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Earliest ceramic drainage system and the formation of hydro-sociality in monsoonal East Asia

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The earliest ceramic drainage system unearthed at the Pingliangtai site on the Central Plains of China represents an unprecedented social and environmental manipulation as societies faced surging environmental crises in the Late Holocene East Asian Monsoon region. Here we present results of excavation and a geoarchaeological survey of the water-management infrastructures and environment which reveal the operation and maintenance of a well-planned and regulated two-tiered drainage system. Rather than a 'centralized hierarchy', the drainage activities were mainly practised at household and communal levels, through which Pingliangtai society was drawn to more pragmatic aspects of social governance. Through their emphasis on spatial uniformity, cooperation in public affairs, and a series of technological innovations, water management at Pingliangtai gravitated to collective shared interest as the society responded to recurrent environmental contingencies. Such a pragmatic focus on public affairs constituted a previously unrecognized, alternative pathway to the development of power structure and social governance on the Central Plains regimes in late Neolithic and later times.

Water situates at the crucial interface between the environment and society. It is not purely natural or cultural. In monsoonal environments, in particular, water profoundly defines the ways people respond to and modify their environment for basic survival and successive developments. Technologies and social organizations of water management are long considered closely intertwined with the seasonality of monsoonal rainfall and cycles of social and economic production and reproduction[1–3]. Among the prominent scholarly advancements on water and society, the hydraulic origins of state and coercive power proposed and developed by Wittfogel and some other scholars have come under rigorous scrutiny in recent studies in East Asia and beyond[4–8]. One such reconsideration is a shift to the devolved form of social governance on water and how this perspective fosters a 'bottom-up' approach to understanding the water–social binary[9,10] and long-term and multi-scalar human behavioural changes. Elsewhere in Asia, systematic efforts have been made to understand the origins, development and importance of water management infrastructures in societies of different times and regions[11–13]. In China, the tale of the legendary Great Yu's heroic taming of floods and the subsequent founding of the Xia Dynasty continues to dominate mainstream scholarly narrative on the formation of China's first state[14–16], albeit with great controversy. The importance of state-organized hydraulic projects and elites' control of water to the evolution of Bronze Age and early imperial societies is also emphasized in recent archaeological studies of water[17]. However, in her recent works, Zhang disputes a state hydraulic despotism in Song-Dynasty China by providing a detailed but sorrowful account of the coordinated local effort to defy state order and battle the insurgent threat from the Yellow River[18,19]. Few scholars now hold a monolithic

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view of hydro-sociality and state formation; more studies have revealed the 'public' nature of hydraulic organizations that existed and functioned across a wide range of social and ecological–environmental settings of ancient China (for example, refs. 20,21). Despite the growing recognition of the importance of variegated ecology to early hydraulic societies[22–24], the environmental and socio-technological foundations upon which diverse forms of social governance were founded, maintained and transformed have been considerably understudied.

The late Neolithic Pingliangtai walled site on China's Central Plains demonstrates how environmental vagaries, technological innovations and social institutions converged to form a 'cooperative social governance' on water management, which provides a different model for the origins of hydro-sociality in ancient East Asia. Because of our focus on water as intangible evidence of cooperative human actions, it also offers a unique perspective on the evolution of human cooperation, which many anthropologists have elaborated on from ritual and other aspects (for example, ref. 25). Hydraulic infrastructures saw prolonged development in prehistoric and historic cities of North China (Supplementary Table 1). Some of the facilities and technological designs became so well embedded in the basic social groups that they are often taken for granted or simplistically associated with a 'centralized hierarchy'. Previous studies on the origins of social power in ancient China have primarily focused on the military and religious aspects[26] through material evidence such as tombs, weapons and altars. Rarely have dynamic human behavioural changes derived from diverse water management practices and their implications for understanding the acquisition of social power been systematically investigated. Data from Pingliangtai allow us to establish the environmental foundation of the hydraulic infrastructures at the site and demonstrate that a ditch-and-pipe drainage system was invented and operated at both household and communal levels. Such water management practices create a water–social binary that features a series of innovations in public hydraulic infrastructures and required cooperation among residents in a monsoonal environment. This deviates from the absolutistic view on intensified irrigation and rice farming as the primary stimulus to the rise of despotic power and state. The cooperative social governance and its ramifications to social evolution differ from the military or divine power that is derived from the competition for luxurious goods between elites and monopoly on ritual affairs in either earlier or contemporary Lower Yellow River[27,28] and Yangtze River[29] as well as elsewhere. In this Article, we present evidence on the multi-levelled water management at Pingliangtai and discuss how this informs the formation of collective and cooperative water management. The Pingliangtai and related examples[30–32] on water management on the Central Plains bear unparalleled importance to compare with other examples in the Yangtze River valleys[23] and contend for the polylithic origins of social governance and power that derived from multi-faceted interactions between water, environment and humans in ancient East Asia.

Late Holocene climate, hydrology and settlement distribution

Pingliangtai is located in the Huaiyang District, Zhoukou City, in the Upper Huai River Plain of the vast Huanghuaihai Plain of Central China (Fig. 1a). Additionally, Huaiyang belongs to the Eastern Central Plains and has a different environment that sets it apart from those in the Western Central Plains, such as the Luoyang Basin and the Linfen-Yuncheng Basins. The temperate monsoonal climate is characterized by a clear seasonality in temperature and precipitation, with dramatic annual and monthly variations (Fig. 1c). Excessive rainfall in summer can reach more than 500 mm per month, exerting great threats on cities and villages. As a commonly used proxy to reconstruct long-term precipitation change (for example, ref. 33), speleothem isotopic data from Huaiyang and neighbouring regions reveal that the region's Holocene precipitation was controlled by East Asia Summer Monsoons, with the seasonality of rainfall similar to the modern one. After the so-called Middle Holocene Optimum, a prolonged trend of climate aridification beginning from 6000 to 5500 BP and culminating at ca. 4200 BP can be recognized in these regions (Fig. 1b), probably linked to the so-called 4.2 ka BP climate event. The mechanisms and effects of this climate event varied from region to region[34–36], but it is clear from the wavelet analysis on isotopic records that the Huaiyang region experienced escalating short-term oscillations in annual precipitation around 4200 BP, including some extreme rainfall events as shown in Fig. 1b.

Our regional geological survey examined 147 cores that cover the most representative sedimentary sequences of the region and revealed that the Holocene deposits are dominated by brown-yellowish alluvial silt and clay (Supplementary Table 2 and Supplementary Figs. 1 and 2) on the predominantly low-lying terrains in a faulty depression basin rifted by small uplifts and depressions[37]. Alluvial aggradation was a region-wide phenomenon that lasted for much of the early to middle Holocene and had a profound impact on the regional landscape, as confirmed by our stratigraphic correlation (Supplementary Fig. 2b) that shows predominant alluvial lowlands (litho-sedimentary group 2) across the region. In the area immediately surrounding the Pingliangtai site, the three well-dated profiles (Fig. 2, Supplementary Figs. 3 and 4 and Supplementary Tables 3–5) show that following a rapid alluvial accretion in the early Holocene, the sedimentation began to slow down from ca. 7000 BP, giving way to a stabilizing geomorphological environment when low-elevation tablelands emerged and palaeosols developed. Micromorphological study confirms soil formation on the elevated grounds with good drainage, favourable vegetative cover and minimum disturbance (Supplementary Fig. 5b–d). This stable landscape was punctuated first by a region-wide erosion event that caused an unconformity and chronological hiatus in the sediment records (Supplementary Fig. 5a and Supplementary Table 5) and then by alluvial aggradation between ca. 6000 and 4500 BP (Fig. 2b), including some widespread floods. The late Neolithic layers are found directly overlying the greyish flood deposits with many sediment laminae (Supplementary Fig. 5a,e), indicative of strong hydrodynamics during the floods as shown by particle size results that contain more coarse-sized sediments (Fig. 2b, red arrow). Overall, the regional landscape before the construction of Pingliangtai and other contemporary settlements was dominated by a mosaic of slightly raised grounds scattered in the overall low-lying alluvial plain that was flooded periodically as the plain continued to aggrade.

The earliest Neolithic remains discovered in the Huaiyang region date back to the Yangshao period (ca. 6000–5000 BP). This was followed by an increased presence of the late Dawenkou culture remains (ca. 5000–4300 BP). However, both the Yangshao and Dawenkou cultures remains are dispersed[38,39]. Neolithic occupation in the Huaiyang region underwent a pronounced acceleration during the Longshan period as lakes and wetlands shrunk substantially when the climate became drier while more emerged land provided more suitable conditions for farming and settlement construction. First, the number of settlements increased evidently, from 7 during the Dawenkou period to 16 during the Longshan period (Supplementary Fig. 6). Second, millet farming, with the contribution of rice cultivation, was widely adopted by these Longshan communities in Huaiyang and greatly stimulated profound socioeconomic changes in diet, land use and human–environment relationship[40–43]. Third, the accumulation of agricultural surplus and population congregation also led to the emergence of medium-sized walled settlements, culminating with the rise of the Pingliangtai walled site. However, the mushrooming Longshan settlements and burgeoning millet-based agrarian economies, however, gave rise to a dilemma facing these communities. Most of the settlements were situated on small low-elevated tablelands on the vast, generally flat floodplains. Such a geomorphological environment and hydrological conditions presented an opportunity as well as a challenge. The locations were optimal to support large-scale construction activities with easy access to water and other resources and plenty

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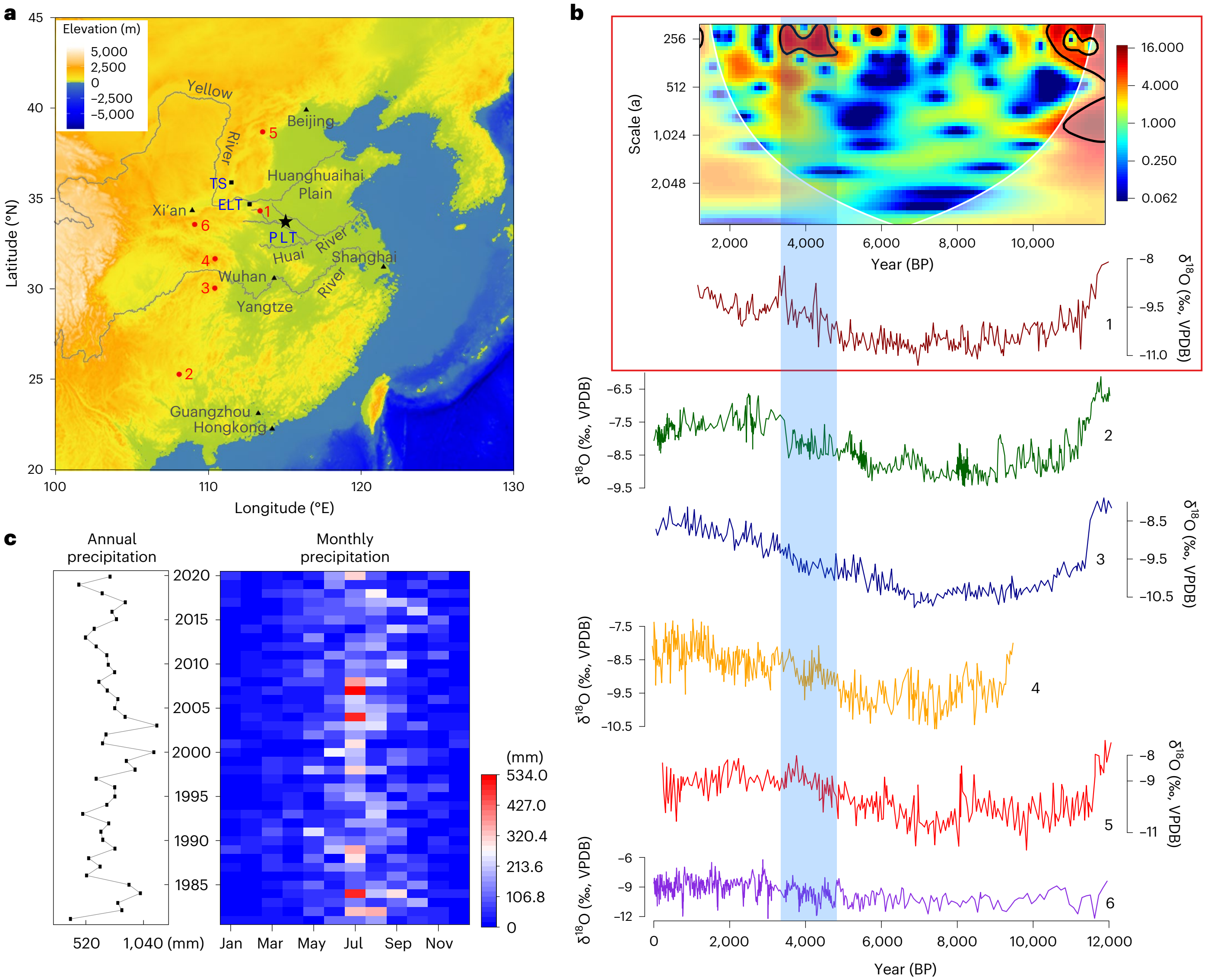

Fig. 1 | Geographic and climatic backgrounds of Huaiyang and adjacent regions. a, Locations of Pingliangtai (PLT), Erlitou (ELT) and Taosi (TS), and speleothems used in the article. **b**, $\delta^{18}O$ records (expressed in relative to Vienna Pee Dee Belemnite (VPDB)) from (1) Magou Cave[62,63], (2) Dongge Cave[64,65], (3) Sanbao Cave[66–68], (4) Heshang Cave[69], (5) Lianhua Cave[70] and (6) Jiuxian Cave[71] and continuous transform wavelet spectral (scale, annual year) for the Magou Cave $\delta^{18}O$ data. The $\delta^{18}O$ records point to a pronounced trend of long-term climate aridity. To various degrees, these curves, particularly curves 4, 5 and 6, also indicate increased short-term rainfall fluctuations. **c**, Monthly and annual precipitations of Zhoukou from 1981 to 2020. Note that in some summer months the monthly precipitation can reach more than 500 mm (marked in red columns), while fluctuations of annual precipitation could be also dramatic, with some dry years having only ca. 260 mm annual rainfall and wet years having an annual rainfall of more than 1,200 mm.

of arable lands. But the residents must have known and experienced the insurgent threat from climate uncertainties, which would have become a more apparent problem as the population grew. Their adaptation to such a hydro-environment proved to be unprecedented too, as best represented by Pingliangtai.

Shortly after the widespread floods, the people at Pingliangtai started building houses and walls on the low-elevation tableland surrounded by wetlands. The landforms and hydrological landscape surrounding Pingliangtai can be further divided into the drainage zone, seasonally flooded zone, and permanently inundated zone based on the high to low gradients of the local terrains (Fig. 2a and Supplementary Fig. 2). The walled site was constructed on a slightly raised tableland of an alluvial terrace, which, despite 1–2 m higher than the surrounding palaeo-surface, was still vulnerable to periodic floods. Surrounding Pingliangtai was the seasonally flooded zone of many wetlands, dominated by thick alluvial facies which were subject to post-depositional alteration (Supplementary Fig. 1c,d). Further away from the site was the permanently flooded zone of floodplains and palaeo-channels. The Pingliangtai site was connected to these zones through its moat and drainage facilities.

Occupation, hydraulic technologies and landscape

Pingliangtai provides us with the best knowledge of how a late Neolithic population built their walled site and transformed its surrounding low-lying monsoonal plain for economic and other purposes. The earthen walls delineated a near square-shape of 3.4 ha (Fig. 3a). A road running through the middle of the enclosed area and extending to the southern and northern gates served as a central axis in the walled site (Fig. 3a and Supplementary Fig. 7). On the two sides of the axis were multi-roomed

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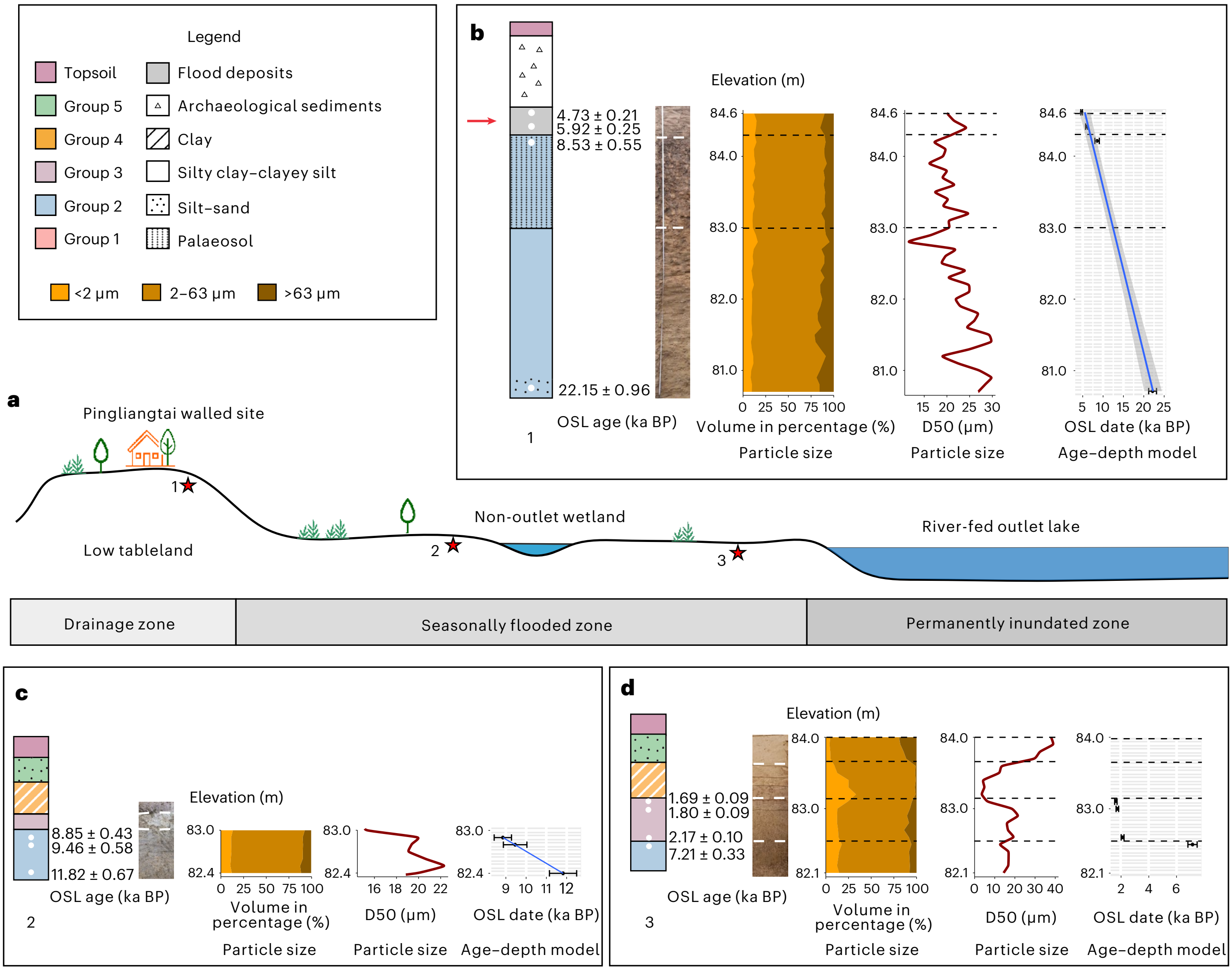

Fig. 2 | Geoarchaeological survey and results in and around the Pingliangtai walled site. a, Schematic sketch of the reconstructed late Neolithic landscape and environment around the walled site. The low tableland where the Pingliangtai site was located belongs to the drainage zone, while the low-lying areas surrounding the tableland are the seasonally flooded zone. The lake is defined as the permanently inundated zone. **b**, Lithostratigraphy of profile 1 located inside Pingliangtai (see Fig. 2a and Supplementary Fig. 3 for location, same below), and results of particle size distribution and OSL dating. The OSL ages are presented as mean values ± standard error of the mean. At least nine to ten aliquots were used for the calculation of OSL age (see source data for *n* number of each sample, same below). D50 is the median particle size, same below. The sediments of the examined section from 120 to 520 cm are generally of fine size with the medium size range gradually decreasing from bottom to up. The age–depth model shows a generally rapid sedimentation rate, especially in the lower half of the stratigraphy. **c**, Lithostratigraphy of profile 2 located outside Pingliangtai, and results of particle size distribution and OSL dating. Compositions of different-sized particles are comparable to those in profile 1. Note the sharp age–depth curve that indicates an even more rapid sedimentation rate during the early Holocene compared with that of profile 1. **d**, Lithostratigraphy of profile 3 located outside Pingliangtai, and results of particle size distribution and OSL dating. Note the interesting sedimentation gap as indicated by the sequence of the OSL dates. The historical period also saw a peak of the contribution of coarse-sized particles, indicative of high-energy sedimentation event. Apart from the sedimentation hiatus, also note the much increased sedimentation rate during the historical period. Detailed descriptions and results of grain size analysis and OSL dating can be found in Supplementary Information.

houses (Supplementary Table 6 and Supplementary Figs. 7–9) that were constructed in rows. These houses adopted a similar structure and architectural techniques (Supplementary Fig. 9) and underwent several stages of construction, repair and expansion (Supplementary Fig. 10). Thirty accelerator mass spectrometry (AMS) ^{14}C dates of bones from the cemetery, residential areas and drainage pipes have firmly situated the occupation of the site to between 4200 and 3900 cal. BP (Fig. 4 and Supplementary Table 7). Most of the graves date to between 4200 and 4000 cal. BP, while the timespan of most houses and occupation deposits (for example, ash pits) as well as the ceramic drainage pipes (that is, possibly installation date) fall between 4100 and 3900 cal. BP. The stratigraphy unearthed during the excavation further reveals that the houses and hydraulic infrastructures, including drainage pipes and ditches, were built, repaired and rebuilt multiple times (Fig. 5a and Supplementary Fig. 10).

In this new alluvial environment, the Pingliangtai people developed innovative hydraulic technologies to tackle acute and chronic problems on water management. One of the chronic problems facing Pingliangtai society was the severe weathering of earthen architecture in the humid monsoonal environment. Sediment texture of the bottom

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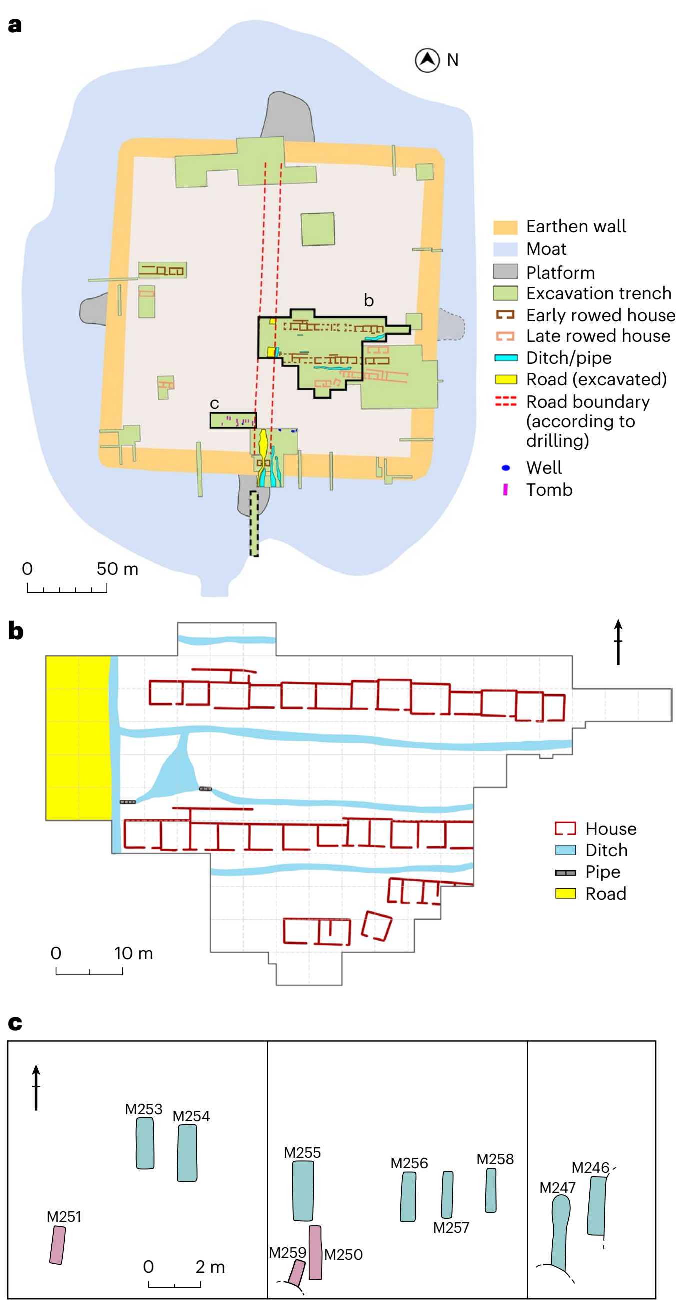

Fig. 3 | Plans at Pingliangtai. a, Plan of the Pingliangtai walled site (after ref. 60). See the text for brief descriptions of the size and structure of the walled site and the legend for different functional parts of the site. **b**, Schematic sketch of the reconstructed houses, the road and the drainage system at the excavation area of 2016 and 2019. For a detailed plan, see Supplementary Fig. 8. **c**, Plan of the communal cemetery (after ref. 61).

ground-raising layers of mudbrick houses is comparatively coarser than that of the upper ones (Supplementary Fig. 11). Engineering mechanics have proved that the porous coarser sediments could have effectively absorbed moisture through capillary actions (Supplementary Table 8) and prevented damp conditions of mudbrick houses at the site. As a technology that probably first occurred on the semi-arid Loess Plateau (for example, the Nanzuo site[44] in Gansu Province), it benefitted from some further improvements at Pingliangtai. The mudbricks at the site were made of locally available sediments (Supplementary Fig. 12), roughly consistent in size (42–44 × 20–22 × 8–12 cm). According to our geotechnical test, the softening coefficient between air-dried and saturated mudbrick samples reached almost 48, suggesting that saturation had a massive impact on the strength of mudbrick (Supplementary Table 9). Some mudbricks contained calcium carbonate and were tempered with grass (Supplementary Fig. 13), which would have increased their durability and moisture resistance. Additionally, mudbricks are commonly plastered with fine silty clay to improve their resistance to weathering. A comparison on the hydraulic conductivity between the mudbricks and plaster showed that the latter had a lower hydraulic conductivity and therefore was more resistant to weathering in damp conditions (Supplementary Fig. 14c). Some mudbrick load-bearing walls seemed to retain a good function throughout the use of the house (for example, house no. F50-2, Supplementary Fig. 15) while the house foundation and other parts of the architecture were often severely damaged and required repairing. Micromorphological study of the mudbrick sample from the south wall of house no. F50-2, for instance, revealed that the mudbrick wall was repaired at least five times after severe weathering (Supplementary Fig. 16).

To mitigate the problem of excessive water during the rainy seasons, the Pingliangtai people constructed and operated their hydraulic system at multiple levels. The drainage ditches running parallel with the houses and the north–south central axis (Fig. 3, Supplementary Table 10 and Supplementary Fig. 17) formed the first tier, household level of the drainage system, which diverted water from the residential area into the drainage area near the southern gate. Sediments in the lower half of these ditches were generally of fine texture and laminar structure, which were deposited repeatedly when the ditches were in active use and subject to regular dredging. Those on the upper half contained more heterogeneous anthropogenic inclusions such as mudbrick and bone fragments as the maintenance of the ditches slacked (Supplementary Fig. 18 and Supplementary Data 1).

As the second tier of the drainage system, the production and installation of a large number of ceramic drainage pipes would have required careful planning and great effort probably involving different working groups of the entire community. Most pipes were installed between 3° and 7°, either along the central axis or concentrated near the southern gate, occasionally being installed in front of houses (Fig. 5, Supplementary Table 10 and Supplementary Figs. 17 and 19). Systematic examination of the pipes shows that, while they vary slightly in decoration, with at least four main types, most of them had similar dimensions, measuring 20–30 cm in diameter and 30–40 cm in length with few exceptions, and textures (Fig. 6 and Supplementary Figs. 20 and 21). Sediments trapped in the pipes installed around the houses are well sorted with occasional inclusions of mudbrick debris, in contrast to the highly mixed sediments in the pipes near the southern gate (Fig. 5d–f and Supplementary Data 1). As a communal space and also a confluence point where water drained into from different households, the southern gate and surrounding area received the most intensive managerial operation. Deep ditches were dug and dredged repeatedly, with their positions shifting horizontally along the southern gate (for example, ditches G4, G1, G6 and G29) and ceramic pipes were installed one after another at the bottom of these ditches or on top of each other (Fig. 5a,b). The particle size results of sediments trapped in the pipes display a unimodal distribution curve with a narrow peak, indicative of moderate to strong hydrodynamics, although it is also clear that the sorting of the trapped sediments became poorer as hydrodynamics fluctuating from the early (G29) to late phase (G6, then G4) (Fig. 5c and Supplementary Table 11). The latter might reflect an increasing need for instant discharge of excessive water. Moreover, excavation at the moat and sedimentological analysis found no apparent difference between the sediments in the moat and those ditches (Supplementary Fig. 22). This indicates a generally well-functioning drainage system that was connected to the wider water system through the moat. This dual aspect of the drainage system at Pingliangtai is the earliest complete one in prehistoric North China, and its emphasis on drainage pipes was unprecedented (Supplementary Table 1). The Pingliangtai people

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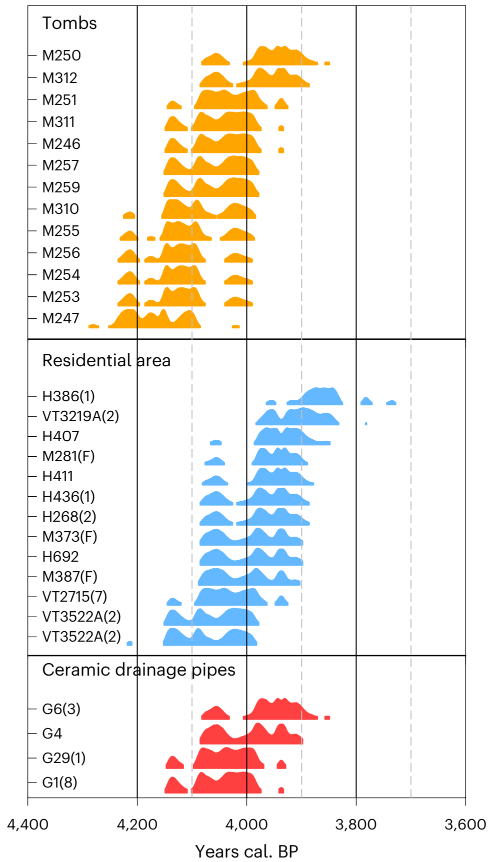

Fig. 4 | Calibrated ^{14}C dates by intCal20 with a 95.4% probability. M, *mu* burial; H, *huikeng* pit; V, quadrant 5; T, *tanfang* excavation trench; G, *gou* ditch. VT3522A(2) is actually the ground-raising layers and waste deposits belonging to the early phase of house no. F43-2, and VT3219A(2) is the ground-raising layers and waste deposits belonging to the late phase of house no. F23. VT2715(7) is one layer of the road near the southern gate. For detailed results of radiocarbon dating, see Supplementary Table 7.

installed the ceramic drainage pipes across the public architectures such as walls, roads or some houses with conscious planning. The drainage ditches, including branch and main canals, ran parallel with individual households, respectively, which would have maximized the efficiency in discharging water, especially during summer rainstorms. However, the fact that some ditches (for example, ditch no. G1) were dug at the same position (Fig. 5a) where the pipes were installed first but subsequently failed to function due to fast blockage provides a vivid snapshot of a flood emergency when the Pingliangtai people needed to discharge excessive water instantly through digging ditches.

Social governance and formation of hydro-sociality

Our evidence above presents palimpsests of the hydraulic landscape at Pingliangtai and the multi-levelled cooperative human responses to intensify water management when climate uncertainty escalated. The water–social binary seen at Pingliangtai is an unprecedented development from an expanding millet-farming, larger-scale lowland occupation, and innovative technological responses to a challenging climate and environment during the Longshan period, which were not encountered in the preceding Dawenkou period. The spatial patterning and underlying governance structure of this water–social binary are distinctive on several aspects.

First, those ditches surrounding the houses were constructed and maintained mainly on a household level, while the ceramic drainage pipes and ditches surrounding the public space required larger-level planning and coordination to install and maintain. The latter was also the precondition for the even larger-scale construction of earthen walls. These human actions formed an infrastructural network which would have been vital for addressing chronic and emergent water problems at both the individual household and entire community levels. Second, these actions consolidated spatial uniformity and gave rise to cooperative social governance for water management. Houses and ditches, despite frequent reconstruction and repairing, were confined within the designated space (Supplementary Fig. 10), while public facilities of roads, city gates and drainage pipes were kept mostly in the central communal space (Fig. 3a,b). Although water was operated through the household and communal levels, this governance structure was under a heterarchical framework of social organization and was not associated with evident social stratification. Indeed, Pingliangtai was a medium-sized community; our estimation of the population based on the number and capacity of the rowed houses suggests 460–600 people at the time (Supplementary Table 12 and Supplementary Fig. 23). Additionally, the houses at Pingliangtai (Supplementary Table 6) are generally small-sized, and the settlements of Pingliangtai and its contemporaries in Huaiyang of the Eastern Central Plains are mostly of medium to small scale, ranging in size from <1 ha to 8 ha. The latter is in great contrast to those in other regions such as the Western Central Plains, as confirmed by the rank–size distributions (Supplementary Fig. 24). These differences clearly suggest a lack of evident social stratification within and between Longshan-period settlements in Huaiyang. Excavation of 11 Longshan-period burials at the communal cemetery near the communal hydraulic infrastructures in the southern gate of Pingliangtai (Fig. 3c, Supplementary Table 13 and Supplementary Figs. 25 and 26) further revealed no clear signs of social stratification among the deceased at the cemetery, different from those at other Longshan-period cemeteries where hierarchy was marked by the staggering differences in many mortuary aspects between burials (for example, at the Taosi site[45] (Supplementary Fig. 27) in the Linfen Basin located further north on the Central Plains). The construction and operation of the hydraulic infrastructures, as well as of the earthen walls, reinforced this social heterarchy at Pingliangtai through cooperative governance as their need to battle floods did not diminish but increased during this time of escalating climate uncertainty.

On a broader perspective, the emergence of the two-tiered drainage system and its operation within a heterarchical social framework at Pingliangtai in the Eastern Central Plains was closely tied to the profound socioeconomic changes during the Longshan period on this low-lying plain. Many new technologies and goods appeared in the Central Plains as both trans-regional interactions and indigenous responses to socio-environmental crises intensified[46]. Born out of the developed ceramic production system[47] and in an environment that required constant damp proofing and drainage, the mudbrick technology and ceramic drainage system were outstanding local innovations as the society responded to new challenges when relocated to the Huaiyang region. Such innovations also demonstrate that water technology had permeated into different sectors of the society and occupied a central position in socioeconomic affairs at the crucial interface between the environment and society at Pingliangtai. The multi-levelled water management and human cooperation at Pingliangtai differ from the top-down model that advocates a centralized process of labour organization, infrastructural construction and the rise of coercive power and hegemonic states. In contrast to the macroscopic scholarly viewpoint that often posits a linear relationship between social power and the organization of hydraulic enterprises, water management at Pingliangtai on the Eastern Central Plains was not simply a top-down or bottom-up operation. Rather, the collective human actions or 'collective struggles'[48] on water management at both household and communal levels in a precarious monsoonal setting gave rise to the cooperative social governance without a centralized

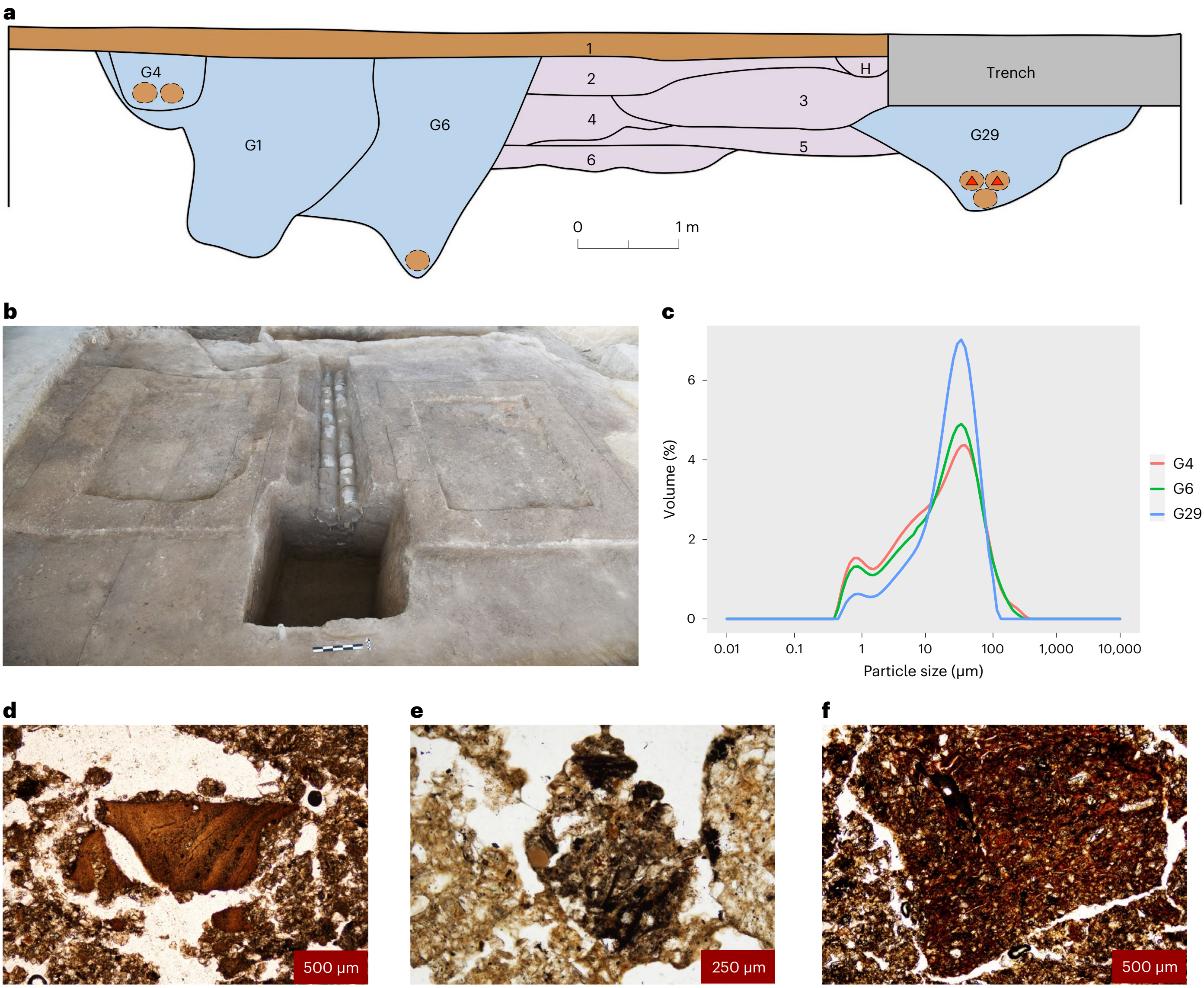

Fig. 5 | Drainage ditches and pipes near the southern gate. a, Profile sketch showing the four drainage ditches near the southern gate. **b**, Photo of the southern gate, the two gate rooms on its two flanks, and the drainage pipes in ditch no. G29 covered under the road that linked to the central axis. **c**, Particle size distribution of sediments collected from pipes near the southern gate. **d**–**f**, Micromorphological images of sediments 'trapped' in the drainage pipes in ditch no. G29. The sampling location is shown by red triangles in **a**. **d**, Eroded fragment of surface crust, plane-polarized light (PPL, same below). **e**, Dung fragment containing rich darkish-coloured organic matter, PPL. **f**, Large heterogeneous soil aggregate rich in limpid and dusty clay coatings, indicating that it may be a debris of mudbrick, PPL.

hierarchy. Although water management continued to foster technological innovation and sequential socioeconomic developments in later periods, its increasing operation scale did not culminate in a pronounced development of social stratification. Water management remained a public affair that required collective cooperation between multi-scalar social units and the states 'can never fully dominate or overcode' (ref. 5: 207). In other words, it is more pertinent to consider this type of societal evolution surrounding water as parallel to other lines of otherwise drastic socioeconomic developments in the late prehistoric Central Plains. Ample examples have demonstrated that the control for rare sources and the production of luxurious goods were inherently linked to the emergence of powerful individuals and pronounced social stratification in some areas of late prehistoric China (for example, ref. 49). On the other hand, the operation of hydraulic systems such as that at Pingliangtai represents the rise of cooperative social governance in precarious environmental settings, which might be associated with the so-called collective power[50]. Water management and competition for rare sources thus represent two separate pathways to social development in the late prehistoric Central Plains.

To conclude, the ceramic drainage pipes, ditches and the relentless household and communal effort to operate these hydraulic infrastructures at Pingliangtai represent an unprecedented social as well as environmental manipulation as the society responded to emergent environmental crises. Critically, our data help us to move away from the 'centralized' versus 'decentralized' paradox[5] on human responses to the initial construction and subsequent development of hydraulic infrastructures and instead to focus on diverse origins of hydro-sociality in heterarchical social settings. Water affairs at Pingliangtai were organized and run by the entire community for different purposes that had wide-ranging political outcomes. This distinctive

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Fig. 6 | Photos of ceramic pipes excavated from Pingliangtai. For better preservation and display in the future, most ceramic pipes were kept in situ after excavation. A few pipes were lifted. **a**,**c**,**e**,**g**, Pipes kept in the warehouse of the Henan Provincial Institute of Cultural Relics and Archaeology in Huaiyang. **b**,**d**,**f**, Some pipes are kept in several museums now, courtesy of the Henan Museum (**b**), courtesy of the National Museum of China (**d**) and courtesy of the Miaodigou Yangshao Culture Museum (**f**).

pathway to hydro-sociality accords with some well-established scholarly viewpoints on the 'differential control of resources' of labour organization and emergent social stratification[51]. It also echoes Flad's recent insights[52] on the 'specialization, 'differentiation' and 'functional interdependence' in the process of socioeconomic intensification as urbanism developed in China that did not necessarily involve a 'centralized hierarchy' (also see ref. 48). Indeed, late prehistoric societies on the Central Plains and neighbouring regions were drawn to pragmatic aspects of social governance on water-related affairs. A similar example can be found at the Liangchengzhen site in contemporary Longshan

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culture in Shandong, where ground-raising layers, drainage ditches and other techniques for water management surrounding houses were found[53,54]. Through their coordinated cooperation, and a series of technological innovations (for example, ref. 55), human practices of water management from Pingliangtai gravitated towards a collective shared interest as the society responded to cyclic environmental contingencies. Such cooperative social governance on water with a pragmatic focus constituted a salient yet long-neglected part of the power structure and social governance on the Central Plains regimes in late prehistoric and historical times[56,57]. Admittedly, the full-scale and *longue duree* of such an unprecedented transformation of hydraulic landscape on the Central Plains and other regions of early China remains to be further unpacked, but it suffices to conclude that the roles of these non-elite occupational activities such as water management offer great potential to disentangle the diverse trajectories to social complexity and eventually rise of early states.

Methods

Experimental design

To reconstruct the earliest ceramic drainage system and its hydraulic landscape as well as the environmental background, we designed a large-scale excavation at Pingliangtai, one of the earliest late Neolithic walled sites in China's Central Plains, and a systematic geological survey in the Huaiyang region. The excavation aimed at obtaining first-hand archaeological data on the technology and structure of this earliest ceramic drainage system, while the regional geological survey was designed to collect environmental data for robust reconstruction of the palaeo-environment.

Sampling and statistical analysis

The oxygen isotope $\delta^{18}O$ data from stalagmites were collected from the cited articles (see captions for Fig. 1) using Origin. The data were plotted together using R software with the combination of wavelet spectral for Magou Cave $\delta^{18}O$ data generated with R package Biwavelet.

The geological survey was carried out in the Huaiyang region in 2019. A total of 147 cores were obtained by using a mechanical percussion drill, and three profiles were selected for further sampling. The environmental sediments collected from the survey were subject to optically stimulated luminescence (OSL) dating, particle size analysis and micromorphological study at various specialized laboratories. The dose rates and OSL ages were calculated by Dose Rate and Age Calculator[58] and AMS ^{14}C dates were calibrated using the IntCal20 calibration curve[59] with a 95.4% probability. The particle size results were processed with Excel and R software; a semi-quantitative method was also adopted to summarize the micromorphological results. These geological core and environmental data were categorized into five litho-sedimentary groups for regional stratigraphic correlation, and the environmental proxy data were used to reconstruct geomorphological and hydrological environmental surrounding Pingliangtai.

A total area of 4,660 m^2 was excavated at Pingliangtai between 2014 and 2019. Many house foundations, water-management infrastructures and burials were revealed. The dimension and spatial distribution of these features and artefacts such as drainage pipes were carefully measured. Their spatial distributions were plotted onto a geographic information system-based map. Rank–size distribution method was applied to estimate population level and rank at Pingliangtai and contemporary sites. A series of archaeological samples were also collected for micromorphological study and civil engineering tests.

The detailed procedures of these methods and information on samples are described in the appendix (Supplementary Text and Supplementary Table 14). All archaeological and geological samples were collected with the permission of local institutes and in accordance with local laws.

Additionally, bone samples from Longshan-period burials were collected for DNA analysis and radiocarbon dating, the results of which are published elsewhere[60,61].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data are available in the main text and Supplementary Information.

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Author contributions
H.Z. and Y.Z. designed the research; C.L., Y.C., C.Z., L.Q., Z.D., Y.C., S.Z., W.L. and J.Y. performed the research; C.L., Y.Z. and H.Z. analysed data; and Y.Z. and H.Z. wrote the paper. C.L. and Y.C. contributed equally.

Competing interests
The authors declare no competing interests.

Additional information
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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Archaeological and palaeo-environmental study that aims to reconstruct palaeo-hydrological and geomorphological context and function of earliest drainage system at a late-Neolithic walled site in Central China.
Research sample	11 OSL dates, 67 bulk samples for grain size analysis and 2 soil/sediment blocks obtained from three profiles in/around the site; 5 bulk samples for grain size analysis collected from the drainage system; and 17 animal bones for radiocarbon dating as well as 59 sediment blocks for micromorphological and engineering (experimental) analyses collected from various archaeological features (e.g., ditch sediments, mudbricks and ground-raising layers) during the excavation. In addition, 147 sediment cores were carefully examined during the regional geological survey.
Sampling strategy	The archaeological and sediment samples collected during the excavation were arranged based on different types of archaeological contexts, which were situated both inside and immediately outside the enclosed area of the site. This arrangement was to make sure that the collected samples could represent a full picture of water management practices at the site. The geological cores were arranged at every 1km in the region. This is a common sampling strategy adopted in large-scale regional geological survey.
Data collection	The collection of the different types of archaeological and environmental samples mentioned above followed strict procedures in recording, packing, shipping, laboratory processing and analyses that are commonly adopted by scholars (see detailed information in the supplementary information folder). These works involved both project participants (including all the authors listed in this article) and some specialized technicians.
Timing and spatial scale	Most samples were collected during the archaeological excavation in 2019. Samples from Profile 2 were collected on November 14, 2020. Samples from Profile 3 and three samples for OSL dating from Profile 1 were collected on August 15 and 16, 2021. All samples were collected at and around the Pingliangtai site and the Huaiyang region in Henan Province.
Data exclusions	No data were excluded from the analyses.
Reproducibility	For OSL dating, the preheating temperature was carefully determined and at least 9 aliquots were measured for each OSL sample. For particle size analysis on Mastersizer, at least three measurements were taken for each sample. Other types of analyses (e.g., micromorphology, measurement of ceramic drainage pipes) generally do not require reproducibility.
Randomization	The samples were naturally categorised into groups based on primarily on the different types/materials they belonged to and different contexts from which they were collected.
Blinding	Archaeological sampling normally does not involve blinding as the sampling is restricted by what is available to sample. Nonetheless, as we have explained above, we tried to collect a wide range of archaeological and sediment samples during the excavation to represent the fullest possible scenarios of water management during the occupation of the site. The geological coring survey was arranged at every 1km, which is a good sampling strategy to avoid bias and hence effectively offset the absence of blinding during the survey.

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	The annual rainfall is about 740mm, and the average annual temperature is about 14 °C.
Location	Profile 1: N33° 42' 29.148", E114° 55' 26.920"; Profile 2: N33° 42' 21.442" , E114° 55' 23.227"; Profile 3: E114° 55' 29.862" , N33° 42' 18.039" .
Access & import/export	All the samples were processed in different laboratories in China and thus not export permission were required. The collection of the archaeological and environmental samples was discussed and agreed by all the project participants and also with permission from local institutes.
Disturbance	N/A

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☐	☒	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

Palaeontology and Archaeology

Specimen provenance	The collection of the archaeological and environmental samples was discussed and agreed by all the project participants and also with permission from local institutes.
Specimen deposition	Most of the bulk samples are stored at Institute of Geographic Studies of the Henan Academy of Science; archaeological samples (e.g., ceramic drainage pipes) are curated at the Henan Provincial Institute of Cultural Relics and Archaeology and Henan Provincial Museum. Thin section samples are stored at School of Archaeology and Museology of Peking University
Dating methods	The OSL dating were performed at the Institute of Geographic Studies of the Henan Academy of Science following standard single-aliquot-regenerative method (see the supplementary information folder). 14C dates were obtained from the Beta Analytic following their standard treatment. IntCal20 was to calibrate the dates.

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Ethics oversight	No ethic requirements were needed as they samples do not involve human specimen and the collection of them followed strictly Chinese laws.

Note that full information on the approval of the study protocol must also be provided in the manuscript.