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Historic sediment yields in a small ungauged catchment controlled by a warping dam, using sediment deposition information and ^{137}Cs dating

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Abstract In the hilly and gully region of the Loess Plateau, China, warping (check) dams are one of the most important engineering measures for controlling soil and water loss, and reducing downstream sediment yields. Based on detailed field observations, the sediment profile upstream of the third warping dam, located in a small ungauged watershed (Guandigou) of the Wangmaogou catchment, was divided into 31 sedimentary layers, and the sediment thickness and ^{137}Cs activity of each layer were measured. Peaks in ^{137}Cs activity in the sediment layers were equated to 1963 (peak in fallout) and 1986 (Chernobyl incident). These dated layers, in combination with historical information on erosive rainstorm events, were used to date the timing of sediment deposition for each layer. Based on the information on sediment thickness for the 31 layers, and field measurements of the surface area of each layer, the specific sediment yields from 1959 to 1987 were estimated. The results indicated that the approach, i.e. the combination of ^{137}Cs dating and the sediment record deposited upstream of a warping dam, could be used to study soil erosion and deposition in small ungauged watersheds in the Loess Plateau region of China.

Key words loess hilly and gully region; warping dam; ^{137}Cs; sediment layers; sediment yields; erosive rainstorm events; dating

INTRODUCTION

The Loess Plateau in China is characterized by highly fragmented terrain, numerous valleys and gullies, extremely poor soil cover, as well as inappropriate and intensive land use, and has one of the most serious water and soil loss problems in the world. This is not only a great threat to society and the natural environment locally and regionally, but also threatens the safety of people and property in the middle and lower reaches of the Yellow River. A warping dam (similar to a check dam) is a dam constructed in a gully within soil loss regions of the Loess Plateau, which is mainly used for flood detention, sediment trapping and also the creation of (relatively flat) cropland. They have played an important role in mitigating flooding and sediment transport problems of the Yellow River, and ensuring the safety of the Yellow River for navigation and other uses (for a review see Chunhong *et al.*, 2004). In addition, the sediment deposited and trapped upstream of the warping dams record the temporal variation in the magnitude and characteristics of soil erosion and sediment yield in the contributing catchment.

The worldwide fallout of ^{137}Cs (half-life of 30.17 years) is associated with atmospheric nuclear tests during the period from the 1950s to the 1970s, with a peak in deposition in 1963, and a secondary peak in many locations due to the Chernobyl incident in 1986 (Owens *et al.*, 1997). Most of the ^{137}Cs fallout deposited on the ground was associated with wet precipitation, and it was strongly and rapidly adsorbed by clay and organic particles in the upper soil layers, with minimal leaching and uptake by plants and animals. Therefore, the movement and distribution of ^{137}Cs fallout is mainly associated with the movement of soil particles. Consequently, ^{137}Cs fallout has been considered a reliable and valuable human-made tracer for studies of soil erosion, and the transportation and deposition of sediment (Ritchie *et al.*, 1974; Longmore *et al.*, 1983; Zhang *et al.*, 1989; Murray *et al.*, 1993; Owens *et al.*, 1997; Li *et al.*, 2005, 2009). In addition, the ^{137}Cs tracing method allows soil erosion to be studied at the watershed scale. In China, a lot of similar studies have been conducted since the 1980s. For example, Zhang *et al.* (1989) used the information on sediment deposition upstream of a warping dam and the ^{137}Cs tracer technique to determine the proportion of the sediment yield derived from gully areas compared to that from inter-gully areas for a small catchment in the hilly region of the Loess Plateau.

The objective of this study is to use the ^{137}Cs dating method and the sediment record deposited upstream of a warping dam in a small ungauged watershed (Guandigou) of the Wangmaogou catchment in the hilly and gully region on the Loess Plateau, to determine variations of sediment deposition and sediment yield during the period from 1959 to 1987.

MATERIALS AND METHODS

Study area

Wangmaogou catchment (Fig. 1), located in Suide County, Northern Shaanxi, China, is a typical catchment in the first sub-area of the hilly and gully region of the Loess Plateau. It has been identifed as an experimental and demonstration site for studies of soil and water conservation in China (Jiang, 1978). The Wangmaogou catchment (37°34′13″ to 37°36′03″E, 110°20′26″ to 110°22′46″N) is a small sub-catchment located on the left bank of the middle reach of the Jiuyuangou catchment. The total drainage area of the Wangmaogou catchment is 5.97 km^2, and the areas of gully and inter-gully land occupy 41.6% and 58.4% of the catchment, respectively. In addition, the main stream length of the catchment is 3.75 km, and the average channel gradient and gully density are 0.027 and 4.3 km km^{-2}, respectively. Slope gradients for much of the ground surface in the catchment are >20°, with 30.4% of the catchment >35°. Thus, the Wangmaogou catchment has a complex topography, with fragmented terrain, gullies, steep slopes and deep valleys.

The Wangmaogou catchment has a typical continental climate with an average annual precipitation of 513.1 mm and an average annual temperature of 10.2°C. Over 70% of annual precipitation is mainly confined to a few rainstorm events with high intensity and short duration during the period from June to September. Soil erosion in the catchment mainly consists of water erosion and gravitational (mass movement) erosion. Before the implementation of soil and water conservation measures in 1953, mean annual sediment yield at the outlet of the catchment was about 18 000 t km^{-2} year^{-1}, and about 95% of the annual sediment yield came from a few heavy rainstorm events in the flood season (prior to 1953).

This study focuses on the Guandigou sub-catchment (Fig. 1), which is one of the first tributaries in the upper Wangmaogou catchment, with a drainage area of 1.18 km^2. There are eight warping dams in the Guandigou sub-catchment, in which the third warping dam was built in spring 1959. The drainage area upstream of the third warping dam is about 0.046 km^2, and the main stream length upstream of the dam is 0.168 km. The silted area upstream of the warping dam reached a maximum value of 4303 m^2 but the dam was destroyed by a storm flood in autumn 1987.

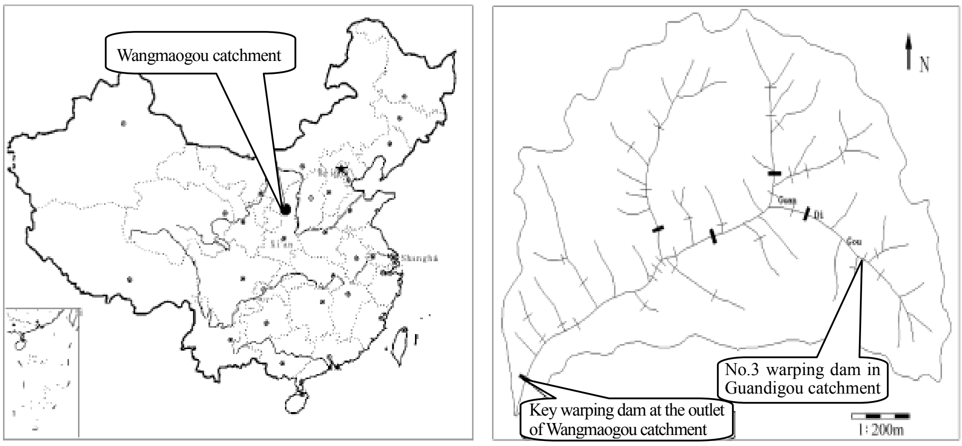

Fig. 1 Location of the study catchment.

Sampling and analysis

Sampling of sediment deposited upstream of the third warping dam was conducted in May 2005. The sampling site was in the middle of the exposed area of sediment deposition, left after the failure of the dam in 1987, which was 40~50 m upstream of the location of the dam. Based on detailed field observations, the sediment profile was divided into 31 sedimentary layers, and the thickness of each layer was measured using a steel tape. For most layers, a sample was collected for determining bulk density. Adjacent layers were mixed uniformly so as to provide a greater mass of sediment for subsequent analysis.

The larger, combined sediment samples were air-dried, weighed, crushed, and passed though a 1-mm sieve, and grass roots and small stones were removed. For each sample, about 400 g was placed in a container for measurement by high purity germanium gamma-ray spectroscopy. ^{137}Cs was measured by counting the γ rays at 662 keV with a high resolution (1.95 keV at 1.33 MeV of ^{60}Co), high efficiency (50%), high-purity germanium detector and an 8192-channel pulse-height analyser. All samples were counted for approx. 28 800 s (Hou, 2007). Based on the measurement accuracy of high-purity germanium gamma-ray spectroscopy and on replicate measurement of samples, the measurement errors were less than ±5%.

The Yellow River Conservancy Commission built runoff plots and rainfall gauging stations in the Wangmaogou catchment in 1954. Data for single rainstorm events during the period 1959 to 1987 were collected and key parameters for each rainstorm event were determined, such as total rainfall amount, average rainfall intensity, and rainfall erosivity.

RESULTS AND DISCUSSION

Depth distribution of ^{137}Cs activity and the timing of sediment deposition

In the study area, every rainstorm flood is likely to transport a certain amount of sediment, which will be deposited upstream of the warping dam. Because of preferential deposition of particles according to grain size, coarse grains are deposited first, then sand, silt, and finally clay particles, resulting in a distinct sediment layer for each rainstorm event, the thickness of which depends on factors such as rainfall characteristics and sediment yield amount. According to the results of field observations, there was a clear boundary between consecutive sedimentary layers (Fig. 2). Based on this, the vertical sediment profile upstream of the third warping dam was divided into 31 sedimentary layers since the construction of the dam in 1959.

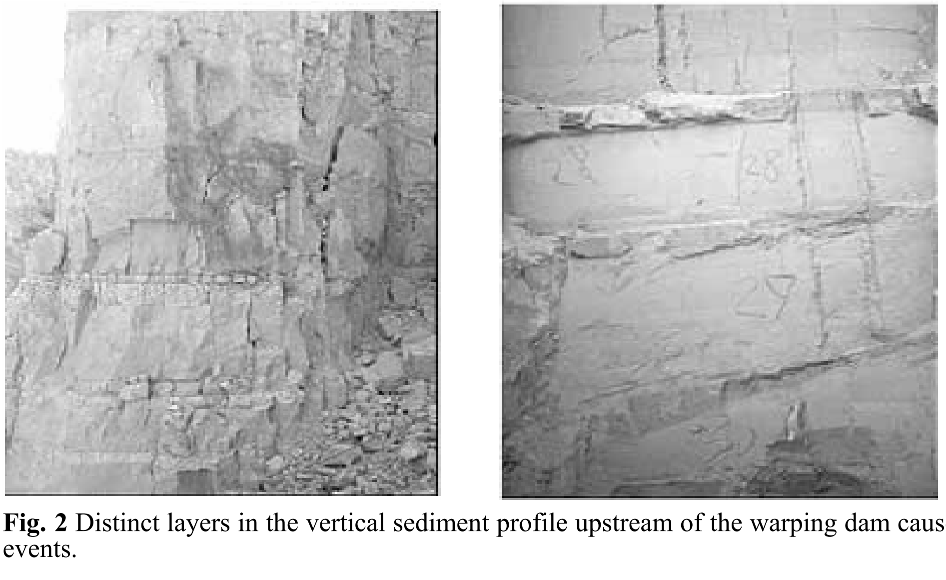

Fig. 2 Distinct layers in the vertical sediment profile upstream of the warping dam caused by rainstorm events.

Most of sediment transported by the rainstorm floods came from surface soil in the catchment, thus ^{137}Cs fallout adsorbed onto the surface soil would be transported with this sediment and subsequently deposited in the area of sedimentation upstream of the warping dam. Using the known peak in ^{137}Cs fallout in 1963, after which levels fell, and a secondary peak in 1986 in parts of the Northern Hemisphere due to the Chernobyl incident, it should be possible to date the sediment layers.

From Table 1, it can be seen that there is variation in the ^{137}Cs content of the deposited sediment layers. The maximum ^{137}Cs content occurs at layer 26 (355–360 cm depth), with another noticeable peak at layer 8 (58–86 cm depth). Based on the pattern of ^{137}Cs fallout, the history of the construction and operation of the dam, and the timing of known rainstorm events in the catchment, it was determined that layer 31 was deposited in 1959 (the time of dam construction), layers 26 and 27 were deposited in 1963, layers 7 and 8 were deposited in 1986, and layers 1, 2 and 3 were deposited in 1987.

Table 1 Depth distribution of ^{137}Cs content in sediment deposited upstream of the warping dam.

Sediment layer	Sampling depth (cm)	^{137}Cs activity (Bq kg^{-1})	Sediment layer	Sampling depth (cm)	^{137}Cs activity (Bq kg^{-1})
Cultivation layer	0–20	1.60	16	124.9–127.5	1.83
1	20–22.9	2.29	17	127.5–129.0	1.57
2	22.9–25.5	0.85	18	129.0–135.8	2.53
3	25.5–29.2	1.26	19	135.8–139.8	2.05
4	29.2–33.1	1.47	20	139.8–142.0	2.82
5	33.1–36.4	1.01	21	142.0–165.5	2.18
6	36.4–40.6	3.13	22	165.5–214.5	1.75
7	40.6–57.6	4.01	23	214.5–288.3	3.07
8	57.6–86.1	4.15	24	288.3–293.3	2.29
9	86.1–101.1	3.74	25	293.3–354.9	3.86
10	101.1–112.6	2.21	26	354.9–359.9	4.57
11	112.6–116.6	1.67	27	359.9–413.9	3.26
12	116.6–119.4	1.3	28	413.9–436.4	4.55
13	119.4–122.0	2.65	29	436.4–464.7	3.79
14	122.0–123.0	0.66	30	464.7–486.7	2.97
15	123.0–124.9	0.83	31	486.7–528.7	3.87

Matching erosive rainstorm events to sediment layers

Not all rainfall events in the Loess Plateau region result in serious soil erosion. Studies (e.g. Zheng *et al.*, 2004) indicate that most of the sediment yield is caused by a few extreme rainstorm events with high intensity and short duration (i.e. erosive rainstorm event). For example, a heavy rainstorm event occurred on 1 August 1961, with mean rainfall of 152.7 mm and duration of 3.1 h. The sediment load at the outlet of Jiuyuangou catchment caused by this rainstorm represented 89% of total annual load for that year. Similarly, the sediment load caused by a rainstorm event that occurred on 19 July 1966 represented 52.6% of total annual load of the Jiuyuangou catchment.

It was possible to associate sediment layers, which had a greater thickness, with particular known heavy rainstorm events. Then, by using the principle of more rainfall results in greater sediment deposition, a corresponding analysis was undertaken, which matched historical erosive rainstorm events and the thickness of sediment layers. However, given the limitation that the number of rainstorm events was more than the number of sediment layers, it was difficult to correlate all of the sediment layers to the historic record of known erosive rainstorm events. This approach, in addition to the layers equated to the ^{137}Cs peaks in 1963 and 1986, and the ^{137}Cs values for each layer (Table 1), was used to determine the age of each sediment layer, which is shown in Fig. 3.

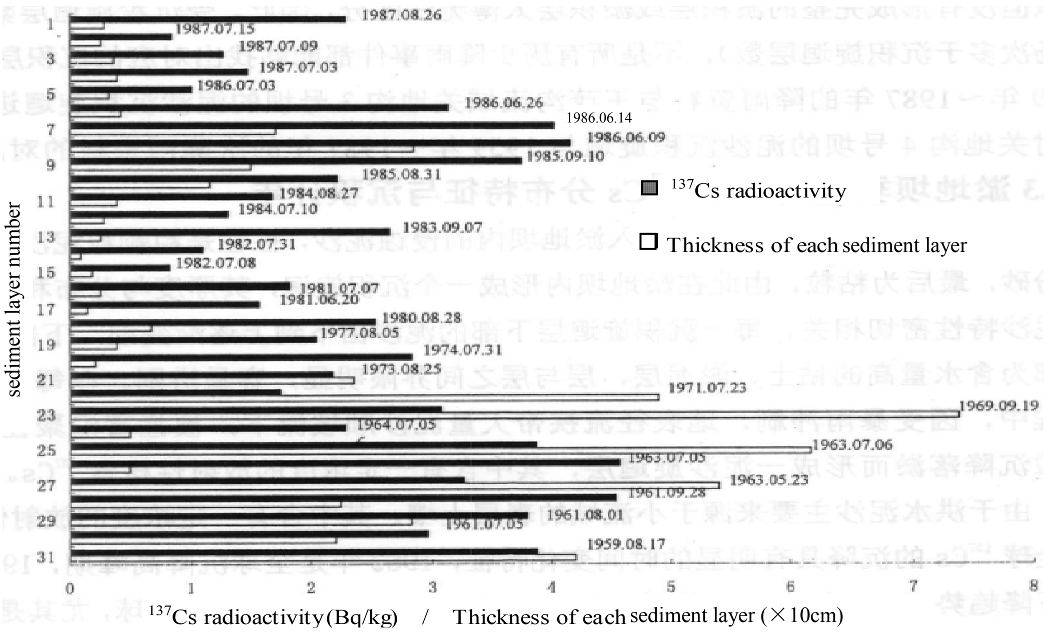

Fig. 3 ^{137}Cs activity and thickness of each sediment layer and the associated date of deposition for the sediment profile upstream of the warping dam in the Guandigou sub-catchment.

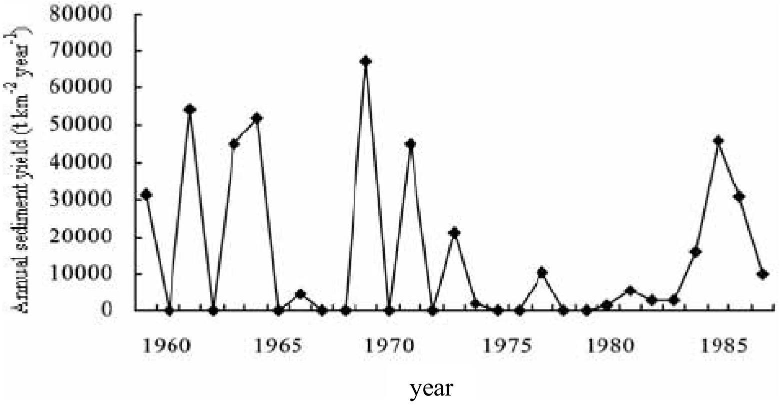

Fig. 4 Variation of soil erosion intensity (as indicated by sediment yields) in the sub-catchment upstream of the warping dam.

Historical variation in sediment yield

Because the warping dam in the Guandigou sub-catchment had no spillway, almost all of the sediment load transported during the erosive rainstorm events was deposited and trapped in the area immediately upstream of the dam. As a result, the sediment deposited in this area can be considered as representing the total sediment yield of this small sub-catchment. Based on the information on sediment thickness for the 31 layers, presented above, and field measurements of the surface area of each layer (determined from cross-section measurements and measurements of slope gradients), it was possible to estimate the specific sediment yield for the period 1959–1987. The total amount of sediment deposited upstream of the dam was estimated at 20 623 t (assuming a sediment dry density of 1.35 t m^{-3}). The mean annual sediment yield for the period 1959 to 1987 was estimated at 16 721 t km^{-2}. Similarly, the mean annual sediment yields from 1959 to 1963 (the construction stage of the dam), from 1964 to 1978 (the development stage) and from 1979 to 1987 (the stable stage), are 28 106, 14 573 and 13 977 t km^{-2} year^{-1}, respectively. The thickness of sediment layers and the estimated sediment yields during the early stages of the dam were generally large, which indicate that soil erosion rates (and sediment delivery) in the contributing sub-catchment was fairly severe. Rates of soil erosion and sediment delivery were lower in the subsequent stages (Fig. 4).

The reasons for the variation in erosion intensity and sediment delivery in the sub-catchment upstream of the warping dam are as follows. First, there were many wet years in the 1960s, for example heavy or extreme rainstorms occurred in 1961, 1963, 1964 and 1969. Second, the area of soil and water conservation in the 1960s occupied a small percentage of the catchment area. Large-scale soil and water conservation measures were adopted during the 1970s and 1980s, which caused a significant increase in the areas of forest and grass land, and an increase in level terraced land, while the area of hillslopes that were cultivated decreased. Hence, the soil erosion and sediment yield that occurred during a storm event in the 1960s was likely to have been more than an equivalent event in the 1970s and 1980s. In addition, the construction of soil and water conservation engineering measures, such as the warping dams, strengthened the stability of gully slopes, which reduced the development of soil erosion at the bottom of gully slopes.

CONCLUSION

We used the ^{137}Cs dating method and the sediment record deposited upstream of a warping dam in a small ungauged watershed in the hilly and gully region of the Loess Plateau, to reconstruct variations in sediment deposition and sediment yield in the upstream sub-catchment from 1959 to 1987. The main conclusions are as follows:

- Based on the information on sediment thickness for the 31 layers, and field measurements of the surface area of each layer, the specific sediment yields from 1959 to 1987 were estimated. The results indicated that the estimated sediment yields during the early stages of the construction and operation of the third warping dam were generally large, which indicate that soil erosion rates (and sediment delivery) in the contributing sub-catchment was fairly severe. Rates of soil erosion and sediment delivery were lower in the subsequent stages. The results indicated that the heavy or extreme rainstorms occurred in the 1960s. Large-scale soil and water conservation measures adopted during the 1970s and 1980s may explain the significant decrease in sediment yields for these periods.
- The approach adopted in this paper, i.e. the combination of ^{137}Cs dating and the sediment record deposited upstream of a warping dam, could be used to study sediment sources, and rates of soil erosion and sediment deposition in small ungauged watersheds in the Loess Plateau region of China.

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