

Mid-to-Late Holocene Hydroenvironmental Constraints on Human Adaptation at Fenghuangzui Site, Hanjiang River Basin, Central China

Aipeng Guo

Ningbo University of Finance & Economics

Hui Tian

Fenghuangzui Cultural Relics Conservation Center

Siwei Shan

Wuhan University

Qian Zhang

Ningbo University of Technology

Longjiang Mao

m1j1214@163.com

Nanjing University of Science and Technology ZiJin College

Duowen Mo

Peking University

Article

Keywords: Holocene, Hanjiang River basin, Fluvial–floodplain dynamics, Fenghuangzui site, Settlement–environment interactions

Posted Date: October 12th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11035665/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Mid-to-Late Holocene Hydroenvironmental Constraints on Human Adaptation at Fenghuangzui Site, Hanjiang River Basin, Central China

Aipeng Guo¹, Hui Tian², Siwei Shan³, Qian Zhang⁴, Longjiang Mao^{5*}, Duowen

Mo⁶

Abstract: Human responses to hydroclimatic variability are difficult to resolve where natural and anthropogenic sedimentary archives are conflated. We integrate OSL-constrained sedimentological and geochemical records from a natural palaeochannel adjacent to the Fenghuangzui site with moat sediments, archaeological evidence, regional pollen records and site distributions. The palaeochannel records progressive shallowing during 5.3–4.2 ka BP, renewed ponding around 4.2–3.9 ka BP and subsequent low-energy infilling with episodic sediment inputs. These hydrological changes were not synchronous with subsistence decline: rice-based production persisted as communities modified drainage, occupation surfaces and settlement organisation. Comparison of natural and engineered water bodies indicates that local water management mediated, rather than simply tracked, regional hydroclimatic change. Fenghuangzui therefore provides evidence for flexible adaptation within a long-lived ecological and cultural interface linking the middle Yangtze and Central Plains.

Keywords: Holocene; Hanjiang River basin; Fluvial–floodplain dynamics; Fenghuangzui site; Settlement–environment interactions

1. Introduction

Hydroclimatic variability shaped prehistoric settlement patterns and human–water

¹ College of Humanities, Ningbo University of Finance and Economics, Ningbo, Zhejiang, 315175, China.

²Fenghuangzui Cultural Relics Conservation Center, Xiangyang, Hubei, 441000, China. ³Department of Archaeology, School of History, Wuhan University, Wuhan, 430072, China. ⁴International Exchange College, Ningbo University of Technology, Ningbo, Zhejiang, 315000, China. ⁵School of Marine Science, Nanjing University of Information Science and Technology, Nanjing, 210044, China. ⁶College of Urban and Environmental Sciences, Peking University, Beijing, 100871, China.*e-mail: mlj1214@163.com

relationships in floodplain environments¹⁻³. During the middle to late Holocene, centennial- to millennial-scale hydroclimatic variability repeatedly altered river regimes, thereby reshaping the environmental settings in which settlements developed^{4,5}. To cope with these hydroclimatic risks, communities adjusted settlement locations, reorganised spatial layouts, diversified subsistence practices and modified their use of riverine resources^{1,2,6}. Evidence from the Nile Delta and northwestern Indus region further suggests that changing flood regimes, sedimentation and soil-moisture conditions prompted shifts in agricultural practices and settlement strategies^{7,8}. Consequently, site-scale reconstruction of palaeohydrological evolution provides a critical basis for examining how prehistoric settlements responded to changing riverine environments.

The Hanjiang River basin provides a particularly informative setting for investigating these interactions. During the Holocene, changes in monsoon-related precipitation were associated with floodplain aggradation, palaeoflood activity, and lacustrine expansion in different parts of the basin^{3,9,10}. Periods of enhanced flooding encouraged settlement relocation towards higher terraces and artificial mounds, while subsistence practices became increasingly dependent on rice cultivation¹¹. In addition, the Hanjiang River basin connects the cultural spheres of the middle Yangtze and Yellow River regions¹², and links the humid alluvial plains with the open inland areas¹³. Against a background of increasing hydroclimatic variability during the mid- to late Holocene¹⁴, the middle Yangtze River region witnessed the emergence of numerous large walled settlements, exemplified by the prehistoric urban centre of Shijiahe (SJH)^{1,15}. Several major centres developed increasingly sophisticated water-management systems, including moats, dams, channels and irrigation facilities, to regulate water supply and cope with flood risks^{1,16}. During 4.5–4.0 ka BP, major centres such as Taosi and Shimao also flourished in the Yellow River basin, while walled settlements such as Pingliangtai developed on the adjacent Central Plains^{16,17}. The contemporaneous development of these regional centres provides a broader comparative context for examining how increasingly complex societies responded to environmental and hydrological variability. Recent palaeoclimatic and archaeological evidence suggests that hydroclimatic change influenced prehistoric settlements in different ways, affecting their expansion, reorganisation and decline^{2,15,18}. However, the mechanisms linking hydroclimatic variability to specific adaptive responses remain insufficiently resolved. Despite the regional significance of the Hanjiang River basin, high-resolution site records that directly connect environmental change with settlement responses remain

limited.

The Fenghuangzui (FHZ) site provides a particularly suitable case for addressing this gap. Located in the Hanjiang River basin, FHZ developed into an important regional centre during the Qujialing–Shijiahe period (~5.3–3.9 ka BP) and occupied a key position along the cultural corridor linking the middle Yangtze and Central Plains regions¹⁹. Archaeobotanical evidence indicates that rice cultivation formed an important component of the local subsistence economy¹². FHZ is closely associated with surrounding riverine settings and evidence of water management. These characteristics make it well suited for examining how a major prehistoric settlement responded to hydroclimatic variability. Previous research on FHZ moat sediments has provided important information on local hydrological change and human activity^{19,20}. Anthropogenic moats are prone to disturbance that may obscure environmental signals, whereas natural sedimentary records from adjacent water bodies provide independent baselines of regional hydrological change. Comparing moat and palaeochannel archives helps distinguish regional fluvial dynamics from local anthropogenic effects, thereby improving assessments of hydroclimate–settlement adaptation relationships.

To address these issues, we analysed a newly recovered sediment core from a palaeochannel adjacent to the FHZ site. Multiproxy sedimentological, geochemical, and chronological data were used to reconstruct palaeohydrological variability and floodplain evolution during the middle and late Holocene. By integrating these records with archaeological evidence, we examine long-term human–environment interactions in the Hanjiang River basin. The objectives of this study are to: (1) reconstruct mid- to late-Holocene palaeohydrological evolution around the FHZ site; (2) characterise landscape dynamics at the FHZ site; and (3) evaluate the role of the FHZ site in regional cultural evolution and its interactions with environmental change.

2. Geographical setting and site description

The FHZ site (32°14′04.3″N, 111°59′20″E) is located in Qianwang Town, Xiangzhou District, Xiangyang City, Hubei Province, on the southern margin of the Nanyang Basin in the middle reaches of the Hanjiang River (Fig. 1a). The Hanjiang River originates from the southern foothills of the Qinling Mountains, flows through the Daba and Wudang mountain regions, and finally enters the Jiangnan Plain. Its basin exhibits a distinct geomorphological transition from mountainous and

hilly regions in the west and north to extensive alluvial plains in the east and south^{19,21} (Fig. 1b, Fig. 1c). The FHZ site lies in a watershed adjacent to that of Shijiahe, separated by the Dahong Mountains, and has been interpreted as an important northern outpost associated with the northward expansion of the Qujialing–Shijiahe cultural sphere into the Nanyang Basin¹³ (Fig. 1b).

Archaeological investigations have revealed a complex water-management system at FHZ, including a surrounding moat, water gates, two internal channels, a dam, spillways and an artificial earthen platform^{19,20} (Fig. 1d). The internal channels were connected with the moat, while external palaeochannels further linked the settlement to the Paizi River system, indicating deliberate integration of natural and engineered waterways. Recent excavations identified a dam and three spillways within the north–south channel, suggesting active regulation of water storage and discharge²⁰. The ancient riverbed in the west is 33–90 m wide and extends from the western upland towards the western moat¹⁹. Previous palaeoenvironmental work sampled moat section deposits to reconstruct local hydrological changes and human activities (Fig. 1d)¹⁹. In the present study, a new sediment core (FHZX) was collected from the natural palaeochannel west of the site, providing a complementary archive for distinguishing regional hydrological variability from local anthropogenic modification (Fig. 1d).

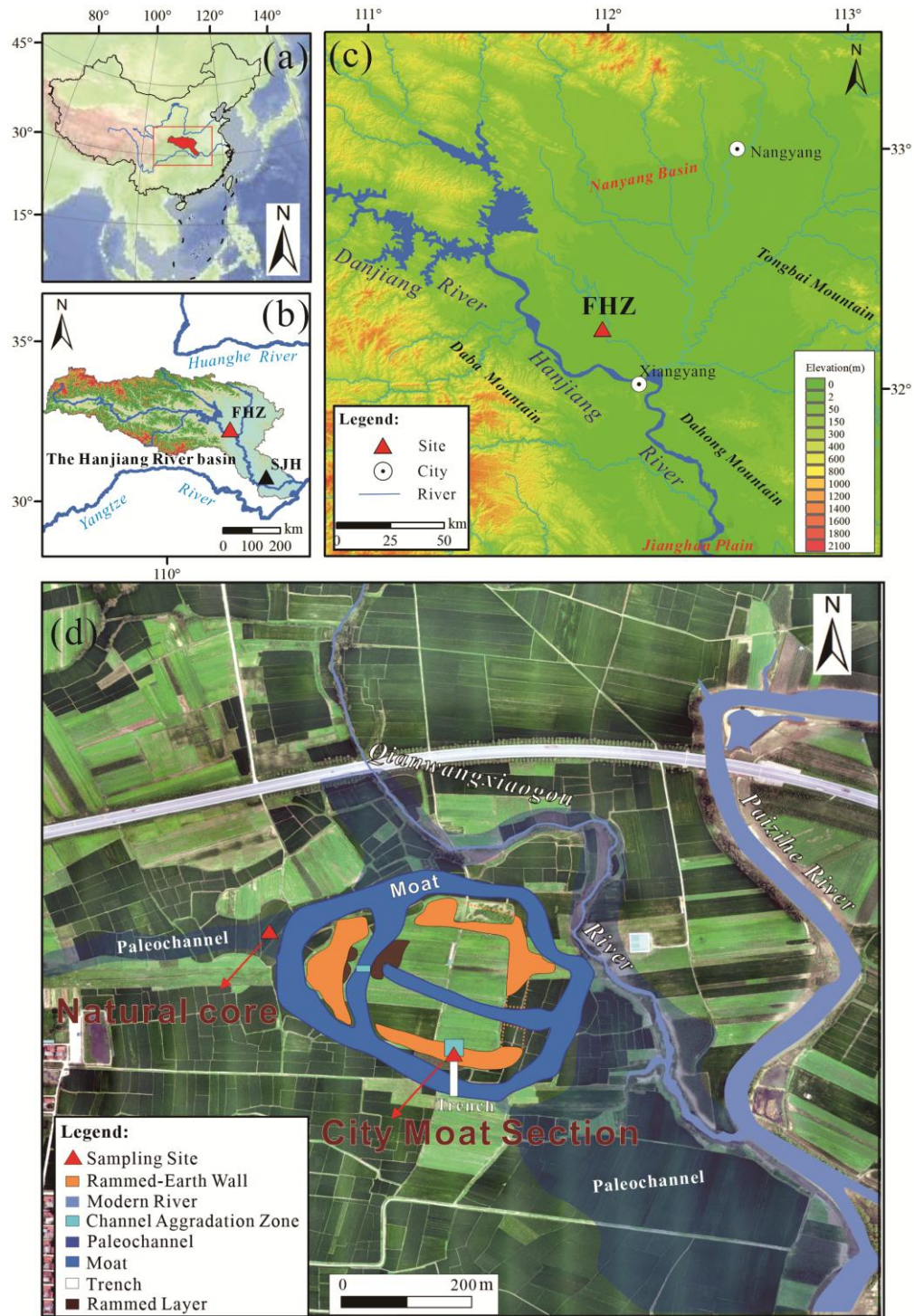


Fig. 1 | Geographical and hydrogeomorphological setting of the FHZ site in the Hanjiang River basin. **(a)** Location of the Hanjiang River basin in China. **(b)** Locations of the FHZ and SJH sites in the Hanjiang River basin. **(c)** Topographic and hydrological setting surrounding the FHZ site. **(d)** Reconstructed layout and hydrogeomorphological setting of the Fenghuangzui walled settlement¹⁹.

3. Materials and methods

3.1 Stratigraphy and chronological sampling

A sediment core was obtained from the western palaeochannel adjacent to the FHZ site and was designated FHZX (Fig. 2). This core provides a natural fluvial record for comparison with the

anthropogenically modified deposits preserved in the southern moat of the settlement. Core lithology was first recorded in the field and subsequently described in detail based on sediment colour, texture, sedimentary structure and inclusions. The 620 cm sequence shows clear vertical lithological variations. The lower part (620–540 cm) is dominated by yellowish-brown silt interbedded with bluish-grey mud, with minor carbonaceous debris near the base. Between 540 and 280 cm, the sequence is dominated by bluish-grey mud and greyish-yellow clay or silty clay, locally containing abundant reddish-brown mottles. The interval from 280 to 180 cm consists mainly of bluish-grey mud with relatively coarse yellow clayey-silt interbeds, whereas the upper 180 cm grades upward from grey mud and yellow clayey silt into modern topsoil (Fig. 2). The FHZX core was continuously subsampled at 5-cm intervals for subsequent geochemical and grain-size analyses.

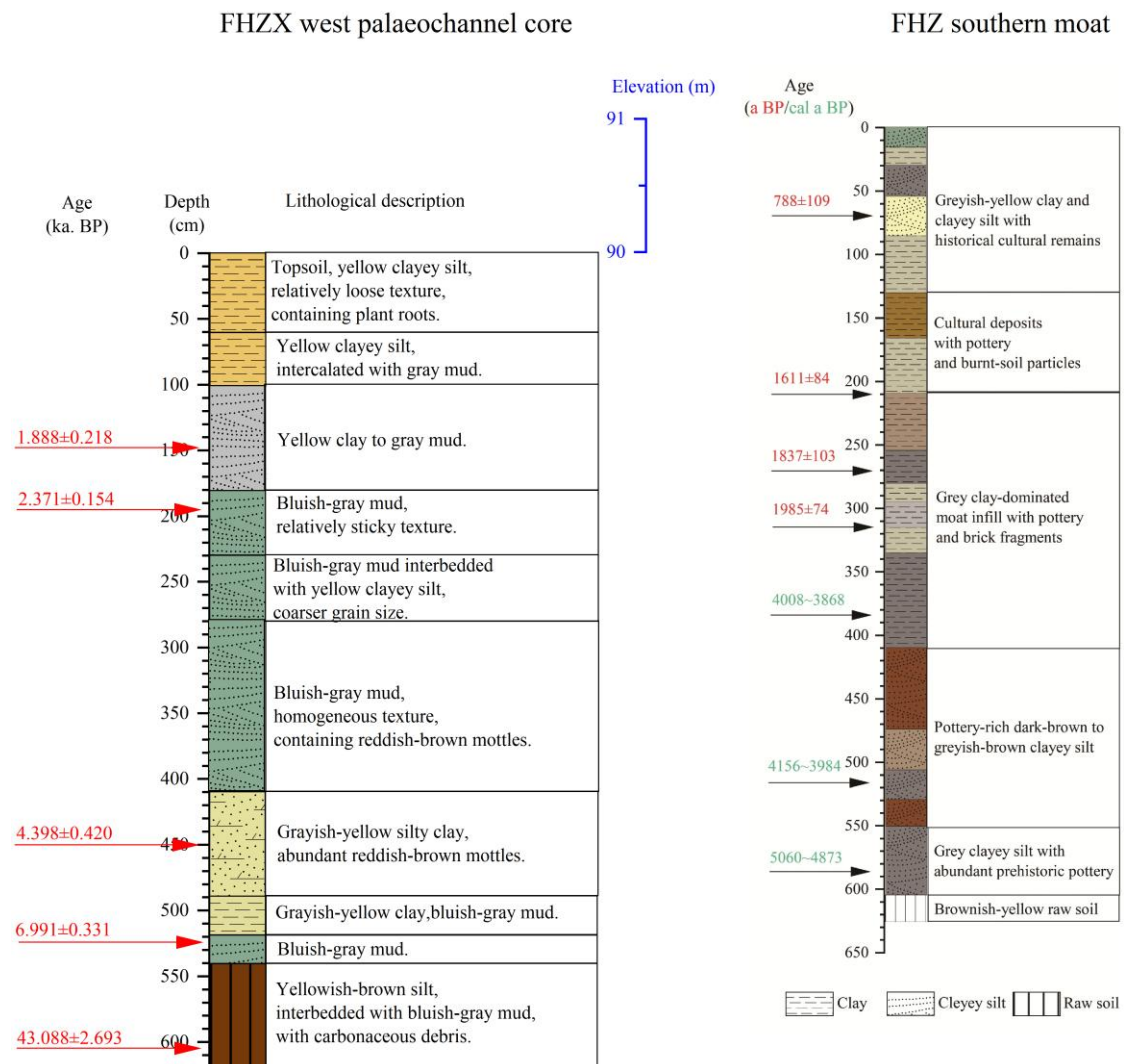


Fig. 2 | Lithostratigraphic and chronological comparison between the FHZ southern moat profile¹⁹ and the FHZX western palaeochannel core.

The FHZX sequence is used here as a natural fluvial–floodplain reference and is compared with the FHZ moat sequence, which contains stronger evidence of anthropogenic disturbance and cultural deposition. The FHZX core was continuously subsampled at 5-cm intervals for subsequent geochemical and grain-size analyses. Five OSL sampling points were established along the FHZX sequence to constrain the chronology of sediment accumulation.

OSL measurements were conducted at the State Key Laboratory of Estuarine and Coastal Research, East China Normal University. Under darkroom conditions, the outer portions of the samples were removed. The inner material was treated with 30% H₂O₂ and HCl to remove organic matter and carbonates. The 45–63 µm grain-size fraction was isolated by wet sieving, and feldspar was removed using 30% fluorosilicic acid to obtain purified quartz. Equivalent dose (D_e) was measured on a Risø TL/OSL DA-20 reader using blue light stimulation (470 ± 30 nm) and the single-aliquot regenerative-dose (SAR) protocol. A ⁹⁰Sr/⁹⁰Y beta source was used for artificial irradiation. Moisture content was estimated at $15 \pm 3\%$ (Table 1).

Table 1 | OSL dating results for the FHZX core.

OSL No.	Depth (cm)	U (mg/kg)	Th (mg/kg)	Rb (mg/kg)	K (%)	Dose rate (Gy/ka)	Aliquots (n)	OD (%)	Age (ka BP)
01	197.5	1.81±0.3	13.06±0.8	94.62±5	1.73±0.04	2.89±0.09	8	24.06	1.888±0.218
02	292.5	2.3±0.3	16.94±0.9	128.84±5	1.97±0.04	3.43±0.10	9	14.52	2.371±0.154
03	442.5	1.93±0.3	15.48±0.8	124.66±5	2.24±0.04	3.46±0.10	3	0.00	4.398±0.420
04	527.5	1.84±0.3	12.09±0.7	84.54±4	1.60±0.04	2.66±0.08	17	8.15	6.991±0.331
05	612.5	2.17±0.3	16.01±0.9	101.73±5	1.85±0.04	3.18±0.10	13	16.53	43.088±2.693

3.2 Major-element and grain-size analyses

Geochemical analyses were performed at Anhui Normal University. Air-dried samples with >1% water were oven-dried at 50–60 °C for 24 h, then ground (<200 mesh) and pressed into 2–4 mm thick, 35 mm diameter pellets under 30 t. Major elements were measured using a ZSX Primus IV XRF spectrometer (Rigaku, Japan), with GSS1 and GSD9 reference standards giving an analytical error within ±1%.

For grain-size analysis at Nanjing University of Information Science and Technology, ~1 g of sediment was treated with H₂O₂ and HCl and then dispersed in 0.5% sodium hexametaphosphate using ultrasonication. Particle-size distributions were measured using a Mastersizer 2000 (0.02–2000 µm; analytical error <2%).

To reconstruct mid- to late-Holocene environmental changes in the Hanjiang River basin, four

complementary proxies were interpreted collectively. The chemical index of alteration (CIA) was calculated from molar oxide proportions using $CIA = Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O) \times 100$, where CaO represents CaO associated with the silicate fraction after correction for non-silicate Ca. CIA was used as a relative indicator of chemical weathering intensity^{22,23}, whereas Ti/Al constrains variations in detrital supply and sediment provenance²⁴. Md primarily reflects changes in sediment transport and depositional energy²⁵, while Fe₂O₃/MnO provides a qualitative indication of sedimentary redox conditions²⁶. Similar combinations of grain-size and geochemical proxies have been successfully applied to Holocene palaeoflood and environmental reconstructions in the Hanjiang–Jiangnan–middle Yangtze region^{27,28}. Given their sensitivity to sediment sorting, provenance and detrital supply, these proxies were interpreted collectively rather than in isolation.

3.3 Regional pollen data and IDW interpolation

Regional pollen data were compiled from published records from the middle Yangtze, Nanyang Basin and adjacent Henan region^{18,29}, supplemented by the standardised Holocene pollen dataset for China. Archaeological distributions were derived from the national Neolithic–Bronze Age site database and published syntheses. Eight pollen taxa were analysed: *Artemisia*, *Carpinus*, *Chenopodiaceae*, *Cyperaceae*, *Pinus*, *Poaceae*, evergreen *Quercus* and *Ulmus*. Records were grouped into 5.3–4.5, 4.5–4.2 and 4.2–3.9 ka BP intervals, with 100-yr time slices used where resolution permitted. Samples older than 5.3 ka BP were excluded to minimise temporal mismatch and avoid introducing vegetation signals predating the study interval.

Pollen percentages were interpolated separately for each taxon and time slice using inverse distance weighting (IDW) in ArcGIS 10.8. The Spatial Analyst default parameters were used, with a power of 2 and a variable search radius incorporating the 12 nearest input points. IDW surfaces are used to visualise relative spatial gradients rather than fixed vegetation boundaries. Evergreen broad-leaved taxa and *Cyperaceae* are interpreted as reflecting comparatively humid forest and local wetland conditions, whereas *Artemisia*, *Chenopodiaceae* and *Poaceae* characterise more open herbaceous landscapes. *Cyperaceae* is not treated as a direct rainfall proxy, nor *Poaceae* as evidence of cultivation. Archaeological site counts are likewise used to describe spatial concentration rather than population size, given spatial variation in pollen source areas and archaeological recovery intensity.

4. Results

4.1 Sediment chronology

Five OSL ages were obtained from the FHZX core (Fig. 3). The sample at 612.5 cm yielded an anomalously old age relative to adjacent horizons and deviated markedly from the overall age-depth relationship; it was therefore treated as an outlier and excluded. The remaining four ages were modelled using a Bacon Bayesian age-depth model³⁰, yielding a monotonic age increase with depth and no reversal. The model provides the chronological framework used for the subsequent reconstruction. Given the four accepted ages, sub-centennial comparisons with regional records are treated as approximate rather than exact synchronisations.

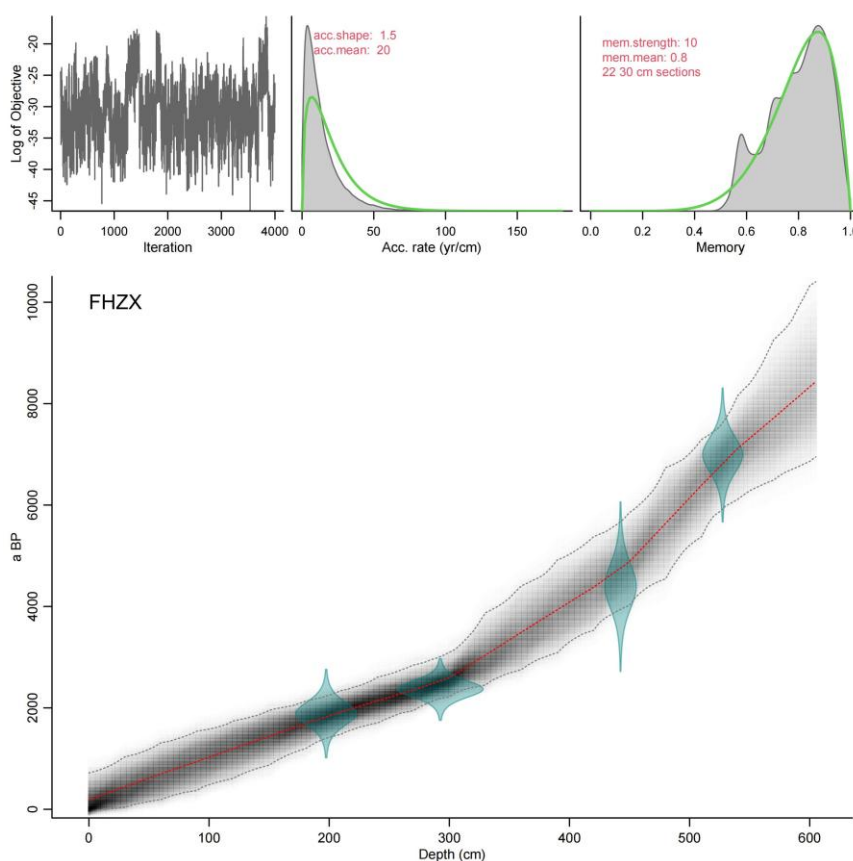


Fig. 3 | Bayesian age-depth model for the FHZX core³⁰.

4.2 Major-element characteristics

Major oxides (TiO_2 , CuO , Al_2O_3 , CaO , Na_2O , K_2O , Fe_2O_3 , MgO and MnO) exhibited distinct down-core variations in the FHZX sequence (Fig. 4). In Lithological Unit V (620–540 cm), most elemental concentrations fluctuated within relatively narrow ranges, with comparatively low Al_2O_3 and K_2O values and relatively high Na_2O values. In Unit IV (540–410 cm), Al_2O_3 , K_2O , Fe_2O_3 , MgO and CuO generally increased upwards from 540 cm, whereas Na_2O showed an overall decrease.

Al₂O₃ reached relatively high values at approximately 480–475 cm, whereas Fe₂O₃ reached a pronounced maximum at approximately 450 cm. Above these intervals, Al₂O₃, K₂O and MgO generally decreased towards 410 cm, whereas Fe₂O₃ remained relatively high and Na₂O continued to fluctuate at low values. In Unit III (410–280 cm), Al₂O₃ and K₂O remained comparatively high, TiO₂ and Na₂O showed overall upward increases, whereas Fe₂O₃ and MgO generally decreased upwards; CuO exhibited moderate fluctuations. Unit II (280–180 cm) was characterised by pronounced elemental variability, with a marked excursion at approximately 255–230 cm, where CuO, Al₂O₃, K₂O, Fe₂O₃ and MgO decreased markedly, whereas Na₂O increased and TiO₂ remained relatively high. In Unit I (180–0 cm), TiO₂, Al₂O₃, K₂O, Fe₂O₃, MgO and CuO generally decreased towards the surface, whereas Na₂O and CaO showed overall increases.

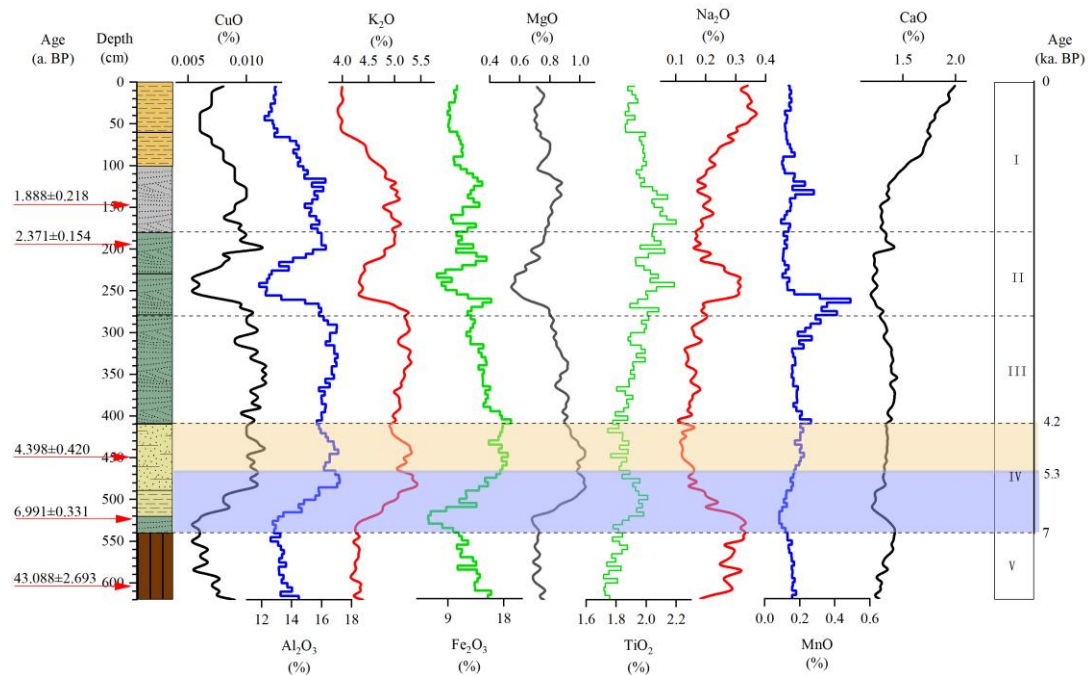


Fig. 4 | Down-core variations in major-element concentrations of the FHZX palaeochannel core. Shaded bands highlight the principal chronological intervals used for comparison.

4.3 Grain-size characteristics

Grain-size data were classified into clay (<3.9 μ m), silt (3.9–62.5 μ m), and sand (>62.5 μ m) following the particle-size classification recommended by Blott and Pye (2012)³¹. Mean grain size (Mz), median grain size (Md), sorting (So), skewness (Sk) and kurtosis (KG) were calculated using GRADISTAT³². Lithological Unit V (620–540 cm) was dominated by silt (86.03%), with clay and sand averaging 12.92% and 1.05%, respectively, and Md ranging from 6.12 to 7.41 μ m. Unit IV

(540–410 cm) was dominated by silt (82.46%), with M_d ranging from 6.44 to 8.00 μm ; clay content and M_d generally increased upwards and reached relatively high values at approximately 445–440 cm, accompanied by a corresponding decrease in silt content. Unit III (410–280 cm) contained 82.04% silt, 15.49% clay and 2.47% sand, with M_d generally decreasing upwards and sand content showing several pronounced peaks, particularly between approximately 310 and 290 cm. Unit II (280–180 cm) showed relatively stable silt content (83.84%) and M_d values of 7.04–7.59 μm . Unit I (180–0 cm) exhibited greater variability, with silt averaging 81.15%, M_d ranging from 3.41 to 9.93 μm , and pronounced fluctuations in sorting, skewness and kurtosis (Fig. 5).

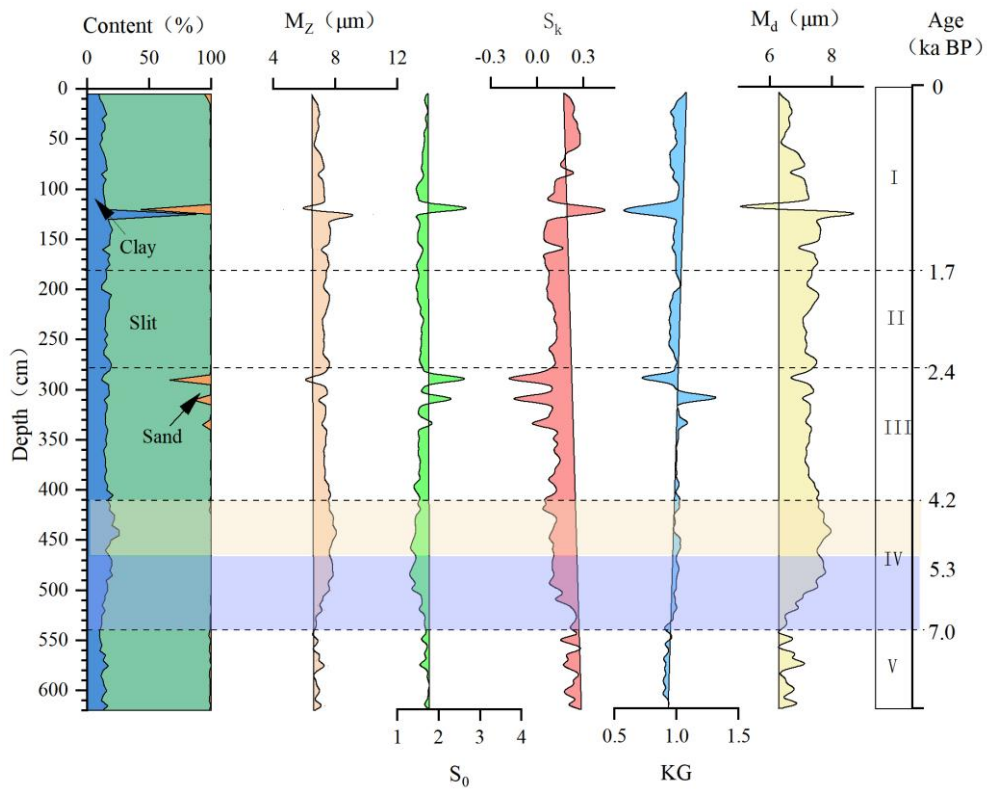


Fig. 5 | Down-core variations in grain-size fractions and particle-size parameters of the FHZX palaeochannel core. Profiles show clay, silt and sand contents, mean grain size (M_z), median grain size (M_d), sorting (S_0), skewness (S_k) and kurtosis (K_G). Shaded bands highlight the principal chronological intervals used for comparison.

5. Discussion

5.1 Palaeoenvironmental evolution of the FHZ area since 7 ka BP

The FHZX palaeochannel provides the principal natural archive for reconstructing the climatic, hydrological and sedimentary evolution of the FHZ area over the past ~7 ka. In contrast, the southern

moat represents an anthropogenically modified depositional basin whose sedimentation was additionally influenced by excavation, water management, cultural input and subsequent infilling^{19,20}. Archaeological investigations showed that the western palaeochannel drained eastwards towards the western moat, while the surrounding moat, internal waterways and other palaeochannels formed an interconnected local drainage network¹⁹. The FHZX and southern-moat sequences therefore record different components of the same hydrological landscape rather than directly equivalent stratigraphic successions. In the following reconstruction, the FHZX lithofacies are used to constrain the environmental significance of CIA, Fe₂O₃/MnO, Ti/Al and grain-size variations, whereas the moat record is used primarily to evaluate how the engineered water system responded to changes in the natural hydrological background (Fig. 6). Based on their coherent changes, the sequence was divided into five stages.

Stage V (7.0–5.3 ka BP): During 7.0–6.0 ka BP, increasing CIA and Fe₂O₃/MnO values in the FHZX palaeochannel (Fig. 6a, b), together with declining Ti/Al (Fig. 6c) and increasing Md (Fig. 6d), indicate enhanced chemical weathering, increasingly reducing depositional conditions and enhanced sediment transport under generally warm and humid conditions. The basal yellowish-brown silt interbedded with bluish-grey mud, together with minor carbonaceous debris, represents a natural fluvial depositional setting characterised by alternating sediment input and waterlogged low-energy conditions. Between 6.0 and 5.3 ka BP, CIA remained relatively high and Fe₂O₃/MnO reached high values around 5.6–5.3 ka BP, whereas the sequence remained predominantly silt-rich (Fig. 6g), suggesting persistent moisture and relatively stable palaeochannel deposition. The transition towards bluish-grey mud near the upper boundary of this interval further indicates weakening flow energy and enhanced local water retention. Regional records nevertheless indicate that this locally wet environment developed against a gradually weakening monsoon background. The Sanbao Cave $\delta^{18}\text{O}$ record shows a long-term weakening of the East Asian summer monsoon after the middle-Holocene optimum (Fig. 6f)³³, and the Dajiuhu pollen-based precipitation reconstruction indicates decreasing annual precipitation after approximately 7 ka BP (Fig. 6h)³⁴. Relatively high *Castanopsis* + *Lithocarpus* pollen percentages (Fig. 6i) nevertheless indicate the persistence of warm and moist evergreen broadleaved vegetation³⁵. The middle-Holocene relative sea-level highstand (Fig. 6e)³⁶ may provide a broad downstream base-level context, although its direct control on water levels in the middle Hanjiang River cannot be established. Thus, local

hydrological conditions at FHZX were not controlled solely by regional precipitation but were also buffered by the low-lying morphology and water-storage capacity of the palaeochannel.

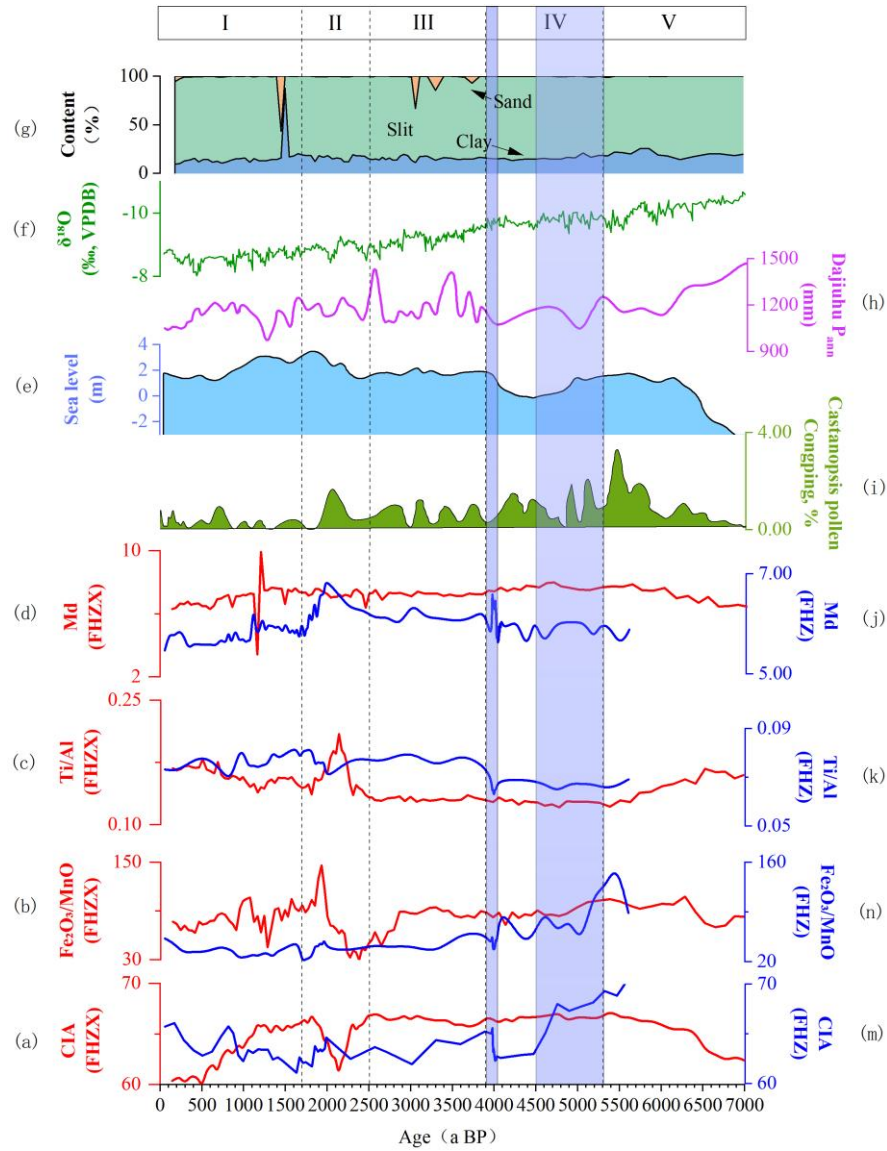


Fig. 6 | Multiproxy reconstruction of palaeoclimate, hydrological and sedimentary evolution in the Fenghuangzui area since 7 ka BP. **a–d**, CIA, Fe₂O₃/MnO, Ti/Al and median grain size (Md) records from the FHZX palaeochannel core, respectively. **e**, Holocene relative sea-level changes along southeastern China³⁶. **f**, stalagmite δ¹⁸O record from Sanbao Cave, central China³³. **g**, clay, silt and sand fractions of the FHZX palaeochannel core. **h**, pollen-based mean annual precipitation reconstruction from Dajiuhu, central China³⁴. **i**, Castanopsis + Lithocarpus pollen percentages from Dajiuhu³⁴. **j–m**, Md, Ti/Al, Fe₂O₃/MnO and CIA records from the FHZ southern moat, respectively¹⁹. Shaded bands denote the principal hydrological intervals discussed in the text; Roman numerals I–V denote the depth-defined lithological units used in the Results.

In contrast, the area subsequently occupied by the southern moat remained subaerial, represented by the basal brownish-yellow raw-soil layer. The top of this raw-soil unit dates to approximately 5.3 ka BP, indicating that excavation and initial use of the southern moat began around this time¹⁹. The difference between contemporaneous aquatic deposition at FHZX and

terrestrial conditions beneath the future moat demonstrates that the pre-Qujialing landscape consisted of a low-lying natural palaeochannel adjacent to a relatively elevated alluvial surface later occupied by the settlement rather than a uniformly inundated floodplain.

Stage IV (5.3–4.2 ka BP): During Stage IV, CIA, Ti/Al and Md remained comparatively stable overall (Fig. 6a, c, d), whereas $\text{Fe}_2\text{O}_3/\text{MnO}$ declined from the high values reached around 5.3 ka BP (Fig. 6b), suggesting gradually weakened reducing conditions and greater fluctuation in local water retention. This interpretation is supported by the lithological succession from bluish-grey mud to greyish-yellow clay interbedded with bluish-grey mud and finally to mottled greyish-yellow silty clay. The fine-grained character indicates generally weak hydrodynamic conditions, whereas abundant reddish-brown mottles record repeated alternation between reducing and oxidising conditions associated with a shallow and fluctuating water table. Thus, the natural palaeochannel underwent progressive shallowing and infilling rather than abrupt desiccation. This hydrological weakening occurred against a broader transition towards more variable mid- to late-Holocene hydroclimatic conditions¹⁸. The regional monsoon record continued its long-term weakening trend (Fig. 6f), while the Dajiuhe precipitation record remained comparatively variable (Fig. 6h). At the same time, relative sea level declined from its middle-Holocene highstand (Fig. 6e)³⁶, although its influence at FHZ should be considered only as a broad regional background.

The most important difference from Stage V was the introduction of an engineered water body at approximately 5.3 ka BP. Sedimentation above the raw-soil surface of the southern moat contained fine sediment together with prehistoric pottery and burnt-soil particles¹⁹, indicating that the newly excavated moat trapped both waterborne and culturally derived material. Its geochemical and grain-size proxies (Fig. 6j–m) also show a different pattern from the FHZX record, reflecting the greater sensitivity of an artificial depression to water-level fluctuations, bank erosion and human management. The FHZ landscape therefore changed from a predominantly natural palaeochannel–floodplain system to a coupled natural–engineered hydrological system during this stage.

Stage III (4.2–2.5 ka BP): Stage III was characterised by pronounced short-term hydrological variability superimposed on generally low-energy palaeochannel sedimentation. CIA fluctuated within a relatively narrow range (Fig. 6a), whereas $\text{Fe}_2\text{O}_3/\text{MnO}$ and Ti/Al showed several marked excursions (Fig. 6b, c). Md remained mostly moderate (Fig. 6d), but several distinct increases in sand content occurred within the otherwise silt-dominated sequence (Fig. 6g), indicating episodic

enhancement of sediment transport rather than continuously strengthened hydrodynamic conditions.

The sedimentary facies provide an important constraint on these proxy variations. FHZX was dominated by relatively homogeneous bluish-grey mud, indicating prolonged low-energy and waterlogged deposition, probably within an abandoned-channel, backwater or shallow standing-water setting. The discrete sand-rich horizons superimposed on this mud-dominated background therefore more likely represent short-lived channel reactivation or flood-related sediment pulses. Such alternations between fine background sedimentation and episodic coarse input are typical of fluvial environments in which flood magnitude, sediment availability and local channel configuration vary through time²⁸. Particular attention should be given to the ~4.2–3.9 ka BP interval. High-resolution hydrological records from central China indicate pronounced changes in precipitation and flooding around the 4.2 ka event², while palaeoflood deposits from the Zhongqiao site in the Jiangnan Plain have been dated to approximately 4.1–3.8 ka BP²⁷. At FHZX, however, the dominance of bluish-grey mud indicates that enhanced water input did not necessarily generate a laterally continuous coarse flood bed. In a broad, low-gradient palaeochannel, increased discharge may instead have enhanced inundation and deposition of suspended fine sediment.

The southern moat exhibited a sharper response around 4.0–3.9 ka BP, with pronounced changes in Md and geochemical proxies (Fig. 6j–m)¹⁹. This contrast suggests that the confined artificial moat was more sensitive to rapid water-level and sediment-input changes, whereas the natural palaeochannel mainly recorded ponding and low-energy sediment settling. The FHZ records therefore indicate a short-lived hydrological perturbation around the 4.2 ka interval, expressed differently in natural and artificial depositional settings. After ~3.9 ka BP, FHZX remained dominated by low-energy mud deposition, punctuated by occasional sand-rich intervals that indicate episodic increases in sediment transport. Increasing precipitation variability in the Dajihu record (Fig. 6h)³⁴ and regional flood records²⁸ further support increasingly variable late-Holocene hydrological conditions.

Stage II–I (2.5 ka BP–present): After 2.5 ka BP, declining CIA (Fig. 6a), increasing Ti/Al (Fig. 6c) and pronounced Fe₂O₃/MnO fluctuations (Fig. 6b) indicate weakened chemical weathering, enhanced detrital input and increasingly unstable depositional conditions. The alternation of bluish-grey mud and yellow clayey silt records episodic higher-energy sediment input within an otherwise progressively infilling palaeochannel, while the upward transition to clayey silt and topsoil indicates

subsequent shallowing and terrestrialisation. Increasing late-Holocene land use may have further enhanced erosion and sediment delivery in the middle Yangtze region^{39,40}. From ~1.7 ka BP onward, continued infilling ultimately transformed FHZX from a low-energy palaeochannel into an abandoned floodplain surface.

5.2 Evolution of the ecological landscape around the FHZ site

The FHZX palaeochannel and southern moat sequences, together with archaeological, archaeobotanical and zooarchaeological evidence, reveal the long-term transformation of the relationship between hydrological conditions, settlement organisation and subsistence practices at FHZ. In this study, hydrological change refers not only to variations in local water levels, but also to the influence of regional precipitation, catchment runoff and floodplain inundation processes. Changes in precipitation altered river discharge, which subsequently affected water availability, channel activity and the duration of inundation within palaeochannels and artificial moats. Based on these interactions, the evolution of the FHZ landscape can be divided into four stages(Fig. 7):

Before ca. 5.3 ka BP, the FHZ area comprised palaeochannels, seasonally waterlogged depressions and relatively stable alluvial surfaces rather than a uniformly inundated floodplain. The lower FHZX sequence records fine-grained deposition within a low-lying palaeochannel, whereas the archaeologically sterile silty-clayey substrate beneath the later southern moat represents a more stable component of the natural fluvial–alluvial surface¹⁹. These deposits should therefore be regarded as laterally differentiated depositional facies within the same floodplain system, not as a single continuous stratigraphic horizon. Regional speleothem, quantitative precipitation and pollen records indicate generally strong monsoon influence and relatively humid conditions during the middle Holocene, which would have maintained comparatively high runoff, persistent lowland moisture and a broad range of aquatic and terrestrial habitats^{33–35}. Direct evidence for subsistence at FHZ before the Qujialing occupation remains limited, so intensive rice cultivation at the site itself should not be projected back into this phase. Nevertheless, archaeobotanical evidence from the middle Hanjiang River valley demonstrates continuous development of rice cultivation and the early formation of rice–millet mixed farming before 5.3 ka BP¹¹. The pre-Qujialing landscape at FHZ is therefore better viewed as a resource-rich floodplain mosaic in which early cultivation could coexist with fishing, hunting, gathering and the use of wetland resources. Water at this stage primarily structured habitat and resource availability rather than forming part of a formally managed

settlement system (Fig. 7a).

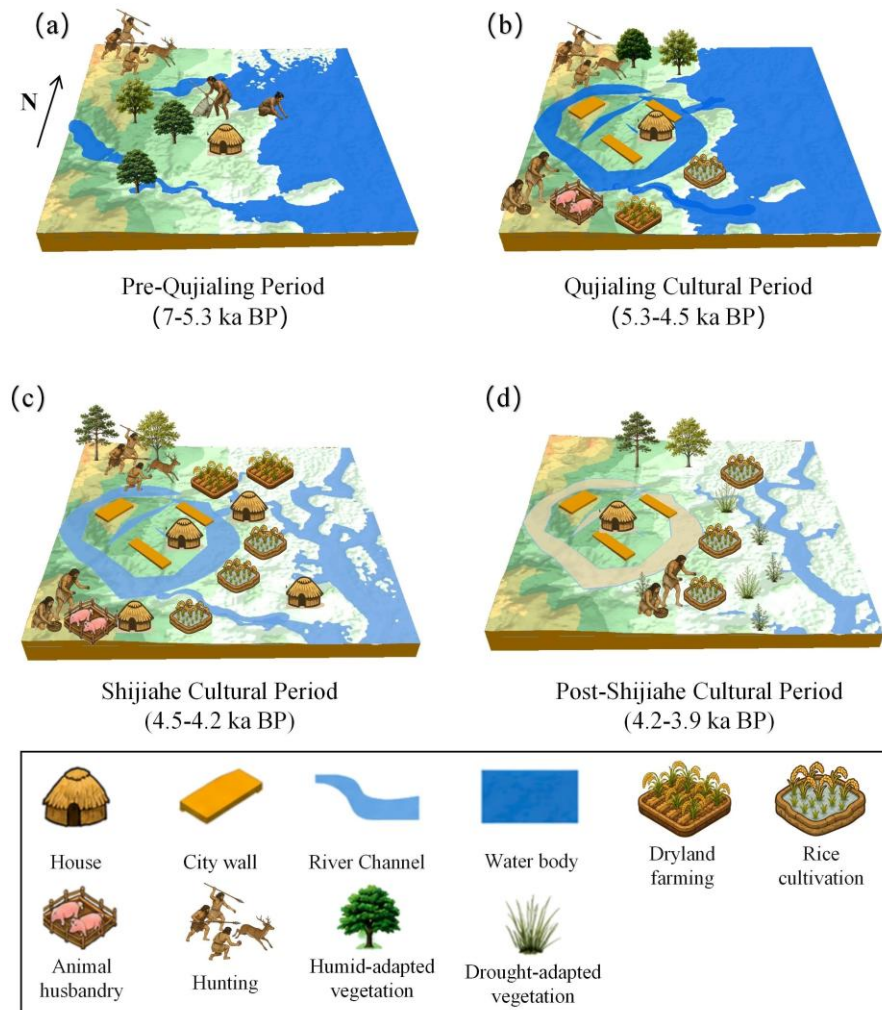


Fig. 7 | Schematic reconstruction of landscape, hydrology and subsistence at FHZ from 7.0 to 3.9 ka BP. **a**, 7.0–5.3 ka BP: natural fluvial–floodplain landscape with palaeochannels and waterlogged depressions. **b**, 5.3–4.5 ka BP: Qujialing walled settlement with moat, internal waterways and water-control facilities, associated with rice-based subsistence. **c**, 4.5–4.2 ka BP: reduced precipitation and lower water levels, with continued rice cultivation, pig husbandry and wild-resource use. **d**, 4.2–3.9 ka BP: increased hydrological variability, moat infilling and transformation towards a moat-surrounded settlement. Symbols indicate relative environmental and subsistence conditions rather than exact palaeogeographic boundaries.

A major reorganisation occurred during 5.3–4.5 ka BP with the establishment of the Qujialing settlement. The southern moat was excavated into the pre-existing natural alluvial substrate, marking the transition from natural floodplain deposition to anthropogenically modified moat sedimentation¹⁹. Archaeological excavation further revealed two internal waterways, an artificial earthen platform of approximately 4000 m², and an earthen dam associated with three spillways¹⁹. The platform directly overlies the natural substrate, and excavated sediment from the waterways

was probably reused, at least in part, for its construction. Settlement construction therefore involved both incision and redeposition of local alluvial sediment, producing artificial depressions and elevated surfaces within inherited floodplain relief. The surrounding palaeochannels were not replaced by this system; rather, they remained part of the local drainage setting, while the moat and internal waterways altered runoff pathways and increased the capacity for drainage, temporary water retention and flow regulation during high-water conditions. Regional hydroclimate records indicate that precipitation began to decline after ca. 5.1 ka BP but remained higher than during the subsequent 4.5–4.2 ka BP minimum¹⁸. The Qujialing water system should therefore be interpreted as a means of accommodating seasonal variation in water supply and runoff, rather than as evidence for complete hydraulic control of the floodplain (Fig. 7b).

This modification of local hydrology coincided with consolidation of an overwhelmingly rice-based agricultural economy. In Qujialing contexts at FHZ, 612 of 618 identified crop grains were rice (99.03%), whereas foxtail millet, broomcorn millet and wheat together accounted for less than 1% of the crop assemblage¹². The contrast is notable because mixed rice–millet farming had already become established in parts of the middle Hanjiang River valley¹¹. The local combination of low-lying water-retaining surfaces, palaeochannels and artificial drainage features would have favoured reliable access to water while allowing excess runoff to be discharged, although there is currently no direct evidence that the moat or internal waterways served as field-irrigation canals. Zooarchaeological evidence further indicates that pig husbandry and deer hunting were already important components of the Qujialing subsistence economy³⁹. The Qujialing landscape was therefore a modified floodplain in which settlement construction, rice cultivation, animal husbandry and exploitation of wild resources were associated with different geomorphic and ecological units, rather than a uniformly engineered agricultural surface (Fig. 7b).

Between 4.5 and 4.2 ka BP, regional hydroclimatic conditions became drier but remained comparatively stable. The Yuwang Cave record shows that rainfall decreased gradually from ca. 5.1 to 4.5 ka BP and reached the driest phase of the 6.0–4.0 ka BP interval between 4.5 and 4.2 ka BP¹⁸. At FHZ, reduced precipitation would have lowered catchment runoff and recharge to local channels and depressions, producing lower or less persistent water levels rather than complete desiccation. The FHZX sequence is consistent with progressively weaker water retention and more frequent exposure of low-lying surfaces. Importantly, this hydrological decline was not accompanied by an

equivalent contraction of subsistence. Of 1,856 crop grains from Shijiahe contexts, 1,840 were rice (99.14%), while millet and wheat remained negligible¹². Domestic pigs remained the principal source of animal protein, with subadult animals of approximately 1–2 years dominating the slaughter profile, whereas deer were the main hunted taxa; the broader faunal assemblage also indicates use of shrub–grassland, woodland and wetland habitats³⁹. Starch residues from 23 lithic artefacts in the Shijiahe-period H13 feature (4.4–4.2 ka BP) were dominated by roots and tubers, while macro-remains and phytoliths demonstrate the simultaneous use of rice and millet⁴⁰. The agricultural core of the FHZ economy thus remained rice-based, but pig husbandry, hunting and the processing of non-cereal plant foods broadened the resource base. The Shijiahe phase therefore shows that declining precipitation and lower floodplain water levels were compatible with continued agricultural production and diversified resource use, rather than producing an immediate economic decline (Fig. 7c).

Hydrological conditions became more variable during 4.2–3.9 ka BP, and this interval should not be treated as a simple continuation of drying. The Yuwang Cave record indicates relatively wetter conditions after ca. 4.2 ka BP, while the quantitative rainfall reconstruction for central China identifies a dry interval around 4.23–4.10 ka BP followed by a pronounced multi-decadal wet interval around 3.95–3.84 ka BP.^{2,18} These high-resolution regional intervals are used as contextual comparisons rather than exact age matches to the OSL-constrained FHZX chronology. Such variability would have produced alternating reductions and increases in runoff, channel recharge and sediment delivery. An already shallowing artificial moat would have been especially sensitive to this regime: lower-flow intervals favoured partial exposure, whereas high-discharge events could deliver substantial suspended sediment and accelerate infilling. The southern moat sequence records a flood episode around 4.0–3.9 ka BP together with the progressive loss of its earlier defensive function¹⁹. Comparable late-Holocene records from the Jiangnan Plain also show that fluvial flooding was closely coupled to monsoon precipitation variability²⁸. Moat infilling at FHZ should therefore be attributed to the combined effects of variable precipitation, runoff, sediment input and declining maintenance, rather than to persistently low water levels alone (Fig. 7d).

Settlement reorganisation accompanied these hydrological changes but was gradual. The enclosing wall had already lost its original function during the Shijiahe period, whereas occupation within the moat continued; by 4.2–3.9 ka BP, FHZ is better characterised as a moat-surrounded

settlement than as an actively maintained walled town^{19,39}. Progressive infilling did not imply immediate abandonment, because the moat remained a topographic depression and sediment trap after its defensive and hydraulic roles weakened. Subsistence also persisted across this transition. All 52 crop grains recovered from Meishan contexts were rice, although the substantially smaller sample requires caution when comparing abundance with the preceding phases¹². Settlement reorganisation at FHZ and progressive infilling of the moat therefore occurred while the established rice-based economy persisted. Taken together, the FHZ sequence shows that precipitation-driven hydrological change, local water levels, hydraulic facilities, settlement form and subsistence followed partly asynchronous trajectories.

5.3 Settlement–environment interplay and regional cultural evolution

The local sequence described above raises a broader question: whether the changing role of FHZ occurred within a persistent regional ecological gradient that also structured cultural interaction across the Hanjiang–Nanyang corridor. To examine this relationship, the phase-specific pollen surfaces are interpreted together with archaeological site distributions^{41,42}.

During 5.3–4.5 ka BP, the IDW surfaces indicate a broad north–south ecological contrast (Fig. 8a). Humid forest–wetland indicators were more strongly represented in Hubei and the middle Hanjiang River sector, whereas open-landscape taxa were more prominent in Henan and the northern Nanyang Basin. FHZ lay close to the transition between these two ecological domains rather than within an environmentally uniform floodplain zone. Archaeological studies of the Nanyang Basin independently show that Qujialing and Shijiahe cultural elements entered a region otherwise strongly influenced by Central Plains traditions, and that the northward spread of southern cultural influences broadly coincided with the expansion of rice-based or rice–millet subsistence systems¹³. The spatial overlay therefore suggests that Qujialing expansion crossed an ecological transition rather than following a single homogeneous environmental zone. FHZ occupied a particularly favourable position at the southern margin of the Nanyang Basin, where access to the Hanjiang River system, cultivable alluvial surfaces and the north–south corridor coincided. Its importance at this stage is better understood as that of a settlement located within an ecological and cultural interface, not simply as the fixed northern boundary of the Qujialing cultural sphere^{9,13}.

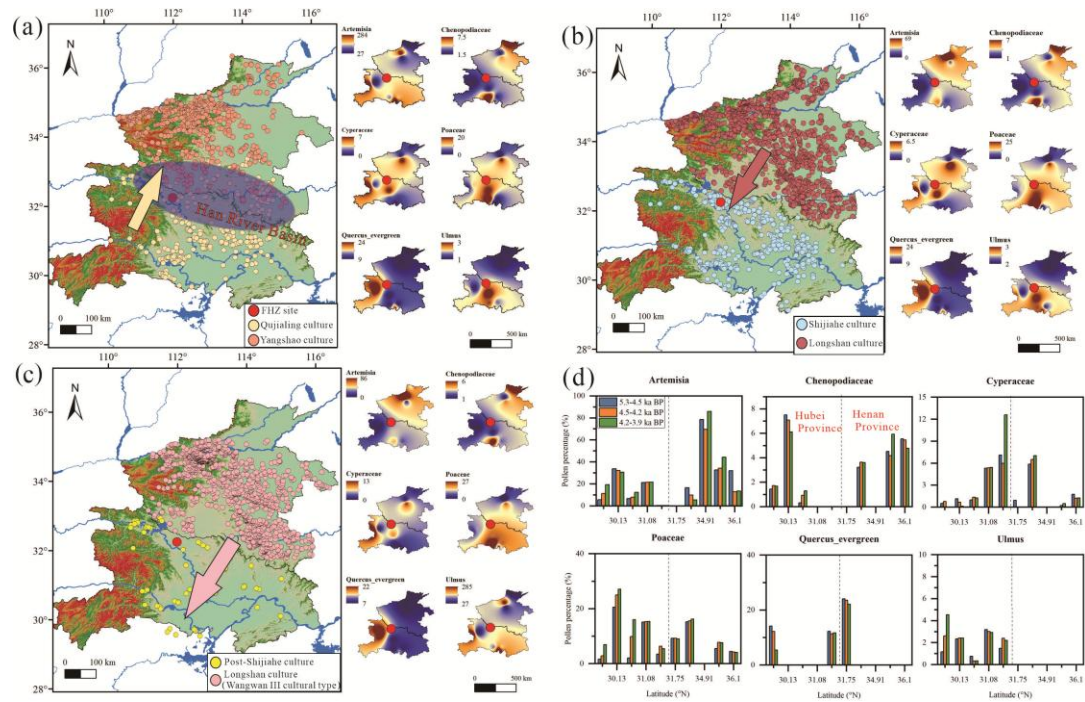


Fig. 8 | Regional ecological gradients and archaeological site distributions across the Hubei–Henan transition during 5.3–3.9 ka BP. **a–c**, phase-specific IDW surfaces derived from the Holocene pollen dataset for China²⁹ for 5.3–4.5, 4.5–4.2 and 4.2–3.9 ka BP, overlain by archaeological sites compiled from the Neolithic–Bronze Age China database⁴² whose dated or cultural ranges overlap each interval. **d**, north–south comparison of pollen indicators across Hubei, the FHZ sector and Henan, showing the relative transition from humid forest–wetland to more open herbaceous landscapes. IDW surfaces represent relative spatial gradients rather than fixed vegetation boundaries; *Cyperaceae* is interpreted primarily as a local wetland indicator, and archaeological site density is not treated as a direct population estimate. Arrows indicate generalised shifts in regional cultural distributions^{13,43} and do not imply climate-driven migration.

During 4.5–4.2 ka BP, the regional ecological gradient persisted while open-landscape indicators became more prominent in the Nanyang Basin and Henan (Fig. 8b). This change did not correspond to a synchronous contraction of the Shijiahe cultural network. Archaeological distributions in the Hanjiang River basin indicate continued occupation of plains and low platforms, while evidence from the Nanyang Basin records sustained interaction between southern Shijiahe traditions and northern Longshan-related cultural groups^{9,13}. At FHZ, the local record likewise shows that reduced precipitation and lower water levels coincided with continued rice production and diversified subsistence rather than immediate economic decline. The regional and local evidence therefore converge on an important point: ecological change altered the conditions under which cultural interaction took place, but did not determine the direction or intensity of that interaction. FHZ remained positioned within the same broad ecological transition while the social

and cultural functions of the corridor continued to evolve.

During 4.2–3.9 ka BP, open herbaceous indicators remained strongly expressed across Henan and the Nanyang Basin, whereas humid forest–wetland signals became more spatially restricted towards Hubei and the middle Yangtze sector (Fig. 8c). Archaeological distributions also record a reorganisation of the regional cultural pattern, with declining prominence of major Shijiahe centres and greater representation of Longshan- and Wangwan III-related elements south of their earlier core areas^{13,43}. At FHZ, this regional transition coincided with the local change from a fortified settlement to a moat-surrounded occupation and with progressive infilling of the moat, but rice cultivation continued into the Meishan phase^{12,19}. The correspondence is therefore chronological and spatial rather than demonstrably causal. The persistence of the ecological gradient while cultural affiliations shifted indicates that the Hanjiang–Nanyang corridor functioned as a long-lived contact zone through which cultural influence could move in different directions at different times.

Taken together, the pollen and archaeological distributions place FHZ within a persistent ecological–cultural interface between the humid middle Yangtze–Hanjiang landscapes to the south and the more open landscapes of the Nanyang Basin and Central Plains to the north (Fig. 8d). The position of this interface was broad and temporally variable, and the IDW surfaces should not be read as fixed ecological frontiers. Nevertheless, the repeated spatial coincidence between ecological transition, settlement concentration and changing cultural distributions helps explain why FHZ retained regional significance through successive phases of Qujialing, Shijiahe and Meishan occupation. The ecological gradient structured differences in water availability, vegetation and subsistence opportunities, while the corridor provided routes for movement and exchange; neither factor alone determined cultural expansion or contraction. FHZ is therefore best interpreted as a persistent interface within a shifting regional network, rather than as a culturally fixed frontier whose history can be reduced to climatic forcing.

Overall, comparison of the natural FHZX palaeochannel with the anthropogenic moat shows that environmental and social trajectories at FHZ were partly asynchronous. The palaeochannel shifted from persistent low-energy wet conditions to progressive shallowing, renewed ponding around 4.2–3.9 ka BP, and later infilling, whereas the engineered moat responded more sharply to local water-level changes, sediment input and maintenance. These hydrological changes did not coincide with an abrupt decline in subsistence: rice remained dominant while settlement form,

drainage and resource use were reorganised. Regional pollen and site distributions further place FHZ within a persistent ecological–cultural interface rather than a fixed climatic frontier. The FHZ case therefore suggests that hydroclimatic variability influenced settlement development through local geomorphic context, engineered water management and flexible subsistence practices, rather than through a simple climate-driven collapse. Natural and anthropogenic sedimentary archives can thus record the same hydrological perturbation differently, making their explicit comparison critical for evaluating human adaptation.

Data Availability

The datasets generated and analysed during the current study, including the FHZX chronological, major-element and grain-size data, are available from the corresponding author on reasonable request. The regional pollen and archaeological site-distribution datasets are available from the published datasets and sources cited in the manuscript, including the Holocene Pollen Dataset for China (ref. 29) and the PANGAEA archaeological-site dataset (ref. 42).

Acknowledgements

This research received financial support from the National Natural Science Foundation of China (Grant No. 42577517) and the Major Project of the National Social Science Foundation of China (19ZDA231).

Author contributions

A.G. conceived the study, developed the methodology, conducted the formal analysis and investigation, and wrote, reviewed and edited the manuscript. H.T. and S.S. participated in the archaeological fieldwork and provided guidance and support for the collection, identification and interpretation of the primary archaeological materials. Q.Z. participated in the investigation. L.M. contributed to the investigation, provided resources, supervised the research and acquired funding. D.M. contributed to validation, investigation and methodology development, provided resources and supervised the research. All authors reviewed and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Longjiang Mao.

References

1. Zhang, J. et al. Tension between spatial pattern and hydrological adaptability in early Yangtze River Basin settlements. *Nat. Cities* 3, 535–544 (2026).
2. Liao, J., Day, C. C., Hu, C., Liu, Y. & Henderson, G. M. Precise chronology of hydrological changes at ~4.2 kyr in Central China to assess the impact of flooding on Neolithic societies. *Natl. Sci. Rev.* 13, nwaf567 (2026).

3. Li, Y. et al. Neolithic human adaptations to the environmental changes in the Jiangnan Plain, middle Yangtze Valley. *Quat. Sci. Rev.* 355, 109271 (2025).
4. Flores, D. G. et al. Vegetation response to soil and morphological properties in an arid region alluvial fan landscape, pre-Andes of San Juan, Argentina. *J. Earth Sci.* 36, 408–427 (2025).
5. Kajita, H. et al. Extraordinary cold episodes during the Mid-Holocene in the Yangtze delta: interruption of the earliest rice cultivating civilization. *Quat. Sci. Rev.* 201, 418–428 (2018).
6. Li, Z. et al. Pollen-based response patterns of vegetation dynamics to environmental changes during the early-mid Holocene in the Ningshao Plain, China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 691, 113754 (2026).
7. Zhao, X. et al. Herding then farming in the Nile Delta. *Commun. Earth Environ.* 3, 88 (2022).
8. Kumari, A., AchutaRao, K., Defliese, W. F. & Dixit, Y. Patterns and seasonality in the mid-Holocene hydroclimate of the Thar Desert in northwestern India. *Commun. Earth Environ.* <https://doi.org/10.1038/s43247-026-03857-6> (2026).
9. Qin, W. et al. Spatial-temporal evolution of the distribution pattern of Neolithic sites in Han River Basin, China. *Environ. Archaeol.* 25, 1–13 (2018).
10. Li, X. et al. Palaeoflood hydrological study in the Baihe Reach in the upper reaches of the Hanjiang River. *Sci. Geogr. Sin.* 32, 971–978 (2012) (in Chinese).
11. Huan, X., Deng, Z., Xiang, J. & Lu, H. New evidence supports the continuous development of rice cultivation and early formation of mixed farming in the middle Han River valley, China. *Holocene* 32, 924–934 (2022).
12. Huang, X. et al. Agricultural foundations of the Late Neolithic walled town at Fenghuangzui in central China. *npj Herit. Sci.* 13, 194 (2025).
13. Li, Z. et al. Geographical distribution, diffusion and subsistence variation of prehistoric cultures in Nanyang Basin, Henan Province. *Acta Geogr. Sin.* 70, 143–156 (2015).
14. Hao, Q. et al. Holocene wildfire regime shifts induced by the enhancement of human activities in the Changjiang (Yangtze River) Basin. *Catena* 240, 107998 (2024).
15. Chen, C. et al. Holocene climatic transition in the Yangtze River region and its impact on prehistoric civilizations. *Catena* 238, 107886 (2024).
16. Li, C. et al. Earliest ceramic drainage system and the formation of hydro-sociality in monsoonal East Asia. *Nat. Water* 1, 694–704 (2023).
17. Chen, Z. et al. Ancient DNA from Shimao city records kinship practices in Neolithic China. *Nature* 648, 659–667 (2025).
18. Hosner, D., Wagner, M., Tarasov, P. E., Chen, X. & Leipe, C. Spatiotemporal distribution patterns of archaeological sites in China during the Neolithic and Bronze Age: an overview. *Holocene* 26, 1576–1593 (2016).
19. Guo, A., Mao, L., Li, C. & Mo, D. Reconstruction of the paleoenvironmental context of Holocene human behavior at the Fenghuangzui site in the Nanyang Basin, Middle Yangtze River, China. *npj Herit. Sci.* 13, 2 (2025).
20. Kuang, M. et al. Brief report on the excavation of inland waterways and artificial earthen platforms at the Neolithic city site of Fenghuangzui, Xiangyang, Hubei. *Cultural Relics of Central China* 6, 4–20 (2025) (in Chinese).
21. Zhang, Y., Huang, C. C., Pang, J., Zha, X., Zhou, Y. & Gu, H. Holocene paleofloods related to climatic events in the upper reaches of the Hanjiang River valley, middle Yangtze River basin, China. *Geomorphology* 195, 1–12 (2013).
22. Nesbitt, H. W. & Young, G. M. Early Proterozoic climates and plate motions inferred from major element

- chemistry of lutites. *Nature* 299, 715–717 (1982).
23. Fedo, C. M., Nesbitt, H. W. & Young, G. M. Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering conditions and provenance. *Geology* 23, 921–924 (1995).
 24. Chen, J. C. et al. The Ti/Al molar ratio as a new proxy for tracing sediment transportation processes and its application in aeolian events and sea level change in East Asia. *J. Asian Earth Sci.* 73, 31–38 (2013).
 25. Folk, R. L. & Ward, W. C. Brazos River bar: a study in the significance of grain size parameters. *J. Sediment. Petrol.* 27, 3–26 (1957).
 26. Naeher, S., Gilli, A., North, R. P., Hamann, Y. & Schubert, C. J. Tracing bottom water oxygenation with sedimentary Mn/Fe ratios in Lake Zurich, Switzerland. *Chem. Geol.* 352, 125–133 (2013).
 27. Wu, Y. et al. Mid-Holocene palaeoflood events recorded at the Zhongqiao Neolithic cultural site in the Jiangnan Plain, middle Yangtze River Valley, China. *Quat. Sci. Rev.* 173, 145–160 (2017).
 28. Guan, Y. et al. River flooding response to ENSO-related monsoon precipitation: Evidence from late Holocene core sediments in the Jiangnan Plain. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 589, 110834 (2022).
 29. Cao, X., Tian, F., Ni, J. & Herzschuh, U. Holocene Pollen Dataset for China. National Tibetan Plateau/Third Pole Environment Data Center <https://doi.org/10.11888/Paleoenv.tpsc.272379> (2022).
 30. Blaauw, M. & Christen, J. A. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Anal.* 6, 457–474 (2011).
 31. Blott, S. J. & Pye, K. Particle size scales and classification of sediment types based on particle size distributions: Review and recommended procedures. *Sedimentology* 59, 2071–2096 (2012).
 32. Blott, S. J. & Pye, K. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surf. Process. Landf.* 26, 1237–1248 (2001).
 33. Dong, J. et al. A high-resolution stalagmite record of the Holocene East Asian monsoon from Mt Shennongjia, central China. *Holocene* 20, 257–264 (2010).
 34. Sun, J. et al. Quantitative precipitation reconstruction in the east-central monsoonal China since the late glacial period. *Quat. Int.* 521, 175–184 (2019).
 35. Zhu, C. et al. A detailed pollen record of vegetation and climate changes in central China during the past 16,000 years. *Boreas* 39, 69–82 (2010).
 36. Zong, Y. Mid-Holocene sea-level highstand along the southeast coast of China. *Quat. Int.* 117, 55–67 (2004).
 37. He, F., Li, S. & Zhang, X. The impact of climate change and human activities on the late Holocene sediment yield of the middle Yangtze River. *Quat. Int.* 380–381, 297–304 (2015).
 38. Zhan, T. et al. Anthropogenic impact on sedimentation in tributary catchments of the middle Yangtze River since the late Holocene. *Geomorphology* 130, 295–306 (2011).
 39. Liu, Y., Zhu, Y., Ai, Q. et al. Animal exploitation of the Fenghuangzui Neolithic walled settlement in the Middle Yangtze River Valley. *npj Herit. Sci.* 13, 539 (2025).
 40. Lou, W., Wang, F., Wei, X. et al. Identification and implications of lithic artifacts starch residues from Fenghuangzui Neolithic site in Central China. *npj Herit. Sci.* 13, 511 (2025).
 41. Cao, X. et al. Human activities have reduced plant diversity in eastern China over the last two millennia. *Glob. Change Biol.* 28, 4962–4976 (2022).
 42. Hosner, D., Wagner, M., Tarasov, P. E., Chen, X. & Lei, C. Archaeological sites in China during the Neolithic and Bronze Age. *PANGAEA* <https://doi.org/10.1594/PANGAEA.860072> (2016).
 43. Shan, S. Cultural evolution and societal transformation in the Neolithic middle Yangtze River valley of China. *npj Herit. Sci.* 14, 24 (2026).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Table1.docx](#)