Evolution of Holocene alluvial landscapes in the northeastern Songshan Region, Central China: Chronology, models and socio-economic impact

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Abstract: A recent suggestion of the existence of an enormous ancient waterbody in Central China had been associated with the intensifying water management that led to the rise of early states. However, the evolution of regional alluvial landscapes remains unclear. Through intensive geoarchaeological surveys and careful field examination of typical sedimentary sequences, we reconstructed Late Pleistocene-Holocene landscapes in the northeastern Songshan Region and identified three distinctive models of landscape evolution. In the loess hills and tablelands areas, rivers were characterized by the large-scale alluvial aggradation during the terminal Late Pleistocene. Following a slight river incision during the Early Holocene, a pronounced alluvial aggradation resumed throughout the Middle Holocene. This gave way to another episode of river downcutting during the Late Holocene. The platform-type plains area witnessed a similar process of landscape evolution. However, the amplitude of the Early Holocene river-incision was smaller, whilst the large-scale Middle Holocene aggradation filled up the valleys, which also led to the formation of buried terraces. The eastern plains area was marked by continuous alluvial-lacustrine aggradation from the Late Pleistocene onwards. Many lakes, marshes and wetlands were formed during the Middle Holocene river aggradation. These waterbodies were separated by the high-elevation landforms, creating a mosaic-like aquatic landscape. The Late Pleistocene-Holocene landscape supported mixed farming of rice and millets from the Neolithic to Bronze Age. After 4000 BP, with another event of river incision, the wetlands shrank, and the extensive area of drylands emerged in the east plains. This change coincided with the emergence of large-scale urban centers in the region.

Keywords: Northeastern Songshan Region; Evolution of Holocene landscape; Alluvial incision and aggradation; Prehistorical settlement distributions and agricultural strategies

1. Introduction: Alluvial landscape and the emergence of Chinese civilization on the Central Plains

The Songshan Region of Central China is considered the heartland of the origins of Chinese civilization. The well-known legend of the Great Yu's combating the floods vividly depicts the close association between the emergence of the first state and the great floods on the Central Plains as attested by both transmitted historical documents and palaeo-environmental evidence. The historicity of the founding of Xia Dynasty (c. 4000 BP) by the Great Yu has been widely debated and the emerging palaeo-environmental evidence of Holocene great floods seems to support this Wittfogelian-type theory that it was through the organization of large-scale hydraulic infrastructures that kingship and the first state rose on the Central Plains (Yang et al., 2000; Xia and Yang, 2003; Xia et al., 2003; Huang et al., 2007; Li et al., 2009; Huang et al., 2010, 2011; Zhang and Xia, 2011). However, the long-term evolution of aquatic landscapes and how this shaped the developmental discourse of prehistorical societies in the Central Plains remain to be demonstrated.

Located in the intermediate region between the Loess Plateau and the North China Plain, the Songshan Region experienced different stages of Holocene environmental changes that were characterized by river aggradation and incision along with surface erosion and formation of river terraces. Multiple reasons were responsible for these episodes of environmental change, including climate changes, tectonic activities and long-term human activities such as deforestation and farming (Rosen et al., 2008; Zhuang and Kidder, 2014; Ren et al., 2019). Fluctuations of hydrological conditions play a decisive role in regional ecological and landscape changes as demonstrated in several recent studies. In her geoarchaeological investigation of the Yiluo river valleys, Rosen (2008) proposed that the stable environment with developed soils and high-water table during the Early Holocene (10,000-8000 BP) favored millet farming by the Peiligang (ca.8000-7000 BP) people. By the end of the Middle Holocene (8000-4500 BP), frequent and rapid hillslope erosion and river valley accretion radically transformed local landscapes. The Yangshao (ca.7000-5500 BP) people started to grow rice on the valley bottoms. Around 2000 BP, with the incision of valley bottoms and the disappearance of wetlands, the scale of rice cultivation was significantly reduced (also see Rosen et al. 2017). Wang et al. (2015) suggested a similar scenario of hydrological fluctuations from the Middle to Late Holocene in the Ying River valley. During the Longshan period (c.5000-4000 BP), the middle Ying River experienced steady sedimentation process as the relative height between the loess tablelands and the river channel beds became stabilized. This favorable hydrological condition enabled rice cultivation and water management through the maintenance of moats and other hydraulic infrastructures. Yu (2016) suggested that there existed an enormous lake in the northeastern Songshan Region between 9000-4000 BP with its size reaching around 390 km^2 at its maximum. But Lu et al.'s recent survey confirms that there was not such an enormous lake with continuously distributed waterbodies around the Shiyuan area of the eastern Songshan region during the Holocene (Lu et al., 2019a). Indeed, despite these recent studies, it remains unclear regarding the scale, chronology, spatial-temporal variations and evolution of Holocene aquatic landscapes on the Central Plains. This hinders our understanding of the relationship between prehistoric settlement distributions and their aquatic environments and how such dynamics fundamentally defined agricultural strategies, water management technologies, and social evolution which led to the emergence of the early state.

The key to disentangle these issues lies in conducting well-designed geoarchaeological surveys that take into account alluvial landforms, hydrological fluctuations, and ecosystem changes within reliable chronological frameworks of different geographic units. Such data can be then synthesized with archaeological data towards establishing a more holistic understanding of the long-term dynamics between environmental fluctuations and cultural adaptations in the Central Plains.

Here we present results of our multiple-season geoarchaeological surveys in the northeastern Songshan Region of the Central Plains. The surveys were conducted following different steps, including fieldwalking surveys along key alluvial landscape and other geomorphological units, collecting environmental samples from representative sedimentary sequences, processing and analyzing sediment samples, and spatial analysis. Through tracing the Late Pleistocene and Holocene sediments, mainly of loess and reworked loess sediments, we confirmed that loess deposition through wind-blown activities and alluvial aggradation and incision, through which loess was eroded, transported and redeposited, were the two main geomorphological processes which shaped diverse geomorphological landforms following different models in the studied region. In particular, we identified a new type of Holocene geomorphological units, the so-called platform-type plain, which prevailed on the loessic landscape on the Central Plains. These data were synthesized with archaeological data for the reconstruction of models of Holocene landscape evolution, characteristics of prehistoric settlement distributions and their geomorphological contexts, and long-term dynamics between prehistoric cultures and Holocene alluvial landscapes.

2. Physical environmental settings and archaeological history of the Songshan Region

Northeastern Songshan Region includes the present Zhengzhou and Xingyang cities. This region lies in the middle of the Central Plains with low mountains and hills (<800m above sea level) standing to the north of the Songshan Mountain range (Fig1). Two tectonic lines fundamentally define the basal geomorphological characteristics of the region. The south-north Laoyachen Line is located in the middle of Zhengzhou city (Hou and Wu, 2000; Fig 2a). The areas to its east experience relative tectonic subsidence and the geomorphological processes are therefore dominated by alluvial aggradation, whilst the areas to its west witness relative tectonic elevation with predominant upward accumulation of loess. Another west-east tectonic line named the Xushui Line sits in the eastern Xingyang city between the loess tablelands and plains (Song and Yuan, 2011; Fig 2a). The areas to its north and south have been elevated and subsided, respectively. There is a loess hill named the Guangwu Mountain with average altitude of around 200 m in the northern edge of the region. Surrounded by these loess hills and tablelands, the studied region displays a culvert-shaped terrain that has a flat central part and elevated northern and southern parts.

The Yellow River runs through the northern edge of the studied region. The rest of the region is also crisscrossed by several river systems, including the Sishui River and Ku River that flow into the Yellow River, and the Suo, Xushui and Jialu rivers that flow into the Huai River (Fig 1b). The region belongs to the continental temperate-monsoon climate, with an average annual temperature of 14 °C and an average annual precipitation of 600 mm. Wheat and corn are the two main crops at present, and rice is also grown in some areas.

Recent archaeological, geoarchaeological, and archaeobotanical studies in the region have provided important evidence for the reconstruction of prehistoric settlement distributions (Lu et al., 2013a, 2013b; Lu et al., 2019b) and subsistence strategies (Jia, 2011; ZMICRA, 2001; Sun, 2018; Bestel et al., 2018). The well-established chronological sequence of Neolithic to Bronze-Age cultures in the Songshan region is summarized in Table 1. Excluding the Lijiagou culture period as not many sites of this period have been found in the region, settlement numbers witnessed steady increase from the Peiligang culture period to the Xia-Shang period (c. 4000-3000 BP) (Table 1; Fig 1b). In terms of the size difference between the contemporary settlements, there was only minor difference between the Peiligang settlements. From the late Yangshao period onwards, considerable difference began to emerge and by the Xia-Shang period, not only did mega-sized sites (>300 hectares) appear, but a marked hierarchy of size and functions was established between these settlements (Lu et al., 2019b).

The Peiligang society had begun millet and rice cultivation (Zhang et al., 2012; Wang et al.,2017a; Bestel et al., 2018), but agriculture did not account for the main source of food production as hunting and gathering still dominated the subsistence strategies during the time. From the Yangshao period onwards, agriculture became the primary food subsistence strategy, with the gradual establishment of mixed farming of millets and rice that was continued through to the Longshan and Xia-Shang periods (Lee et al., 2007; Rosen et al., 2017; Wang et al., 2017a). This mixed agriculture was not only practiced at sites that were located on low-elevation locations on the alluvial plains, but also on loess tablelands with relatively higher altitudes (Liao et al., 2019). It is therefore critical to investigate palaeo-hydrological fluctuations around the sites and understand the relationship between subsistence strategies and hydrological fluctuations within the context of long-term evolution of Holocene alluvial landscapes.

3. Fieldwork methods and laboratory analyses

3.1 Geoarchaeological fieldwork

We carried out four seasons of geoarchaeological fieldwork in the studied region from 2016 to 2019. Before the fieldwork, we compiled and analyzed topographic maps, geologic maps and remote sensing images of the region. Based on these data, we categorized geomorphological types according to their altitudes and sedimentation histories, and plotted these geomorphological types onto a map. During the field investigation, these different geomorphological landforms and their spatial boundaries were ascertained; and the information was fed backed into our modification of a new geomorphological map (Fig 2a).

Across the loess regions, the well-studied Pleistocene and early Holocene loess and palaeosols have become diagnostic hallmarks for relative dating and stratigraphic correlation because of their distinctive colour, sedimentation and distribution. For instance, the Holocene palaeosol (normally called S0) is easy to recognize in the field due to its darker color than common loess. The S0 (8000-3000 BP) overlays the Late Pleistocene Malan loess. Similarly, the reworked loess and alluvial sediments, often with fine laminae and darker colour than the loess and palaeosols, are directly identifiable in the field. We examined more than 200 exposed stratigraphic sections in the field. The majority of them represent continuous loess sequences from the late Pleistocene to Holocene. The rest of them represent alluvial sedimentation alternating with events of loess deposition. We chose 35 of such typical alluvial-loess sequences, which are discussed here (Fig 2a and Table 3). The depth, color, texture, composition, sediment sorting of each layer in each stratigraphic section were recorded in detail. The approximate relative ages and sedimentary environment at some typical stratigraphic sections were determined in the field. Through these methods and fieldwork procedures, we identified many Late Holocene and Early Holocene alluvial sequences. We also plotted the RTK-GPS coordinates of these stratigraphic sections on the map and calculated the rough distributions of the alluvial sediments.

These representative stratigraphic sections were systematically sampled for OSL dating and particle size distribution analysis. The particle size samples were collected at equal intervals (5cm) from bottom to top of each stratigraphic section or according to their stratigraphic units.

3.2 OSL dating

The standard single-aliquot regenerative-dose procedure of OSL dating was performed to measure the equivalent dose (*De*) at the Laboratory of Digital Environmental Archaeology, Institute of Geographical Sciences, Henan Academy of Sciences of China. In the analytical process, quartz particles of the main component (4-11μm) were extracted, after removing the organic matters with 10% H_2O_2 and dissolving the carbonate minerals with 10% HCl. The measuring device was the Lexgyresearch, made in Germany. The uranium, thorium and potassium contents of the samples were measured by neutron-activation-analysis (NAA). When calculating the ages, the *in-situ* water contents measured in the field were adopted, and the standard errors were set at 5%. Additionally, every Aliqouts Num made use of the practical aliquots in the calculation (Zhang et al., 2009; Lai and Ou, 2013).

3.3 Particle size analysis

The Particle size analysis was also performed at the same laboratory using the Malvern Particle Size Analyzer 2000 made in UK. Following the standard procedure, the percentage content of clay, silt, sand and median grain size were determined on the machine. Then the data was calculated using the Folk-Ward method and plotted on Grapher to draw the graphs.

4. Results

4.1. Characterizing geomorphological landforms and landscape diversity

In the results, we first present our broad-brush reconstruction of Holocene geomorphological processes and diversity of landscape in different areas of the studied region, supported by our results of OSL dating and some published 14C dates (Tables 2 and 3). This will be followed by a more detailed definition of temporal and spatial variations of Late Pleistocene-Holocene alluvial landscapes in the following session.

According to elevation, shape and sedimentation histories, we divided the region into six different geomorphological units/areas, including mountains, loess hills, loess tablelands, platform-type plains, alluvial plains and sand dunes. These units were distributed in two parts of the region demarcated by the tectonic line of Laoyachen: uplands and lowlands. The uplands, including mountains, loess hills, loess tablelands and platform-type plains, are located in the west, whilst the lowlands, including alluvial plains and sand dunes, lie in the east (Fig 2a). Based on our field survey results, we drew two schematic diagrams to show typical sedimentary sequences along two cross-sections in the region, which helped our characterization of diverse geomorphological processes and landforms below.

The western uplands are the extension of the Loess Plateau. The mountains, loess hills, tablelands, platform-type plains and another loess hill (Guangwu Mountain) are situated successively from south to north. In front of the scattered mountains, the loess hills are dominated by deeply incised erosion gullies with the formation of terraces during river incision. Typical sedimentary sequence on the valley bottoms consists of Middle to Late Pleistocene loess or reworked alluvial silts from loess parent material at the bottom, which are overlain by thin layers of Holocene loess. Sandy lenses are embedded in the sedimentary sequences on places with relatively low elevations. Most sandy lenses which represented an accretion event were deposited during the Late Pleistocene, judging from their underlying and overlying strata (Fig 2b and c).

Compared to the loess hills, the loess tablelands are of relatively lower altitudes, with much broader flat surfaces. Even though the incision on loess tablelands is not as deep as that on loess hills, at some places the incision reaches up to 20 m deep. Similar sedimentary sequences are present, but with more embedded sandy and silt lenses of Late Pleistocene and Holocene ages (Fig 2b and c). But the distribution areas of these lenses are very small. The main sediments are dominated by loess in the tablelands.

Intermediate between the loess tablelands and the Guangwu Mountain are the so-called platform-type plains, 110-140 m above sea-level. This is a new geomorphological type that we identified during our fieldwork. In terms of geomorphological genesis, platform-type plains represent a new geomorphological category between the tablelands and alluvial plains. Although the flat and broad surface of the platform-type plains is similar to that of alluvial plains, platform-type plains are characterized by deep gullies surrounding them. . This new type of geomorphological landforms is also different from typical tablelands or platforms which are normally deeply and intensively incised by rivers, creating more dramatically fragmented landscapes surrounding them. Because the platform-type plains are mostly situated in the broad loess area, their sediments were also dominated by loess, with embedded alluvial lenses (Fig 2b).

The eastern lowlands are composed of the alluvial plains and sand dunes. The alluvial plains in the north were the products of the alluvial activities of the Yellow, Jialu and other rivers. On the edges of the alluvial plains, underlying the alluvial sediments were Pleistocene loess deposits. Sand dunes are mainly distributed in the southern part of the lowlands. The top of the sand dunes is around 3-5 m higher than the surrounding surface. These sand dunes were formed by localized wind-blown activities which transported sands from the nearby Yellow River floodplains to the sand dunes (also see Shi, 1983).

To sum up, loess deposition and alluvial activities were the two main geomorphological processes that shaped the Pleistocene-Holocene landscapes in the studied region. First, the distribution of Pleistocene-Holocene loess deposits occupied most of the western areas and extended to the edge of the eastern plains. The loess deposition is fundamental to the formation of hills, tablelands, and platform-type plains. Second, river aggradation and downcutting created alluvial plains and erosion gullies and terraces across the eastern and western parts of the studied region. Both Late Pleistocene and Middle Holocene alluvial and fluvial sediments were predominant in the sedimentary sequences representative of tablelands and platform-type plains at the Zhangwuzhai, Zhuzhuang, Sima, Dashigu, Xiaodiaogou (Fig 3a) and Shumuyuan, Mazhuang (Fig 3b) locations, while Middle Holocene alluvial and fluvial sediments were present at the Damiao, Zhaizhai, Zhilubei, Xuecun, Zhencun, Xifeng, Dashigu, Dianjuntai (Fig 3c), Xisulou (Fig

3d), Guanzhuang, Zhanmatun, and Xiaowan locations (Fig 2 and Table 3). It is noted that such deposits in the western loess area were buried more shallowly than that in the plains area. The widespread presence of the alluvial and fluvial sediments on top of loess deposits convincingly demonstrates two major Holocene events of alluvial aggradation in the region, following loess deposition.

4.2 Defining the temporal-spatial characteristics of Pleistocene-Holocene alluvial cycles

Our characterization of Pleistocene-Holocene geomorphological processes just discussed confirms the existence of a diverse range of waterbodies, including lakes, wetlands and rivers, in the region. Even on top of the loess hills, there is evidence of Pleistocene-Holocene lakes (Fig 3 e). Yu (2016) has provided some ^{14}C and OSL dates of several alluvial and lacustrine sequences in the region. Our OSL dating of sediment samples collected from typical alluvial and lacustrine sequences after careful geomorphologic examination of their sedimentary and stratigraphic contexts in the field significantly supplements the existing data towards the establishment of a reliable chronological framework for the Pleistocene-Holocene alluvial dynamics (Table 2). Combined with Yu's data, these data and field observations (Table 3) enable us to reconstruct the temporal-spatial framework of alluvial cycles of river aggradation and incision from the Late Pleistocene to Late Holocene.

Stage one: Late Pleistocene and Early Holocene regional alluvial accretion

In the loess area, following the large-scale valley incision during MIS-3 (55-25 ka BP) which led to the formation of erosion gullies of more than 10 m deep was the Late-Pleistocene alluvial accretion. This process is best illustrated in the Shumuyuan profile located on a tableland near the loess hills (Nos. 3 and 11 in Fig 2a). Situated on the second-order terrace of the Jialu River, the relative height difference between the terrace surface and the present river water table is more than 20 m. The 6 m-deep profile can be divided into five layers stratigraphically (Fig 4; Table 4). The alluvial sediments in the Layer 5 contain more medium-sized and coarse-sand-sized particles compared to the underlying layer, which can be associated with a strong hydrodynamic sedimentary condition. Layer 3 represents typical lacustrine facies that was dominated by fine silt-sized particles. Although this size range is close to that of typical wind-blown loess in the overlying and underlying layers of the same sequence, the grayish colour sediments and their fine-laminae sedimentation structure clearly indicate a reducing depositional environment under water (Fig 4a and 4c). Two OSL dates obtained from the bottoms of layers 5 and 3 firmly falls into the timespan of the Terminal Late Pleistocene (10253±644 BP, note this OSL date situates within the boundary between the Pleistocene and Holocene) and Early Holocene (9356±462 BP), respectively (Table 2).

Two layers of typical lacustrine facies with fine laminae were also present in the 7.5 m-deep stratigraphy of the Xisulou-Lizhai (XSL-LZ) profile in the platform-type plains (Nos. 10 and 23 in Fig 2a). The particle sizes of these two darkish-coloured layers (layers 3 and 6) were dominated by fine-sized particles (Fig 4 and Table 5), indicative of a sedimentation regime close to a still water environment. The lower layer 6 is directly dated by OSL dating to 9452±485 BP (Table 2). One of the direct consequences of this Late-Pleistocene alluvial accretion was rapid filling up of the eroded gullies and the rising ground water level (Fig 5b; Table 5). The existence of sizable waterbodies during this stage is clearly evidenced by the thick alluvial sediment on the higher geomorphological position.

Late-Pleistocene and Early Holocene alluvial sediments were also found in the eastern plains area. There was a set of fluvial sediments 13.8-28.6 m below the ground surface at the Putian location, which was OSL dated to between 11000-6000 BP (Table 3). A similar stratum is also present at the Dahecun location. The age of the alluvial sediments 13.3 m below the ground surface is 12000-9000 BP (Table 3). As discussed in section 4.1, the wide distribution of such alluvial sediments indicated that the Late-Pleistocene and Early-Holocene alluvial accretion was a prominent event taken place across the region.

Stage two: Early Holocene river incision in the loess area

Evidence of the Early Holocene alluvial incision is present in both the tablelands and platform-type plains areas. At the XSL-LZ location of the platform-type plains area, the Early-Holocene lacustrine layer was cut by a shallow channel (Fig 5b). The river incision around the Shumuyuan location was at a much larger scale, resulting in the formation of 10 m deep erosion gully. This phenomenon can be more commonly seen in the tablelands area, although the depth of gullies formed at that time was shallower than that of modern valleys.

Unlike the loess area, the eastern plains area was marked by the continuous alluvial-lacustrine aggradation at the same time. The ^{14}C dates of alluvial sediments extend to the Early-Middle Holocene at both the Putian (11,000-6000 BP) and Dahecun (12,000-9000) locations (Table 3, but note that results of the ^{14}C dating at Putian is not desirable due to the large timespan it covers).

Stage three: Middle Holocene regional alluvial aggradation

There was a prolonged episode of alluvial aggradation in the loess area after the Early-Holocene river incision. This process resulted in different geomorphological features in the tableland and platform-type plains areas. At the XSL-LZ location of the platform-type plains area, the gully formed in the Early Holocene was filled up during the Middle Holocene, overlain by typical lacustrine sediments with fine laminae (Fig 5a). The age is OSL dated to 4709±216 BP (Table 2). The Middle-Holocene alluvial sediments were absent in the high-elevation position of tablelands.

The eastern plains area continued to be silted up in the Middle Holocene as evidenced by the presence of alluvial sediments at the Putian and Dahecun locations (Table 3).

Stage four: river incision in loess area after 4000 BP

As mentioned above, the Middle Holocene witnessed the recommencement of alluvial aggradation. At the XSL-LZ location of the platform-type plains area, the age of loess covering on top of lacustrine facie is OSL dated to 3193±161 BP (Table 2). The lakes and wetlands were drained by river downcutting process before the onset of loess accumulation. In the tablelands area, the rivers cut the surface more deeply with lateral erosion. The present deep and wide valleys were formed during this stage.

In the meantime, the eastern plains area continued to be silted up. The date of alluvial sediment extends to as late as 2900 BP at the Putian location (Yu, 2016).

4.3 Reconstructing models of the evolution of alluvial landscapes

According to our preliminary reconstruction of chronological frameworks and geomorphological processes discussed in sections 4.1 and 4.2, the Late Pleistocene and Holocene alluvial landscapes in the Songshan Region followed several episodes of incision-aggradation cycles. The scale and magnitude of these alluvial landscape cycles, however, vary from area to area. Such temporal-spatial variations can be attributed to the formation of the three models of alluvial landscape evolution summarized below, including the hill-tableland model, the platform-type plain model, and the alluvial plain model (Fig 6), which are demonstrated in the schematic illustrations in Figure 6 and summarized below.

During the Late Pleistocene the hills and tablelands in the region were already incised more than 10 m in depth. This was followed by a large-scale alluvial accretion, during which the deeply incised erosion gullies were filled up by alluvial deposits and reworked loess deposits. This episode of valley accretion was continued through to the Early Holocene. This lengthy period of valley accretion resulted in rising water table because of the significantly reduced height difference between the valley bottom and river water level. From around 9000-8000 BP, another episode of valley downcutting resumed. Even though the scale of this new episode of valley incision was small, it effectively drained the lakes, wetlands, and swamps in the region. A process similar to the Late Pleistocene and Early Holocene valley accretion was repeated during the Middle Holocene, which lasted to until 4000 BP. The modern landscape in this area that is characterized by extremely deep erosion gullies is largely a product of another episode of valley incision after 4000 BP. Along with this deep incision of valley bottoms was an equally large-scale river bank erosion. The valleys now became broad and deep. Although there was another cycle of accretion-incision in the valleys taken place during the historical period, the scale was far smaller and it was never able to fill up the valley to a substantial level (Fig 6a).

The evolution of alluvial landscapes on the platform-type plains area since the Late Pleistocene followed a very similar path to that of the hills and tablelands areas, but the associated sedimentation processes and timing of these geomorphological changes are quite different. The Late Pleistocene witnessed a large-scale alluvial aggradation in the broad valleys. This event of alluvial aggradation ceased during the Early Holocene, giving way to another cycle of smaller-scale alluvial incision and large-scale alluvial aggradation. The former drained low-lying areas, whilst the latter was divided into two stages that were caused by different climate-environmental mechanisms. The early stage was dominated by loess accumulation; during the later stage, with the return to a warm and humid climate, rivers began the aggradation again with the formation of typical aquatic landscape that was dominated by lakes and wetlands. Because the magnitude of the Middle Holocene alluvial aggradation exceeded the depth of Early Holocene valley incision, the alluvium continued to accumulate after completely filling up the valley. This alluvial landscape can be considered a typical buried terrace. The Late Holocene (4000 BP) also witnessed a large-scale alluvial incision that cut the valley to up to 10 m deep, with the disappearance of lakes, wetlands and swamps. The present landscape of the area was fundamentally shaped by this Late-Holocene alluvial incision and smaller-scale aggradation-incision cycle during the historical period (Fig 6b).

Significantly different from the two models discussed above, the alluvial plains area (including the sand dunes area) experienced multiple episodes of alluvial aggradation of thick alluvial-fluvial sediments since the Late Pleistocene (Fig 6c).

5. Discussion

5.1 The Holocene aquatic landscape: revisiting the enormous-lake hypothesis

The existence and scale of the Xingze wetlands near Zhengzhou has long been debated (cf. Wang et al. 2012). The enormous scale and long duration of the Holocene lake in the northeastern

Songshan Region suggested by Yu (2016) is striking, even compared to the suggested size of the Xingze wetland. According to Yu, the size of this lake reached 390 km^2 during the Early Holocene (Fig 1) and retained a remarkable size of 9800 ha even during the Late Holocene dry period. Our survey results, however, do not support Yu's reconstruction of the Holocene aquatic landscapes. Although many lakes, marshes and wetlands did exist in the studied region between 9000-4000 BP, these waterbodies were separated by loess tablelands. The size of them was much smaller than suggested by Yu (2016). For instance, we have found that, according to the distribution area of the lacustrine sediments (Fig 7), the Xisulou wetland only measured around 200 ha. This is in stark contrast to Yu's reconstruction in terms of the size of the wetlands or lakes (see Fig 7 for the comparison of the different scales of them by Yu and us). Around 1000 m to the northwest of Xisulou was the Dianjuntai location (No.24 in Fig 2a and Table 3) where lacustrine sediments were also present. The late Yangshao (5500-5000 BP) Dahecun-style pottery sherds found here indicate that the sedimentation age was also around Middle to Late Holocene. These two wetlands were not connected but clearly separated by the high loess belt as confirmed in our field survey (Fig 7).

Our field survey also found that the western loess area experienced several fluvial deposition-erosional cycles since the terminal Late Pleistocene. A large-scale alluvial aggradation took place in the Middle Holocene, resulting in the formation of lakes, marshes and wetlands. Our field survey confirmed a close spatial correlation between these ancient waterbodies and present river courses as shown in Figure 8. The alluvial-lacustrine sediments were often found located on both sides of modern valleys or beside ancient river channels (Fig 8). These small-scale waterbodies dried out during the following event of river incision in historical periods.

Contrary to the western loess area, the eastern plains area experienced continuous siltation. Relatively larger-scale waterbodies such as at the Dahecun location (No.15 and 32 in the Fig 2a and Table 3) and the Putian location (No.16 and 34 in the Fig 2a and Table 3) were formed. In the low-lying area, some of these lakes converged into large water areas and lasted throughout the Late Pleistocene and Early-Middle Holocene period. During 4000-3000 BP, these large lakes shrank and gradually disappeared under a dry and cool climate (Chen et al., 2015).

To sum up, the western loess area has experienced several fluvial deposition-erosional cycles since the terminal Late Pleistocene. In particular, a large-scale aggradational process took place in the Middle Holocene. We therefore suggest that the Middle Holocene aquatic landscape in the studied region was a mosaic one, different from what is suggested by Yu (2016) that large areas of the region were covered by water. These isolated, mosaic wetlands, marshes and lakes and the rich ecosystems surrounding them supported the development and growth of prehistoric societies in the region.

5.2 Relationship between Holocene alluvial landscapes, prehistoric settlement distributions, and development of agricultural strategies

As the regional cross-section (Fig 2c) and schematic reconstruction (Fig 9) show, prehistoric settlements were mainly distributed on flat land surrounded by rivers and small lakes with rich biomass (Wang et al, 2019) to sustain subsistence practices. On the temporal scale, the changing distribution patterns of Neolithic and Bronze-Age settlements were closely related to evolution of Holocene landscapes (Lu et al., 2014). Our mapping of prehistoric settlements shown in Figure 1 clearly demonstrates such a close relationship between settlement distributions and Holocene landscape evolution. With the Laoyachen Tectonic Line as the boundary, the ancient settlements were distributed differently between the western loess area and eastern plains area. A large number of early settlements (Peiligang, Yangshao and Longshan periods) were distributed in the loess area. By contrast, only very few early settlements were distributed in the edge of the plains area (Fig 1b), although the possibility that some settlements might be buried by later Holocene alluvium cannot be ruled out entirely. After 4000 BP, the Xia-Shang people began to occupy the eastern plains area. Settlements began to mushroom in the plains area. This development coincided with the evolution of regional alluvial landscapes. The waterlogged environment in the eastern plains area during the Early-Middle Holocene was uninhabitable. It was only after 4000 BP when waterbodies began to shrink and land started to emerge under a drier and cooler climate which made the area hospitable.

A similar process of settlement-landscape dynamics can be seen in the platform-type plains of the western loess area. During the Early-Middle Holocene alluvial aggradation, only a few Peiligang, Yangshao and Longshan settlements were situated on the platform-type plains. After 4000 BP, the lakes and swamps in the area began to drain along with the river incision process and increasingly more Xia-Shang settlements were built on the platform-type plains.

In terms of the development of settlement hierarchy, Lu et al. (2013a) suggest that there was not obvious size difference between the Peiligang period settlements. During the late Yangshao period, the scale of settlements began to diverge. Some settlements became much larger than others, with more complicated configurations of settlement structures (e.g., multi-circular moats). By the Longshan period, a well-developed three-tier settlement hierarchy was established. The growth of Longshan period settlements on the loess areas was profoundly restrained by the local landforms. The largest settlements in the areas did not exceed 100 ha in size. With the expansion of Xia-Shang period settlements to the eastern plains area after 4000 BP, a more complex settlement structure emerged. This was characterized by the development of a four-tier settlement hierarchy (Liu, 2005; Lu et al., 2019b) and the appearance of mega-scale site at the first-tier such as the Zhengzhou Shang City (25 km^2) as the capital of Early-Shang Dynasty (c. 1600 BC) on the plains area. The region was characterized by the mixed agriculture including dry farming and rice farming from the Neolithic to Bronze Age periods (Zhang et al, 2012; Wang et al, 2017a). Carbonized millet and rice grains were found at many sites (Bestel et al. 2018; Wang et al, 2017b) that were occupied for a lengthy period from the Peiligang, Yangshao, Longshan and Xia-Shang periods. Some early settlements (from Peiligang to Longshan periods) were even situated on the high-elevation geomorphological units such as the loess hills and tablelands (Liao et al, 2019). The lengthy, multiple-episode alluvial aggradation created many small lakes, marshes and wetlands, interlacing with the higher loess areas during the Middle Holocene. Such environments supported the development of mixed farming practice that included planting rice on places close to the waterbodies and dryland crops such as foxtail and broomcorn millets on relatively drier grounds (Rosen et al., 2017). With the river incision and reduction of wetlands after 4000 BP, the hydrological condition became unsuitable for rice farming. The loess areas began to be dominated by dryland agriculture. Rice farming became rare even on low-lying areas of the platform-type plains area during the Xia-Shang period (Qiu et al., 2018).

6. Conclusions

In the northeast Songshan Region, through intensive geoarchaeological survey, we identified three distinctive models of the evolution of alluvial landscapes in three geomorphological areas. In the higher loess hills and loess tablelands areas, the rivers were characterized by large-scale alluvial aggradation during the terminal Late Pleistocene. Following a slight alluvial incision during the Early Holocene, alluvial aggradation was predominant throughout the Middle Holocene. After 4000 BP, a marked episode of river-downcutting started again. The platform-type plains area experienced a similar process of Holocene landscape evolution. The rivers incised slightly during the Early Holocene, but the Middle Holocene alluvial aggradation was of a high magnitude. Many areas were mantled by the overflowing alluvial deposits, forming the buried terrace. Dissimilar from the aforementioned loess area, the east plains area was marked by continuous alluvial aggradation from the Late Pleistocene onwards, although the scale of aggradation varied in different periods.

The prolonged Middle Holocene alluvial aggradation has resulted in the formation of many lakes, marshes and wetlands. However, these waterbodies were not interlinked with each other directly. Rather, the Middle Holocene aquatic landscape was characterized by mosaic waterbodies separated by high-elevation tablelands. Such aquatic landscape and hydrological condition were most typical in the platform-type plains area. The spatial distribution of the lacustrine deposits indicated that these Holocene wetlands and lakes were often connected with the contemporary river valleys. Therefore, their spatial variations were closely related to Holocene alluvial incision and aggradation.

The Middle Holocene aquatic landscape laid the environmental foundation for the development of mixed rice and millet agriculture in the region from the Peiligang to Longshan periods. Similarly, the spatial and temporal changes of prehistoric and Bronze-Age settlement patterns were profoundly constrained by the evolution of Holocene alluvial landscapes. The Peiligang period settlements were mainly distributed on the loess hills and tablelands near the mountain. In the Yangshao-Longshan periods, people started to exploit the flat and open platform-type plains area with optimal hydrological condition for intensifying agricultural production. During the Bronze Age period when the climate became drier and cooler, the size of the waterbodies in the plains area was significantly reduced. This change coincided with the rapid expansion of Bronze-Age settlements and thus would have impelled the Bronze-Age occupants to reclaim the flatter and open lands on the plain.

Our systematic investigation of the evolution of Holocene alluvial landscapes clearly demonstrates that even within a moderate-sized region, the models and spatial-temporal variations of long-term geomorphological changes followed much more complicated and diverse discourses. The dynamics between geomorphological changes, hydrological fluctuations and human activities fundamentally shaped characteristics and paths of prehistoric and Bronze-Age social development in the heartland of Central China. Disentangling such dynamics holds significance to further understanding the rise of early Chinese civilization and its environmental foundation. Our case also offers a meaningful comparison to similar studies in other civilization regions of the world.

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