also partly explain the abandonment, as the sharp change of climate broke the equilibrium of the SHS during the long cool-dry period (about 500 yr, as shown in Fig. 4b). For example, long period of dry conditions could result in the shrinking of the river channel section and consequently low flood carrying capacity. When climate became wet, more water may have discharged into the previously shrunk river, leading to frequent floods and causing disastrous consequences for the TRB society. Once the SHS evolved into a new equilibrium state, society could again become more stable and fewer settlements were abandoned since the 9th century AD, as shown in Fig. 4b.

At local scales, social factors could also play a significant role in the evolution of SHSs during some specific periods. The social structure of city-states within the TRB presented a new city-centered pattern of agricultural activities (Wei, 2008), and flow of the Tarim River was undoubtedly reduced as more water was diverted for irrigation, which aggravated downstream water shortage and shrinkage of lower river reaches. More importantly, due to the interactions between the TRB socio-hydrological system and external social factors, the rise and fall of eastern agricultural dynasties had a great impact on the SHSs within the TRB. An interesting phenomenon was that when the West Regions were effectively managed by strong eastern agricultural dynasties such as the Han and the Tang, the farmland and population increased significantly as society developed a higher level of social productive force. During the Han and Tang dynasties, the reclamation of arable land by the army from middle China improved agricultural techniques through the introduction of advanced tools and expertise (Liao, 2011). More water infrastructures such as irrigation canals were constructed, which played an important role in farmland growth from the riverside into the desert and led to increasing water consumption (Wei, 2008).

4 Exploitation stage (from 18th century to mid-20th century): increasing impact of humans

4.1 Change of river systems

During the 18th century, the mainstream of the South Tarim River gradually disappeared, which left several smaller separated river systems in the southern edge of TRB. For the North Tarim River, the downstream channel shifted frequently, which led to a southward movement, together with its terminal lakes (i.e. Lop Nor) (Han, 2010). According to historical record in the books of He-Yuan-Ji-Lue (written by JI Yun in the mid-18th century) and the Record of Rivers in the West Regions (written by XU Song in 1821), the Tarim River system presented a 7-source-1-mainstream pattern, of which

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the mainstream was the North Tarim River. At the end of the little ice age in the late 19th century and early 20th century, the climate changed back again to warm-wet pattern, which resulted in increased flow in the mainstream and source rivers, such as the Weigan River in the middle Tarim Basin. The increased discharge expanded the main channel of the Tarim River into two courses within the Luntai County, but it merged back into one again when it flowed out of Luntai, whereas Lake Lop Nor expanded its surface area to hundreds of square kilometers, with an abundant coverage of Euphrates Poplars and Tamarisks. But restoration of natural vegetation was limited by increasing water extraction within the source and upstream areas of the Tarim River due to the extension of farmland. During the 1910s to 1940s, at least eight major channel shifts occurred within the lower Tarim River and caused the degradation of the local and regional eco-hydrological system (Han, 2010, 2012). In the mid-20th century, several source rivers gradually lost contact with the mainstream of the Tarim River, including Weigan River in the middle part of the basin and Kashigar River in the upper part. Only four main source rivers were left, namely the rivers of Aksu, Yarkand, Hoton and Kaidu-Kongqi, as shown in Fig. 3c.

4.2 Expansion of traditional agriculture until mid-20thcentury

In the TRB traditional agricultural society lasted for a long period until the mid-20th century. Generally, the utilization level of water resources was low, and especially before the 18th century, the development of the socio-economy was rather sluggish. However, since the 18th century, the TRB society has experienced fast growth due to reforms of technology, social organization and management, which can be divided into two sub-periods.

The first sub-period was from the 18th century to late 19th century. During the 1760s the Qing Dynasty brought together the nomadic civilizations and overcame the influence of Tsarist Russia. A reclamation and settlement policy was adopted to supply the army stationed in the region. There were four different kinds of stations for reclamation and settlement, i.e. a soldier station run by the resident army, a household station run

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by farmers who had migrated from central China, a Hui station operated by idle people of the Eight Banners (a military organization in Qing Dynasty), and a transfer station operated by criminals and political prisoners exiled from central China (Fang et al., 2007). Another important policy reform was Tan-Ding-Ru-Mu in the late 18th century, which linked taxation with the area of farmland instead of number of people. The previous census based tax system was called Head Tax or Poll tax which had been used for thousands of years in China. With this tax reform the enthusiasm of farmers was aroused and both agricultural production and government revenue increased significantly, which in turn promoted agriculture development by more reclamation and canal construction (Wang, 1971). Also, innovative farming and engineering methods were introduced such as better seeds, new crops, and the Qanat irrigation system. Social reform and advancement of technology led to the expansion of farmland and increased agricultural yield, which reached the average per unit yield of central China at the end of Qing Dynasty (Lu and Fan, 2009). According to records and maps of Xinjiang (written by WANG Shunan in early 20th century with further additions in subsequent decades), irrigated land in TRB was over 11 million mu in early 20th century (mu is an area unit in China, one mu equals 1/15 of a hectare, and so 11 million mu is about 7500 km^2), most of which was newly reclaimed during Qing Dynasty and located mainly in source river basins and the upper Tarim River area.

The second sub-period was from the late 19th century to the mid-20th century, during which China had experienced one hundred years of unrest. The invasion from western powers (i.e. Opium war in 1840, Second Opium War in 1860, Eight-Nation Allied Forces invasion in 1900, First Sino–Japanese War in 1904–1905, Second Sino–Japanese War, which was also called Anti-Japanese War, in 1937–1945) and civil wars (i.e. the Taiping Heavenly Kingdom War in 1851–1864, the Revolution of 1911 that overthrew the Qing monarchy, wars between warlords, two Kuomingtang–Communist Wars before and after the Anti-Japanese War in 1927–1936 and 1946–1949 respectively), along with natural disasters and social problems such as diseases interrupted normal development of TRB society. The expansion of farmland ceased and some farmland

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retrogressed back to natural landscapes of grassland. For instance, the irrigated land in Hotan areas (an important agricultural county in south TRB) decreased while the population continued to grow, as Fig. 6 shown. The floating population, including migrants, refugees and idle persons occupied over half the total population in agricultural counties like Hotan and Pishan (a nearby county), and became a serious hidden threat to social stability (Xie, 2008). In order to settle down the floating population and support the civil wars and the anti-Japanese War, the Government of the Republic of China launched a reclamation campaign from the 1930s to the 1940s, which was unprecedented in history and highly influential. As a result farmland area increased fast, and similar to during the Qing Dynasty, most reclamation concentrated in source river basins and upper Tarim River area (Xie, 2008).

A remarkable feature of the SHS during this period is that its spatial extent significantly enlarged. With progress of politics, economy and culture, the different societies within TRB melted into the Chinese nation gradually. Also, with the expansion of agriculture, more water was diverted for irrigation and the activities of upstream society obviously influenced the downstream. As a result, the ancient separated SHSs at the oasis scale were combined and evolved into a complex and intertwined system at sub-basin scale.

4.3 Impact of industrial technology since mid-20th century

Since the 1950s, especially after the establishment of the People's Republic of China, industrial technologies were introduced into the TRB and traditional agriculture was upgraded to modern (i.e. industrialized) agriculture. With the aid of modern technologies, large scale irrigation infrastructures were constructed and farmland area dramatically expanded (Jiang et al., 2005; Han, 2012). As shown in Fig. 6, irrigated farmland and population in this period have grown at a much faster rate than ever before. Two new reclamation areas operated by the Xinjiang Construction Corps were developed, respectively, in the Alaer area by the 1st Division (lately became Alaer City since 2002) and Korla area by the 2nd Division. Supported by large newly constructed diversion

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canals, the total farmland area of TRB has now reached 16 million mu (approximately 10 000 km^2) in 1999 according to the Statistical Yearbook of Xinjiang (1999 version).

Also, agricultural production has dramatically increased due to implementation of new farming methods, seeds, modern machines and techniques. According to the Statistic Yearbook of Xinjiang (1999 version), crop production per mu in the late 20th century had reached 150 to 200 kg, which was much higher than that of 50 to 75kg that existed at the end of the Qing Dynasty (i.e. 1900s) (Lu and Fan, 2009). The expansion of agriculture elevated irrigation requirements dramatically. Since the 1950s, the increased water consumption led to the disconnection of rivers of Kashigar, Weigan and Kaidu-Kongqi from the mainstream of the Tarim River. Groundwater table depth in the lower reaches was 3–5 m in the 1950s but has dropped to 7–10 m in 1982 and to 11 m in 1986, and in the middle reaches it dropped from 0.5–0.6 m in the 1950s to more than 2 m in 2004 (Feng et al., 2005).

Industrial products, such as fertilizers and pesticides, began to be applied in agriculture since the 1950s, which began to cause serious water quality problems. Vast quantities of sulfate, sodium, calcium, nitrogen and phosphorus have been applied to the soil in the form of fertilizers and these have leached into groundwater, resulting in higher salinity and other forms of contamination in rivers and lakes. Also, irrigation induced groundwater table rise led to secondary salinization, which happened frequently in the source and upper Tarim areas, especially during the dry season (Wang et al., 2010).

In addition, the construction of reservoirs changed the hydrological and eco-environmental systems considerably. According to the Statistics Yearbook of Xinjiang (2012 version), by 2012 there were 125 reservoirs within the TRB. They are important for society since they provide water for agriculture, industry, and household use, and also reduce flood risk. At the same time, the reservoirs changed the pattern of river systems, leading to serious ecological and environmental problems. For instance, construction and operation of Daxihaizi Reservoir in the 1970s cut off the discharge to the downstream river and a 321 km stretch of river dried up quickly, contributing to a lower-

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ing of the groundwater level and the drying-up of the terminal lake. As a consequence, natural vegetation cover (mainly consisting Euphrates Poplars and Tamarisks forests) that used to separate Taklimakan Desert and Kumtagh Desert experienced massive die-off (Gao et al., 2007).

5 Degradation and recovery stage (since mid-20 century): getting back to balance

After two centuries of rapid development, the hydrological system within TRB has been substantially altered by humans. The over-exploitation of water resources has caused serious degradation of the natural ecological system together with significant invasion of desert. Since the 1990s, ecological disaster along the so-called green corridor of downstream Tarim River attracted considerable attention from researchers, journalists, the public and finally the government. In 1992, the Tarim River Basin Authority was set up to lead the integrated management of water resources within the TRB. Water diversion quotas were assigned for each district, a series of water conservancy projects were implemented to save water from irrigation. Estimated total investment towards this restoration was 10.8 billion Yuan during the past 11 yr (2001–2012).

The most direct measure to save the green corridor was emergency water transfers, which were implemented from the Bosten Lake to the terminal Taitema Lake for restoration of riparian vegetation. Since 1987, TRB has been experiencing a warm-wet trend (Fan et al., 2011). The wetting signal is strong in Kaidu-Kongqi River Basin, which is a source river of Tarim River and lost contact with the mainstream of Tarim River during the natural period. Now it rejoined the mainstream with human assistance and has been used for emergency water transfers from Bosten Lake to Taitema Lake. Emergency water transfers have been completed a total of 13 times since 2000 and 4 billion m^3 water was released from Daxihaizi reservoir to Taitema Lake (http://news.h2o-china.com/html/2012/11/110765_1.shtml). The seasonal flow reappeared in the dry downstream channel and the empty Taitema Lake was recharged

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to form a large water surface of over 200 square kilometers in the late 1990s. The groundwater depth in the lower reach of the Tarim River increased from 8–10 m to 2–4 m, which enabled the regrowth of Euphrates Poplars, Tamarisks and reeds in the green corridor covering an area of over 800 km^2 (Deng, 2005; Chen et al., 2007b). Grass vegetation responded faster to the rising groundwater table than woody plants. The areas that used to be covered by Euphrates Poplars are less likely to be restored to their original vegetation but would be substituted by herbs or shrubs (Sun et al., 2004; Chen et al., 2006, 2007b). Nevertheless, the reappearance of the green corridor is essential for preventing the re-merging of the Taklimakan desert with the Kumtagh desert (Gao et al., 2007). Besides, water quality has also improved through fresh water recharge and shows a decreasing trend in the lateral direction, with a range of influence of 750 to 1000 m from the riverside, which basically spatially coincides with the area of groundwater table rise (Deng, 2005; Li et al., 2010).

However, ecological recovery was only realized under special human intervention, especially emergency water transfers. The water transfer can be implemented only if it is pushed by the administrative power of the central government. Besides, it is just an emergency measure rather than a sustainable institutional measure. Also, the water conservancy projects were originally planned to save water from irrigated farmlands, to be released to the downstream for ecological recovery. However, in practice the saved water was intended to be used for newly reclaimed farmland. The wish to provide water for natural vegetation was usually defeated by the impulse to make money through agriculture. A set of systematic measures including engineering, economic, administrative, and institutional aspects should be designed to provide the ecological water requirement in a sustainable manner.

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6 Taiji–Tire Model: a general framework for analyzing the interactions between humans and water

In the last few sections we have presented essential features of the co-evolution of the human–water relationship within TRB during the various historical development stages. The SHS within the TRB has experienced different stages during which the human–water relationship is dominated by different drivers, first the natural hydrometeorological factors and then human factors, due to the upgrading of the social productive force. The direct human–water interaction could be interpreted by water consumption processes, with all the natural and societal factors (e.g. climate, geology, social regime and policies) influencing the supply of water resources being outer environmental conditions. The direct water consumption and the relevant factors together reflect the nature of human–water relationship. In order to better understand the co-evolution process of a socio-hydrological system, in this section we introduce a concept that may help understand and put in context the historical socio-hydrology of the Tarim River Basin.

The SHS within TRB can be seen as an intertwined system consisting of the human, hydrological and environmental subsystems. As illustrated in Fig. 8a, the inner solid circle is a specific social-hydrological system under study (in this case the TRB), and the outer dashed circle is its environmental system composed of both humans and nature. Within the inner circle itself the water and human parts interact via their water-centered inner eco-environment in a complex way, which may be represented by relationships that may eventually be quantified through detailed socio-hydrological studies. These interactions can be compactly depicted by a Taiji wheel, as shown in Fig. 8a. The term Taiji is a special concept in Chinese philosophy, which means the evolution of a system because of interactions among the two opposite components (Yin and Yang poles). The two poles are contradictory but also depend on each other. Generally Yang pole dominates the system evolution, but the Yin pole can convert to Yang pole under some specific conditions and vice versa. The outer environment could be composed of various natural factors (e.g. broad climate, underlying geology, ecological system etc.) and

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human factors (e.g. other SHSs, neighboring regions or states). The outer environment could itself be a Taiji style system as well (e.g. a SHS operating at a larger scale), i.e. an evolutionary system driven by its own internal interactions, but this is beyond the scope of the study of a specific SHS such as the TRB. The change/evolution of the outer environment shall always force the evolution of inner Taiji SHS, just like the tire of the wheel forces the movement of inner tire. Notionally, we can call the outer circle as the outer tire (see Fig. 8b), and for this reason the framework we have proposed is called Taiji–Tire Model.

The co-evolution of a specific SHS is driven by the inner Taiji and the outer Tire simultaneously. From the outer Tire, environmental change, especially climate variability (and change) will directly impact the hydrological system within a specific SHS (e.g. water part in the inner Taiji), which will then impact the human part by way of interactions between water and humans. Therefore, climate variability/change can serve as an important external force for the evolution of a given SHS. For the inner Taiji, all the internal interactions between humans and water assume various forms via water consumption activities, which are dominated by human behavior and their personal and societal motivations. In some political-economic discourses (e.g. marxism), a so-called social productive force is assumed to be the principal driver of societal evolution. All those forces which are applied by people in the production process (body and brain, tools and techniques, materials, resources and equipment) are encompassed by the concept of social productive force, including those management and engineering functions technically indispensable for production. It is an integrated measure of tool, technology, societal organization, management, and so on, which serves as an important internal force driving the evolution of the SHS.

The co-evolution of the human–water system is therefore governed by both internal and external drivers. Considering the nature of the human–water relationship, including the interactions between water quantity and quality and human water consumption, the water condition can be considered stationary from a long-term perspective without regard to the evolution of the outer tire, with the key driver being the social productive

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force, which is determined by technology, social regimes, social scales etc. For example, the growth of the social productive force has underpinned 200 yr of agricultural development in the Mississippi River Basin, which in the end has caused significant changes in water quality (Turner and Rabalais, 2003). The social productive force represents the abilities of humans to exploit natural resources. However, when it advances beyond some critical threshold value, it may drive the SHS into a new stage. External factors, divided into natural factors such as climate, weather, vegetation, soil, landforms and geological condition, and social factors such as culture, policies, wars, diseases, as shown in the outer tire in Fig. 8a, drive the co-evolution of the SHS by affecting water quantity and quality, and also by embracing the key role of the social productive force. According to our Taiji–Tire Model, the natural variation and social productive force are the two key drivers for the development of any given SHS.

From the historic viewpoint, the social productive force is the key driver for human societal development. For example, the invention and application of iron tools enabled humans to cultivate larger land area than that during the Age of Copper. The industrial revolution has enabled humans to use machines and the same goes for discoveries of electricity and the invention of computers. The upgrade of social productive force determined the productive relationship and governed the formation of cultures, economy, politics and the human–environment relationship including human–water relationship. On the other hand, natural factors such as climate change and geographic/geological effects have for long dominated the fundamental landscape of the eco-hydrological environment and impacted human societies living on it. The variability of natural factors such as hydrology and meteorology restricted the spatial extent of human activities and gradually formed specific regulation of behaviors and thoughts which evolved into culture and values.

Therefore, when social productive force is low and the human–water relationship is dominated by natural factors, changes of the SHS usually happened with hydrological or meteorological variations and followed the social responses. With the upgrade of

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social productive force, the SHS grew to become larger and social factors (represented by social productive force) became the main driver for the system shift.

7 Summary

The historical analysis of the coevolution of the SHS within TRB has brought out distinct features of the different social economic formations, which are expressed in terms of system characteristics, human–water relationship, and the dominant driving force. We have suggested that the co-evolutionary changes that have occurred in the 2000 yr history of the Tarim Basin can be summarized in terms of the Taiji–Tire Model, a refinement of a special concept in Chinese philosophy relating to the co-evolution of a system because of interactions among system components. Accordingly, the study has shown that the socio-hydrological system within the TRB can be classified into four different types according to the social economic formation of society, i.e. primitive agricultural SHS, traditional agricultural SHS, industrialized agricultural SHS, and urbanized SHS.

7.1 Primitive agricultural socio-hydrological system (before the 18th century in TRB)

Before the advent of the agriculture industry, people lived on fishing, hunting and picking, which had a negligible impact on the natural ecosystem and also the water system. For the evolutionary study of SHS, we will ignore this social economic formation. The earliest example of a simple SHS is the primitive agricultural SHS that included low level agricultural activities, simple tools and primitive social organization. The farmlands are linearly distributed along rivers and restricted within isolated areas (such as the oases within TRB primitive agricultural society). The societies relied principally on local water and land resources. No technologies and management tools had been developed to solve water shortage problems. Therefore, the size of primitive agricultural SHSs was constrained to be within a very small size range. In the TRB, the existence of numerous abandoned settlements suggests the vulnerability of the primitive agricultural SHS due to small scale and low social productive force (and thus low complexity of SHS). The primary driving force for the evolution of primitive agricultural SHS is the variability of natural factors, especially climatic and hydrological factors.

7.2 Traditional agriculture socio-hydrological system (from the 18th to early 20th century in TRB)

The highly developed traditional agriculture since the 18th century exhibited different features in terms of scale and coupled human–water relationship. Diversion canals began to be constructed but on a limited scale, which led to a transition of the spatial pattern of farmland from linear to planar distribution. The complexity of the SHS increased and its scale was enlarged, which was still limited by social factors such as institutional and technological advancement. Generally the evolution of traditional agricultural SHS is dominated by the variability of natural factors but human activities could dominate the SHS dynamics at the local scale.

7.3 Industrialized agriculture socio-hydrological system (early to mid-20th century)

The industrial revolution has completely changed the intensity and extent of human practical activities. Also, it changed how people understand themselves and the natural environment. The social-organization of the SHS must be suitable for industrial production and for modern societies with urban and rural differences. Large and complicated hydraulic projects and reservoirs have been constructed and the artificial water gradient has been greatly intensified. The comprehensive application of fertilizers and other modern tools have raised agricultural production remarkably and have caused severe soil salinization and water pollution. The society has become totally dominant in the human–water relationship of industrialized agricultural SHSs.

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7.4 Urban socio-hydrological system (since mid-20th century in TRB)

In a modern industrialized society, the population and wealth are centered in the cities. The landscapes in urban and rural areas are totally different and the eco-hydrological and meteorological environment show different features. Modern cities are much larger and wealthier, with more functions, diverse landscapes and more complicated cultures, governance, economy and politics (Seto et al., 2010). They are not always located close to the riverside, as is the case with old cities. The presence of a large population and industries demand a large quantity of water. This often leads to artificial water diversion from other river basin(s) to avoid over-exploitation of local water resources (surface water and groundwater). An alternative example, located in California, USA, is the Central Valley Project and the State Water Project, both of which divert water from the northern Sacramento River and the San Joaquin River to large southern cities such as San Francisco and Los Angeles. Another example in China is the ongoing South North Water Transfer Project in China, which diverts a huge amount of water from the Yangtze River to large northern cities such as Beijing and Tianjin. The scale of the SHS in urbanized societies is beyond the location of a river basin. With the rapid upgrading of social productive force, more crops can be grown with less water, world markets and world trade has led to flow of large quantities virtual water and many societies can afford large scale trans-basin water diversion projects. All of these developments provide an opportunity to re-balance the human–water relations in a sustainable manner.

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(a) (b)

Fig. 1. The landscape of **(a)** main stream of Tarim River (adapted from http://travel.sina.com.cn/china/2009-03-16/165869875.shtml) and **(b)** the lower reaches of Tarim river (adapted from http://my.opera.com/frampa62/albums/showpic.dml?album=12297572&picture=160178642).

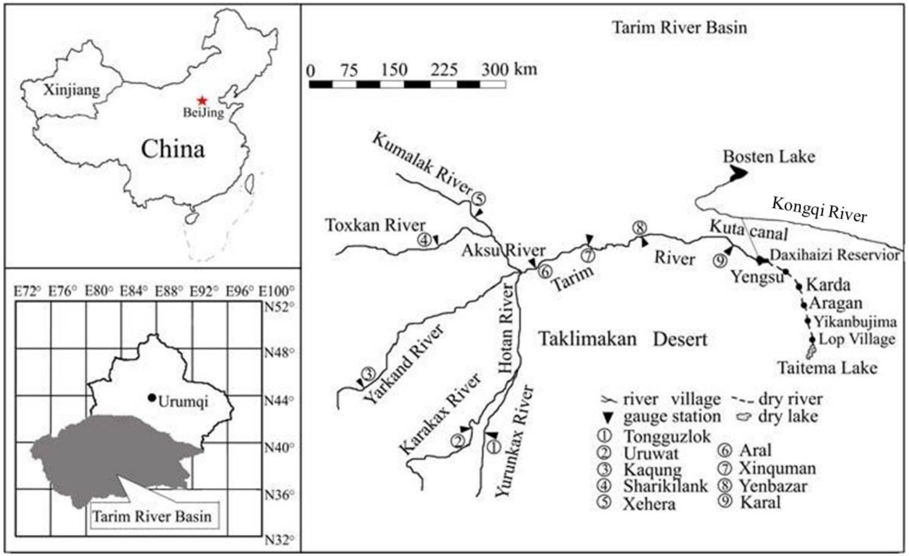

Fig. 2. Overview of Tarim River Basin and its river system (adapted from Hao, 2009).

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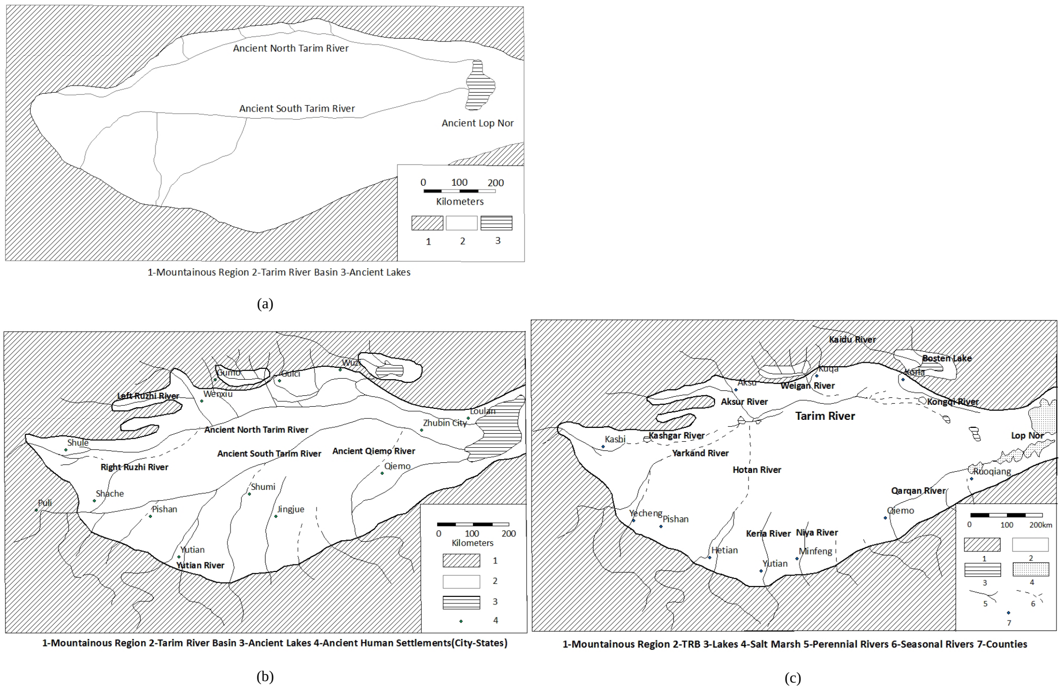

Fig. 3. Evolution of Tarim river system during past tens of thousands of years: **(a)** TRB in late Pleistocene (about ten thousand years ago); **(b)** TRB in 4 to 5th century; **(c)** TRB today (adopted from Fan, 1991; Bai, 1994).

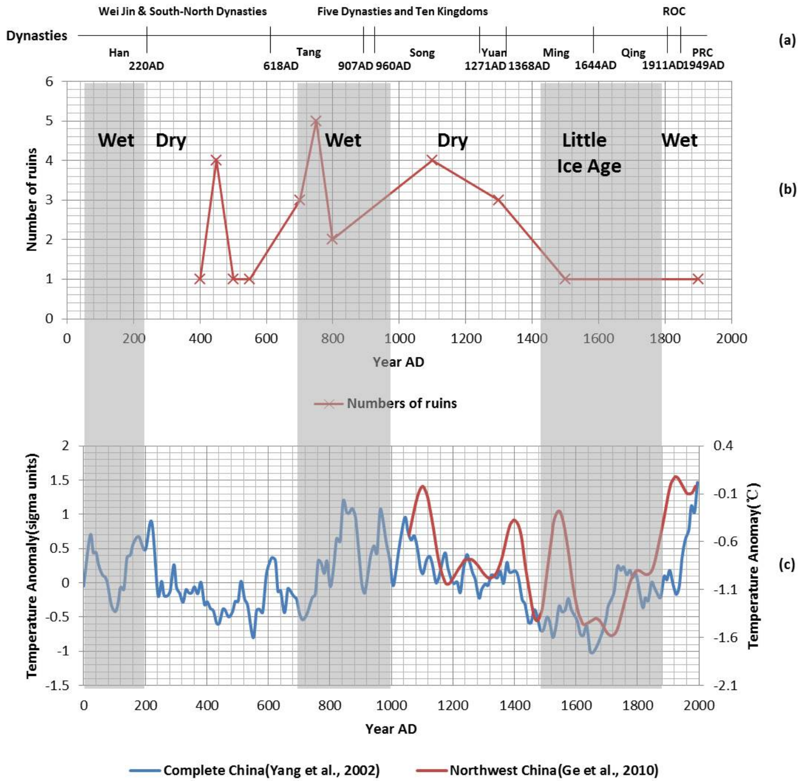

Fig. 4. Climate change and settlements abandonments during past 2000 yr in Tarim River Basin: **(a)** main imperial dynasties in China's history; **(b)** numbers of ruins, which indicates the abandonment of human settlements; **(c)** temperature variation. To be noted, the whole period was divided into wet and dry sub-periods according to the reconstructed record of precipitation (Yang et al., 2002; Ge et al., 2010), of which the wet period is illustrated with grey color.

Fig. 5. Ruins of Lolan which was abandoned at around 6th century (adopted from http://info.hotel.hc360.com/2010/06/091417209847-2.shtml).

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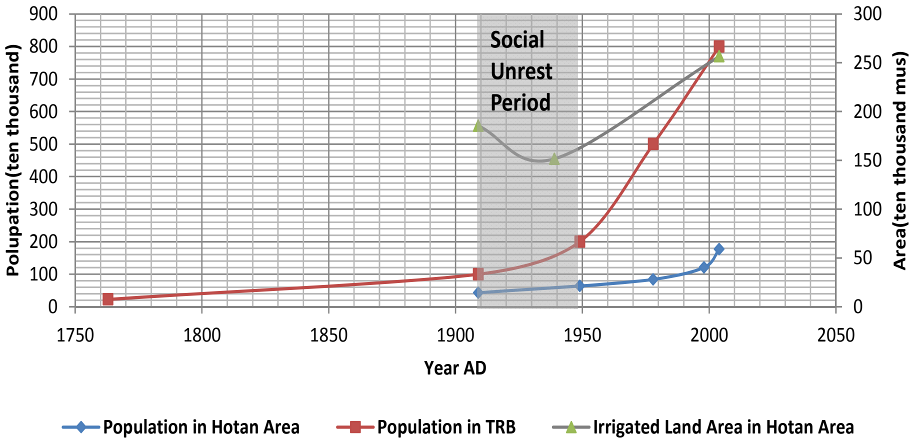

Fig. 6. Dynamics of population and farmland in Hotan area and the whole Tarim River Basin.

(a) (b)

Fig. 7. Landscape of Taitema Lake that **(a)** has been dry since the 1970s (adapted from http://pp.fengniao.com/photo_3809084.html); **(b)** and then refilled since 2000 (adapted from http://a3.att.hudong.com/60/91/01300000633919130041912253732_s.jpg).

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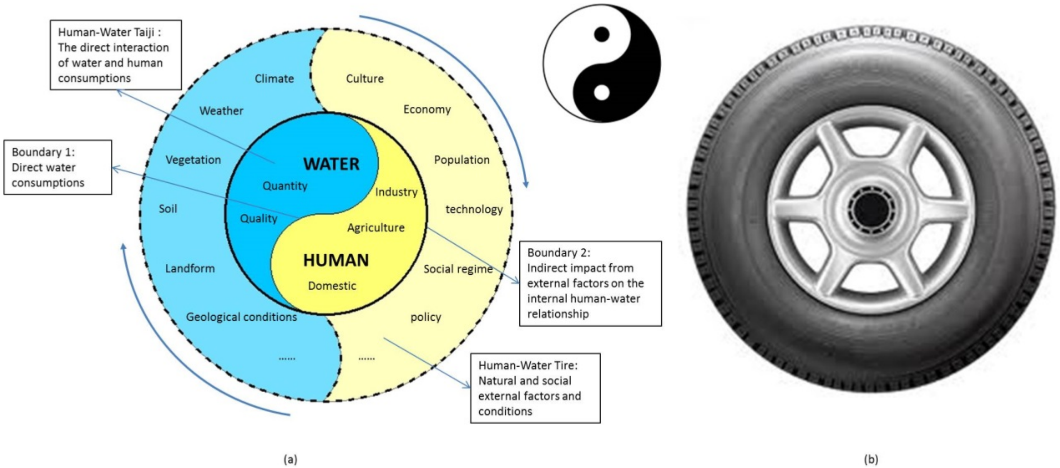

Fig. 8. The Taiji–Tire Model applied for historical socio-hydrological analysis in TRB. The human–water Taiji represents the core of human–water relationship for a specific SHS. The Human-water tire contains the external natural and social conditions. Two boundaries are illustrated and represents two kind of relations: (i) the direct human–water interaction as water consumption in the inner Taiji, which is the internal human–water relationship, and (ii) the indirect impact of external factors that affect the water quantity and quality as well as the social productive force. The center picture is a commonly used symbol for Taiji in Chinese literature.

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