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Reconstruction of flood events over the last 150 years in the lower reaches of the Changjiang River

ZHAN Wang[1], YANG ShouYe[1*], LIU XiaoLi[1], LI JianWei[1] & CHOI ManSik[2]

[1] *State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China;*
[2] *Division of Earth and Environmental Sciences, Chungnam National University, Daejeon, 305–764, Republic of Korea*

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The reconstruction of paleofloods in the Holocene has become one research highlight for the present global change study. The core sediments from one newly-emerged bar in the lower Changjiang River (Yangtze River) mainstream were collected for grain size and organic elemental measurements, with aim to reconstruct the flood events over the past 150 years. Major grain size parameters such as mean grain size, probability cumulative curve and C-M diagram of the core sediments clearly indicate the flood event deposition. Furthermore, the TOC/TN ratios in the sediments can indicate flood events considering that during the flash floods, strong surface erosion in the upper and lower reaches of the Changjiang River can transport a large amount of undecomposed plant debris and organic components with relatively low C/N ratios into the lower mainstream. Based on ^{210}Pb dating and sedimentary geochemical results, the research profile recorded several large floods happened from 1850 to 1954, which agrees well with the historical documents and hydrological observations. Interesting to note that the flood events since the 1960s cannot be distinctly recognized on the basis of sediment grain size and organic elemental compositions of the profile, which mainly reflects the intensive human activities over the last fifty years, especially condense dam construction, have significantly changed the characters of suspended sediment into the lower mainstream.

flood events, Changjiang River, sediment, grain-size parameters, organic elements

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As the largest river in China, the Changjiang River (Yangtze River) has been famous for flood catastrophes happening frequently in its large drainage basin over the last century, which has significantly affected the socioeconomic development and human being's life. In the past decades, global warming results in regional variability of rainfall in China and thus, causes serious floods in the large drainage basins [1]. According to the statistics of flood disasters in seven large river basins from 1840 to 1992, the floods happened mostly in the Changjiang River basin, reaching 76 times in total, more frequent than in other basins such as the Huanghe River (Yellow River) [2]. The paleoflood research has been carried out all over the world, among which the hydrologic study of paleofloods in many rivers in USA can be dated back to 1938 and even earlier [3]. Over the last decade, the reconstruction of paleoflood events has become a hot topic for global change research, and also received broad attention in China. Previous studies reconstructed the Holocene paleofloods in the upper and middle Changjiang and Huanghe River basins, using various methods such as archaeology and Quaternary geology, and achieved many important findings [4–8]. Nevertheless, the high-resolution reconstruction of paleoflood events in the lower reaches of the Changjiang River close to the river mouth has never been done thus far, especially using sedimentological and organic geochemical methods. In the present study a profile was selected from a newly emerging bar in the mainstream of the lower reaches of Changjiang River for sedimentological and organic geochemical study. The main aim is to find the proxy of flooded sediments in the profile, primarily

*Corresponding author (email: syyang@tongji.edu.cn)

based on grain size and organic elemental compositions, and then to reconstruct the flood events in the upper-middle Changjiang River basin over the past 150 years.

1 Sedimentary characteristics of the profile and research methods

The investigated profile (LGZ) is located in a newly-emerging bar in of the lower Changjiang River mainstream in Yangzhong County, Jiangsu Province. The geographic coordinate of the bar is 32°18.393°N, 119°45.218°E, with the elevation of 7.2 m. According to the historical documents of *Yangzhong County Annals*, the bar was subaerially exposed in the Qing Dynasty (1862–1874). As the local people said, it has occupied a large land area before the 1950s and since then has steadily grown till today, reaching an area of about 8 km^2 nowadays. At moment few farmers and fishermen live in the bar without any industrial activities, which makes it remain a natural depositional environment in the lower reaches of the Changjiang River and suitable for the study of paleoenvironmental reconstruction. In March 2008, we excavated the LGZ profile, with the depth of 2.0 m, and collected a total of 101 samples at the sampling interval of 1–2 cm. Reed roots occur often at the top 20 cm of the profile. The profile sediments primarily consist of silty clay and show distinct variations in color and grain size. The upper 70 cm is composed of brown-yellowish soil, and 75–112 cm is brown-reddish clayey to silty sediments with ubiquitous Fe-Mn concretions and stains; the lower part from 124 cm to the bottom is olive and grey clayey sediments, interbedding with several silty and very fine sandy layers of variable thickness (Figure 1).

In order to estimate the local depositional rate and chronology of the profile, a 1.49-m-long core was taken near the LGZ profile, subsampled and respectively sent to Nanjing University and Chungnam University in Republic of Korea for ^{210}Pb dating measurements using α- and γ-counting methods. The measured accumulation rate is about 0.97 cm/a, and then was corrected by the compaction ratio inside the sampling PVC tube which is related to water content of the sediment and sorting coefficient [9]. The average water content is about 25% and the sorting coefficient is 1.75. Accordingly, the compaction ratio is estimated to be about 1.39 according to the equation proposed by Wang et al. [9]. After correcting the compaction ratio, the actual accumulation rate of this profile measured by the ^{210}Pb method averages about 1.34 cm/a.

Sediment grain size was analyzed by the laser size analyzer (Coulter LS230) at the State Key Laboratory of Marine Geology in Tongji University, after processing the samples with 10% H_2O_2 and 1 mol/L HCl to remove organic matter and carbonate, respectively. The measurement error is ⩽±1%. The organic elements of carbonate-free samples were measured on split subsamples treated with 10% HCl, washed and dried. Total organic carbon (TOC) and total nitrogen (TN) were analyzed using a CHNS Analyzer (EA1110, Carlo-Erba). For monitoring the analytic quality, the repetitive measurements of standards of Crystine and Sulphanilamide and unknown samples yielded a precision of about 0.5%.

2 Sediment grain-size and organic elemental compositions in LGZ profile

The sediment grain-size and organic elemental contents in LGZ Profile are shown in Figure 1.

The LGZ profile sediments are dominated by silty clay and clayey silt. The median diameter (*Md*), as a main grain-size parameter of sediment, indicates central tendency of frequency distribution of sediment diameter, and reflects

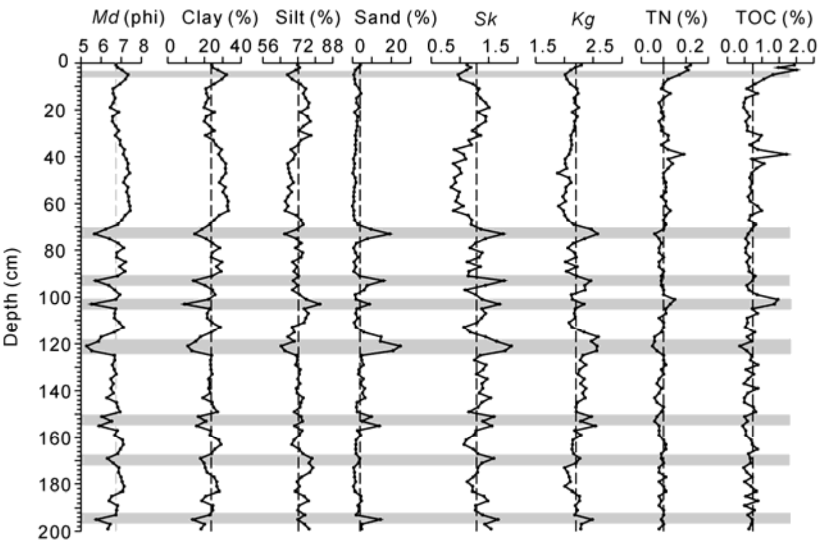

Figure 1 Downcore variations of sediment grain-size and organic elemental compositions in the LGZ profile. The gray bars indicate peak values or large variations.

the average energy of ambient environment, in which particles transport and deposit. The *Md* in the profile varies between 5.3 and 7.4 *Φ* and the standard deviation (*SD*) is about 1.5–2.0, suggesting poor sorting and large variation of sediment grain size. The silt and clay contents average 64%–82% and 10%–35% respectively, while the sand content is mostly less than 5%. Nevertheless, several sandy layers occur in the profile, with the sand contents being up to about 25%. Overall, the variation of sediment grain size in the profile presents two parts (Figure 1). In the upper part (0–70 cm), the grain size becomes coarser towards the top, shown as decreasing clay but increasing silt contents, while the sand contents remain stable. In the lower part (70–200 cm), the sediment grain size yields a large variation, with peak sand contents at depths of 73, 93, 95, 103, 120 and 155 cm. Skewness (*Sk*) and kurtosis (*Kg*) also change significantly in these layers (Figure 1).

Probability cumulative curves can reflect the distribution characteristics of sediment grain size and the mode of particle transport. The mode of particle movement is closely related to certain sedimentary environment. Therefore, probability cumulative curves of sediment grain size are widely used to study sedimentary dynamic processes and environments. The probability cumulative curves of LGZ profile reveal that several sandy layers (e.g. 73, 119, 155 cm) have obvious four- or five-section patterns (Figure 2). The coarsest fraction indicates rolling mass (0–2 *Φ*), with large slopes and good sorting, indicating a sudden increase in hydrodynamic environment. The saltation mass has a dividing point (about 3 *Φ*) between erosion and reflux. A small difference of *SD* and *Md* between the two segments of the saltation fraction, reflects a slight change in hydrodynamics. The suspension mass is overall gentle, accounting for 50% and even more of the whole cumulative percent. The silty and clayey sediments in the profile show typical three-section curves features of the fluvial deposition [10], lacking rolling mass and suspension mass accounting for 70%–80% or more.

Depositional environments can be identified by the C-M patterns. C represents the coarsest 1-percentile, which indicates the upper limit of competence of a depositional agent, provided that a full range of sizes was available for particle transport. M represents the median 50 percentile of grain size, which reflects the average energy of ambient agent [10]. C-M patterns not only reflect the transport and depositional mechanisms of sediments as a whole, but also indicate the movement way of coarse components. Therefore, it has been widely used to reconstruct modern and ancient depositional environments, especially for the sedimentary environment of a typical traction current. The distribution ranges of the sandy layers and other non-sandy layers of the profile are obviously different in the C-M pattern. The non-sandy sediments are plotted together and nearly parallel to the limit C=M, which suggests that they are characterized by uniform suspension in static water of a traction current, reflecting the typical depositional environment in floodplain. The sandy sediments are relatively loosely clustered, uniform suspension under a strong and mixed depositional environment, probably diagnostic of flood deposition (Figure 3).

The contents of TOC and TN in the profile sediment are 0.30%–2.34% and 0.04%–0.23% respectively with small variations (Figure 1), which basically fall in the range of those in the Changjiang River sediments [11]. The TN contents are positively correlated with TOC (r^2=0.83). It is noteworthy that TOC and TN increase upward significantly in the top 10 cm and arrive at the maximum values at top. We interpret the abrupt increase of TOC and TN contents at top may be due to the increasing input of organic pollutants from the drainage basin into the Changjiang River with intensive human activities over the past decades. Also, the

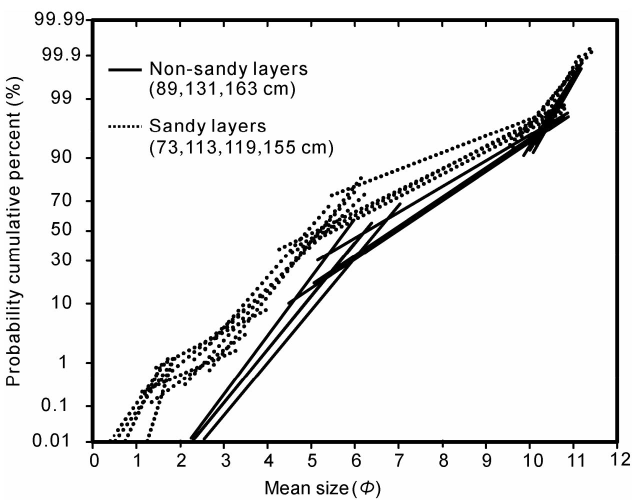

Figure 2 Probability cumulative percent plotted against mean grain size of the selected samples in the LGZ profile.

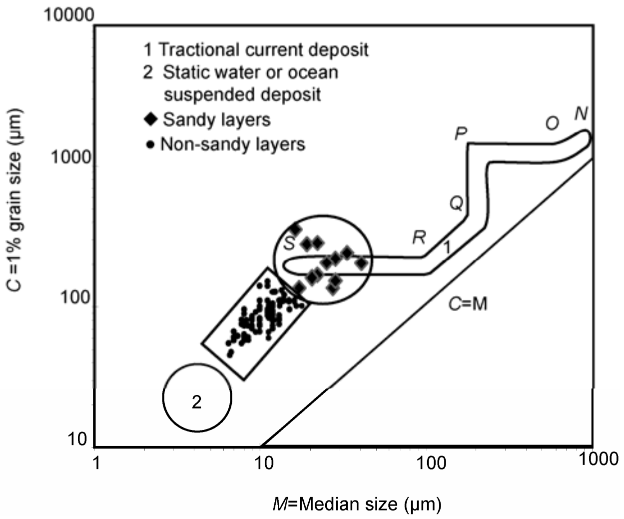

Figure 3 The C-M pattern of sediment grain size in the LGZ profile. *NO*, Rolling; *OP*, rolling and suspension; *PQ*, suspension and rolling; *QR*, graded suspension; *RS*, uniform suspension.

wide occurrence of reed roots in topsoil of the profile may cause the sharp jump of TOC and TN contents. The decomposition of plant roots and defoliation can provide organic matter to the soil [12,13].

3 Compositions of grain size and organic elements as indicators of flood events

Distribution characteristics of sediment grain size has been well used to identify modern and ancient flood deposition [14,15]. In the early period of flood happening, strong and significantly changing hydrodynamic environment causes rapid deposition of coarse particles with poor sorting. In contrast, the grain size becomes fine with good sorting during the period of reflux after flood peak because of the weak hydrodynamic environment and slow deposition. Therefore, flood deposition is characterized by cycle changes in sediment grain size which has peak values of size parameters, abrupt coarsening at the bottom and then gradual fining upward [16]. The major parameters of grain size in the LGZ profile below 70 cm appear several typical peak values of *Md*, clay and sand contents, and Sk. Each of these sandy layers has similar grain size patterns, showing abrupt jump of median size at the bottom and then fining upward (Figure 1), which suggests the typical deposition of flood events. The sandy layers in the profile have obvious four- or five-section cumulative curves. High proportion of rolling mass indicates a sudden increase of hydrodynamic conditions. The dividing point between erosion and reflux of the saltation mass is near 3Φ, much different from typical pattern of normal fluvial deposition (Figure 2). In the C-M pattern, the clear difference of size distributions between sandy and non-sandy sediment layers also suggests the strong and highly mixed hydrodynamic conditions (Figure 3). Based on the sediment grain size patterns, we infer that the sandy layers in middle and lower part of the research profile are flood deposition, which share similar probability cumulative curves of grain size with those of flood sediments happened in the Holocene at Zhongba in the middle reaches of the Changjiang River [5].

The contents of TOC and TN as well as TOC/TN ratios in sediments are mainly controlled by sources and degradation rate of organic matter, grain size and mineral compositions of sediments, and secondary changes after burial [17,18]. In general, clayey sediments contain more organic matters than sandy sediments do. The correlation coefficients between the contents of TOC or TN and *Md* are all below 0.1, suggesting that the compositions of organic matter in the LGZ profile sediments are not controlled by sediment grain size, and sources of organic matter are probably the primary control.

It is well known that C/N ratios vary mostly between 3 and 8 in fresh aquatic algae, but can reach 20 and even higher in terrestrial high plants. The rapid degradation of organic matter after burial, however, can reduce the C/N ratios significantly [17]. For example, the organic matter in the Changjiang River sediments mainly come from C3 plants in the drainage basin [11], but their C/N ratios are mostly below 10 [11,18]. The range of TOC/TN ratios in the LGZ profile is 5.3–10.8, with an average of 7.3, very closed to that in the floodplain sediments of the modern Changjiang. It implies that the sources of LGZ profile sediments are mainly from soil erosion in the upper and middle reaches of the Changjiang River, and thus, the TOC/TN ratios of the profile sediments accord with those of the topsoil and weathered sediments in whole basin. The TOC/TN ratios in the LGZ profile exhibit a large fluctuation. The peak values appear in the top 10 cm layer and lower ratios in the 10–25 cm layer (Figure 4). The most significant change is the marked peak values of TOC/TN in the middle and lower parts. At the depth of 120 cm, the TOC/TN ratio has the highest value of 10.8 (Figure 4). Poor correlation between TOC/TN and *Md* occurs in the upper 70 cm, but good correlation exists below 70 cm, especially in the section of 70–155 cm, showing higher TOC/TN ratios with grain size increasing (Figure 4).

During the flood period, especially flash flood, erosion of ground surface is enhanced. The flood runoff can carry a large volume of humic substance and incompletely degraded fresh organic detritus into rivers. The organic matter is transported with suspended particulate materials to downstream, and then deposit on floodplain and estuarine areas. As suggested by previous studies, sandy fluvial sediments enrich organic detritus, such as plant roots and debris [15,18,19]. The C/N ratios in fresh organic detritus and in-

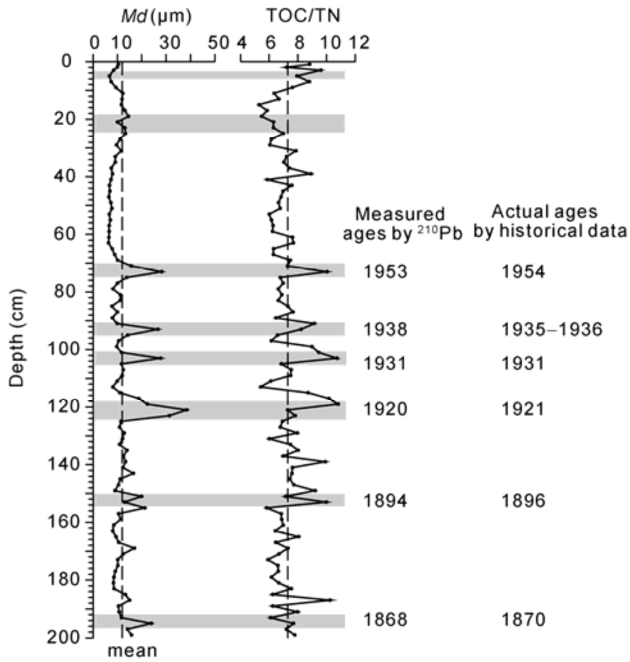

Figure 4 Reconstructing flood events over the last 150 years by the TOC/TN ratios and median grain size of the LGZ profile. The gray bars indicate the major variations of TOC/TN ratios and median size.

completely degraded humus are obviously higher than those in completely degraded organic matter in mature soil [18–20]. The study by Wu et al. [11] suggests that the C/N ratios in soils are much higher than in the suspended sediments from the mainstream and tributaries of the Changjiang River. In the highlands of the upper and middle Changjiang River basins, the floods in summer can transport a large volume of coarse-grained sediments, fresh organic detritus and incompletely degraded humus into the lower reaches. Therefore, both the TOC/TN and grain-size parameters in the middle and lower parts of the LGZ profile can indicate flood events because of their good correlation (Figure 4).

4 Reconstruction of flood events in the lower reaches of the Changjiang River over the past 150 years

Shi Yafeng et al. [21] compiled the flood events happened in the Changjiang River basin from 1840 to 1999 based on historical documents. According to the ^{210}Pb dating result that corrected by compression, the accumulation rate of LGZ profile averages 1.34 cm/a, representing the sedimentation in the mainstream of the lower reaches of the Changjiang River over the past 150 years. The compositions of grain size and TOC/TN ratios clearly reveal the remarkable flood events. The depositional ages of the peak values of *Md* and TOC/TN at the depths of 73 and 103 cm are 1953 and 1931 respectively, which correspond well with the catastrophic floods in the middle Changjiang River basin in 1954 and 1931. Extrapolating from this, the depositional ages of other sandy layers at 92, 118, 153 and 187 cm are respectively 1938, 1920, 1894 and 1868 (Figure 4), corresponding well with the extreme flood events in 1935–1936, 1921, 1896 and 1870 recorded in historical documents [21]. The differences of 2–3 years between some individual flood events and historical documents may be caused by analytic error of ^{210}Pb dating, and by the instability of fluvial environment as well. Obviously, this difference actually reflects the complexity of sedimentary environment in nature.

To test the reliability of the measured accumulation rate of 1.34 cm/a, we assumed that the peak values in the curves of *Md* and TOC/TN represented the major floods, and the 73 cm layer corresponds to the historical flood in 1954. Then, we recalculated the average depositional rate of LGZ profile is about 1.37 cm/a. Extrapolating from this, the rate of 1.36 cm/a for the peak value at 103 cm corresponds to the flood in 1931 and 187 cm to the flood in 1870. Considering the instability of floodplain environment and rapid deposition during floods, the calculated depositional rate of 1.36 cm/a is very close to the measured rate of 1.34 cm/a. This also proves that it is reliable to identify several major floods in the upper and middle Changjiang River basin since 1850 based on the compositions of sediment grain size and organic elements in the LGZ profile. Thus far, there have been few reports on the ^{210}Pb dating method used in floodplain (point bar, channel bar) environment. Depositional rates of floodplain environments are also rarely studied by domestic and international communities. In the present study, we selected a profile which is situated in the end of an elongated stable sandbar in the lower mainstream. The end of the sandbar is undergoing fast growth and represents the most stable depositional environment in the shoal, much weaker than in the bar head and both sides. Even in flood periods there is no obvious erosion in the end of the shoal and thus, the average depositional rate of the profile remains relatively stable. Since the sandbar exposed to surface about one hundred years ago, the sedimentary strata near the profile mainly reflects the changes of water level in the lower Changjiang River mainstream, rather than the lateral migration of the mainstream banks or erosion and accumulation in the floodplain.

It is noteworthy that grain size parameters such as *Md* and TOC/TN peaks exhibit consistent variations below 70 cm in the profile, but poor correlation above the 70 cm (Figures 1 and 4). According to observation data in hydrological gauging stations, 9 large floods in the Changjiang River basin occurred during the period of 1954–1990, which implies that at least 9 peak values of grain size and organic elemental compositions corresponding to the floods should be recorded in the upper 70 cm of the profile. Nevertheless, none of these is shown in these curves (Figures 1 and 4). Especially, the catastrophic flood in 1998 cannot be identified by the values of TOC/TN and *Md*, without significant increase at the corresponding depth of about 12–13 cm calculated by the deposition rate of 1.34 cm/a. The elevation of the profile surface is estimated to be about 7.2 m at the sampling in March, 2008. According to the local hydrological data, the water level of the Changjiang River mainstream at Yangzhong was as high as 7.53 m on July 14, 1991. While on August 1, 1998, the historical highest water level of about 8.04 m was documented. Both high water levels during the floods exceed the elevation of the profile surface, suggesting that the studied profile should be certainly flooded at those times. Accordingly, the floods in the Changjiang River basin over the recent 50 years should be recorded in the profile.

Poor correlations between grain size and TOC/TN in the upper 70 cm may be caused by two reasons. One is that the reed roots widely distributed in the upper sediments may alter the compositions of grain size and organic elements inherited from the sediments sources. Another more likely reason is that since 1950–1960 (equivalent to the depth of about 70 cm), human activities in the whole Changjiang River basin have significantly altered natural settings [22,23]. The sources and composition of suspended sediments and particulate organic matter transported by the Changjiang River into the sea have been unlike the nature state of 50 years ago. According to the observations of runoff and sediment load at Datong gauging station, the Changjiang River runoff since 1953 has changed little, whereas the sediment flux and concentration have continuously decreased [24]. In particular, a large number of reservoirs with different capacities and sizes were constructed in the Changjiang River basin since the 1960s. Most coarse-grained sediments transported by rivers are trapped in the reservoirs, which might have significantly changed the compositions of grain size and organic matter of the suspended matter. Taking the Three Gorges Reservoir for example, after impoundment in 2003–2005, the median sizes of suspended sediments observed in the main hydrological stations (Cuntan, Yichang, Hankou and Datong Stations) are significantly lower than the multi-year average as well as the measured value in 2002. This clearly implies that the impoundment of the Three Gorges Reservoir retains a large volume river sediments, especially the coarse-grained sediments in the reservoir area. The less-turbid water released from the Three Gorges Dam cause serious erosion in the mainstream channel between Yichang and Shashi. The eroded coarse-grained sediments gradually settled again in the channel between Shashi and Hankou with the declining channel gradient and river flow, causing the grain size of suspended sediments in the downstream Hankou to decrease significantly [25]. Therefore, It is difficult to apply the compositions of sediment grain size and organic elements in the lower reaches of the Changjiang River to reliably reflecting the large flood events over the past 50 years because of the intensive dam constructions in the drainage basins.

5 Conclusions

The sediments of LGZ profile taken from a sandbar in the lower Changjiang River mainstream at Yangzhong consist primarily of silty clay and clayey silt, and are poorly sorted. The grain size in the upper 70 cm sediments shows the variation from coarsening to fining towards the top. Several sand levels with peak values of grain size parameters are observed below 70 cm. The *Md* and sand content rapidly increase, and skewness and kurtosis also change significantly in these layers. The probability cumulative curves and C-M pattern of sediment grain size clearly reveal that the non-sandy sediments were transported in suspension and deposited under a normal fluvial environment, whereas the sandy layers have obvious four- or five-section probability cumulative curves. The high proportion of rolling mass indicates the suddenly increased hydrodynamic conditions during flood events. The characteristics of sediment grain size of the flood deposits in the studied profile are almost the same as that in the middle reaches of the Changjiang River.

The compositions of organic elements in the profile sediments overall fall within the range of the suspended particulate and floodplain sediments of the modern Changjiang River, suggestive of similar sources of organic matter. The TOC/TN ratio and *Md* have a high correlation below 70 cm in the profile, both indicating the flood deposition. During the large floods, strong erosion of topsoil can carry a large number of coarse-grained sediments and non-degraded organic debris into the rivers, resulting in coarse-grain size and high TOC/TN ratio. According to the measured ^{210}Pb accumulation rate, the compositions of sediment grain size and organic elements in the LGZ profile clearly record the major flood events in the Changjiang River mainstream during the period of 1850–1954. The reconstructed large floods in this study correspond well with the historical documents and hydrographic observation data. However, since the 1960s, due to the intensive human activities and constructions of reservoirs in the Changjiang River basin, the sediment flux and concentration in the Changjiang River have been continuously decreased because of the trapping effect. The compositions of grain size and organic elements of the sediments into the estuary have also significantly changed from the previous nature state, which makes it difficult to identify flood events over the past 50 years in the lower reaches.

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