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A Dam Construction Event Recorded by High-Resolution Sedimentary Grain Size in an Outflow-Controlled Lake (Hulun Lake, China)

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Abstract: The distribution of sediment grain size can record past environmental conditions and human activity. In this study, radioisotope of ^{210}Pb and ^{137}Cs and a grain size of a 41 cm core in Hulun Lake were applied to reconstruct the high-resolution sedimentation history. The profiles of the grain size of the lake sediments show that silt (4–63 μm) was the largest contribution with an average content of 84.05%, and the second largest contribution was sand (>63 μm) with an average content of 15.68%. The median grain size and the mean grain size in the whole sediment core was 22.39 μm and 36.85 μm, respectively. Correlations of the sedimentological variables with instrumental measurements were also analyzed. The peak–trough value of the mean grain size of the sediments in Hulun Lake can reflect the magnitude of rainfall intensity and river discharge. The clay and silt contents at a depth of approximately 32–38 cm was different from other depths throughout the core, which showed continuous maxima with an average content of 0.35% and 94.08%. These changes in grain size correspond to the period of dam construction in 1963–1970. Therefore, the sediment grain size of Hulun Lake effectively recorded the dam-building activity.

Keywords: sedimentary grain size; dam construction; precipitation; paleoenvironmental reconstruction; Hulun Lake

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1. Introduction

To better understand past climatic and environmental changes beyond the available short instrumental record, a high-resolution geological archive of lake sediment can provide important clues [1–4]. In addition, detailed reconstructions of the history of environmental changes may improve our understanding of potential future environmental changes.

Lake sediment grain size has been used widely for paleoenvironmental reconstructions, such as of regional climate change and lake level fluctuations [5], dust storms [6], and human activities [7], since it provides important information about the depositional environmental, and migration processes. However, the interpretation of past environmental conditions from sediment core grain size is difficult because of the complexity of sediment processes [8]. Numerous studies have shown that the characteristics of sediment grain size have different interpretations on different time scales [9]. For long-term scales and low resolution (10^2 a or 10^3 a) studies, sediment grain size indicates the history of changes in lake levels, which can be interpreted as coarser grains being easily transported and deposited because of a fall in the lake level and the shrinkage of lake area, while finer grains are difficult to deposit because of the strong hydraulic disturbance at low lake levels during dry periods. The opposite can be illustrated during wet periods. However, for short time scales and high resolution (a or 10 a) studies, large coarse sediment grain sizes indicate wet years with high regional precipitation, because the increased regional precipitation causes increases in the erosion intensity of the watershed. In contrast, a decrease in coarse grain size and an increase in fine grain size indicates drought years with low rainfall [7,10].

In addition, the distribution of sediment grain size in the sediment core can also reflect information on recent human activity, such as artificial dam construction, water conservancy projects, and land use changes in the surrounding lake watershed [11,12]. Previous studies have shown that artificial dam construction has a significant impact on the deposition and transport of grains in water bodies [11,13]. The rivers entering the lake usually carry grains, including coarse and fine grains. Some of the relatively fine grains and a smaller amount of the large grains could be carried out with the outflow, and the remaining coarse and fine grains are deposited at the bottom of the lake. However, only a small amount of the fine grains could be carried out with the outflow, and most of the coarse grains and the remaining fine grains were deposited at the bottom of the lake when the dam was built due to the decreasing sediment transport capacity, which resulted in a relatively large proportion of the fine grains being deposited at the bottom at this time. Therefore, the palaeoenvironmental implications of grain size cannot be routinely applied to palaeolimnological studies, and credible conclusions can be obtained only after comprehensively analyzing the historical meteorological observations, process-related information, and the extent of all factors in sedimentary records.

Hulun Lake, situated in a semiarid area in the northeastern part of Inner Mongolia, China, is an important water body maintaining the grassland ecological environment of the lake basin. Currently, the lake faces a serious ecological crisis, namely, eutrophication, a shrinking area, and a gradual impact on the ecological function in the lake ecosystem [14]. However, few studies on the environmental changes of Hulun Lake and its influencing factors have been performed due to insufficient historical instrumental data, and difficulties in conducting field experiments because of the cold weather and inconvenient traffic.

A continuous sediment record could preserve in Hulun Lake because there was no historic dredging. Therefore, the reconstruction and interpretation of the proxies archived in the lake sediment provide a feasible approach for obtaining a better understanding of the past climatic and environmental changes in the lake. Previous studies for the reconstruction of sediment proxy records in Hulun Lake have mainly focused on topics with a long time scale and low resolution. Hu [15] found that muddy sediments deposited during a high-water level period (corresponding to a humid climate) have comparatively high κ (magnetic susceptibility) values in Hulun Lake sediment. In contrast, the sandy sediments deposited during the low-water level period (corresponding to an arid climate) have low κ values. Wen [16] described changes in the vegetation and climate of the East Asian monsoon margin during the Holocene, applied pollen-assemblage data from a sediment core of Hulun Lake, and revealed that the changes in the monsoon precipitation on the millennial to centennial scales are related to ocean–atmosphere interactions in the tropical Pacific. Xiao [17] used a lognormal distribution function fitting method of sediment grain size distributions, and the results indicated that the lake levels fluctuated in response to the intensity of monsoonal precipitation. Higher percentages of nearshore components accompanied by more sand-fraction proportions and coarser median grain sizes reflect lower lake stands.

Little research has been conducted on lake sediment with high resolution to determine the past deposition processes and environmental changes in Hulun Lake. In addition, previous findings on the interpretation of proxies of lake sediment from Hulun Lake were applied on a long time scale, and with low resolution [15–17]; it is necessary to advance the determination of whether the results can be used for the reconstruction of lake environments on short time scales.

The objective of this study was to interpret the proxies of sediment grain size in Hulun Lake. In addition, we combined the use of radioisotope analyses of ^{210}Pb and ^{137}Cs with grain size analyses to reconstruct the high-resolution sedimentation history and interpret the lake deposition process and paleoenvironment. Furthermore, the correlation of the sedimentological variables with instrumental measurements (local precipitation and lake inflow discharge) were analyzed. The results of the proxy interpretation provide insights into the past and potential future environmental changes in and around the lake.

2. Materials and Methods

2.1. Study Area

Hulun Lake (48°31′–49°20′ N, 116°58′–117°48′ E), located in the northeast part of Inner Mongolia, China (Figure 1), is the largest lake in northern China, with a maximum surface area of 2339 km^2 and a maximum water depth of 8 m [18]. The lake adjoins the Greater Khingan Mountains and the Mongolian Plateau, which is a grassland-type lake wetland ecosystem with biodiversity and ecological functions found in cold and arid regions across the world. There are two rivers that control the main input sources of Hulun Lake, in which the Kherlen River is from Mongolia and the Urshen River is derived from Beier Lake. Another artificial river named the Xinkai River lies in the northern part of the lake and is an intermittent river that flows out when the lake elevation exceeds 543.4 m.a.s.l. According to records, this artificial river was built with the approval of the government due to the rising lake water level threatening the production of coal mines downstream. A dam was constructed to block the water outlet from the artificial river started build on 15 June 1965 to drained outward through the river on 8 September 1971 [18]. The lake water could not be discharged because the dam blocked the outlet of the river during the construction stage of the project, so that the lake became a closed lake. In addition, the water level was high during this period.

Since the water level has declined sharply in the last 10 years, Hulun Lake has become a closed lake without an outlet. The study area is located in a semiarid area, and the climate around the Hulun Lake basin is controlled by westerly winds and the East Asian monsoon. Its mean annual precipitation is 247–319 mm, most of which occurs in summer. The mean annual air temperature is 0.3 °C, and the mean annual evaporation reaches 1400–1900 mm, which is 5–6 times the mean annual precipitation [19].

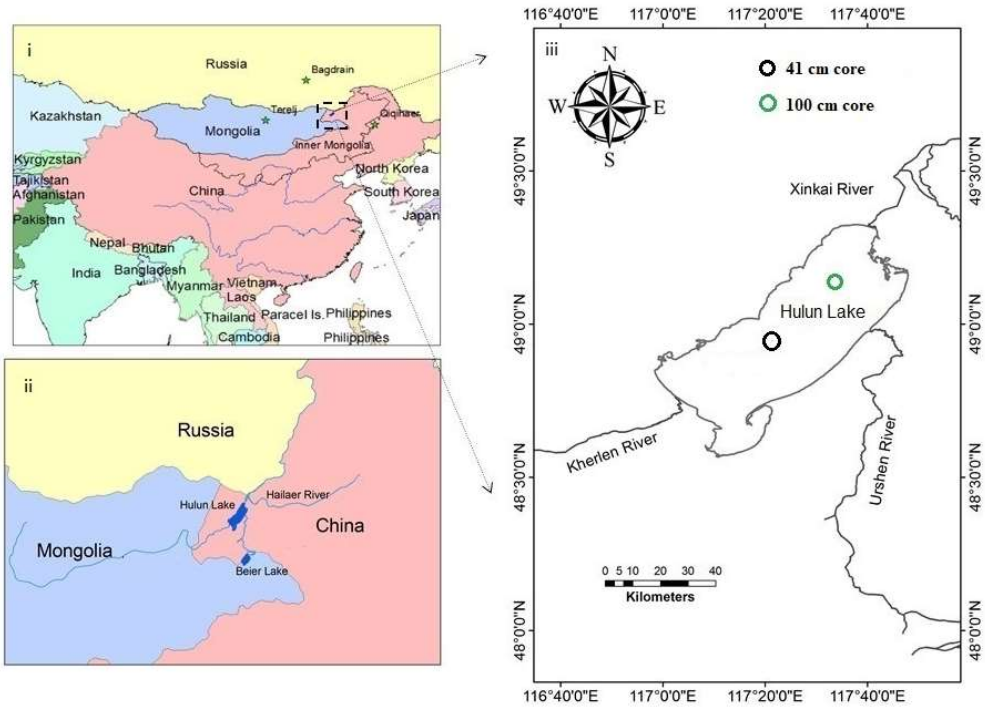

Figure 1. Location of study area: (**i**) study area on a country-scale map; (**ii**) whole Hulun Lake basin; (**iii**) core sampling site (black circle indicates the location of the 41 cm core of this study, while the green circle indicates the location of the 100 cm core sampled by Liang (2017) from the Inner Mongolia water environment group [20]).

2.2. Sampling

A 41 cm-long sediment core was obtained at the deepest site, with a 5.6 m water depth (Figure 2) in Hulun Lake, China, in July 2015 using a Glew Corer [21]. The core samples were sliced immediately in 1 cm intervals on board. Then, 41 subsamples were stored in sealed bags in an ice cooler and transferred to a refrigerator (<4 °C) after being transported to the laboratory.

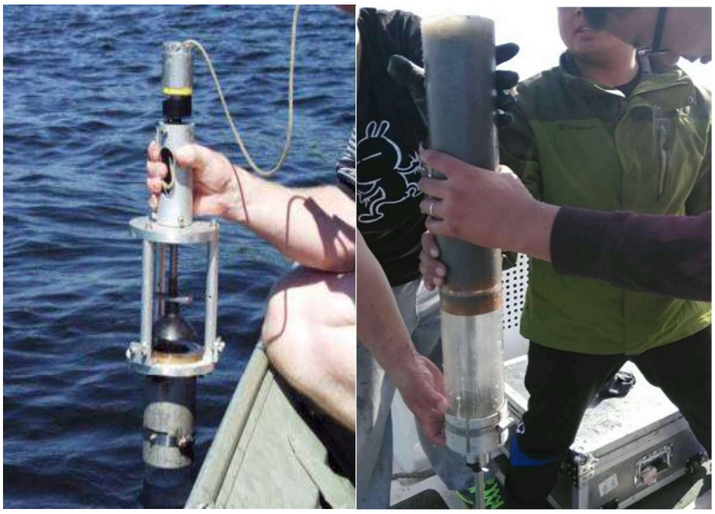

Figure 2. Sampling of sediment core in Hulun Lake.

To compare the results, another sediment core of Hulun Lake was employed as a referenced sample core (100 cm), which was sampled northeast of the core sampling site in this study in March 2015 by Liang (2017) from the environment group of Inner Mongolia Agricultural University Water [20] (Figure 1).

2.3. Experiments and Methods

2.3.1. Sediment Core Chronology

To determine the age of the sediment core, ^{137}Cs and ^{210}Pb chronologies were conducted by gamma spectrometry at the Nanjing Institute of Geography and Limnology Chinese Academy of Sciences. The profile of ^{210}Pb dating was calculated by the constant initial concentration model (CIC), which was described previously [22,23]. Based on the constant initial concentration model (CIC), the $^{210}Pb_{ex}$ activity C (Bq/g) in a layer at depth z' (cm) can be expressed as:

$$C = C_0 \cdot \exp\left(-\frac{\lambda}{S} Z'\right) \tag{1}$$

where C_0 (Bq/g) is the ^{210}Pbex activity at the top of the sediment core, λ is the ^{210}Pb radioactive decay constant, 0.031a^{-1}, and S is the sedimentation rate (cm year^{-1}).

Correspondingly, the sedimentary age (t) at a certain depth of the sediment can be calculated as:

$$t = \lambda^{-1} ln(C_0/C) = Z'/S \tag{2}$$

The radionuclide ^{210}Pb (half-life of 22.26 years) is a natural radioactive isotope derived from ^{238}U decay. The ^{238}U in the Earth's crust decays to ^{226}Ra and further to ^{222}Rn, which then escapes to the atmosphere and decays to ^{210}Pb. This fallout fraction derived from the atmosphere is termed "unsupported" or "excess" ^{210}Pb ($^{210}Pb_{ex}$). In addition, ^{210}Pb also forms within the sediment itself as a product of the decay of ^{238}U; this fraction in sediment is termed "supported" ^{210}Pb. $^{210}Pb_{ex}$ concentrations can be estimated by subtracting the ^{226}Ra-supported ^{210}Pb concentrations from the total ^{210}Pb concentrations [24,25].

The artificial nuclide ^{137}Cs (half-life of 30.17 years) is a fission product that was introduced into the environment as a result of atmospheric nuclear weapons tests conducted initially in the early 1950s. The highest ^{137}Cs activity may represent the period of maximum radionuclide fallout in the Northern Hemisphere, which is associated with the peak of atomic weapons testing in 1963 [26,27]. In summary, the onset (1950) and peak (1963) of the ^{137}Cs concentration in the sediment depth profile can be used as validation of ^{210}Pb dating results.

2.3.2. Grain Size of the Sediment Core

For pretreatment of the 41 sediment samples for grain size analysis, carbonates were removed by 10% HCl, and organic matter was removed by 30% H_2O_2. Following the HCl and H_2O_2 treatments, the samples were rinsed at least three times with deionized water. Furthermore, the samples were dispersed by adding 10 mL of 0.05 M sodium hexametaphosphate as the dispersing agent for treatment in an ultrasonic vibrator for 15 min. Finally, grain size analysis of the bulk sediment was carried out with a Mastersizer 2000 laser particle analyzer detecting a 0.02–2000 μm size range. Each sample was analyzed twice, and the relative error was no more than 2%. The grain size parameters were calculated following Folk and Ward (1957). The parameters of grain size (median size and mean size) and sediment component (%) of sand (>63 μm), silt (4–63 μm), and clay (<4 μm) were chosen for the analysis.

3. Results

3.1. Sediment Core Chronology

The experimental data for the concentrations of $^{210}Pb_{ex}$ in the Hulun Lake sediment core is plotted as a logarithmic profile versus depth in Figure 3. Using a least-squares weighted fit, a straight trend line can be achieved with a coefficient of determination (R^2) equal to 0.80 (Figure 3). Then, a mean sedimentation rate of approximately 0.72 cm year^{-1} of the core was calculated by Equation (1). Defining the surface sediment as the age of 2015, a chronology frame of the whole core was established, which responded to a 57 years age series from 1958 to 2015 (Figure 4). The experimental data for the concentrations of ^{137}Cs in the sediment at each depth interval is presented in Figure 4. The ^{137}Cs activity that reached a "peak" at 37 cm is associated with the 1963 fallout in Hulun Lake sediment, this mark fits very well with the age series based on ^{210}Pb data, which is at a depth of 37 cm, corresponding to 1963 (Figure 4).

3.2. Characteristics of the Profile Distribution of Sediment Grain Size in Hulun Lake

The results of the sediment grain component (clay, silt, and sand) of Hulun Lake are shown in Figure 5. The profiles of the grain size of the lake sediments show that silt was the component of grain with the largest contribution in the entire sediment core, with an average content of 84.05%, changing from 72.79% at 24 cm to 95.11% at 35 cm. The component with the second largest contribution was sand, with an average content of 15.68%, in which the maximum content of 27.00% was at 24 cm and the minimum content of 4.51% was at 35 cm of the sediment core. The clay content was the lowest of the components in the entire sediment core, with an average of 0.27%.

The contents of different grain sizes in lake sediment reflects different depositional environments. A high sand content may indicate a strong potentiality of sediment transport, while a high clay or silt content indicates a stable depositional environment and weak sediment transport capacity [28]. The sediment core of this study was collected from the center of the lake, where the potentiality of sediment transport is considered poor. The contents of clay and silt in the sediment were much higher than the contents of sand in this study, indicating that the sedimentary environment of the lake was relatively stable in the center of the lake due to the larger water depth and weak sediment transport capacity.

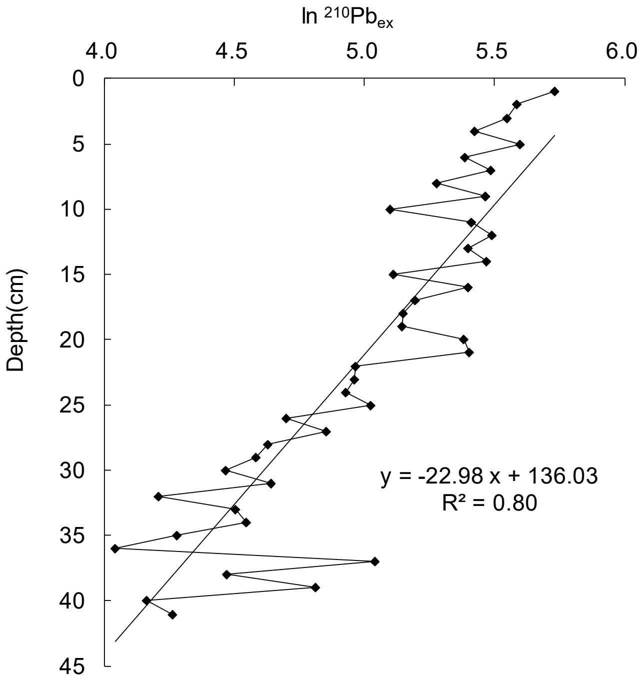

Figure 3. Log plots of ^{210}Pbex with its depth and its correlation in the sediment core.

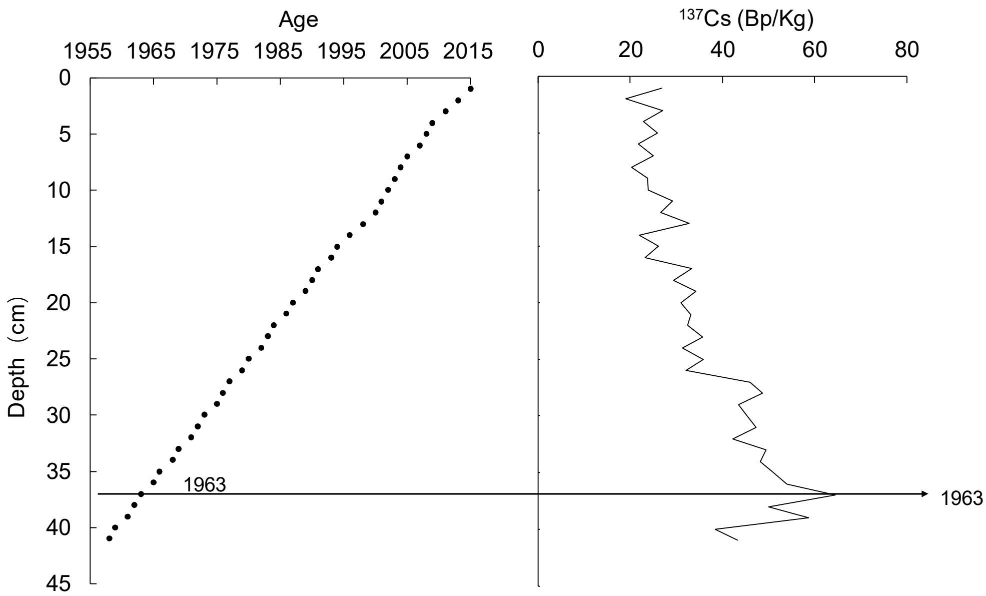

Figure 4. The age profiles determined by ^{210}Pb and ^{137}Cs.

In particular, it can be seen from the grain component profiles that the contents of the grain at a depth of approximately 32–38 cm was different from other depths throughout the core. The clay and silt contents showed continuous maxima with an average content of 0.35% and 94.08%, while the sand contents showed continuous minima with an average content of 5.57% (gray dotted box in Figure 5). These results may indicate that changes occurred in the sediment transport capacity or deposition patterns during this period.

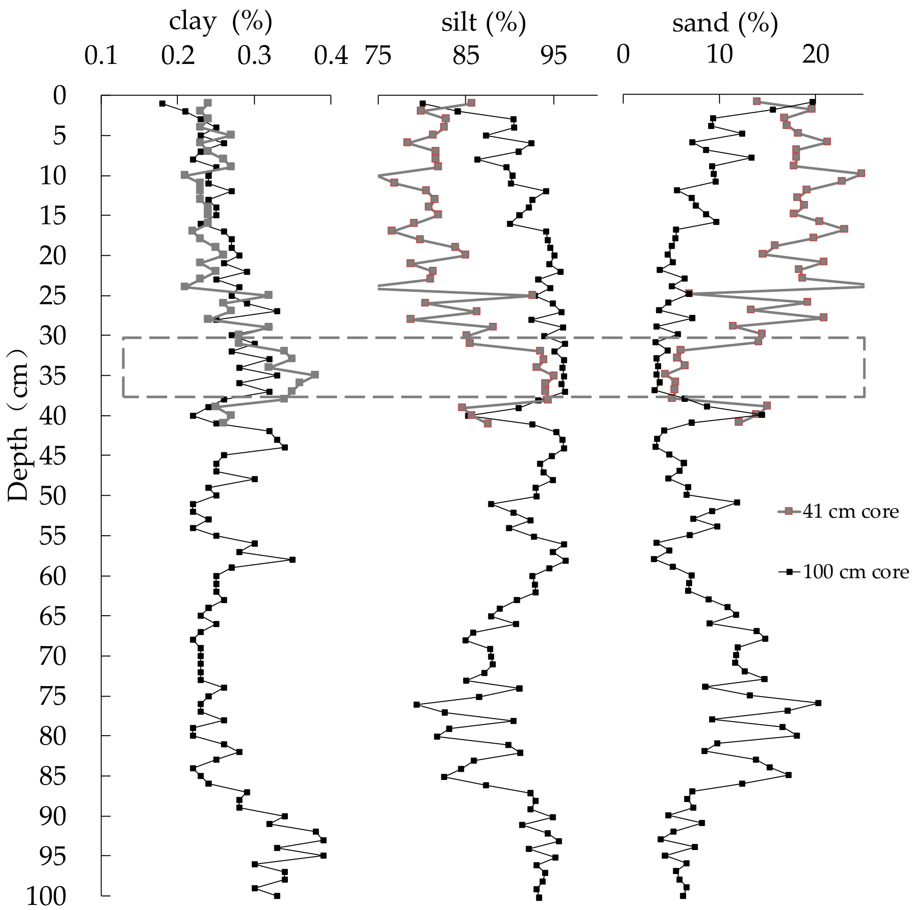

Figure 5. Profiles of the sediment grain components (clay, silt, sand; %) in the 41 core and 100 cm core of Hulun Lake.

To verify the reliability of the grain size proxy analysis results in this study, a referenced 100 cm core was employed for comparison. The grain size classification results of the 100 cm core are shown in Figure 5. In the entire sediment core profile, the average contents of clay, silt, and sand were 0.27%, 91.46%, and 8.27%, respectively. The grain size distribution of the 100 cm core varied widely, however, the characteristics of the grain size distribution at sediment depths of 31–37 cm was different from other depths throughout the core, in which the clay and silt contents showed continuous large values with an average content of 0.30% and 95.99%, while the sand contents showed continuous small values with an average contents of 3.70% (gray dotted box in Figure 5). This is consistent with the distribution characteristics in the range of 32–38 cm of the 41 cm core in this study, and shows that the sediment transport capacity or deposition process changed at this stage.

The profiles of the median and mean grain size of the 41 cm core are shown in Figure 6, which shows that the average value of the median grain size in the whole sediment core was 22.39 μm, with a maximum value of 30.91 μm at a depth of 24 cm and a minimum value of 14.81 μm at a depth of 35 cm. The average value of the mean grain size in the entire sediment core was 36.85 μm, with a maximum value of 51.71 μm at a depth of 24 cm and a minimum value of 22.64 μm at a depth of 35 cm. Compared to the median grain size, the mean grain size is larger than the median grain size, indicating that fine grains are the main component in the sediment of Hulun Lake. Similarly, the distribution of grain size at depths of 32–38 cm showed continuous minima with an average median size of 16.13 μm and an average mean size of 24.30 μm.

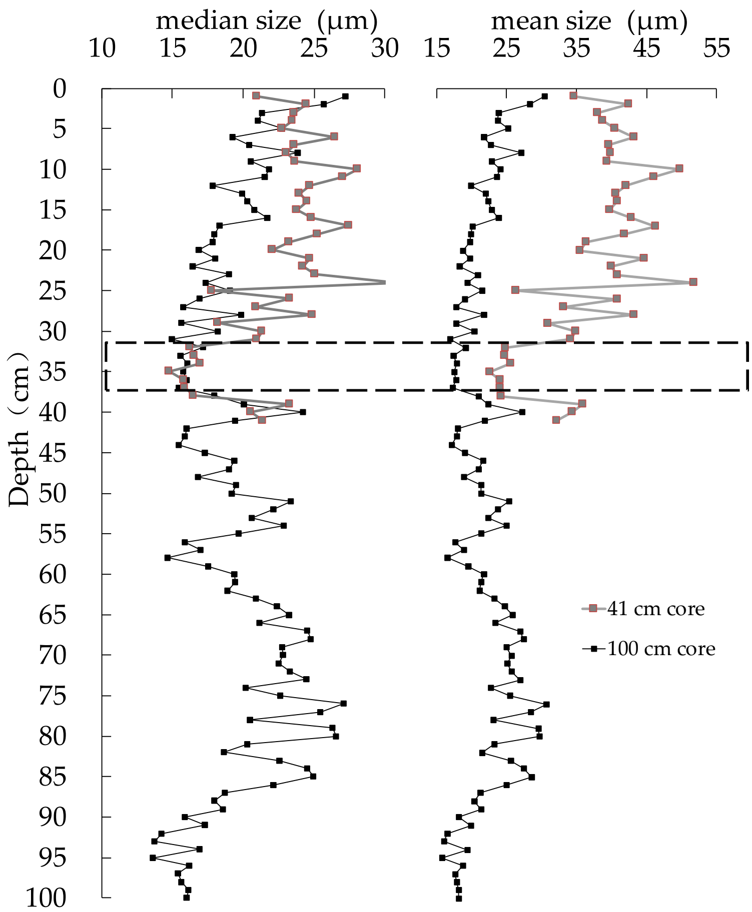

Figure 6. Profiles of the sediment grain parameters (median size and mean size) in the 41 core and 100 cm sediment core of Hulun Lake.

Compared to the grain size parameters of the 100 cm core (Figure 6), the mean and median grain sizes are smaller than those of the 41 cm core. This could be related to the sampling area of the core, where the sediment transport capacity and distance from the estuary are different. More studies are needed to further demonstrate the result. In addition, comparing the 100 cm core, it can be found that the characteristics of the mean and median grain size distributions at 31–37 cm are different, showing continuous minimum values throughout the core profiles. This is consistent with the distribution characteristics of the 41 cm core in this study.

4. Discussion

4.1. The Relationship between Precipitation and Sedimentary Grain Size

The grain size composition of lake sediments in arid and semiarid regions is mainly affected by the action of water and wind. As previously discussed, the distribution of the grain size of lake sediments at a short scale and high resolution is related to the variation in rainfall in the basin, which mainly depends on the intensity and quantity of the water source that feeds the lake. The impact of wind and waves may be relatively small due to the large lake surface and the increasing water depth. To explore the relationship between the sediment grain size of Hulun Lake and rainfall in the basin, the rainfall data from meteorological stations in the Hulun Lake basin during the past 60 years were compared to the changes in sediment grain size.

According to the chronology determined by the ^{210}Pb and ^{137}Cs of the 41 cm core, the mean grain size of the sediments and the hydrological elements (precipitation and river discharge) of the lake at the corresponding times are plotted in Figure 7. It should be noted here that the age of the sediment core was determined based on the calculated average deposition rate of 0.72 cm/a. However, the amount of debris entering the lake in different time periods and the depositional environment were different. Therefore, a discrepancy of one to two years between the hydrological element data and sediment chronology may have occurred, which was reported in another study [7].

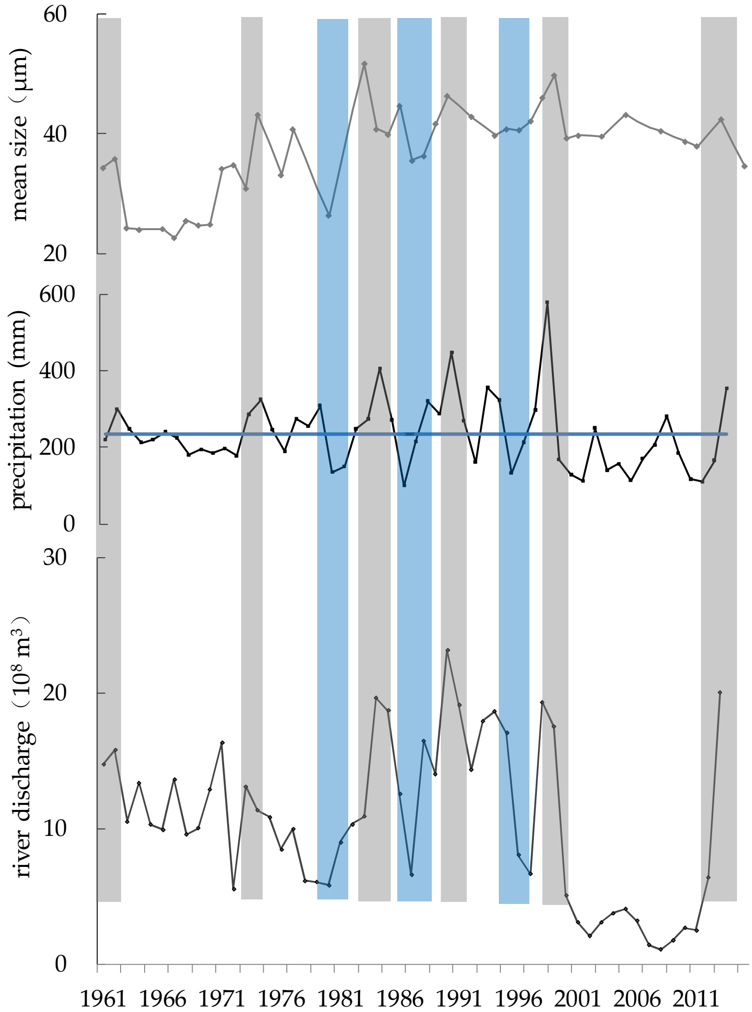

Figure 7. Comparisons the mean grain size in the lake sediment with the precipitation and river discharge records (gray boxes indicate the peaks of precipitation correspond to peaks of the mean grain size, blue boxes indicate the troughs in the precipitation correspond to the troughs of the mean grain size, blue horizontal line is the annual average precipitation).

The consistent tendency between precipitation and mean grain size varies in peaks and troughs, as shown in Figure 7. The peaks of precipitation in 1962, 1974, 1984, 1990, 1998, and 2013 correspond to peaks of the mean grain size of the sediment core in 1962, 1974, 1983, 1990, 1999, and 2013, respectively (gray boxes). Similarly, the troughs in the precipitation in 1980, 1986, and 1995 roughly correspond to the troughs of the mean grain size in 1980, 1987, and 1994, respectively (blue boxes). Although the peaks and troughs of the mean grain size in the sediments do not correspond fully to the peaks and troughs of precipitation, the errors are within the range of one to two years. As discussed above, the radionuclides were calculated using the average deposition rate, and a discrepancy of one to two years of the chronology is acceptable. Therefore, the peak–trough value of the mean grain size of the sediments in Hulun Lake can reflect the magnitude of rainfall intensity, indicating that the sediment grain size is affected by regional rainfall changes. In wet periods, the grains entering the lake water body from the ground may increase due to the increased erosion intensity on the ground with heavy rainfall. In addition, the coarse grains can also reach the center of the lake, resulting in strong sediment transport capacity. In contrast, the grains entering the lake water body from the ground may decrease due to low rainfall, and coarse grains may reach the center of the lake with difficulty because of insufficient sediment transport capacity. Therefore, the grain size of the sediment can reflect the amount of past rainfall in the lake basin, and then the past climatic conditions can be interpreted using the lake sediment.

4.2. The Relationship between River Discharge and Sedimentary Grain Size

Similarly, comparing the river discharge over the past 50 years to the changes in mean grain size indicates that the changes in the peak and trough values are similar to the corresponding relationship between precipitation and mean grain size. As shown in Figure 7, the peak values of river discharge in 1962, 1973, 1984, 1990, 1998, and 2013 correspond to the peak values of the mean grain size of sediment cores in 1962, 1974, 1984, 1990, 1998, and 2013, respectively (gray box). Similarly, the trough of river discharge in 1980, 1987, and 1996 corresponds to the valleys of the mean grain size of the sediment cores in 1980, 1987, and 1994, respectively (blue box). This is mainly because the river discharge in the Hulun Lake basin is related to rainfall, which determines the amount of river discharge. Therefore, the change in sediment grain size in Hulun Lake can also indicate the amount of river discharge and allows to interpretation of past climatic conditions.

4.3. A Dam Construction Event Recorded by Sedimentary Grain Size

The stratigraphic distribution of the grain size characteristics of Hulun Lake sediment shows that intervals between 32 and 38 cm are different from other depths, continuously presenting the minimum value in the whole core. As shown in Figure 7, the precipitation and river discharge in this period are nearly equivalent to the annual average precipitation and average river discharge, but the changes in the mean grain size of the sediment do not correspond to the precipitation and river discharge here. Therefore, the different changes in grain size distribution in this period may be controlled by factors other than the change in hydrological conditions. In addition, the distribution characteristics of the grain size parameters of the 100 cm core northwest of the lake also continued to show the minimum values in the whole core at the same depth, indicating that the changes in these two cores at 32–38 cm were affected by the same factor.

The changes in grain size were found at a depth of approximately 32–38 cm, which corresponds to the period of approximately 1963–1970. During this period, the dam was built to block the water outlet from the lake. Construction of the dam may have significantly affected the sedimentation processes in Hulun Lake. In order to demonstrate the difference in grain size distribution between the lake with and without a dam, the sediment grain size frequency curves at 32–38 cm and other depths were selected for comparison, as shown in Figure 8. The distribution of the 32–38 cm sedimentary section during the period when the dam was constructed was different, and its peak appeared earlier than at other sedimentary depths, indicating that the part occupied by fine grains increased. This result is consistent with the previous findings proposed by Nahm [7], highlighting that large grains were difficult to transfer due to a lack of hydraulic gradient generated by the flow when the outlet was blocked by artificial dam construction. In addition, smaller grains could not be flow out of the lake because there was no outflow, resulting in an increase in the grain size of the clay content in the sediment while the sand content decreased. Therefore, the distribution of the sediment grain size of Hulun Lake clearly shows that the lake was affected by dam-building activities, and the lake sediment effectively recorded the information of this human activity. It is rather remarkable that not only did the sedimentary environment of the lake change, but also a large amount of sediment was deposited on the bottom of the lake due to the building dam.

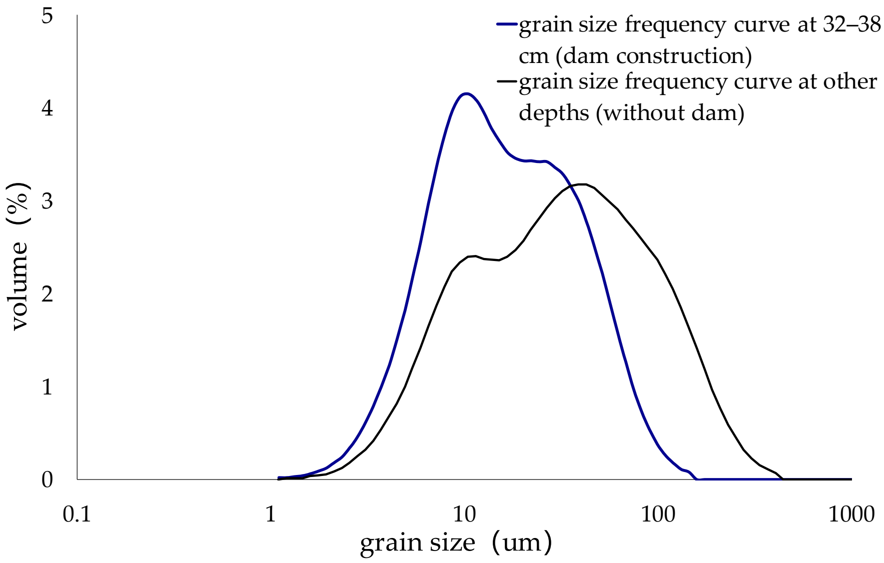

Figure 8. The sketch map of sediment grain size frequency curves at 32–38 cm of the 41 cm core corresponding to the period of dam construction and other depths corresponding to the period without dam.

5. Conclusions

In the present study, we combined the use of radioisotope analyses of ^{210}Pb and ^{137}Cs with grain size analyses to interpret the lake deposition process and historical environment. Furthermore, the correlation of the sedimentological variables with instrumental measurements were analyzed. The results of the proxy interpretation provide insights into the past and potential future environmental changes in and around the lake. The grain size of the sediment can reflect the amount of past rainfall in the lake basin and river discharge into the lake, and then the past climatic conditions can be interpreted using the lake sediment. The changes in grain size at a depth of approximately 32–38 cm correspond to the period of dam construction in 1963–1970. Therefore, the sediment grain size of Hulun Lake effectively recorded the dam-building activity. The results of this study show that the sediments in the lake are well suited for high-resolution paleoenvironmental investigations. The credible conclusions of the palaeoenvironmental implications of grain size in lakes can be obtained by comprehensively analyzing the sedimentation process-related information.

Author Contributions: H.G. and Y.F. designed and performed research. H.G., R.Z. and G.W. wrote the paper. X.Z., J.W. and L.W. assisted experiment and provided comments. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available from the authors upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

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