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Settlement adaptation and social evolution under mid-holocene environmental duress in the Yellow River Basin

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ABSTRACT

This study aims to elucidate the adaptation mechanisms of prehistoric settlements in the Yellow River Basin to extreme climate events spanning from the pre-Yangshao period (9.0–7.0 cal. ka BP) to the Bronze Age (4.0–2.0 cal. ka BP). By integrating archaeological site data with ancient environmental records and employing spatial statistical methods such as kernel density estimation and nearest neighbor analysis, this research reconstructs the spatial and temporal evolution of settlement patterns under climate stress. Furthermore, it discusses the relationship between these patterns and natural disasters, uncovering the mechanisms of human-land interaction and the adaptive strategies that shaped regional resilience during periods of environmental stress. The results reveal three key findings. Firstly, the distribution of settlements exhibits significant spatial differentiation; while the middle reaches consistently maintained high density, a secondary core emerged in the upper Hehuang Valley during the Yangshao period. Secondly, settlement patterns demonstrate simultaneous trends of expansion in scale and reduction in number, indicating an increase in social complexity and stratification, which laid the groundwork for early state formation. Thirdly, the selection of settlement sites reflects clear climate adaptation: the average elevation rose by 56.98 m from the Yangshao to Longshan periods, and the proportion of settlements located farther from water sources increased by 12.3 % during the late Longshan period, strongly correlating with flood sediment records. Additionally, erosion and sedimentation in downstream areas provided fertile land, playing a crucial role in sustaining social development. This study illustrates that mid-Holocene climate variability, particularly in the form of intensified flooding and environmental pressures, drove adaptive strategies such as elevation migration and spatial differentiation. These dynamics, coupled with emerging sociopolitical structures, facilitated the rise of early complex societies in the middle and lower Yellow River Basin.

1. Introduction

The dynamic interplay between prehistoric human development and mid-Holocene environmental change has emerged as a central research focus across archaeology, paleoclimatology, and environmental history (Chen et al., 2015b; Kawahata et al., 2009; Kidder et al., 2018; Su et al., 2025; Wang et al., 2024; Weiss et al., 1993),. Growing evidence suggests that prehistoric settlement dynamics were shaped not only by resource availability but also significantly influenced by climate variability—particularly in regions where human–land interactions were highly sensitive to environmental stressors (An et al., 2005; Dong et al., 2017; Staubwasser and Weiss, 2006). These dynamics are particularly pronounced during the Holocene (Jiang et al., 2025a), a period characterized by alternating phases of climatic stability and abrupt environmental disturbances, which presented both opportunities for agricultural expansion and challenges that necessitated societal adaptation (Bond, 2001; Costanza et al., 2009; Pederson et al., 2014; Tan et al., 2018; Yang et al., 2019; Zhao et al., 2020).

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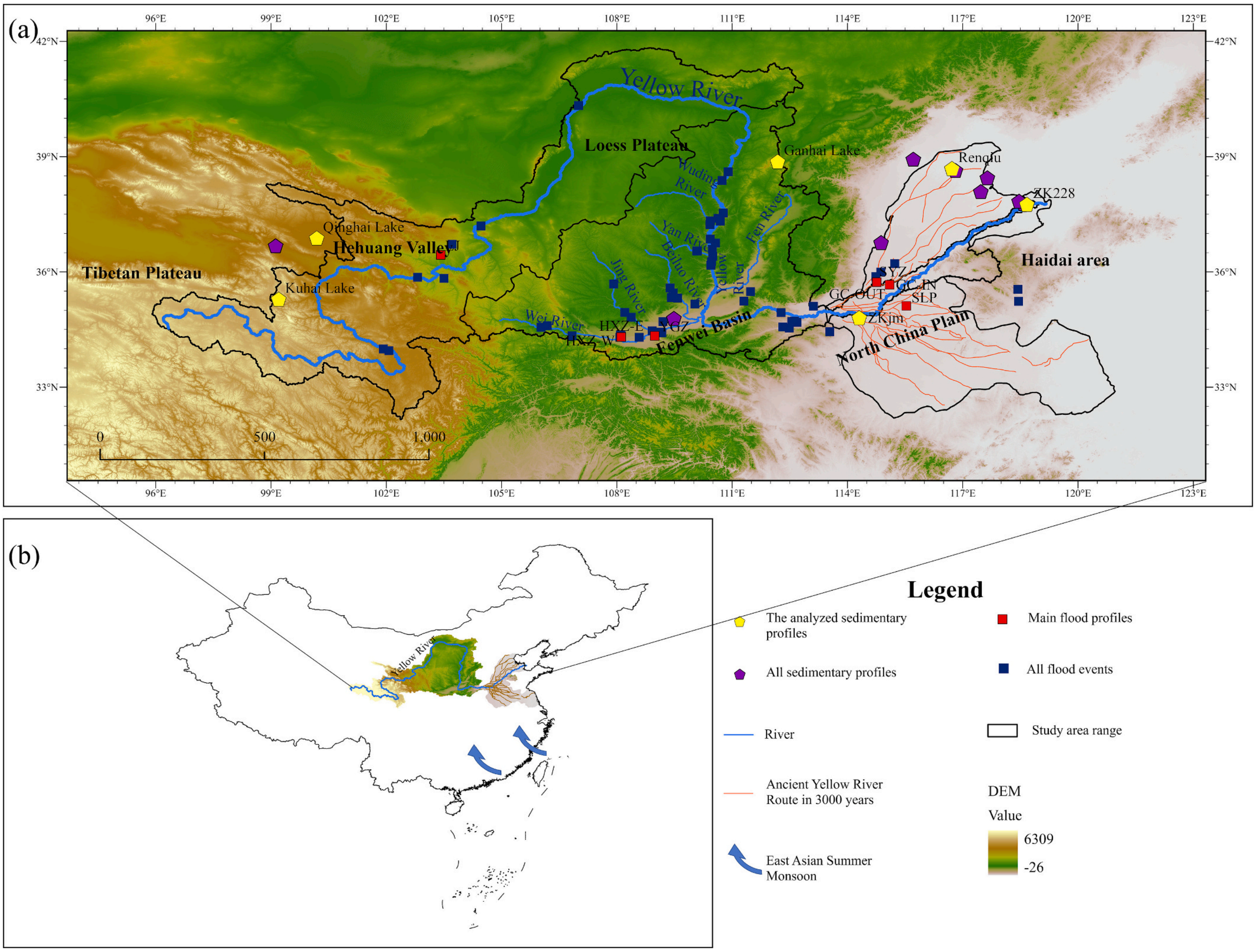

Fig. 1. Location of the Yellow River Basin and distribution of studied sites. The distribution of palaeochannel changes in the lower reach of the Yellow River form the literature(Xue, 1993). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Warm and humid climatic phases during the early to middle Holocene (9.0–5.0 cal. ka BP) created favorable conditions for agricultural intensification, demographic expansion, and the development of permanent settlements across various early cultural regions, including the Fertile Crescent, the Nile Valley, the Indus-Gangetic Plain, and East Asia (Costanza et al., 2009; Huzayyin, 1939; Pederson et al., 2014; Sun et al., 2019a; Yang, 2013). In Egypt, improved precipitation regimes facilitated the transition from mobile foraging to sedentary farming by 9.0 cal. ka BP (Huzayyin, 1939; Vermeersch et al., 2015) with similar dynamics observed in the arid American Southwest (Hall, 1977). In the Chinese context, this climatic window supported the flourishing of the Dadiwan and Majiayao cultures in the Gansu–Qinghai region and enabled the rapid expansion of the Yangshao and Longshan cultures along the middle and lower Yellow River (An et al., 2002; Hou et al., 2019; Jiang and Cui, 2017). These cultures experienced rising settlement densities, increased social differentiation, and early signs of political complexity under climate-favorable conditions.

Conversely, abrupt mid-Holocene climatic deteriorations—particularly the 5.5 and 4.2 cal. ka BP cooling events—posed severe ecological and societal challenges, often resulting in the restructuring of settlement systems and sociopolitical organization (Zhang et al., 2024). The 4.2 cal. ka BP event, in particular, is widely regarded as a global tipping point, associated with widespread aridification (Jiang et al., 2022), frequent flooding, and the collapse or transformation of early civilizations in Mesopotamia, the Indus Valley, and northern China (Jiang et al., 2025b; Pederson et al., 2014; Weiss and Bradley, 2001; Yin et al., 2025). In the Yellow River Basin, these disruptions coincide with the decline of the Yangshao culture and the emergence of more hierarchical, fortified Longshan settlements, indicative of strategic adaptations to worsening environmental conditions (Liu and Chen, 2017; Wang and Gong, 2000). Notably, these transitions were driven not only by climate itself but also by cascading secondary disasters such as soil erosion, floodplain instability, and agricultural stress (Shi et al., 2025). In this context, the "climate–disaster–response" model provides a robust explanatory framework for understanding how environmental stress shaped spatial decisions, social fragmentation, and cultural innovation (Costanza et al., 2009; Guo et al., 2024; Li et al., 2014; Wu and Liu, 2004; Yang et al., 2019). However, despite its increasing global adoption adoption, systematic applications of this model to basin-wide prehistoric transformations in East Asia remain limited.

As the core cradle of Chinese civilization, the Yellow River Basin offers an ideal natural laboratory for investigating how environmental stress influenced prehistoric settlement systems and social trajectories. Its vast loess loess plateaus, fertile alluvial plains, and dynamic fluvial networks provided both opportunities and constraints for early human occupation (An et al., 2005; Wu and Liu, 2001; Yan, 1997). Over the past two decades, a substantial body of archaeological, and paleoenvironmental research has documented long-term cultural sequences from the pre-Yangshao period through the Longshan and Bronze Age, alongside significant climatic events and geomorphological shifts (Dong et al., 2017; Gao et al., 2022; Hou et al., 2019). Currently, researchers have employed site distribution mapping, elevation and slope analysis, and localized stratigraphic records to explore the relationship between settlement dynamics and environmental conditions (Dong et al., 2022; Li and Gao, 2021; Lu et al., 2014; Su et al., 2025; Wang et al., 2023).

However, despite this growing interest, current research on prehistoric settlements in the Yellow River Basin still faces three major limitations. First, most studies are temporally anchored around discrete climatic events—such as the 8.2, 5.5, or 4.2 cal. ka BP episodes (He et al., 2021; Li et al., 2016; Sun et al., 2019a; Yu et al., 2020) , while lacking a systematic exploration of continuous climate-driven hazard regimes, particularly those involving high-frequency flood events and intensified soil erosion. Second, spatial analysis often remains confined to localized case studies (Liu, 2007a; Lu et al., 2016; Su et al., 2025), leading to a fragmented understanding of settlement evolution across the entire basin. The absence of an integrated spatial-temporal database for prehistoric sites has further hindered the identification of macro-scale patterns and long-term adaptive strategies. Third, existing interpretations frequently isolate single environmental drivers (e.g., drought or flood), overlooking the compound and synergistic nature of climate-induced disaster chains and their cumulative impacts on societal transformation (Jiang and Cui, 2017; Song, 2017; Yu et al., 2000). Consequently, the dynamic coupling between environmental perturbation, disaster frequency, and sociopolitical reorganization remains underexplored at the basin scale.

To address current research gaps, this study constructs an integrated framework linking mid-Holocene climate forcing, environmental disasters, and human adaptive responses in the Yellow River Basin. The research objectives of this study are twofold: (1) To develop and validate a “climate-driven–disaster transmission–societal response” conceptual model, systematically revealing the mechanisms through which flooding and erosion events influenced prehistoric settlement location strategies, adaptive vertical migration, and social structural differentiation; (2) To elucidate the processes by which mid-Holocene climate forcing triggered environmental disasters across the Yellow River Basin, and to uncover the formation and evolution of human adaptive strategies from the pre-Yangshao period through the Bronze Age.

2. Study area

Since the beginning of the Holocene, the Yellow River Basin has experienced major environmental changes characterized by notable shifts in climate, changes in vegetation, and the development of its river systems, all of which have had a substantial impact on patterns of human habitation (Chen et al., 2015a; Zhao et al., 2022c; Zheng et al., 2020) (Fig. 1).

During the early Holocene (11.5–9.0 cal. ka BP), postglacial warming prompted the retreat of ice sheets, resulting in a gradual increase in temperature and the expansion of temperate steppe and open forest vegetation. The climate became significantly warmer and more humid during the Holocene Climatic Optimum (9.0–5.0 cal. ka BP), which facilitated widespread forest development in the middle and upper reaches, stabilized hillslopes, and supported the growth of early Neolithic cultures (Ruo et al., 2020; Shi, 1959). In this phase, the hydrological regime of the Yellow River became increasingly dynamic, with intensified summer monsoons enhancing runoff, flood frequency, and sediment transport. Sedimentary archives reveal high-energy fluvial processes and increased floodplain dynamics, particularly in the middle and lower reaches (Zhao et al., 2022b). These environmental conditions fostered the expansion of agriculture and permanent settlements, especially along low terraces and near water sources (Huang et al., 2011). From the late Holocene onward (after 5.0 cal. ka BP), the climate began to trend cooler and drier, marked by notable events such as the 5.5 and 4.2 cal. ka BP cooling phases. Vegetation shifted toward drought-tolerant grassland and shrub species, particularly in the northwestern basin (Sun et al., 2019b). Concurrently, river activity became more

Table 1
Data source and general characteristics.

Type		Time range	Spatial resolution	Reference
Sites	shp	2.0–9.0 cal. ka BP	–	(National Cultural Heritage Administration, 1998)
Profile	shp	0–10.0 cal. ka BP	–	Table 2
DEM	tif	–	30 m	SRTM, http://datamirror.csdb.cn
Soil erosion(t/ha/a)	–	0–10.0 cal. ka BP	–	(Zhao et al., 2022b)
Flood frequency	–	0–10.0 cal. ka BP	–	(Zhou and Yu, 2013)
MG-δ^{18}O/‰	–	1.133–10.0 cal. ka BP	–	(Cai et al., 2021)
MAP/mm	–	0-10.0 cal. ka BP	–	(Chen et al., 2015b)
Temperature (K)	–	0–10.0 cal. ka BP	–	(Shi et al., 2012)
Vegetation cover/%	–	0–10.0 cal. ka BP	–	http://paleodata.ieecas.cn

unstable, characterized by enhanced lateral channel migration and incision in some segments, while sedimentation and aggradation occurred in others—especially in the lower reaches, where frequent avulsions reshaped the floodplain structure (Chen et al., 2012). These changes increased environmental risks such as soil erosion, water-logging, and flood hazards, requiring more adaptive settlement strategies.

The historical and archaeological records reveal significant long-term feedbacks between environmental shifts and human land use (Dong et al., 2019; Dong et al., 2016; Dong et al., 2013; Pauline et al., 2021; Yan et al., 2017). The transition from early Neolithic dispersed hamlets to late Neolithic fortified settlements and Bronze Age urban centers coincided with increasing environmental pressures and hydrological instability (An et al., 2002; Li and Gao, 2021; Yang et al., 2023). These evolving physical conditions provide the ecological backdrop against which this study evaluates how prehistoric societies responded to multi-scalar environmental stress through spatial reorganization and institutional adaptation.

3. Materials and methods

3.1. Data collection and preprocessing

To investigate the settlement dynamics and environmental responses in the Yellow River Basin from the pre-Yangshao period to the Bronze Age, this study developed a multi-source geospatial database that integrates archaeological, paleoenvironmental, and geomorphological data. A total of 23,031 settlements were collected from China’s cultural relics atlas, excavation reports and regional surveys spanning four cultural periods: pre-Yangshao (2151), Yangshao (4201), Longshan (8168), and the Bronze Age (8511) (**Appendix A**). Considering that Considering that this study primarily focuses on the macro-level distribution and evolutionary patterns of settlements in the Yellow River Basin, a certain degree of chronological uncertainty for individual sites is acknowledged. Paleoenvironmental datasets—including floodplain stratigraphy, loess-paleosol sequences, and borehole records—were used to reconstruct mid-Holocene climatic and geomorphic changes (Table 1). All spatial data were georeferenced using the CGCS2000 coordinate system and enriched with topographic variables (elevation, slope, hydrological proximity) derived from DEM data.

Data preprocessing involved the removal of duplicates, correction of coordinate errors, and standardization of site attributes. Sites with ambiguous chronology or inadequate spatial accuracy were excluded from the analysis. Environmental data were either interpolated or

Table 2
Related erosion deposition profiles collected in this study.

No.	Name	Location	Lon. (E)	Lat. (N)	Reference
1	ZKjm	Fluvial	114.30	34.81	(Ma et al., 2012)
2	Renqiu	Fluvial	116.71	38.70	(Cui et al., 2005)
3	QZ	Fluvial	114.87	36.77	(Wang et al., 2015a)
4	Bai_4	Fluvial	115.71	38.94	(Wang et al., 2015a)
5	QX01	Delta	116.81	38.65	(Wang et al., 2015b)
6	YS1	Delta	117.47	38.10	(Xu et al., 2015)
7	SD01	Delta	118.58	37.79	(Xian and Jiang, 2005)
8	ZK1	Delta	118.46	37.85	(Li et al., 2013a)
9	BXZK11	Delta	117.64	38.46	(He et al., 2019)
10	ZK228	Delta	118.67	37.77	(Zhou et al., 2014)
11	Luyang Lake	Lake	109.48	34.80	(Yan et al., 2016)
12	Kuhai Lake	Lake	99.20	35.30	(Mischke et al., 2010)
13	Chaka Salt Lake	Lake	99.12	36.69	(Liu et al., 2008)
14	Qinghai Lake	Lake	100.19	36.89	(Shen et al., 2005)
15	Ganhai Lake	Lake	112.18	38.88	(Zhang et al., 2018)

categorized to facilitate spatial analyses, including kernel density estimation, proximity analysis, and clustering. Detailed descriptions of data types and sources are provided in Table 1.

In parallel, this study compiled stratigraphic profiles of paleofloods and erosionded sediments from 73 sites across the upper (No. 1–8), middle (No. 9–59), and lower (No. 60–73) Yellow River Basin (Table 2, **Appendix B**). To ensure comparability, all profiles were standardized in format and age calibration. Radiocarbon dates were corrected to calendar years ($\pm 2\sigma$), and sediment deposition rates (DSR) were calculated at 50-year resolution using the function:

$$\mathrm{DSR} = (\mathrm{d_{i+1}} - \mathrm{d_i})/(\mathrm{t_{i+1}} - \mathrm{t_i}) \tag{1}$$

where *d* is depth and *t* is calibrated age. Spatial interpolation of DSR was performed using simple kriging in ArcGIS (Saito et al., 2000), providing high-resolution reconstructions of flood and erosion intensity. The 50-year resolution of the sedimentation rate is primarily considered in relation to the time series of settlements and paleofloods to elucidate their correlation. This approach facilitates a rapid determination of the relationship between settlement development and environmental change, thereby enhancing the reliability of mutual verification among various environmental factors. However, it is essential to exercise caution when analyzing data that requires higher accuracy. In this study, the 50-year sedimentation rate resolution serves as a crucial foundation for assessing the relationship between environmental disasters and settlement recombination.

3.2. *Coupling analysis of spatiotemporal dynamics of prehistoric settlements*

3.2.1. *Environmental determinants of settlement location: Altitude, slope, and water access*

To evaluate the influence of environmental conditions on prehistoric settlement distribution, this study focuses on three key terrain factors: altitude, slope, and water accessibility. Based on the geomorphological characteristics of the Yellow River Basin, an altitude classification system was developed with reference to the terrain division framework of China proposed in the 1950s (Shen, 1961). Elevation categories were adjusted to fit regional landform patterns and include: low-altitude plains and gently undulating hills (<500 m), low-altitude moderately undulating hills (500–1000 m), mid-altitude moderately undulating mountains (1000–1500 m), and mid-altitude strongly undulating mountains (1500–2000 m). Settlement site elevations were extracted and assigned to these classes to examine changes in vertical. Distribution across cultural periods. Additional statistics were generated for sites situated above 1500 m to assess the dynamics of high-altitude occupation.

Slope classification adhered to the standards established by the Landform Survey and Mapping Committee of the International Geographical Union for detailed landform mapping. Slopes were categorized into five distinct groups: flat to micro-slopes ($<2^\circ$), gentle slopes (2°–6°), moderate slopes (6°–15°), steep slopes (15°–25°), and very steep slopes ($\geq 25^\circ$). Utilizing digital elevation model (DEM) data, slope values were computed for each site to assess terrain preferences and their evolution from the Yangshao period to the Bronze Age.

Water accessibility was assessed by calculating the distance between each settlement site and the nearest major river. Given that prehistoric populations typically selected locations within a practical daily walking range of water sources, a 6 km buffer zone was established as an analytical threshold. This distance corresponds to an estimated one-hour walking range, considering terrain, slope, and physical condition, based on a typical human walking speed of 3.6–7.2 km/h (Aghabayk et al., 2021; Vita-Finzi and Higgs, 1970). Sites located within 6 km of a river were classified as near-water settlements, whereas those situated beyond this distance were categorized as distant-water settlements. This framework allows for a systematic assessment of hydrophilic preferences and adaptive shifts in response to changing climatic and hydrological conditions across time.

3.2.2. *Spatial dynamics detection: Nearest neighbor, kernel density and clustering*

To examine the spatial organization and evolution of settlement patterns from the pre-Yangshao to the Bronze Age, this study employed a combination of nearest neighbor analysis, kernel density estimation (KDE), and clustering algorithms using GIS and Python platforms. Nearest neighbor analysis quantified the degree of spatial dispersion or aggregation among settlement sites. By calculating the average shortest distance between each site and its nearest neighbor. This method captures changes in site density across different cultural phases; a decreasing average distance indicates increased spatial clustering, while increasing values reflect dispersion. Kernel density estimation was utilized to visualize spatial concentrations and identify core settlement areas in each period. By employing the “Kernel Density” tool in the GIS Spatial Analyst module, KDE calculates the density of point features (settlement sites) surrounding each raster cell, producing a continuous surface that reflects the intensity of site distribution (Silverman, 1986). his methodology facilitates the assessment of spatial aggregation dynamics and the shifting of population centers over time.

In addition, HDBScan (Hierarchical. Density-Based Spatial Clustering of Applications with Noise) was used to detect settlement clusters with varying densities and to identify outlier (noise) points. This unsupervised algorithm is well-suited for archaeological datasets characterized by heterogeneous spatial patterns. The formula for the mutual reachable distance between the two points is as follows:

$$\mathrm{d_k(p,q)} = \max\{\mathrm{c_k(p)}, \mathrm{c_k(q)}, \mathrm{d(p,q)}\} \tag{2}$$

where $d(p,q)$ represents the distance between p and q, the core distance $c_k(p) = d(p, N^k(p))$ value represents the distance between the core point p and the k th adjacent point (Leland et al., 2017).

To evaluate the clustering quality, the Total Sum of Squares (TSS) was decomposed into Within-cluster Sum of Squares (WSS) and Between-cluster Sum of Squares (BSS). A lower WSS indicates higher internal consistency within clusters, while a higher BSS reflects greater differentiation between clusters. The ratio BSS/TSS was used as an index of clustering effectiveness, with values approaching 1 indicating stronger inter-cluster separation and more distinct settlement clusters.

4. Results

4.1. *Settlement shift from river proximity to terrain adaptation*

The number of settlements increased continuously from the pre-

Table 3
Number of settlement sites in the pre-Yangshao, Yangshao, Longshan and Bronze Age in the Yellow River Basin.

Period	Pre-Yangshao	Yangshao	Longshan	Bronze Age
Quantity	2151	4201	8168	8511
Percentage	9.34 %	18.24 %	35.47 %	36.95 %
Increase	–	95.30 %	94.43 %	4.20 %

Yangshao to the Bronze Age, but the growth rate varied significantly across periods, reflecting shifting patterns of population expansion and regional occupation. From the pre-Yangshao to the Yangshao period, the number of settlements nearly doubled, increasing by 95.30 %. In contrast, from the Longshan to the Bronze Age, the increase was only 4.20 % (Table 3). This early-stage expansion suggests broad territorial occupation and population growth, while the later-stage stabilization implies spatial reorganization or regional consolidation of settlements.

Settlement elevation patterns exhibit a distinct upward migration trend from the pre-Yangshao to the Longshan period, followed by a partial regression during the Bronze Age, indicating shifting adaptive strategies in response to topographic and possibly climatic factors. The average altitude of settlements rose from 686.10 m (pre-Yangshao) to 1318.09 m (Yangshao) and peaked at 1375.08 m during the Longshan period, before slightly declining to 1307.50 m in the Bronze Age. Notably, the proportion of sites above 1500 m increased significantly during the Yangshao–Longshan transition. A bimodal elevation pattern emerged in the Longshan period, with over 20 % of settlements concentrated in both the [1000–1500) m and ≥ 2000 m ranges, while in the Bronze Age, the pattern shifted toward a dual concentration below 500 m and above 2000 m, both exceeding 30 % (Fig. 2).

Slope selection reflects a dynamic balance between agricultural suitability and terrain adaptability, with an increased tolerance for steeper slopes during the Longshan period. While prehistoric settlements consistently favored gentle terrain, the proportion of sites on slopes <2° declined from the pre-Yangshao to the Longshan period, before rebounding to 65.2 % in the Bronze Age. In contrast, settlements on [6°–15°) and [15°–25°) slopes increased by 12.7 % and 8.9 % respectively during the Yangshao–Longshan transition, suggesting an adaptation to more complex terrain (Fig. 2). This pattern indicates that as low-slope land became saturated or prone to risks, settlements expanded into marginal yet usable zones.

Hydrological proximity analysis reveals a clear shift from water-dependent to water-avoidant settlement strategies, reflecting an increasing awareness and response to flood hazards. In the pre-Yangshao period, near-water settlements accounted for only 0.45 %, due to the low total number of sites. During the Yangshao period, both near- and distant-water settlements increased. In the Longshan period, distant-water sites rose to 29.84 %, and by the Bronze Age, they surpassed near-water sites, reaching 51.08 % (Fig. 3b). Millennium-scale trends (Fig. 3a) show that before 5.0 cal. ka BP, near-water site selection was dominant, but after 4.0–3.0 cal. ka BP, the proportion of distant-water sites overtook near-water sites by 12.3 %, suggesting a strategic

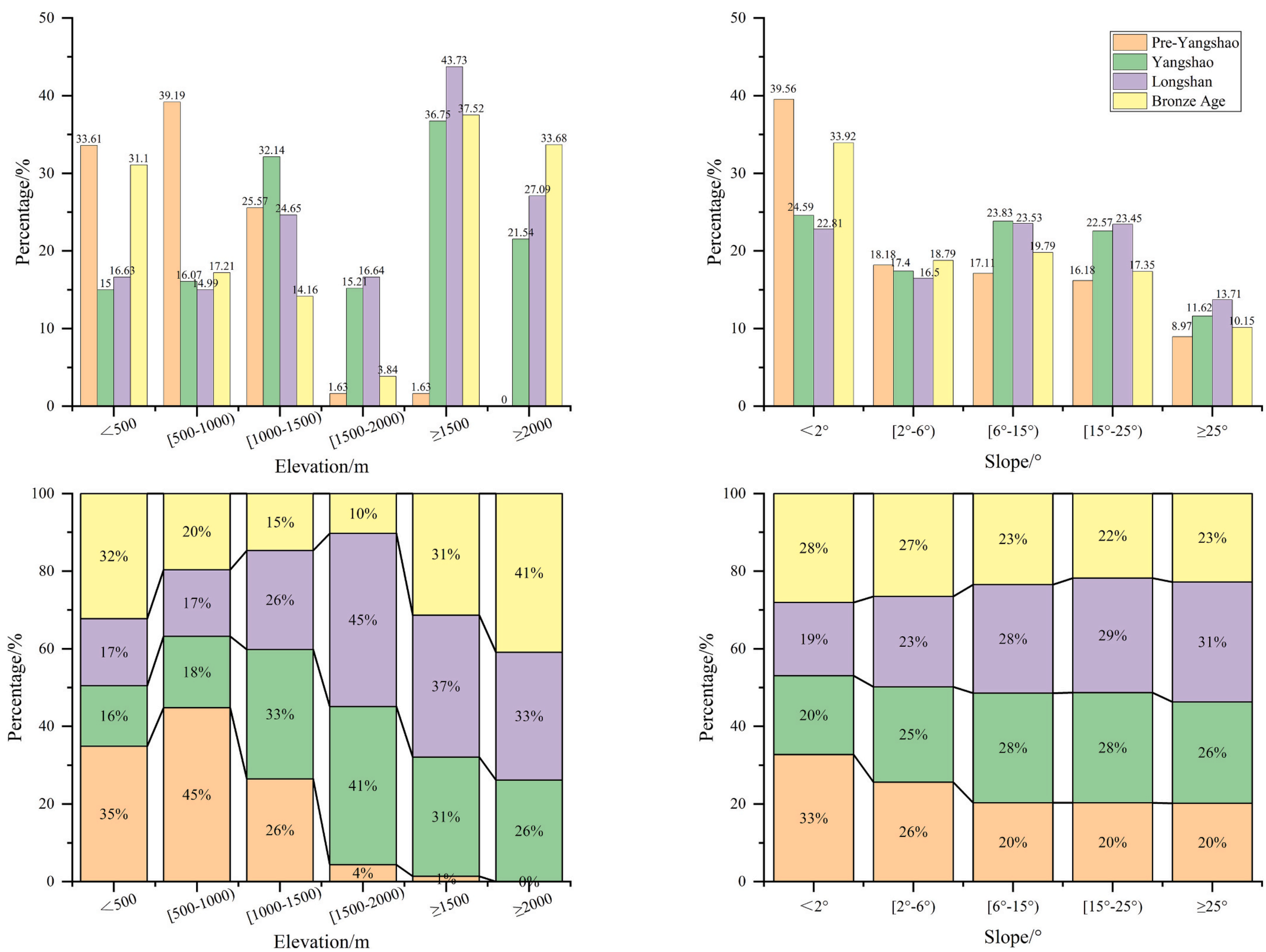

Fig. 2. Statistics of the elevation and slope data of the pre-Yangshao to Bronze Age settlement sites.

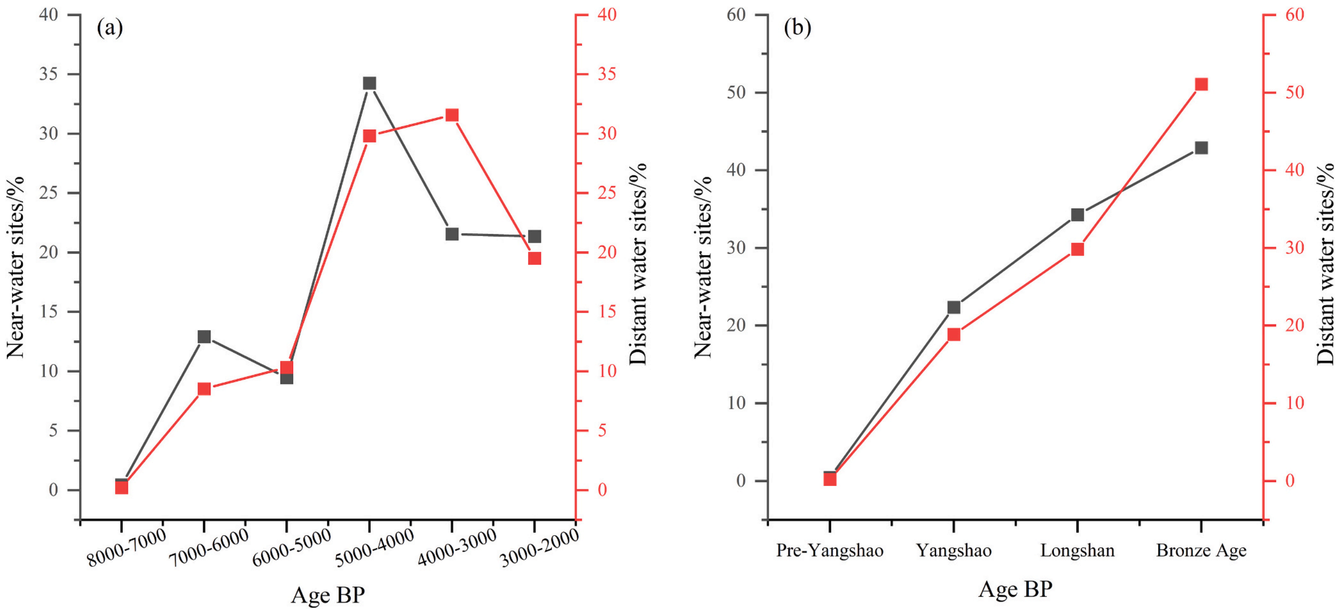

Fig. 3. Proportion of settlement sites far from and near water sources (a: distance between settlement sites and water sources divided by thousand years; b: distance between settlement sites and water sources from pre-Yangshao to Bronze Age).

Table 4
Summary table of nearest neighbor analysis.

Period	Average observation distance / m	Expected average distance / m	Nearest neighbor ratio	z score	p
Pre-Yangshao	4090.21	9859.07	0.41486	−51.91638	0.000000
Yangshao	2562.82	9753.09	0.26277	−91.40254	0.000000
Longshan	2195.02	6273.83	0.34986	−112.39219	0.000000
Bronze Age	1666.94	6881.36	0.24224	−133.73737	0.000000

withdrawal from flood-prone zones as hydrological risks intensified.

Settlement clustering became increasingly pronounced over time, reflecting intensifying social aggregation and spatial centralization. Nearest neighbor analysis indicates that clustering was statistically significant across all periods ($p = 0$), with the nearest neighbor ratio consistently remaining below 1 (Table 4). The average inter-site distance decreased from 4090.22 m (pre-Yangshao) to 1666.94 m (Bronze Age), suggesting stronger spatial cohesion and potentially indicating institutionalized settlement planning or defense-driven aggregation.

Kernel density analysis reveals a spatial transition from linear to multi-core settlement organization, with the emergence of stable regional centers by the Bronze Age. High-density clusters during the pre-Yangshao period were concentrated along the Wei River and Jing River. By the Yangshao period, the Hehuang Valley emerged as a new center. The Longshan period experienced peak aggregation intensity and a polarization trend, while in the Bronze Age, a tri-polar pattern formed: the Hehuang Valley (upper reaches), the Fenwei Basin (middle reaches), and the Haidai region (lower reaches) **(**Fig. 4**)**. Although peak density declined slightly during the Bronze Age, the overall level of aggregation remained significantly higher than in earlier periods.

The spatial evolution trajectory of settlements indicates that the middle reaches of the Yellow River have consistently served as the core development zone supporting a continuous high-density settlement distribution. The upper reaches have formed a secondary center in the Hehuang Valley since the Yangshao period, hich continued into the Bronze Age. In contrast, the lower reaches exhibited a long-standing settlement gap, with substantial aggregation only emerging in the Bronze Age.

4.2. Cluster differentiation and the emergence of regional settlement centers

The evolution of prehistoric settlements in the Yellow River Basin from the pre-Yangshao period to the Bronze Age, demonstrates increasingly distinct cluster differentiation and the emergence of stable regional centers. This evolution reflects both demographic expansion and institutional transformation. Results from cluster analysis indicate that the BSS/TSS ratio exceeded 0.8 across all cultural periods (Table 5), suggesting that between-cluster variability was consistently greater than within-cluster variability. This finding confirms that settlement groups were not randomly distributed; rather, they exhibited significant spatial structuring. In combination with the nearest neighbor analysis, which revealed decreasing average inter-site distances over time, these results demonstrate a phased intensification of spatial aggregation and a transition from dispersed habitation to more organized settlement systems (Fig. 5a).

Chronological cluster distributions reveal a transition from early spatial dispersion to progressive consolidation and core–periphery structuring. In the pre-Yangshao period (9.0–7.0 cal. ka BP), 27 settlement groups were identified; however, their activity was primarily concentrated in two centuries (8.0–7.0 cal. ka BP). Particularly around 7.0 cal. ka BP, settlement clusters displayed internal differentiation and spatial dispersion, likely reflecting the experimental and exploratory nature of early settlement activities. During the Yangshao period (7.0–5.0 cal. ka BP), the number of clusters decreased to 9, yet their distribution extended across 8 consecutive centuries, suggesting increasing continuity and regional integration. This pattern indicates the formation of more stable, territorially anchored communities. The Longshan period (5.0–4.0 cal. ka BP) marked a pivotal turning point in

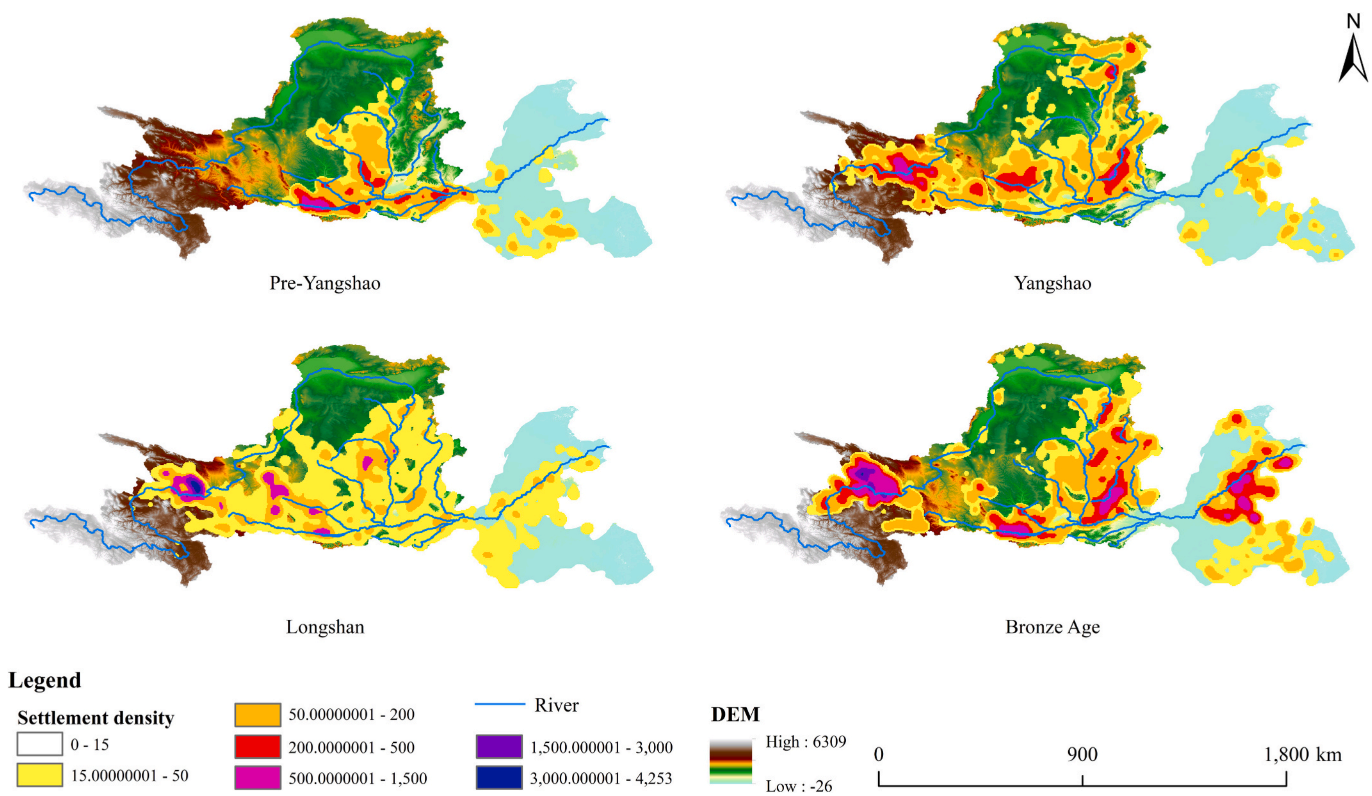

Fig. 4. Density distribution of settlement sites from pre-Yangshao to Bronze Age in the Yellow River Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Distribution characteristics of settlement groups from Yangshao to Bronze Age before the Yellow River Basin.

Period	Pre-Yangshao	Yangshao	Longshan	Bronze Age
WSS	141.22	807.34	4440.41	1885.63
BSS	4899.80	10,978.70	17,785.60	19,780.02
BSS/TSS	0.97198	0.93150	0.80021	0.91296

settlement dynamics. Fourteen clusters were distributed across 10 century-scale intervals, indicating an increased frequency of site relocation or reorganization. This may reflect growing pressure from environmental stress (e.g., flood risk) or competition for resources, prompting flexible spatial strategies. By the Bronze Age (4.0–2.0 cal. ka BP), both the number of clusters (17) and their temporal persistence had increased. Twelve consecutive periods exhibited stable clustering patterns, demonstrating sustained spatial cohesion and the emergence of long-term core areas, often associated with early forms of sociopolitical centralization.

The internal evolution of settlement groups indicates an increasing spatial concentration and hierarchical organization from the Longshan to Bronze Age periods. As population density and settlement quantity increased, so too did the need for effective resource management and spatial governance. The spatial contraction of individual cluster areas, coupled with the overlapping distribution of multiple clusters in core zones, signifies a trend toward spatial centralization and planned organization (Fig. 5b). From the Longshan period onward, clusters began to overlap significantly, particularly in middle and upper basin areas, marking a departure from earlier expansionary settlement models.

The spatial trajectory of cluster development reflects the shifting political and economic cores of the basin over time**.** In the pre-Yangshao period, settlement activity was predominantly concentrated in the middle and lower reaches, with expansion into peripheral areas. During the Yangshao and Longshan periods, clusters expanded into the upper Yellow River Basin, especially the Hehuang Valley, forming secondary centers that persisted into the Bronze Age. This phenomenon reflects not only environmental adaptation but also the redistribution of political and economic functions along the river corridor. By the Bronze Age, the spatial overlap between clusters intensified, and an increasing number of settlements displayed signs of defensive architecture (e.g., moats), urban features, and functional differentiation (Liu, 2007b; Sun et al., 2017).

The emergence of regional centers during the Bronze Age represents a culmination of spatial, social, and political transformation. The Bronze Age witnessed the transition from community-based clusters to proto-urban systems (Du and Gong, 2023). Settlements increasingly formed large, centralized clusters, many of which evolved into administrative or ceremonial centers. The rise of towns, walled settlements, and differentiated spatial hierarchies indicates the institutionalization of governance structures and the spatial imprint of early state formation (Liu, 2005). This transformation did not occur uniformly but emerged through the spatial consolidation of overlapping settlement groups, which served as nuclei for early political. Units. These developments accelerated social complexity and reshaped the settlement landscape of the Yellow River Basin.

4.3. Paleoflood and erosion-deposition under environmental stress

Frequent and intensified paleoflood events between 4.2 and 3.0 cal. ka BP significantly reshaped the distribution of settlements in the Yellow River Basin, underscoring the critical role of hydrological stress in driving human spatial reorganization. A compilation of paleoflood data from 73 representative locations across the basin (**Appendix B**) shows that 68.91 % of dated flood records are concentrated in the middle reaches, where loess–paleosol sequences provide high-resolution flood archives. These areas, particularly the Wei River and Fen River systems, exhibit well-preserved overbank flood deposits that have been primarily

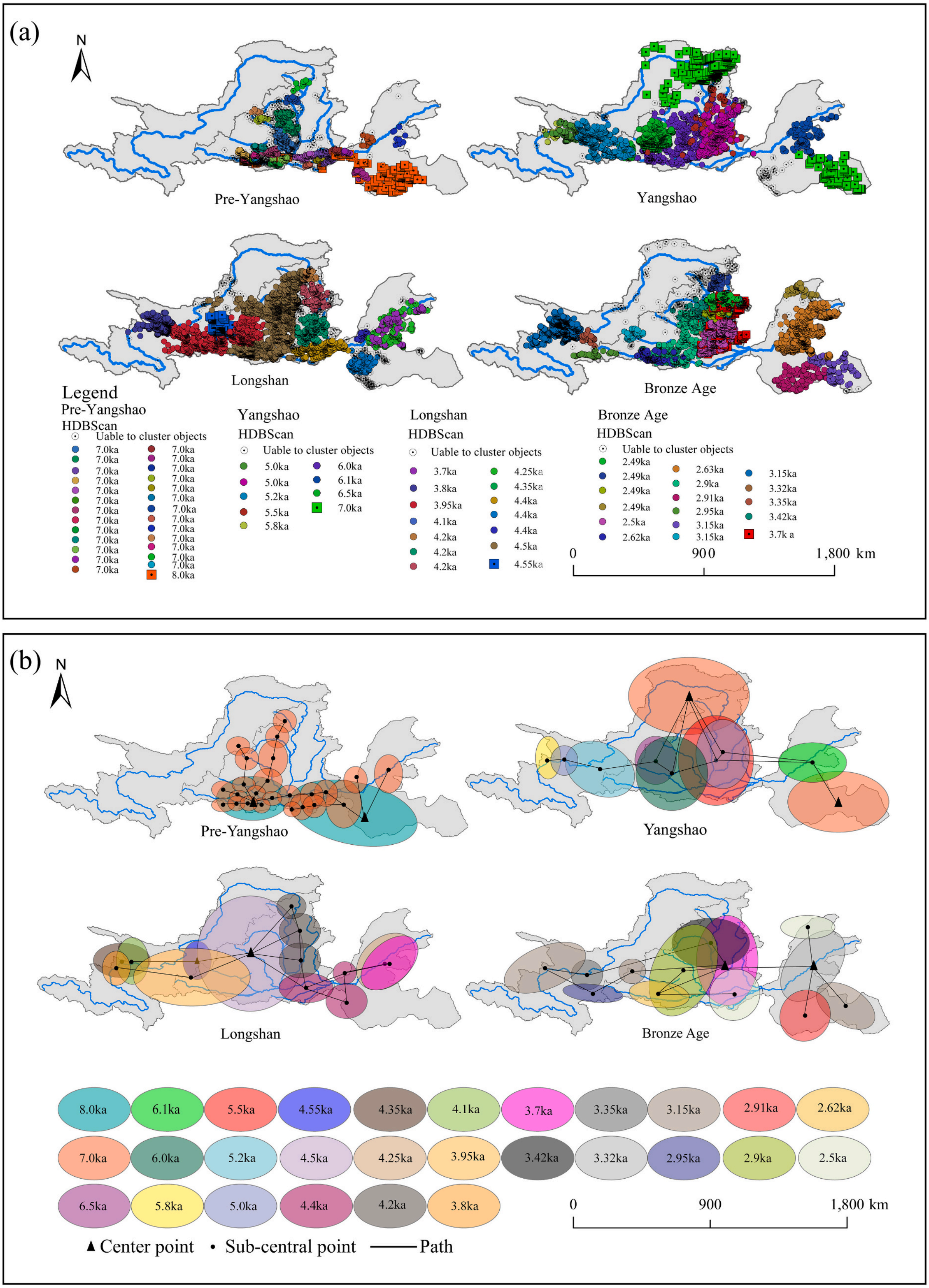

Fig. 5. Distribution (a) and development path (b) of settlement groups in the Yellow River Basin from pre-Yangshao to Bronze Age. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

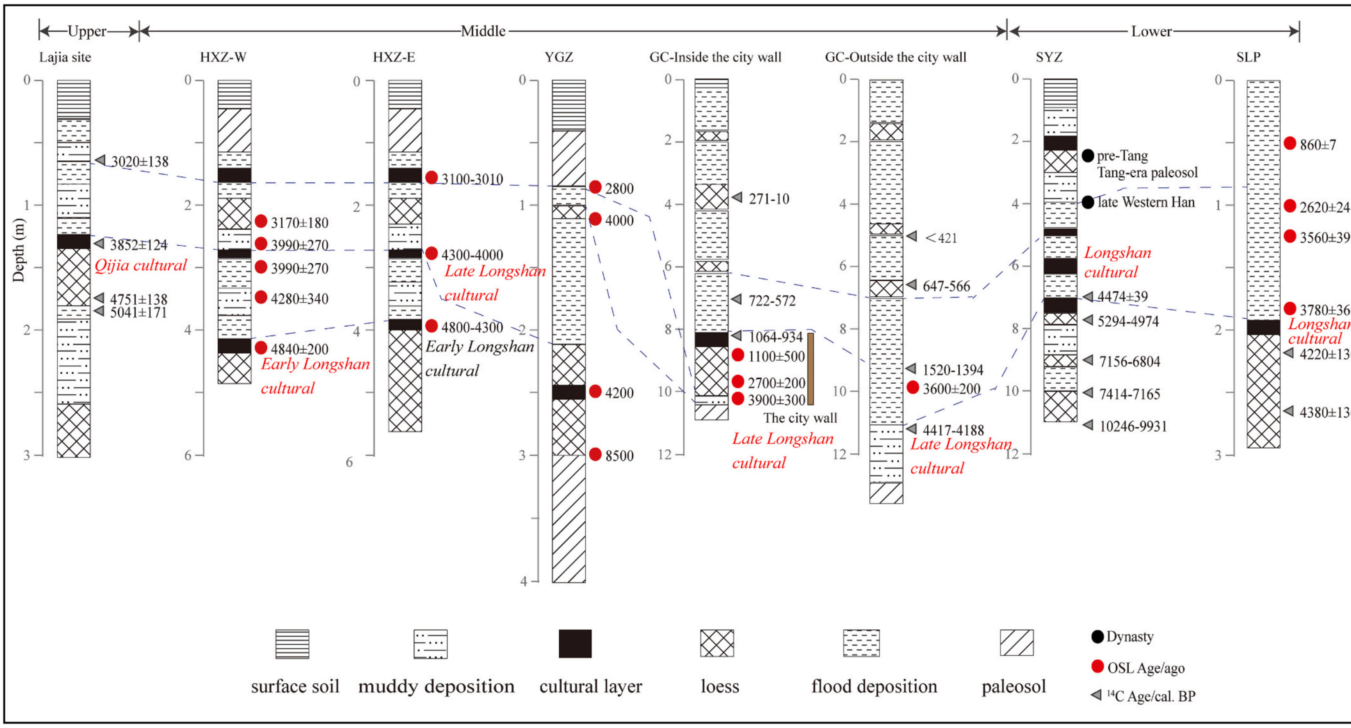

Fig. 6. Major flood events and cultural changes in the Yellow River Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dated using ^{14}C and OSL methods. Temporal clustering analysis reveals two major peaks in flood frequency: 4.2–4.0 cal. ka BP and 3.2–3.0 cal. ka BP, which correspond to periods of climatic instability and significant social transformation. These bimodal flood episodes coincide with the late Longshan and early Bronze Age, respectively, suggesting a strong linkage between environmental stress and shifting settlement behavior.

Settlement responses to flood disturbances adhered to a recurring spatial logic: retreat from flood-prone areas during peak hydrological stress, followed by rapid reoccupation upon environmental stabilization. Stratigraphic analyses of typical floodplain profiles (Fig. 6) reveal thin, discontinuous cultural layers during periods of high flood frequency, indicating short-term site use and repeated abandonment. This supports the hypothesis of a cyclical human–flood interaction model characterized by "water enters, people retreat; water retreats, people return." During the late Longshan period, in particular, the thinning of archaeological horizons corresponds with intensified fluvial activity. These patterns reflect not only the disruption of settlements induced by floods but also an increased capacity for rapid rebuilding and spatial mobility, indicating adaptive flexibility under environmental stress.

The erosion-sedimentation processes in the Yellow River Basin exhibit clear regularity. Climatically driven erosion-sedimentation processes demonstrate extensive synchronicity (Wang et al., 2014; Xue, 1993; Zhao et al., 2020), with simultaneous occurrences of intense erosion events documented across various geographical locations and geomorphological units (Fig. 7). The intensity of erosion-sedimentation shows systematic correlations with climatic zones, topographic features, and vegetation distribution, For instance, under identical precipitation conditions, areas with natural vegetation that have lower coverage experience significantly enhanced erosion (Liu et al., 1994; Yao, 2009). Furthermore, the phases of erosion-sedimentationalign closely with palaeoclimatic reconstructions (Fig. 8b, c).

In contrast, anthropogenically induced erosion-sedimentation displays a distinct hysteretic nature (Yao, 2009), wherein the initiation of accelerated erosion conspicuously lags behind the emergence of pivotal anthropogenic indicators in the region (He et al., 2004; Saito et al., 2001; Xu, 2001) (Fig. 7b). Moreover, core erosion-sedimentation zones exhibit substantial spatial overlap with documented areas of agricultural activity and settlement distribution (Fig. 5b) (Fig. 7).

Sedimentary data reveal a two-phase acceleration in erosion–deposition processes, with the first stage driven by climate and early agriculture, and the second stage increasingly influenced by human disturbance. In the upper reaches of the Yellow River, lake sedimentation rates between 8.0 and 3.0 cal. ka BP reached 0.08–0.125 cm/a, with a clear peak around 3.5–3.0 cal. ka BP (Fig. 7b-1). In the middle reaches, loess-derived colluvial and alluvial deposition during the early Holocene peaked between 8.0 and 6.0 cal. ka BP at rates of 0.15–0.8 cm/a, forming extensive fertile layers that supported agricultural expansion. This high depositional phase corresponds with the peak of the Yangshao culture, indicating a strong climate–agriculture–sedimentation coupling. In the lower reaches, sedimentation remained high (>0.12 cm/a) from 7.0 to 4.0 cal. ka BP, reflecting sustained alluvial accumulation along the floodplain margins.

The second phase of sedimentary acceleration (3.0–2.0 cal. ka BP) signifies intensified anthropogenic disturbance, marking the transition from climate-dominated to human-dominated landscape processes. Following the mid-Holocene climatic optimum, environmental stress increased due to declining moisture levels and growing human land use pressures. Warm and humid conditions during 8.0–4.0 cal. ka BP (average temperatures ~1.5–2.5 °C higher than present) enabled agricultural intensification, but also led to deforestation, slope instability, and rising soil erosion. By the late Holocene, erosion rates in the basin significantly surpassed natural baselines (Jos et al., 2017; Nearing et al., 2017). The resulting increase in sediment load in the middle and lower reaches suggests extensive land clearance, field expansion, and increasingly centralized water management systems.

5. Discussion

5.1. From dispersion to aggregation: The spatial logic of early social organizations

The transition from dispersed to aggregated settlement patterns in

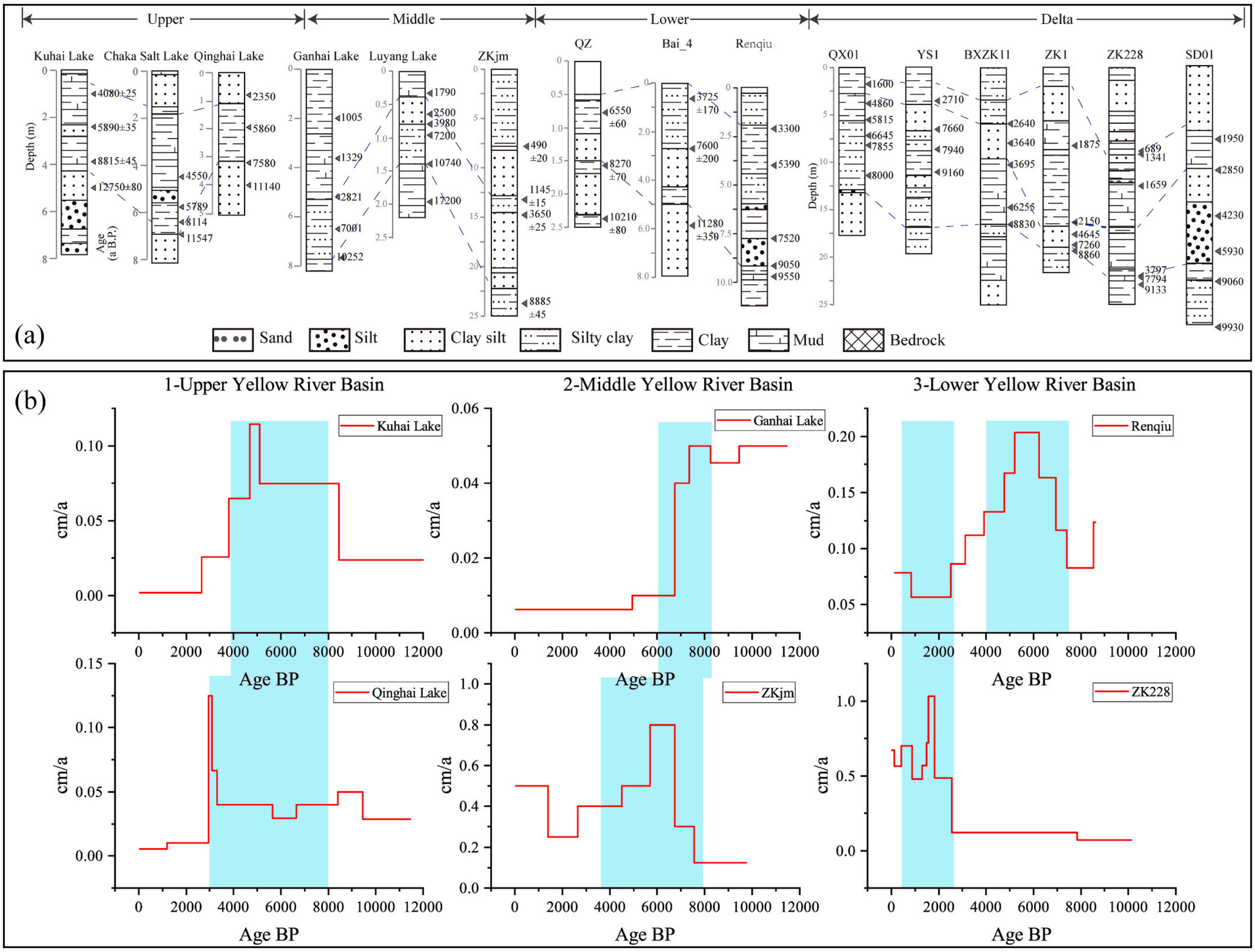

Fig. 7. Sedimentary change process in the upper, middle and lower reaches of the Yellow River Basin. (a) The main sedimentary profile; (b) is the deposition rate of the sedimentary section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Yellow River Basin reflects an adaptive spatial strategy shaped by environmental opportunity, population growth, and sociopolitical transformation. Quantitative analysis of settlement data from the pre-Yangshao to the Bronze Age reveals significant spatiotemporal differentiation. Although the total number of settlements increased continuously, the growth rate varied across periods (Table 3), reflecting the complex interplay between environmental conditions, demographic expansion, and technological advances (Li et al., 2022; Liu and Reid, 2020; Xu et al., 2019). The most rapid increase occurred from the pre-Yangshao to the Yangshao period, coinciding with the mid-Holocene climatic optimum. Paleoenvironmental reconstructions indicate that during 6.2–5.6 cal. ka BP, the Wei River Basin experienced an average temperature of 14.8 °C and annual precipitation of 831.1 mm—warmer and wetter than present conditions—providing favorable ecological conditions for settlement expansion and agricultural intensification (Chen et al., 2015b; Li et al., 2025; Sun et al., 2016; Wei, 2022).

The domestication of foxtail and broomcorn millet, which began in the pre-Yangshao period, entered a phase of intensified production by the mid-Yangshao period (Liu et al., 2012). Archaeobotanical studies show a significant increase in millet consumption between 6.3 and 5.5 cal. ka BP, marking a transition to fully developed millet farming systems (Ma et al., 2023). These agricultural advances provided the material foundation for increased settlement density and territorial expansion. By the Longshan period, this trend accelerated with the emergence of proto-urban centers and increasingly complex settlement hierarchies (Demattè, 1999; Wang and Guo, 2016). For example, Shimao, a massive walled site on the northern Loess Plateau, covered over 4 million square meters (Cui, 2024; Sun et al., 2017), while Taosi in the Central Plains region reached approximately 2.8 million square meters (Li et al., 2013b),both signaling the rise of centralized power and social complexity.

The process of settlement centralization in the Yellow River Basin presents distinct characteristics of macro spatial-temporal continuity and regional differentiation, influenced by socio-political conditions. Spatial aggregation patterns varied across the upper, middle, and lower reaches of the Yellow River. The middle reaches consistently maintained high settlement densities from the Yangshao to the Bronze Age (Fig. 4), serving as a core zone for cultural and demographic development (Dong et al., 2022). In contrast, the Hehuang Valley in the upper basin began to exhibit significant agglomeration only during the late Yangshao period. Archaeobotanical data from the Guanting Basin show an increase in carbonized millet and sorghum from 0.71 to 34.1 grains/l between early and late Yangshao, reflecting a marked intensification of agriculture and permanent occupation in upland areas (Cui et al., 2017; Dong et al., 2013). The lower Yellow River remained relatively underdeveloped until the Bronze Age, likely due to the environmental instability of its floodplain (Wang, 1993). Settlement development in the North China Plain (NCP) within the lower Yellow River during the early to middle Neolithic period significantly lagged behind that of the middle-upper reaches. The primary reason for this disparity was not resource

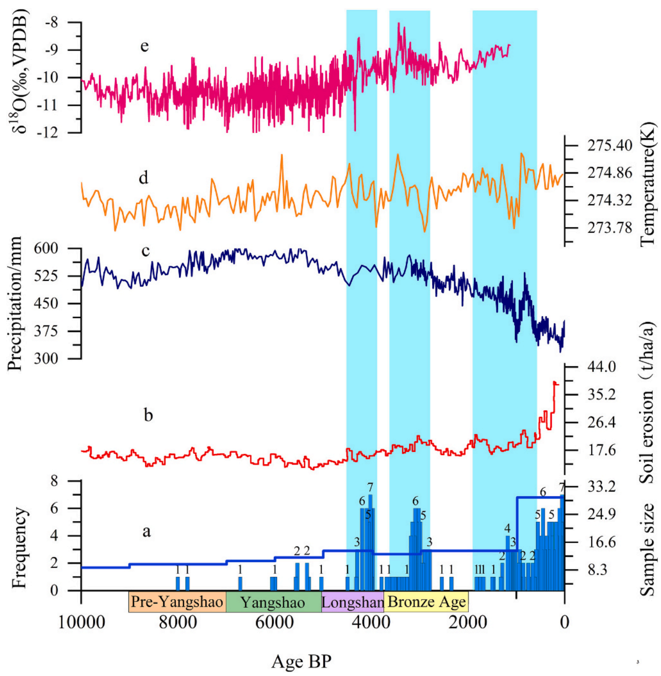

Fig. 8. Proxy indexes of climate change and environmental change in the Yellow River Basin in recent ten thousand years. (a) is the ancient flood frequency in the Yellow River Basin, the sample size represents the ancient flood record points collected.(Zhou and Yu, 2013); (b) The amount of soil erosion in the reconstructed Yellow River Basin(Zhao et al., 2022b); (c) Precipitation based on pollen reconstruction in the high seas(Chen et al., 2015b); (d) Global temperature change for reconstruction(Shi et al., 2012); (e) is the $\delta^{18}O$ variation of Magou Cave (Cai et al., 2021). The blue band indicates the correspondence between the increase of flood frequency, the increase of soil erosion and climate change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scarcity, but rather the region's unique and dynamic paleoenvironmental setting, particularly the combined effects of the mid-Holocene marine transgression, coastal subsidence, and the synergistic impact of fluvial dynamics, such as river diversion.

First, sea-level rise and coastline transgression occurred under the warm and humid mid-Holocene climate, resulting in global sea-level rise (Lambeck et al., 2014). This transgression event is extensively documented in the North China Plain (NCP). Numerous studies utilizing drill cores, marine microfossils (such as foraminifera and diatoms), and radiocarbon dating have reconstructed the paleo-coastline positions (Li et al., 2001; Liu et al., 2016). Diatom analysis of drill cores from the western coast of Bohai Bay indicates that brackish-saline species predominated in the transgressive sediment layers, while freshwater diatoms were exceedingly rare (Li et al., 2013; Shang et al., 2013). This finding confirms that the region's aquatic environment was persistently saline rather than intermittently inundated. Consequently, what is now the flat eastern NCP was once a vast expanse of shallow sea, lagoons, and salt marshes, lacking the fundamental conditions for large-scale agriculture and settlement.

Second, the NCP itself is a massive sedimentary basin filled by sediments from the Yellow River and other rivers, with relatively poor geological stability and subject to tectonic subsidence and compaction-induced subsidence (Saito et al., 2001; Xue, 1993). This ongoing subsidence, coupled with sea-level rise, further prolonged the scope and duration of seawater inundation, thereby delaying delta progradation and the formation of new land.

Finally, it is crucial to emphasize that marine transgression was not the sole factor; it interacted synergistically with the high avulsion frequency of the lower Yellow River (Saito et al., 2001). Although the substantial sediment load delivered by the Yellow River supplied material for land building, under high sea-level conditions, rapid sediment accumulation at the river mouth diminished the channel gradient, which in turn increased the likelihood of channel breaches and avulsions. Each avulsion event caused floodwaters to spread extensively across the low-lying plain, remobilizing salts, sediments, and organic matter, and prolonging the environmental recovery cycle.

Therefore, the delayed formation of prehistoric settlements in the North China Plain resulted from the combined effects of marine transgression, coastal subsidence, and the high avulsion frequency of the Yellow River. The mid-Holocene sea-level rise created a paleoenvironment characterized by high salinity, limited land availability, and frequent natural disasters—a conclusion strongly supported by diatom and geochemical proxy data. This specific environment posed fundamental constraints on Neolithic societies dependent on dryland agriculture. It was not until the late Longshan period through the Bronze Age, alongside advancements in water management technology and the increasing complexity of social organization (**Appendix C**), that humans finally acquired the capacity for large-scale exploitation and sustained settlement of this vast alluvial plain. Stratigraphic comparative research at the Gaocheng site in Henan demonstrates that defensive structures, such as walls, effectively mitigated flood risk and provided conditions for long-term habitation in low-lying areas (Yang et al., 2023) (Fig. 6).

Vertical and hydrological shifts in site selection reflect a dual strategy of resource acquisition and disaster avoidance. During the Yangshao and Longshan periods, settlements migrated to higher altitudes and farther distances from rivers (Fig. 2). This spatial adjustment reflects a growing awareness of flood risks and the need to balance access to water with safety (Gao et al., 2022; Hou and Zhu, 2000; Li and Gao, 2021; Wu et al., 2016). Domain analysis in the Gaogang region shows that sites located at the intersection of rivers and hills enjoy greater resource diversity—access to aquatic resources, arable land, and stone—than riparian zones (Yan et al., 2017). Geological evidence from the late Holocene indicates widespread flooding in the lower basin, supporting the hypothesis that flood risks drove upland migration and encouraged more dispersed, resilient site selection (Li and Gao, 2021; Qin et al., 2022; Storozum et al., 2017; Yu et al., 2020).

The spatial development of settlement clusters illustrates the dynamic structuring of early social complexity. From the pre-Yangshao to the Yangshao period, settlements expanded outward from a core zone in the middle reaches (Fig. 5b). By the Longshan period, this evolved into a multi-center network, marking the rise of a chiefdom society characterized by regional leadership and symbolic centrality (Liu and Chen, 2017). During the Bronze Age, overlapping cluster zones became prevalent, particularly in regions with regime-type settlements. These overlapping patterns suggest a legacy of settlement continuity and indicate enhanced coordination, hierarchy, and territorial governance (Du and Gong, 2023). This core-to-periphery diffusion model reflects both the ecological constraints of land suitability and the centripetal force of emerging political centers.

5.2. Climatic hazards as a catalyst for the reorganization of settlement landscapes

The climatic volatility of the mid to late Holocene, particularly the frequency of abrupt precipitation anomalies driven by the East Asian summer monsoon, served as a significant external force that reshaped prehistoric settlement landscapes in the Yellow River Basin (Chen et al., 2005; Liu and Feng, 2012; Ruo et al., 2020; Sun et al., 2019b). While environmental change has long been acknowledged as a backdrop to prehistoric transformation, this study demonstrates that abrupt climate events—specifically those resulting in floods, erosion, and habitat instability—played a catalytic role in reorganizing settlement patterns from the pre-Yangshao period to the Bronze Age. By integrating key paleoclimatic proxies (Fig. 8), including $\delta^{18}O$ records from Magou Cave (Cai et al., 2021), pollen precipitation reconstruction in the Gonghai

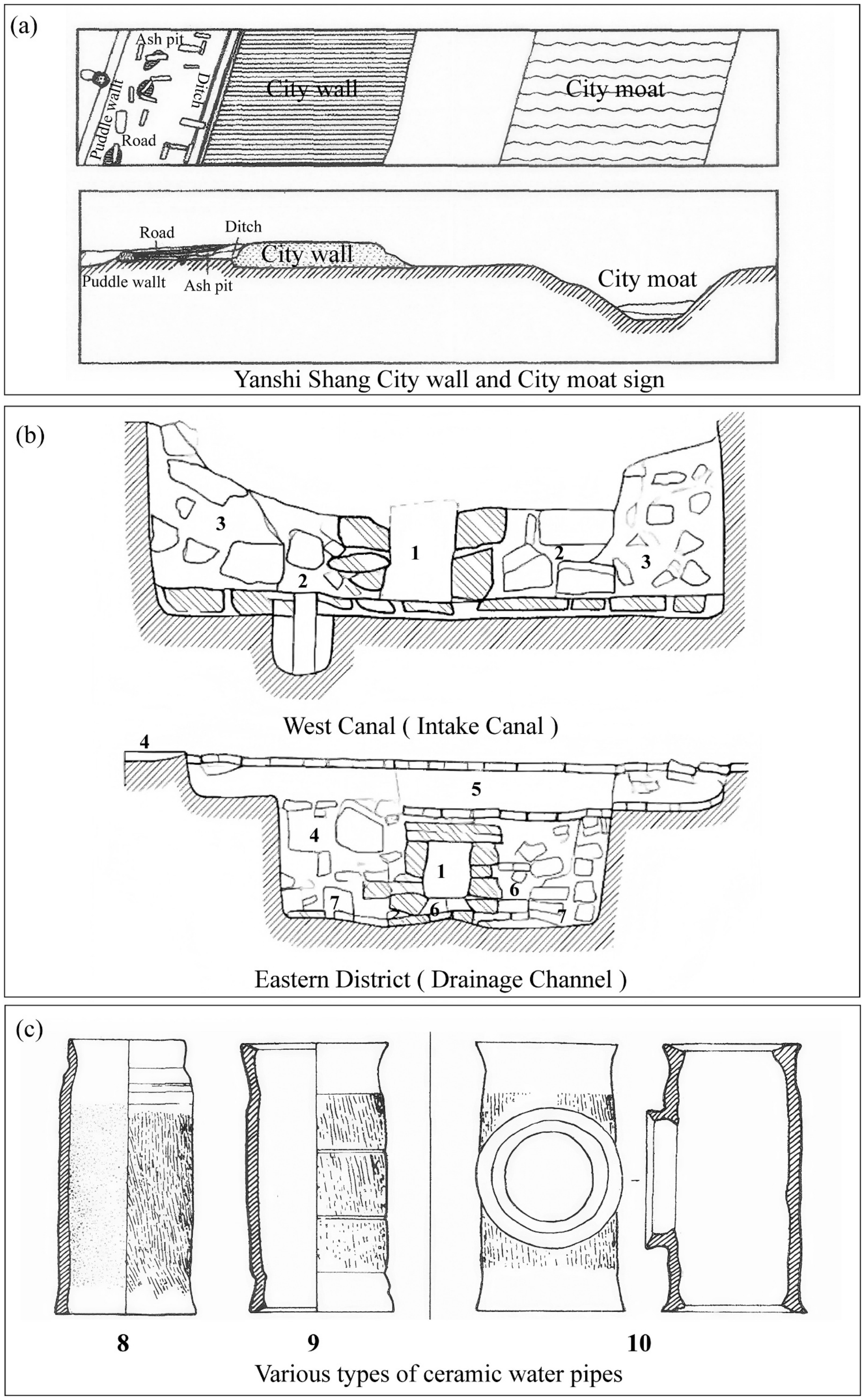

Fig. 9. Anyang Yinxu Gathering and Drainage System. According to 'Henan Yanshi Shangcheng Gongcheng Chiyuan Site' (Zhang, 2015). (a) Yanshi Shang City wall and City moat sign; (b) Yanshi Shangcheng palace city pool garden drainage channel section; (c) All kinds of pottery water pipes in Yanshi Shangcheng. 1. The reconstructed waterway; 2. Reconstruction part; 3. Early waterway stone wall; 4. Gray soil layer; 5. Soil layer; 6. Silt in the early waterway; 7. Early waterway stone plug; 8. Plug-in ceramic tube; 9. Flat mouth type ceramic tube; 10. Three-way ceramic tube.

(Chen et al., 2015b), global temperature trends (Shi et al., 2012), soil erosion indices (Zhao et al., 2022b), and flood frequency records (Zhou et al., 2014), we constructed a basin-wide environmental stress timeline to assess its correlation with spatial settlement dynamics.

The Holocene climate phases in the Yellow River Basin were characterized by a cold–dry early Holocene, a warm–humid mid-Holocene, and a late Holocene return to cooler, drier conditions—with 4.0–3.0 cal. ka BP marking a pivotal climatic transition (Cui et al., 2017; Huang et al., 2004; Lu et al., 2013). Within this broader climatic framework, several abrupt events are noteworthy: dry-cold episodes around 5.5, 4.0, and 3.3–3.0 cal. ka BP coincide with cultural transitions between Yangshao, Longshan, and early Bronze Age societies (Fig. 8c, Fig. 8e). These episodes were associated with increased environmental unpredictability, notably greater rainfall seasonality and extreme flood events. Sedimentary archives and archaeological stratigraphy reveal widespread settlement relocations during these period (Wei, 2022; Yang, 2013). Climatic instability, rather than uniform environmental deterioration, appears to have disrupted existing settlement structures and triggered spatial reorganization.

Flooding, as a direct consequence of intensified climate variability, has significantly influenced settlement siting, duration, and form. Flood frequency reconstructions across 73 dated sites (**Appendix B**) reveal two major peaks at 4.2–4.0 and 3.2–3.0 cal. ka BP, concentrated in the middle and lower Yellow River (Zhang et al., 2019). These periods coincide with substantial social transitions and phases of site abandonment. From the Qijia cultural strata in the upper basin (Ma et al., 2012) to the YGZ (Yang, 2013), HXZ (Zha et al., 2009), GC (Yang et al., 2023), and SYZ sites (Situ et al., 2020) in the middle and lower reaches (Fig. 6), multiple archaeological layers exhibit flood-induced sedimentary hiatuses or cultural thinning. The Longshan cultural horizon is particularly affected, with high flood frequency correlating with widespread relocation of settlements to higher elevations and increased distances from rivers (Huang et al., 2011). Defensive architectural features such as moats and raised platforms, evident in Erlitou and other Bronze Age sites, reflect a transition from reactive retreat to proactive urban planning in response to hydrological threats (Li and Gao, 2021; Liu and Chen, 2017; Yang et al., 2023; Zhang et al., 2019).

Furthermore, significant differences exist in flood frequency and mechanisms between settlement sites in the upper-middle and lower reaches of the Yellow River Basin. In the middle-upper reaches, numerous flood layers indicate a high frequency of occurrence, driving deep valley incision and sediment redistribution (Zha et al., 2009; Zhang et al., 2019). Societies in these regions primarily adapted through vertical migration (relocating to higher terraces) as a key strategy (Fig. 2). In contrast, the lower reaches are characterized by large-scale, low-energy, yet prolonged inundation due to channel avulsions (Xue, 1993) and overbank flooding across the extremely gentle gradient (Shi et al., 2025). This environmental setting has created vast, uninhabitable marshlands and frequent catastrophic floods, necessitating larger-scale and more centralized management coordination. The emergence of large-scale settlements (Chen et al., 2012) became feasible only during the late Longshan period and into the Bronze Age, coinciding with the development of more complex political structures, which also helps explain the delayed development observed in the North China Plain of the lower Yellow River region.

Soil erosion and accelerated sedimentation, as secondary hazards, not only degrade land quality but also redefine the spatial suitability of settlement zones. Reconstructed erosion curves (Fig. 7b) show increasing rates from 5.0 to 3.0 cal. ka BP, forming a distinct erosion peak in the late Longshan period. In the middle reaches, anthropogenic disturbance—have including slope agriculture and vegetation clearance—amplified natural erosion processes (Jing and Chen, 1983). By the late Holocene, human-driven erosion fundamentally altered the depositional landscape:, impacting sediment composition, catchment stability, and river morphology. As observed in lake records from the upper basin, sedimentation rates reached 0.125 cm/a during 8.0–3.0 cal. ka BP (Fig. 7b-1), while in the midstream alluvial plains, peak deposition between 8.0 and 6.0 cal. ka BP (up to 0.8 cm/a) corresponded with the flourishing of Yangshao agriculture(Fig. 7b-2) (Yang and Yuan, 2001). In the lower basin, multiple cultural layers in profiles like SYZ suggest recurring abandonment and reoccupation, indicating the dual role of floods and erosion in displacing populations and renewing agricultural land (Situ et al., 2020).

Paleofloods and accelerated sedimentation jointly constrained settlement stability while simultaneously contributing to the formation of fertile land, producing a dual impact on prehistoric socio-environmental systems. On one hand, repeated flood events displaced human populations and disrupted settlement continuity, especially in low-lying alluvial plains. On the other hand, sedimentation contributed to the formation of agriculturally productive floodplains, which became the basis for reoccupation and long-term development. This dual role of disaster and opportunity shaped settlement decision-making throughout the Holocene. The spatial shift toward distant-water settlement patterns during and after the 4.2 cal. ka BP event further supports the conclusion that flood risk increasingly influenced site selection strategies.

The erosion-sediment system of the Yellow River Basin functioned both as a constraint and an enabler of settlement evolution, with paleofloods serving as key agents of spatial restructuring. This dynamic feedback loop between environmental disturbance and social response—where flood-induced displacement was followed by strategic resettlement and land-use adaptation—demonstrates that climate-driven processes were not merely destructive but were integrally woven into the fabric of settlement evolution and state emergence in the basin.

The spatial retreat from floodplains and the movement to upland areas during periods of climate stress reflect a deliberate adaptation strategy that evolved over time. Initially, settlements clustered close to rivers to maximize access to water and fertile land. However, as flood risk intensified and social systems evolved, human responses shifted toward elevational migration, buffer distancing, and engineered protection. Settlement site analysis during the Longshan period confirms increased average elevation and expanded distance from riverbanks (Fig. 2**,** Fig. 3b). This trajectory—retreat, adaptation, and reoccupation—captures the adaptive flexibility of prehistoric societies in balancing productivity with safety.

The spatial impacts of climate-induced hazards were ultimately mediated through social transformation, especially during the Bronze Age. By the second millennium BCE, advancements in productivity, governance, and infrastructure enabled societies not only to cope with environmental fluctuations, but also to centralize inresponse to these challenges. The emergence of the Erlitou capital and other regime-type cities in the Yiluo Basin and Zhengzhou region (Yang et al., 2019; Zhang et al., 2019)marks a turning point: settlement distribution during this period was increasingly shaped by political control rather than environmental constraints. The excavation report of the Yanshi Shang City reveals that the capital of the Shang Dynasty established a multi-level water management system characterized by diverse scales and sophisticated designs (Zhang, 2015). This system included not only protective moats and walls surrounding the capital but also an intricate network of drainage facilities within the city (Fig. 9). Notably, artificial trench systems were constructed along the periphery of rammed-earth walls, serving dual purposes of drainage and defense. The advanced functional zoning reflects significant progress in productivity, urban governance, and infrastructure development during this period. These innovations positively influenced both the city and the regime by enhancing the environmental adaptability and safety resilience of the capital (Li et al., 2023). Furthermore, hydraulic infrastructures underwent prolonged development in prehistoric and historic cities of North China (**Appendix C**). Efficient drainage and flood prevention mechanisms mitigated waterlogging risks and ensured urban security, while the coordinated design of moats and walls strengthened military defense capabilities (Zhao, 2021). This also reflects that with the development of the regime in the Bronze Age, the subjective initiative of human society to cope with environmental changes gradually increased.

Furthermore, The relocation of the Zhou capital exemplifies how early state development shaped settlement patterns.The relocation of the Zhou capital, as documented in the Book of Poetry·Daya·Mian (Zhou, 2019), illustrates how state development drove settlement movement. Pressured by the Rongdi tribes, a nomadic group, the ancient Danfu led his people from Bin to the foot of Mount Qi. After three generations of consolidation on the Zhouyuan plateau, continued threats and expansionist aims prompted King Wen to establish Feng and King Wu to build Hao (Zhang, 2014). Their establishment was motivated not only by political and military strategies aimed at confronting the Shang Dynasty but also by the eastward expansion of Zhou's political influence (Pan, 2011). These capitals functioned as strategic hubs for eastern operations and evolved into the political core of the Western Zhou, underscoring

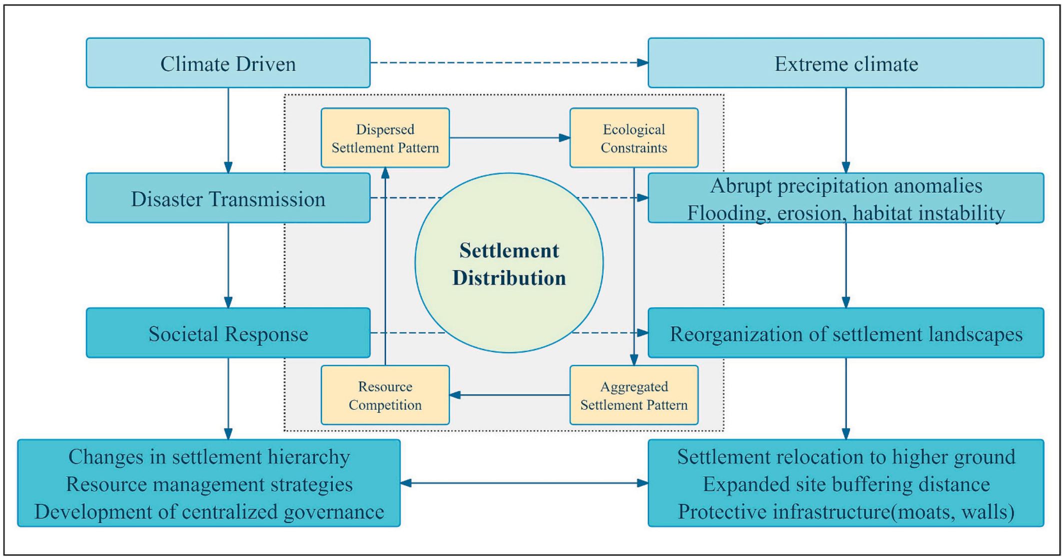

Fig. 10. "Climate-driven-disaster transmission-social response" process model diagram.

how state power directly shaped the shift of settlements.

Climatic hazards such as floods and erosion, served as both constraints and catalysts in the evolution of settlement landscapes (Fig. 10). Thse hazards necessitated relocation, prompted the development of new spatial strategies, and ultimately stimulated institutional responses that laid the groundwork for early state formation. The close temporal correspondence between peaks of paleofloods and erosion and the restructuring of settlement distributions strongly supports the conclusion that environmental stress—especially in the form of compound disasters—was a decisive force in shaping the prehistoric human–land relationship in the Yellow River Basin.

6. Conclusions

This study systematically examined the spatial and temporal dynamics of prehistoric settlements in the Yellow River Basin, integrating archaeological site distribution, geomorphic characteristics, and climate-induced environmental stress to elucidate how human–environment interactions influenced settlement evolution. This research highlights several major conclusions regarding prehistoric settlement dynamics.

Firstly, the temporal evolution of settlement patterns from the pre-Yangshao to the Bronze Age exhibits a progressive transition from dispersion to agglomeration. Although the total number of settlements increased over time, the growth rate fluctuated across periods. Spatially, three distinct distributional phases were observed: an initial dispersed pattern centered on the Wei River Basin during the pre-Yangshao period; a reorganization phase during the Yangshao and Longshan periods, characterized by vertical expansion (higher elevations, greater distance from rivers) and horizontal diffusion (notably toward the upstream Hehuang Valley); and a multi-center agglomeration pattern during the Bronze Age, marking spatial integration at the basin scale. Throughout this process, the middle reaches consistently remained the core settlement zone, while the upper reaches developed into a stable secondary center from the Yangshao period onward, and the lower reaches experienced delayed but rapid intensification of settlement clustering in the Bronze Age.

Secondly, settlement clustering evolved toward increased scale and differentiation. While the overall number of settlement groups exhibited a decreasing trend, the spatial structure became more complex. The emergence of more concentrated settlement cores and overlapping settlement zones—especially during the Bronze Age—reflects a rise in social stratification and institutional coordination. This spatial reorganization indicates that the Yellow River Basin underwent a profound division of social and economic functions across settlements, laying the groundwork for the formation of early state regimes.

Finally, the spatial reconfiguration of prehistoric settlements was closely linked to environmental changes, particularly climate-driven disasters such as floods and soil erosion. During the Yangshao and Longshan periods, settlements increasingly relocated to higher altitudes, steeper slopes, and greater distances from rivers, corresponding with stratigraphic records of frequent flood events and elevated sedimentation rates. These spatial adjustments confirm the presence of adaptive strategies aimed at disaster avoidance in response to increased hydrological risk. By the Bronze Age, however, the formation of a multi-center settlement network and the rise of early political centers suggest that spatial expansion mechanisms had begun to transcend passive environmental responses, reflecting a regime-led reorganization of human–land relationships.

CRediT authorship contribution statement

Tingting Zhou and Hongming He collected the research data, analyzed data, and wrote the original draft. Hongming He, Nufang Fang and Jianxin Cui designed the research and provided suggestions for improving the manuscript. Hongfei Zhao provided data correction. All authors modified the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2025.113280.

Data availability

The authors confirm that all data necessary for supporting the scientific findings of this paper have been provided.

References

Aghabayk, K., Parishad, N., Shiwakoti, N., 2021. Investigation on the impact of walkways slope and pedestrians physical characteristics on pedestrians normal walking and jogging speeds. Saf. Sci. 133, 105012. https://doi.org/10.1016/j.ssci.2020.105012.

An, C.-B., Chen, F., Feng, Z., 2002. Vegetation changes and human activities in the middle and late Holocene in Gansu and Qinghai areas. Arid Land Geogr. 25, 0160 (in Chinese with English abstract).

An, C.-B., Tang, L., Barton, L., Chen, F.-H., 2005. Climate change and cultural response around 4000 cal yr B.P. In the western part of Chinese Loess Plateau. Quat. Res. 63, 347–352. https://doi.org/10.1016/j.yqres.2005.02.004.

Bond, G., 2001. Persistent Solar Influence on North Atlantic climate during the Holocene. Science 294, 2130–2136, 10.1126%25252Fscience.1065680.

Cai, Y., Cheng, X., Ma, L., Mao, R., An, Z., 2021. Holocene variability of East Asian summer monsoon as viewed from the speleothem δ 18 O records in Central China. Earth Planet. Sci. Lett. 558, 116758. https://doi.org/10.1016/j.epsl.2021.116758.

Chen, Z., Wang, Z., Schneiderman, J., Taol, J., Cai, Y., 2005. Holocene climate fluctuations in the Yangtze delta of eastern China and the Neolithic response. The Holocene 15, 915. https://doi.org/10.1191/0959683605hl862rr.

Chen, Y., Syvitski, Jaia, Gao, Shu, Kettner, Albert J., 2012. Socio-economic Impacts on Flooding: a 4000-year history of the Yellow River, China. China Ambio 41. https://doi.org/10.1007/s13280-012-0290-5.

Chen, F., Dong, G., Zhang, D., Liu, X., Jia, X., An, C.-B., Ma, M., Xie, Y., Barton, L., Ren, X. Y., Zhijun, Z., Wu, X., 2015a. Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 BP. Science 347, 248–250.

Chen, F., Xu, Q., Chen, J., Birks, H., Liu, J., Zhang, S., Jin, L., An, C.-B., Telford, R., Cao, X., Wang, Z., Zhang, X., Kandasamy, S., Lu, H., Li, Y., Zheng, Z., Wang, H., Zhou, A., Dong, G., Rao, Z., 2015b. East Asian summer monsoon precipitation variability since the last deglaciation. Sci. Rep. https://doi.org/10.1038/srep11186.

Costanza, R., Graumlich, L., Steffen, W., Crumley, C., Dearing, J., Hibbard, K., Leemans, R., Redman, C., Schimel, D., 2009. Sustainability or Collapse: what can we Learn from Integrating the history of Humans and the rest of Nature? AMBIO 36, 522–527. https://doi.org/10.1579/0044-7447(2007)36%255B522:SOCWCW%255D2.0.CO;2.

Cui, J., 2024. Mapping landscape in Longshan period's hierarchical society (3000–2000BCE) of North Loess Plateau: from archaeological predictive model to GIS spatial analysis. Herit. Sci. 12. https://doi.org/10.1186/s40494-024-01194-5.

Cui, J., Zhou, S., Wang, J., Han, H., 2005. Fluvial-lacustrine sediments and Holocene climatic and hydrologic events in the middle of the Hebei Plains. Mar. Geol. Quat. Geol. https://doi.org/10.1109/IGARSS.2005.1526879.

Cui, Y., Liu, Y., Ma, M., 2017. Spatiotemporal evolution of prehistoric Neolithic-Bronze Age settlements and influencing factors in the Guanting Basin, northeast Tibetan Plateau. Sci. China Earth Sci. 61, 1–14. https://doi.org/10.1007/s11430-017-9138-8.

Demattè, P., 1999. Longshan-era urbanism: the role of cities in Predynastic China. Asian Perspect. 38.

Dong, G., Jia, X., Elston, R., Chen, F., Li, S., Wang, L., Cai, L., An, C.-B., 2013. Spatial and temporal variety of prehistoric human settlement and its influencing factors in the upper Yellow River valley, Qinghai Province, China. J. Archaeol. Sci. 40, 2538–2546. https://doi.org/10.1016/j.jas.2012.10.002.

Dong, G., Zhang, S., Yang, Y., Chen, J., Chen, F., 2016. Agricultural intensification and its impact on environment during Neolithic Age in northern China. Chin. Sci. Bull. 61. https://doi.org/10.1360/N972016-00547.

Dong, G., Liu, F., Chen, F., 2017. Environmental and technological effects on ancient social evolution at different spatial scales. Sci. China Earth Sci. 60. https://doi.org/10.1007/s11430-017-9118-3.

Dong, G., Ruo, L., Lu, M., Zhang, D., James, N., 2019. Evolution of human-environmental interactions in China from the late Paleolithic to the Bronze Age. Prog. Phys. Geogr. 44. https://doi.org/10.1177/0309133319876802.

Dong, G., Lu, Y., Zhang, S., Huang, X., Ma, M., 2022. Spatiotemporal variation in human settlements and their interaction with living environments in Neolithic and Bronze Age China. Prog. Phys. Geogr. 46. https://doi.org/10.1177/03091333221087992, 030913332210879.

Du, Xinyu, Gong, Wei, 2023. Spatial and temporal evolution of prehistoric settlement sizes and clusters in the Dongting Lake Area. Areal Res. Dev. 42, 143–149 (in Chinese with English abstract).

Gao, W., Hu, H., Hou, W., Zhang, P., Gong, P., Jia, W., Liu, X., Li, K., 2022. The spatiotemporal patterns of human settlement during the longshan and erlitou periods in relation to extreme floods and subsistence strategy in the Upper and Middle Qin River Reaches, Central China. Land 11, 1088. https://doi.org/10.3390/land11071088.

Guo, C., Ma, Y., Li, J., Meng, H., 2024. Cyclic climate impacts on human activity in northern Central China recorded by varve evidence from the western Loess Plateau. Palaeogeogr. Palaeoclimatol. Palaeoecol. 644, 112205. https://doi.org/10.1016/j.palaeo.2024.112205.

Hall, S.A., 1977. Late Quaternary Sedimentation and Paleoecologic History of Chaco Canyon. Geological Society of America Bulletin, New Mexico. https://doi.org/10.1130/%25200016-7606(1977)%252088%253C1593:LQSAPH%253E%25202.0.CO;2.

He, X., Tang, K., Zhang, X., 2004. Soil Erosion Dynamics on the Chinese Loess Plateau in the last 10,000 years. Mt. Res. Dev. 24, 342–347.

He, L., Xue, C., Ye, S., Amorosi, A., Yuan, H., Yang, S., Laws, E., 2019. New evidence on the spatial-temporal distribution of superlobes in the Yellow River Delta complex. Quat. Sci. Rev. 214, 117–138. https://doi.org/10.1016/j.quascirev.2019.05.003.

He, P., Liu, J., Wang, B., Sun, W., 2021. Understanding global monsoon precipitation changes during the 8.2 ka event and the current warm period. Palaeogeogr. Palaeoclimatol. Palaeoecol. 586, 110757. https://doi.org/10.1016/j.palaeo.2021.110757.

Hou, Y., Zhu, Y., 2000. Important climatic events showed by history records from middle and lower reach plain of the Yellow River during 5-2.7 ka and their environmental significance. Mar. Geol. Quat. Geol. 20, 23–29.

Hou, G., Xu, C., Lu, C., Chen, Q., Zhuoma, Lancuo, 2019. The environmental background of Yangshao culture expansion in the mid-Holocene. Geogr. Res. (2), 437–444 (in Chinese with English abstract). 10.11821/dlyj020171214.

Huang, C.C., Pang, J., Zhou, Q., Chen, S., 2004. Holocene pedogenic change and the emergence and decline of rain-fed cereal agriculture on the Chinese Loess Plateau. Quat. Sci. Rev. 23, 2525–2535. https://doi.org/10.1016/j.quascirev.2004.06.003.

Huang, C.C., Pang, J., Zha, X.P., 2011. Prehistorical floods in the Guanzhong Basin in the Yellow River drainage area. Sci. China Earth Sci. 41, 1658–1669.

Huzayyin, S., 1939. Some new light on the beginnings of Egyptian civilization. Bull. Egypt. Geogr. Soc. 20, 203–273.

Jiang, Baoming, Cui, Jianxin, 2017. Spatial characteristics of the Yangshao-Longshan sites and its environmental background in Qishuihe basin. J. Arid Land Resour. Environ. 31, 63–68 (in Chinese with English abstract). 10.13448/j.cnki.jalre.2017.248.

Jiang, Q., Meng, B., Wang, Z., Qian, P., Zheng, J., Jiang, J., Zhao, C., Hou, J., Dong, G., Shen, J., Liu, W., Liu, Z., Chen, F., 2022. Exceptional terrestrial warmth around 4200–2800 years ago in Northwest China. Sci. Bull. 67, 427–436. https://doi.org/10.1016/j.scib.2021.11.001.

Jiang, S., Luo, W., Zhou, X., Li, Z.-B., Luo, Y., Chen, A., Liu, X., Zhao, H., Zhang, G., Zhang, J., 2025a. Collapse of prehistoric cultures in Central-Eastern China linked to the El Niño-like states during the 4.2 ka event. Glob. Planet. Chang. 248, 104772. https://doi.org/10.1016/j.gloplacha.2025.104772.

Jiang, J., Zhang, Y., Kong, D., Lu, H., Wang, H., Liang, Y., Lee, C.W.M., Liu, H., Meng, B., Xie, Z., Yan, H., Liu, W., Liu, Z., 2025b. Enhanced East Asian summer monsoon circulation during the early to Middle Bronze Age. Quat. Sci. Rev. 363, 109439. https://doi.org/10.1016/j.quascirev.2025.109439.

Jing, K., Chen, Y., 1983. Preliminary study of the erosion environment and rates on the loess plateau. Geogr. Res. 1–11 (in Chinese with English Abstract). 10.11821/yj1983020001.

Jos, A., Guerra, T., Fullen, M.A., Jorge, M.D.C.O., Bezerra, J.F.R., Shokr, M.S., 2017. Slope processes, mass movement and soil erosion: a review. Soil Circle 27, 27–41.

Kawahata, H., Yamamoto, H., Ohkushi, K., Yokoyama, Y., Kimoto, K., Yamaoka, K., 2009. Changes of environments and human activity at the Sannai-Maruyama ruins in Japan during the mid-Holocene Hypsithermal climatic interval. Quat. Sci. Rev. 28. https://doi.org/10.1016/j.quascirev.2008.12.009.

Kidder, T., Henry, E., Arco, L., 2018. Rapid climate change-induced collapse of hunter-gatherer societies in the lower Mississippi River valley between ca. 3300 and 2780 cal yr BP. Sci. China Earth Sci. 61, 178–189. https://doi.org/10.1007/s11430-017-9128-8.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the last Glacial Maximum to the Holocene. Proc. Natl. Acad. Sci. 111, 15296–15303. https://doi.org/10.1073/pnas.1411762111.

Leland, M., Healy, J., Astels, Steve, 2017. Hdbscan: Hierarchical Density Based Clustering. Open Source Softw.

Li, K., Gao, W., 2021. Human settlement distribution patterns during the Longshan and Xinzhai-Erlitou periods and their hydrogeomorphic contexts in the Central Plains, China. CATENA 204, 105433. https://doi.org/10.1016/j.catena.2021.105433.

Li, C.X., Zhang, J.Q., Fan, D.D., Deng, B., 2001. Holocene regression and the tidal radial sand ridge system formation in the Jiangsu coastal zone, East China. Mar. Geol. 173, 97–120. https://doi.org/10.1016/S0025-3227(00)00169-9.

Li, G., Hu, B., Bi, J., Song, Z., 2013. Stratigraphic evolution of the huanghe delta (Bohai Sea) since the late Quaternary and its Paleoenvironmental Implications: evidence from Core ZK1 LI Guo. Acta Sedimentol. Sin. 31.

Li, G., Hu, B., Bi, J., Song, Zhuoli, 2013a. Stratigraphic evolution of the huanghe delta Bohai Seasince the Late Quaternary and lts Paleoenvironmental Implications: evidence from Core ZK1. Acta Geograph. Sin. 31, 1050–1058 (in in Chinese with English abstract). 10.14027/j.cnki.cjxb.2013.06.019.

Li, T.Y., Mo, D.W., Hu, K., 2013b. The environmental and cultural background of the Taosi site, Xiangfen county, Shanxi Province. Sci. Geol. Sin. 33, 443–449.

Li, T., Mo, D., Kidder, T., Zhang, Y., Wang, H., Wu, Y., 2014. Holocene environmental change and its influence on the prehistoric culture evolution and the formation of the Taosi site in Linfen basin, Shanxi province, China. Quat. Int. 349. https://doi.org/10.1016/j.quaint.2014.07.054.

Li, D., Tan, L., An, Zhisheng, 2016. 5 ka BP event in monsoonal China. J. Earth Environ. 468–479. https://doi.org/10.7515/JEE201605003.

Li, H., Yifu, C., James, N., Ritchey, M., Liu, F., Junna, Z., Ma, M., Dong, G., 2022. Spatiotemporal variation of agricultural patterns in different geomorphologic and climatic environments in the eastern Loess Plateau, north-Central China during the late Neolithic and Bronze Ages. Sci. China Earth Sci. 65, 1–15. https://doi.org/10.1007/s11430-021-9879-x.

Li, C., Cao, Y., Zhang, C., Qin, L., Deng, Z., Chen, Y., Zhu, S., Li, W., Yuan, J., Zhang, H., Zhuang, Y., 2023. Earliest ceramic drainage system and the formation of hydro-

sociality in monsoonal East Asia. Nat. Water 1, 694–704. https://doi.org/10.1038/s44221-023-00114-4.
Li, Y., Zheng, W., Liu, Wenfei, Su, K., Liu, Wei, Zhang, J., Ning, K., Yang, Z., Jin, G., 2025. Quantitative climate reconstruction of the Mid- to late Holocene based on pollen records from Northern Shandong, China. Palaeogeogr. Palaeoclimatol. Palaeoecol. 665, 112815. https://doi.org/10.1016/j.palaeo.2025.112815.
Liu, L., 2005. The Chinese Neolithic: Trajectories to Early States, pp. 1–310. https://doi.org/10.1017/CBO9780511489624.
Liu, J., 2007a. The Research of Settlements Archaeology Supported by GIS. China University of Geosciences, Beijing.
Liu, L., 2007b. The Chinese Neolithic: Trajectories to Early States.
Liu, L., Chen, X., 2017. The Archaeology of China from the Late Paleolithie to the Burly Bronze Age.
Liu, F., Feng, Z., 2012. A dramatic climatic transition at ~4000 cal. Yr BP and its cultural responses in Chinese cultural domains. The Holocene 22, 1181–1197. https://doi.org/10.1177/0959683612441839.
Liu, X., Reid, R., 2020. The prehistoric roots of Chinese cuisines: mapping staple food systems of China, 6000 BC–220 AD. PLoS One 15, e0240930. https://doi.org/10.1371/journal.pone.0240930.
Liu, B.Y., Nearing, M.A., Risse, L.M., 1994. Slope Gradient Effects on Soil loss for Steep Slopes. Trans. ASAE 37, 1835–1840. https://doi.org/10.13031/2013.28273.
Liu, X., Dong, H., Rech, J.A., Matsumoto, R., 2008. Evolution of Chaka Salt Lake in NW China in response to climatic change during the Latest Pleistocene–Holocene. Quat. Sci. Rev. 24, 867–879. https://doi.org/10.1016/j.quascirev.2007.12.006.
Liu, X., Zhijun, Z., Liu, G., O'Connell, T., 2012. The erliest evidence of millet as a staple crop: new light on Neolithic foodways in North China. Am. J. Phys. Anthropol. 149, 283–290. https://doi.org/10.1002/ajpa.22127.
Liu, Y., Huang, H., Qi, Y., Liu, X., Yang, X., 2016. Holocene coastal morphologies and shoreline reconstruction for the southwestern coast of the Bohai Sea, China. Quat. Res. 86, 144–161. https://doi.org/10.1016/j.yqres.2016.06.002.
Lu, H., Yi, S., Liu, Z., Mason, J., Cheng, J., Stevens, T., Xu, Z., Zhang, E., Jin, L., Zhang, Z., Guo, Z., Wang, Y., Otto-Bliesner, B., 2013. Variation of East Asian monsoon precipitation during the past 21 k.y. and potential CO2 forcing. Geology 41, 1023–1026. https://doi.org/10.1130/g34488.1.
Lu, P., Tian, Y., Chen, P., Yan, L., Song, L., 2014. The relationship between settlements distribution and regional tectonics around the Songshan Mountain during 9000-3000 aBP. Acta Geograph. Sin. 69, 738–746. https://doi.org/10.11821/dlxb201406002.
Lu, P., Tian, Y., Chen, P., Mo, D.W., 2016. Spatial and temporal modes of prehistoric settlement distribution around Songshan Mountain. Acta Geograph. Sin. 1629–1639. https://doi.org/10.11821/dlxb201609013.
Ma, M., Dong, G., Chen, F., Meng, X., Wang, Z., Elston, R., 2012. Process of paleofloods in Guanting basin, Qinghai Province, China and possible relation to monsoon strength during the mid-Holocene. Quat. Int. 321. https://doi.org/10.1016/j.quaint.2012.05.031.
Ma, M., Jiajia, D., Yang, Y., Wang, J., Chen, G., Gang, L., He, L., Wei, W., Xu, Y., Lu, Y., Ren, L., Dong, G., Chen, F., 2023. Isotopic evidence reveals the gradual intensification of millet agriculture in Neolithic western Loess Plateau. Fundam. Res. https://doi.org/10.1016/j.fmre.2023.06.007.
Mischke, S., Zhang, C., Borner, A., Herzschuh, U., 2010. Lateglacial and Holocene variation in aeolian sediment flux over the northeastern Tibetan Plateau recorded by laminated sediments of a saline meromictic lake. J. Quat. Sci. 25, 162–177. https://doi.org/10.1002/jqs.1288.
National Cultural Heritage Administration, 1998. Atlas of Chinese Cultural Relics.
Nearing, M.A., Xie, Y., Liu, B., Ye, Y., 2017. Natural and anthropogenic rates of soil erosion. Int. Soil Water Conserv. Res. 5, 77–84. https://doi.org/10.1016/j.iswcr.2017.04.001.
Pan, M.J., 2011. The evolution of the status of the Zongzhou capital and the capital system of the Western Zhou Dynasty. In: Human Activities and Environmental Changes in Guanzhong Region. Sanqin Publishing House, Xi'an, pp. 65–75.
Pauline, S., Williams, J., Liu, X., Lixin, W., 2021. Changing settlement patterns and subsistence strategies in Northeast China: results of the Yueliang regional survey. Archaeol. Res. Asia 25, 100250. https://doi.org/10.1016/j.ara.2020.100250.
Pederson, N., Hessl, A.E., Baatarbileg, N., Anchukaitis, K.J., Di Cosmo, N., 2014. Pluvials, droughts, the Mongol Empire, and modern Mongolia. Proc. Natl. Acad. Sci. 111, 4375–4379. https://doi.org/10.1073/pnas.1318677111.
Qin, Z., Storozum, M., Liu, H., Kidder, T., 2022. Holocene landscape evolution in northern Henan Province and its implications for archaeological surveys. Geoarchaeology 38. https://doi.org/10.1002/gea.21938.
Ruo, L., Lv, F., Liu, Y., Liu, F., Liu, R., Dong, G., 2020. Spatial-temporal variation of cropping patterns in relation to climate change in Neolithic China. Atmosphere 11, 1–12. https://doi.org/10.3390/atmos11070677.
Saito, Y., Wei, H., Zhou, Y., Nishimura, A., Sato, Y., Yokota, S., 2000. Delta progradation and chenier formation in the Huanghe (Yellow River) Delta, China. J. Asian Earth Sci. 18, 489–497. https://doi.org/10.1016/S1367-9120(99)00080-2.
Saito, Y., Yang, Z., Hori, K., 2001. The Huanghe (Yellow River) and Changjiang (Yangtze River) deltas: a review on their characteristics, evolution and sediment discharge during the Holocene. Geomorphology 41, 219–231. https://doi.org/10.1016/S0169-555X(01)00118-0. The Yangtze River: an Introduction.
Shang, Z., Li-Zhu, Tian, Jian-Fen, Li, Yong-Sheng, Chen, Hong, Wang, 2013. Evolution of the Holocene sedimentary environment and terrestrial-marine interaction revealed by the borehole CH114 in the west coast of the Bohai Bay of China. Mar. Sci. Bull. 05.
Shen, Y., 1961. The discussion on geomorphological compartment. Geography 33–41.
Shen, J., Liu, X., Sumin, W., Matsumoto, R., 2005. Palaeoclimatic changes in the Qinghai Lake area during the last 18,000 years. Quat. Int. 136, 131–140. https://doi.org/10.1016/j.quaint.2004.11.014.
Shi, N., 1959. People's habitation and settlement distribution in the Stone Age.The. J. Humanit. 03, 41–54 (in Chinese with English abstract).
Shi, Z., Liu, X., Cheng, X., 2012. Anti-phased response of northern and southern East Asian summer precipitation to ENSO modulation of orbital forcing. Quat. Sci. Rev. 40, 30–38. https://doi.org/10.1016/j.quascirev.2012.02.019.
Shi, T., Miao, X., Shen, H., Zhai, Q., Wang, S., 2025. Extreme flood events in the Yi and Shu river basins of the Haidai region (Shandong Province, China) during the late Holocene: Implications for future risk prediction. Palaeogeogr. Palaeoclimatol. Palaeoecol. 674, 113011. https://doi.org/10.1016/j.palaeo.2025.113011.
Silverman, B.W., 1986. Density Estimation for Statistics and Data Analysis. Chapman and Hall.
Situ, K., Qin, Z., Liu, H., Qi, D., 2020. The alluvial geoarchaeology of Neihuang County, Henan Province. Quat. Sci. 40, 579–593. https://doi.org/10.11928/j.issn.1001-7410.2020.02.26.
Song, J., 2017. Study on the phenomenon of central-area transfer from prehistory to Qin and Han dynasties in Guanzhong Basin: and discussion the reason on the tremendous connotation difference between Zhou Yuan and Feng Hao site. Cult. Relics South. China 106–110 (in Chinese with English abstract).
Staubwasser, M., Weiss, H., 2006. Holocene climate and cultural evolution in late prehistoric–early historic West Asia. Quat. Res. 66, 372–387. https://doi.org/10.1016/j.yqres.2006.09.001.
Storozum, M., Liu, H., Qin, Z., Ming, K., Fu, K., Wang, H., Kidder, T., et al., 2017. Early evidence of irrigation technology in the North China Plain: Geoarchaeological investigations at the Anshang Site, Neihuang County, Henan Province, China: STOROZUM. Geoarchaeology 33. https://doi.org/10.1002/gea.21634.
Su, Y., Zhang, Y., Zhai, Q., Shi, T., Songna, W., Chen, P., Liu, X., Jin, L., Miao, X., 2025. Prehistoric archaeological site changes and their causes with paleofloods in Southern Shanxi Province, China. Quat. Sci. Rev. 351, 109182. https://doi.org/10.1016/j.quascirev.2025.109182.
Sun, N., Li, X., Dodson, J., Xinying, Z., Zhao, K., Yang, Q., 2016. The quantitative reconstruction of temperature and precipitation in the Guanzhong Basin of the southern Loess Plateau between 6200 BP and 5600 BP. The Holocene 26, 1200–1207. https://doi.org/10.1177/0959683616638417.
Sun, Z., Shao, J., Liu, L., Cui, J., Bonomo, M., Guo, Q., Wu, X., Wang, J., 2017. The first Neolithic urban center on China's north Loess Plateau: the rise and fall of Shimao. Archaeol. Res. Asia 14. https://doi.org/10.1016/j.ara.2017.02.004.
Sun, Q., Liu, Y., Salem, A., Marks, L., Welc, F., Ma, F., Zhang, W., Chen, J., Jiang, J., Chen, Z., 2019a. Climate-induced discharge variations of the Nile during the Holocene: evidence from the sediment provenance of Faiyum Basin, North Egypt. Glob. Planet. Chang. 172, 200–210. https://doi.org/10.1016/j.gloplacha.2018.10.005.
Sun, Q., Liu, Y., Wünnemann, B., Peng, Y., Jiang, X., Deng, L., Chen, J., Maotian, Li, Chen, Z., 2019b. Climate as a factor for Neolithic cultural collapses approximately 4000 years BP in China. Earth Sci. Rev. 197, 102915. https://doi.org/10.1016/j.earscirev.2019.102915.
Tan, L., Shen, C.-C., Cai, Y., Cheng, H., Edwards, R., 2018. Great flood in the middle-lower Yellow River reaches at 4000 a BP inferred from accurately-dated stalagmite records. Sci. Bull. 63, 206–208. https://doi.org/10.1016/j.scib.2018.01.023.
Vermeersch, P.M., Linseele, V., Marinova, E., Van Neer, W., Moeyersons, J., Rethemeyer, J., 2015. Early and middle holocene human occupation of the Egyptian Eastern Desert: Sodmein Cave. Afr. Archaeol. Rev. 32, 465–503. https://doi.org/10.1007/s10437-015-9195-6.
Vita-Finzi, C., Higgs, E., 1970. Prehistoric economy in the Mount Carmel Area of Palestine: site catchment analysis. Proc. Prehist. Soc. 36, 1–37. https://doi.org/10.1017/S0079497X00013074.
Wang, Q., 1993. On the diversion of the lower Yellow River and the development of ancient culture. Cult. Relics Cent. China 65–74.
Wang, S., Gong, Y., 2000. Chinese temperatures during several characteristic periods of the Holocene. Prog. Nat. Sci. 39–46.
Wang, W., Guo, X., 2016. Research on the Settlement Pattern and Society during the Longshan and Xia Periods in the Northern Shaanxi Region. Archaeology and Cultural Relics.
Wang, H., Chen, J., Zhang, X., Chen, F., 2014. Palaeosol development in the Chinese Loess Plateau as an indicator of the strength of the East Asian summer monsoon: evidence for a mid-Holocene maximum. Quat. Int. 334–335, 155–164. https://doi.org/10.1016/j.quaint.2014.03.013. ED@80: Loess in China and Europe - a Tribute to Edward Derbyshire.
Wang, Y., Long-rui, M.I.N., Jin, D.O.N.G., Pei-yi, Y.A.O., Zhen-qing, C.H.I., 2015a. Sedimentary characteristics and stratigraphic division of holocene series in Baiyang Dian, Hebei Provence. Acta Geosci. Sin. 36, 575–582.
Wang, F., Li, J., Chen, Y., Fang, J., Zong, Y., Shang, Z., Wang, H., 2015b. The record of mid-Holocene maximum landward marine transgression in the west coast of Bohai Bay, China. Mar. Geol. 359, 89–95. https://doi.org/10.1016/j.margeo.2014.11.013.
Wang, S., Zhang, Y., Wang, N., Huang, C.C., 2023. Relationship between the transition of Longshan Culture-Erlitou Culture and the hydro-climatic in the Luoyang Basin. Earth Sci. 1–19.
Wang, H., Yang, J., Xia, D., 2024. Middle to late Holocene climate change in the monsoon-dominated southeastern Tibetan Plateau and its relationship with human activity. Palaeogeogr. Palaeoclimatol. Palaeoecol. 645, 112209. https://doi.org/10.1016/j.palaeo.2024.112209.
Wei, Y., 2022. The Holocene Stalagmite Records from the Monsoon Fringe Zone in Northern China. Institute of Earth Environment, Chinese Academy of Science, Xi'an, pp. 53–57 (in Chinese with English abstract).

Weiss, H., Bradley, R., 2001. What drives societal collapse? Science 291, 609–610. https://doi.org/10.1126/science.1058775.
Weiss, H., Courty, M.-A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., Curnow, A., 1993. The genesis and collapse of third millennium North Mesopotamian Civilization. Science (New York, N.Y.) vol. 261, 995–1004. https://doi.org/10.1126/science.261.5124.995.
Wu, W., Liu, D., 2001. Event and its implications for the origin of ancient Chinese civilization. Quat. Sci. 21, 443–451 (in Chinese with English abstract).
Wu, W., Liu, T., 2004. Possible role of the "Holocene Event 3" on the collapse of Neolithic Cultures around the Central Plain of China. Quat. Int. 117, 153–166. https://doi.org/10.1016/S1040-6182(03)00125-3.
Wu, Q., Zhijun, Z., Liu, L., Granger, D., Wang, H., Cohen, D., Wu, X., Ye, M., Bar-Yosef, O., Lu, B., Zhang, J., Zhang, P., Yuan, D., Qi, W., Cai, L., Bai, S., 2016. Outburst flood at 1920 BCE supports historicity of Chinas Great Flood and the Xia dynasty. Science 353, 579–582. https://doi.org/10.1126/science.aaf0842.
Xian, B., Jiang, Z., 2005. Environment evolution and eustatic change of holocene in the Yellow River Delta. Mar. Geol. Quat. Geol. 25, 1–7.
Xu, J., 2001. Historical bank-breachings of the lower Yellow River as influenced by drainage basin factors. Catena 45, 1–17. https://doi.org/10.1016/S0341-8162(01)00136-9.
Xu, Q., Yang, J., Yuan, G., Chu, Z., Zhang, Z., 2015. Stratigraphic sequence and episodes of the ancient Huanghe Delta along the southwestern Bohai Bay since the LGM. Mar. Geol. 367. https://doi.org/10.1016/j.margeo.2015.05.008.
Xu, D., Lu, H., Chu, G., Liu, L., Shen, C., Li, F., Wang, C., Wu, N., 2019. Synchronous 500-year oscillations of monsoon climate and human activity in Northeast Asia. Nat. Commun. 10, 1–10. https://doi.org/10.1038/s41467-019-12138-0.
Xue, C., 1993. Historical changes in the Yellow River delta, China. Mar. Geol. 113, 321–330. https://doi.org/10.1016/0025-3227(93)90025-Q.
Yan, W., 1997. The prosperity and development of the civilization in the Yellow River basin. Huaxia Archaeol. 49–54 (in Chinese with English abstract). 10.16143/j.cnki.1001-9928.1997.01.004.
Yan, Y., Zhou, J., He, Z., Sun, Q., Fei, J., Xinying, Z., Zhao, K., Yang, L., Long, H., Zheng, H., 2016. Evolution of Luyang Lake since the last 34,000 years: climatic changes and anthropogenic impacts. Quat. Int. 440. https://doi.org/10.1016/j.quaint.2016.06.009.
Yan, L., Shi, S., Lu, P., 2017. Relationship between Prehistoric Settlements Location and River around Songshan Mountain Area. Areal Res. Dev. 36, 169–174 (in Chinese with English abstract).
Yang, Y., 2013. Environmental Records and Interdependence between Climatic and the Ancients in the Middle — Late Yangshao Culture Age Yangguanzhai Relic Site, Shaanxi Province, China. Northwest University.
Yang, X., Yuan, M., 2001. A study on interaction between human activities and past soil and water loss in Holocene. Bull. Soil Water Conserv. 21, 11–14 (in Chinese with English abstract).
Yang, L., Deo, R., AghaKouchak, A., Adamowski, J., Stone, R., Yin, Z., Liu, W., Si, J., Wen, X., Meng, Z., Cao, S., 2019. Domino effect of climate change over two millennia in ancient China's Hexi Corridor. Nat. Sustain. 2, 957–961. https://doi.org/10.1038/s41893-019-0397-9.
Yang, J., Liu, Z., Yin, J., Tang, L., Zhao, H., Song, L., Zhang, P., 2023. Paleoflood reconstruction in the lower Yellow River Floodplain (China) based on sediment grain size and chemical composition. Water 15, 4268. https://doi.org/10.3390/w15244268.
Yao, W.B., 2009. The Evolution of the Dongzhi Yuan Landscape during the Historic Period and its Causes. Shaanxi Normal University, Xian, China (in Chinese).
Yin, J.-J., Wang, Z., Wu, X., Tang, W., Li, J., Lan, G., Cheng, H., 2025. Hydroclimate change during the transition of mid-to late Holocene and its potential impacts on late Neolithic settlements in middle Yangtze Basin, Central-South China. Glob. Planet. Chang. https://doi.org/10.1016/j.gloplacha.2025.104834, 104834.
Yu, S.-Y., Zhu, C., Song, J., Qu, W., 2000. Role of climate in the rise and fall of Neolithic cultures on the Yangtze Delta. Boreas 29, 157–165. https://doi.org/10.1111/j.1502-3885.2000.tb01208.x.
Yu, S.-Y., Hou, Z., Chen, X., Wang, Y., Song, Y., Gao, M., Pan, J., Sun, M., Fang, H., Han, J., Kidder, T., Chen, F., 2020. Extreme flooding of the lower Yellow River near the Northgrippian-Meghalayan boundary: evidence from the Shilipu archaeological site in southwestern Shandong Province, China. Geomorphology 350, 106878. https://doi.org/10.1016/j.geomorph.2019.106878.
Zha, X., Huang, C.C., Pang, J., 2009. Palaeofloods recorded by slackwater deposits on the Qishuihe River in the Middle Yellow River. J. Geogr. Sci. 19, 681–690. https://doi.org/10.1007/s11442-009-0681-0.
Zhang, Q., 2014. A Survey of the Impact of Ecological Environment on the Historic Development of Western Zhou Dynasty. Zhengzhou University, Zhengzhou.
Zhang, X., 2015. Study of water supply and drainage in cities and settlements of the shang period. Huaxia Archaeol. https://doi.org/10.16143/j.cnki.1001-9928.2015.01.008.
Zhang, Shuwei, Yang, Z., Cioppa, M.T., Liu, Q., Wang, X., Eichhorn, H.S., Qiao, Y., Chen, F., Shao, Z., Liu, J., Zhang, Shihong, Gagnon, J.E., Huo, J., Sheng, M., 2018. A high-resolution Holocene record of the East Asian summer monsoon variability in sediments from Mountain Ganhai Lake, North China. Palaeogeogr. Palaeoclimatol. Palaeoecol. 508, 17–34. https://doi.org/10.1016/j.palaeo.2018.01.030.
Zhang, Yuzhu, Huang, C.C., Tan, Z., Chen, Y., Qiu, H., Huang, C., Li, Y., Zhang, Yunxiang, Li, X., Shulmeister, J., Patton, N., Liu, L., Zhu, Y., Wang, N., 2019. Prehistoric and historic overbank floods in the Luoyang Basin along the Luohe River, middle Yellow River basin, China. Quat. Int. 521. https://doi.org/10.1016/j.quaint.2019.06.023.
Zhang, Y., Zhang, G., Zhao, K., Wang, Ji, 2024. Mid to late Holocene climate changes and grazing activities in northern Loess Plateau, China. Palaeogeogr. Palaeoclimatol. Palaeoecol. 647, 112261. https://doi.org/10.1016/j.palaeo.2024.112261.
Zhao, H., 2021. New insights into the settlement patterns of the capital city at Erlitou. Chin. Archaeol. 21, 162–172. https://doi.org/10.1515/char-2021-0012.
Zhao, J.-B., Ma, Y.-D., Cao, J.-J., Hao, Y.-F., Shao, T.-J., Liu, X.-M., 2020. Holocene pedostratigraphic records from the southern Chinese Loess Plateau and their implications for the effects of climate on human civilization. CATENA 187, 104410. https://doi.org/10.1016/j.catena.2019.104410.
Zhao, H., Lin, Y., Delang, C., Ma, Y., Zhou, J., He, H., 2022b. Contribution of soil erosion to the evolution of the plateau-plain-delta system in the Yellow River basin over the past 10,000 years. Palaeogeogr. Palaeoclimatol. Palaeoecol. 601, 111133. https://doi.org/10.1016/j.palaeo.2022.111133.
Zhao, H., Lin, Y., Zhou, J., Delang, C., He, H., 2022c. Simulation of Holocene soil erosion and sediment deposition processes in the Yellow River basin during the Holocene. CATENA 219, 106600. https://doi.org/10.1016/j.catena.2022.106600.
Zheng, J., Wen, Y., Fang, X., 2020. Changes of climate and land cover in the middle and lower reaches of the Yellow River over the past 2000 years. Resour Sci 42, 3–19 (in in Chinese with English abstract).
Zhou, X.T., 2019. Book of Poetry: Anthology of Ancient Chinese Poems. Sichuan People's Publishing House, Chengdu.
Zhou, X., Yu, X., 2013. Correlation studies on palaeoflood events in the drainage area of Yangtze and Yellow River during the Holocene. J. Earth Environ. 4, 1427–1436. https://doi.org/10.7515/JEE201305001.
Zhou, L., Liu, J., Saito, Y., Liu, J.P., Li, G., Liu, Q., Gao, M., Qiu, J., 2014. Fluvial system development and subsequent marine transgression in Yellow River (Huanghe) delta and its adjacent sea regions during last glacial maximum to early Holocene. Cont. Shelf Res. 90, 117–132. https://doi.org/10.1016/j.csr.2014.06.012. Sediment Dynamics and Related Biogeochemical Effects in the Eastern China Shelf Seas.