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Influence of rainfall changes from 4.6 to 3.0 ka BP on ceramic pipes

Shuaiqi Wang[1], Xiangyu Zhu[1] and Ye Tian[1*]

Abstract

The impact of climate change on human social development has been a topic of research for a long time. Ceramic pipes, which are vital components of urban drainage engineering, are crucial means of managing rain hazards and floods. Exploring the historical evolution of ceramic pipes can help in better understanding the interplay between climate change and human behavior. This study examined the diameters of 86 ceramic pipes unearthed from six cultural sites in central China, including Pingliangtai, Taosi, and Erlitou, dated to 4600–3040 a BP. By combining speleothem records from the excavation sites with precipitation and temperature composite curves for China using Pearson correlation analysis, and verifying with pollen records. The results show that changes in rainfall were the main factor influencing the diameters of the ceramic pipes. This indicates that during this period, ancient people in the Central Plains of China were able to adjust the size of the ceramic pipes to regulate the water management capacity of urban water systems, thereby adapting urban development to climate change.

Keywords Ceramic pipes, Ancient climate, Variations in precipitation

Introduction

Several researchers have conducted extensive macrolevel studies to evaluate the impact of climate change on the decline of civilizations. Decreasing temperatures and reduced precipitation levels often result in a significant decline in agricultural output, resulting in shortages of essential resources for human survival. This scarcity can potentially instigate wars and widespread–scale social upheavals [1–6], Li analyzed multiple indicators of Longshan Culture sites in Henan Province, including spatial distribution, proximity to rivers, and spatial clustering. The analytical results, in combination with ancient climate records, speculated that natural disasters such as droughts, floods, and low temperatures were frequent in the Henan region around 4000 years ago. These events prompted humans to rapidly expand their habitat in pursuit of more resources [7].

The relationship between human society and climate change is more than simple interaction. When significant climate changes occur, humans adjust their strategies to ensure the continuation of reproduction and survival in alignment with the changing climate. Furthermore, humans have designed buildings to ensure they are safe in the natural environment. Maintaining safety requires not only resisting attack from wild animals but also protection from harsh natural environments. Therefore, the initial impacts of climate change frequently manifest in the structural integrity of buildings, and previous researchers have investigated human adaptive responses to climate change, beginning with the structural attributes of buildings. By reconstruction of snowfall data from 1000 to 200 a BP, Li revealed that roof slopes vary with snowfall to improve the efficiency of clearing roof snow. This correlation ensures that buildings are prevented from being negatively impacted by excessive snow accumulation [8].

*Correspondence:
Ye Tian
tianyekian@kust.edu.cn
[1] Faculty of Art and Communication, Kunming University of Science and Technology, Jingmingnan Street, Kunming 650500, Yunnan, China

The drainage engineering design is another remarkable accomplishment in human adaptation to climate change; the design and construction of drainage facilities have become crucial in the prevention and control of urban water disasters. Early Chinese water facilities (for example, Anyangyinxu site) can be roughly divided into five categories: (1) natural rivers, which provide essential water for human life and agriculture and also serve as one of the endpoints for urban sewage, (2) ponds and gardens, typically connected water channels and can drain into ponds. The construction of ponds and gardens addresses the challenge related to the use of earth for rammed earth buildings and mitigates drainage issues within palace areas. Additionally, it improves the aesthetic appeal of the landscape, and can also serve as an alternate source of firefighting water [9], (3) large ditches, which are the most common units in urban drainage systems, serve as outlets for urban sewage, ultimately directing it towards surrounding rivers. Additionally, they store firefighting water and serve as the safety net of the city moat [10], (4) waterways, with stone or wooden slabs laid on the bottom and sides; stone slabs are effective in preventing sewage infiltration and the impact of water flow on the waterway, while wooden slabs prove more suitable for the installation and replacement of longer distance waterways. Waterways are predominantly used for sewage discharge from individual buildings to large ditches [11], (5) ceramic pipes, which are pivotal components of early urban water systems, are typically employed for sewage discharge within individual buildings, as well as safeguarding rammed earth foundations from erosion due to rainwater. During the Han Dynasty, these pipes were also integrated with water wells and other water storage systems to fulfill the domestic water needs Of urban residents [12].

The primary function of ceramic pipes (Fig. 1) is to facilitate the drainage of rainwater from buildings, making them part of the internal structure of buildings. These pipes are particularly responsive to rainfall variations. A retrospective analysis of the historical changes in ceramic pipe diameters offers insights into the adaptive changes undertaken by early humans in response to climate change. In this study, we selected 86 Ceramic pipes unearthed from six major excavation sites in the Central Plains region and compared them with contemporaneous $\delta^{18}O$ records from four speleothems, China's temperature composite curve, and precipitation composite curve to discuss the changes that humans have made to adapt to climate change.

Study region, data sources and analysis methods

Study region

The selected regions were the Pingliangtai site in central-western Henan Province (33° 42′N, 114° 55′E), the Erlitou site in western Henan Province (34° 41′N, 112° 41′E), the Yanshishangcheng site (34° 43′N, 112° 45′E), the Zhengzhoushangcheng site in the north-central part of Henan Province (34° 44′N, 113° 40′E), the Anyangyinxu site in northern Henan Province (36° 07′N, 114° 19′E) and the Taosi site in southwestern Shanxi Province (35° 53′N, 111° 29′E). These sites represent large-scale urban sites from the same period. They also serve as the major sites where ceramic pipes have been discovered.

For the reconstruction of ancient precipitation levels, we selected the $\delta^{18}O$ record from the MG-64 speleothem in Magou Cave, Henan Province (50 km southwest of the Zhengzhoushangcheng site), as the primary basis for meteorological changes [13], and compared it with the temperature composite curve [14] and precipitation composite curve [15] of China from 4600 to 3040 a BP, along with Holocene climate change data recorded by speleothems from Lianhua Cave in Shanxi Province [16], Jiuxian Cave in Shaanxi Province [17], and Xianglong Cave in Shaanxi Province [18]. See Fig. 2.

Discharge of ceramic pipes and precipitation data

Figure 3 shows that the selected Ceramic pipes in this study span the following periods: 20 Ceramic pipes from the Pingliangtai period (4600–4180 a BP) [19, 20], 2 Ceramic pipes from the late Taosi culture (4000–3900 a BP) [21], 16 Ceramic pipes from phases III-IV of the Erlitou culture (3547–3462 a BP) [22], 10 Ceramic pipes from the Erligang culture period (3530–3340 a BP) [23, 24], and 38 Ceramic pipes from phases III–IV of the Yinxu period (3150–3040 a BP) [25–28]. In total, 86 Ceramic pipes were included in the study. While ceramic pipes were still used in the later periods of the Zhou, Qin, and Han dynasties, the continuous improvement in production techniques during later periods led to increasingly sophisticated drainage systems. Additionally, the diversification of the forms and functions of ceramic pipes contributes to the complexity of the factors influencing ceramic pipes. Therefore, this study focused primarily on ceramic pipes between 4600 and 3040 a BP.

The primary factors affecting the flow rate of a ceramic pipe are the diameter of the pipe and the velocity of the water within it. In the absence of external pressurization, the water velocity can only be inferred from the slope and burial depth of the pipe. If the height or angle of inclination of the ceramic pipes is not recorded during excavation, determining the water flow speed is impossible. Unfortunately, such information is rarely

Fig. 1 **a** Ceramic pipes unearthed from Pingliangtai site (image source: National Museum of China), **b** Ceramic pipes unearthed from Anyangyinxu site (image source: Yin Xu Museum), **c** Schematic illustration depicting the application of ceramic pipes

found in archaeological reports [11], so we can use only the pipe diameter as the criterion for determining the flow rate. Due to the nested structure of the spigot and socket of the ceramic pipes, as well as the limitations of manual production in achieving standard circular shapes, only approximate values can be obtained. Therefore, the average diameter of each section of the ceramic pipe was chosen as the representative diameter of the ceramic pipe.

Chinese speleothem oxygen isotope records have become a global benchmark for paleoclimate comparisons due to their absolute dating and high resolution. Currently, the meanings of speleothem $\delta^{18}O$ include proxies for "Asian monsoon intensity" [29–32], "Indian monsoon intensity" [33, 34], "summer monsoon precipitation" [17, 35], and "circulation conditions" [36, 37]. In northern China, oxygen isotope records of stalagmites are negatively correlated with summer monsoon precipitation: heavier $\delta^{18}O$ values indicate lower rainfall, while lighter values indicate higher rainfall [38, 39]. In southern China, these isotopes do not correlate with summer monsoon changes and are unsuitable for gauging East Asian summer monsoon intensity [29, 40, 41]. Due to the controversy over different $\delta^{18}O$ records from stalagmites in northern and southern China, we selected $\delta^{18}O$ records from stalagmites in northern China, near the excavation sites of ceramic pipes, to reflect changes in Holocene summer monsoon precipitation (Fig. 4). The oxygen isotope records from Magou Cave reflect changes in the $\delta^{18}O$ of summer monsoon precipitation and demonstrate that precipitation changes due to variations in monsoon intensity dominated the long–term dynamics

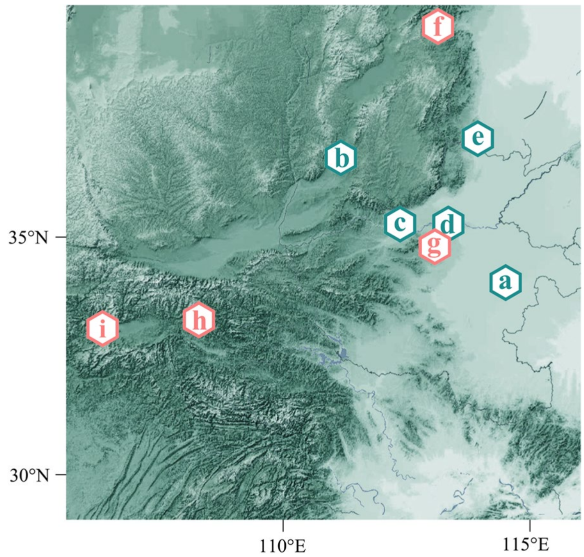

Fig. 2 a Pingliangtai Site, b Taosi Site, c Erlitou Site, Yanshishangcheng Site, d Zhengzhoushangcheng Site. e Anyangyinxu Site, f Lianhua Cave, Shanxi Province, g Magou Cave, Henan Province, h Jiuxian Cave, Shaanxi Province, i Xianglong Cave, Shaanxi Province. Green marks the locations where Ceramic pipes were unearthed, and red marks the locations where speleothem records were collected

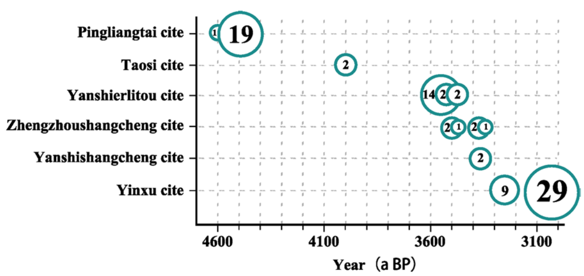

Fig. 3 Shows the number and dates of the Ceramic pipes unearthed at the different sites. The vertical position of each circle corresponds to the site where the Ceramic pipes were found, and the horizontal position represents the dates of the Ceramic pipes (since pipes from the same site may have different dates, multiple circles are used). The size of the circle and the number inside it represent the quantity of Ceramic pipes

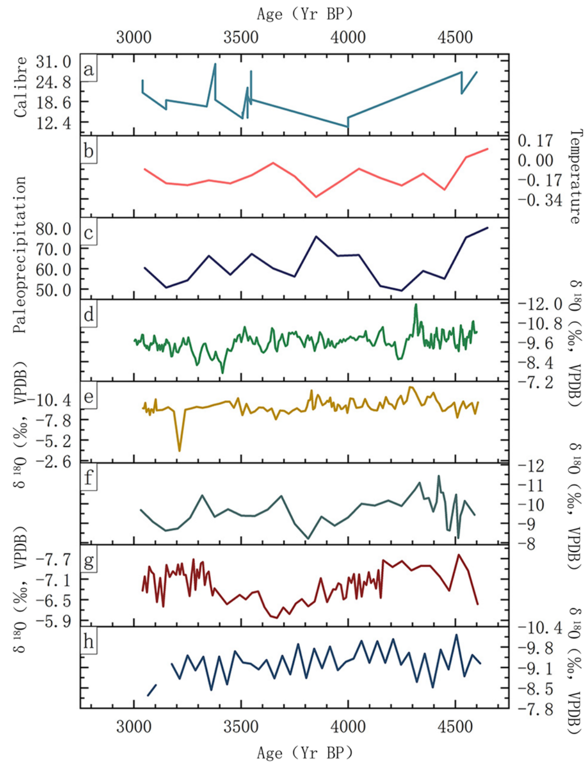

Fig. 4 **a** Diameters of Ceramic pipes unearthed in China from 4600 to 3040 a BP [19–28]. **b** 4600-3040 a BP Chinese temperature composite curve. [14]. **c** 4600–3040 a BP Chinese precipitation composite curve [15]. **d** $\delta^{18}O$ records of speleothem MG-64 from Magou Cave, Henan Province [13]. **e** $\delta^{18}O$ records of speleothem C996-1 from Jiuxian Cave, Shaanxi Province [17]. **f** $\delta^{18}O$ records of speleothem C996-2 from Jiuxian Cave, Shaanxi Province [17]. **g** $\delta^{18}O$ records of speleothem XL16 from Xianglong Cave, Shaanxi Province [18]. **h** $\delta^{18}O$ records of speleothem LH-1 from Lianhua Cave, Shanxi Province [16]

of precipitation $\delta^{18}O$ [13]. Cai, through a comprehensive analysis of the factors influencing oxygen isotopes, found that the $\delta^{18}O$ records of speleothems C996-1 and C996-2 from Jiuxian Cave exhibit a significant negative correlation with local monsoon precipitation [17]. The $\delta^{18}O$ data from speleothems in Lianhua Cave, Shanxi Province, serve as qualitative proxies for regional precipitation and East Asian Summer Monsoon (EASM) intensity, primarily recording summer precipitation data [16]. The $\delta^{18}O$ records from speleothems in Xianglong Cave, Shaanxi Province, display monsoon precipitation in the upper Han River region on centennial to decadal scales [18]. These records were compared with the 4600-3040 a BP Chinese precipitation composite curve to verify the accuracy of the data [15]. We also selected the 4600–3040 a BP Chinese temperature composite curve as a proxy for temperature changes in this region [14].

analysis methods

In data analysis, Pearson correlation analysis was used to verify the correlation among diameters of ceramic pipes from 4600 to 3150 a BP and between $\delta^{18}O$ records of stalagmites. Archaeological dating of excavated artifacts often involves a combination of typology and radiocarbon dating techniques to establish a relative chronological sequence of site cultures, typically dating artifacts in centuries. Thus, only the approximate time interval for the production and use of ceramic pipes can be determined. Generally, human response to climate change can lag by 5–30 years [42]. Therefore, the earliest time in the archaeological period was chosen (for example, in the case of ceramic pipes unearthed from the late period of Taosi culture dated 4000–3900 a BP, 4000 a BP was chosen as the reference time for precipitation data).

Results

As shown in Fig. 5, we can clearly observe a negative correlation between the historical changes in the diameter of the Ceramic pipes and the $\delta^{18}O$ records of the speleothem MG-64 from Magou Cave (R=− 0.47, P<0.01). This negative correlation is also evident in comparisons with speleothems C996-1 (R=− 0.30, P<0.01) and C996-2 (R=− 0.59, P<0.01) from Jiuxian Cave, XL16 (R=− 0.49, P<0.01) from Xianglong Cave, and LH-1 (R=− 0.54, P<0.05) from Lianhua Cave, where smaller $\delta^{18}O$ values indicate higher rainfall and larger values indicate lower rainfall. The negative correlation between the diameter of the Ceramic pipes and the $\delta^{18}O$ records of the speleothems indicates that humans adjust the diameter of the pipes in response to changes in precipitation. This adjustment allowed the pipes to meet the functional requirements of rainwater drainage while minimizing material usage. The strong positive correlation between the diameter of the Ceramic pipes and the 4600-3040 a BP Chinese precipitation composite curve (R=0.62, P<0.01) also supports this conclusion. Similarly, suggesting that changes in rainfall were the primary influencing factor in the design of pipe sizes during the 4600–3040 a BP. The dynamic changes in the diameter of Ceramic pipes reflect human adaptive behaviors to climate change. During this

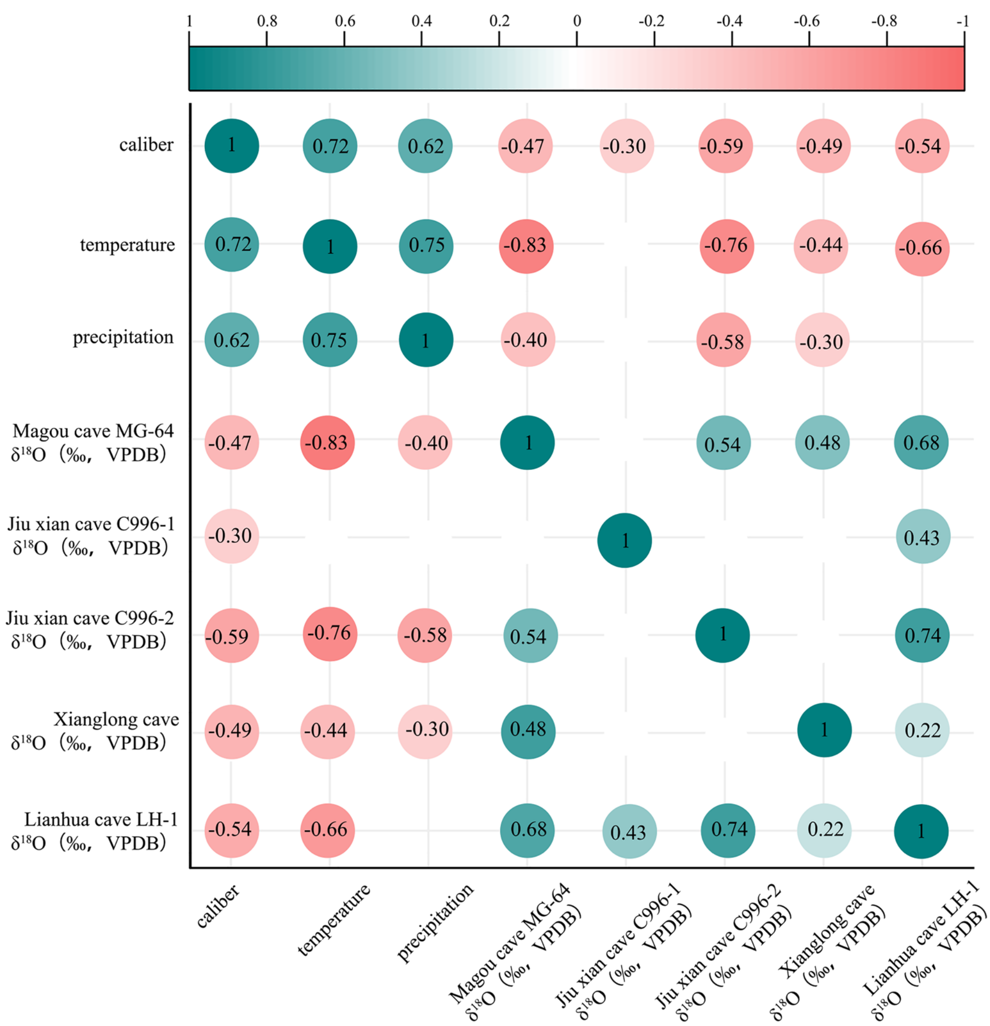

Fig. 5 Pearson correlation between the diameter of ceramic pipes and stalagmite $\delta^{18}O$ records, along with the integrated precipitation curve for China. The degree of correlation is indicated by a color gradient, ranging from -1 to +1. Only significant correlations (P<0.05) are shown

period, pottery craftsmen and urban planners in the Central Plains region adjusted the diameter of Ceramic pipes to manage urban water systems in response to climate change.

Discussion

Factors affecting the variation in ceramic pipe diameterFactors affecting the variation in ceramic pipe diameter

Research on the factors influencing the diameter variation of ceramic pipes due to social complexity

In this study, the variations in the diameter of ceramic pipes during the period from 4600 to 3040 a BP exhibited a trend characterized by approximately bimodal variation. The average diameter of the ceramic pipes decreased by approximately 57%, from 27.5 cm at the Pingliangtai site (4600–4180 a BP) to 11.875 cm at the Taosi site (4000–3900 a BP). The diameter of the ceramic pipes unearthed during the third phase of Erlitou site (3547 a BP) excavation rapidly increased to 20.1 cm, followed by a decrease to 14.26 cm during the fourth phase of Erlitou site excavation (3507 a BP). During the late phase of the Erligang culture (3430–3340 a BP), the diameter recovered to 21.16 cm, and during the Yinxu period (3150–3040 a BP), it decreased again to 20.27 cm. First, we analyze the impact of social development on changes in the diameter of Ceramic pipes from the perspective of social development complexity. The hierarchy of prehistoric settlement sites and the area of the largest settlement sites can reflect the population density, social complexity, and level of civilization at that time [43]. As shown in Table 1

Normally, the larger the pottery is, the more difficult the forming and firing process, and the greater the technical requirements for the craftsmen. As the complexity of human society increases, productivity also increases, and the ability to make large artifacts grows accordingly [47]. Larger Ceramic pipes also indicate better drainage performance. However, during the period of 4600-3040 a BP, the development of ceramic pipe diameters showed a trend different from the complexity of society and the level of civilization.

Artifacts excavated from different areas vary in size and quality, with individuals in palace areas having higher social status and using larger and higher quality artifacts, while users in craft production and common residential areas, limited by social status, use relatively smaller and lower quality artifacts [47]. Therefore, we attempted to compare the sizes of Ceramic pipes by categorizing them into palace areas and common residential areas based on their excavation regions and time periods. Only one set of comparable ceramic pipe data is available from the Erlitou site. Ceramic pipes were found only in common residential areas at the Pingliangtai, Yanshishangcheng, and Anyangyinxu sites, while they were found only in palace areas at the Taosi. At the Zhengzhoushangcheng site, the time difference between the Ceramic pipes in the palace areas and those in the common residential areas is too large for comparison. The Erlitou site may exhibit a similar phenomenon. The Erlitou site may exhibit a similar phenomenon, with the average diameter of Ceramic pipes from palace areas (excavated from 3547 to 3530 a BP) being 20.03 cm, which is much larger than the 14.65 cm average diameter of those from common residential

Table 1 Geographic information for the ceramic pipe excavation sites

Sites	Site area	Topographic features	Bordering a mountain range	Riverine	Longitude and latitude
Pingliangtai site	50000m^2	Southern margin of the Yellow River alluvial fan		Western bank of Xincai River	33° 42′N, 114° 55′E
Taosi site	2800000m^2	Alluvial fan on the northwest slope of Taer Mountain	Northwest foothills of Taer Mountain	Nan River and Zhongliang Gully	35° 53′N, 111° 29′E
Erlitou site	3000000m^2	Yellow River alluvial fan plain	Southern foothills of Mang	Luo River and Yi River	34° 41′N, 112° 41′E
Zhengzhoushangcheng site	3000000m^2	Foothills and frontiers of the Yellow River alluvial plain	Northeast foothills of the residual ridges of Song Mountain	Suoxu River, Jialu River, Jinshui River, Xionger River, etc.	34° 44′N, 113° 40′E
Yanshishangcheng site	2000000m^2	Yellow River alluvial fan plain	Southern foothills of Mang Mountain	Luo River and Yi River	34° 43′N, 112° 45′E
Anyangyinxu site	3000000m^2	Alluvial plain at the foot of Taihang Mountains, front edge of Zhanghe alluvial fan, front edge of Huanhe alluvial fan	Eastern foothills of Taihang Mountain	Huang River, Zhang River, Qi River	36° 07′N, 114° 19′E

areas (excavated from 3507 a BP). This indicates that the use of Ceramic pipes in Erlitou culture might have been influenced by the social status and culture of the users. No other sites have yet provided comparable ceramic pipe data suitable for this kind of study.

Study on the adaptability of ceramic pipes to their usage environment

Comparative experiments, conducted by Li et al., on the chemical properties of ceramic pipes and fragments unearthed from Anyangyinxu indicate that the raw material of ceramic pipes might be a type of easily fusible clay. Alternatively, grass and wood ash might have been artificially added to sedimentary clay to reduce the porosity of ceramic pipes, thereby making them denser. This method prevented water seepage to a certain extent [48]. An analysis of the firing temperature of ceramics by Li revealed that the firing temperature of ceramic pipes unearthed from Anyangyinxu was also higher than that of contemporary pottery. The average firing temperature of ceramic pipes is 1002.5°C, whereas that of pottery is 969.5°C [49].

The aforementioned two experiments highlight the uniqueness of Ceramic pipes design concerning raw materials and firing temperatures. This unique finding underscores the importance of Ceramic pipes in the daily lives of urban residents. As early as 3040 a BP, designers of Ceramic pipes intentionally modified their raw materials and production techniques based on the usage environment. Lower permeability rates indicate greater drainage efficiency and more stable performance, which could be one of the reasons for the variation in ceramic pipe diameters; however, 3040 a BP was at the tail end of our study period, and these material changes and differences in firing temperature cannot explain the bimodal curve of diameter variation in earlier periods (Fig. 4a), nor can they explain why the ceramic pipe diameters from the Taosi site period were at the trough of the bimodal structure, but this does prove that potters adapted Ceramic pipes to their usage environments by altering material properties.

Climate change has significantly influenced the evolution of human societies [50, 51]. The Central Plains region serves as a transition zone between subtropical humid climates and warm temperate semi–humid climates and is a core area of ancient agricultural civilization, making social development in this area highly sensitive to climate change [13]. In adapting to climate change, innovations in production technology and improvements in resource allocation are relatively low-cost, low-risk strategic choices and thus often become the preferred choices for humans [52]. Consequently, we initially examined the correlation between changes in the diameters of ceramic pipes and climate change from a climate perspective.

Research on natural environmental changes and variations in ceramic pipes diameters

Analysis of temperature changes and ceramic pipes diameter variations

Given the high environmental sensitivity of ancient Chinese Ceramic pipes, we first analyzed the diameter variations of these pipes alongside the integrated Chinese precipitation curve to investigate this relationship. Pearson correlation analysis suggests that temperature variations might be one of the factors causing changes in the diameters of ceramic pipes ($R=0.72$, $P<0.01$). The most significant impact of temperature changes on ceramic pipe diameters occurs in winter. The direct impact of winter temperatures on the use of Ceramic pipes is that when temperatures drop below 0°C, the undrained water inside the pipes may freeze, causing blockage. Moreover, when the water temperature reaches 4°C, the water volume begins to expand [53]. Therefore, the expansion of water when it freezes puts additional pressure on the structure of the Ceramic pipes. In Henan Province, the average January temperature is −3°C, with extremely low temperatures reaching −23.6°C, necessitating design strategies to mitigate pipe freezing during the design stage. However, our analysis shows that freezing from low winter temperatures does not seem to have a direct impact on pipe diameter variations. The diameter of the Ceramic pipes shows a positive correlation with temperature changes, increasing with increasing temperature and decreasing with decreasing temperature. Smaller-diameter pipes are evidently less efficient at draining water than larger-diameter pipes and are less capable of handling the pressure from internal freezing.

The main reason for the lack of correlation between pipe diameter variations and winter temperatures is probably related to the seasonal distribution of precipitation in the region. As observed in the rainfall distribution in Anyang, Henan Province, over the past fifty years, most precipitation occurs in summer, with more than 90% of the annual rainfall falling in June, July, and August. [54] Thus, we initially examined the correlation between changes in ceramic pipe diameters and climate change. As shown in Fig. 5, there is a strong positive correlation between temperature and rainfall in this region ($R=0.75$, $P<0.01$). Hence, the positive correlation between ceramic pipes and temperature changes is likely due to synchronous changes in temperature and rainfall. Since the primary function of pottery water pipes was to discharge rainwater from courtyards, we propose that precipitation variations led to changes in their diameters from 4600-3040 a BP.

Study of topographic changes and changes in the diameter of ceramic pipes

The majority of urban sites from 4600 to 3040 a BP were located in piedmont areas combining mountainous and plain regions, predominantly in the alluvial fan landforms of the foothills. The advantageous water and soil conditions in the piedmont zones often render alluvial fans as hubs for human economic activities [55], becoming the core of plain agriculture [56]. Consequently, residential areas and farmlands were largely concentrated in these regions. The foothills alluvial fan areas possessed natural conditions conducive to the early development of cities, including abundant water resources, favorable land conditions, and reduced threats from natural disasters, which provided crucial support for the rise and development of ancient cities in the Central Plains region. The necessity of ensuring continued urban development naturally led to a demand for water resource management, thus prompting further enhancements in urban water conservancy systems.

The variation in terrain significantly influences the spatial distribution of precipitation, with heavy rain areas mainly located on the windward slopes of mountains, and the southeastern part of Shanxi Province serves as a high precipitation zone [57]. Consequently, we compared the diameters of ceramic pipes between the Erlitou site and Zhengzhoushangcheng site at 3507 a BP and between the Yanshishangcheng site and Zhengzhoushangcheng site at 3380 a BP. We observed that during the 3507 a BP period, the diameter of the ceramic pipes at the Erlitou site, which is situated in the southern foothills of Mangshan (14.65 cm), slightly exceeded that at the Zhengzhoushangcheng site, which is located in the northeastern foothills of the residual ridges of Songshan (13.5 cm). Conversely, during the 3380a BP period, the diameter of the ceramic pipes at the Yanshishangcheng site positioned in the southern foothills of Mangshan (28.25 cm) significantly surpassed that at the Zhengzhoushangcheng site situated in the northeastern foothills of the residual ridges of Songshan (19.95 cm). Thus, we postulate that the differential precipitation induced by terrain may likewise result in varied alterations in ceramic pipe diameters.

Relationship between precipitation changes and variations in ceramic pipe diameter

Due to the time scale constraints in the archaeological dating of artifacts mentioned previously, certain errors still exist in the Pearson correlation analysis, elucidating the relationship, between variations in ceramic pipe diameter and climate change. Therefore, further analysis was conducted by combining the results of paleoclimate studies at ceramic pipe excavation sites to validate the accuracy of the Pearson correlation analysis.

Relationship between ceramic pipe diameter and variations in precipitation at the Pingliangtai site

The Pingliangtai site in Huaiyang serves as a late Neolithic site of the Longshan culture in China, dating 4600–4180 a BP [20]. This period occurred towards the end of the Holocene warm period, characterized by a warm and humid climate. The subsequent period might have been affected by a 4200 a BP event, marked by enhanced fluctuations in precipitation, higher frequency of drought events, and flood events. Pollen records from the marginal areas of the monsoon indicated that the mid–Holocene period (8000–4000 a BP) was characterized by sufficient precipitation and a humid climate. However, precipitation gradually decreased, leading to drought conditions after 4000 a BP [58]. Pollen records, spanning approximately 7900–4450 a BP, from the central part of Lake Daihai in northern and central China, demonstrated extensive distribution of mixed forests comprising coniferous and broad-leaved trees. Thus, these records indicated a warm and humid climate during this period, with 4800-4450 a BP being considered the period with the best climate of the Holocene in northern and central China [59].

Extensive studies on ancient climates revealed that the early period of the Pingliangtai site was the period of optimum climate of the Holocene. During this stable and mild climate period, the late Neolithic cultures in the Central Plains region witnessed rapid development. The emergence of five coexisting cities, including the Wangchenggang site, Guchengzhai site, Puchengdian site, Pingliangtai site, and Taosi site, indicated prosperity. While the warm and humid climate facilitated the advancement of human society, it also posed the risk of floods due to excessive rainfall. During this period, different cultures devised a range of water management facilities to protect buildings and residents against floods. The Pingliangtai site was at the forefront of China's earliest ceramic pipe technology to mitigate urban water disasters. Settlements with moats, such as the Haojiatai site, Wangchenggang site, and Xinzha site abandoned tall city walls prone to waterlogging in favor of moats that facilitated wastewater drainage [60].

The ceramic pipes unearthed from the Pingliangtai site represent the earliest known pipes discovered so far. The records indicated diameters for a total of 20 ceramic pipes unearthed. A comparison with ceramic pipes from other sites revealed that the sizes of the ceramic pipes at Pingliangtai site were larger than those used at other sites such as Taosi site (10–13.75 cm), Erlitou site (13.5–27.8

cm), and Yinxu (13.7–30 cm). This observation is also related to the fact that the Pingliangtai site was located during the optimum climate period of the Holocene. Among the ceramic pipes unearthed from the Pingliangtai site, those used in Phase II exhibited a larger diameter, averaging around 27.5 cm, while those used in Phase III exhibited smaller diameters, ranging from 21 to 27.5 cm. The decrease in diameter from Phase II to Phase III reflects changes in precipitation during this period.

Relationship between ceramic pipe diameter and variations in precipitation at the Taosi site

The Taosi site is one of the largest-scale sites of the Longshan Culture, dating between 4300 and 3900 a BP [61]. The 4200 a BP climate anomaly event has been the most notable climatic event since the Holocene, leading to a wet climate in central and southern China [62, 63]. Northern China experienced reduced rainfall due to the weakening of the East Asian Summer Monsoon (EASM) caused by the influence of summer insolation in the Northern Hemisphere [40, 64, 65]. Northern China was generally in a drought state during this period [66, 67]. Pollen records from Lake Duck in northern China reveal a “dry-wet-dry” hydroclimatic pattern during the 4200 a BP climate anomaly period [68]. High-resolution stalagmite $\delta^{18}O$ records from Wuya Cave in the Asian summer monsoon marginal zone indicate a pattern of “weak-strong-weak” intensity of the Asian summer monsoon during the 4200 a BP climate anomaly period [69]. Northern China also experienced extreme rainfall events during this period of overall drought, resulting in floods at approximately 4200–4000 a BP [69]. The floods during the 4200a BP event had a significant impact on human societal development during that period, leading to a substantial reduction in the number of human settlements [7, 70]. Many settlements were relocated to higher elevations to escape flooding and construct fortifications [71, 72], which even directly led to the destruction of the Liangzhu culture located in the lower reaches of the Yangtze River [73]. Similarly, the late period of the Taosi site was also affected by floods, with certain sections of the outer city walls being destroyed by floods. The remains of two major flood diversion channels were also found in the late period of the Taosi site [74].

The late period of the Taosi site was significantly affected by the intense influence of the 4200a BP event, during which the climate exhibited a trend toward dry and cold compared to the Holocene warm period, resulting in a corresponding increase in the proportion of xerophytic herbaceous plants [75]. During the middle period of the Taosi culture, the climate was warm and humid, characterized by abundant trees, few shrubs and herbs, more broad–leaved trees, fewer conifers, and the development of mixed forests with subtropical plant components. In the late stage of the Taosi period, the climate began to deteriorate, with noticeable climate fluctuations. Wet periods may have witnessed concentrated heavy rainfall, but the duration of dry climates was long, mainly characterized by cool and dry conditions. The proportion of woody plants decreased, while that of herbaceous plants increased. There were fewer Artemisia species and more Chenopodiaceae, transitioning from forest grasslands to sparse tree grassland vegetation [76].

During the nearly thousand-year span from the Pingliangtai site to the third phase of the Erlitou site, only two ceramic pipes were discovered in Chinese archaeological sites, both from the late stage of the Taosi culture.This period, influenced by the 4200 a BP event, was marked by extreme droughts and rainfall events causing widespread floods. Under the influence of this extreme drought, the diameter of the unearthed ceramic pipes at the Taosi site was only 10–13.75 cm, with an average of 11.875 cm, and both the size and quantity were the lowest among the ceramic pipes unearthed from 4600 to 3040 a BP. However, the frequent occurrence of extreme rainfall and flood events during this period did not lead to an increase in the diameter of the ceramic pipes at the Taosi site. The first reason is that the drainage effect of ceramic pipes is limited during urban waterlogging. In the late stage of the Taosi period, the climate fluctuated significantly, with short wet periods, concentrated rainfall leading to flood events, and long drought periods, which were generally dominated by cold and dry conditions. [76] However, under prolonged drought conditions, there is not much demand for large ceramic pipes. Additionally, during large–scale flood events, the size of ceramic pipes has a relatively low impact on rapid drainage. Therefore, there is no need to produce larger drainage pipes to assist in drainage. The second reason is the design of large-scale drainage systems. Under these climatic conditions, different civilizations adopted various drainage measures. There are records of abnormal flood events at sites such as Haojiatai, Wangchenggang, Xinzhai, and Taosi during the period of 4150-3800 a BP, but ceramic pipes were only unearthed at the Taosi site. The flood prevention strategy of the Haojiatai and Wangchenggang city sites was to abandon the city walls and raise the surface height inside the city, with an elevation 1–1.5 ms higher inside than outside the city, to facilitate rapid drainage of water while constructing ditches outside the city for drainage. This change in drainage protected their city sites until the Dongzhou period [77]. The Xinzhai site chose to construct a large moat for drainage outside the city walls due to flooding and expanded the moat three times after it was blocked [78]. The abandonment of tall city walls prone to waterlogging and the use of moats conducive to flood drainage allowed the Haojiatai, Wangchenggang, and Xinzhai periods to persist for a long time. This change in flood management methods rendered ceramic water pipes unnecessary for drainage. Consequently, following the 4200 a BP event, most archaeological sites in China ceased using ceramic pipes after the Pingliangtai site. Only two were found at the Taosi site, with sizes of 10–13.75 cm. ceramic pipes did not see widespread use again until the Erlitou site.

As shown in Fig. 3, the excavation time of ceramic pipes from the Taosi site is around 4000 a BP. This closely coincides with the low precipitation period (3996 a BP) recorded by stalagmites from the Jiuxian cave during the 4200 a BP event. However, a discrepancy in timing was observed compared to the lowest recorded precipitation points (namely, 4233 a BP, 3813 a BP, 3803 a BP and 4250 a BP) from the Magou cave stalagmites, Xianglong cave stalagmites, Lianhua cave stalagmites and the integrated precipitation curve of China. This discrepancy could be attributed to significant regional differences in response to the 4200 a BP event. This event occurred globally approximately during 4200-3900 a BP [79, 80]. The analysis of pollen records from the Taosi site revealed that the occurrence of the 4200 a BP event in the Taosi site took place at a later period, around 4000 a BP. The late phase of the Taosi culture experienced an extremely dry climate due to the influence of the 4200 a BP event, resulting in the unearthing of ceramic pipes, with the smallest sizes observed among those unearthed throughout millennia. In the late Taosi period, due to the extremely arid climate influenced by the 4200 a BP time, and the large–scale floods caused by extreme rainfall events, under the influence of this complex climatic environment, the ceramic pipes were unable to cope with all kinds of heavy precipitation and large-scale floods, and due to the upgrading of the urban water system, the ceramic pipes were only an auxiliary tool of the water system during this period, so that the ceramic pipe dimensions during this period were the lowest in the millennial scale and were used sparingly.

Relationship between ceramic pipe diameter and precipitation changes at the Erlitou site and Sites of the Shang Dynasty

Figure 4 illustrates that from the end of the 4200 a BP event until 3000 a BP, precipitation continued to decrease, but generally remained relatively stable without extreme climatic events. During these stable climatic conditions, the usage rate of ceramic pipes further increased. Additionally, 64 ceramic pipes with diameters ranging from 13.5 to 30 cm, with an average diameter of 20.66 cm, were unearthed. Among them, 58 ceramic pipes had diameters ranging from 15 to 25 cm.

As shown in Fig. 4, the early precipitation at the Erlitou site had already returned to levels comparable to those before the 4200 a BP climate event. Pollens collected from cultural layers during the period 4000-3600 a BP also suggested sufficient early precipitation at the Erlitou site. From the late period of the Henan Longshan culture to the fourth phase of the Erlitou site, the proportion of herbaceous plants was higher than that of woody plants. Except for pine, all the woody plants were deciduous broad–leaved trees. The pollen content of broad-leaved trees exhibited a decreasing trend in the later period. The climate at the Erlitou site changed gradually from warm and humid to dry and cold [44]. The diameter of ceramic pipes unearthed from the Erlitou site also indicated the climate change pattern [81]. During Erlitou phase III, 14 ceramic pipes were unearthed with diameters ranging from 17.8 to 27.8 cm (average = 20.1 cm). The diameter of ceramic pipes was significantly higher than that of earlier pipes unearthed from the Taosi site, almost close to the diameter of ceramic pipes from the third phase of Pingliangtai. During Erlitou phase IV, the diameter of ceramic pipes further decreased to only 13.5–15.3 cm, with an average of 14.26 cm. This change in ceramic pipe diameter also indicated the pattern of dry climate at the Erlitou site.

The Yanshishangcheng site, the Zhengzhoushangcheng site in the central and northern parts of Henan Province, the Anyangyinxu site in the northern part of Henan Province, and the Panlongcheng site in Hubei Province belong to the cultural sites of the Shang Dynasty in China. Archaeology divides the Shang Dynasty culture into early and late cultures; the Erligang culture represents the early culture and the Yinxu culture represents the late culture. The analysis of pollens from the Erligang period revealed that the lower layers of Erligang were predominantly herbaceous pollen, including Chenopodiaceae, Poaceae, Asteraceae, and Cucurbitaceae. This suggested a relatively dry and cold climate at that time, with slowly increasing temperatures. The upper layers of Erligang primarily comprised pollens from trees such as pine, birch, liquidambar, oak, willow, and walnut, indicating a subtropical nature of the climate at that time. This climate was warmer and more humid compared to the lower layers of Erligang [82]. From the lower layer of Erligang, 5 ceramic pipes, with diameters ranging from 13.5 to 22.8 cm and an average of 17.84 cm, were unearthed. From the upper layer of Erligang, 5 ceramic pipes, with diameters ranging from 17.1 to 30 cm and an average of 22.7 cm, were unearthed. The changes in the diameter of ceramic pipes during this period broadly reflected the change in the climate from dry to humid during the Erligang period.

The climate during the late Shang Dynasty exhibited significant fluctuations, characterized by both dry and wet periods. Based on the ecological climate reconstruction results from the natural profiles of pollens and charcoal, the climate at the end of the Yinxu II period was relatively dry, with an average precipitation of 620.9 mm. The climate transitioned to a humid phase during the Yinxu III period, with an increase in precipitation to 624.7 mm. During the start of the Yinxu IV period, it entered a fully humid phase, with precipitation rapidly increasing to 639 mm. During the late stage represented by the Yinxu IV period, the average precipitation rapidly increased to 677.9 mm, and the climate in the later stage of the late Shang Dynasty returned to a humid phase [83]. A total of 38 ceramic pipes were unearthed from Yinxu; all dating to the late period. In the third period, 9 ceramic pipes, with diameters ranging from 16.25 to 19 cm, were unearthed. Similarly, in the fourth period, 29 ceramic pipes were unearthed, with diameters ranging from 21.3 to 25 cm. The trend of variation in the diameter of ceramic pipes during this period also closely aligned with the change in precipitation from dry to wet.

A comparison of ceramic pipe diameters with precipitation records from excavated sites indicated a significant correlation between the complex variations in ceramic pipe diameters and precipitation changes. During periods of abundant precipitation, humans would increase the diameter of ceramic pipes for effective protection of the rammed earth foundations of buildings from rainwater damage, thereby ensuring rapid drainage of rainwater. During drier periods, influenced by resource scarcity and social unrest, humans would reduce the diameter and number of ceramic pipes for the conservation of ceramic materials while ensuring normal operations of the water management system and maximizing resource utilization.

Similarly, the study identified anomalies that deviated from the expected pattern of precipitation changes. This deviation could be attributed to the fact that the production and use of ceramic pipes spanned centuries, during which the precipitation levels fluctuated. The ceramic pipes produced during wetter periods would have larger diameters compared to those produced during drier periods. Moreover, ceramic pipes are buried beneath the ground and typically covered by walls and buildings, making their replacement complicated. In such cases, as long as ceramic pipes could retain their normal function, they remained in use. Therefore, the occurrence of anomalous data, which cannot perfectly correlate with precipitation levels during the period of ceramic pipe production, does not affect our hypothesis that precipitation was the major driving factor for changes in ceramic pipe diameters.

Conclusions and perspective

By excavating 86 ceramic pipes from 4600 to 3040 a BP and comparing them with the $\delta^{18}O$ records of stalagmites from Magou cave in Henan Province, Jiuxian cave and Xianglong cave in Shaanxi Province, and Lianhua cave in Shanxi Province, as well as the integrated temperature and precipitation curves of China from 4600 to 3040 a BP, we found that the development of ceramic pipe diameter during this period exhibited different trends corresponding to the complexity and civilization level of society. This study revealed a strong correlation between changes in the diameter of ceramic pipes and climate change. The results offer new perspectives and insights for understanding the design and development of ancient urban water management systems. This research is imperative for promoting the development of related fields and addressing practical challenges. It also offers valuable insights and suggestions for future research and practice. The design insights for adapting to changes in the natural environment carry significant learning value for the sustainable development of humanity in the future. In contrast, our research revealed that over nearly a thousand years, precipitation changes dominated the evolution of ceramic pipe size. Differences in precipitation caused by different terrains were also detected among the potters during that period, leading to different changes in ceramic pipe diameter. This indicates the long-term adaptive behavior of ancient Chinese people in response to different natural environments and climate changes. Four thousand years ago, urban planners consciously incorporated climate conditions as a primary consideration factor in the design of urban water systems and adjusted the design of water systems according to different climatic scenarios to ensure the sustainable development of cities. Furthermore, we discovered that in the Erlitou culture, the diameter of ceramic pipes was influenced by the social status of the users; higher-status individuals used larger pipes. This indicates greater social stratification compared to earlier periods. In Erlitou society, ceramic pipes were important symbols of status, but this phenomenon was observed only at the Erlitou site. Thus, on a millennial scale, precipitation changes remained the main factor affecting the diameter of ceramic pipes.

This study revealed a significant finding, which was the strong correlation between the changes in the diameter of ceramic pipes and climate change. The results offer new perspectives and insights for understanding the design and development of ancient urban water management systems. This research becomes imperative for promoting the development of related fields and addressing practical challenges. It also offers valuable insights and suggestions for future research and practice. The design insights for adapting to changes in the natural environment carry significant learning value for the sustainable development of humanity in the future.

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Author contributions
Conceptualization, S.W and Y.T; methodology, S.W and X.Z; validation, X.Z, and Y.T; formal analysis, Y.T; resources, S.W and X.Z; data curation, S.W; writing original draft preparation, S.W; writing review and editing, S.W and Y.T; visualization, S.W; supervision, Y.T; funding acquisition, Y.T. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials
The data used in this research are published in this paper, and they are all available from the corresponding author upon reasonable request. Chinese precipitation composite curve and Chinese temperature composite curve are available from the National Earth System Science Data Center (NESDC) and the National Platform for Science and Technology Infrastructure (NPSTI). (http://www.geodata.cn). The stalagmite data from Magou Cave are available from the East Asian Paleoenvironmental Science Database (http://paleodata.ieecas.cn/index.aspx), and the carbon and oxygen isotope dataset of stalagmites from Jiuxian Cave is available from [17]. The carbon and oxygen isotope dataset of stalagmites from Xianglong Cave is available from [18], and the carbon and oxygen isotope dataset of stalagmites from Lianhua Cave was provided by Dong, J, author of [16]. All data required for the conclusions of this paper have been provided in the text.

Declarations

Competing interests
The authors declare no Competing interests.

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References

1. Yin J, Su Y, Fang X. Climate change and social vicissitudes in China over the past two millennia. Quat Res. 2016;86(2):133–43. https://doi.org/10.1016/j.yqres.2016.07.003.
2. Zhang Z, Tian H, Cazelles B, Kausrud KL, Bräuning A, Guo F, et al. Periodic climate cooling enhanced natural disasters and wars in China during AD 10–1900. Quat Res. 2010;277(1701):3745–53. https://doi.org/10.1098/rspb.2010.0890.
3. Lee HF, Fok L, Zhang DD. Climatic change and Chinese population growth dynamics over the last millennium. Clim Chang. 2008;88(2):131–56. https://doi.org/10.1007/s10584-007-9329-1.
4. Zhang D, Jim C, Lin C, He Y, Lee F. Climate change, social unrest and dynastic transition in ancient China. Chin Sci Bull. 2005;50:137–44. https://doi.org/10.1007/BF02897517.
5. Liu Y, An Z, Linderholm HW, Chen D, Song H, Cai Q, et al. Annual temperatures during the last 2485 years in the mid-eastern Tibetan Plateau inferred from tree rings. Sci China Series D Earth Sci. 2009;52(3):348–59. https://doi.org/10.1029/2022EA002777.
6. Pei Q, Zhang DD. Long-term relationship between climate change and nomadic migration in historical China. Ecol Soc. 2014. https://doi.org/10.5751/ES-06528-190268.
7. Li Z, Zhu C, Wu G, Zheng C, Zhang P. Spatial pattern and temporal trend of prehistoric human sites and its driving factors in Henan Province, Central China. J Geogr Sci. 2015;25:1109–21. https://doi.org/10.1007/s11442-015-1222-7.
8. Li S, Ding K, Ding A, He L, Huang X, Ge Q, et al. Change of extreme snow events shaped the roof of traditional Chinese architecture in the past millennium. Sci Adv. 2021;7(37):eabh2601. https://doi.org/10.1126/sciadv.abh2601.
9. Du J. The archaeological discoveries and the values of the water-control historic heritages in the capital settlements of the Xia and Shang Dynasties. Archaeology. 2016;1:88–102+2 (**in Chinese**).
10. Yuling H. Huanbei Shang city and Yinxu waterway systems and related issues. Archaeology. 2021;9:82–94+2 (**in Chinese**).
11. Baoling S. Pauling sebillaud sewerage facilities in the central Plains of China around 2000 B. C. Stories Relics. 2016;1:3–12 (**in Chinese**).
12. Zhang X. Study of water supply and drainage in cities and settlements of the Shang Period. Huaxia Archaeol. 2015;1:53–62 (**in Chinese**).
13. Cai Y, Cheng X, Ma L, Mao R, Breitenbach SF, Zhang H, et al. Holocene variability of East Asian summer monsoon as viewed from the speleothem $\delta^{18}O$ records in central China. Earth Planetary Sci Lett. 2021;558(1–4): 116758. https://doi.org/10.1016/j.epsl.2021.116758.
14. Zhao Y. National temperature integration curve for the last 22 ka (20,000 B. C–2000 A. D). https://doi.org/10.12041/geodata.70190551261470.ver1.db.
15. Zhao Y. National precipitation integration curve for the last 22 ka (20,000 B.C. to 2000 A.D.). https://www.geodata.cn/main/#/face_science_detail?id=57939 &guid=49812447714395.
16. Dong J, Shen CC, Kong X, Wang HC, Jiang X. Reconciliation of hydroclimate sequences from the Chinese loess plateau and low-latitude east Asian summer Monsoon regions over the past 14,500 years. Palaeogeogr Palaeoclimatol Palaeoecol. 2015;435(127–135):21–31.
17. Cai Y, Tan L, Cheng H, An Z, Edwards RL, Kelly MJ, et al. The variation of summer monsoon precipitation in central China since the last deglaciation. Earth Planetary Sci Lett. 2010;291(1–4):21–31. https://doi.org/10.1016/j.epsl.2009.12.039.
18. Tan L, Li Y, Wang X, Cai Y, Lin F, Cheng H, et al. Holocene monsoon change and abrupt events on the western Chinese loess plateau as revealed by accurately dated stalagmites. Geophys Res Lett. 2020;47(21):e2020GL090273. https://doi.org/10.1029/2020GL090273.
19. Cao G. Pottery Yan and pottery water pipe unearthed at the longshan culture city site in Pinggiantai. Huaiyang Huaxia Archaeol. 1991;2:111–2 (**In Chinese**).
20. Cao G, Ma Q. Briefing on the trial excavation of longshan culture City Site in Pingliangtai, l Huaiyang, Henan Province. Herit conservat. 1983;3:21–36+99 (**in Chinese**).
21. He N, editor. Taosi Wuhua Taosi Ruins Unearthed Artifacts Overview. Shanghai: Science Press; 2022. (**In Chinese**).
22. Institute of Archaeology Chinese Academy of Social Sciences. The Erlitou site in Yanshi excavations in 1959–1978. Beijing: Encyclopedia of China Publishing House; 1999. (**in Chinese**).
23. Henan province Institute of Cultural Relics and Archaeology. Zhengzhoushangcheng—reports on archaeological excavations, 1953–1985. Beijing: Cultural Relics Press; 2001. (**in Chinese**).
24. Hubei Provincial Institute of Cultural Relics and Archaeology. Panlong City: archaeological excavation reports 1963–1994. Beijing: Cultural Relics Press; 2001. (**in Chinese**).
25. Wang X. Excavation briefing on the site of building complex No.2 of Yanshi Shang City. Archaeology. 1995;11:963–78 (**in Chinese**).
26. Institute of Archaeology. Chinese academy of social sciences. Discovery and study of Yin xu. Shanghai: Science Press; 1994. (**in Chinese**).
27. Institute of Archaeology, Chinese Academy of Social Sciences. Excavation of Yinxu 1958–1961. Beijing: Cultural Relics Press; 1987. (**in Chinese**).

28. Institute of Archaeology, Chinese Academy of Social Sciences. Dasikong in anyang report of the excavation in 2004. Beijing: Cultural Relics Press; 2014. (**in Chinese**).
29. Wang YJ, Cheng H, Edwards RL, An Z, Wu J, Shen CC, et al. A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave. China Sci. 2001;294(5550):2345–8. https://doi.org/10.1126/science.1064618.
30. Cheng H, Edwards RL, Wang Y, Kong X, Ming Y, Kelly MJ, et al. A penultimate glacial monsoon record from Hulu Cave and two-phase glacial terminations. Geology. 2006;34(3):217–20. https://doi.org/10.1130/G22289.1.
31. Cheng H, Edwards RL, Broecker WS, Denton GH, Kong X, Wang Y, et al. Ice age terminations. Science. 2009;326(5950):248–52. https://doi.org/10.1126/science.1177840.
32. Zhang N, Yang Y, Cheng H, Zhao J, Yang X, Liang S, et al. Timing and duration of the East Asian summer monsoon maximum during the Holocene based on stalagmite data from North China. Holocene. 2018;28(10):1631–41. https://doi.org/10.1177/0959683618782606.
33. Pausata FS, Battisti DS, Nisancioglu KH, Bitz CM. Chinese stalagmite $\delta^{18}O$ controlled by changes in the Indian monsoon during a simulated Heinrich event. Nat Geosci. 2011;4(7):474–80. https://doi.org/10.1038/ngeo1169.
34. Liu Z, Wen X, Brady E, Otto-Bliesner B, Yu G, Lu H, et al. Chinese cave records and the East Asia summer monsoon. Quat Sci Rev. 2014;83:115–28. https://doi.org/10.1016/j.quascirev.2013.10.021.
35. Johnson KR, Ingram BL. Spatial and temporal variability in the stable isotope systematics of modern precipitation in China: implications for paleoclimate reconstructions. Earth Planetary Sci Lett. 2004;220(3–4):365–77. https://doi.org/10.1016/S0012-821X(04)00036-6.
36. Ming T. Circulation effect: climatic significance of the short term variability of the oxygen isotopes in stalagmites from monsoonal China—dialogue between paleoclimate records and modern climate research. Quat Sci. 2009;29:851–62 (**in Chinese**).
37. Maher BA, Thompson R. Oxygen isotopes from Chinese caves: records not of monsoon rainfall but of circulation regime. J Quat Sci. 2012;27(6):615–24. https://doi.org/10.1002/jqs.2553.
38. Zhang P, Cheng H, Edwards RL, Chen F, Wang Y, Yang X, et al. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. Science. 2008;322(5903):940–2. https://doi.org/10.1126/science.1163965.
39. Wang Y, Cheng H, Edwards RL, He Y, Kong X, An Z, et al. The Holocene Asian monsoon: links to solar changes and North Atlantic climate. Science. 2005;308(5723):854–7. https://doi.org/10.1126/science.1106296.
40. Cheng H, Wang X, Wang Y, Kong X, Yuan D, Zhang M, et al. Oxygen isotope records of stalagmites from Southern China. Quat Sci. 2005;25(2):157–63.
41. Tan M. Circulation background of climate patterns in the past millennium: Uncertainty analysis and re-reconstruction of ENSO-like state. Sci China Earth Sci. 2016;59:1225–41. https://doi.org/10.1007/s11430-015-5256-6.
42. Zhang DD, Lee HF, Wang C, Li B, Pei Q, Zhang J, et al. The causality analysis of climate change and large-scale human crisis. Proc Natl Acad Sci. 2011;108(42):17296–301. https://doi.org/10.1073/pnas.1104268108.
43. Liu L, Chen X, Wright H, Xu H, Li Y, Chen G, et al. Rise and fall of complex societies in the Yiluo region, North China: the spatial and temporal changes. Quat int. 2019;521:4–15. https://doi.org/10.1016/j.quaint.2019.05.025.
44. Pan M. The main and accompanying capitals of the early Shang Dynasty as seen from the relationship between Zhengzhou Mall and Yanshi Mall. Archaeology. 2008;2:55–63+2 (**in Chinese**).
45. Yang Y. Revisiting the age, nature and related issues of Zhengzhou mall. Huaxia Archaeol. 2004;3:52–70 (**in Chinese**).
46. Tang J, Jing Z. Reviewing the Yinxu Archaeology on Its 90th anniversary: from "great settlement Shang" to world cultural heritage. Archaeology. 2018;10:3–21+2 (**in Chinese**).
47. Deng L, Cao H, Tian M, Chen G, Gu F. Quantitative analysis of the degree of standardization of pottery dimensions: an example of a large-mouthed Zun from the Yanshi Shangcheng site. J Natl Museum China. 2022;5:124–33 (**in Chinese**).
48. Li N, Li Q, Guo Z, He Y, Yue H, Yue Z. A comparative study of ceramic water pipe and ceramic tile excavated from Anyang Yinxu in Henan. J Instrument Anal. 2008;9:936–41 (**in Chinese**).
49. Li Q. A study on the producing technics of 'ceramic water pipes' from Yinxu site. Jianghan Archaeol. 2011;2:103–7 (**in Chinese**).
50. Kennett DJ, Kennett JP. Competitive and cooperative responses to climatic instability in coastal southern California. Am Antiq. 2000;65(2):379–95. https://doi.org/10.2307/2694065.
51. Field JS, Lape PV. Paleoclimates and the emergence of fortifications in the tropical Pacific islands. J Anthropol Archaeol. 2010;29(1):113–24. https://doi.org/10.1016/j.jaa.2009.11.001.
52. Wenxiang W, Quansheng G. 4.5–4.0 kaB.P. climate change, population growth, circumscription and the emergence of chiefdom-like societies in the middle-lower yellow river valley. Quat Sci. 2014;34(1):253–65. https://doi.org/10.3969/j.issn.1001-7410.2014.29.
53. Akyurt M, Zaki G, Habeebullah B. Freezing phenomena in ice-water systems. Energy Convers Manag. 2002;43(14):1773–89. https://doi.org/10.1016/S0196-8904(01)00129-7.
54. Xu C, Feng X, Shen Z. Spatial and temporal distribution of rainfall characteristics of Henan Province. J Anhui Agric Sci. 2014;42(25):8655–9 (**in Chinese**).
55. Department of Economic Geography. Chinese academy of sciences. general introduction to Chinese agricultural geography. Institute of geography. Beijing: Science Press; 1980. (**in Chinese**).
56. Yang J, Li Y, editors. Principles of geomorphology. Beijing: Peking University Press; 2001. (**in Chinese**).
57. Li Y, Zhi H, Zhang D. Analysis of temporal and spatial distribution and large-scale circulation features of extreme weather events in Shanxi Province, China in recent 30 years. J Geosci Environ Protect. 2019;7(3):160–76. https://doi.org/10.4236/gep.2019.73009.
58. Zhao Y, Yu Z. Vegetation response to Holocene climate change in East Asian monsoon-margin region. Earth-Sci Rev. 2012;113(1–2):1–10. https://doi.org/10.1016/j.earscirev.2012.03.001.
59. Xiao J, Xu Q, Nakamura T, Yang X, Liang W, Inouchi Y. Holocene vegetation variation in the Daihai Lake region of north-central China: a direct indication of the Asian monsoon climatic history. Quat Sci Rev. 2004;23(14–15):1669–79. https://doi.org/10.1016/j.quascirev.2004.01.005.
60. Li L. A test analysis of the phasing and dating of Longshan-era city sites in the Central Plains region. Cult Relics Southern China. 2022;2:190–200+168 (**in Chinese**).
61. He N. A comprehensive study of Taosi culture pedigree. Archaeol Collectanea. 2006;0:151–77 (**in Chinese**).
62. Wenxiang W, Tungsheng L. Possible role of the "Holocene Event 3" on the collapse of neolithic cultures around the central plain of China. Quat Int. 2004;117(1):153–66. https://doi.org/10.1016/S1040-6182(03)00125-3.
63. Hu C, Henderson GM, Huang J, Xie S, Sun Y, Johnson KR. Quantification of Holocene Asian monsoon rainfall from spatially separated cave records. Earth Planetary Sci Lett. 2008;266(3–4):221–32. https://doi.org/10.1016/j.epsl.2007.10.015.
64. Zhang H, Ait Brahim Y, Li H, Zhao J, Kathayat G, Tian Y, et al. The Asian summer monsoon: teleconnections and forcing mechanisms—a review from Chinese speleothem δ18O records. Quaternary. 2019;2(3):26. https://doi.org/10.3390/quat2030026.
65. Tan L, Li Y, Wang X, Cai Y, Lin F, Cheng H, et al. Holocene monsoon change and abrupt events on the western Chinese loess plateau as revealed by accurately dated stalagmites. Geophys Res Lett. 2020;47(21):e2020GL090273. https://doi.org/10.1029/2020GL090273.
66. Yang X, Scuderi LA, Wang X, Scuderi LJ, Zhang D, Li H, et al. Groundwater sapping as the cause of irreversible desertification of Hunshandake Sandy Lands, Inner Mongolia, northern China. Proc Natl Acad Sci. 2015;112(3):702–6. https://doi.org/10.1073/pnas.1418090112.
67. Xiao J, Zhang S, Fan J, Wen R, Zhai D, Tian Z, et al. The 4.2 ka BP event: multi-proxy records from a closed lake in the northern margin of the East Asian summer monsoon. Climat Past. 2018;14(10):1417–25. https://doi.org/10.5194/cp-14-1417-2018.
68. Wang H. How to bridge the paleoclimate to present climate studies? J Earth Sci. 2022;47(10):3811–2 (**in Chinese**).
69. Tan L, Shen CC, Cai Y, Cheng H, Edwards RL, et al. Great flood in the middle-lower Yellow River reaches at 4000 a BP inferred from accurately-dated stalagmite records. Sci Bull. 2018;63(4):206–8. https://doi.org/10.1016/j.scib.2018.01.023.
70. Liu J. Preliminary exploration of prehistoric water control civilization in China. Cult Relics South. 2021;6:5–11 (**in Chinese**).

71. Wang T, Li D, Cheng X, Lan J, Edwards RL, Cheng H, et al. Hydroclimatic changes in south-central China during the 4.2 ka event and their potential impacts on the development of Neolithic culture. Quat Res. 2022;109:39–52. https://doi.org/10.1017/qua.2022.11.
72. Zeng M, Ma C, Zhu C, Song Y, Zhu T, He K, et al. Influence of climate change on the evolution of ancient culture from 4500 to 3700 cal. yr BP in the Chengdu Plain, upper reaches of the Yangtze River. China Catena. 2016;147:742–54. https://doi.org/10.1016/j.catena.2016.08.028.
73. Zhang H, Cheng H, Sinha A, Spötl C, Cai Y, Liu B, et al. Collapse of the Liangzhu and other Neolithic cultures in the lower Yangtze region in response to climate change. Sci Adv. 2021;7(48):eabi9275. https://doi.org/10.1126/sciadv.abi9275.
74. He N. Water use and water control at the Taosi site. Palace Museum J. 2019;11:85–98+111 (**in Chinese**).
75. Yao Z, Wu Y, Wang C, He N, Zhao Z. Analysis of phyllosilicates from the Taosi site, Xiangfen, Shanxi. Agric Archaeol. 2006;4:19–26 (**in Chinese**).
76. He N, editor. Taosi: the beginning of the formation of the core of China civilization. Shanghai: Shanghai Classics Publishing House; 2022. (**in Chinese**).
77. Liang F, Zhang H, Li W, Liu C, Wu L, Quan P, et al. Major achievements in the 2015–2016 Field Archaeology on the Haojiatai Site in Luohe City. Henan Province Huaxia Archaeol. 2017;3:14–49 (**in Chinese**).
78. Zhao C, Zhang S, Xie S, Zhang J, Wei X. Excavation of the Eastern City-wall of the Xinzhai Site in Xinmi City, Henan. Archaeol. 2009;2:16–31 (**in Chinese**).
79. Anderson DG, Maasch KA, Mayewski PA. Chapter 1—climate and culture change: exploring Holocene transitions. In: Anderson DG, Maasch KA, Sandweiss DH, editors. Climat Change Cult Dynam. San Diego: Academic Press; 2007. p. 1–23.
80. Wang S, Zhang Y, Wang N, Huang C, Zhu Y, Huang X, et al. Relationship between the transition of Longshan culture-Erlitou culture and the hydro-climatic in the Luoyang basin. Earth Science. 2023;1–19. (In Chinese).
81. Song Y, Zheng G, Han Y, Wu Y. Information on the environments of the Erlitou Site in Yanshi city. Henan Archaeol. 2002;12:75–9 (**in Chinese**).
82. Song G, Jiang Q. Analysis report on spore pollen and phytolith in Zhenzhou City of Shang Dynasty. In: Zhou K, editor. Environ Archaeol Res Series II. Beijing: Science Press; 2000. p. 180–7 (**in Chinese**).
83. Wang S, Yue H, Yue Z. Ecological reconstruction of high resolution in the Yin-Shang period. Cult Relics South China. 2016;2:148–57 (**in Chinese**).