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# Aquatic landscape and the emergence of walled sites in late Neolithic Central Plains of China: Integrating archaeological and geoarchaeological evidence from the Guchengzhai site

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ABSTRACT

The emergence of many late-Neolithic and early Bronze-Age walled sites on China's Central Plains coincided with some prominent Holocene climate events. Recent excavation and geoarchaeological investigation at one of the largest walled sites of Guchengzhai provide important data to examine some of the questions concerning the long-term relationship between the formation of aquatic landscape and social evolution in late prehistoric Central Plains. We collected fine-grained paleo-environmental and archaeological evidence from a range of on- and off-site contexts to reconstruct the late-Holocene paleo-environment surrounding the walled site, and examine the construction, maintenance and abandonment processes of its large-size moat. Our results show that there existed many small-to-large-sized waterbodies during the late Holocene, which, together with local rivers, were the main source of water to the site. The Guchengzhai population was drawn to the low-lying land near the river and other waterbodies with an optimal hydrological condition. During its use, the moat might have been linked to the nearby wetlands and/or rivers. The hydrological regime was dominated by gentle but relatively sediment-laden flow, being punctuated by several high-energy flood events. The sedimentation of light yellowish silt and sand with some anthropogenic inclusions during the use of the moat gave way to a quick siltation with the deposition of rich organic matter when the moat ceased to function as a main channel for water flow, although other land-use activities such as fire (land clearance?) continued to occur in the vicinity. The reconstructed 'life-history' of the moat demonstrates the increasingly acute challenge facing the growing population living at Guchengzhai as the climate was becoming drier. The construction and operation of the moat signified technological innovations and intensified water management at Guchengzhai, which led to the formation of distinctive aquatic landscape that featured large-scale hydraulic infrastructures in a hydrologically optimal environment. We contend that such was a common characteristic or trend shared by many contemporary or later-period walled sites on the Central Plains.

## 1. Introduction

The late-Neolithic and early Bronze-Age saw profound socio-economic and political changes on the Central Plains and its neighboring regions due to a series of intra-regional cultural developments and intensified inter- and trans-regional interactions. These changes include notably the expansion of settlements and population growth (e.g., Liu and Chen, 2012), the movement of crops and livestock (e.g., Cai et al., 2011; Flad et al., 2010), and the increasingly pronounced social stratification at both large-scale and medium-scale sites with growing regional conflicts (e.g., He, 2013; Sun et al., 2018). As have been illustrated by many studies, such changes greatly stimulated economic intensification, rapid urbanization and large-scale landscape modification (e.g., He, 2018; Owlett et al., 2018). Amongst these trends, the emergence of walled sites on China' Central Plain at a time of increasing aridification in the transition from the middle to late Holocene (ca.5000-4000BP) (Chen et al., 2015; Wang et al., 2005) continues to fascinate archaeologists and environmental scientists. Whilst recent excavations and archaeological studies have provided new insights on the scale, structure and social stratification of these late-Neolithic walled sites

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(some call them ‘walled towns’ or ‘cities’) on the Central Plains, many fundamental questions remain unanswered. For instance, despite many environmental studies that endeavor to reconstruct climatic and environmental backgrounds of the rise of these walled sites (Wang et al., 2015; Xia and Zhang, 2011), what are the relationships between the environment, technology and population that led to profound social evolution is still poorly understood. More importantly, apart from the broad-brush paleo-environmental reconstructions, fine-grained paleoenvironmental and archaeological evidence collected from on- and off-site contexts is needed to better understand how and why some of the large-scale infrastructures were built and operated during a period of increasing climate and environmental fluctuations. Understanding the organization of water management offers a unique analytical perspective to examine such complicated relationships.

As one of the most critical resources for human survival and societal growth, water profoundly defines the ways humans interact with their environment and the technologies and social organizations they develop to utilize water. Anthropologists and historians have long theorized the diverse relationships between water and the society. Proposed >70 years ago, Wittfogel’s ‘Oriental Despotism’ remains one of the most important theoretic advancements that pivoted the close relationship between the construction and operation of large-scale hydraulic infrastructures and the rise of coercive, centralized power in labor-intensive and water-demanding rice farming regions. A fundamental departure from classic models of power acquisition (e.g., through military activities), this Wittfogelian ‘ontology’ with an emphasis on hydrosociality (to borrow a term from Banister (2014)) continues to attract rigorous scholarly scrutiny and adjustments on its implications to understand the importance of water and its climatic-environmental background and technological configuration to social evolution (Butzer, 1976; Davies, 2009; Harrower, 2009). It is increasingly difficult and unnecessary, however, to adopt a monolithic view on the interactions between water, power and the society. The archaeology of walled sites with substantial and diverse hydraulic infrastructures provides an invaluable opportunity to develop a holistic understanding of labor organization, power acquisition and social complexity under different environmental settings. Many archaeologists have demonstrated that large-scale hydraulic undertakings predate state formation and/or do not necessarily link to social hierarchy in regions such as the ancient Egypt (Adams, 2017; Mithen, 2010). Indeed, even within China, a key region upon which the Wittfogel’s theory was developed, there are archaeological examples that significantly derivate from the classical Wittfogelian scholarship on water, power and the society. Discoveries of the late-Neolithic and early Bronze-Age walled sites and related water management facilities in the middle and lower Yangtze River and northern China in the past decades reveal that these hydraulic systems were constructed and operated at different scales and that their environmental and climatic conditions and technological underpinnings also differ drastically from one another (Li et al. in preparation). Naturally, the diverse and truly multi-scalar interactions between these hydraulic systems, environments and social organizations contest for polygenetic origins of social power and statecraft in late Neolithic and Bronze-Age China.

To date, there are ca. 15 walled sites being found in the Central Plains, dating from the late Yangshao to Longshan period; and the number of Bronze-Age walled sites is even higher. These walled sites range greatly in size, ranging from hundreds of hectares to one or two dozen hectares, and vary in layout and structure (see discussion). Being discovered in the 1980s, the Guchengzhai site (Fig. 1) is one of the largest late-Neolithic walled sites that supports the aforementioned polygenesis of hydro-social power on the Central Plains. The climatic background and geomorphological condition upon which the walled site was built, and the technological innovations and socio-economic institution that sustained its large-scale hydraulic undertaking profoundly differed from those of other Neolithic walled sites in the Yangtze River and Southern Inner Mongolia (e.g., the Liangzhu City and the Shimao stone walled sites, respectively, Liu et al., 2017; Sun et al., 2018). We synthesize the excavation and geoarchaeological data from Guchengzhai, with an emphasis on multi-proxy environmental data from the excavated moat, and discuss the relationship between the environment

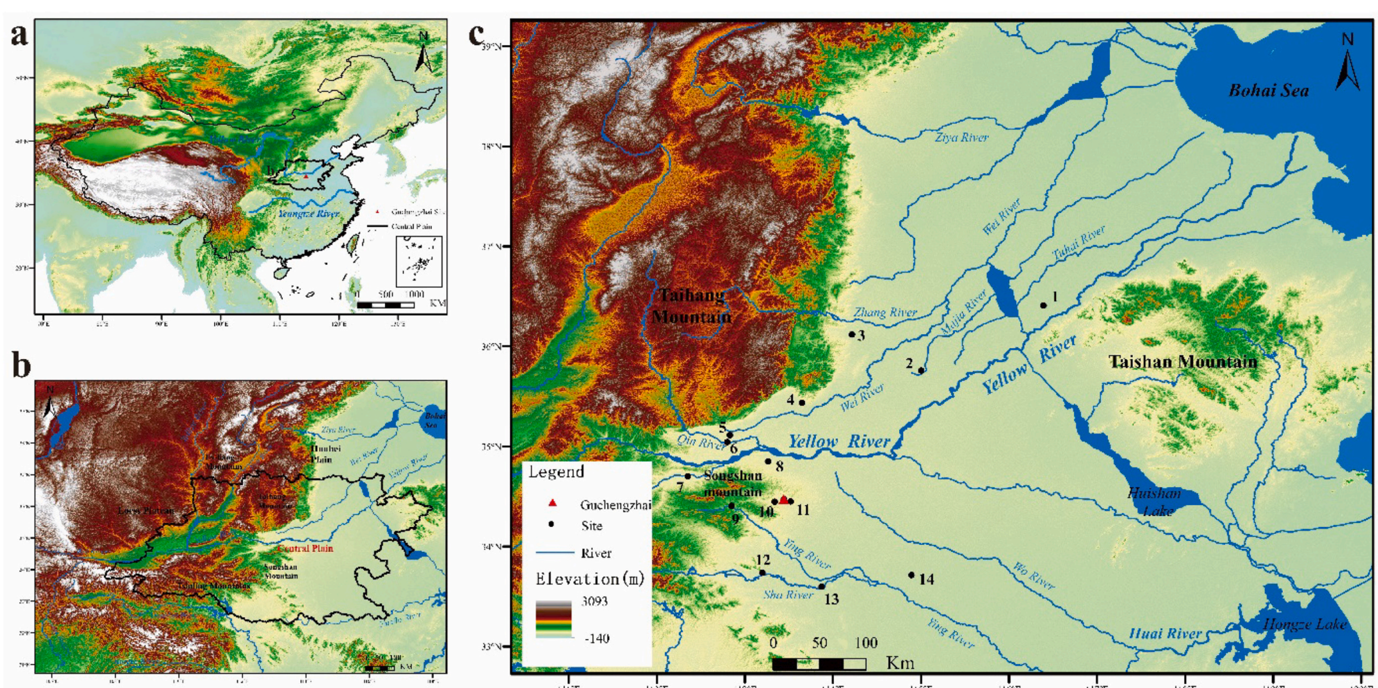


Fig. 1. Geographic location and environment of the Zhenshui River and Guchengzhai and other contemporary sites on the Central Plains. a: Geographic location of the Central Plains (delineated by the dark black lines) in China; b: A closed look of the Central Plains with a diverse range of landforms; c: Locations of key sites mentioned in the text. 1: Jiaochangpu; 2: Qicheng; 3: Hougang; 4: Mengzhuang; 5: Xijincheng; 6: Xubao; 7: Erlitou; 8: Dashigu; 9: Wangchenggang; 10: Xinzhai; 11: Wangjinglou; 12: Puchengdian; 13: Haojiatai; 14: Pingliangtai.

and organization of water management at the site. This offers a detailed and pertinent example to understand the formation of aquatic landscape and how this was related to changes in technologies and social structures at a time of escalating climate uncertainties. The Guchengzhai archaeological and geoarchaeological evidence will not only allow us to contest some of the long-debated theories on water and early state formation in China's Central Plains, including the aforementioned Wittfogelian theses, but also to compare it with examples of large-scale urban transformation and water management in some other early civilizational regions (e.g., Brughmans et al., 2021; Fletcher et al., 2008; Giosan et al., 2012; Leadbetter, 2022; Pournelle, 2003; Pournelle, 2012).

## 2. The middle-to-late-Holocene climate and environment on the Central Plains and the Zhenshui River

Despite the persisting scholarly disagreement on the spatial and temporal variations of Holocene monsoon rainfall, there is a growing consensus that the middle-to-late-Holocene climate in China experienced a gradual but steady trend of aridification as the intensity of the Asian summer monsoons weakened. In the Central Plains, this trend began ca. 5500-5000BP as shown by high-resolution speleothem records (Cai et al., 2021; Dong et al., 2010; Mao et al., 2016; Zhang et al., 2018), in accordance with the timing of some prominent global and regional climate events (e.g., Chen et al., 2015; Wang et al., 2005). Punctuated by a few short-term and smaller-scale oscillations, this trend of climatic deterioration culminated in ca. 4200-4000BP, coinciding with the so-called 4.2kaBP event (Bond et al., 2001; Booth et al., 2005; Walker et al., 2012; Weiss, 2017). The reduction in precipitation and temperature during this event on the Central Plains might not be, however, as pronounced as that observed in other global regions. Reconstructed precipitation curves based on speleothem data and site-specific pollen records on the Central Plains suggest that the precipitation experienced a protracted but steady decrease beginning from ca. 5000BP, which culminated around 4200BP when the average annual precipitation dropped from between 800 and 700 mm to below 500 mm. But at several studied sites, this trend of prolonged aridification reached the peak at a much earlier date at ca. 4700-4500BP (also see Herzschuh et al., 2019).

Apart from this broad climate background, of direct relevance to the rise of the late-Neolithic walled sites on the Central Plains are their local geomorphological environments which determined the planning, construction and operation of the walled sites and the burgeoning urban systems they represented. A range of models of the evolution of Holocene geomorphology have been proposed for different sub-regions of the Central Plains that are under the influence of diverse geological backgrounds and tectonic activities, but most importantly, of alluvial processes on different temporal and spatial scales (Lü et al., 2019; Lu et al., 2019, 2021). Broadly speaking, the middle to late Holocene geomorphological environment on the Central Plains enjoyed an overall stable tectonic history and was instead, characterized by several episodes of alluvial aggradation and incision along the major rivers and their tributaries. Lu and colleagues, for instance, recently proposed three models of the evolution of Holocene alluvial landscape in the northeastern Songshan region of the Central Plains that shaped characteristic landforms and geomorphological units on the loess tablelands, alluvial plains and low-lying floodplains as well as wetlands of the region (Lu, 2019, 2021, 2022).

As a relatively small but distinctive geographic region on the Central Plains, the Zhenshui River valley, where the Guchengzhai site is located, covers an area of ca. $100 km^2$ in southeastern Songshan. It has a continental temperate climate, with an average annual temperature of 14 °C and average annual precipitation of ca. 700 mm. The regional topography tilts from west to east. Originated in the eastern Songshan Mountain in northwestern Xinmi County, the Zhenshui River flows through diverse terrains, including hilly mountainous valleys, flat loess tablelands and alluvial terraces and plains (Fig. 2). The major event of alluvial incision that took place in the late Pleistocene cut the loess landform into an exceptionally deep valley, which also elevated the oldest alluvial terrace to a high position. The incision in the middle to lower Zhenshui River reached >15 m below the modern riverbed.

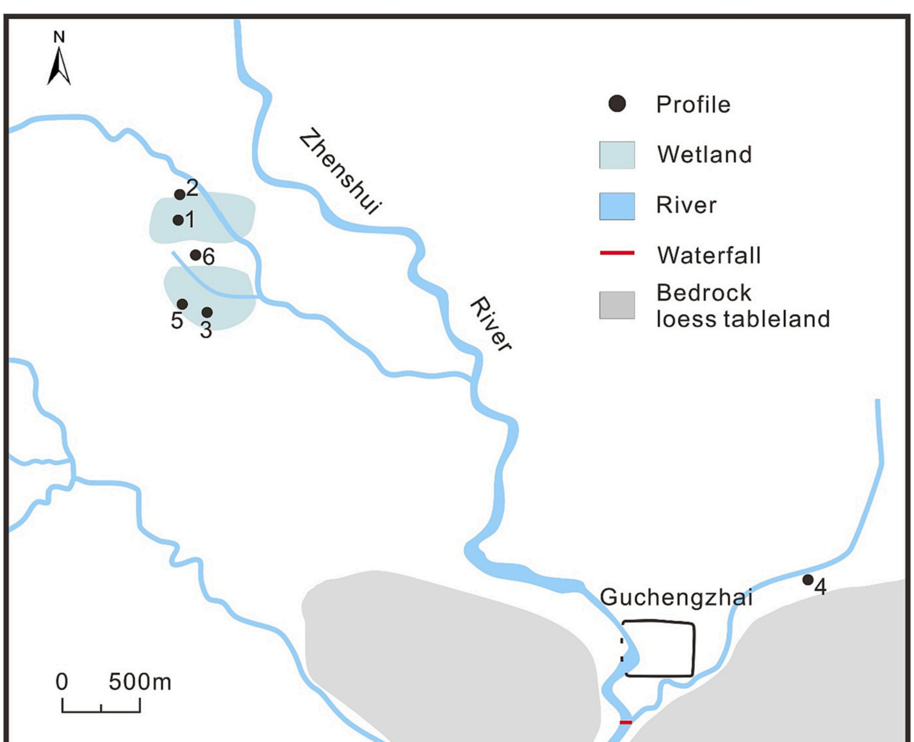


**Fig. 2.** The Guchengzhai site and examined sedimentary sequences in the Zhenshui River. 1: Shiyuan (SY); 2: Shiyuan02 (SY02); 3: Niuyuhuan (NYH); 4: Huangzhuang (HZ); 5: Niuyuhuan02 (NYH02); 6: Shiyuan03 (SY03). See Figs. 8, S1 and S3 for profile photos.

 

Around Guchengzhai, the river even incised the geological bedrock and created a small waterfall. This was followed by an aggradation of thick alluvial sediments especially in the lower Zhenshui River (ca. 20 m of alluvium), as evidenced by the well-preserved profiles of reworked loess and lacustrine sediments (Fig. S1). This large-scale late Pleistocene alluvial aggradation gave way to another episode of alluvial incision during the terminal Pleistocene, especially on the river channel below Guchengzhai waterfall. The well-drained river floodplain now became a stable terrace surface (T3). Another event of alluvial aggradation resumed in the early Holocene and lasted till ca. 6000 cal.BP. This was followed by a second event of river down-cutting, which began first in the lower Zhenshui River and only started to occur in the middle Zhenshui River in ca. 4000 cal.BP as the headwater erosion slowly reached the middle and upper streams of the river (Xu et al., 2013). A few distinctive characteristics in the alluvial landscape of the Zhenshui River can be observed from the broad-brush reconstruction above. First, many of the geomorphological units, such as hills and flat loess highlands, in the region are running parallel with the river valley. These serve as watersheds that separate the Zhenshui River valleys with other nearby river catchments. Situated between these relatively high-altitude hills and loess highlands and the low-lying river valley are the broad loess tablelands and alluvial terraces generally with gentle terrains. In particular, the lower Zhenshui River is dominated by the gentle loess tablelands because of its lack of high-altitude hills (Fig. 2). Second, the alluvial processes occur at a relatively larger scale in the lower than the middle and upper Zhenshui River. During the dry late-Holocene period, these alluvial terraces and other associated terrains in the middle to lower Zhenshui River would have presented both opportunities and challenges to the increasingly large-scale inhabitation of the region, as can be seen at Guchengzhai.

## 3. Materials and methods

### 3.1. Excavation of the Guchengzhai walled site

The terrains inside and outside the enclosed earthen walls at Guchengzhai are 10 m and 2-5 m higher than the modern riverbed, respectively. Some well-preserved sections of the walls still stand 5–16.5 m above the surrounding ground (Fig. 3). Several excavations have been carried out at the site since 1998. The excavation in 1998–2000 revealed that the walls were constructed during the late-Neolithic Longshan era but might not have been occupied for long. Large-sized and potentially high-rank architectural foundations were also found during the excavation (Cai et al., 2000; Cai and Ma, 2002).


**Fig. 3.** Excavation photos of the Guchengzhai earthen walls. 1: Numerous holes left after application of the pounded-earth technology, after Cai and Ma 2002; 2: Impression of bamboo planks used to build the pounded-earth wall, after Cai and Ma 2002; 3: Excavation photo of the western end of the excavated moat and wall, showing clear pounded-earth layers in multiple building units which were built directly on top of fine grayish silty sediments.

The excavation of the eastern moat in 2016–2017 further confirmed the construction time, procedure and structure of the moat and related wall sections (Zhang et al., 2019). Overall, the Guchengzhai walled site is of a rough rectangular shape. It measures 460 m east-west and 370 m north-south. There are also Neolithic archaeological remains found outside the enclosed area.

The dimensions of the earthen walls and moat at Guchengzhai are summarized in Table 1. Although some walls and moat must have been constructed piecemeal and subject to regular repairing and restoration, they represented the largest-scale earthen construction in contemporary Central Plains which would have been supported by some centralized planning and logistic organization (SAMPKU and HPICHA, 2006; Xie et al., 2021). The construction was, however, constrained by local terrains and the Guchengzhai builders must have taken this factor into consideration. The pre-construction terrain was low on the southeastern part; and in other wall sections, there were also small ponds on the uneven surfaces before construction. This problem was overcome by building wide and solid foundations through the pounded-earth technology to level the surfaces before the walls were erected by applying the same technology. The material used to build the wall foundation must have also been purposefully selected. Red clay mixed with gravels and calcrete nodules was used to build the bottom part of the foundation layer, as revealed in the excavation (Fig. 3). Such a mixture of materials must have significantly increased the drainage, permeation and structural stability of the foundations and walls as suggested by modern engineering studies (e.g., Wu et al., 2011; Yuan et al., 2014; Professor Junping Yuan, personal communication). This foundation layer can be seen in almost all of the excavated wall sections, although the thickness and the material used to build it varied. In the west section of the northern wall, for example, a foundation ditch was dug, inside which pounded earth layers were applied before the wall was built, whereas in the eastern section of the northern wall, only a thin layer of clay mixed with small pottery sherds was built as the foundation (also see Cai and Ma, 2002).

Dimension of the excavated moat at Guchengzhai is given in Table 1 too. Unlike natural river channels which often have an asymmetric shape, with convex and concave-shaped banks due to changing directions of water flow and bank erosion, the moat at Guchengzhai displays a roughly symmetric shape with gentle, slightly concave-sloping banks (Fig. S2). Similar to the construction of the walls, the construction and maintenance of the moat were of an equally large scale and would have demanded collective effort to build, operate and repair it. A total of >800m$^2$ was excavated in 2016–2017. The excavated stratigraphy is described in Table S1. We collected 19 sediment blocks from different layers (Table S2 and Fig. 4) for micromorphological examination, a technique that is increasingly used to reconstruct sedimentation history in moats or similar contexts and understand long-term land-use history (Macphail and Goldberg, 2018). 170 bulk samples were collected from trench no. T4 located in the middle part of the moat at an internal of 2 cm for particle size analysis. Five 14C dating samples were collected different layers in trench no. T4 (Table 2).

**Table 1**
Dimension of the walls and moat at Guchengzhai.

| Location | Dimension |
|---|---|
| Northern wall | Wall foundation 500 m long and 42.6–53.4 m wide; wall body 460 m long and 12-22 m wide at the base and 1-5 m wide at the top; 7–16.5 m tall. |
| Southern wall | Wall foundation 500 m long and 42.6–62.6 m wide; wall body 460 m long and 9.4-40 m wide at the base and 1-7 m at the top; 5-15 m tall. |
| Eastern wall | Wall foundation 353 m long and 85.4-102 m wide; wall body 345 m long and 36-40 m wide at the base and 13.8-15 m tall. |
| Southern wall | Severely damaged, reconstructed length of the wall body ca. 370 m. |
| Moat | 34–90 m wide and > 4.5 m deep. The excavated section of the eastern moat is ca. 55 m in width and 5.9 m in depth. The northern moat might be ca. 10 m deep. |

### 3.2. Geoarchaeological survey and sampling

Alongside the sedimentological and micromorphological studies of the moat sediments, we also conducted a geoarchaeological survey around the Guchengzhai site. The site and its surrounding area are situated on the alluvial terrace T2 (134m above the sea-level) of the middle-to-lower Zhenshui River (Fig. 2). As aforementioned, the area experienced hydrological fluctuations and geomorphological change during the Holocene. We first focused our survey on the incised gullies located to the east of Guchengzhai and then expanded it further to the area northwest of it. The late-Holocene sedimentary sequences in these places reflect sedimentation histories both in the immediate surrounding and wider environment of Guchengzhai. These sequences were carefully examined, from which a range of environmental and dating samples were collected and analyzed. We also identified distinctive alluvial landforms such as lakes and wetlands during the survey. Six profiles that represent lacustrine and related sediments were examined along the paleo-lake at Shiyuan (Fig. 2). We used handheld GPS device to make rough estimation of their distribution range, which was considered to be representing the size of the lake. 211 sediment samples were collected from the Shiyuan profile at an interval of 2 cm whilst 12 samples were collected from the Huangzhuang profile at an interval of 10 cm for particle size analysis. Detailed procedures for the OSL (Optically Stimulated Luminescence) dating, 14C dating and particle size distribution are described in the appendix.

## 4. Results

### 4.1. Reconstructing the sedimentation history of the moat

The construction date of the walls and moat at Guchengzhai is established by both direct 14C dates and archaeological evidence, the latter including pottery typology and archaeological stratigraphy. Table 2 summaries the 14C dates obtained from different layers of the moat deposits. In combination with anthropogenic inclusions especially pottery sherds with distinctive stylistic changes from these layers, we can suggest that the moat was dug during the late Longshan period (the Wangwan Phase III) and used for a few hundred years, between ca.4080–3800/3700BP, before being completely silted up and deserted.

Based on the excavated stratigraphy and micromorphological study, we divide the sedimentation process in the moat into stages 1–3, representative of the stages when the moat was in use, being gradually silted up, and eventually abandoned, respectively. More detailed results of the micromorphological study are summarized in Table S3. The pre-construction environment, as aforementioned, is characterized by an uneven terrain. As shown by the excavated sections, parts of the eastern wall were built directly on a layer of grayish silty sediments (20-40 cm thick) (Fig. 3) which resemble the limnetic sediments found near the site (Table 3) and clearly suggest this location was on a marshland before the wall was built. Contrary to this, on the eastern end of the excavated moat, the sediments cut by the moat digging were characterized by light yellowish silt containing abundant sand. Micromorphology of the slides collected here confirms the presence of abundant moderately to poorly sorted sand and coarse-sized sediments, including some very large-sized gravels. The presence of iron nodules and calcitic nodules (Fig. 5:1–2) further suggests a weak to moderate degree of soil formation. Before the construction, this area was situated on the relatively higher ground on the river floodplain which was influenced by floods periodically but remained overall dry.

In stage 1, the sediments are characterized by relatively coarser-sized particles that were poorly to moderately sorted and contained small pebbles, calcrete aggregates and other large-sized heterogeneous sediment aggregates (Fig. 5:3). The percentage of these coarser-sized sediments remained small (below 10%) with noticeable fluctuations, however. Two main sedimentation processes can be observed in this stage: alluvial process, and colluvial process and/or sheet-wash erosion.

**Fig. 4.** Photos showing collection of thin section samples from different sections of the moat. See Table S1 for sediment descriptions.

**Table 2**
14C dates from the moat at Guchengzhai.

| Lab no. | Field no. | Depth (cm) | Dating material | Calibrated Age(BC) | | Calibrated age (cal. BP) |
|---|---|---|---|---|---|---|
| | | | | 1σ (68.2%) | 2σ (95.4%) | |
| Beta –573,424 | T4s-68 | 414 | Charcoal | (68.2%) 1691–1625 cal BC | (94.7%) 1745–1611 cal BC<br>(0.7%) 1572–1566 cal BC | 3690–3560 ;<br>3520–3520 cal BP |
| Beta-573,423 | T4s-54 | 442 | Charcoal | (41.4%) 1829–1769 cal BC<br>(26.8%) 1878–1839 cal BC | (93.4%) 1893–1741 cal BC<br>(2.0%) 1711–1700 cal BC | 3840–3690;<br>3660–3650 cal BP |
| Beta- 573,422 | T4s-51 | 448 | Charcoal | (57.1%) 1945–1878 cal BC<br>(6.9%) 1840–1826 cal BC<br>(4.2%) 1793–1784 cal BC | (67.7%) 1975–1861 cal BC<br>(27.1%) 1853–1772 cal BC<br>(0.6%) 2008–2003 cal BC | 3920–3810;<br>3800–3720;<br>3960–3950 cal BP |
| Beta- 573,421 | T4s-33 | 484 | Wood Material | (68.2%) 2036–1950 cal BC | (79.7%) 2056–1921 cal BC<br>(15.7%) 2133–2084 cal BC | 4010–3870;<br>4080–4030 cal BP |
| Beta- 573,420 | T4s-1 | 550 | Charcoal | (56.1%) 2039–1962 cal BC<br>(12.1%) 2118–2098 cal BC | (95.4%) 2135–1939 cal BC | 4080–3890 cal BP |

The former mostly took place in the middle part of the moat. The latter was predominant along the two banks of the moat and on the nearby slopes where human activities also contributed to the sedimentation process by, for instance, disposing of abundant eroded materials and anthropogenic inclusions into the moat (Figs. 4 and 5:5–6). These anthropogenic sediments were then subjected to further sorting and transportation through water, alternating with the colluvial deposits. These alternative layers became thinner and eventually disappeared from the banks to the center of the moat. The alluvial sediments in the middle of the moat were deposited under fluctuating hydrological regimes. The particle size results (Fig. 6) show frequent variations of clay, silt and sand-sized sediments due to changing hydrodynamics in the moat. Micromorphological study further reveals that whilst some layers are dominated by light grayish well-sorted fine sediments, indicative of standstill water regime that led to iron depletion, other layers are dominated by light yellowish silt or sandy silt, which are associated with strong hydrodynamics. Indeed, the poorly sorted groundmass in some thin sections (Fig. 5:4) from the layers closer to the banks and slopes clearly suggest that some of the sedimentation events were rapid, representative of high-energy flows which brought in abundant coarse-sized sediments and heterogeneous sediment aggregates to the moat without proper sorting as water quickly receded. Similar to these events was the deposition of alternating fine and coarse sediment laminae (Fig. 5:8–9), which represent frequently changing but predominantly gentle hydrological regimes in the moat (e.g., Pagliai and Stoops, 2010; Russo and Fox, 2012). In addition to abundant redoximorphic features such as iron nodules, there are also calcitic coatings (Figs. 5:7 and 7:1). The latter, albeit of a scattered appearance, suggests that the moat also experienced some localized dry conditions (drainage or drying?).

To sum up, sediments close to the west bank (where the earthen wall is situated) are generally poorly sorted and contain abundant eroded sediment and calcrete aggregates (Fig. 4). There are also fine sediment

**Table 3**
Sediment descriptions of the Huangzhuang and Shiyuan profiles.

| Profile | GPS coordinates | Layer no. | Depth (cm) | Description |
|---|---|---|---|---|
| Huangzhuang | 34.474°N, 113.655°E, H: 129 m. | 1 | 0–105 | Brownish paleosol layer, clayey silt with a dense structure, containing abundant snails and plant roots. |
| | | 2 | 105–175 | Lake and marsh deposits, dominated by clay and silt with obvious horizontal beddings. The percentage of silt is the largest (71–73%) compared to other layers, and the middle size is the smallest with 32-35 μm, indicating a sustained and stable depositional environment. |
| | | 3 | 175–300 | The late-Pleistocene Malan loess and early-Holocene loess layer, grayish yellow clayey silt. |
| Shiyuan | 34.490°N, 113.616°E, H: 132 m. | 1 | 0–40 | Late-Holocene loess layer, grayish yellow silt, containing some clay and abundant sand. |
| | | 2 | 40–100 | Brownish paleosol layer, with a dense structure and containing abundant plant roots. |
| | | 3 | 100–140 | Grayish yellow alluvial sandy layer, containing horizontal beddings typical in alluvial settings. |
| | | 4 | 140–422 | Brownish lake and marsh deposits with abundant horizontal beddings. The predominant silt (70–91%) and the smallest middle size (3-37 μm) of this layer indicate a sustained and stable depositional environment. |

laminae, some of which contain abundant calcite or plants remains which are distributed horizontally (Fig. 5:9). Comparatively, sediments in the middle part of the moat are generally better sorted and of finer-size. Fine sediment laminae occur more abundantly, without the presence of calcite or plant remains, with exceptions (e.g., GS11 in Table S3) that contain particularly high calcite contents and charcoal which are distributed randomly without a horizontal structure. Whilst it was noted during the excavation that the sediments in this part of the moat were relatively 'clean', small-sized anthropogenic inclusions are commonly present in the thin sections (Fig. 5: 5–6). Except for a few waterlogging events, the overall hydrological regime was dominated by gentle but relatively sediment-laden flow, punctuated by small floods, with formation of abundant redoximorphic features (Fig. S5 and Table S3). The water depth remained shallow and as can be expected, became even shallower towards the banks.

The sedimentation environment became much drier, as evidenced by the formation of more abundant in-situ calcitic pedofeatures in the transition to stage 2 (Table S3), represented by layer 21 distributed in excavation trenches no. T1-T6. The sediments are characterized by several thin peat-like organic-rich layers in the upper and lower parts of layer 21, sandwiching some fine-sand and silty layers between them (Fig. 4:2 and 4, Fig. 7:2–3, and Fig. S4:1–2). The fine sand and silt are generally well sorted in a relatively 'clean' groundmass that does not contain other inclusions such as charcoal. The peat-like layers also contain abundant rounded-shaped and medium-sized sand well embedded in the organic-rich groundmass. The distribution of such peat-like layers might seem to be continuous, but our micromorphological study shows that the deposition is uneven and often disrupted (Fig. 7:2), indicating severe post-depositional alteration caused by mechanic pressure and/or bioturbation. Most of these plant remains (charcoal and ash), which are amorphous in shape and vary greatly in size and abundance, are deposited horizontally (Figs. 7:3 and S4:3), suggesting that they were (re)deposited through water. The deposition of two different types of groundmasses (the organic-rich groundmass and 'clean' groundmass) (Fig. S4:4) and their common alternations in layer 21 suggest not only fluctuating hydrological regimes but also changes of sediment sources during stage 2. Based on the above, we suggest that as the environment became drier and almost half of the moat was silted up, the moat ceased to function and became a low-depression area with a small water flow. Plants started to grow, and organic matter accumulated, resembling the condition of peat formation commonly encountered in wetlands. However, the peat-like layers were subject to large-scale disturbance possibly from intensified land use such as land clearance and firing around the area, as evidenced by the presence of ash, charcoal and other micromorphological features described above. This was followed by flash floods that washed up, transported and redeposited the organic matter and ash.

Stage 3 marked the complete abandonment of the moat, accompanied by drastic change in the sedimentation process. The environment became drier as evidenced by the more calcitic-related pedofeatures in the examined slides (Fig. 7:6–7 and 9; Table S3). This was, however, frequently punctuated by wet episodes which resulted in the formation of iron nodules and other redoximorphic pedofeatures. Whilst the fine-sized sediments predominated in the poorly to moderately sorted groundmass, there are also plenty of coarse-sized minerals, calcite nodules, and other heterogeneous inclusions such as amorphous-shaped organic matter (Fig. 7:7–8). Such a sedimentation regime is also illustrated by results of the particle size analysis, which show evident changes of clay-sized particles and a dramatic decrease in sand-sized particles whilst the percentage of silt also varies (Fig. 6). Some coarse-sized minerals and calcite nodules occur as sediment laminae well embedded in the groundmass. Some of these laminae consist of plant remains or calcite alternating with coarse-sized sediments (Fig. 7:9). These heterogeneous materials were eroded from nearby areas and were subjected to further water-borne transportation before eventually being deposited in the moat, which contributed to rapid siltation and eventual abandonment of the moat.

To sum up, the sedimentological and micromorphological evidence described above provides detailed information for the reconstruction of the use and corresponding sedimentation regimes at different stages of the life-history of the moat, which is further contextualized with the wider geomorphological and hydrological environment through our regional geoarchaeological survey.

### 4.2. *Reconstructing the late-Holocene aquatic environment around the Guchengzhai site*

Results of the OSL and 14C dating and particle size analysis of the Huangzhuang and Shiyuan profiles (Fig. 8) are summarized in Tables 4 and 5. The dates are in good stratigraphic order and confirm that these two profiles represent the middle-to-late Holocene (ca.8000-3000BP) sedimentation environment near Guchengzhai. Based on this and combined with our field observation and particle size results, these two sedimentary sequences represent several middle-to-late Holocene episodes of alluvial aggradation and incision, and soil formation on the terraces in the region. At Shiyuan, the lacustrine sediments (layer 4 in Table 3, same below), characterized by many horizontal beddings observable in the field, point to the existence of lake and/or wetlands which lasted until around 5000BP (Table 4) when the climate became

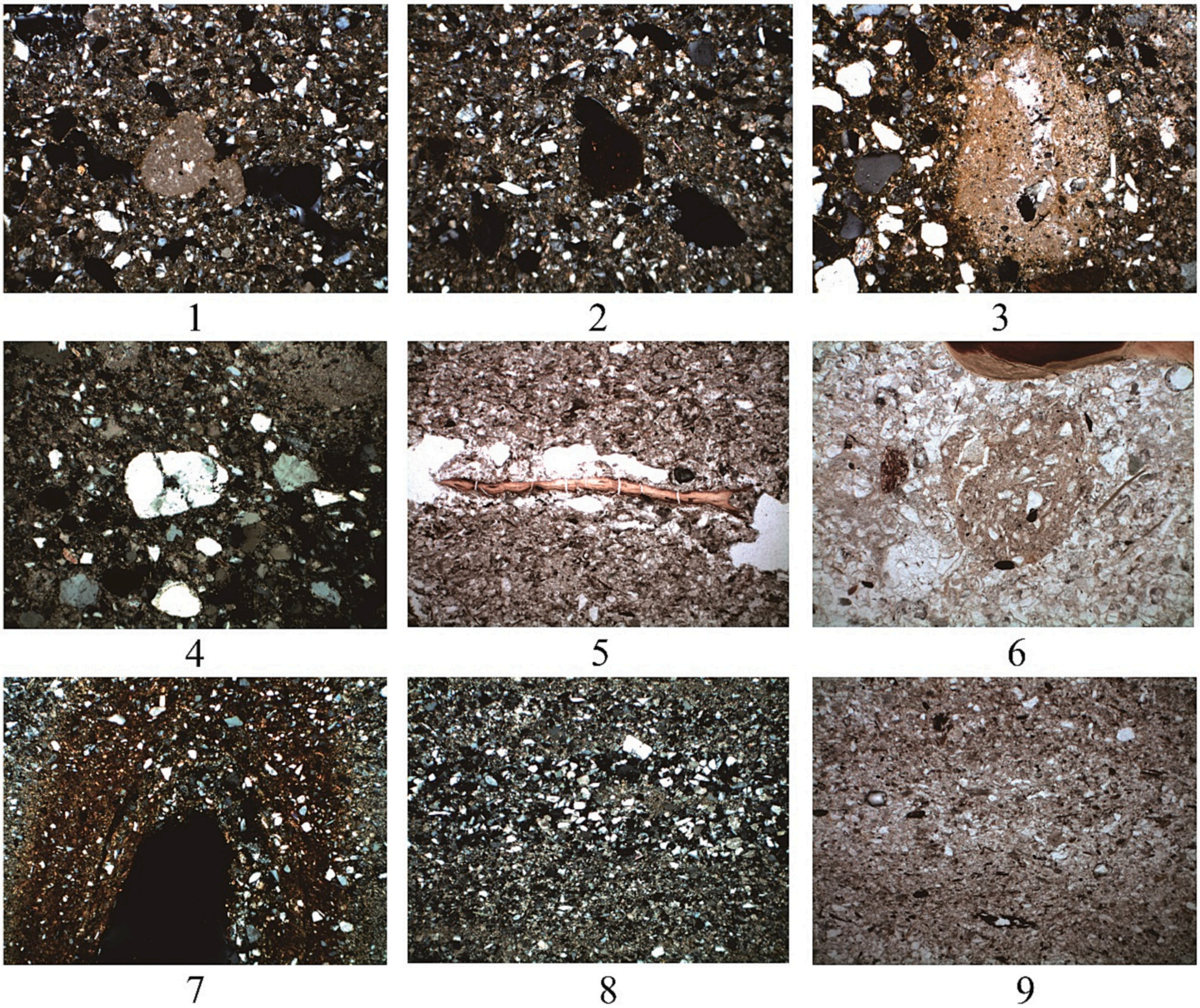

**Fig. 5.** 1: Calcite nodule in a groundmass with poorly to moderately sorted minerals, GS-19, XPL (Cross Polarized Light, same below), frame width 2.8x2mm (same below unless otherwise stated). 2: Well impregnated iron nodule with sharp boundary with the groundmass, GS-19, XPL. 3: Calcite nodule or calcrete aggregate with diffuse boundary with the poorly sorted groundmass, GS-05-up, XPL. 4: Poorly sorted highly mixed groundmass with sub-rounded to sub-angular shaped minerals, GS-05-upper, XPL. 5: Elongated shaped bone fragment with vertical fractures and dark orange colour possibly caused by burning, GS-10, PPL (Plain Polarized Light, same below). 6: Rounded-shaped aggregate (dung fragment?) well embedded in the groundmass that contains abundant fine organic matter, GS-16-upper, PPL. 7: Iron coatings and hypo-coatings with a concentric structure, alternating between iron-depleted and iron-concentrated areas, GS-11, XPL. 8: Sedimentary laminae (or cross-beddings) of coarse-sized minerals alternating with fine-sized (mostly calcite) sediments, GS-05-lower, XPL. 9: Sedimentary laminae of coarse-sized sediments alternating with fine-sized sediments with most organic matter and charcoal being deposited horizontally, GS-17, PPL. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

drier in the region. The size of the lake measured ca.15.6 ha according to our rough estimation (Figs. 2, 8 and S3 and Table S4). The lacustrine sediments contained a relatively higher percentage of sand than that of the reworked loess but this decreased gradually as the water became shallower when the lake and/or wetland shrunk substantially. This was followed by the onset of an aggradation event (layer 3) which resulted in the deposition of sandy sediments with many horizontal sediment beddings, indicative of much stronger hydrodynamics compared to layer 4. Another drastic change took place in the following stage (layer 2) when alluvial aggradation gave way to incision from ca. 4000BP, resulting in soil formation on the terrace. The region enjoyed several hundred years of landscape stability as soil continued to develop until ca. 3300-3200BP when loess accumulation resumed (layer 1) (Fig. 9). At Huangzhuang east of Guchengzhai, a similar sedimentation history can be reconstructed. Following an episode of early-Holocene landscape stability, the sedimentation was also dominated by the accumulation of limnetic sediments between ca. 6750-3400BP (Table 5; Fig. 8). They were thinner compared to those at Shiyuan, and possibly with a few sedimentation hiatuses. In addition, the sediments contained more sand, organic matter and shells but without evident horizontal beddings, compared to the limnetic sediments at Shiyuan. Mostly distributed along the incised gully, which is a tributary branch of the Zhenshui River, the Huangzhuang wetland spread out as a long stretch but with shallower water, which explains the sedimentation of coarser-sized particles that were less well sorted due to weakened hydrodynamics.

The foregoing summary suggests that before and during the occupation at Guchengzhai some lakes and wetlands still existed in the immediate and nearby environment (Fig. 2). Although these waterbodies varied greatly in size and were shrinking as the climate became drier, they constituted a vital part of the aquatic landscape surrounding Guchengzhai. These lakes and wetlands were connected to the Zhenshui River and its tributaries and formed a two-tiered aquatic system surrounding Guchengzhai. The Zhenshui River and the small-sized but deep-water lakes that fed into it formed the first tier of the system.

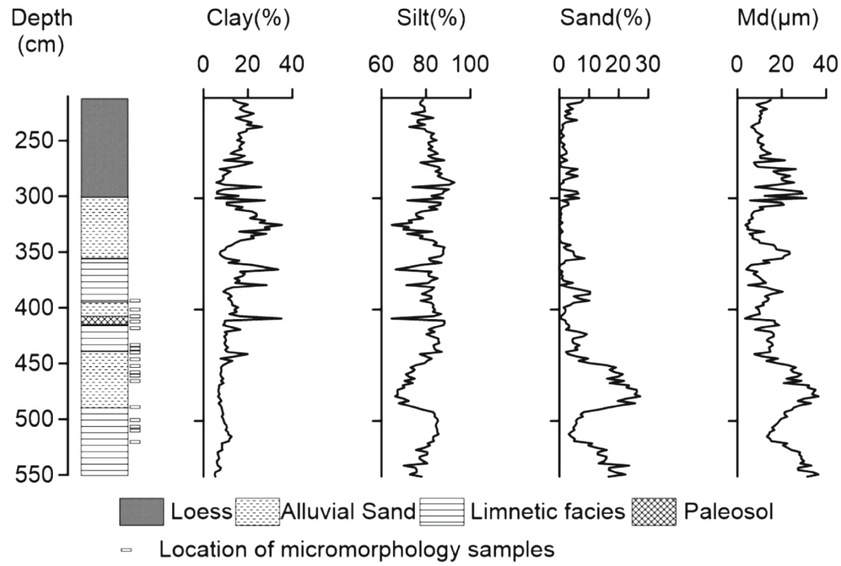


**Fig. 6.** Results of particle size analysis of sediments collected from the moat at Guchengzhai.

Whilst the exact spatial relationship between the Zhenshui River and the Guchengzhai walls remains unclear due to the severe damage of that part of the site, it was possible that the (western) moat was linked to the river (Fig. 2). The second tier of the system consisted of the wetland and the tributary branches surrounding Guchengzhai. Although the wetland had shallower water, its larger size and closer vicinity to the site meant that it would have been an important and reliable source of water to Guchengzhai, especially during droughts. In this regard, the construction of the Guchengzhai walled site at the confluence of the aforementioned waterbodies with abundant water might have been a deliberate choice. The particle size results of the limnetic sediments at Huangzhuang broadly accord with those of the Guchengzhai moat in terms of sediment sources, sorting and other sedimentological parameters, although as noted above, the fluctuations of clay and sand contents in the moat sediments were more pronounced (Figs. 6 and 9). This suggests similar sedimentation environments of the moat and its surrounding wetland at Huangzhuang, both on naturally low-lying places of the region. Whilst it cannot be said with certainty if the moat was connected directly through some small channels to the wetland, the transition to a peat-like environment in the moat from stage 1 to stage 2 does resemble a change to wetland environment.

## 5. Discussion

### *5.1. Aquatic environments of the late-Neolithic walled sites on the Central Plains*

The water management practice at Guchengzhai can be briefly reiterated as follows. The Guchengzhai builders first leveled the ground and dug the moat whilst building the walls. During its use (stage 1), the excavated eastern moat might have been linked to the nearby wetland at Huangzhuang, and the sedimentation process in the moat resembled that in the wetland to some extent. As the region was getting drier because of climate change (but one cannot rule out the possibility that intensified water usage at Guchengzhai might have partly, albeit of a small scale, contributed to the localized drying process), the sedimentation processes in the moat (stage 2) and the Huangzhuang wetland became more synchronous, characterized in particular by the deposition of abundant organic matter. The relationship between the increasing demand for water at Guchengzhai and the persisting aridity in the region became even more acute. Such further stimulated the formation of an aquatic landscape of which water management, society and the environment all became integral parts and closely inter-related to each other.

Across the late-Neolithic Central Plains, (re)locating the walled sites towards or surrounding natural waterbodies on low-lying terrains became increasingly common as communities, with growing population, all facing challenges in water usage. Table 6 summarizes local landforms and alluvial settings surrounding several typical Longshan (4500-4000BP) and Erlitou period (4000-3800BP) walled sites on the Central Plains (Fig. 1). The aquatic environments of these walled towns share some common characteristics. These walled sites were normally situated on relatively higher points such as terraces, but all close to or surrounded by wetlands or other types of natural waterbodies. As illustrated by Liao et al. (2022) recent geoarchaeological survey, the construction of the Wangchenggang walled site coincided with a rising water level. This trend was interesting compared to the preceding Yangshao period occupation at the site when the riverine landscape experienced a prolonged period of alluvial aggradation, 'forcing' people to move to higher ground to avoid the flooding river. The Longshan period's relocation closer to the alluvial terraces and riverine lowland benefited from technological developments such as digging moats and building pounded earth walls, and was a clear indication of the increasing need to get access to abundant and reliable water resources. As one of the largest Longshan-period walled sites on the Central Plains, the Mengzhuang site was occupied for a long time. The site was situated on an alluvial plain that was historically surrounded by lakes and wetlands (Yuan, 2000). The Longshan walled site suffered from environmental disasters which might have contributed to its eventual demise. The fact that the site saw (re)construction and expansion during the following Erlitou and Shang periods demonstrates, on the one hand, its incredible resilience to environmental change, and on the other, the constant challenge to acquire sufficient water for survival and prosperity. It was through dealing with such a dilemma that the society was drawn closer to the lowland environment.

From a broad regional perspective, a significant development amongst these late-Neolithic and early-Bronze-Age walled sites was that some of them started to venture into the vast lowland alluvial plains of the Yellow River, as best illustrated by the recent excavation at the Qicheng site in Neihuang County (Fig. 10). Historically a low-lying area that often suffered from massive-scale Yellow River floods, Neihuang is home to several important archaeological sites, such as the well-known Han-Dynasty site of Sanyangzhuang where archaeologists have been able to reveal its well-preserved farming compounds and landscape which were covered by thick alluvium (Kidder et al., 2012). The Qicheng site suggests, however, the history of direct and large-scale

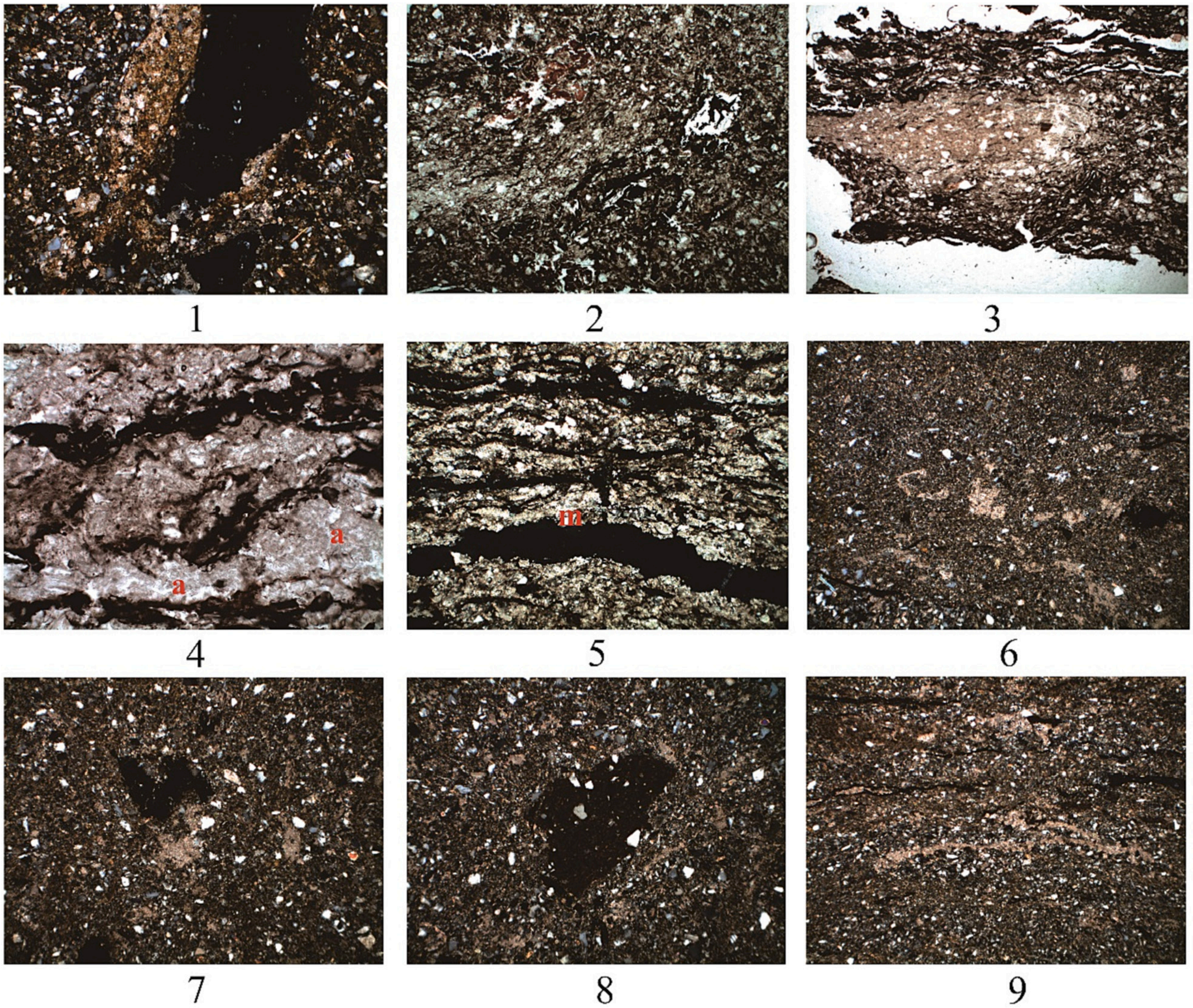

**Fig. 7.** 1: Calcite coating being superimposed by iron hypo-coating, GS-05-upper, XPL. 2: Organic-rich (peat-like) sediments that were highly disrupted and bioturbated, also note the iron-rich aggregates dispersing with the organic matter, GS-02-lower, XPL. 3: Organic matter, horizontally deposited or disrupted, sandwiching or coalescing sediment aggregates, GS-02-lower, PPL. 4: Waterlaid calcite-rich ash (a) with dense silica structure in organic-rich (dark thin strips) sediments, GS-12-upper, PPL, frame width 700x500μm. *5: Horizontal waterlaid calcite-rich ash deposits interspersing with thin organic layers, note the secondary microsparite in voids (m), GS-12-upper, XPL. 6: Calcite nodules, also note that the coarse-fraction sediments tend to be distributed horizontally, GS-02-upper, XPL. 7: Amorphous-shaped charcoal and calcite nodules in poorly to moderately sorted groundmass, GS-07-lower, XPL. 8: Burnt-earth fragment in calcite-rich groundmass, GS-07-lower, XPL. 9: Sedimentary laminae of coarse-sized sediment dominant beddings alternating with calcite-rich and organic-rich thin strips, GS-07-lower, XPL.*

occupation on the low-lying plains of the Yellow River began at least from the Longshan period. Yuan and Nan (2015) have recently pointed out that some 30 Longshan period sites have been found on low 'mounds' on the Yellow River floodplains with only 2-3 m relative height and many of them are covered in deep alluvium (up to 10 m below the present surface). This echoes Qin et al. (2022)'s recent suggestion that many late-Holocene sites in the Neihuang region, often invisible during surface surveys, might be buried in meters of alluvial sediments or being eroded away by later-period channel erosion.

### *5.2. Earthen construction, water management and formation of the aquatic landscape*

Whilst these walled sites vary significantly in scale, most of them have moats and other water management infrastructures, which became vital components of the increasingly complex settlement structures. The construction and maintenance of these infrastructures were achieved by the much improved earth-working technologies and more sophisticated labor organization. The late-Neolithic era saw pronounced developments in pounded-earth technologies in north China. One of the most important technological innovations was the so-called *banzhu* technology that used wooden planks or frames (or sometimes woven bamboo) as 'portable molds for effective compression' of earth using bundled sticks or cobblestones (Xie et al., 2021). Its widespread application not only increased structural stability of the earthworks but also significantly improved labor efficiency. Xie et al., (2021) estimation, based on parameters collected from their experimental work, shows that only a tiny proportion of the population and 30 working days would have been needed to build the pounded-earth walls at Taosi (1.2–4% of the estimated population) and Erlitou (0.3–0.5%). Such a relatively low labor demand would have meant that many small-to-medium sized communities (e.g., Pingliangtai) could also arrange earthen work construction without incurring enormous labor investment and economic expenditure. Evidence of the *banzhu* technology has been widely identified. At Pingliangtai, for instance, the earthen walls were similarly divided into small multiple units, measuring between 1 and 1.3 m in width and 1.4-2 m in length, to maximize efficiency and flexibility in labor organization (also see Cao and Ma, 1983).

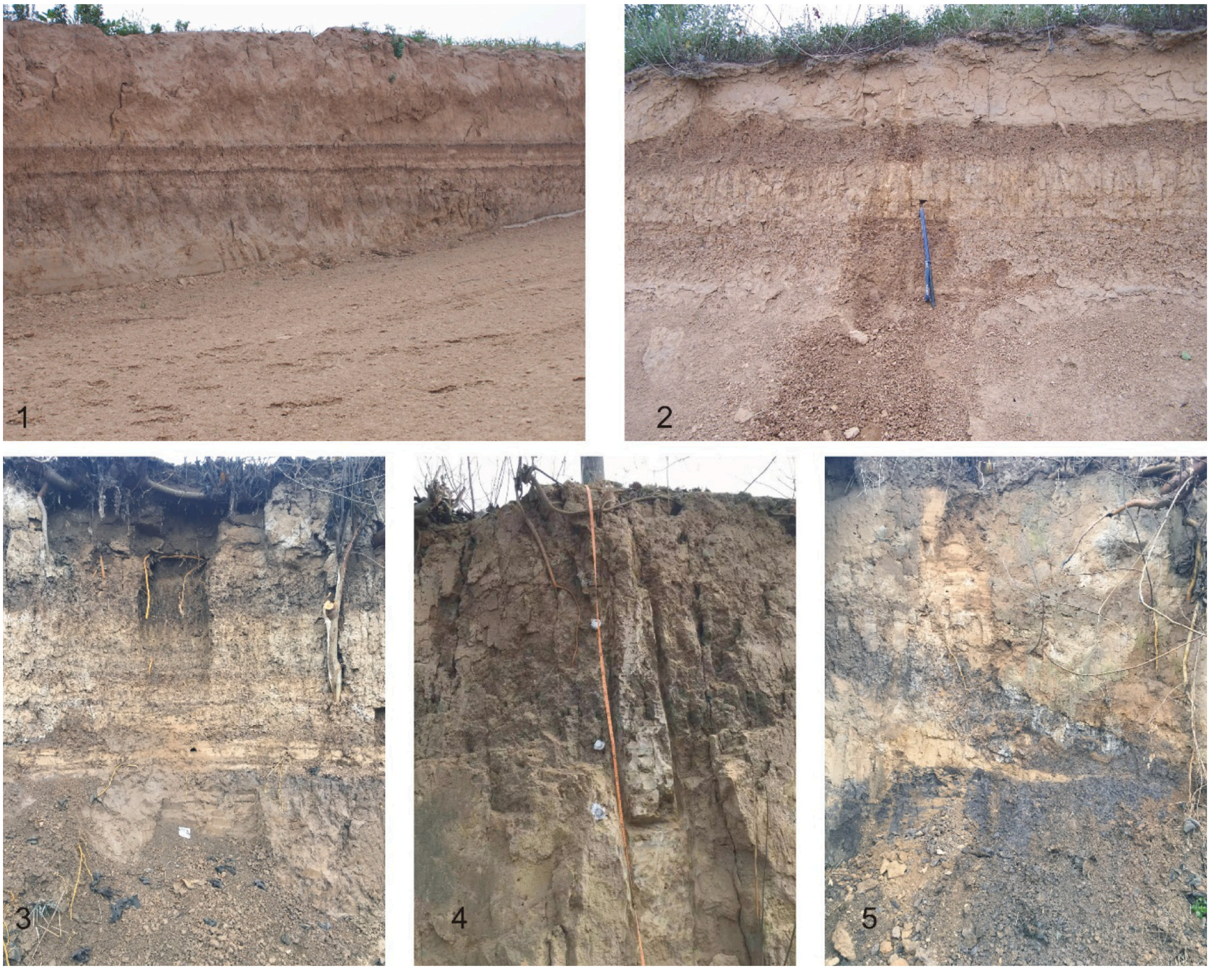


**Fig. 8.** Photos of several examined profiles during the survey. 1: Shiyuan (SY); 2: Shiyuan02 (SY02); 3: Niuyuhuan (NYH); 4: Huangzhuang (HZ); 5: Niuyuhuan02 (NYH02); 6: Shiyuan03 (SY03). See Fig. 2 for their locations and Table S4 for detailed descriptions of the sediments.

**Table 4**
14C dates from the Shiyuan profile.

| Lab no. | Field no. | Depth (cm) | Dating material | Calibrated Age (BC) | | Calibrated age (cal. BP) |
|---|---|---|---|---|---|---|
| | | | | 1σ (68.2%) | 2σ (95.4%) | |
| BA07079 | Sy18 | 386 | Charcoal | (63.4%) 6700–6560 cal BC<br>(4.8%) 6550–6520 cal BC | 6820–6470 cal BC | 7800 ± 60 |
| BA07081 | Sy74 | 274 | Charcoal | (60.8%) 5010–4890 cal BC<br>(7.4%) 4870–4850 cal BC | 5060–4800 cal BC | 6045 ± 45 |
| BA07083 | Sy117 | 188 | Charcoal | (32.6%) 4350–4315 cal BC<br>(35.6%) 4300–4260 cal BC | 4370–4230 cal BC | 5455 ± 40 |
| BA07085 | Sy177 | 68 | Charcoal | (56.6%) 1980–1870 cal BC<br>(6.9%) 1850–1820 cal BC<br>(4.6%) 1800–1780 cal BC | 2030–1770 cal BC | 3560 ± 40 |
| BA07086 | Sy189 | 44 | Charcoal | (37.7%) 1670–1600 cal BC<br>(30.5%) 1590–1530 cal BC | (3.1%) 1740–1710 cal BC<br>(92.3%) 1700–1510 cal BC | 3330 ± 40 |
| BA07087 | Sy205 | 12 | Charcoal | (53.6%) 980–890 cal BC<br>(14.6%) 880–840 cal BC | (95.4%) 1020–820 cal BC | 2775 ± 40 |

**Table 5**
OSL dates from the Huangzhuang profile.

| Sample N. | Depth(cm) | U/ppm | Th/ppm | K/% | Rb/ppm | Q-De(Gy) | aliqouts Num. | w.c (%) | Q-Dose rate | Q-Age(ka) |
|---|---|---|---|---|---|---|---|---|---|---|
| HZ 01 | 110 | 2.08 ± 4.0 | 11.4 ± 3.2 | 1.67 ± 0.13 | 85.3 ± 2.3 | 12.60 ± 0.10 | 10 | 1.95 | 3.719 ± 0.881 | 3.388 ± 0.803 |
| HZ 02 | 172 | 2.06 ± 1.7 | 10.5 ± 2.2 | 1.50 ± 0.88 | 86.8 ± 2.7 | 22.86 ± 0.10 | 10 | 3.11 | 3.387 ± 0.824 | 6.750 ± 1.643 |
| HZ 03 | 205 | 1.93 ± 2.1 | 10.8 ± 2.7 | 1.60 ± 0.96 | 80.4 ± 1.8 | 30.29 ± 0.23 | 10 | 1.87 | 3.514 ± 0.934 | 8.620 ± 2.293 |

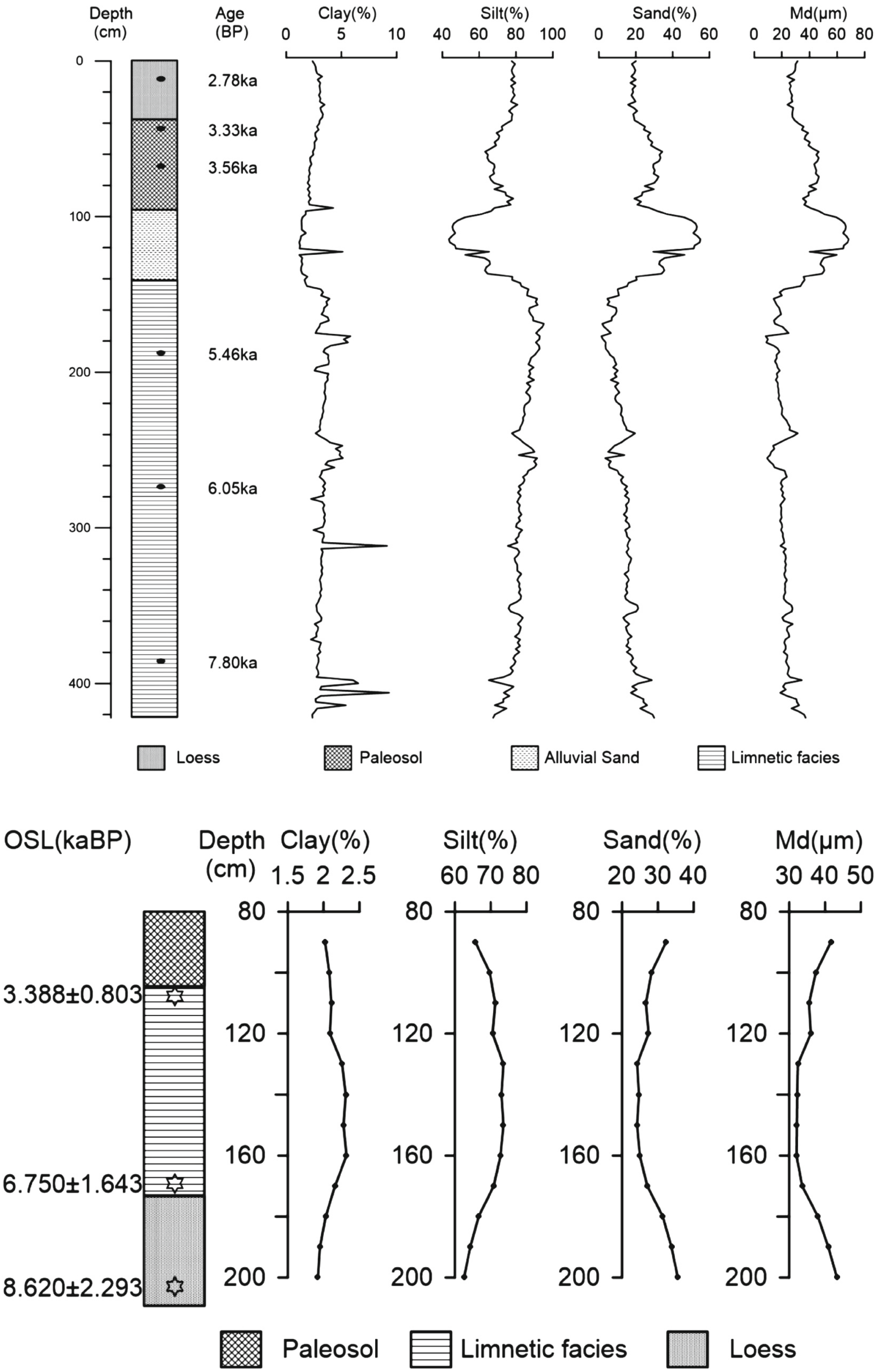


**Fig. 9.** 1: Results of particle size analysis of sediments from the Shiyuan (SY) and Huangzhuang (HZ) profiles. The dots in the upper image (SY) and stars in the lower image (HZ) are where the OSL dating samples were collected.

**Table 6**
Size and structure of late-Neolithic and early-Bronze Age walled towns on the Central Plains.

| Site and date | Coordinates | Structure and scale of walled site | Walls | Water management facilities | Surrounding environment | Sources |
|---|---|---|---|---|---|---|
| Hougang (see Fig. 1 for location, same below) (4500-4100BP) | E114.340345, N36.118509 | Oval shape, ca. 10 ha in size | Preserved walls are 70 m long and 2-4 m wide | – | Riverine highland to the south of the Huanhe River | Yang and Xu, 1985 |
| Mengzhuang (4400-4100BP) | E113.841036, N35.435167 | Near rectangular shape, 16 ha in size including the walls | Different walls are between 260 and 375 m long and ca. 20 m wide | Moat: ca.20 m wide and 3.8–4.8 m deep | Alluvial plain surrounded by wetlands and lakes | Yuan, 2000; Yuan et al., 2000 |
| Qicheng (Hougang phase II culture, ca. 4100BP) | E115.031892, N35.757749 | Near rectangular shape with rounded corners, 17 ha in size including the walls | Early-phase walls are between 240 and 325 m long; Late-phase walls, preserved parts 16.5 m are wide and 8.3 m high | A U-shaped moat outside the northern wall, 9-10 m wide and 6 m deep | Eastern bank of the Yellow River | Ma et al., 2017 |
| Xijincheng (mid-to-late Longshan period) | E113.121349, N35.111884 | Near rectangular shape with rounded corners, 30.8 ha including the walls | Different walls are between 400 and 560 m long, 10-25 m wide, with remaining height of 2-3 m | A small creek/moat flowing outside northern and eastern walls, 10 m wide. Along the eastern wall, the creek bifurcated into two narrow branches, sandwiched by a sand bar (250 m long and 2-25 m wide). | On old crevasse splay of the alluvial plain of the Qinhe River and its tributaries (evidence of floods that destroyed the walled site is reported by Zhang and Xia, 2011) | Wang, 2010; Wang and Wang, 2010 |
| Xubao (4500-4000BP) | E113.095836, N35.042912 | Near rectangular shape with rounded corners, ca.20 ha | Different walls are between 200 and 500 m long, lower bases of wall bodies are 23.9-34 m wide whilst the upper parts are ca.10 m wide | Moats outside southern and western walls | Alluvial plain of the Qinhe River (evidence of floods that destroyed the walled site is reported by Zhang and Xia, 2011) | Wu et al., 2007 |
| Wangchengang (construction date of small "city" 4190-4110BP, predating that of the large "city"; in use for a few hundred years) | E113.138091, N34.406306 | Small "city" of rectangular square shape, ca. 1 ha; large "city" of square shape, 34.8 ha | Small "city": preserved parts of the walls are 29-92 m long. Large "city": preserved parts of the walls are 350 m long, 580-600 m long after restoration. | Moats of the large "city" ca.600-620 m long, 16.4 m wide and 7 m deep. | Alluvial terrace surrounded by the Wudu and Ying Rivers | Fang, 2006; Liao et al., 2022; School of Archaeology and Museology, Peking University SAMPU & Henan Provincial Institute of Cultural Relics and Archaeology HPICHA, 2006 |
| Puchengdian (mid-to-late Longshan period) | E113.446788, N33.735867 | Rectangular shape, enclosed area 2.65 ha. | Preserved parts are 124-246 m long. | 23.4 m wide and 4.3 m deep. | Floodplain of the Chenhe River (part of it being destroyed by the river) | Wei et al., 2008 |
| Haojiatai (ca. 4700-4500BP) | E114.036767, N33.598006 | Rectangular shape, ca.3.3 ha. | 5-12 m wide | Moats outside the walls | Floodplain of the Shahe River | Zhang and Li, 2017; Wang et al., 2017 |
| Pingliangtai (ca. 4300-3900BP) | E114.933971, N33.713598 | Near square shape, 3.4 ha. | Lower cases of the walls are ca.13 m wide, and upper parts are 8-10 m wide, with a remaining height of ca. 3 m. | Easter moat has an regular shape, >25 m in width; other moats are of irregular shape, very wide (>50 m wide at the widest part). | On slightly higher ground of the vast floodplain of the local rivers | Cao and Ma, 1983; and unpublished drilling report, courtesy of Mr. Yanpeng Cao. |
| Jiaochangpu (mid-to-late Longshan period) | E116.253385, N36.407975 | Rectangular shape with rounded corners, 5 ha. | Lower bases of the walls are ca.30 m wide, upper parts are ca. 27 m wide, average 28-30 m wide; 3.2-7 m high. | One oval-shaped moat outside the walls, 13.35 m wide. | Floodplain close to the river | Liang et al., 2005 |
| Xinzhai (construction date 4000-3900BP) | E113.567759, N34.445888 | Square shape, 100 ha including the walls (enclosed area 70 ha) | Different walls are between 160 and 924 m long and 2.5-5 m high | Three-ringed moats. Mostly are 15-20 m wide; some parts are 60-80 m wide, and 5-7 m deep. An additional outer moat was connected with an erosion gully, 1500 m long, 6-14 m wide and 3-4 m deep | Low-lying floodplain of the Shuangji River, some of the walls were built directly on some incised gullies on the floodplain. Evidence of floods is reported in recent report ( Aurora Research Center for Ancient Civilizations, Peking University, and Zhengzhou Municipal Institute of Cultural Relics | Zhao, 2004 |

(continued on next page)

**Table 6** (*continued*)

| Site and date | Coordinates | Structure and scale of walled site | Walls | Water management facilities | Surrounding environment | Sources |
|---|---|---|---|---|---|---|
| | | | | | and Archaeology, 2008), also see Wei, 2020 | |
| Erlitou (3900-3500BP) | E112.701669, N34.699965 | Enclosed palatial area of square shape, 10.8 ha; entire site >300 ha | Walls of the palatial area: preserved parts are 120-330 m long | | Second river terrace (T2) sandwiched by the Luohe and Yihe Rivers, ca. 10 m higher than riverbed. Evidence of flood is reported by Zhang and Xia, 2011. | Li, 2010 |
| Dashigu (Erlitou phase II) | E113.501413, N34.849077 | Rectangular shape, 51 ha | Discovered parts are 80-480 m long, lower bases are 16 m wide, top parts are 7 m wide, remaining height 3.75 m | Two-circled, slope-shaped moats with rounded base; ca. 2900 m in total length, 5-9 m wide and 2–2.8 m deep. | Low-lying alluvial plain surrounded by lakes and wetlands | Li, 2010; Li et al., 2014; Li, 2018 |
| Wangjinglou (Erlitou phase II to phase IV) | E113.72834, N34.449391 | Near square shape, 30 ha | Preserved parts are 31–625 m, 1.1–6.6 m wide. | Moat no. G12 is 11 m wide and 3 m deep; the northern section of it is ca. 110 m long; outside G12 is the outer moat (no. G13). | | Gu, 2016 |

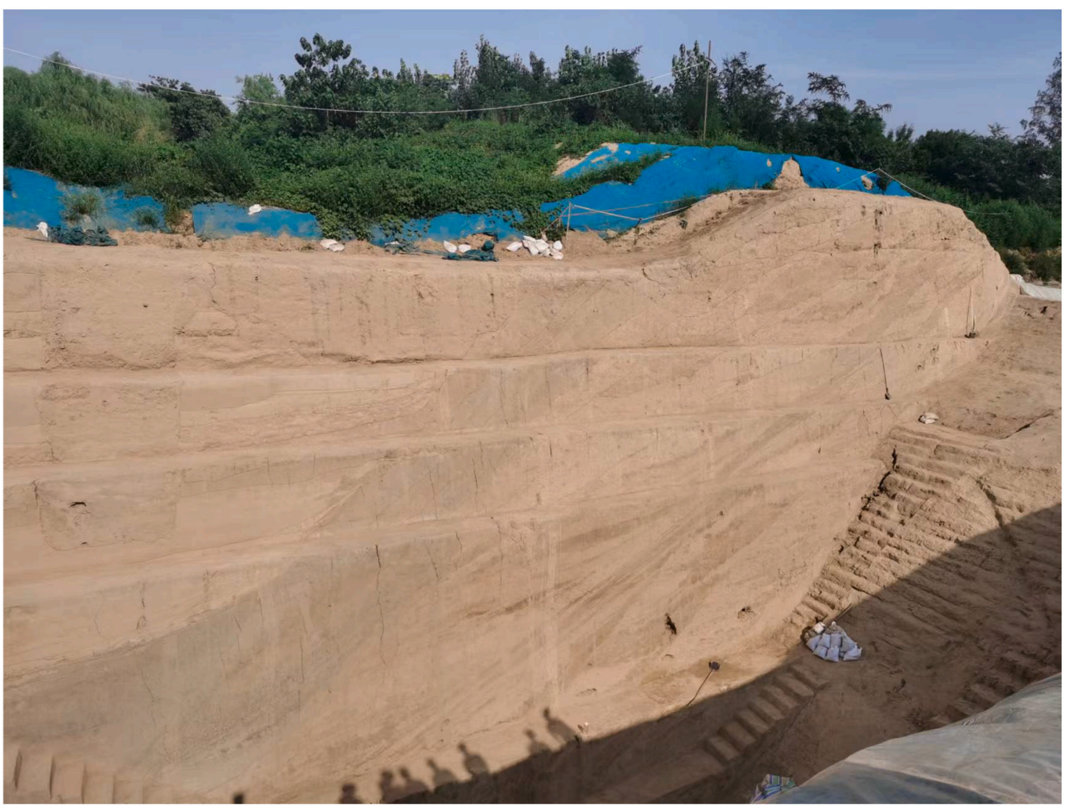

**Fig. 10.** Excavation photo at the Qicheng site. The pounded-earth wall (the steps are where the slope protection structure was while the area above it was the wall) was overlain by light yellowish silt and sand with abundant clay-rich aggregates and clear horizontal beddings, which were deposited during recurrent floods.

Just as the Guchengzhai site, moats were the main type of water management infrastructures at other late-Neolithic walled sites in the Central Plains (Fig. 1). Compared to the construction of the earthen walls which commonly adopted some regular plans, the digging of the moats seemed to follow more flexible arrangements, depending on local terrains and/or if the digging was carried out to supply earth for wall construction. As shown in Table 6, the moats at some walled sites have some distinctive plans and shapes. Parts of the moat at Xijincheng might have used natural waterbodies which were connected with the artificial branches of the moat in the southeast corner where wetlands also existed. The two bifurcating branches here were separated by a sand bar and the sediments in the moat and other parts of the walled site suggest that during occupation, the low-lying area near the moat was often inundated by over-bank flow with gentle hydrodynamics (Wang, 2010; Wang and Wang, 2010). Recent geological surveys and excavations have revealed the unusually large moat systems at the Pingliangtai and Haojiatai sites. The moat at Haojiatai saw an expansion in two phases and the later-phase moat reached an enormous size. It is suggested that the later-phase moat was dug because of increasing demand for earthwork construction, but it also coincided with the transformative operation in water management with increasing floods as flood deposits are commonly found in the moat and surrounding areas (Zhang and Li, 2017). Such an expansion of moat and water-management system culminated at the Xinzhai site in the succeeding Erlitou period, with the construction of deep, multi-ringed moats (Table 6). In addition, evidence of clearing and repairing of the moats can be clearly seen from the excavations and analyses of moat sediments at Guchengzhai and other sites such as Xijincheng and Haojiatai. At Pingliangtai, additional water management infrastructures including the earliest ceramic drainage pipes and drainage ditches that were associated with different social units (e.g., households and communities) were brought to light in recent excavations (Li et al. in preparation).

Through construction, operation and expansion of moats and related hydraulic infrastructures at a time of increased climate changes and hydrological fluctuations, the societies and their technologies and environments at these walled sites on the Central Plains became more closely intertwined. Not only was such intensified water management a powerful response to environmental vagaries, it also became deeply entrenched in the social and economic lives at these walled settlements. Certain resources and personnel were required to the frequent clearing and repairing of the moats. Whilst the scale of these repairing activities and the resources needed are to be further demonstrated, there is no doubt that these would have stimulated profound socio-economic changes, with some recent suggestions that these activities prompted to the formation of a new social space and/or social class specialized in water management (Li et al. in preparation; Zhang, 2021). Another arena that saw fundamental changes and might have been associated with intensified water management was the formation of new agricultural system, including the cultivation of rice in many places such as Guchengzhai, Xijincheng, Wangchenggang, and Wadian (Chen et al., 2010; Chen et al., 2012; Li et al., 2021; Zhao and Fang, 2007). Although it is currently unclear how exactly these large water management systems fostered growth of rice farming (but see Zhuang et al., 2017), the radical transformation of local agrarian systems for rice farming would have constituted another vital part of the local aquatic landscapes in late-prehistoric Central Plains.

## 6. Concluding remarks

We have provided both detailed accounts and broad-brush summaries of the developments of water management practices at Guchengzhai and other late-Neolithic walled sites on the Central Plains. The evidence is mostly qualitative and does not allow us to conduct quantitative investigations of some of the fundamental questions on the origins and development of large-scale water management in late Neolithic north China. For instance, we proposed above that the construction and expansion of moats and associated facilities represented an intensification of water management. This might be a rather tentative, if not premature, suggestion. What exactly might such 'intensified' water management practices entail? Was the process achieved through investing more labour power in the initial earthwork construction or during subsequent operation and repeated repairing of the water management infrastructures? As questioned by Xie et al. (2021), were such operations all of large-scale? And did the contemporary sites follow a similar path of water management intensification?

These questions are beyond the scope of the present article and merit more future research effort. However, our data have contributed to further understand the scholarly debate on the relationship between intensified water management and early state formation. Several important implications are worth highlighting. First, the emergence of large-scale hydraulic infrastructures predated the construction of mega-sized walled sites such as Xinzhai and Erlitou, which represent the formation of early state polities on the Central Plains. Whilst this is different from what has been suggested by many archaeologists working in different global regions that 'complex systems of canals and irrigation came after the appearance of cities and the indicators of bureaucratic statehood' (Mithen, 2010:5252, also see Adams, 2017; Scarborough, 2003), it does not directly comply with typical Wittfogelian theory either. Its difference from the Wittfogelian theory mainly lies in the fact that communities on late-prehistoric Central Plains with different socio-economic institutions and of different scales all developed sophisticated water management practices but not all of them 'evolve into states' (phrase from Mithen, 2010). For instance, the excavation of cemetery and houses did not reveal evident social stratification at Pingliangtai (Cao et al., 2017; Zhang et al., 2022). Yet the water-management infrastructures at the site are amongst the most sophisticated ones. Even at Erlitou, widely considered to be the first state-level polity in north China, it has been argued that water management was organized and operated by specialized social units/groups independent from the elite group who had control of large economic sources and social power (Zhang, 2021). These examples demonstrate complex and diverse relationships between water management and social evolution that are beyond the 'Wittfogel's linear chain of causality' (Banister, 2014:206). Second, environmental conditions and technologies contributed to the development of water management practices at these sites. These are the aspects that are significantly overlooked in Wittfogelian and related theories, but our geoarchaeological and archaeological evidence from Guchengzhai greatly supplements to them. Coinciding with the increased late-Holocene climate uncertainty with intensified short-term fluctuations on rainfall in the monsoon-influenced areas of the Central Plains was not only the general trend to relocate to places with optimal hydrological conditions, but also the technological innovations in water management as discussed in this paper. It was these responses and adaptations to aridity and environmental degradation that helped to shape some of the salient and long-lasting characteristics of social and economic lives of the region, such as the collective societal effort to tackle chronic and emergent environmental problems facing the societies (e.g., floods and droughts). These water management practices are apparently multi-faceted and multi-directional processes involving societal, environmental and technological aspects, some of which the Wittfogelian-type inquiries fail to take into account, and thus their significance to understand social evolution remains understudied.

To conclude, whilst short-term climate events such as floods would certainly have significant impact on the society, for a region like the Central Plains which is situated between the Loess Plateau and peripheral monsoon zone, long-term aridification would equally exert a significant challenge to the society. Capturing such intricate interactions between climate and the society has proved to be notoriously difficult. Our reconstruction of how the moat was dug, maintained, repaired and eventually abandoned at Guchengzhai and our contextualization of such a life cycle of water-management infrastructure within its broader geomorphological and hydrological environment have provided fresh insights into the dynamic relationship between water and the late-Neolithic walled settlements at Guchengzhai and other sites on the Central Plains. Our integration of archaeological and geoarchaeological data obtained from on- and off-site contexts has proved to be a valuable approach to reconstruct formation of late-Neolithic aquatic landscapes on the Central Plains. We conclude that the causal relationship between intensified water management and early state formation is much more complex than suggested by previous scholarship and that understanding the hydrological environment, technological innovations and societal adaptations is key to disentangle such complex interactions.

## Author statement

Y Zhuang, X Zhang and J Xu planned, designed and carried out the research. Y Zhuang and J Xu analyzed the data. Y Zhuang wrote the article.

## Declaration of Competing Interest

None.

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## Appendix A. Supplementary data

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