Sedimentary records of extraordinary floods at the ending of the mid-Holocene climatic optimum along the Upper Weihe River, China

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Abstract
Sedimentary records of the Holocene extraordinary floods were investigated in the upper reaches of the Weihe River, a major tributary in the middle Yellow River basin. Palaeoflood slackwater deposits (SWD) were identified at several sites on the riverbanks. These clayey silt beds are inserted into the Holocene aeolian loess-soil profiles and slope clastic deposits. They have recorded the extraordinary palaeoflood events which occurred between 3200 and 3000 yr BP as dated by OSL method and checked by the archaeological remains of the Neolithic and Bronze Age retrieved from the profile. The minimum flood peak discharges were estimated at between 22,560 and 25,960 m³/s by using palaeohydrological methods. It is 4.5–5.0 times the largest gauged flood (5030 m³/s) that has ever occurred since 1934. The palaeoflood slackwater deposits were found inserted into the pedostratigraphic boundary between the late-Holocene loess (L₀) and the mid-Holocene Luvisol (S₀) in the riverbank profile. This indicates that the extraordinary flood events were synchronous with the pedogenic regression at the end of the mid-Holocene climatic optimum. The climatic proxies from the studied profile and the correlative profiles in the river valley and the Loess Plateau show that the pedogenic regression was forced by climatic aridity and intensified dust storms and dust falls in connection with monsoonal shift over the Yellow River basin at about 3100 yr BP. The extraordinary flood events were documented not only on the Weihe River, but also on the mainstream and other tributaries of the Yellow River. These suggest that both extraordinary floods and droughts were parts of the climatic variability during the monsoonal shift. These findings are of great importance in understanding the interactions between hydrological system and climatic change in the semi-arid and subhumid regions of the world.

Keywords
China, climatic change, Holocene, palaeoflood, palaeohydrology, slackwater deposit, Weihe River, Yellow River

Introduction
Increasingly intensified hydroclimatic disasters are causing economic losses and human casualties worldwide. These catastrophic floods and droughts may have resulted from global climate change. Documentation of the long timescale hydroclimatic variations is of great significance for assessing the influence that global change might have on regional hydroclimatic systems. Palaeohydrological studies can provide specific information to address questions of hydroclimatic change and the resultant hazards, to mitigate flood risks and to improve flood design in hydraulic engineering (Benito and Thorndycraft, 2005; Benito et al., 2004). Bedded sequences of flood slackwater deposits along a river valley record individual floods. These slackwater deposits (SWD) are actually suspended sediment load in flood flow deposited in areas of flow separation and preserved after the flood recession (Ely and Baker, 1985). They are studied with the multidisciplinary methods of fluvial geomorphology, Quaternary sedimentology and geochronology for identification of palaeoflood stages, and further for estimation of palaeoflood discharges using hydraulic calculation models (Baker, 1987, 2000, 2006, 2008). A series of sedimentological criteria can be used for identifying palaeoflood slackwater deposits during fieldwork (Baker and Kochel, 1988; Benito and Thorndycraft, 2005; Benito et al., 2003; Huang et al., 2010). The age of palaeoflood events recorded by SWD can be determined by using the methods of OSL dating, 14C dating, archaeological dating and pedostratigraphic correlations. An integration of the results generated by these studies would be able to provide a palaeoflood chronology of long timescale for evaluating the global change impact on the regional hydroclimatic system (Knox, 2000).

Past flood recurrences were found to be correlated closely with climatic variations. It was noted that periods of climatic deterioration, combined with more humid conditions, often led to an increase in the recurrence of flooding over the Holocene (Saint-Laurent, 2004). The study of past hydrological events reflected in fluvial records of Europe showed that flood frequency and magnitude were higher during relatively cool-wetter periods (Macklin et al., 2006). While in northern China, two episodes of extraordinary floods at the ending of the mid-Holocene climatic optimum along the Upper Weihe River, China
flood events during the Holocene were identified on the Jinghe River, the Beiluohe River and the Qishuihe River that drain the central Loess Plateau and join the Weihe River in its middle-lower reaches (Huang et al., 2010, 2011). Several riverbank settlements of the late Neolithic and Bronze Age were inundated by overbank floodwater. These episodes are correlated with the well-known global climatic events of 4200–4000 yr BP and 3200–2800 yr BP that were defined as the dry-cold periods (Mayewski et al., 2004). These results show that, in the semi-arid to subhumid regions, the time of rapid or abrupt climate change has a tendency to be associated with more frequent occurrence of large and extreme floods (Knox, 2000). Thus, the relations between extreme floods and climate change during the Holocene are still open for discussion.

The upper reaches of the Weihe River drains the southwestern part of the Loess Plateau that is isolated by tall mountains. The environment is much drier in contrast to the middle-lower reaches of the river that drain the central part of the Loess Plateau. This paper presents the results of our palaeohydrological investigations in the upper reaches of the Weihe River. It focuses on identification of the palaeoflood events recorded by slackwater deposits, and examination of their links to past climatic change, and to check the hydrological difference between the upper and the middle-lower Weihe River basin during the Holocene.

Study area and sites

The mainstream of the Weihe River is 818 km in length and flows from west to east. It drains a catchment area of 134 760 km² in the middle Yellow River basin. The upper reach of the mainstream is 430 km long and drains an area of 30 660 km² including the west part of the semi-arid Loess Plateau, the Qinling and the Liupanshan Mountains (Figure 1A, B). The elevation decreases from over 2500 m a.s.l. in its headwaters to 500 m a.s.l. at the Linjiacun gauge station, where the river emerges from the mountains and flows into the Guanzhong Basin, a historical cultural centre in China. The mean annual precipitation varies between 400 mm and 600 mm regionally, c. 70% of which occurs in the form of rainstorm between June and September. The mean discharge of the Weihe River at the Linjiacun gauge station is 70 m³/s, and the mean suspended sediment load is 65 kg/m³ which is sourced from the semi-arid loess lands predominantly. The gauged largest flood event since 1934 at the Linjiacun station was 5030 m³/s which occurred in the year of 1954. The highest suspended sediment load was measured to be 866 kg/m³ in 1995 (Song, 2000).

In the upper stream from the Linjiacun gauge station, the Weihe River cuts through granitic and metamorphic rocks forming the deep and narrow Baojixia Gorges of about 200 km in length. Some small basins occur sporadically at the bends along the river, in which modern villages are situated at the riverbank terrace which is about 15–20 m above the river water-table (Figure 2A, B). In the exposed riverbank cliffs, a blanket of aeolian loess-soil (5–6 m in thickness) of late Pleistocene–Holocene age was often seen overlaying the past fluvial deposits of floodplain and/or riverbed gravels (Yue et al., 1997). The cultural layers of the Neolithic and Bronze Age ruins were often found interbedded in the loess-soil blanket on the riverbank terrace in these basins. The riverbank terrace in the Guanzhuanzhun Basin was investigated by archaeologists (Institute of Archaeology, CASS, 1991; State Administration of Cultural Heritage, 1998). The Neolithic ruins of the Longshan Culture (4800–4000 yr BP) was found interbedded in the mid-Holocene Luvisol (S₄) in the pedostratigraphy. The Bronze Age ruins of the Western Zhou dynasty (3000–2720 yr BP) was identified in between the late-Holocene loess (L₀) and the mid-Holocene Luvisol (S₄).

Methods

Palaeohydrological investigations were carried out along the upper reaches of the Weihe River between 2005 and 2010. Several Holocene sediment profiles were found in the gorges and the basins along the river (Figures 1B, 3A–D). The profile at the GCZ-A site was measured and sampled for detailed study because the pedostratigraphy is complete and the subdivisions are well correlatable with the studied Holocene loess-soil profiles elsewhere in the Weihe River basin, and also because a set of three clay beds of fluvial deposits were found interbedded in the profile which may be able to provide information of the hydrological change on the Weihe River (Figure 3). The cultural layers of the Neolithic and the Bronze Age ruins interbedded in the profile could be used to check the OSL dates. These facilitated an in-depth investigation of the Holocene hydroclimatic change in the Weihe River basin chronologically.

After pedostratigraphic subdivisions, a total of 55 sediment samples were taken every 4 cm continuously from the top to the bottom in the GCZ-A profile at the Guchuanzhen site (Figure 3D). Magnetic susceptibility was measured on a mass of 10 g of ground sediment with a Bartington MS2 magnetic susceptibility meter (0.47/4.7 kHz). Particle-size distribution of the samples was determined using a Mastersizer-S laser analyser. Chemical analysis was carried out on a Panalytical PW2403 X-ray Fluorescence Spectrometer.

Eight samples for OSL dating were taken from the profile at the GCZ-A site during the fieldwork. OSL dating on the fine-grain fraction (4–11 μm) of polynminerals was carried out by using the SAR protocol (Banerjee et al., 2001; Murray and Wintle, 2000). All measurements were performed on a Riso-TL/OSL-DA15 dating system equipped with a combined blue (470 nm, 50 mW/cm²) and infrared (875 nm, 150 mW/cm²) LED unit, and a 90Sr/90Y beta source for irradiation (Butter-Jensen and Duller, 1992). The content of U, Th and K in the samples was determined with an inductively coupled plasma mass spectrometry (ICP-MS). Effective dose rate (Dₑ) was figured out with the elemental concentrations by using the revised dose-rate conversion factors (Adams et and Atik, 1998). Water content of the fresh samples was measured after drying at 105°C for 12 h.

Two groups of pottery shards were retrieved from the cultural layers in the profile, which belong to the Neolithic Longshan Culture (4800–4000 yr BP) and the Western Zhou dynasty of the Bronze Age (3000–2720 yr BP), respectively (Figure 4). The chronological framework in the GCZ-A profile was established with the OSL dates and checked by the anthropogenic remains which were studied and 14C dated by archaeologists (Institute of Archaeology, CASS, 1991; State Administration of Cultural Heritage, 1998).

The hydrological parameters for reconstruction of the palaeoflood peak stage and discharge were acquired during fieldwork. The river channel geometries were measured at the YGZ-B site using an electronic distance measurer and GPS in association with the large-scale contoured maps. Flood hydraulic parameters, the roughness values (Manning’s n value) of the channel were assigned by referring to the Hydrological Calculation Norms for Hydraulic Engineering in China. The minimum peak discharges
of the palaeoflood were calculated by using the slope-area method of streamflow measurement with the end-point of the SWD as the palaeostage (Yang et al., 2000). The method is based on Man-ning’s Equation (Gordon et al., 2004):

\[ Q = \frac{1}{n} \left( \frac{AR^{2/3}}{S^{1/2}} \right) \]  

(1)

in which \( A \) is the cross-sectional area of the stream at the flood stage, \( n \) is Manning’s \( n \) which is an index of the roughness of the stream bed, \( R \) is the hydraulic radius which is the ratio of the cross-section area \( (A) \) of the stream to its wetted perimeter, which is the cross-sectional distance along the stream bed and banks that is in contact with the water, \( S \) is the hydraulic gradient or energy slope.

**Results and interpretations**

During our fieldwork, palaeoflood slackwater deposit (SWD) was identified in various Holocene sediment profiles at many sites.
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along the upper reaches of the Weihe River, among which four sites were initially judged to be synchronous by stratigraphic correlations. At the Nanhechuan site (NHC), a set of five overlapping palaeoflood SWD beds was found interbedded in the stony slope deposit. The stratigraphic breaks between the beds are very clear because of the formation of clay cap by upward fining during the sorted deposition in floodwater (Figures 1B, 3A). At the Duijiaping site (DJP), a set of three palaeoflood SWD with wavy bedding was identified also in the slope clastics (Figures 1B, 3B). It has recorded extraordinary floods during 3200–3000 yr BP with minimum peak discharges between $23460$ and $25480$ m$^3$/s as reconstructed by using the slope-area method of streamflow measurement (Zhu et al., 2010). A set of palaeoflood beds was identified in the loess-soil blanket in the riverbanks at the GCZ-A and the GCZ-B site in the Guchuanzhen basin (Figures 1B, 3C, D). They are easily differentiated from aeolian loess and soil because of the parallel or wavy bedding. The elevation of these palaeoflood SWDs varies between 15 m and 20 m above the normal water level at different sites. The elevation and number of the SWD beds are site-specific depending on the morphology of the river channel. The upward fining feature formed by sorted deposition in the individual SWD beds was seen at the sites where the SWD beds were horizontally deposited and undisturbed after deposition (Figure 3A).

In the Guchuanzhen basin, the riverbank terrace land is 15–20 m above the present normal water level of the Weihe River (Figure 1C). It formed an outstanding threshold or censoring level for registration of extraordinary overbank floods through deposition of the suspended sediment load. Overbank floods exceeding this elevation have left their sedimentary records on the riverbank terrace. At the GCZ-A site, a bedset of three palaeoflood SWD was identified in the depth range of 66–46 cm in the riverbank profile. Each of the palaeoflood SWD beds is $c. 5–8$ cm in thickness with a pale brown colour. They consist of compacted clayey silt with massive structure. The stratigraphic breaks between the beds are visible. As shown in Figure 4, a group of pottery shards belonging to the Neolithic ruins of the Longshan Culture (4800–4000 yr BP) was retrieved from the mid-Holocene Luvisol ($S_0$) beneath the palaeoflood SWD beds in the pedostratigraphy. Another group of pottery shards belonging to the Bronze Age ruins of the Western Zhou dynasty (3000–2720 yr BP) was found in the late-Holocene loess ($L_0$) above the palaeoflood SWD beds (Institute of Archaeology, CASS, 1991; State Administration of Cultural Heritage, 1998).

Magnetic susceptibility was used as a major climatic proxy in the study of Chinese loess for pedostratigraphic subdivisions and for climatic reconstruction (Maher, 1998; Maher et al., 1994). Magnetic susceptibility varies between $65 \times 10^{-8}$ and $210 \times 10^{-8}$ m$^3$/kg in the GCZ-A profile in the Guchuanzhen basin (Figure 5). The lowest values ($60–80 \times 10^{-8}$ m$^3$/kg) are present in the Malan Loess ($L_1$) of the last glacial (MIS-2), whereas the highest values ($160–210 \times 10^{-8}$ m$^3$/kg) are found in the mid-Holocene Luvisol.
In the late-Holocene loess (L₀) and topsoil (MS), the susceptibility values decline to between 115–160 × 10⁻⁸ m³/kg. Thus, the changing intensity of pedogenic modification to the accumulated dust is well defined on the curves of magnetic susceptibility in the profile at the GCZ-A site. The susceptibility values are relatively low in bedded clay that is inserted into the depth range of 66–46 cm in the profile.

Figure 3. Photograph showing the studied profiles in the upper reaches of the Weihe River. (A) Horizontal palaeoflood slackwater deposit beds inserted in the slope clastic deposit at the NHC site. (B) Wavy palaeoflood slackwater deposit beds inserted in the slope clastic deposit at the DJP site. (C) Palaeoflood slackwater deposit beds inserted into the boundary between the late-Holocene loess (L₀) and the mid-Holocene Luvisol (S₀) at the GCZ-B site. (D) Palaeoflood slackwater deposit beds inserted into the boundary between the late-Holocene loess (L₀) and the mid-Holocene Luvisol (S₀) at the GCZ-A site.

(S₀). In the late-Holocene loess (L₀) and topsoil (MS), the susceptibility values decline to between 115–160 × 10⁻⁸ m³/kg. Thus, the changing intensity of pedogenic modification to the accumulated dust is well defined on the curves of magnetic susceptibility in the profile at the GCZ-A site. The susceptibility values are relatively low in bedded clay that is inserted into the depth range of 66–46 cm in the profile.

The frequency of particle-size distribution in the sediment samples from the GCZ-A site is shown in Figure 6A. The curves of the aeolian loess and soil peak between 30 and 40 µm, and 25 and 30 µm, respectively, in the fraction of coarse silt in the diagrams, and are classified as silt. In contrast, the curves of the bedded clays inserted into the depth range of 66–46 cm in the GCZ-A profile peak between 8 and 10 µm and are classified as well-sorted...
Figure 4. Stratigraphic subdivisions in the GCZ-A profile and its correlation with the studied Holocene loess-soil profile at the Shiliucun site (SLC) in the Weihe River valley and the Ertangcun site (ETC) on top of the loess tableland (Huang et al., 2003, 2009). Two groups of pottery shards were retrieved from the cultural layers during sampling in the GCZ-A profile.
Figure 5. Pedostratigraphy, magnetic susceptibility and particle-size distribution in the Holocene loess-soil profile at the GCZ-A site in the upper reaches of the Weihe River.
The change in particle-size distribution in GCZ-A profile is manifested in Figure 5. The clay (<2 µm) and fine silt (2–16 µm) are higher in the mid-Holocene Luvisol (S0) and lower in the loess levels (L1, L0, L0). The medium silt (16–32 µm), coarse silt (32–63 µm) and fine sand (>63 µm) are lower in the mid-Holocene Luvisol (S0) and higher in the loess levels (L1, L0, L0). The bedded clay in the depth range of 66–46 cm in the GCZ-A profile is well defined by very high content of clay fraction (25–35%).

Figure 6. (A) The frequency of particle-size distribution in the Holocene loess-soil profile at the GCZ-A site in the upper reaches of the Weihe River. (B) Modern flood slackwater deposit after the 2 July 2005 flood in the upper reaches of the Weihe River.

The changes in element concentrations in the loess-soil profiles are closely related to the change in the intensity of pedogenesis in connection with monsoonal climatic variation in East Asia (Huang et al., 2009). The results of chemical analysis in the GCZ-A profile are present in Figure 7. The High concentrations of Fe₂O₃, Al₂O₃ and MnO are present in the mid-Holocene Luvisol (S0). This must be related to the intensified pedogenesis that resulted in the enrichment of these elements. Their concentrations are very low in the aeolian loess (L0) that accumulated during the last glacial (MIS-2). The pedogenic processes also caused the leaching of the soluble elements, thus, the concentrations of CaCO₃ and Sr are very low in the mid-Holocene Luvisol (S0). The aeolian loess (L0) contains a large amount of CaCO₃ and Sr because it remains as accumulated dust and is almost unaltered by weathering and pedogenic processes. In the recent loess (Lm) and modern soil (MS), the concentrations of Fe₂O₃, Al₂O₃ and MnO decreased in response to an increase in CaCO₃ and Sr. This could be related to a drier climate and weakened pedogenesis during the late Holocene. In the bedded clay in the depth range of 66–46 cm in the GCZ-A profile, the concentrations of Fe₂O₃, Al₂O₃ and MnO are relatively low and CaCO₃ and Sr are high, which means it was not much affected by weathering and pedogenesis after deposition.

The result of the OSL dating is given in Table 1 and Figure 4. It provides a chronology for the subdivisions and pedostratigraphic correlations with other studied Holocene loess-soil profiles in the Weihe River basin (Figure 4). The clay beds inserted into the depth range of 66–46 cm are therefore dated to 3200–3000 yr BP and are checked by the Neolithic remains retrieved below it and the Bronze Age remains retrieved above it (Figure 4).

**Discussion**

**Identification of palaeoflood events by SWD**

Field investigations along the upper reaches of the Weihe River showed that the modern river channel is formed in bedrock with
patches of well-rounded gravels deposited in the small flood-plains in the river bends. Past gravel deposits of riverbed and/or floodplain faces were found blanketed by aeolian loess in the terraces in the small river basins. Slope clastic deposits were often seen at the base of the bedrock cliffs. Subangular gravel deposits from tributary rivers and gullies were always seen at the confluences. A modern rainstorm and flood occurred on 2 July 2005 with a peak discharge of 1680 m³/s and a suspended sediment load of 320 kg/m² at the Linjiacun gauge station on the Weihe River. Our investigations after the flood indicated that the flood SWD consisted of pale orange-coloured silt and/or pale red-brown-coloured clayey silt (Figure 6B).

This immediate reference and the sedimentological criteria summarized in our previous studies enabled an accurate identification of palaeoflood SWD along the upper reaches of the Weihe River. These sedimentological criteria include (1) sediment consisting of silt, clay and fine sand with parallel or wavy bedding; (2) abrupt vertical change in particle-size, colour, texture and structure; (3) stratigraphic break between the beds; (4) a thin clay cap on top of a bed resulting from sorted deposition; (5) mud cracks in clay and clayey silt beds; (6) bioturbation including anthropogenic remains between the beds; (7) presence of aeolian loess and/or palaeosols between the beds; (8) presence of slope cracks in clay and clayey silt beds; (9) presence of slope wash, slope clastics and tributary coarse-sized alluvium between the beds, etc. (Huang et al., 2010).

On the riverbanks along the mainstream in the upper reaches of the Weihe River, the clayey silt SWD beds were found interbedded in the Holocene loess-soil profiles and slope clastic sediments at many sites (Figure 3). At the GCZ-A site, a bedset of three palaeoflood SWD is inserted into the depth range of 66–46 cm in the Holocene loess-soil profile on the riverbank, in which the aeolian loess has lower clay content and lower magnetic susceptibility, and the Luvisol has higher clay content and higher magnetic susceptibility because of the pedogenic alteration to the accumulated dust (Huang et al., 2009). In the palaeoflood SWD beds in the depth range of 66–46 cm, the concentrations of CaCO₃ and Sr are high, and the concentrations of Fe₂O₃, Al₂O₃ and MnO are low (Figure 7). This further confirms the judgement that these palaeoflood SWD beds are fresh sediment deposited in a very short time period and preserved immediately after flood recession. Thus, they were not affected by weathering and pedogenesis. These analytical data enabled a differentiation of the palaeoflood SWD from loess and soil in the profile at GCZ-A site.

In the Guchuanzhen basin, the riverbank palaeoground surface covered by the palaeoflood SWD was about 660 m above sea level (Figure 6B). It formed a threshold for registration of extraordinary overbank floods through deposition of the suspended sediment load. Overbank floods exceeding this elevation have left their sedimentary records on the riverbank terrace. Using the end-point of the slackwater deposits as the flood stage, along with the river channel geometric and hydraulic parameters, the minimum peak discharge was estimated to between 22 560 and 25 960 m³/s with the slope-area method of streamflow measurement (Gordon et al., 2004). This is very close to the discharges reconstructed by palaeoflood SWD at the DJP site in the upper stream (Zhu et al., 2010). They are 4.5–5.0 times the largest gauged flood (5030 m³/s) that has ever occurred since 1934 at the Linjiacun gauge station on the Weihe River.

### Age of the palaeoflood events

In the riverbank profiles at the GCZ-A and GCZ-B sites in the Guchuanzhen basin, the palaeoflood SWD bedset occurs at the pedostratigraphic boundary between the mid-Holocene Luvisol (S₀) and the recent loess (L₀). This L₀/S₀ boundary is visible everywhere over the loess region in the middle reaches of the Yellow River (Figure 4). It has been dated to c. 3100 yr BP at many sites (Huang et al., 2003, 2004, 2009). This means that the palaeoflood events recorded by SWD occurred at c. 3100 yr BP on the Weihe River.

On the other hand, the Neolithic remains of the Longshan Culture (4800–4000 yr BP) were found in the Luvisol (S₀) beneath the palaeoflood SWD beds. Pottery shards of the West Zhou dynasty of the Bronze Age (3000–2720 yr BP) were retrieved in the recent loess (L₀) immediately above the palaeoflood SWD beds (Figure 4). These ancient settlements were investigated and dated by archaeologists (State Administration of Cultural Heritage, 1998). The ages of these cultural layers provide a chronological bracket between 4000 and 3000 yr BP for the palaeoflood events on the Weihe River.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Depth (cm)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K₂O (%)</th>
<th>Water content (%)</th>
<th>Equivalent dose De (Gy)</th>
<th>Dose rate Dy (Gy/ka)</th>
<th>OSL age (yr)</th>
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<tr>
<td>Pottery shards</td>
<td>47.5</td>
<td>2.85 ± 0.11</td>
<td>13.60 ± 0.39</td>
<td>2.27 ± 0.05</td>
<td>18.0</td>
<td>12.13 ± 0.16</td>
<td>4.04 ± 0.13</td>
<td>3000 ± 140</td>
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<tr>
<td>Palaeoflood SWD</td>
<td>62.5</td>
<td>2.30 ± 0.11</td>
<td>10.60 ± 0.42</td>
<td>2.29 ± 0.05</td>
<td>17.0</td>
<td>12.84 ± 0.50</td>
<td>4.07 ± 0.16</td>
<td>3160 ± 250</td>
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<td>Soil</td>
<td>76.0</td>
<td>2.79 ± 0.12</td>
<td>14.20 ± 0.41</td>
<td>2.30 ± 0.05</td>
<td>19.0</td>
<td>14.90 ± 0.47</td>
<td>4.53 ± 0.16</td>
<td>3290 ± 220</td>
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<tr>
<td>Soil</td>
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<td>2.74 ± 0.12</td>
<td>12.00 ± 0.45</td>
<td>2.38 ± 0.05</td>
<td>22.0</td>
<td>21.78 ± 0.68</td>
<td>4.22 ± 0.17</td>
<td>5160 ± 370</td>
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<tr>
<td>Soil</td>
<td>126.0</td>
<td>2.73 ± 0.11</td>
<td>15.50 ± 0.45</td>
<td>2.33 ± 0.05</td>
<td>18.0</td>
<td>25.92 ± 0.33</td>
<td>4.70 ± 0.16</td>
<td>5520 ± 260</td>
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<td>Transitional loess</td>
<td>164.0</td>
<td>2.99 ± 0.12</td>
<td>15.00 ± 0.45</td>
<td>2.25 ± 0.05</td>
<td>18.0</td>
<td>51.49 ± 0.71</td>
<td>4.66 ± 0.17</td>
<td>11 050 ± 560</td>
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<td>1.91 ± 0.05</td>
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<tr>
<td>Loess</td>
<td>216.0</td>
<td>3.04 ± 0.12</td>
<td>12.90 ± 0.39</td>
<td>1.98 ± 0.05</td>
<td>16.0</td>
<td>59.83 ± 0.95</td>
<td>4.31 ± 0.15</td>
<td>13 880 ± 650</td>
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*Table 1. Summary of dosimetry, equivalent dose simulated with infrared light and OSL ages in the GCZ-A profiles in the Guchuanzhen basin in the upper reaches of the Weihe River.*
Figure 7. Pedostratigraphy and contents of Fe$_2$O$_3$, Al$_2$O$_3$, MnO, CaCO$_3$, and Sr elements in the Holocene loess-soil profile at the GCZ-A site in the upper reaches of the Weihe River.
The results of OSL dating provide a more specific age for the palaeoflood events on the Weihe River. A sample from the top part of the soil (S₀) immediately beneath the SWD beds was OSL dated to 3290 ± 220 yr (Table 1, Figure 4). A sample from the SWD beds was dated to 3160 ± 250 yr. A grey pottery shard from the Bronze Age cultural layer of the West Zhou dynasty (3000–2720 yr BP) immediately above the SWD beds was OSL dated to 3000 ± 140 yr. These results have the palaeoflood events dated to between 3200 and 3000 yr BP precisely.

Climate nature of the palaeoflood events

Pedastratigraphic subdivisions in the sediment profile at the GCZ-A site are well correlated with those at the Shihezhen site (SLC) in the Weihe River valley and the Ertangcun site (ETC) on top of the loess tableland in the central part of the Loess Plateau (Figure 4). As manifested in Figures 5 and 7, the variations of magnetic susceptibility, particle-size distribution and chemical elements indicate that the development of the profile includes three main stages as documented elsewhere over the middle reaches of the Yellow River (Huang et al., 2003, 2004, 2009). These include (1) the developing chemical differentiation in loess (L₀) in response to early-Holocene climatic amelioration and weakening dust storms and dust falls (11 500–8500 yr BP); (2) intensified element differentiation by syndepositional pedogenesis of the Luvisol (S₀) and reduced dust storms and dust falls during the mid-Holocene climatic optimum (8500–3100 yr BP); (3) pedogenic regression in loess (Lₚ) forced by intensifying aridity and dust storms and dust falls in connection with monsoonal climatic shift during the late Holocene from c. 3100 yr BP to the present time. Because the L₀/S₀ boundary is very sharp and visible everywhere along roadcuts and riverbanks over the middle reaches of the Yellow River, it has been used as a marking-line indicating the prominent monsoonal shift and climatic aridity at c. 3100 yr BP.

The extraordinary floods documented in the upper reaches of the Weihe River occurred just in the same episode of climatic aridity and pedogenic regression that were forced by monsoonal shift. The 3200–3000 yr BP floods were not unique events on the Weihe River. For instance, on the Qishuie River, a tributary in the middle reach of the Weihe River, extreme floods of the same age were documented by palaehydrological investigations (Huang et al., 2011). Extraordinary floods of the same age were also reported in the upper stream of the well-known Hukou Falls on the Yellow River (Li et al., 2010). During our 2010 fall fieldtrip, a bedset of palaeoflood SWD was identified at the newly excavated Neolithic ruins, named the Yangguanxianzhe archaeological site, north of Xi’an city in the riverbanks of the Jinghe River. The flood events were OSL dated to 3200–3000 yr BP precisely (Zhang et al., 2011). These show that the 3200–3000 yr BP floods were widespread hydrological phenomena over the middle Yellow River basin. It is therefore inferred that the monsoonal shift and the resultant climatic variability at about 3100 yr BP are responsible for the occurrence of the intensive rainstorms and extraordinary floods in this semi-arid and subhumid region.

In the middle Yellow River basin and the adjacent semi-arid and arid regions, significant climatic drying and cooling were documented also at around 3100 yr BP by multiproxy studies of the lake sediments (Chen et al., 2003; Peng et al., 2005; Shi et al., 1992; Sun and Zhao, 1991; Xiao et al., 2004, 2009). This episode was the demise and eventual collapse of the Shang dynasty (3550–3000 yr BP) in China’s Bronze Age that occupied the middle and lower reaches of the Yellow River. During this time, frequent droughts, intensified dust storms, drying-up of rivers, harvest failures, great famines, plague and social upheavals were recorded in many ancient Chinese literature (Wang and Wang, 1987). The climate-related deterioration of the land and water resources destroyed the dry-farming based economy and resulted in a drastic social change finally. These disasters are obviously related to the monsoonal shift and climatic aridity around 3100 yr BP (Huang and Su, 2009). The synchronology of the flooding episode in the Weihe River basin and the literal records of climatic aridity over the entire Yellow River basin suggest that climate was very dry when extreme rainstorms and the resultant floods occurred. These mean that both the extraordinary floods and severe droughts were part of the climatic variability during the monsoonal shift at about 3100 yr BP over the Yellow River basin. It suggests that intensive rainstorms and extreme flooding were not necessarily associated with humid conditions over the semi-arid and subhumid regions.

Conclusions

Highly unstable and variable climate conditions are usually responsible for the incidence of hydrological events. Extraordinary floods are often associated with unique rainstorms and atmospheric circulation patterns in connection with climatic change. The hydrological system in the semi-arid and subhumid regions within the Yellow River basin is very sensitive to monsoonal climatic change. Global warming might induce increased social vulnerability to flood risks in these regions. The studies on the Holocene palaeoflood events and the associated climatic patterns will not only increase our understanding of the interactions between fluvial environment and climatic change, but also provide information that is useful for interpretation and calibration of the modern short-term gauged records.

Palaeoflood slackwater deposits were identified at several sites along the upper reaches of the Weihe River. They are the geological records of the past extreme floods that really occurred. The minimum peak discharge was estimated to between 22 560 and 25 960 m³/s with palaehydrological method. It is similar to the flood magnitude (23 460–25 480 m³/s) as that reconstructed at the DJP site in the upper stream. These extraordinary flood events were dated to between 3200 and 3000 yr BP and just coincided with the ending of the mid-Holocene climatic optimum. On the mainstream and other tributary rivers of the Yellow River, extraordinary flood events of the same age were also documented by palaehydrological investigations. During this episode, a monsoonal shift resulted in climatic aridity and increased dust storms and dust falls, as well as pedogenic regression over the middle Yellow River basin. The facts of climatic aridity and the occurrence of extraordinary floods suggest that climate was highly unstable and variable in the region. Climatic variability resulted in an increased frequency of extreme hydroclimatic events in the semi-arid and subhumid regions.

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