Sediment Grain-Size Characteristics and its Sources of Ten Wind-Water Coupled Erosion Tributaries (the Ten Kongduis) in the Upper Yellow River

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Abstract: Understanding the composition and sources of deposited sediments in watersheds has great significance on exploring the processes of sediment erosion and deposition, and controlling soil losses in rivers. In this paper, we investigate the grain-size composition parameters and their reflections on sediment erosion, transport and deposition processes in the Ten Kongduis, which are large arroyos carrying a large volume of coarse sediment into the upper Yellow River. The sediments delivered by the Ten Kongduis come from three kinds of sources, including the clasolite (mudstone, sandstone and conglomerate) and loess in the upstream reaches and the aeolian sand in the middle stream reaches. A portion of the sediments is carried to the Yellow River and another portion is deposited in the alluvial fans in the lower reaches of the kongduis. We found two types of deposits in the drilling cores on the alluvial fans and in the sediment profiles, i.e., the sediments deposited by hyperconcentrated flows and those by non-hyperconcentrated or ordinary sediment-laden flows. The deposits of hyperconcentrated flows were only found in some natural sediment profiles exposed on the riverbank slopes. They have a mean size in a narrow range of 0.016-0.063 mm but are very or extremely poorly sorted according to nine samples collected from four kongduis. Most of the sediments carried by the non-hyperconcentrated flows have a mean grain size in the range of 0.05–0.25 mm. We calculated the contributions of sediment from the sources using the grain-size fingerprint method based on grain-size data of the sediment sources and deposits in the alluvial fans for both the hyperconcentrated flows and non-hyperconcentrated flows. It was found that a proportion of 69% or above of sediment carried by the hyperconcentrated flows mainly comes from the clasolite and loess strata in the upper reaches, and 8%–31% from the desert in the middle reaches. The clasolite and loess strata contribute 64%, on average, of the particles above 0.05 mm carried by the hyperconcentrated flows, and the desert in the middle reaches contributes the other 36% or so. The sediments carried by non-hyperconcentrated flows down to the alluvial fans come from the clasolite, loess and dune sand in different proportions in different kongduis with the contributions of both clasolite and dune sand being related roughly to the ratio of upper drainage area to the width of desert in the middle reaches of kongduis. Over 90% of the sediments carried by the non-hyperconcentrated flows into the Yellow River are below 0.05 mm.

Keywords: the Yellow River; grain size; sediment sources; Ten Kongduis; hyperconcentrated flows
1. Introduction

An important topic in the study of rivers is sediment properties [1], including physical properties, e.g., grain-size distribution and the mineral composition, and chemical properties, e.g., chemical composition and pollutants absorbed by the sediment [2]. It has drawn concerns from scholars in hydrology, geomorphology, hydraulics and environmental sciences [3–6]. Among the sediment properties, particle size is one of the most important controls on hydrodynamic conditions and river morphology [7], as it holds important implications for sediment transport and river ecology [8]. By investigating the sediment grain-size characteristics of bed materials and suspended sediment, many studies explore the erosion, deposition, and sorting processes in different types of rivers [2,7,9,10], and thereby improve the soil erosion model [11]. Moreover, through the analysis of ancient and modern sedimentary environments, many studies have established the correlation of sediment grain size parameters with transport process or deposition mechanism [12–15].

Sediment properties are also used in tracing sediment sources [9,16]. Information on sediment sources is of fundamental importance in understanding the sediment dynamics and sediment budget of a catchment in designing programs of both on-site soil loss control and downstream sediment management [17–22]. Meanwhile, it is important to manage sediment sources directly in order to reduce uncertainty in the potential operational funding required to maintain and operate viable water supply networks [23]. In the 1970s, some scholars made a pioneering use of the “source fingerprinting” or “sediment fingerprinting” approach to define the source of the sediment transported by a river or stream [24]. This approach is based on the concept that one or more of the natural physical or biogeochemical properties of the sediment (i.e., fingerprints) will reflect its source, and therefore can be used diagnostically to identify sediment origin(s) [21]. Application of this approach has been widely and increasingly reported in the past decades [21,23,25–30].

The Ten Kongduis (the transliteration of ephemeral flood gullies in Mongolian), are ten tributaries in the upper reaches of the Yellow River in Inner Mongolia, China. With the hills and gullies in the upper reaches and sand dunes in the middle reaches, and the arid and semi-arid climatic conditions, the kongduis are dominated by the strongly coupled wind and water erosion and the frequent hyperconcentrated flows, giving a large amount of coarse sediment to the Yellow River [31]. Referring to the erosion, most researchers preferred to study the wind and water erosion separately [32–34]. However, because of the temporal and spatial interplay superposition of erosion dynamics and diversity of material sources, the aeolian-fluvial interaction exhibits more intense and complex characteristics than single type of erosion in the process of sediment erosion [35], which explains the large amount of coarse-grain material that enters the Yellow River from the watersheds with wind-water coupled erosion [36]. For the Ten Kongduis, Lin et al. [37] estimated the average annual sediment discharge of these rivers to be $193.9 \times 10^4$ t/a during 1951 to 2010. The contribution of the Ten Kongduis to the sediment deposition of channel in the Bayagaole—Toudaoguai reaches of the Yellow River increased from 50.5% in 1954 to 87.8% in 2000 [38,39]. With the input of a large amount of coarse sediments, the riverbed and floodplain materials become coarser downstream the confluences of the Ten Kongduis [9]. At present, most research efforts have focused on the qualitative descriptions of the relationships and principles of the aeolian-fluvial interplay erosion [40,41], with few identifying the sources of sediment. Meanwhile, due to the lack of data (except Zhang et al. [36] who studied one of the kongduis, the Dongliugou Kongdui), no one has investigated the composition of sediment grain size, the contributions of sediment sources, and the grain-size fractions of outputs to the Yellow River for both the sediments carried by the hyperconcentrated flows and ordinary sediment-laden flows of the Ten Kongduis.

The objectives of this paper are to quantify aeolian-fluvial interplay erosion by investigating sediment grain-size characteristics and reckoning the contributions of main sediment sources based on the grain-size fingerprint method in the Ten Kongduis. The findings can be a reference to further studies on aeolian-fluvial interaction processes in semi-arid and arid areas and provide a theoretical basis for controlling the sediment output of the Ten Kongduis to the Yellow River.
2. Study Area

The Ten Kongduis originate in the Ordos Plateau and, through the Kubuqi Desert from south to north, flow into the Yellow River between Sanhuhekou and Toudaoguai from the south bank (Figure 1).

The upper reaches of the Ten Kongduis belong to the hilly and gully region of the Ordos Plateau, with thin loess and residual soil on the surface, which contain 60% of grains larger than 0.05 mm in diameter. The substrata are the so-called “pisha” in Chinese, which are highly erodible interbedded thick sandstone, sandy shale and mudstone of the Permian, Triassic, Jurassic and Cretaceous periods. The Kubuqi Desert across the middle reaches of the kongduis is wide in the west and narrow in the east (Figure 1), with a width from 28 to 8 km. The area of the desert in the Ten Kongduis is 2762 km$^2$. To the west of the Hantaichuan Kongdui are mainly shifting dunes, with an area of 1963 km$^2$, which accounts for 71.1% of the desert area; to the east of the Hantaichuan Kongdui are semi-shifting dunes, with an area of only 799 km$^2$. In the lower reaches, the kongduis flow on a flat alluvial plain and each has a wide and shallow channel, which has been subjected to heavy siltation [42].

The Ten Kongduis have a temperate continental monsoon climate. The average annual precipitation is 200–400 mm, decreasing gradually from the east to the west, and it is 200 mm in the Kubuqi Desert. The rainfall in the Ten Kongduis appears mainly in the form of rainstorms and concentrates in the months from July to September, accounting for 71.2% of the annual precipitation. These rainstorms usually generate short-lived, but high hyperconcentrated flows. Strong wind and sandstorms often happen in winter and spring with an annual average frequency of 24 days and the average wind speed is 2.7 m/s [43]. Under the special physical conditions, the study area is a typical water-wind coupled erosion zone.

3. Materials and Methods

3.1. Sediment Sampling and Analysis Methods

We collected 118 sediment samples in nine 5-m deep cores drilled in the alluvial fans of nine kongduis, except for the Haoqinghe Kongdui and a 5.79-m high profile in a manmade pit. The nine cores are MBLZ1 (11 samples), DHGZ (8 samples), HLGZ (10 samples), XLGZ (9 samples), HTCZ (10 samples), HSLZ (19 samples), MHRZ (10 samples), DLGZ (11 samples) and HSTZ (10 samples), and
the profile is MBLZ2 (18 samples). Samples were collected layer-by-layer with layers being identified visually. Also, we collected the pisha and loess samples in the upper stream and the aeolian sand in the middle stream of five kongduis. The distribution of samples is shown in Figure 1.

The 118 sediment samples were collected during November 2014 to November 2015. In the laboratory, the samples were air-dried and sieved to separate the >1 mm from <1 mm fractions. The particle size distributions of >1 mm fractions were determined by the sieving method and were calculated by weight percentage. Following the chemical pre-treatment procedure described by Konert and Vandenberghe [44], the <1 mm fractions were first treated with 30% H2O2 to remove organic materials. Carbonate present in the samples was subsequently removed with 10% HCl and the particle size distribution was determined using a Mastersizer 2000 (Malvern Instruments Ltd., Malvern, UK; the measurement range is 0.02–2000 µm) at the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (IGSNRR, CAS, Beijing, China). Finally, the particle size distribution of whole size range of each sample was calculated.

We calculated the average grain diameter (Mz), standard deviation or sorting coefficient (σ), skewness (SK) and kurtosis (KG) of each sample using the formula reported by McManus [45].

3.2. Sediment Source Tracing Methods

In the Ten Kongduis, the sediments come from the slope and gully erosion in the upper reaches and the aeolian sand erosion in the middle reaches [46]. Therefore, the source tracing investigation mainly includes two source regions and three potential sources comprised i.e., the pisha and loess in the upper stream and the aeolian sand in the middle stream of five kongduis, including the Maobula, the Heilaigou, the Xiliugo, the Hantaichuan, and the Dongliugou (Figure 1). Sediment fingerprinting in rivers needs to select proper fingerprint properties of tracers [25], and selection of fingerprint properties is usually up to the biogeochemical and physical composition of the soil in the study area [18]. The selected tracers can be particle size, organic matter and chemistry elements, including Li, B, Na, Mg, Al and P and so on only if they are both measurable and conservative [29,47].

The relative contribution of each potential sediment source for the virtual sample mixtures was assessed assuming that the tracer properties come exclusively from the possible sources by a conservative mass balance, where:

\[
\sum_{j=1}^{m} a_{ij} \times x_j = b_i
\]

which satisfies the following constraint:

\[
\sum_{j=1}^{m} x_j = 1, 0 \leq x_j \leq 1
\]

where, \(a_{ij}\) is the mean concentration of tracer property \(i\) in source type \(j\) \((j = 1 \text{ to } m)\), \(b_i\) is the value of tracer property \(i\) \((i = 1 \text{ to } n)\) in the sample mixture, \(x_j\) is the relative weighting contribution of source type \(j\) to the virtual sample mixture, \(m\) is the number of potential source types, and \(n\) is the number of tracer properties [48].

According to the data of soil in the study area, which was extracted from the 1:1,000,000 Soil Database of China provided by Institute of Soil Science, Chinese Academy of Sciences, showed that the surface materials (0–30 cm) in the Ten Kongduis consist of five soil types, namely arenosols, kastanozems, fluvisols, regosols and calcisols, and the largest area of the Ten Kongduis is occupied by kastanozems, followed by arenosols. The content of chemical properties among the latter two soil types, including organic carbon, carbonate (CaCO3) and sulfate (CaSO4) is very low. Their values range from 0.4–1.42 g/kg, 0–9% and 0, respectively. Therefore, in this paper, we chose the grain size as the fingerprinting property and tried to trace the sources of the sediment carried by hyperconcentrated flows and ordinary sediment-laden flows in the Ten Kongduis using the particle size of sediments in the sources and in the deposits on the alluvial fans. Thus, among the items in Equation (1) for
this investigation, $a_{i,j}$ is the mean percentage of particle size group $i$ in source type $j$ ($j = 1$ to $m$), $b_i$ is the mean percentage of particle size group $i$ ($i = 1$ to $n$) in the deposit sample mixture, $x_j$ is the relative weighting contribution of source type $j$ to the sediment output of a kongdui, $m$ is the number of potential source types, and $n$ is the number of particle size groups.

The grain size of sediments is usually considered to be not conservative, as the particle size selectivity and grain abrasion in sediment transport and deposition generally results in downstream fining of sediment diameter \([11,21,49]\). Nevertheless, the grain size can be assumed to be still conservative for tracing sediment sources in this study. Firstly, particle size selectivity of sediments carried by hyperconcentrated flows that have been frequent in the Ten Kongduis should be much lower because settling velocity of large particles in the hyperconcentrated flows is greatly reduced and all particles can be carried downstream \([50]\). Secondly, the size sorting of sediments delivered by ordinary sediment-laden flows can be considered to be negligible in a long term in the erosion and transport processes in the study area because the Ten Kongdui catchments are on the uplifting Ordos Plateau and their erosion intensity and sediment delivery efficiency are as high as the loess catchments on the Loess Plateau which, as mentioned by Walling \([51]\), have a long-term sediment delivery ratio of unity. Besides, we use particles finer than gravel in source fingerprinting, so the effect of grain abrasion is minor because according to Jerolmack and Brzinask \([52]\), the abrasion of grains which are below 1 mm is unlikely since kinetic energy transfer during collision is minimal. The issue that should be taken into account is selective deposition in the downstream alluvial fans, which makes it necessary to estimate the grain size composition of sediment delivered by flows from that of deposits on the fluvial fans for tracing the sources of the sediment carried to the alluvial fans.

Here, we presume that the proportion of the sediment deposited in the alluvial fans accounts for $\alpha$ of all the sediment inputs from the sources and the sediment output to the Yellow River is $1 - \alpha$. Then, if the percentage of the $i$th particle size fraction in the sediment output is $d_i$, that in the sediment inputs from all sources will be $\alpha b_i + (1 - \alpha) d_i$. Thus, Equation (1) is revised as follows:

$$\sum_{j=1}^{m} a_{i,j} x_j = \alpha b_i + (1 - \alpha) d_i$$

or

$$\sum_{j=1}^{m} \frac{a_{i,j}}{\alpha} x_j + \frac{\alpha - 1}{\alpha} d_i = b_i$$

The percentage of the $i$th particle size fraction in the sediment output, $d_i$, is estimated as follows.

When water flows enter the alluvial fans, the gradient of the kongduis decreases considerably, so a large portion of the sediments carried by the flows are deposited on the fans. This means that the flows should have sediment content higher than their carrying capacity after entering the alluvial fans. It is reasonable to assume that the flows have sediment content close to their carrying capacity when they pour into the Yellow River after unloading the oversaturated sediment. This should be applicable to all particle size fractions, except for the fine clay particles. At the sediment content equal to sediment carrying capacity, the content of the $i$th particle size fraction, $d_i$, should be proportional to the flow capacity carrying particles in this fraction. According to Zhang \([53]\) and Morris et al. \([54]\), the sediment carrying capacity of flows ($S^*$) is proportional to the settling velocity of particles ($\omega$) powered by the minus sediment carrying capacity index ($-m$), $\omega^{-m}$. The $m$ value is equal to 0.76 for the Yellow River. Chien and Wan \([1]\) found that the settling velocity is proportional to the square root of the particle size ($D^{0.5}$). Therefore, $S^*$ is proportional to $D^{-0.38}$, and the ratio of contents between different particle size fractions can be calculated by the ratio between their diameters powered by $-0.38$.

Due to the limited representativeness of samples, the errors of grain size analysis, and other reasons, there is no analytical solution to the above equations. We used the least square method and calculated the approximate values of $x_1$ through $x_m$, which makes the error minimum and are regarded as the optimal estimates for the contributions of different sources.
4. Results

4.1. Sediment Grain-Size Characteristics

4.1.1. Sediments in Sources

According to the main landforms of the Ten Kongduis, the sediment sources are divided into three types, including the pisha and loess in the hilly and gully region in the upper reaches and aeolian sand in the desert region in the middle reaches. The means and ranges of four grain-size classes of the sediment samples in the three sources are shown in Table 1. We use the means of grain-size classes of each sediment source to calculate the weighting contributions.

| Sediment Source | Number of Samples | Values | Grain-Size Classes |
|-----------------|-------------------|--------|--------------------|
|                 |                   |        | <0.02 mm | 0.02–0.05 mm | 0.05–0.5 mm | 0.5–2 mm |
| Pisha           | 13                | Mean value | 17.50% | 18.84% | 25.73% | 37.93% |
|                 |                   | Range   | 7.28%–41.59% | 5.17%–29.02% | 5.59%–51.16% | 2.12%–81.96% |
| Loess           | 5                 | Mean value | 57.39% | 28.58% | 13.63% | 0.40% |
|                 |                   | Range   | 45.35%–61.65% | 26.77%–29.05% | 9.30%–27.88% | 0–1.2% |
| Aeolian sand    | 5                 | Mean value | 0 | 0 | 100% | 0 |
|                 |                   | Range   | 0–0 | 0–0 | 100%–100% | 0–0 |

4.1.2. Deposits of Hyperconcentrated Flows

In semi-arid climate conditions, wind erosion and water erosion often occur simultaneously or alternately, causing more severe erosion by aeolian-fluvial interactions. Xu [55] pointed out that the coupled wind-water erosion was most conducive to the development of hyperconcentrated flows and led to a higher sediment concentration. For the Ten Kongduis, water erosion dominates the hilly and gully areas of the upper reaches, which are covered by thin loess and widely exposed “pisha” sandstone. Heavy rains in summer often generate hyperconcentrated flows. The aeolian sand fed by the wind erosion in the desert area of the middle reaches in spring and winter further promotes the sediment concentration of the hyperconcentrated flows [31]. Finally, a large amount of coarse sediment is carried by the hyperconcentrated flows into the Yellow River. Once the hyperconcentrated flows lose transport power, all the sediments they carried will be deposited without sorting, forming a kind of mixed deposits. The particle size composition of the deposits should be basically the same as the sediments carried by the hyperconcentrated flows.

In the field investigation, we collected nine sediment samples in four natural profiles in the lower reaches of the kongduis, including 4 in the Dinghonggou Kongdui, 1 in the Hashila Kongdui, 3 in the Muhaer Kongdui and 1 in the Dongliugou Kongdui. As shown in Table 2, the average grain diameter and median diameter of the mixed deposits are not different between kongduis and they mainly distribute from 4 φ to 6 φ. The sorting coefficient is in the range of 2.28–4.73 φ, which belongs to the degrees of very to extremely poorly sorted. The kurtosis is greater than 1, meaning that the frequency curves of particle size are narrower and sharper than the normal distribution and the size distributions are more concentrated. Except for the two samples of the Dinghonggou and the Muhaer kongduis, the skewness of else samples is in the range of −0.33 and 0.33, which belongs to the near symmetric distribution. In contrast, the skewness of most river deposits is generally much greater than zero because a higher portion of fine particles is transported downstream.
Table 2. Grain size parameters and median particle size of sediment deposits of hyperconcentrated flows in the Ten Kongduis.

| Sampling Sites | Grain-Size Parameters | Median Grain Size (φ) |
|----------------|-----------------------|-----------------------|
|                | Mean Grain Size (φ)   | Sorting Coefficient (φ) | Skewness | Kurtosis |
| DHG1           | 5.90                  | 3.96               | −0.60    | 2.36      | 7.10     |
| DHG1-1         | 3.43                  | 4.73               | 0.08     | 1.47      | 5.64     |
| DHG1-2         | 4.87                  | 3.48               | −0.12    | 2.34      | 5.65     |
| DHG1-3         | 3.50                  | 3.84               | 0.16     | 1.97      | 4.33     |
| DHG1-4         | 4.03                  | 3.60               | 0.20     | 2.05      | 4.33     |
| HSL            |                       |                    |          |           |          |
| MHR1           | 5.68                  | 3.37               | 0.19     | 2.32      | 3.85     |
| MHR2           | 5.00                  | 2.80               | 0.03     | 3.90      | 4.85     |
| MHR3           | 5.10                  | 2.28               | 0.61     | 5.08      | 4.56     |
| DLG            | 5.04                  | 3.35               | −0.27    | 2.62      | 5.63     |

In order to prove that the nine samples were carried by hyperconcentrated flows, we made a comparison of grain-size composition between the samples and the sediment carried by the hyperconcentrated flows in the Huangfuchuan River, which is located in the middle reaches of the Yellow River and has similar surface materials as the Ten Kongduis. According to the suspended sediment data of the Huangfuchuan River, there were 17 flood events when the river had sediment concentration greater than 400 kg/m$^3$. The size fraction of $<0.005$ mm accounted for 5%–17%, 0.005–0.01 mm for 2.5%–8%, and $>0.01$ mm for 75%–90% in 88.3% samples of these hyperconcentrated floods [56]. In 88.89% of the collected deposit samples of hyperconcentrated flows in the Ten Kongduis, the size fractions of $<0.005$ mm, 0.005–0.01 mm, and $>0.01$ mm are 12%–24%, 8%–15%, 61%–79%, respectively. It can be seen that the deposits of hyperconcentrated flows in the Ten Kongduis have a similar size composition as the sediment carried by the hyperconcentrated flows of the Huangfuchuan River. Thus, both the deposition process of hyperconcentrated flows and the above comparison suggest that the size composition of sediments deposited by the hyperconcentrated flows is nearly the same as that carried by the hyperconcentrated flows in the Ten Kongduis. The composition of the mixed deposits of hyperconcentrated flows is unsorted and has an approximately symmetrical distribution inherited from the parent soils. Overall, the fraction above 0.05 mm is 24%–57%, 42% on average, which can also be regarded as the percentage of coarse sand delivered into the Yellow River by the hyperconcentrated flows in the Ten Kongduis.

4.1.3. Drilling Cores in the Alluvial Fan

According to the calculation of grain size parameters, the mean grain size of samples from drilling cores is in the range of 1–7 $\phi$, but mainly concentrates in the range of fine sand size (0.05–2 mm). The sorting is poor or very poor, ranging from 1.12–2.82 $\phi$ and most of the sand-sized sediments have a lower sorting coefficient. All samples collected from the cores have a positive skewness (in the range of 0.26–3.40). The kurtosis of most of the samples is greater than 4.5, indicating that the size distribution is very leptokurtic and the very narrow frequency peak is related to a high content of coarse particles.

As mentioned above, we collected some samples of sediment deposited by hyperconcentrated flows from natural profiles. Their particle size distribution reveals that they are poorly sorted and have a low skewness with some gravel-size particles. With these features, we can determine whether there exist deposits of hyperconcentrated flows in the drilling cores. It can be seen that the samples in the drilling cores are different from those of the deposits of hyperconcentrated flows in the diagrams of $M_z-\sigma$ and $C-SK$ (Figure 2), so the samples in the drilling cores are mainly carried by the non-hyperconcentrated flows.
4.2. Sediment Sources Identification

4.2.1. Hyperconcentrated Flows

As mentioned above, the samples of hyperconcentrated flow deposits have almost the same grain size composition as the input sediment. Therefore, we can use Equation (1) and the method mentioned in Section 3.2 to calculate the sediment sources. The results are shown in Figure 3. In order to examine the results, we calculated the percentages of grain size fractions at the outlets of the kongduis with the estimated contributing ratios of sources, and found that they are nearly same as those of the hyperconcentrated flow deposits with a maximum relative error of 1.46%.

Figure 3 shows that the proportions of sediment yield from the sandstone are in the range of 3.11%–35.69%, those from loess are in the range of 36.97%–80.69%, and those from the desert are in the range of 8.33%–30.55% in the nine events of hyperconcentrated flows. The sum of proportions of sediment yield from both the pisha and loess in the upper reaches range from 69.45% to 91.67%, which are higher than those from the desert in the middle reaches. Thus, sediments carried by the hyperconcentrated flows have come mainly from the upper reaches of the kongduis.

Figure 2. The Mz-σ (a) and C-SK (b) diagrams for deposit samples of the Ten Kongduis. DC sample—Drilling core sample; HC sample—Hyperconcentrated flows deposit sample.
4.2.2. Non-Hyperconcentrated Flows

Unlike the sediment deposited by hyperconcentrated flows, the difference of grain size composition of deposits in the alluvial fans not only exits between the kongduis but also between the different deposit layers in the alluvial fan of one kongdui. In order to reflect the grain size characteristics of sediment in the long-term deposition process, we classified the strata in each core and merged the similar ones. Sorting is closely related to the properties of the transporting medium and to the transporting distance, so the sorting coefficient is commonly used in the analysis of the material sources and sediment dynamic conditions. A break point of slope in the plots of standard deviation with depth marks a break in deposition associated with a transition to a lower or higher sedimentary dynamics [57]. Therefore, we made a cluster analysis on the sorting coefficient of samples in each core sequentially and identified the break points. The Kruskal-Wallis test was done with a significance level of 95% [36]. The results are shown in Table 3.

Table 3. Results of sequential cluster and Kruskal-Wallis test of sediment samples in cores based on their sorting coefficients.

| Cores or Sections | Samples | Depth (m) | p Values | Cores or Sections | Samples | Depth (m) | p Values |
|-------------------|---------|-----------|----------|-------------------|---------|-----------|----------|
| MBLZ1             | MBLZ1-1-3 | 0-2.1    | 0.017    | MBLZ2            | MBLZ1-1-3 | 0-1.27    | 0.025    |
|                   | MBLZ1-4-9 | 2.1-4.6  |          |                   | MBLZ2-4-6  | 1.27-1.8  |          |
|                   | MBLZ1-10-11 | 4.6-5 |          |                   | MBLZ2-7-18 | 1.8-5.79  |          |
| DHGZ              | DHGZ1-1-2 | 0-0.9    | 0.046    | HLGZ             | HLGZ1-1-4 | 0-2.2     | 0.089    |
|                   | DHGZ1-3-8 | 0.9-5    |          |                   | HLGZ1-5-11 | 2.2-5     |          |
| XLGZ              | XLGZ1-1-3 | 0-3.02   | 0.212    | HTCZ             | HTCZ1-1-3 | 0-1.45    | 0.053    |
|                   | XLGZ1-4-5 | 3.02-3.65 |    | HTCZ1-4-10 | 1.45-5   |          |
|                   | XLGZ1-6-9 | 3.65-5   |          | HTCZ1-4-10 | 1.45-5   |          |
| HSLZ              | HSLZ1-1-12 | 0-3.25  | 0.085    | MHRZ             | MHRZ1-1-9 | 0-4.4     | 0.223    |
|                   | HSLZ1-13-19 | 3.25-5  |          | MHRZ1-10 | 4.4-5    |          |
| DLGZ              | DLGZ1-1-5 | 0-2.45   | 0.011    | HSTZ             | HSTZ1-1-2 | 0-1.2     | 0.036    |
|                   | DLGZ1-6-11 | 2.45-5 |          |                   | HSTZ1-3-6 | 1.2-3.8   |          |
|                   |           |          |          |                   | HSTZ1-7-10 | 3.8-5     |          |

The $p$ values in Table 3 show that the sedimentary dynamic conditions of deposits in the cores in the Maobula, Dinghonggou, Dongliugou and Husitai kongduis had changed significantly. We recalculated the grain size composition of the layers with a statistically same sorting coefficient in each core or section by depth weighting, and used it to estimate the sources of sediment carried by non-hyperconcentrated flows to the alluvial fan of a kongdui. The sediments deposited by non-hyperconcentrated flows usually have a different grain size distribution with those they carried, so Equation (3) was applied to the estimate of sediment sources here. The results are given in Table 4. The maximum relative error was found to be 3.80%.

Figure 3. Sources of sediment carried by hyperconcentrated flows in the Ten Kongduis.

The maximum relative error was found to be 3.80%.
Table 4. Sources of sediments carried by non-hyperconcentrated flows to the alluvial fans of the Ten Kongduis.

| Kongduis | Proportion of Different Sources (%) | Kongduis | Proportion of Different Sources (%) |
|----------|--------------------------------------|----------|--------------------------------------|
|          | Sandstone | Loess | Aeolian | Sandstone | Loess | Aeolian |
| MBLZ1    |            |       |         |            |       |         |
| 0–2.1 m  | 59.42      | 26.23 | 14.35   | 0–5 m     | 3.68  | 30.84   |
| 2.1–4.6 m| 77.45      | 10.78 | 11.77   | 0–5 m     | 15.79 | 19.22   |
| 4.6–5 m  | 81.11      | 8.07  | 10.82   | 0–5 m     | 47.67 | 16.38   |
| Weighted average | 70.17 | 17.05 | 12.78   | MHR 0–5 m | 1.70  | 26.56   |
| MBLZ2    |            |       |         |            |       |         |
| 0–1.27 m | 44.13      | 31.61 | 24.26   | 0–2.45 m  | 1.84  | 24.22   |
| 1.27–1.8 | 39.31      | 31.93 | 28.76   | DLG 2.45–5 m | 2.57  | 28.78   |
| 1.8–5.79 | 38.99      | 36.79 | 24.22   | Weighted average | 2.21  | 26.55   |
| Weighted average | 40.15 | 35.21 | 24.64   |            | 68.75 | 1.35    |
| DHG      |            |       |         |            |       |         |
| 0–0.9 m  | 3.71       | 24.53 | 71.77   | HST 1.2–3.8 m | 0.16  | 28.75   |
| 0.9–5 m  | 3.00       | 30.95 | 66.06   | 3.8–5 m   | 44.91 | 12.81   |
| Weighted average | 3.12 | 29.79 | 67.09   | Weighted average | 27.36 | 18.35   |
| HLG      |            |       |         |            |       |         |
| 0–5 m    | 2.06       | 24.56 | 73.38   |            |       |         |

5. Discussion

5.1. The Causes for Changes in Sediment Yield Proportion from Different Sources

Our data show that 69.45% to 91.67% of the sediments carried by the hyperconcentrated flows come mainly from the pisha and loess in the upper reaches of the Kongduis. Moreover, although the desert in the west five Kongduis is much wider than that in the east five Kongduis as mentioned above, the proportions of sediment yield from the desert in the middle reaches of the Dinghonggou Kongdui are close to those from the desert in the middle reaches of the three eastern Kongduis (Figure 3). Thus, in the events of hyperconcentrated flows, the contributions of different source types do not change noticeably between Kongduis. The reason for this phenomenon may be associated with the grain size composition needed for the formation of the hyperconcentrated flows that remain in the regime of turbulent two-phase flow and thus are stable [58]. The two-phase hyperconcentrated flows have their liquid phase composed of water and fine particles and their solid phase of coarse particles. The fine particles form an intricate network of floc structure to keep the coarse particles in suspension. Yet, if the content of fine particles surpasses a limit, the flow will turn to a one-phase muddy flow, which is unstable and needs a large slope to keep in flow because its friction loss is much larger [59]. Therefore, the measured highest sediment concentration decreases from the basins covered by loess with coarse particles to those with fine particles on the Loess Plateau [59], and that the highest sediment concentration of flows have a certain size composition [2]. As the pisha, loess, and aeolian sand generally have their distinctive grain size composition, the hyperconcentrated flows generated in the upper hill slopes and gullies will entrain a certain combination of pisha and loess materials and replenish themselves with a proportional amount of wind-blown sand in the middle reaches in the Kongduis. Consequently, the contribution of a sediment source type to the hyperconcentrated flows is similar between different Kongduis and the sediment size composition of the flow load remains nearly unchanged.

As shown in Table 4 for the sediment carried by non-hyperconcentrated flows, the proportion of sediment yield from pisha strata is different between Kongduis. It is about 50% in the Maobula and Hashila Kongduis, and less than 30% in the rest Kongduis. The difference of the proportion of sediment yield from the pisha strata between Kongduis may result from the different ratios of upper drainage areas to the width of desert in middle reaches of the Kongduis, as shown in Figure 4a. The proportions of sediment yield from the desert in the middle reaches are in the range of 12.78%–73.38%, and the proportion of sediment yield from the desert is also related with the ratio of upper drainage areas to the width of desert (Figure 4b).
Ten Kongduis has mainly been implemented by hyperconcentrated flows. For instance, Yao et al. [61] reported that the hyperconcentrated flows carried 83% of the total sediment load of the Xiliagou Kongdui during the 35 years in 1964–1990 and 2006–2013. Thus, the contributions of coarse sediment sources in the kongduis are close to those in the cases of hyperconcentrated flows, and the pisha and loess strata contribute a larger portion of coarse particles. According to the grain size composition of materials in the three sources and their contributing proportions in the cases of hyperconcentrated flows, 64% of grains above 0.05 mm have been yielded from the pisha and loess, and 36% from the desert in the middle reaches. In the non-hyperconcentrated flows, owing to hydraulic sorting, coarser sediments tend to be deposited in the alluvial fans and, hence, the sediments being carried into the Yellow River have a higher portion of fine particles. The estimated percentages of different size fractions of sediment output into the Yellow River in fingerprinting the sediment sources disclose that the fraction above 0.05 mm of the sediment carried by non-hyperconcentrated flows into the Yellow River is 10% or below. Sediment transport in the Ten Kongduis has mainly been implemented by hyperconcentrated flows. For instance, Yao et al. [61] reported that the hyperconcentrated flows carried 83% of the total sediment load of the Xiliagou Kongdui during the 35 years in 1964–1990 and 2006–2013. Thus, the contributions of coarse sediment sources in the kongduis are close to those in the cases of hyperconcentrated flows, and the pisha and loess strata provide a total proportion of coarse particles (>0.05 mm) higher than the desert.

It is worth mentioning that the sediment samples collected in the upper stream of kongduis have some coarse gravels (>2 mm) and gravels larger than 16 mm in some pisha samples account for 46%. The fraction of >8 mm doesn’t exist in all the deposit samples of hyperconcentrated flows. Field survey disclosed that the mean size of riverbed materials decreases downstream along the kongduis. Thus, it can be inferred that the coarse gravels tend to be deposited on the river bed in the upper and middle reaches and can seldom be carried into the Yellow River owing to hydraulic sorting in the two-phase hyperconcentrated flows.

Also, Table 4 shows that the proportions of sediment yield from loess are below 30% in all the kongduis and those from the desert in the middle reaches are over 50% in seven kongduis. The ratio of the proportions of sediment yield from the upstream reaches to those from the middle streams in the Maobula and Hashila kongduis is more than 1:1, and it is about 1:1 in the Husitai Kongdui and about 0.5:1 in the rest kongduis. Therefore, we can conclude that the sediments carried to the alluvial fans by the non-hyperconcentrated flows in the Maobula and Hashila kongduis have been mainly from the hilly and gully regions, equally from both the upper and the middle reaches in Husitai Kongdui, and mainly from the desert regions in the Dinghonggou, Heilaigou, Xiliugou, Hantaichuan, Muhaer and Dongliugou kongduis.

5.2. The Coarse Sediment Sources

Previous studies argue that the coarse particles of riverbed materials in the Inner Mongolian reach of the Yellow River come mainly from the Wulanbuhe and Kubaqi deserts and the sand of the Kubuqi Desert has been delivered to the Yellow River through the Ten Kongduis [9,60]. Through sediment source tracing in this study, we found that the Kubuqi Desert has been indeed a principal source of the coarse sediment carried by the Ten Kongduis, but the pisha and loess strata contribute a larger portion of coarse particles. According to the grain size composition of materials in the three sources and their contributing proportions in the cases of hyperconcentrated flows, 64% of grains above 0.05 mm have been yielded from the pisha and loess, and 36% from the desert in the middle reaches. In the non-hyperconcentrated flows, owing to hydraulic sorting, coarser sediments tend to be deposited in the alluvial fans and, hence, the sediments being carried into the Yellow River have a higher portion of fine particles. The estimated percentages of different size fractions of sediment output into the Yellow River in fingerprinting the sediment sources disclose that the fraction above 0.05 mm of the sediment carried by non-hyperconcentrated flows into the Yellow River is 10% or below. Sediment transport in the Ten Kongduis has mainly been implemented by hyperconcentrated flows. For instance, Yao et al. [61] reported that the hyperconcentrated flows carried 83% of the total sediment load of the Xiliagou Kongdui during the 35 years in 1964–1990 and 2006–2013. Thus, the contributions of coarse sediment sources in the kongduis are close to those in the cases of hyperconcentrated flows, and the pisha and loess strata provide a total proportion of coarse particles (>0.05 mm) higher than the desert.

It is worth mentioning that the sediment samples collected in the upper stream of kongduis have some coarse gravels (>2 mm) and gravels larger than 16 mm in some pisha samples account for 46%. The fraction of >8 mm doesn’t exist in all the deposit samples of hyperconcentrated flows. Field survey disclosed that the mean size of riverbed materials decreases downstream along the kongduis. Thus, it can be inferred that the coarse gravels tend to be deposited on the river bed in the upper and middle reaches and can seldom be carried into the Yellow River owing to hydraulic sorting in the two-phase hyperconcentrated flows.

Figure 4. The relation between the percentage of contribution of pisha strata and the ratio of upper drainage area to the width of desert in the middle reaches of kongduis (a) and between the percentage of contribution of dune sand and the same ratio (b).
6. Conclusions

The frequent hyperconcentrated flows and a long-term sediment delivery ratio of nearly 1 in the study area make it possible for us to fingerprint the sediment sources from the particle size of sediment deposits, and the results are as the follows. In the Ten Kongduis, the sediment carried by the hyperconcentrated flows came mainly from the pisha and loess strata in the upper reaches, with a percentage of 69% and above, and the desert in the middle reaches contributed a proportion of below 31%. About 64% of grains above 0.05 mm in the sediments carried in hyperconcentrated flows came from the pisha and loess strata, and the remaining 36% from the desert in the middle reaches, on average. Since sediment transport in the kongduis has been dominated by hyperconcentrated flows, the pisha and loess strata in the upper reaches contributed over half of the total load and its coarse portion. The sediments carried to the alluvial fans by the non-hyperconcentrated flows came from clasolite, loess and dune sand in different proportions in different kongduis, with both the contributions of clasolite and dune sand being related to the ratio of upper drainage area to the width of desert in the middle reaches of kongduis. The main fraction of sediments carried by the non-hyperconcentrated flows into the Yellow River is below 0.05 mm with a percentage of 10% or lesser being above.

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