A Field Investigation on Gully Erosion and Implications for Changes in Sediment Delivery Processes in Some Tributaries of the Upper Yellow River in China

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Abstract: Erosion and sediment delivery have been undergoing considerable variations in many catchments worldwide owing to climate change and human interference. Monitoring on-site erosion and sediment deposition is crucial for understanding the processes and mechanisms of changes in sediment yield from the catchments. The Ten Kongduis (kongdui is the transliteration of ephemeral creeks in Mongolian) are 10 tributaries of the upper Yellow River. Severe erosion in the upstream hills and gullies and huge aeolian sand input in the middle reaches had made the 10 tributaries one of the main sediment sources of the Yellow River, but the gauged sediment discharge of the tributaries has decreased obviously in recent years. In order to find out the mechanisms of changes in the sediment load of the tributaries, topographic surveys of four typical gullies in 3 of the 10 tributaries were made repeatedly in the field with the terrestrial laser scanning (TLS) technique. The results show that all the monitored gullies were silted with a mean net rate of 587–800 g/m² from November 2014 to June 2015 and eroded by a mean net rate of 185–24,800 g/m² from June to November 2015. The monitoring data suggest that the mechanism of interseasonal and interannual sediment storage and release existed in the processes of sediment delivery in the kongduis. The contrast of the low gauged sediment load of the kongduis in recent years against the high surveyed gully erosion indicates the reduction in their sediment delivery efficiency, which can be attributed to the diminution in hyperconcentrated flows caused mainly by the increase in vegetation coverage on slopes and partly by construction of sediment-trapping dams in gullies.

Keywords: ten kongduis; soil erosion; sediment delivery process; terrestrial laser scanning; Yellow River

1. Introduction

Soil erosion is an important land degradation process and creates serious negative on-site and off-site effects on environment and societies [1–7]. Typically, in semiarid regions, soil erosion is severe and largely irreversible [8]. A modelling approach is a common and useful way to project soil erosion under climate change [9,10]. Various soil erosion models have been developed in previous studies, including empirical models, conceptual models and physically based models [11], while monitoring on-site erosion is the preliminary and fundamental step to investigate erosion. Loss of soil predominantly occurs as sheet erosion, rill erosion, and gully erosion [12]. Gully erosion is the main source of sediment in a range of environments [2,13], resulting in severe environmental and economic problems such as the degradation of agricultural soil and surface water quality and damage to infrastructure and transportation corridors [14], and less information is available on gully erosion processes...
compared with sheet or rill erosion [15]. As gully erosion is often much more intensive and thus more detectable than slope erosion and gully erosion contributes overall soil loss and sediment production at various temporal and spatial scales under different climatic and land use conditions [16–24], considerable effort has gone into monitoring gully erosion.

To help researchers better understand erosion mechanisms, both ground-based and airborne techniques have been used to assess eroded volumes by gullying in the field [19,25]; for example, establishing runoff plots in catchments [26], regularly measuring the change in distance between the edge of the gully head or wall and benchmark pins installed around the gully wall [27] or by measuring the three-dimensional morphology of the gully wall using a direct contact protractor system [28]. These methods involve the use of different devices, i.e., ruler, pole, tape, microtopographic profiles, total stations and laser profilemeters, which may provide a simple and affordable approach for erosion evaluation but have a heavy workload and are time consuming for achieving measures of high accuracy and precision [29,30]. Developments in remote mapping technologies such as aerial LiDAR [31] can determine the volume of soil erosion in larger areas but are subject to high costs [30]. Compared with those techniques, terrestrial laser scanning (TLS) techniques can obtain high-resolution data of a large area in a relatively short period and estimate the gully erosion more accurately in the field [32]. Therefore, major advances have been made recently in the application of TLS technique for the assessment of erosion and deposition volumes and channel change in a proglacial river [33]; the analysis of gully headward erosion [34]; the sediment sources of debris flow [35]; generating models suitable for characterizing the multi-scale morphology and rapid evolution common to braided rivers and similar landforms and the process of gully erosion development [36]; and measuring and monitoring coastal sand dune evolution [37]. Here, we use this technique for the quantitative analysis of gully erosion in the 10 kongduis (kongdui is the transliteration of ephemeral creeks in Mongolian) in the upper Yellow River in Inner Mongolia, China. With the hills and gullies in the upper reaches, sand dunes in the middle reaches and the arid and semi-arid climatic conditions, the 10 kongduis are dominated by strongly coupled wind and water erosion [38,39], and they are one of the primary sediment sources of the Yellow River. The sediment from these tributaries is the main reason for the severe siltation in the Sanhuhekou-Toudaoguai reach of the Yellow River [40].

The susceptibility of eroded soil to being transported is high, typically occurring in discrete hyperconcentrated sediment flow and sand-dust storms due to concentrated rainstorm events, strong winds, sparse vegetation, vulnerable surface material, complicated landforms, and excessive or unreasonable land use practices [8]. Previous studies suggest that the main sources of sediment are the gully erosion in the upper reaches and the aeolian sand of the middle reaches of the kongduis [41,42]. At present, the research about the 10 kongduis mainly focuses on the characteristics of water and sediment based on the gauged hydrological data at 3 hydrographic stations [43], with few investing in sediment yield processes by using in situ measured data. Thus, both gully erosion in the upstream and the aeolian sediment input into rivers in the middle reaches were monitored at some plots using the TLS technology. The results of the aeolian sand input into the river have been reported in the study by Yang and Shi [39], and this present study focuses on analyzing the monitoring data of gully erosion.

This study aims at exploring the mechanisms of changes in erosion and sediment delivery in the catchments subjected to wind–water coupled erosion. The specific objectives are to investigate gully erosion process in the 10 kongduis by repeatedly measuring the surfaces of some gullies with a 3D laser scanner, estimating changes in gully volume and the erosion modulus and to probe into the variations of sediment yield and sediment delivery and the driving factors in recent years.

2. Study Area

As shown in Figure 1, the 10 kongduis originate in the Ordos Plateau, including the Maobula, the Dinghonggou, the Heilaigou, the Xiliugou, the Haoqinghe, the Hashila,
Muhaer, the Dongliugou and the Husitai kongduis from west to east. From south to north, they flow into the Yellow River between Sanhuhekou and Toudaoguai [44]. Each of the kongdui watersheds mainly consists of three topographic units: (1) The upper reaches of the kongduis belong to the hilly and gully region of the Ordos Plateau, with thin loess, residual soil and aeolian soil on the surface, which contains 60% grains larger than 0.05 mm in diameter. The underlying strata are a kind of terrestrial clasolite, which is called “pisha” (meaning arsenic sandstone literally) in Chinese as it is highly erodible and causes harmful consequences. (2) Across the middle reaches of the kongduis is the Kubuqi Desert with a width of 28 km in the west and 8 km in the east. The area of desert in the 10 kongduis is 2762 km² [45]. (3) In the lower reaches, the kongduis flow on a flat alluvial plain and have a wide and shallow channel, which has been subjected to heavy siltation [46].

With a temperate continental monsoon climate, the 10 kongduis belong to the eastern Ordos Plateau desert region in the physical regionalization of China [46]. In the bioclimatic zonation, they are located in the dry steppe zone but transit to the semi-desert zone in the western part. According to meteorological records, the average annual temperature is 6.8–7.4 °C in the southern hilly and gully area. In the 10 kongduis, the average annual precipitation is only 200–400 mm, decreasing gradually from the east to the west, and the annual potential evaporation is 2200 mm. The rainfall 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 (>17.2 m/s) and sandstorms often happen in winter and spring with an average frequency of 24 d/yr, and the average wind speed is 2.7 m/s [47]. Under the special physical conditions, the study area is a typical water–wind coupled erosion zone.

The 10 kongduis have a drainage area of 213 to 1301 km² each and a total of 8269 km², and the stream length of each kongdui ranges from 37.1 to 114.7 km [45]. The channel is

![Figure 1. Locations of the 10 kongduis and the plots surveyed (MBLC is a surveyed gully of the Maobula Kongdui named by us; XLGBC and XLGNC are two surveyed gullies of the Xiliugou Kongdui named by us; DLGC is a surveyed gully of the Dongliugou Kongdui named by us).](image-url)
short while the slope is steep with a range from 3.59 m/km to 8.09 m/km. The drainage area of the Maobula Kongdui is 1293 km², and its stream length is 114.7 km with a slope of 5.24 m/km. The drainage area of the Xiliugou Kongdui is 1301 km², and its stream length is 110.8 km with a slope of 4.91 m/km. The drainage area of the Dongliugou Kongdui is 432.8 km², and its stream length is 69.5 km with a slope of 5.92 m/km.

3. Methods and Data

3.1. Topographic Survey

We monitored four gullies in the upper reaches of three kongduis during 2014 to 2015 (Table 1), which are located in the west, middle and east of the 10 kongduis, and their locations are shown in Figure 1, including MBLC in the Maobula Kongdui, XLGBC and XLGNC in the Xiliugou Kongdui and DLGC in the Dongliugou Kongdui.

Table 1. Details of surveyed plots in gullies.

| Kongduis       | Surveyed Plots * | Scanned Area (m²) | Scanned Length (m) |
|----------------|------------------|-------------------|-------------------|
| Maobula Kongdui| MBLC             | 4712              | 137               |
|                | XLGBC            | 579               | 48                |
| Xiliugou Kongdui| XLGNC        | 271               | 23                |
| Dongliugou Kongdui| DLGC      | 810               | 62                |

* Referring to Figure 1 for the abbreviations.

All the plots were surveyed three times, i.e., November 2014, which was before the windy season; June 2015, which was between the windy season and the rainy season; and November 2015, which was after the rainy season.

Each of the plots were measured from many stations (Table 2); a relative coordinate system was chosen through fixing several pins at each plot before the first measurement as the reference and some spheres were set in every station, which makes the merging process less cumbersome and more accurate [39]; and the scanning data were processed by a series of steps, including co-registering, georeferencing using FARO’s scene software and removing the noises caused by vegetation and merging with Geomagic Studio software. Then, using ArcGIS, we obtained the DEMs with a resolution of 0.1 m for each plot and used them to calculate the areas and volumes of the gullies [39]. The details of scanning data, including the number of stations, registration errors and average point spacing are shown in Table 2.

Table 2. Details of scanning plots.

| Surveyed Plots * | Surveying Dates | Number of Stations | Registration Errors (m) | Data Points | Average Point Spacing (m) |
|------------------|-----------------|--------------------|--------------------------|-------------|--------------------------|
| MBLC             | November 2014   | 20                 | 0.0060                   | 668,025     | 0.01                      |
|                  | June 2015       | 26                 | 0.0070                   | 631,230     | 0.01                      |
|                  | November 2015   | 24                 | 0.0044                   | 539,964     | 0.01                      |
|                  | November 2014   | 7                  | 0.0064                   | 495,146     | 0.003                     |
| XLGBC            | June 2015       | 9                  | 0.0059                   | 581,038     | 0.002                     |
|                  | November 2015   | 9                  | 0.0031                   | 646,205     | 0.002                     |
|                  | November 2014   | 9                  | 0.0057                   | 831,983     | 0.0016                    |
| XLGNC            | June 2015       | 9                  | 0.0068                   | 939,226     | 0.0015                    |
|                  | November 2015   | 7                  | 0.0052                   | 1,084,957   | 0.0014                    |
|                  | November 2014   | 10                 | 0.0028                   | 828,291     | 0.003                     |
| DLGC             | June 2015       | 13                 | 0.0052                   | 828,928     | 0.003                     |
|                  | November 2015   | 13                 | 0.0036                   | 815,876     | 0.003                     |

* Referring to Figure 1 for the abbreviations.
3.2. Error Estimate

We used the average value of vertical root mean square error (RMSEsurf) of DEM to measure the error of the calculated volume of erosion and deposition. The value of RMSEsurf is calculated by [48]:

\[
\text{RMSE}_{\text{surf}} = \sqrt{\frac{5}{9} \text{RMSE}_{\text{SDE}}^2 + (a \text{SDHD}^b N^c)^2}
\]

(1)

where RMSE_{SDE} is the sample data error, expressed as the root mean square error (m), SDHD is the standard deviation of the height difference ($\Delta Z_p$) between adjacent grid points in the DEM (m), $N$ is the sampling density (points/m$^2$) and $a$, $b$ and $c$ are empirical parameters. The item $a \text{SDHD}^b N^c$ refers to the error induced by the information loss related to the terrain roughness and the density of original sample points as well as to the resolution of DEM to be generated.

In the study of Aguilar et al. [48], the three parameters $a$, $b$ and $c$ were determined to be 0.4168, 0.9506 and $-0.4703$, respectively, for the DEM with a resolution of $2 \times 2$ m$^2$. As the gullies in the present study have a small dimension and were measured by dense sample points, DEMs of $0.1 \times 0.1$ m$^2$ were generated. Following the methods given in Aguilar et al. [48], we recalculated the parameters $a$, $b$ and $c$ to be 0.379, 0.615, and $-0.145$, respectively.

The value of $\Delta Z_p$ is defined as:

\[
\Delta Z_p = \frac{\sum_{k=1}^{8} |Z_p - Z_k|}{8}
\]

(2)

where $Z_p$ is the elevation at the central point of a $3 \times 3$ node mobile window (node $P$) in the DEM, and $Z_k$ is the elevation of each of the eight points surrounding the node $P$.

The propagated error from two DEM surfaces can be derived as follows [49–51]:

\[
U_{\text{crit}} = \sqrt{(\sigma_1)^2 + (\sigma_2)^2}
\]

(3)

where $U_{\text{crit}}$ is the critical threshold error, and $\sigma_1$ and $\sigma_2$ are the standard deviation of error (RMSEsurf in Equation (1)) in each surface, respectively (assuming a Gaussian distribution of errors).

3.3. Data

The rainfall data were downloaded from China Meteorological Data (http://data.cma.cn/, 3 March 2022). The Normalized Difference Vegetation Index (NDVI) data were downloaded from the website of Geospatial Data Cloud (http://www.gscloud.cn/, 3 March 2022). The runoff and sediment data were collected from the hydrologic year books issued by Yellow River Conservancy Commission.

4. Results

Since the 10 kongduis are rainy from July to October and windy from November to the next June, the scanning data recorded in November 2014 and in June 2015 were used to investigate the wind erosion in spring and winter and those recorded in June and November 2015 were used for disclosing the water erosion in summer.

4.1. Erosion and Deposition in the Gully as a Whole

Using 12 DEMs of the gullies built from the TLS measurements, we derived 8 DEMs of difference (Figures 2 and 3) and calculated the net variations of gully volume in 2 periods, with the negative values for erosion and the positive for deposition (Table 3). The gullies are underlain by pisha sand stone and loess, in which the pisha sand stone has a dry bulk density of 1.625 g/cm$^3$, and it is 1.34 g/cm$^3$ for the loess [52,53]. Here, we use the average
value of the dry bulk density of the two strata, 1.48 g/cm$^3$, for approximately transforming volume to weight as given in Table 3.

**Figure 2.** Changes in surface elevation of gullies (DEMs of difference) between November 2014 and June 2015 (Refer to Figure 1 for the abbreviations).

**Figure 3.** Changes in surface elevation of gullies (DEMs of difference) between June and November 2015 (Refer to Figure 1 for the abbreviations).
Table 3. Volume changes in each gully over two monitoring periods.

| Gully Name * | Scanned Area of Gullies (m²) | Volume Changes and Errors (m³) November 2014–June 2015 | June 2015–November 2015 | Siltation Modulus (g/m²) November 2014–June 2015 | June 2015–November 2015 | Erosion Modulus (g/m²) November 2014–June 2015 | June 2015–November 2015 |
|--------------|-----------------------------|--------------------------------------------------------|------------------------|---------------------------------------------------|------------------------|-----------------------------------------------|------------------------|
| MBLC         | 2419                        | 0.959 ± 0.568                                          | −0.302 ± 0.512         | 587                                               | 185                    | 856                                           | 24,800                 |
| XLGNC        | 54                          | 0.031 ± 0.030                                          | −0.906 ± 0.029         | 856                                               |                        | 24,800                                        |                        |
| XLGBC        | 146                         | 0.073 ± 0.059                                          | −0.425 ± 0.058         | 735                                               |                        | 4300                                          |                        |
| DLGC         | 435                         | 0.205 ± 0.064                                          | −0.072 ± 0.064         | 697                                               |                        | 244                                           |                        |

* Refer to Figure 1 for the abbreviations.

As shown in Table 3, during the first period, net siltation occurred in all gullies, and the siltation modulus was 587 to 856 g/m². During the second period, all gullies had net erosion, and the erosion modulus was 185 to 24,800 g/m².

4.2. Erosion/Deposition on the Slopes and Beds of Gullies and Yearly Gully Erosion

Erosion and deposition may coexist in a gully in a period. For disclosing the sediment storage and release in the gully itself and considering the topographic character, a gully here is divided into two units, i.e., gully slope and gully bed. We calculated the volumes of erosion and sediment deposition on both gully slopes (GS) and gully beds (GB) in the two observation periods, and the results are given in Table 4.

Table 4. Volume changes in gully slopes and gully beds during two monitoring periods.

| Gully Name * | Area (m²) | Volume Changes and Errors (m³) November 2014–June 2015 | June 2015–November 2015 | Siltation Modulus (g/m²) November 2014–June 2015 | June 2015–November 2015 | Erosion Modulus (g/m²) November 2014–June 2015 | June 2015–November 2015 |
|--------------|-----------|--------------------------------------------------------|------------------------|---------------------------------------------------|------------------------|-----------------------------------------------|------------------------|
| MBLC         | GS 2186   | −5.977 ± 0.551                                         | 13.108 ± 0.503         | —                                                  | 8875                   | 4047                                          | —                      |
|              | GB 236    | 6.937 ± 0.138                                          | −13.411 ± 0.096        | 44,060                                            | —                      | 85,183                                        | —                      |
| XLGNC        | GS 33     | −0.892 ± 0.024                                         | −0.345 ± 0.023         | —                                                  | —                      | 40,000                                        | 15,500                 |
|              | GB 21     | 0.923 ± 0.018                                          | −0.561 ± 0.018         | 65,000                                            | —                      | 39,500                                        | —                      |
| XLGBC        | GS 122    | −0.118 ± 0.053                                         | −0.803 ± 0.051         | —                                                  | 1430                   | 9740                                          | —                      |
|              | GB 24     | 0.190 ± 0.027                                          | 0.378 ± 0.027          | 11,700                                            | 23,300                 | —                                             | —                      |
| DLGC         | GS 400    | −0.557 ± 0.061                                         | 0.357 ± 0.061          | —                                                  | 1320                   | 2060                                          | —                      |
|              | GB 35     | 0.762 ± 0.017                                          | −0.429 ± 0.016         | 32,200                                            | —                      | 18,100                                        | —                      |

* Refer to Figure 1 for the abbreviations.

As shown in Table 4, the gully slopes were eroded and the gully beds were silted up in dry seasons. In rainy seasons, the gully slopes of two surveyed gullies were eroded, but sediment accumulation occurred on gully slopes of the other two, and three of the four gully beds were eroded.

A sum of sediment erosion and deposition on the gully slopes and bed of a gully can give an estimate of gully erosion in the period of November 2014 to November 2015, but the sediments accumulated on the gully slopes in rainy season should be excluded because these sediments come from water erosion on the inter-rill slopes. Thus, the gully erosion in MBLC is 12.45 m³, which gives a specific sediment yield of 7618 g/m². The volume and specific sediment yield of gully erosion are 0.875 m³ and 24,000 g/m², respectively, in the XLGNC gully; 0.352 m³ and 3570 g/m², respectively, in the XLGBC gully; and 0.224 m³ and 763 g/m², respectively, in the DLGC gully. The weighted mean specific sediment yield of gully erosion is 13,700 g/m² for the XLGNC and XLGBC gullies in the Xiliugou Kongdui.
5. Discussion

5.1. Erosion and Deposition in Gullies

In the 10 kongduis, the water erosion and wind erosion are coupled through the following processes. In spring and winter, a large number of coarse particles are transported from slopes and sand dunes to the gullies, main channels and floodplains and temporarily stored there. In the following summer, high flows may be generated in the upstream hilly and gully regions and develop into hyperconcentrated flows through incorporating a large amount of fine sediment, which forms a part of the homogeneous liquid phase of the hyperconcentrated flows. The hyperconcentrated flows can transport downward the coarse sediment stored in spring and winter. When the hyperconcentrated flows formed in the upper reaches flow through the desert, it will result in the erosion of the sandy banks and carry a large volume of sand downstream. This is the mechanism of highly efficient sand delivery in the study area proposed by Xu [38]. Therefore, the gullies and main streams of the kongduis tend to be silted up in spring and winter and to be eroded in summer. In other words, interseasonal sediment storage and release exists in the sediment delivery processes in the study area. The data of all the surveyed gullies in the three kongduis prove the existence of the interseasonal sediment storage and release. In dry seasons, all the surveyed gullies have an increase in sediment storage (Table 3), which should come mainly from wind erosion on inter-rill slopes, and in the gullies themselves, sediment storage on the gully bed is further enlarged by sediment erosion on the gully slopes (Table 4). In rainy seasons, most of the gully beds were eroded, reflecting the process of sediment release. Nevertheless, Table 3 also shows that the storage in winter and spring was larger than the release in summer in the measured gullies, and an increase in storage might also occur in summer, as indicated by the accumulation on the gully slopes of sediment from water erosion on inter-rill slopes in MBLC and bed siltation in XLGBC (Table 4). In addition, according to Yang and Shi [39], the dunes on the bank slope in the Maobula Kongdui were silted up both in the winter and spring from November 2014 to June 2015 and in the summer from June 2015 to November 2015. Thus, in addition to interseasonal sediment storage and release, interannual sediment storage and release also exist in the sediment delivery processes in the 10 kongduis. In the 10 kongduis, the occurrence of interannual sediment storage may result from the reduction in the carrying capacity of summer flood flows and the attenuation of coupling between wind erosion and water erosion. The dimension of sediment storage and the causes for the reduction in the carrying capacity of summer flood flows and the attenuation of coupling between wind erosion and water erosion will be further discussed below.

5.2. Comparison of Specific Sediment Yield between Gullies and Catchments

According to the hydrological data recorded at Tugerige and Longtouguai stations (Figure 1), the drainage areas for those 2 hydrological stations are 1036 km$^2$ and 1157 km$^2$, respectively, the suspended sediment load of both the Xiliugou and Maobula kongduis varied considerably but has kept on a low level since 2004 (Figure 4). The average annual suspended sediment discharge was $550 \times 10^4$ t/yr at Tugerige in the Maobula catchment and $504 \times 10^4$ t/yr at Longtouguai in the Xiliugou catchment during 1960 to 2003, and they had decreased to $31.5 \times 10^4$ t/yr and $43.7 \times 10^4$ t/yr, respectively, during 2004 to 2015. In 2015, the annual suspended sediment load was only $0.142 \times 10^4$ t/yr at Tugerige and $0.026 \times 10^4$ t/yr at Longtouguai.

The bed load has not been measured in the two kongduis. Here, the bed load of the two kongduis is roughly estimated using a relation between the ratio of bed/suspended load and drainage area of catchments given by Zhu [54]. The relation is $R = 33/A^{0.63}$, where $R$ is the ratio of bed/suspended load, and $A$ is the drainage area in km$^2$. It is based on data of flume experiments or sediment budgets of reservoirs of 20 cases in the Yellow River and the Yangtze River in China. With the drainage areas of the Maobula and Xiliugou kongduis, the ratio of bed/suspended load was estimated to be about 0.4 for both of the kongduis, so the total load is 1.4 times of the suspended load of the 2 kongduis. Multiplying the mean
sediment loads of the 2 kongduis by 1.4 and dividing them by the corresponding drainage area of the 2 kongduis, the specific sediment yield of the Maobula and Xiliugou catchments was calculated to be 7432 t/km² and 6099 t/km² over 1960–2003, 426 t/km² and 529 t/km² over 2004–2015 and only 1.93 t/km² and 0.31 t/km² from November 2014 to November 2015, respectively.

![Figure 4. Changes in sediment load of the Maobula and Xiliugou kongduis.](image)

As mentioned above, the surveyed gullies in the Maobula and Xiliugou kongduis had a specific sediment yield of 7618 g/m² and 13,700 g/m², respectively. Measured on the satellite images, the area of gullies accounts for about 17.3% of the Maobula catchment and 15.5% of the Xiliugou catchment. Thus, even taking the gully erosion as the only sediment sources in the two kongduis, the specific sediment yield of the two kongduis was roughly about 1310 t/km² and 2080 t/km², respectively. These figures are much higher than the specific sediment yield derived from both the river loads in 2015 and during 2004 to 2015. Clearly, the sediment discharge of these two rivers reduced greatly during recent years as a result of storage of a large portion of the eroded sediment in their catchments. In other words, the sediment delivery ratio (SDR) of the two kongduis has declined to a very low value much lower than unity in recent years.

As mentioned in the studies by Mou and Meng [55] and Walling [56], the SDR in the catchments on the Loess Plateau in China approaches unity owing to the dominance of active gully erosion and the occurrence of hyperconcentrated flows. Erosion in the kongdui catchments is also dominated by gully erosion as illustrated by the above estimate of the gross erosion in the period from November 2014 to November 2015. Moreover, most of the sediment load of the kongduis was carried by hyperconcentrated flows [38,41,57]. In addition, both the 10 kongdui basins and the Loess Plateau are on the uplifting Ordos block. Thus, the 10 kongdui basins are similar to the loess catchments in the processes of sediment yield and delivery and have a long-term SDR of unity. The much lower specific sediment yield and SDR of the two catchments in recent years suggests that sediment delivery processes in the kongduis had changed considerably.

5.3. Causes for Changes in Sediment Delivery Processes

The reduction in sediment load and sediment delivery capacity can be ascribed to the changes in hyperconcentrated flows, which had been the main sediment conveyor in the kongduis. For certifying this ascription, we made a statistic on the sediment load of hyperconcentrated flows in both the Maobula and Xiliugou catchments. Here, the flows with a daily mean sediment concentration of over 200 kg/m³ are regarded as hyperconcentrated flows following Yao et al. [57]. In the Maobula catchment, the sediment load of hyperconcentrated flows accounted for 96% of the total load in 1982–1990 but the percentage decreased to 41% in 2006 to 2015. Furthermore, the annual mean sediment load of hyperconcentrated flows in 2006 to 2015 was only 1% of that in 1982 to 1990. Similarly, in the Xiliugou catchment, the proportion of sediment load of hyperconcentrated flows to total load reduced from 85% in 1964–1990 to 36% in 2006–2015, and the annual mean
sediment load of hyperconcentrated flows in 2006–2015 was only 4.3% of that in 1964 to 1990. Hence, the reduction in the SDR of the two kongduis should be attributed to the decrease of hyperconcentrated flows in recent years.

Then, what are the main factors that result in the decrease in hyperconcentrated flows? The two key factors determining the runoff generation and soil erosion are the changes in rainfall and land cover. In regard to the rainfall, as shown in Figure 5, the frequencies of different daily rainfalls in 1960–2003 were nearly same as those in 2004–2015, while both the Maobula and Xiliugou kongduis carried a very large sediment load in the former period than in the latter period (Figure 4). Therefore, the reduction in hyperconcentrated flows should be attributed mainly to the alteration of land cover. Since 1999, soil and water conservation projects, including biological measures on slopes and engineering measures in gullies, have been implemented in the 10 kongduis on a large scale [58]. Subsequent to the implementation of biological measures on slopes, such as returning agricultural land to forestland or grassland, planting forest and grass, building enclosures, etc., the vegetation cover was significantly improved (Figure 6). The engineering measures in gullies are the construction of sediment-trapping dams. According to the survey data of the Soil and Water Conservation Bureau in Ordos, by the end of 2015, there were 113 sediment-trapping dams in the Xiliugou catchment with a total capacity of $5514 \times 10^4$ m$^3$ and a controlling area of $261.3$ km$^2$, and there were 66 sediment-trapping dams in the Maobula catchment with a controlling area of $124.13$ km$^2$. Through trapping sediment, uplifting the base level of erosion and reducing the slope of gullies, the sediment-trapping dams can reduce the occurrence of hyperconcentrated flows. Yet, comparing the controlling areas of the dams in gullies with the drainage areas of the gullied upstream catchments of the Xiliugou and Maobula kongduis, which are about $1070$ km$^2$ and $1110$ km$^2$, respectively, the engineering measures could not be the main contributor for the reduction of hyperconcentrated flows.

![Figure 5](image-url)  
**Figure 5.** Comparison of percentages of different daily rainfalls at Dongsheng station between two periods.

![Figure 6](image-url)  
**Figure 6.** Changes in NDVI in two kongduis.
Therefore, the biological measures on slopes are effective in controlling soil loss in the 10 kongduis. It is mainly the recovery of vegetation promoted by these biological measures in the kongduis that lowers the sediment yield and sediment delivery ratio through reducing the inter-rill slope erosion and the frequency of the hyperconcentrated flows. With less hyperconcentrated flows in recent years, most of the sediment accumulated in the upstream gullies could not be delivered downstream as indicated by the gully monitoring data.

6. Conclusions

Owing to the low coverage of high-quality surveying data, our knowledge is still insufficient about the mechanisms of soil erosion and sediment delivery in many catchments interfered by human activities and climate change. This study demonstrates that repeated survey of gullies can reliably quantify the intensity of gully erosion, which is often one of the main sediment yield processes in catchments and help us to further disclose the variations in erosion and sediment delivery in catchments under changing environment. Our conclusions obtained were as below: (1) The mechanism of interseasonal and inter-annual sediment storage and release existed in the three monitored kongduis. The gully erosion was still at a high rate with a yearly specific sediment yield of 7618 g/m², 763 g/m² and 13,700 g/m² in the surveyed gullies of the Maobula, the Dongliugou and the Xiliugou kongduis, respectively, over the period from November 2014 to November 2015.

(2) The sediment delivery ratios of the Maobula and Xiliugou kongduis were much lower than their counterparts in the long term. The reduction in sediment delivery ratios in recent years and the higher storage than release of sediment in gullies and main channels could be related mainly to the increase in vegetation coverage by applying biological measures on slopes. The increased vegetation coverage has effectively hindered the occurrence of hyperconcentrated flows that were responsible for the high efficiency of sediment delivery in the 10 kongduis in the past. The sediment-trapping dams built in gullies have also made a minor contribution to the reduction in the sediment delivery ratio in the kongduis.

(3) The annual sediment yield of the Maobula and Xiliugou catchments in this paper is a rough estimate as only several small gullies in the catchments had been surveyed. The changes in the calculated sediment yield and the sediment delivery ratio are generally in accordance with the possible impacts of changes in the natural conditions and human activities in the two catchments and therefore are reliable, at least qualitatively. Nevertheless, a substantial improvement in the estimate could be anticipated by a large amount of field surveys in the future.

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