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Climate of the Past
Discussions

Changes in paleo-underground water levels revealed by water wells and their relationship with climate variations in imperial China

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Abstract. Based on the records of the bottom elevations of 482 ancient water wells collected from published archaeological reports, we reconstructed the paleo-underground water levels (PUWL) in the urban areas of Chengdu, Changsha, Nanjing, Suzhou, Suqian, and Yancheng cities in the vicinity of 30°N in China. The PUWL fluctuations varied between the inland and the coastal regions and their transitional areas. There were four PUWL phases in the inland areas: low in Han (206 B.C.–A.D. 220), high in Tang (A.D. 618–907), low in Song (A.D. 960–1279), and high in Ming (A.D. 1368–1644). In contrast, there were five PUWL phases in the coastal regions: high in Han (206 B.C.–A.D. 220), low in Jin-Northern & Southern Dynasties (A.D. 266–589), high in Tang-Song (A.D. 618–1279), low in Ming (A.D. 1368–1644), and high in Qing-Republic of China (A.D. 1644–1949). Yet, there were no apparent changes in PUWL in the transitional areas between the inland and the coastal regions. Regional hydrological factors cause the geographic variations of the PUWL fluctuations. Precipitation changes drove the rise and fall of PUWL in the inland areas. In contrast, the variations of PUWL in the coastal regions were attributed to the temperature-induced sea-level changes. This study illustrates the potential of using PUWL in tracing paleo-environment changes and their driving factors, which is a novel approach in environmental archaeology.

1 Introduction

The water resource is an essential guarantee for human survival and sustainable social development (Büntgen et al., 2011; WWAP, 2020). Therefore, for the long-term sustainability of agricultural production and regional development, it is necessary to explore the variations in water resources and their influencing factors (WWAP, 2020). Furthermore, the past processes and mechanisms of water resource fluctuations may provide a scientific basis for forecasting the future. Hence, it is crucial to reconstruct the paleo hydrological variations over the past 2000 years (PAGES 2k Consortium, 2013; IPCC, 2013) – the critical stage of social development in human history. However, there are considerable challenges in reconstructing the water resource fluctuations of the past.

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For many years, ~~the~~ variations ~~of the~~ paleo-water levels were reconstructed by using geomorphological, sedimentological, and bio-geo-environmental proxies. For instance, ~~the~~ paleo-coastal levels and lakeshores were employed to reconstruct the past geographic coverage of the water surfaces (Long et al., 2010; Rohling et al., 2014; Tomonaga et al., 2017; Li et al., 2018; Jiang et al., 2020), while ~~the~~ river terraces were often used to indicate the height of ~~the~~ riverbeds ~~of the past~~ (Chang et al., 2005; Larsen et al., 2017; Bender et al., 2020). Also, ~~the~~ diatoms and testate amoebae were taken as indicators for the sea or lake level changes (Charman and Warner, 1997; Lamarre et al., 2013). However, most studies ~~can~~ only cover ~~the~~ prehistoric periods owing to ~~the~~ low temporal resolution of ~~the~~ sediment samples used by ~~the~~ widely employed dating methods, such as cosmogonic nuclides, optically stimulated luminescence, and radiocarbon. On the other hand, ~~the~~ changes of paleo-water levels in the imperial period, which is closely related to the rapid development of human societies, ~~were~~ rarely examined.

Many well-known ancient civilizations originated in the vicinity of 30°N, such as Mesopotamia, Egypt, and India. Nurtured by the East Asian Summer Monsoon, some ~~splendid~~ civilizations also originated in the vicinity of 30°N in China, such as the ancient Shu civilization (e.g., Baodun Culture, Sanxingdui Culture, Jinsha Culture, etc.), Qujialing-Shijiahe Culture, and Liangzhu Culture that are located in the upper, middle, and lower reaches of the Yangtze River, respectively (Institute of Archaeology, CASS, 2003 and 2010). Numerous historical heritages are well preserved in these areas, including water conservancies facilities such as dams and water wells (Yu, 2001; Liu et al., 2020). These facilities are of great significance for ~~the~~ research on paleo-hydrology.

Water wells are built by excavating the ground and digging, driving, boring, or drilling to access groundwater in aquifers, while groundwater was one of the first sources of water to meet human needs since prehistoric times. ~~A~~ncient Chinese created sophisticated tools for drilling water wells that ~~is~~ similar to modern machines (Voudouris et al., 2019). It is worth noting that many well-preserved ancient water wells are direct indicators of groundwater levels (Jorgensen and Walid, 2003). At the same time, as the architectural designs and shapes of water wells are different across different dynasties, the ages of water wells ~~could~~ be traced easily. In this study, we made a pioneering attempt to reconstruct PUWL in the vicinity of 30°N in China by using ancient water wells (Fig. 1).

2 Methods and Materials

Water well drilling aims to obtain groundwater resources, so the bottom elevation must be lower than the phreatic water levels. In other words, the elevations of the bottom of the ancient wells likely represented the height of the groundwater

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levels. On the other hand, the superb skills in the water well building could be reflected in many aspects. Craftsmen tended to construct water wells in different shapes in different dynasties. Therefore, it is easy for archaeologists to distinguish the construction period of each water well according to its shape (Liu, 1991; Jia, 2007; Zheng, 2020).

In this study, we chose the Yangtze River Basin in the vicinity of 30°N in China to be our study area. This is because the earliest ruins of water wells dated back to approximately 6174–5921 BP were discovered in He Mu Du of Zhijaing, which is located in the Yangtze River Basin. Although Chinese civilization arose in the mid-basins of the Yellow and Yangtze Rivers, wells were used in the Yangtze River basin around 1,000 years before the Yellow River basin because the aquifer in the Yangtze River basin is higher (Voudouris et al., 2019).

We based on three principles to select the ancient water wells in the Yangtze River Basin. First, the ancient water wells in cities rather than counties were chosen to ensure the sufficiency of data. Compared with counties, the demand for water resources in cities is more remarkable because of the larger population. Hence, there are more ancient water wells in cities. Second, some cities with flat and less undulating terrain were chosen. This is because large undulating terrains influence the groundwater level changes (e.g., Chongqing). In contrast, those cities located in relatively flat areas were chosen (i.e., Chengdu, Changsha, and Nanjing). Furthermore, each archaeological site was analyzed individually because there were plentiful water wells. For instance, 171 ancient wells were excavated in the Chenghu site in Suzhou City. Finally, 482 ancient wells were chosen from nine cities, namely: Chengdu, Changsha, Wuhan, Ezhou, Nanjing, Suzhou, Shanghai, Suqian, and Yancheng.

Represented by the bottom elevations of the ancient water wells, since 2000 B.P., the mean PUWL is 497.3 m a.s.l. in Chengdu, 47.7 m a.s.l. in Changsha, 35.8 m a.s.l. in Wuhan, 19.2 m a.s.l. in Ezhou, 6.7 m a.s.l. in Nanjing, –1.5 m a.s.l. in Suzhou, 1.9 m a.s.l. in Shanghai, 6.0 m a.s.l. in Suqian, and –3.9 m a.s.l. in Yancheng, respectively. However, it is difficult to reconstruct the changes of PUWL in Wuhan (6), Ezhou (7), Jiujiang (10), and Shanghai (6), owing to their small number of ancient water wells. Therefore, six cities were finally chosen to reconstruct the variations of the PUWL, including Chengdu, Changsha, Nanjing, Suqian, Yancheng, and Suzhou (Fig. 2). Besides, the relative elevation, which indicates the elevation difference between each ancient water well and the modern land surface, was calculated to minimize the influence of terrain differences on the PUWL fluctuations.

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3 Results and Discussion

3.1 Variations of PUWL in the vicinity of 30°N in China

Temporally, we based on PUWL to divide all dynasties into two types: the PUWL was above or below mean. Geographically, after comparing ~~the~~ differences of PUWL, our chosen cities were divided into three types, namely inland (Chengdu and Changsha), coastal (Yancheng and Suqian), and inland-coastal transitional zones (Nanjing and Suzhou). As Fig. 2, in the inland regions, the relatively high mean PUWL in Chengdu and Changsha occurred in the Tang (A.D. 618–907) and Ming (A.D. 136–1644) Dynasties, including –2.3 m a.s.l. (Tang) in Chengdu, and –4.6 m a.s.l. (Tang) and –2.9 m a.s.l. (Ming) in Changsha. In contrast, the low PUWL happened in the periods of Warring States (403–221 B.C.), Han (206 B.C.– A.D. 220), and Song (A.D. 960–1279), with the PUWL values of –3.75, –3.0, and –3.6 m a.s.l. in Chengdu and –4.7, –5.0, and –3.2 m a.s.l. in Changsha. In Changsha, the abnormal value in the Song Dynasty was slightly higher than the mean PUWL, as it might slightly be lagged behind until the Yuan Dynasty (A.D. 1271–1368). Similarly, some records in historical documents indicate the inrush and drought caused by the changes in groundwater levels. Those records apparently match with the changes in our reconstructed groundwater levels based on the ancient water wells. For instance, the *Chorography of Jiangnan* indicates that water outflowed from nine dry wells in Anhui in A.D. 741. In the *Book of Ming*, the springs gushed and kept running for eight days in Sichuan in A.D. 1540. In contrast, there are records of dried wells in Anhui in A.D. 1595 (*Chorography of Jiangnan*) and Hunan in A.D. 1769 (*Chorography of Hunan*).

In contrast, the variations of PUWL in the littoral region such as Yancheng and Suqian were opposite to the ones in the inland areas. In Yancheng, PUWL was high during Han (–5.2 m a.s.l.), Tang (–6.6 m a.s.l.), and Song (–5.9 m a.s.l.). In Suqian, PUWL was high in Tang (–9.6 m a.s.l.), Song (–6.5 m a.s.l.), Qing (–8.0 m a.s.l, A.D. 1644–1912), and The Republic of China (ROC) (–7.2 m a.s.l., A.D. 1912–1949). On the contrary, in the Ming Dynasty, the mean PUWL was down to –14 m a.s.l. in Yancheng and –15.8 m a.s.l. in Suqian. Besides, in Yancheng, PUWL was extremely low during Jin (A.D. 266–420) and Northern & Southern Dynasties (NSD) (A.D. 420–589), dropping to –7.9 m and –8 m a.s.l., respectively. These changes were also recorded in historical documents. According to the *Chorography of Zhejiang*, there were lots of outflows of water wells in Huzhou of Zhejiang in A.D. 1277, suggesting that the water table was high in the Song Dynasty. Conversely, some water wells and rivers were dried up in the Jin (in A.D. 309 and 402) and Ming Dynasties (in A.D. 1240, 1247, 1458, and 1462 in Zhejiang and A.D. 1471 in Yangzhou), indicating the drop of the water table in these periods.

The variations of PUWL in Suzhou and Nanjing were different from the former two areas, probably owing to the differences in their determining factors of PUWL. Even so, there were some extremely low values of PUWL in Nanjing (–13.3 m a.s.l.) and Suzhou (–3.5 m a.s.l.) in the Six Dynasties (A.D. 222–589), and in Suzhou (–3.0 m a.s.l.) in the Song Dynasty. And these records of low water levels correspond to the drought events in these periods, which were also recorded in historical documents. For instance, in the *History of Song*, there were records of severe droughts in Jiangsu in A.D. 1192 and 1200.

3.2 Determining factors of the variations of PUWL in the vicinity of 30°N in China

The three regional patterns of the PUWL variations were likely attributed to different determining factors of PUWL in different areas. In the inland region such as Chengdu and Changsha, PUWL was probably affected by paleo-precipitation changes. On the other hand, unlike the inland region, PUWL in the coastal areas such as Suqian and Yancheng was probably influenced by the paleo-temperature changes. Besides, the influencing factors of PUWL were complicated in the transitional zone between the inland and the coastal areas such as Nanjing and Suzhou.

The variations of PUWL in inland regions were almost synchronous with the precipitation changes (Fig. 3). Two periods of PUWL with high values appeared in the Tang and Ming Dynasties (Figure 3, red shadows), which were synchronized with the strengthening of the East Asian Summer Monsoon (EASM) (Dykoski et al., 2005; Wang et al., 2005) and the increased precipitation (Zheng et al., 2006). On the contrary, two low values of PUWL took place in the Han and Song Dynasties (Fig. 3, blue shadows), which were coincident with the weakening of EASM (Dykoski et al., 2005; Wang et al., 2005) and the decreased precipitation (Zheng et al., 2006). However, it is worth mentioning that the high value of PUWL in Chengdu (–2.3 m a.s.l.) and Changsha (–2.9 m a.s.l.) was synchronous with the precipitation reconstructed by historical documents in the Ming Dynasty, which was in contrast with the low value of EASM reconstructed by the oxygen isotope records of stalagmites from the Dongge Cave. This likely reflects the asynchronous relationship between EASM and the precipitation in the Ming Dynasty. There were very few records of drought records in the Western Han Dynasty. In contrast, while a total of 42 drought events in the Song Dynasty (42 in total) were recorded in the *Yue Shi Bian*. There were also three mega droughts recorded in historical documents, including a severe nationwide drought lasting from June to December in A.D. 414 (*Book of Jin*), a prolonged drought in Hunan set in A.D. 930 (*Chorography of Hunan*), and another prolonged drought in Sichuan in A.D. 1193 (*History of Song*).

Different from the inland area, the variations of PUWL were likely affected by paleo-temperature changes in coastal areas (Fig. 4). Previous studies indicated that there was a significant correlation between the PUWL variations and the sea-level fluctuations (Shen and Zhu, 2004). And it was suggested that the temperature changes drove the fluctuations

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of sea levels. That is, the increase and decrease in temperature would lead to the melting and the growth of glaciers, resulting in the rise and the fall of sea level (Clark et al., 2001). Unfortunately, there are few studies on sea-level changes since 2000 B.P. owing to the low temporal resolution of the sedimentary records. Therefore, the paleo-temperature records were employed to compare the variations of PUWL in coastal areas. There were three periods with high PUWL, such as Han, Tang-Song, and the Qing-ROC, which corresponded to the high-temperature phases (Fig. 4, red shades). Conversely, there were two periods with low PUWL, such as Jin-NSD and Ming. It is worth noting that the mean PUWL in Suqian and Yancheng dropped drastically to –14.0 and –15.8 m a.s.l. during the Ming Dynasty. This was likely to be the superposition effect of the low temperature and the extreme drought in the coastal areas. First, the mean winter half-year temperature dropped in the late-Yuan Dynasty significantly (Fig. 4c and d). The Little Ice Age began in the Ming Dynasty in China, with a mean winter half-year temperature of 0.14 ℃ (Ge et al., 2010). Secondly, the precipitation was generally high in the Ming Dynasty. However, according to the ancient literature and historical records, there was an obvious and perennial extreme drought event in Eastern China (Fig. 3d, Zheng et al., 2005 and 2006). There were 71 famines records resulting from the worst drought in the Ming Dynasty (Song, 1992), which was described in the *Yue Shi Bian* as "*there was no rain from June to winter, and all of the water wells and rivers were dried up*" in A.D. 1644. Besides, the relatively arid climate was also recorded in the sedimentary strata in Eastern China, including the climate record reconstructed by the peat from Jinchuan in Jilin (Sun et al., 2019) and Xiyaohu in Jiangxi (Zhang et al., 2019). Furthermore, this extreme drought event was suggested to be driven by the volcanic eruption based on climate modeling (Chen et al., 2020).

By comparing PUWL with the paleoclimate records, the different driving mechanisms of PUWL in the vicinity of 30°N in China were revealed. The rise and fall of PUWL in the inland regions (Chengdu and Changsha) were driven by the increase and decrease of precipitation, which was resulted from the strengthening and weakening of EASM. In comparison, the variations of PUWL in the coastal areas (Suqian and Yancheng) were attributed to the fluctuations of sea levels, which were further caused by the diversifications of the temperature.

4 Conclusions

Based on the bottom elevations of 403 ancient wells in six cities, we reconstructed the PUWL in the vicinity of 30°N in China. There were three regional patterns of the PUWL variations. In the inland areas such as Chengdu and Changsha, there were two periods of high PUWL values and two periods of low PUWL values. The high PUWL happened in the Tang and Ming Dynasties, which corresponded to the wet periods. In contrast, the low PUWL occurred in the Han and

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Song Dynasties, corresponding to the dry periods. The variations of PUWL were likely caused by the changes in precipitation driven by the fluctuations of EASM. The variation pattern of the PUWL in the coastal regions such as Suqian and Yancheng was entirely different from the one in the inland areas. The three high PUWL values occurred in the Han, Tang-Song, and Qing-ROC periods, corresponding to the warm periods. In contrast, two low PUWL values happened in the Jin-NSD and Ming periods, corresponding to the cold periods. The change of PUWL was likely caused by the fluctuations of sea levels driven by the changes in temperature. There were no apparent changes in PUWL in the transitional areas between the inland and the coastal regions, such as Nanjing and Suzhou. This study illustrates the potential of using PUWL in tracing paleo-environment changes and their driving factors, which is a novel approach in environmental archaeology.

Code/Data availability

All data of ancient wells are available from the corresponding author upon reasonable request.

Author contributions

All authors participated in the experimental design and analysis processes. JCY and JX conducted all data collection and data processing with assistance from JX, KXG, LHF. JCY and JX prepared the paper with contributions from all authors.

Competing interests

The contact author has declared that neither they nor their co-authors have any competing interests.

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Figures

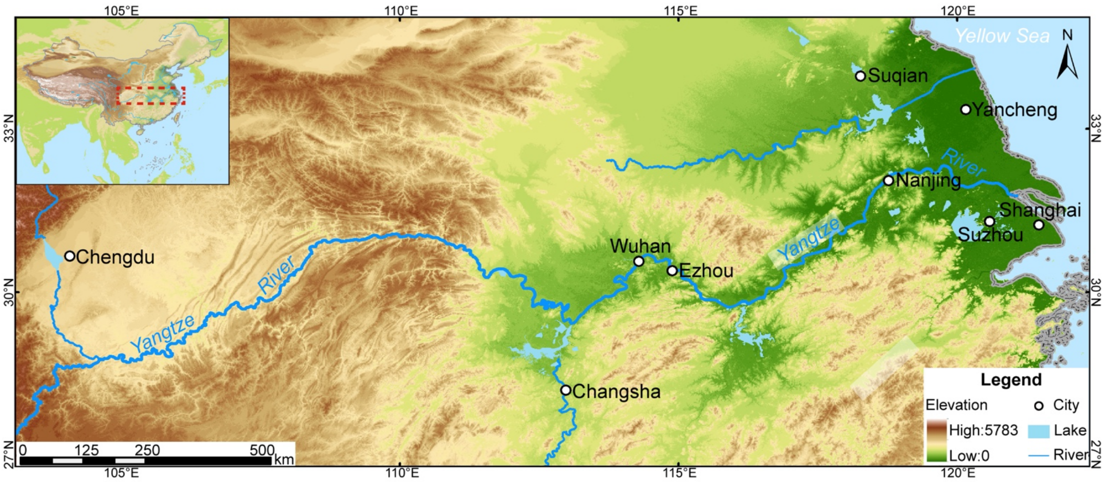
295 

Figure 1: Location of the vicinity of 30°N, China.

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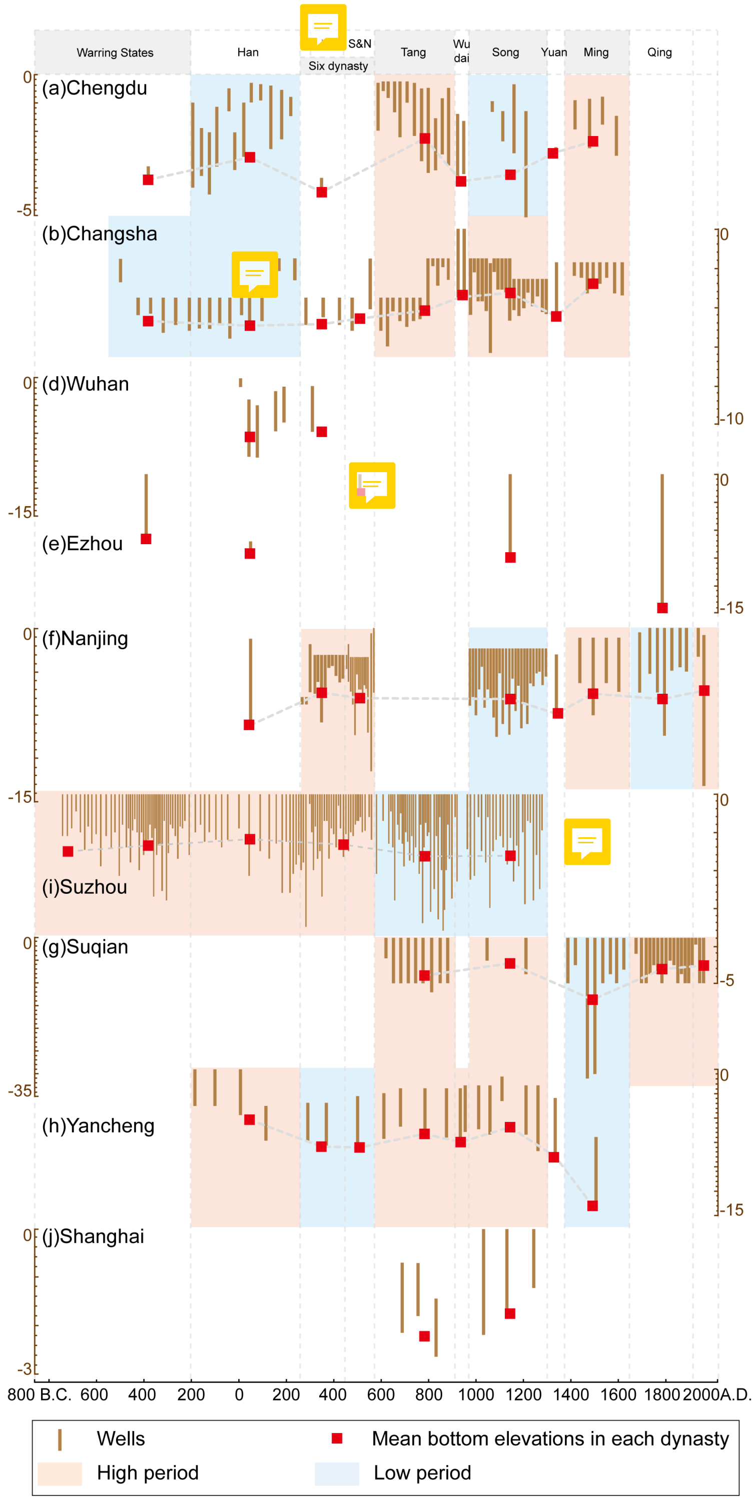

300 **Figure 2: PUWL reconstructed by ancient water wells (relative elevation) in the vicinity of 30°N in China (brown bars denoted the elevations of ancient water wells; red squares denoted the mean bottom elevations of all ancient water wells in each dynasty; unit = m).**

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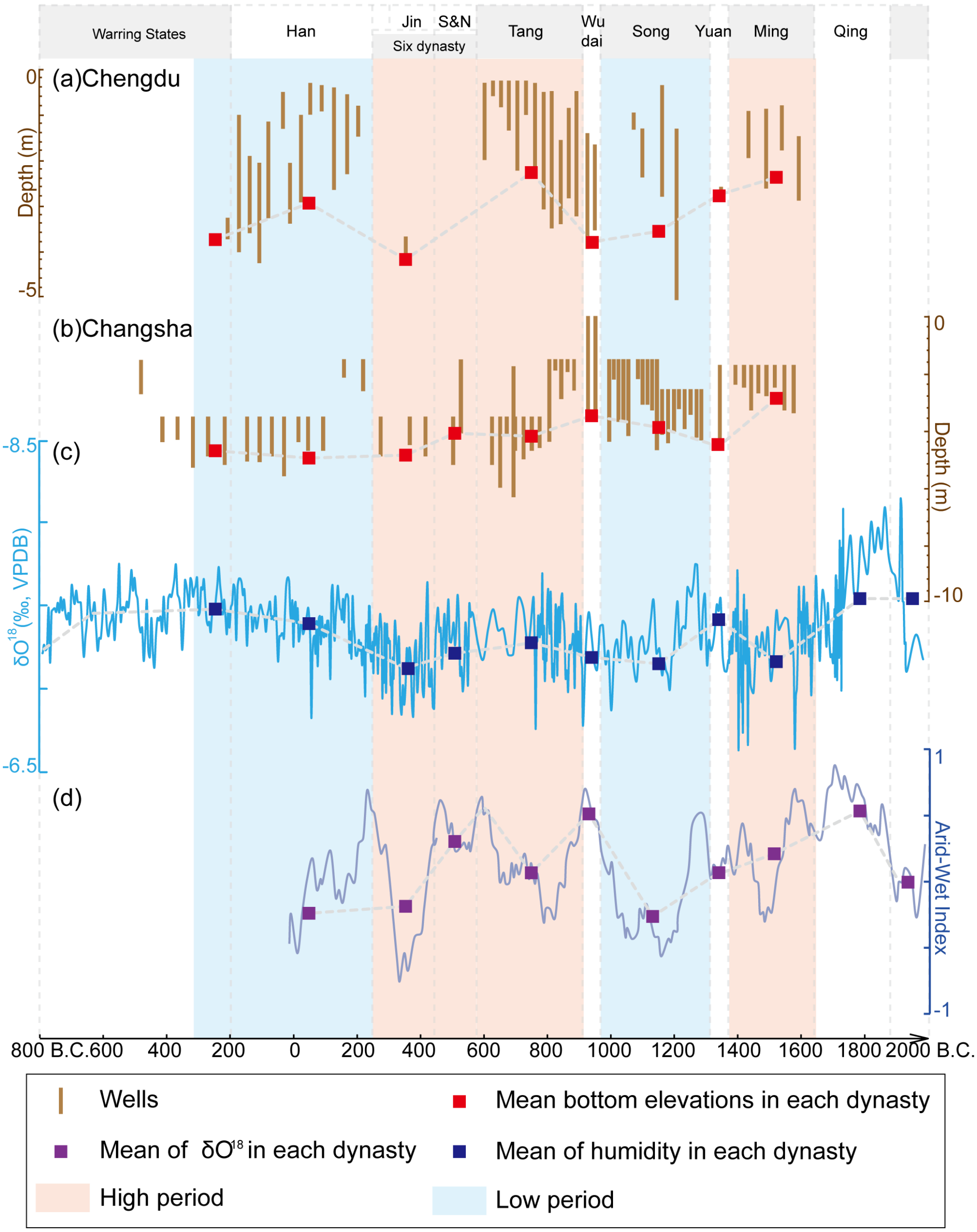

Figure 3: Comparison among PUWL, EASM, and precipitation in Chengdu and Changsha.

(a) PUWL in Chengdu; (b) PUWL in Changsha; (c) $\delta^{18}O$ records derived from the stalagmites in the Dongge Cave (Wang et al., 2005); (d) Wet/dry Index in Jiangnan Region reconstructed from historical documents (Zheng et al., 2006)

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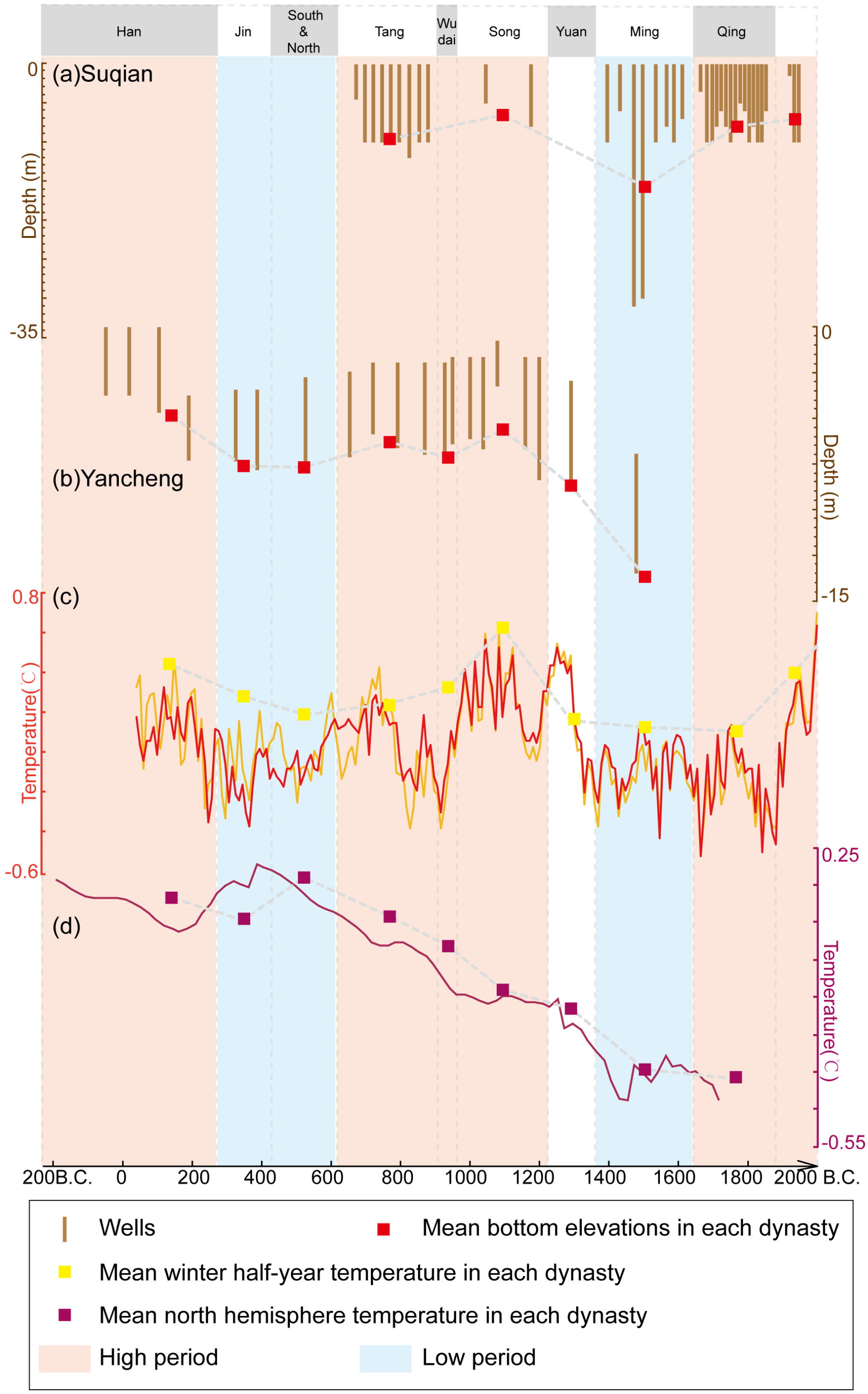

305 **Figure 4: Comparisons between PUWL and temperature in Suqian and Yancheng.**

(a) PUWL in Suqian; (b) PUWL in Yancheng; (c) Winter half-year temperature changes in eastern-central China (Ge et al., 2010); (d) Temperature stacks in 90°N–30°N (Marcott et al., 2013).