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Analysis of Processes and Drivers of River Evolution in Arid Zones Under the Influence of Natural and Different Levels of Human Activities: A Case Study of the Shule River

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Abstract: Based on regional paleoclimate sequences, records of human activities, paleoclimate simulations, and detailed environmental historical records, we discuss the impacts of Holocene climate change and human activities on the evolution of the Shule River in the western Qilian Mountains, China. The results indicate that during the early to mid-Holocene, the river evolution of the Shule River alluvial fan was closely related to regional climate fluctuations. In the late Holocene, flood agriculture began to emerge along the Shule River. During the historical period, population growth and the expansion of arable land led to increased river water usage, resulting in decreased access to the expected distribution of water resources in other regions, which in turn has caused imbalances in the regional hydrological ecosystem.

Key words: river evolution; arid region; human activity; ancient climate; driving factors; Shule River

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1 Introduction

In arid zones, humans have clustered next to rivers due to the lack of water, and the historical and prehistoric development of river communities is consistent with this observation[1]. Flood fans are often considered ideal places for human settlements because they provide access to water resources and agricultural cultivation, as well as opportunities to connect with ecological corridors in the modern world[1-2]. In previous studies on river evolution in arid zones, the main focus has been on analyzing the formation of river terraces, channel migration, and changes in river flows in the context of climate change[3-5]. However, as the research progressed, some of the shifts in river morphology could often not be explained by climatic factors, and attention was drawn to the impact of human activities. Key research questions arise: At what point do human activities begin to influence river evolution? What is the degree of control?

As human societies shifted from hunter-gatherers

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to farmers, the global environment changed considerably as a result of human activities, and rivers were no exception[6-7]. The establishment of permanent human settlements and the modification of local river environments for flood agriculture were among the earliest human-river relationships[7]. Most of the world's classical centres of civilisation, such as China and Mesopotamia, are close to modern active river branches or former river branches of the Late Holocene[8]. Irrigation and drainage, construction of reservoirs, etc., have caused river evolution to change in both manner and direction due to agricultural, industrial, and urban development[9-10]. It is worth noting that there are similarities in how human activities have influenced river evolution in different parts of the globe, but the timing of human impacts on river evolution is not the same in different regions[11].

The Qilian Mountains are located at the intersection of the Qinghai-Tibet Plateau, the arid region of Northwestern China, and the monsoon region of Eastern China. It consists of a series of northwest-southeast trending mountain ranges, which can be divided into eastern, central and western sections. As altitude increases, temperature decreases and precipitation increases. Controlled by various atmospheric circulation systems, the Qilian Mountains are the sensitive zone for the synergy of the East Asian Summer Monsoon (EASM) and the Westerly Winds (WW), which is a key area for understanding climate interaction[12-13]. The Shule River floodplain fan is located in the western part of the Qilian Mountains, and modern climate studies have shown that the Asian summer monsoon water vapour transport is limited to the eastern Qilian Mountains, and that the climate evolution pattern of the Shule River Basin on the millennial scale of the Holocene is not yet clear[14]. Mao investigated the sedimentary profile of the front edge of the Shule River alluvial fan and found that there have been at least three fluctuations in the groundwater overflow zone of the Shule River since the Holocene due to climate warming and wetting, resulting in the formation of the black peat layer[15]. Zheng *et al* analysed the grain size of Holocene sediments from the Anxi palaeo-marsh in the lower Shule River. They found that the climate in the western part of the Hexi Corridor was generally warmer and wetter from the end of the Late Pleistocene to the Holocene. However, the climate often alternated between cold-dry and warm-wet conditions[16]. Although the evolution of flood fans and their surrounding paleolakes and marshes is well known, the evolution of rivers throughout the basin and their relationship to climate change has not been adequately investigated, as most of the available studies are based on a single site.

The foothills, alluvial fans, and rivers of the Qilian Mountains form an ideal environment for flood agriculture, with glacial and snowmelt floods providing an abundant source of water for agriculture[17]. Using Bayesian modelling, Yang *et al* found that the earliest human activity on the Shule River can be traced back to 3 700–3 400 BP[18]. Using radiocarbon dating, zooarchaeology, archaeobotany and carbon isotope analysis, Dong *et al* found that humans during this period were mainly engaged in agriculture, growing barley and wheat[19]. By examining the spatial distribution of anthropogenic sites and comparing them with palaeoclimate proxies, Yang *et al* hypothesized that the cold climate was responsible for the migration of early humans and the change in production methods[20]. The richness of the historical period gives us new perspectives. Using mathematical methods to analyse historical data, Yang *et al* found that climate change in the Hexi Corridor during the historical period did not directly lead to human migration, but that climate-induced regional and long-term food shortages were the direct triggers of nomadic migration to the south and the conflicts between nomadic and agricultural civilisations in Chinese history[21]. However, most of these existing studies have focused on changes in the locations of human settlements in the basin and shifts in livelihood patterns, as well as the impact of climate change on human activities. Less attention has been paid to the importance of rivers, particularly their impact on human agricultural production and settlement, and human responses to river development, which limits our understanding of the relationship between environmental change and human activities in the Holocene Shule River Basin. By collecting evidence from anthropogenic and natural data from the Shule River region during the Holocene, including independent regional climate sequences, anthropogenic archaeological records and detailed environmental history records, we provide a comprehensive overview of changes in the hydrologic environment since the Holocene and human activities from the Neolithic to the Qing Dynasty. Our study focuses on major hydrological events in the region. The main objectives of our study are to identify the major climatic and anthropogenic events during the Holocene, correlate these events with the regional hydrological record, and assess the relationship between climate change, hydrological changes and human activity since the Holocene. On this basis, we discuss the changing relationship between human settlements and rivers in global drylands.

2 Study region

The Shule River originates from the Shagorinamujimu Ridge between the two major mountains, Taolainan Mountain and Shulannan Mountain, inside the Qilian Mountains (Fig. 1(a)). It lies between 38°00′—42°48′N, and 92°11′—98°30′E, with an average annual precipitation of 54.3 mm and an annual evaporation of 3 046.3 mm, which is a typical temperate continental arid climate. The river source to Changma Gorge is the upstream, Changma Gorge to Shuangtabao Reservoir is the middle reaches, and Shuangtabao Reservoir to Hala Lake is the downstream. In the middle section of the Shule River, the river carries a large amount of gravel and sediment into the plain area of the Hexi Corridor, forming the largest and most complete alluvial flood fan landscape in the Hexi Corridor[24]. Two lakes to the east and west of the floodplain fan, now completely desertified. The northern part of the alluvial fan is an oasis plain zone with extensive swamps and a long history of human activity. Historically, agricultural and nomadic civilizations combined here, and it was also an important part of the eastern section of the Silk Road.

3 Methods

3.1 Regional raleoclimate records

Here we comprehensively reorganize various paleoclimate records throughout the western part of the Qilian Mountains to reconstruct long-term climate

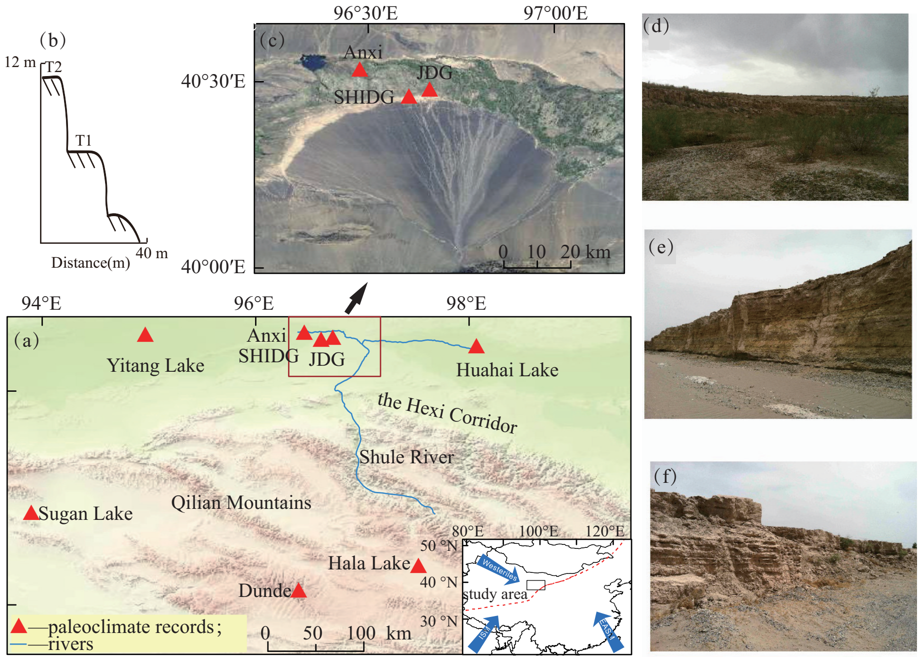


Fig. 1 (a) Overview map of the study area and the distribution of paleoclimate record sites selected in this study. The red dashed line indicates the modern Asian summer monsoon limit[22-23], and the red rectangle indicates the extent of the Shule River flood fan. (b) Terraces of the Shule River. (c) Remote sensing images of the Shule River floodplain fan (from Map World, https://www.tianditu.gov.cn/). (d)-(f) Alluvial channels on the margins of the floodplain fan

changes since the Holocene (Fig. 1(a) and Table 1). We primarily pay close attention to paleo-ecological and paleo-hydrologic changes since the Holocene, so TOC, TN, grain size, and pollen are mainly selected in this paper. Three criteria are considered: (1) the selected records must have a reliable chronology; (2) the record length should cover most of the Holocene; (3) the proxies derived from the records must include at least one type of ecological and hydrologic proxy. Following the above criteria, we selected five records from lacustrine and eolian sedimentary sequences in the western Qilian Mountains, using other records as a basis for our discussion.

Table 1　Detailed information of typical paleoclimate records in the western part of the Qilian Mountains

Record name	Lat (N, °)	Lon (E, °)	Dating method	Record type	Proxies	References
Sugan Lake	93.90	38.85	AMS ^{14}C	Lacustrine	–	[25]
Yitang Lake	94.97	40.52	OSL	Lacustrine	TN	[26]
Anxi Lake	96.47	40.52	AMS ^{14}C	Lacustrine	grain size	[14]
Hala Lake	97.58	38.30	AMS ^{14}C	Lacustrine	TOC	[27]
Huahai Lake	98.06	40.43	AMS ^{14}C	Lacustrine	–	[28]
JDG	96.67	40.47	AMS ^{14}C	Eolian	TOC, pollen	[18]
SHIDG	96.61	40.45	AMS ^{14}C	Eolian	TOC, grain size, pollen	[15]
Dunde	96.40	38.10	AMS ^{14}C	Ice-core	–	[29]

3.2　Paleoclimate simulation

We selected multi-models of CNRM-CM5, CCSM4, FGOALS-g2, MIROC-ESM, IPSL-CM5A-LR, GISS-E2-R, MPI-ESM-P, and MRI-CGCM3 from the PMIP3 (Paleoclimate Modeling Intercomparison Project phase 3) database to perform time slice paleoclimate simulation of understand the role of the atmosphere circulation system and analyze the dynamic mechanism of climate conditions in the Shule River Basin during the mid-Holocene (MH) and pre-industrial (PI) (Table 2). The variables used are precipitation, evaporation, meridional winds, and zonal wind, which are available at https://esgf-node.llnl.gov/search/esgf-llnl/ (Table 3). Due to the different resolutions of PMIP3 models, we preprocessed the datasets with a unified resolution of 1°×1°.

Table 2　Prescribed boundary conditions of PMIP3

Periods	Eccentricity	Obliquity /(°)	Longitude of perihelion /(°)	CO_2/ 10^{-6}	CH_4/ 10^{-9}	N_2O/ 10^{-9}	Ice sheet	Vegetation
MH (6 ka BP)	0.0186 82	24.105	0.87	280	650	270	0 ka Peltier. 2004	Present-day
PI (0 ka BP)	0.0167 24	23.450	102.04	280	760	270	0 ka Peltier. 2004	Present-day

Table 3　Basic information about climate models from PMIP3 used in this research

Model name	Grid number (lon×lat)	Levels	variables	References
CCSM4	192×288	17	ua, va, zg	[30]
CNRM-CM5	128×256	17	ua, va, zg	[31]
FGOALS-g2	60×128	17	ua, va, zg	[32]
GISS-E2-R	90×144	17	ua, va, zg	[33]
IPSL-CM5A-LR	96×96	17	ua, va, zg	[34]
MIROC-ESM	64×128	35	ua, va, zg	[35]
MPI-ESM-P	96×192	25	ua, va, zg	[36]
MRI-CGCM3	160×320	23	ua, va, zg	[37]

3.3　Human activity data

We have made several field trips to the edge of the Shule River flood fan, focusing on washes, depressions, and human activity sites. In a previous study, we compiled a database (Neolithic-Qing Dynasty) containing information on archaeological sites, disasters, and populations in Gansu using data from archaeological sources, documents, and historical records, and categorized these various archaeological sites and finds according to age and type[38]. SRTM DEM data were used to combine hydrological information, topographic information, and information on human activities to assess the relationship between human settlements and rivers in the region.

4 Results

The Shule River formed two fluvial terraces during the Holocene based on the trace of outflow from the floodplain fan to the north, northwest, and northeast. It has the remains of channels connecting it to several lakes and swamps in the region, suggesting that the Shule River was once a source of water for several caudal lakes and swamps. Ecological and hydrological changes in the Shule River were reconstructed based on the analysis of ecological and hydrological proxies from lacustrine and eolian records (Fig. 2(c)-(h)). In the early Holocene, lacustrine sediments with high TOC and pollen content were formed at the edge of the flood fan. During this period, the moisture index of Huahai Lake was high, and lacustrine sediments were formed in the Anxi Marsh. The pollen content of the basin gradually decreased during the MH, and the TOC content was maintained at a low level. The Anxi Marsh is covered by desert and the grain size increases, while the humidity index of Huahai Lake is high. There were several fluctuating increases in pollen and TOC in the Late Holocene watershed, but the overall downward trend did not change.

The difference in the 200 hPa wind fields between the MH and PI winter in the PMIP3 multi-model shows that the wind direction changed from the normal west-north to east-south, indicating that the WW intensified significantly in the PI (Fig. 3 (a)). The location of the westerly jet axis was also more southerly in the PI than in the MH (Fig. 3(b)). These results suggest that the westerly jet has increased in both extent and intensity since the MH.

The earliest human activity in the middle reaches of the Shule River can be traced back to the Siba Culture, a bronze culture (Fig. 4(a)). Two Siba sites have been discovered in the western and northwestern parts of the floodplain fan. The area remained uninhabited for almost a millennium until the Han Dynasty. In the western part of the floodplain fan, vast areas of abandoned ancient farmland and remnants of ancient cities, including those of the Han, Tang and Qing dynasties, are scattered throughout the ancient farmland (Fig. 4(b)-(d)). The Han Dynasty ancient cities are scattered at the edge of the floodplain fan at higher elevations, the Tang Dynasty sites are around the northwest outflow of the floodplain fan, and the Qing Dynasty sites are at lower elevations compared to the Han Dynasty sites, and most of them are located around the modern river channel.

5 Discussion

5.1 Impacts of climate change and human activities on the Shule River

5.1.1 Impact of Holocene climate change on river evolution No large-scale tectonic movements have occurred in the Hexi Corridor since the last glacial period, and climate change is the main reason for the formation of river terraces[44]. When the climate is dry and cold, precipitation decreases, surface vegetation cover is low, and the reduced river flow and increased sediment content leads to increased river accretion, which is not conducive to the formation of river terraces. On the contrary, when the climate becomes hot and humid, precipitation increases, surface vegetation cover is high, and river erosion increases, favouring the formation of river terraces[45]. Due to the unique hydrological structure of the alluvial fan, surface rivers are closely connected to groundwater. River water in the alluvial fan infiltrates and recharges the groundwater, while at the edge of the alluvial fan, groundwater overflows and recharges the river water, forming a series of headwater streams. Groundwater and surface water are often transformed in the process of top-down flow, and the water cycle is complex. Lacustrine deposits provide evidence for the identification of groundwater overflow zones in the alluvial fan, which, based on sedimentological and chronological evidence, indicate that the Shule River flood fan formed a groundwater overflow zone during three periods[15]. Combined

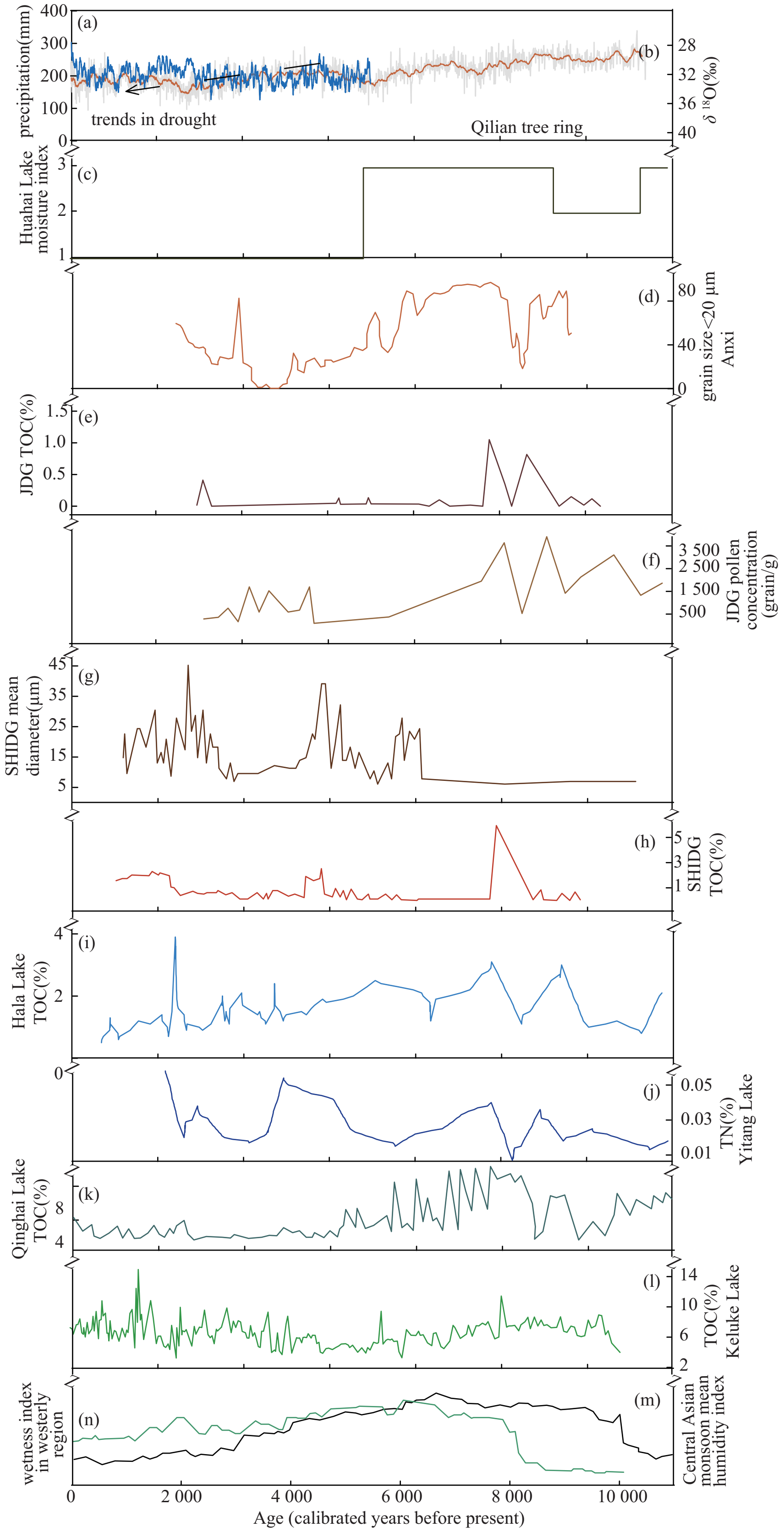
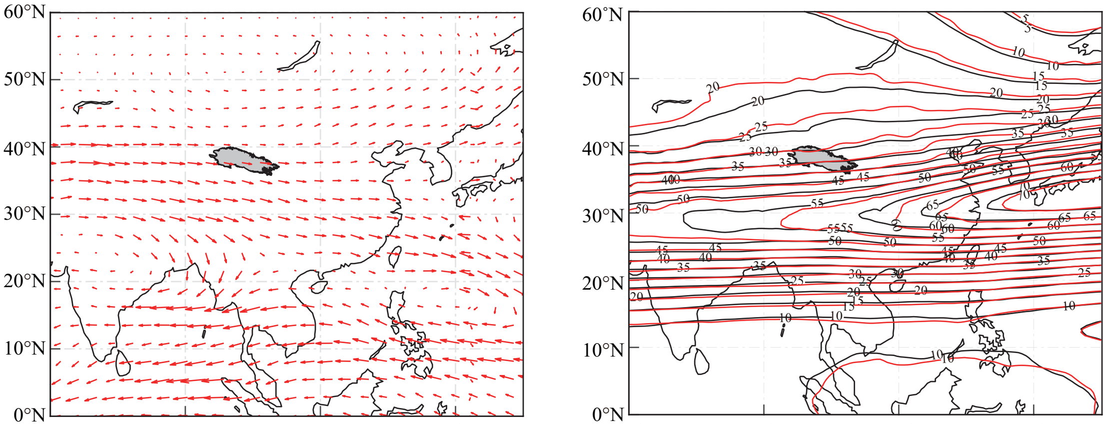


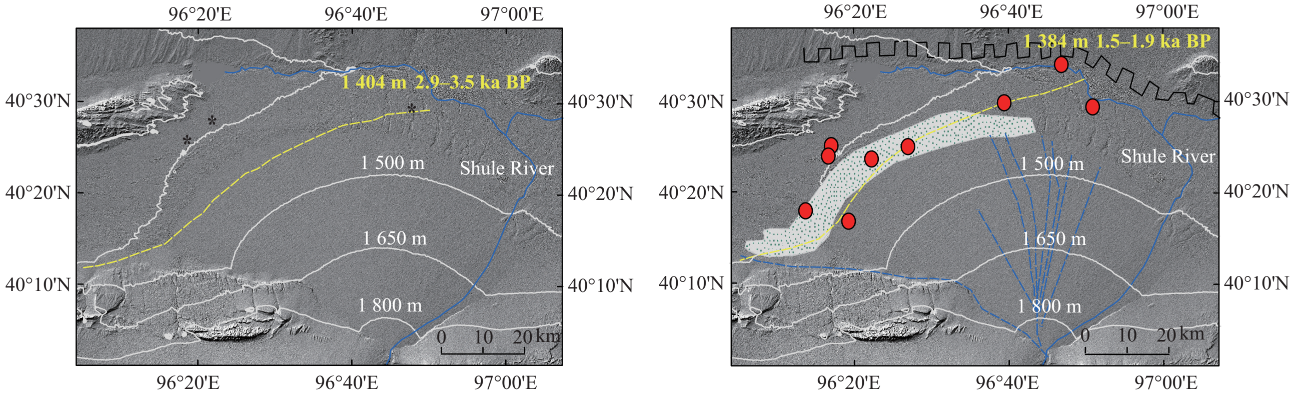
Fig. 2 Proxy records of climate change from the Shule River. (a) The gray line is the reconstructed annual precipitation by tree-ring record from the Qilian Mountains[39]. The blue line is the mean fitting curve calculated. (b) The gray line is $\delta^{18}O$ of the DLH tree-ring[40]. The orange line is the mean fitting curve calculated. (c) The moisture index of Huahai Lake[28]. (d) The grain size of Anxi[16]. (e)-(f) TOC and pollen concentration of JDG[15]. (g)-(h) TOC and Mean diameter of JDG[15]. (i) TOC of Hala Lake[27]. (j) TN of Yitang Lake[26]. (k) TOC of Qinghai Lake[41]. (l) TOC of Keluke Lake[42]. (m) Central Asian monsoon mean humidity index[43]. (n) Wetness index in the westerly region[23]



(a) winter half-year 200 hPa wind field for MH-PI according to the PMIP3 multi-model ensemble simulatios

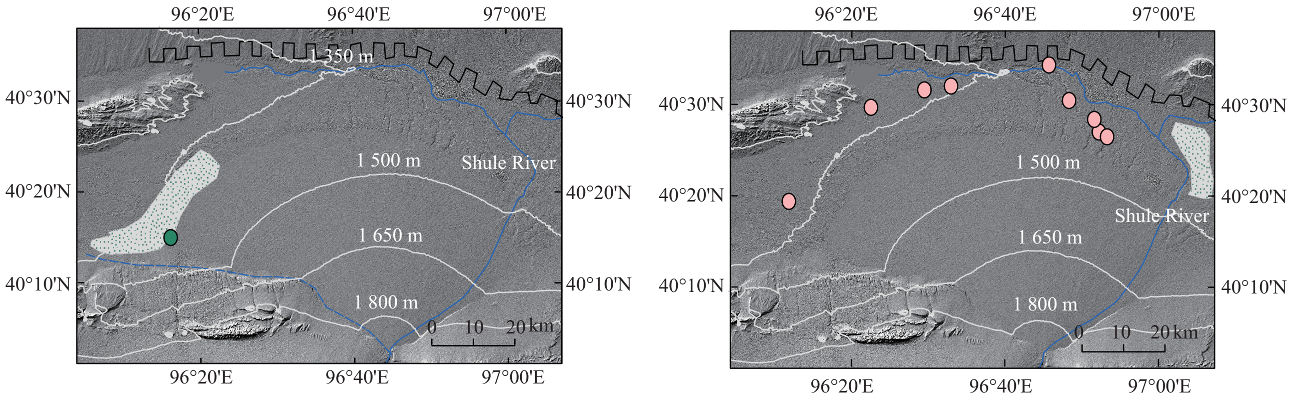
(b) positions of the westerly jet in winter during the MH and PI

Fig. 3 The shaded area represents the Qilian Mountains



(a) Siba Culture(3.3–3.7 ka BP)

(b) Han Dynasty(121BC–220 AD)



(c) Sui and Tang Dynasties(581–755 AD)

(d) Qin Dynasty(1644–1911 AD)

*—Siba ruins; ●—ancient city(Tang); ———the Great Wall; ▨—ancient oasis; ●—ancient city(Han);
○—ancient city(Ming-Qing); ———rivers

Fig. 4 Human sites and changes in groundwater levels in the Shule River Basin. The yellow dotted line represents the groundwater level, the blue dotted lines represent paleochannels, and the grey line represents the contour line

with the surrounding sediments and regional paleoclimate proxies, we discuss the impact of Holocene climate change on the fluvial evolution of the middle reaches of the Shule River.

During the Late Glacial to Early Holocene, climate change from cold to warm led to rapid glacial melting and increased atmospheric precipitation through positive temperature feedback, resulting in increased river flow and erosion[44]. The river began to cut into the glacial deposits on the riverbed, forming the T2 river terrace, which is also found in the eastern part of the Qilian Mountains [4,46] (Fig. 1(b)). The increased river discharge led to extensive marsh development in the middle and lower reaches of the river. A 1—2 cm peat layer formed in the Anxi Marsh [16] (Fig. 2(d)), the surface area of Huahai Lake increased[28] (Fig. 2(c)), and the rivers carried sediments that accumulated in the middle reaches of the rivers and formed temporary rivers and lakes on the left side of the floodplain fan[47]. The pollen and TOC of the JDG and SHIDG profiles reached the highest levels in the Holocene, and lacustrine sediments were formed (Fig. 2(e)-(f)). As the climate warms and becomes wetter, rainfall in the catchment increases, plant cover increases, the water level of the flood fan rises and the groundwater overflow zone moves towards the center of the flood fan[15]. The early Holocene is one of the most favorable periods for the climatic environment of the Shule River[15]. Since the mid-Holocene, climatic aridity led to reduced river flows, which enhanced vertical downcutting of rivers but reduced sediment transport capacity[47]. The T1 terrace was formed by erosion at 6 ka BP (Fig. 1(b), Fig. 2 (a)-(b))[46]. However, the water level in the groundwater overflow zone showed an increasing trend during this period, suggesting that changes in the groundwater overflow zone may have lagged behind climate change[15]. Anxi Marsh was completely desertified, and Huahai Lake experienced water level fluctuations during this period (Fig. 2(c)-(d)). During the historical period, the climate of the Shule River Basin gradually warmed, and precipitation and runoff increased. The Anxi Swamp started to develop again, and peat deposition replaced wind-sand deposition again, while the Huahai Lakes started to gradually recede[16,28].

Although modern climatological results show that the Shule River Basin is mainly controlled by the westerly jet and hardly influenced by the Asian summer winds[48], the monsoon control and water vapour transport on longer time scales still need to be analysed. Simulated and reconstructed studies confirm that increased insolation due to the early to mid-Holocene modulation of orbital forcing leads to increased continental surface temperatures, which can lead to low surface pressure, prevailing southerly winds, and radiation of water vapour fluxes, further expanding the extent of the East Asian monsoon and rainfall, and the influence of summer winds can even reach the Shule River Basin (Fig. 3(a)-(b)). Combining proxy indicators from the Shule River Basin with typical indicators from the western part of the Qilian Mountains, and comparing them with typical indicators from the monsoon region (Qinghai Lake) and the western region (Keruk Lake), we find that there are differences in the change trends of the proxy indicators and the two regions (Fig. 2(c)-(j))[27,29,41-42,49]. Early and Middle Holocene proxies for the Shule River and the western Qilian Mountains reflect an overall wetter climate, consistent with a monsoon-influenced area[41] (Fig. 2(k)). In the Late Holocene, the western Qilian Mountains showed signals of wetting under the overall arid trend, which is similar to the area of influence of the westerly wind zone[42] (Fig. 2(l)). Previous studies have shown that aridification in the Shule River Basin has been occurring since 2000 a BP, which is later than the onset observed in the Shiyang River Basin in the eastern Qilian Mountains, and that erosion rates are lower than those in the Shiyang River Basin[47]. These suggest that the Shule River Basin may have been under the control of a wetter westerly wind belt in the late Holocene.

In summary, the hydrological changes of the flood fan in the middle reaches of the Shule River, terrace evolution, and the evolution of the two mire zones indicate that the Shule River branched left and right during the Holocene state of nature. The weakening of the Asian monsoon since the Holocene, the drying of the climate and low precipitation affected the runoff of the Shule River, which in turn led to the drying up of the marshes in the coccyx area. In the Late Holocene, enhanced westerly winds led to increased precipitation and climate fluctuations, but the overall regional climate remained relatively dry.

5.1.2　Impacts of different levels of human activity on river evolution　The earliest sites of human activity on the Shule River flood fan are the Tuhulu and Yingwoshu sites, located in the northwestern part of the flood fan, and belong to the Siba Culture, a bronze culture type [50-51]（Fig. 4（a））. Based on the study of barley， wheat， and other crops found at the Donghuishan site in the eastern part of the Shule River， it has been determined that people were mainly engaged in agricultural activities during the Siba Culture period. Gramineae are the plants most closely associated with human production and subsistence， and the increase in Gramineae pollen at SHIDG at 3.5 ka BP reflects human planting activities in the Shule River Basin（Fig. 5（e））. Humans on the desert margins， however， were mainly engaged in animal husbandry. This may be because the high water levels of the flood fans and the rich alluvial deposits provide soil and water more suitable for agricultural activities.

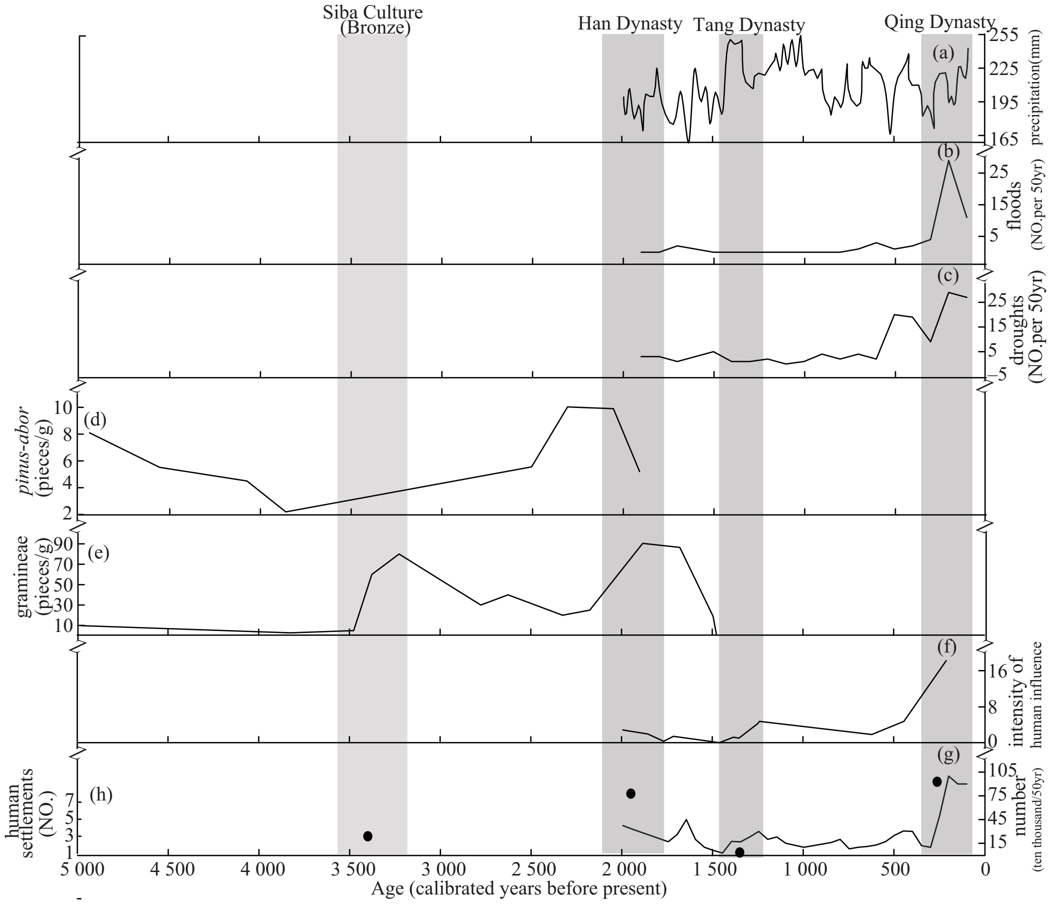


Fig. 5 Record of human activities in the area around the Shule River since the MH.（a）Precipitation in the Qilian Mountains over the last 2 000 years[39].（b）-（c）Floods and droughts in the Hexi Corridor in the last 2 000 years[38].（d）*Pinus* and *abor* of SHIDG[15].（e）Gramineae of SHIDG[15].（f）Intensity of human activity in the Hexi Corridor over the past 2 000 years[52].（g）Population changes in the Hexi Corridor over the past 2 000 years[38].（h）Human settlements in the Shule River Basin since the MH [38]

After the Siba Culture， no sites of human activity was found in the area until the rulers of the Han Dynasty， who had defeated the ethnic minorities， reoccupied and developed the area[53]. The scattered distribution of ancient cities on the edge of the flood fan during the Han Dynasty implies dramatic changes in human lifestyles， agricultural production， social complexity， and population（Fig. 4（b））. Remains of large areas of farmland have been found in the northwest of the flood fan， reflecting the high level of agriculture during this period. The development of oases and migration resulted in the clearing of large areas of forest， leading to a decrease in pollen of woody plants（such as *Pinus* and *Arbor*）and an increase in Gramineae pollen in the profile（Fig. 5（d）-（e））. At the same time， as agricultural production uses a large amount of water in the middle and upper reaches of the floodplain fan， the amount of water flowing downstream gradually decreases. In the context of the overall drying of the Hexi Corridor during the Holocene， the groundwater level in the floodplain fan area declined， and the downstream Anxi Marsh was desertified[11,15,54]. During the Tang Dynasty, the rivers in the north direction of the floodplain fan dried up, and the oases were desertified, leaving only rivers in the northeast and northwest directions (Fig. 4 (c)). Reconstructed precipitation results indicate that precipitation was more abundant during the Tang Dynasty, suggesting that climate may not have been responsible for the abandonment of the oasis (Fig. 5 (a)). After the outbreak of the An-Shi Rebellion (the Tang Dynasty's civil war for dominance), the Hexi Corridor was occupied by Uyghurs (minority tribes), and the war and different livelihoods led to the destruction of waterworks and cultivated land, which may be the main reason for the abandonment of the oasis during this period[55]. The Qing Dynasty was the peak of the population in the Hexi Corridor, as well as the strongest period of human activity in the feudal period (Fig. 5 (f) - (g)). For agricultural development, local governments built dams to divert water to the northeast and canals to divert water to the east, leading to the formation of new man-made oases and Bulu Lakes in the northeast of the floodplain fan, and the abandonment of the city of Suoyang due to the decrease in the volume of river water (Fig. 4(d))[56]. However, due to the natural oscillation of the river, the flow direction of the Shule River changed to the west again, which fundamentally deprived Lake Bulu of surface runoff recharge, and by the end of the Qing Dynasty, Lake Bulu had dried up[56]. Before the Qing Dynasty, the floods and droughts in the Hexi Corridor were in good agreement with the rainfall in the Qilian Mountains (Fig. 5 (a) - (c)). This consistency was broken during the Qing Dynasty. Studies have shown that human activities can cause hydrological droughts in the region[57]. High-intensity human activities in the Qing Dynasty may have led to unusual drought events.

Reviewing the evolutionary history of the Shule River during the Holocene, we find that water resource changes in the Shule River Basin on long time scales are more influenced by dry-wet and cold-warm fluctuations in the climate during the geologic history period, and that the overall riverine climate since the Holocene has been trended toward aridity, albeit with small fluctuations during the period (Fig. 6). Climatic transitions between wet and dry, warm and cold during the early to Middle Holocene led to the formation of terraces. Short wet periods increase regional water resources, as expressed through proxy indicators. The Siba Culture migrated

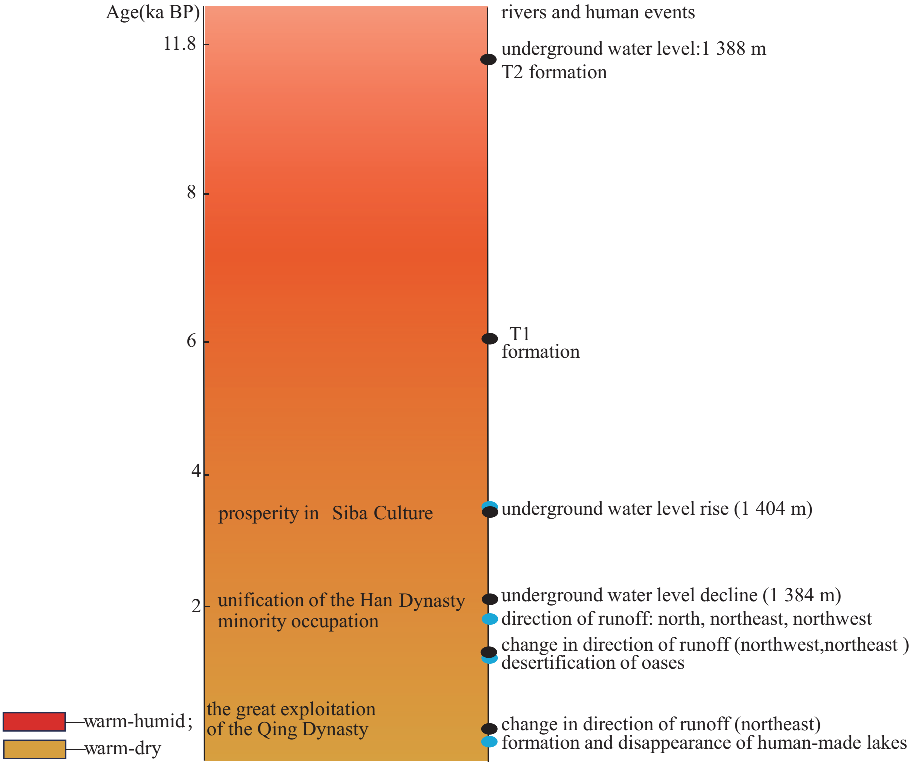


Fig. 6　Human activity events and riverine events of the Shule River during the Holocene

to the Shule River Basin and conducted flood agriculture on alluvial fans in the Late Holocene. Although they inherited the tradition of agricultural life in the Hexi Corridor, they seemed not to be a 'conservative faction' and, where water was scarce, they began to engage in animal husbandry as an alternative to agriculture. In the historical period, the middle reaches of the Shule River had a water balance when the climate was stable and there were no drastic changes in the amount of water in the river. Human activities can affect the distribution of water in different river channels through the construction of crossings and dams, but they do not change the location of the river channels; the diversion of rivers is the result of geological formations. When increased human activity leads to excessive water use in one oasis or section of a river, other areas receive less water than required, resulting in water resource imbalances and the degradation of regional hydrological ecosystems. The rise and fall of agriculture along the Shule River during the historical period were influenced by factors such as differences in production methods and political upheavals, not solely by climate change.

5.2 River and human settlements in the global arid zone

Drylands are a vital part of the Earth's human and physical environment. In hyperarid, arid, and semi-arid regions, water is almost always scarce, and human settlements may cluster around rare water sources such as rivers, springs, wells and oases[58]. However, this 'clustering' creates a paradox. On the one hand, people need to be close to rivers to use water for agriculture; on the other hand, they need to stay away from rivers in case of flooding and erosion. The relationship between humans and rivers has been characterized by alternating cycles of proximity and distancing. We have reviewed the changes in human settlement patterns relative to rivers in the Hexi Corridor region since the MH period and selected several typical civilizations in arid regions to discuss this relationship.

In the Hexi Corridor, human livelihoods underwent a transition from agriculture to mixed agriculture/animal husbandry, and ultimately to animal husbandry from the MH to the Late Holocene[51]. During the warm climate of the MH, people developed agriculture in the pre-mountain alluvial areas located in the upper reaches of rivers that had good water and heat conditions along with rich loess accumulation. Since 4 ka BP, the climate has become dry and cold. To continue agricultural development, people migrated to alluvial plains or areas around terminal lakes, while in the less favorable desert margins, a combination of agriculture and pastoralism became the main livelihood. As the climate continued to deteriorate, agricultural production had completely disappeared, settlements were abandoned, and only a few people continued grazing livestock downstream. Generally speaking, in the early stages of civilisation, when faced with water scarcity due to environmental changes, they adopted two adaptation strategies to the environment. Either they changed their production methods to reduce their dependence on water, or they maintained their old ways and moved closer to water sources.

The dependence of human settlements on water is not an isolated phenomenon. In Xinjiang, statistical analysis of the relationship between settlements and their distance from rivers shows a U-shaped distribution pattern from the Palaeolithic to the Bronze Age[59]. Neolithic settlements demonstrated more diverse water preferences due to varied subsistence patterns. In the Nile Basin, the reduction of river flows and declining lake levels led to a settlement hiatus between 7.5—7.1 ka BP. Around 4.4 ka BP, as the climate became drier, occupation sites shifted from alluvial plains to channel margins[60-61]. In Lower Mesopotamia, the multiple channel networks existing between 3 500 and 1 300 BC enabled the expansion of irrigated floodplains, increased agricultural productivity, and growth in settlements[62]. Later, delta development led to canal abandonment and settlement decline.

Human capacity to alter the natural environment increased with advances in productivity, knowledge, and governance. By building aqueducts and dams, humans can change the distribution of water in rivers and divert water to agricultural areas. Advanced irrigation systems helped improve resilience to rainfall deficits or floods. Subsequent settlement expansion increasingly reflected cultural preferences rather than water availability. However, human interventions also caused negative impacts, including increased erosion rates, reduced runoff, lower lake levels, and pollution that have reduced river system diversity[5,11,63-65].

6 Conclusion

We present a comprehensive discussion of climate change and river dynamics in the Shule River Basin in the Qilian Mountains, China, during the Holocene and relate it to human occupation from the Neolithic to the Qing Dynasty. River dynamics in the Shule River flood-fan front were closely linked to regional hydroclimatic fluctuations during the early to middle Holocene. Humans began to settle in the region and to choose suitable livelihoods in response to local conditions since the Late Holocene. During the historical period, human activities dominated the evolution of the Shule River and a water balance existed in the middle and lower reaches of the river. A surge in water use by human activities in one direction of a river can lead to a decrease in the amount of water in the other direction, which leads to a series of hydrological events such as declining groundwater levels, desertification, and drought.

Future studies on the water resources evolution of the Shule River during the Holocene should focus on the reconstruction of the regional high-resolution continuous climate change process. Based on the reconstructed climate change process, future studies should compare climatic differences between Holocene cold and warm periods and further clarify the synergistic circulation response and hydrological effects of the monsoon and westerly winds during long-time-scale transitions between cold and warm periods. Regarding research on the historical period, more attention should be paid to the impact of extreme climate events on regional water resources and human production and life.

References:

[1] MACKLIN M G, PANYUSHKINA I P, TOONEN W H J, *et al.* The influence of Late Pleistocene geomorphological inheritance and Holocene hydromorphic regimes on floodwater farming in the Talgar catchment, Southeast Kazakhstan, Central Asia[J]. Quaternary Science Reviews, 2015, 129: 85-95.

[2] MARKOFSKY S, NINFO A, BALBO A, *et al.* An investigation of local scale human/landscape dynamics in the endorheic alluvial fan of the Murghab River, Turkmenistan[J]. Quaternary International, 2017, 437: 1-19.

[3] BROOKS G R. Holocene lateral channel migration and incision of the Red River, Manitoba, Canada [J]. Geomorphology, 2003, 54(3/4): 197-215.

[4] XIAOFEI H, BAOTIAN P, HONGSHAN G, *et al.* Development of Holocene fluvial terraces in the eastern Qilianshan Mountain and its relationship with climatic changes[J]. Quaternary Sciences, 2013, 33(4): 723-736.

[5] YU Guo'an, DISSE M, HUANG Heqing, *et al.* River network evolution and fluvial process responses to human activity in a hyper-arid environment: Case of the Tarim River in Northwest China [J]. Catena, 2016, 147: 96-109.

[6] BETTI L, BEYER R M, JONES E R, *et al.* Climate shaped how Neolithic farmers and European hunter-gatherers interacted after a major slowdown from 6,100 BCE to 4,500 BCE [J]. Nature Human Behaviour, 2020, 4(10): 1004-1010.

[7] MACKLIN M G, LEWIN J. The rivers of humankind [M]//MYERS S, HEMSTOCK S, HANNA E. Science, faith and the climate crisis, Leeds: Emerald Publishing Limited, 2020: 29-46. DOI:10.1108/9781839829840.

[8] LU Peng, XU Junjie, ZHUANG Yijie, *et al.* Prolonged landscape stability sustained the continuous development of ancient civilizations in the Shuangji River Valley of China's Central Plains [J]. Geomorphology, 2022, 413: 108359. DOI: 10.1016/j.geomorph.2022.108359.

[9] DOWNS P W, PIéGAY H. Catchment-scale cumulative impact of human activities on river channels in the Late Anthropocene: Implications, limitations, prospect[J]. Geomorphology, 2019, 338: 88-104.

[10] MCDERMID S, NOCCO M, LAWSTON-PARKER P, *et al.* Irrigation in the Earth system [J]. Nature Reviews Earth & Environment, 2023, 4(7): 435-453.

[11] GAO Mingjun, LI Yu, ZHANG Zhansen, *et al.* The evolution of river systems under the influence of climate change and human activities in the endorheic zones during the Holocene[J]. The Holocene, 2024, 34(7): 795-805.

[12] WANG Keli, JIANG Hao, ZHAO Hongyan. Atmospheric water vapor transport from westerly and monsoon over the Northwest China[J]. Advances in

Water Science, 2005, 16(3): 432-438.

[13] ZHANG Qiang, ZHANG Jie, SONG Guowu, *et al.* Research on atmosphere water-vapor distribution over Qilian Mountains[J]. Acta Meteologica Sinica, 2007, 65:633-643.

[14] LI Yu, PENG Simin, LIU Hebin, *et al.* Westerly jet stream controlled climate change mode since the Last Glacial Maximum in the Northern Qinghai-Tibet Plateau[J]. Earth and Planetary Science Letters, 2020, 549: 116529. DOI:10. 1016/j. epsl. 2020. 116529.

[15] MAO Hongliang. Study on the Paleohydrogeology evolution of the Shule River alluvial fan oasis in Holocene[D]. Beijing: Chinese Academy of Geological Science, 2008.

[16] ZHENG Guozhang, YUE Leping, HE Junfang, *et al.* Grain-size characteristics of the sediments at palaeoswamp in Anxi County in downstream of Shulehe River during Holocene and its paleoclimatic significance[J]. Acta Sedimentologica Sinica, 2006, 24(5):733-739.

[17] CHEN Fahu, DONG Guanghui, CHEN Jianhui, *et al.* Climate change and silk road civilization evolution in Arid Central Asia: Progress and issues [J]. Advances in Earth Science, 2019, 34(6): 561-572.

[18] YANG Yishi, ZHANG Shanjia, OLDKNOW C, *et al.* Refined chronology of prehistoric cultures and its implication for re-evaluating human-environment relations in the Hexi Corridor, Northwest China[J]. Science China Earth Sciences, 2019, 62: 1578-1590.

[19] DONG Guanghui, LIANG Huan, ZHANG Zhixiong. Human-environment interaction along the eastern Silk Road during the Neolithic and Bronze Age [J]. Palaeogeography, Palaeoclimatology, Palaeoecology, 2024, 649: 112340. DOI: 10. 1016/j. palaeo. 2024. 112340.

[20] YANG Liu, SHI Zhilin, ZHANG Shanjia, *et al.* Climate change, geopolitics, and human settlements in the Hexi Corridor over the last 5, 000 years[J]. Acta Geologica Sinica, 2020, 94(3): 612-623.

[21] YANG Linshan, FENG Qi, ADAMOWSKI J F, *et al.* Causality of climate, food production and conflict over the last two millennia in the Hexi Corridor, China[J]. Science of the Total Environment, 2020, 713: 136587. DOI:10. 1016/j. scitotenv. 2020. 136587.

[22] CHEN Fahu, CHEN Jianhui, HUANG Wei, *et al.* Westerlies Asia and monsoonal Asia: Spatiotemporal differences in climate change and possible mechanisms on decadal to sub-orbital timescales[J]. Earth-Science Reviews, 2019, 192: 337-354.

[23] CHEN Fahu, YU Zicheng, YANG Meilin, *et al.* Holocene moisture evolution in Arid Central Asia and its out-of-phase relationship with Asian monsoon history[J]. Quaternary Science Reviews, 2008, 27(3/4): 351-364.

[24] WANG Ping, LU Yanchou, DING Guoyu, *et al.* Response of the development of the Shule River alluvial fan to tectonic activity[J]. Quaternary Sciences, 2004, 24(1): 74-81.

[25] WANG Hangfeng, SHI Linfeng. Climatic and environmental changes since 22. 7 ka in Sugan Lake region[J]. Acta Geologica Sinica, 2012, 87: 270-271.

[26] ZHAO Liyuan, LU Huayu, ZHANG Enlou. Lake-level and paleoenvironment variations in Yitang Lake (Northwestern China) during the past 23 ka revealed by stable carbon isotopic composition of organic matteroflacustrine sediments [J]. Quaternary Sciences, 2015, 35(1): 172-179.

[27] WüNNEMANN B, WAGNER J, ZHANG Yong zhan, *et al.* Implications of diverse sedimentation patterns in Hala Lake, Qinghai Province, China for reconstructing Late Quaternary climate[J]. Journal of Paleolimnology, 2012, 48: 725-749.

[28] LI Zhuolun, ZHANG Naimeng, WANG Naiang, *et al.* Lake evolution and its response to climate change during the Late Glacial: A record from the Huahai Lake in the Hexi Corridor of Northwest China[J]. Journal of Desert Research, 2014, 34(2): 342-348.

[29] YAO Tandong, THOMPSON L G. Dunde ice core record and past 5 a temperature change[J]. Science in China(Earth Sciences), 1992, 22(10): 1089-1093.

[30] GENT P R, DANABASOGLU G, DONNER L J, *et al.* The community climate system model version 4 [J]. Journal of Climate, 2011, 24(19): 4973-4991.

[31] VOLDOIRE A, SANCHEZ-GOMEZ E, Mélia D S Y, *et al.* The CNRM-CM5. 1 global climate model: Description and basic evaluation[J]. Climate Dynamics, 2013, 40: 2091-2121.

[32] LI Lijuan, LIN Pengfei, YU Yongqiang, *et al.* The flexible global ocean-atmosphere-land system model, Grid-point Version 2: FGOALS-g2[J]. Advances in Atmospheric Sciences, 2013, 3:543-560.

[33] SCHNEIDER T, BISCHOFF T, HAUG G H. Migrations and dynamics of the Intertropical Convergence Zone[J]. Nature, 2014, 513(7516): 45-53.

[34] DUFRESNE J L, FOUjOLS M A, DENVIL S, *et al.* Climate change projections using the IPSL-CM5 earth system model: From CMIP3 to CMIP5 [J]. Climate Dnamics, 2013, 40: 2123-2165.

[35] WATANABE S, HAjIMA T, SUDO K, *et al.* MIROC-ESM 2010: Model description and basic results of CMIP5-20c3m experiments [J]. Geoscientific Model

Development, 2011, 4(4): 845-872.

[36] RADDATZ T J, REICK C H, KNORR W, *et al.* Will the tropical land biosphere dominate the climate-carbon cycle feedback during the twenty-first century? [J]. Climate Dynamics, 2007, 29: 565-574.

[37] YUKIMOTO S, ADACHI Y, HOSAKA M, *et al.* A new global climate model of the Meteorological Research Institute: MRI-CGCM3: Model description and basic performance[J]. Journal of the Meteorological Society of Japan, 2012, 90(A): 23-64.

[38] GAO Mingjun, LI Yu. Description to the historical records dataset on human activity in the Hexi Corridor of China (from Neolithic to Qing Dynasty) [J]. Global Change Research Data Publishing & Repository, 2023, 7(2): 195-203.

[39] YANG Bao, QIN Chun, WANG Jianglin, *et al.* A 3, 500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau[J]. Proceedings of the National Academy of Sciences, 2014, 111(8): 2903-2908.

[40] YANG Bao, QIN Chun, BRÄUNING A, *et al.* Long-term decrease in Asian monsoon rainfall and abrupt climate change events over the past 6, 700 years[J]. Proceedings of the National Academy of Sciences, 2021, 118 (30) : e2102007118. DOI: 10. 1073/pnas. 2102007118.

[41] JI Shen, LIU Xingqi, WANG Sumin, *et al.* Palaeoclimatic changes in the Qinghai Lake area during the last 18, 000 years[J]. Quaternary International, 2005, 136(1): 131-140.

[42] ZHAO Liyuan, LU Huayu, ZHANG Enlou, *et al.* Lake-level and paleoenvironment variations in Yitang Lake (Northwestern China) during the past 23 ka revealed by stable carbon isotopic composition of organic matter of lacustrine sediments[J]. Quaternary Sciences, 2015, 35(1): 172-179.

[43] HERZSCHUH U, KüRSCHNER H, MISCHKE S. Temperature variability and vertical vegetation belt shifts during the last 50,000 yr in the Qilian Mountains (NE margin of the Tibetan Plateau, China) [J]. Quaternary Research, 2006, 66(1): 133-146.

[44] LI Youli, YANG Jingchun. Response of alluvial terraces to Holocene climatic changes in the Hexi Corridor Basins, Gansu, China[J]. Scientia Geographica Sinica, 1997, 17(3):249-252.

[45] XU Liubing, ZHOU Shangzhe. Formation process and driving mechanisms of fluvial terrace[J]. Scientia Geographica Sinica, 2007, 27(5):672-677.

[46] CAO Xingshan. Holocene series in the Hexi Corridor [J]. Gansu Geology, 1989, 10: 1-9.

[47] LI Yu, WANG Yue, ZHANG Chengqi. Interactions among millennial-scale geomorphic processes in different parts of a drainage basin, Arid China[J]. Physical Geography, 2015, 36(5): 367-394.

[48] HUANG Lingxin, CHEN Jie, YANG Kun, *et al.* The northern boundary of the Asian summer monsoon and division of westerlies and monsoon regimes over the Tibetan Plateau in present-day [J]. Science China Earth Sciences, 2023, 66(4): 882-893.

[49] ZHAO Yan, YU Zicheng, CHEN Fahu, *et al.* Holocene vegetation and climate history at Hurleg Lake in the Qaidam Basin, Northwest China [J]. Review of Palaeobotany and Palynology, 2007, 145(3/4): 275-288.

[50] LI Shuicheng. East wind and westward progress: The process of prehistoric culture in Northwest China[M]. Beijing: Cultural Relics Press, 2009.

[51] LI Shuicheng, SHUI Tao, WANG Hui. Report on the prehistoric archaeological survey of the Hexi Corridor [J]. Archaeology, 2010, 2:229-274.

[52] LU Zhixiang, WEI Yongping, XIAO Honglang, *et al.* Evolution of the human-water relationships in the Heihe River Basin in the past 2 000 years[J]. Hydrology and Earth System Sciences, 2015, 19(5): 2261-2273.

[53] AN Chengbang, WANG Wei, DUAN Futao, *et al.* Environmental changes and cultural exchange between east and west along the Silk Road in Arid Central Asia [J]. Acta Geographica Sinica, 2017, 72(5): 875-891.

[54] FENG Shengwu. Evolution of the Shulehe River system[J]. Journal of Lanzhou University, 1981(4): 138-143.

[55] LI Yu, WANG Nai'ang, LI Zhuolun, *et al.* Climatic and environmental change in Yanchi Lake, Northwest China since the Late Glacial: A comprehensive analysis of lake sediments[J]. Journal of Geographical Sciences, 2013, 23: 932-946.

[56] WANG Maoying. Study on the changes of river and lake systems in the Shule River Basin during the Qing Dynasty[D]. Xi'an:Shaanxi Normal University,2010.

[57] SAKAI A, INOUE M, FUjITA K, *et al.* Variations in discharge from the Qilian Mountains, Northwest China, and its effect on the agricultural communities of the Heihe Basin, over the last two millennia[J]. Water History, 2012, 4: 177-196.

[58] GAUR M. K, SQUIRES V R. Climate variability impacts on land use and livelihoods in drylands[M]. New York: Springer International Publishing, 2018.

[59] TAN Bo, WANG Hongwei, WANG Xiaoqin, *et al.* The study of early human settlement preference and settlement prediction in Xinjiang, China[J]. Scientific Reports, 2022, 12(1): 5072. DOI: 1038/s41598-022-

09033-y.

[60] MACKLIN M G, LEWIN J, JONES A F. River entrenchment and terrace formation in the UK Holocene [J]. Quaternary Science Reviews, 2013, 76: 194-206.

[61] HONEGGER M, WILLIAMS M. Human occupations and environmental changes in the Nile Valley during the Holocene: The case of Kerma in Upper Nubia (Northern Sudan) [J]. Quaternary Science Reviews, 2015, 130: 141-154.

[62] MOROZOVA G S. A review of Holocene avulsions of the Tigris and Euphrates Rivers and possible effects on the evolution of civilizations in Lower Mesopotamia [J]. Geoarchaeology, 2005, 20(4): 401-423.

[63] SHANG Hao, LI Yu, GAO Mingjun, *et al.* Analysis of environmental changes in the shiyang River Basin at millennial scale [J]. Journal of Ningxia University (Natural Science Edition), 2024, 45(4): 397-405.

[64] LI YU, GAO Mingjun, ZHANG Zhansen, *et al.* Time-scale effects in human-nature interactions, regionally and globally [J]. Journal of Geographical Sciences, 2023, 33(8): 1569-1586.

[65] LI Yu, GAO Mingjun, ZHANG Zhansen, *et al.* Phased human-nature interactions for the past 10 000 years in the Hexi Corridor, China [J]. Environmental Research Letters, 2023, 18(4): 044035. DOI: https://doi.org/10.1088/1748-9326/acc87b.

自然和不同程度人类活动对干旱区河流演变过程与驱动因素的影响

——以疏勒河为例

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摘 要:基于区域古气候序列、人类活动记录、古气候模拟和详细的环境历史记录,探讨全新世气候变化和人类活动对中国祁连山西部疏勒河河流演变的影响。结果表明,在全新世早中期,疏勒河洪积扇的河流演变与区域气候波动密切相关。全新世晚期,疏勒河开始出现洪水农业。进入历史时期,人口增加和耕地面积扩大使河水使用量的增加,其他地区无法获得应得的水资源供给,进而导致区域水文生态系统失衡。

关键词:河流演变;干旱地区;人类活动;古气候;驱动因素;疏勒河

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Research Progress on Ruthenium Oxide-Based Catalytic Electrodes Modified by Doping Strategies

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Abstract: In light of the recent advances made by researchers in ruthenium oxide catalysts, this review systematically summarizes the relevant progress in employing doping strategies to enhance ruthenium dioxide catalysts, analyzes the internal mechanisms by which doping with precious metals, rare-earth metals, non-precious metals, and non-metals improves performance, and discusses the future directions for this field. This review is significant for the advancement of the hydrogen energy field, particularly in the context of acidic water electrolysis.

Key words: hydrogen energy; ruthenium oxide; doping; electronic structure; proton exchange membrane (PEM) electrolyser

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