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SEDIMENT YIELD DEDUCTION FROM CHECK–DAMS DEPOSITION IN THE WEATHERED SANDSTONE WATERSHED ON THE NORTH LOESS PLATEAU, CHINA

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ABSTRACT

As the basic unit of erosion and sediment yield, it was critical to determine the amount of soil erosion and sediment yield in the small watersheds for sustaining a reasonable water resource and sediment regulation system. In this study, we determined the sediment yield from the dams-controlled watershed on the North Loess Plateau. Three check dams in the watershed were investigated by drilling ten-hole sedimentation cores. The corresponding flood couplets were dated according to thickness of deposition layers, distribution of sediment particle size and historical erosive rainfall events. On the basis of the check dams capacity curve, the soil bulk density and the thickness of couplets, the deposit mass of check dams, and then the sediment yield of watershed at different temporal and spatial scale were deducted. In total of the 33, 60 and 55 couplets were corresponded to individual flood events in the dam MH1# from 1976 to 1984, the dam MH2# from 1985 to 2007, and the dam MH4# from 1981 to 2009, respectively. The specific sediment yield for flood events was 1,188.5–11,527.9 Mg km^{-2}, 1,278.6–17,136.7 Mg km^{-2}, and 3,395.9–33,698.5 Mg km^{-2}, and the annual average sediment yield was 10,728.6 Mg (km^2 · a)$^{-1}$, 12,662.9 Mg (km^2 · a)$^{-1}$, and 16,753.3 Mg (km^2 · a)$^{-1}$ in dam MH1#, MH2# and MH4# controlled watershed, respectively. The sediment yields were inversely proportional to the dams – controlled areas. For the whole watershed, the annual average sediment yield was 14,011.1 Mg (km^2 · a)$^{-1}$ from 1976 to 2009. There were large amounts of sediments (42.3–50.5%) were intercepted gradually along the way from small watersheds to the river channel. And the minimum rainfall for sediment deposited in the dams was greater than 20 mm in this watershed. The results of this study suggested that the sediments retained behind check dams were helpful to quantifying the amount of erosion sediment yield and understanding the soil erosion evolution in the small and ungauged watersheds. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: soil erosion; check dams; sedimentation couplets; capacity curve; loess Plateau

INTRODUCTION

Soil erosion, as an important global environmental issue, has already greatly affected the environmental quality and social economy (Cerdà *et al.*, 2013; Fu *et al.*, 2011). Severe soil erosion has led to the loss of about 10 million hectares of cropland per year in the world, not only reduces the cultivable land for food production, but also causes land degradation and river siltation (Onyando *et al.*, 2005; Pimentel, 2006). Land degradation is related to accelerated soil erosion rates because of the mismanagement of humans (Novara *et al.*, 2016; Prosdocimi *et al.*, 2016; Taguas *et al.*, 2015). Agriculture land is one of the most affected on account of the millennia old tillage manners, the mechanisation and chemical farming in the last century (López-Vicente *et al.*, 2015; Rodrigo Comino *et al.*, 2015; Rodrigo Comino *et al.*, 2016; Seutloali & Beckedahl, 2015). The long-term land quality deterioration led to substantial financial loss, farmers in Ethiopia lost about USD 220 ha^{-1} and 150 ha^{-1} because of the loss of N and P, respectively (Erkossa *et al.*, 2015). More than 60% of the land on the Chinese Loess Plateau once has been subjected to serious soil erosion, caused the river bed uplift and flood disasters in the lower Yellow River (Shi & Shao, 2000; Xin *et al.*, 2012). In addition, the soil erosion was still a major ecological problem, and the soil erosion rate was higher than 3,600 Mg (km^2 · a)$^{-1}$ in areas with slope gradient over 8° in the Loess Plateau (Fu *et al.*, 2011). Therefore, severe soil erosion has posed a great threat to the sustainable development of resources and environment throughout the world (Wang *et al.*, 2016).

In order to sustain a reasonable water resource and sediment regulation system, it was critical to determine the amount of soil erosion and sediment yield in the small watersheds (Abedini *et al.*, 2012), which are the basic unit of erosion and sediment yield (Wang *et al.*, 2011). Different measures are being applied to reduce soil losses owing to soil erosion is widespread (Cerdà *et al.*, 2009), and a large number of check dams were installed in small watersheds to mitigate soil erosion for their effective sedimentation mitigation (Polyakov *et al.*, 2014). In the SE of Spain, 425 and 58 check dams were constructed in Segura and Rogativa catchments in order to reduce sedimentation, and about 40% and 72% were

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filled with sediments, respectively (Boix-Fayos *et al.*, 2007; Romero-Diaz *et al.*, 2012). A total of 37 loose rock semi-permeable check dams were installed in two small watersheds located in southern Arizona, USA (Polyakov *et al.*, 2014). The 4,400 check dams within four watersheds were constructed on DoiLuang Wildlife Sanctuary in Thailand, which covered an area of 606.3 km^2 (Khonkaen & Cheng, 2011). Up to 2011, a total of 58,446 check dams have been built in China, with a silted land area of 927.57 km^2 (Ministry of Water Resources and National Bureau Statistics P.C., 2011). Sediments trapped in check dams could be an important indicator of environmental change and record of the process of soil erosion and deposition for small watersheds (Wang *et al.*, 2014). Martin-Rosale *et al.* (2003) proved that check dams were very useful for estimating sediment yield in small and ungauged basins by the trap efficiency to reveal the minimum values of the net erosion rate of a basin. Romero-Diaz *et al.* (2012) also concluded that check dams could be regarded as useful tools for estimating the physical losses of soils and erosion rates. By a multi-method comparison, Romero-Diaz *et al.* (2007) calculated the erosion rates from sediments accumulated in the check dams and compared the results with those of the Bathymetric method, the Fournier's and USLE equation and believed that the erosion rates obtained from the check dams more accurate for the sub-basin in the SE Spain.

At present, considerable researches have been undertaken in check dams and reservoirs to determine sediment yield. By using the inventory data, the surface area of the corresponding sub-basins and the age of the check dams, Martin-Rosale *et al.* (2003) determined an approximate estimate of the minimum sediment yield in a semiarid area of southern Spain. Because of the lack of monitoring data on early built check dams, Boix-Fayos *et al.* (2008) and Wang *et al.* (2009) estimated the total sediment yields at the subcatchment level in SE Spain and the total sediment volume in Yangjuangou watershed of the Loess Plateau by field surveys with the high precision differential GPS technique, respectively. Furthermore, Xue *et al.* (2011) based on ^{137}Cs dating, the check dam capacity curve and bulk density curve to estimate the sediment volume in Wangmaogou watershed in the Chinses loess hill and gully region. The radionuclide tracer technique has been widely used to indicate the source of soil erosion, estimate the soil erosion rates and document the erosional response of the small watersheds in many studies (Ben Slimane *et al.*, 2016; Sutherland, 1989; Walling & Quine, 1990; Yang *et al.*, 2006; Zhang *et al.*, 1997; Zhang *et al.*, 2006). Porto *et al.* (2013) used the radionuclides of ^{137}Cs and $^{210}Pb_{ex}$ as sediment tracers to investigate the sediment budget in a small forested catchment of southern Italy, the results confirmed that ^{137}Cs and $^{210}Pb_{ex}$ measurements can provide a valuable tool for quantifying both erosion and sediment redistribution compared with the traditional monitoring techniques. The Soil and Water Assessment Tool model was also used to evaluate the effect of check dam on soil and water conservation at the catchment scale, modelling results indicated that approximately 630 Mg of sediment was estimated to be stored behind check dams over the 3–year simulation at the West Turkey Creek watershed in southeast USA (Norman & Niraula, 2015). Meanwhile, researches attempted to use the deposition record of check dam or reservoir and the monitoring data at the watershed outlet to validate sediment yield model, such as WATEM/SEDEM model (Alatorre *et al.*, 2010) and Annualized Agricultural Nonpoint Source model (Zema *et al.*, 2012; Zema *et al.*, 2016). Thus, the sediment deposition records in check dams, reservoirs or lakes can provide accurate information to obtain soil erosion rate (Alatorre *et al.*, 2010; Romero-Diaz *et al.*, 2007; Zhang *et al.*, 2009).

The main geomorphological characteristics are plateau, ridge, mound and various gullies on the Loess Plateau, where the soil erosion occurred frequently and numerous gullies and fragmented landforms were formed gradually (Xu *et al.*, 2004). Check dam has a long history of development and utilisation in the Loess Plateau region. Furthermore, the spatial pattern of soil erosion indicated that check dams might be suitable for loess hilly plateau (Zhao *et al.*, 2013). The earliest dam was documented from the Ming Dynasty 400 years ago, located in Fenxi County of Shanxi Province. Since the establishment of People's Republic of China, check dam construction in the Loess Plateau has undergone five stages of development. There are the pilot stage in 1949–1957, the demonstration stage in 1958–1970, the development stage in 1971–1980, the consolidation and improvement stage in 1981–2002, and the integrated development stage since 2003. According to the safety survey database of check dams by the end of 2008 in the Loess Plateau, launched by the Ministry of Water Resources, about 91,093 check dams had been built, created 30×10^4 hm^2 dam lands with high productivity, developed 5,300 hm^2 irrigated farmland, and intercepted 10.4 billion m^3 of sediments pouring into the Yellow River (Upper and Middle Yellow River Bureau, 2011). Compared with other soil conservation measures, check dams are the most effective engineering measure to rapidly decrease the amount of sediment entering the Yellow River (Ran *et al.*, 2008; Wang *et al.*, 2011; Xu *et al.*, 2004).

The sediments retained by check dams could provide important information about sediment deposition process, soil erosion evolution and environmental changes in the small watersheds. What's more, understanding the soil erosion and sediment deposition rates in a small watershed was also crucial for designing soil and water conservation measures (Li *et al.*, 2009; Yang *et al.*, 2006). Therefore, the objectives of this research were to (i) interpret the flood couplets and the corresponding sediment deposits in check dam; (ii) estimate the sediment yield in dam-controlled watershed; and (iii) discuss the main influence factors on sediment yield. The results of this study will be helpful for understanding the soil erosion evolution of ungauged and dam-controlled watershed and providing the references on the planning of soil and water conservation measures and watershed management on the North Loess Plateau.

MATERIALS AND METHODS

Study Area

The Huangfuchuan tributary is located in the transitional zone of the Loess Plateau and Ordos Plateau, belongs to the wind–water erosion crisscross region, also is a first-order tributary of the middle reaches of the Yellow River basin (Figure 1; Tian *et al.*, 2013). The Huangfuchuan tributary covers an area of 3,246 km^2 (Wang *et al.*, 2012). The tributary is located in the transitional belt of warm temperate and mesothermal zones, characterised by a semiarid continental climate with average annual rainfall of 380 mm and a mean annual temperature of 7.5 °C (Zhao *et al.*, 2015a). Frequently occurring rainstorms in the summer often cause severe soil erosion in the catchment (Zuo *et al.*, 2016). The landscape was described as "hilly and gully", and the soil types is characterised by weathering sandstone, loess, and desert sand and the land surface is dominated by dense gullies with poor vegetation cover (Wang *et al.*, 2012). The weathering sandstone (locally called *pisha* rock) is a loose rock that specifically refers to an interbedded rock consisting of the Paleozoic Permian (about 2.5 hundred million years) and the Mesozoic Triassic, the Jurassic and the Cretaceous thick sandstone, sand shale and argillaceous sandstone. The annual average sediment discharge at the Huangfu outlet gauging station (Figure 1, the upstream area is 3,199 km^2) was 12,011.3 Mg $(km^2 \cdot a)^{-1}$ from 1955 to 2014 (YRCC (Yellow River Conservation Committee, Ministry of water resources conservancy, China), 2014).

The Manhonggou watershed (39°25′09″–39°26′43″ N,110°58′30″–111°02′14″E) is located within the lower reaches of the Huangfuchuan tributary, at 10.5 km apart away from the mainstream of the Yellow River (Figure 1). The Manhonggou watershed covers a drainage area of 6.8 km^2, the altitude between 915 m and 1150 m. The slope is focused on 15–45°, accounting for 78.4% of the entire watershed. The check dams were constructed step by step from downstream to upstream in Manhonggou watershed, and the basic information was shown in Table I. The land surface is characterised by dense gullies with a gully density of 4.3 km km^{-2}. The watershed was weathered sandstone hilly–gully region, the vegetation coverage was extremely low, and the bedrock was widely exposed so that the gully erosion was very active (Wang *et al.*, 2012).

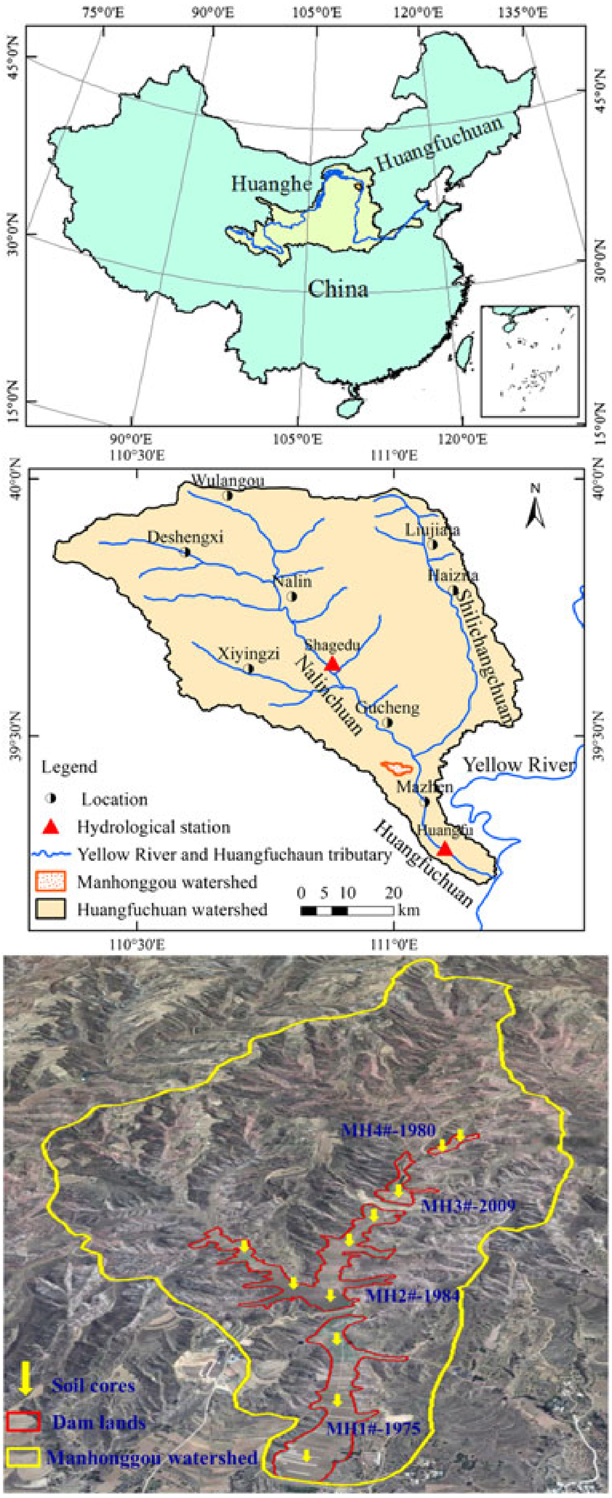


Figure 1. Location of the study area and sampling sites. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Establishment of the Capacity Curve of Check–Dams

We obtained the topography maps (1:10,000) of 1981 and benchmarks of Manhonggou watershed from the Shaanxi Geomatics Center, State Bureau of Surveying and Mapping. Among them, the topography maps were used to establish the capacity curve of check dams, while the benchmarks were used to measure the average elevation of sediment surface and the silt area of check dams by a Total Station with

Table I. The basic information of check dams in the Manhonggou watershed

Dam	Performance period	Deposition years	Watershed area (km^2)
MH1#	1975–1983	9	6.78
MH2#	1984–2008	25	6.10
MH3#	2009–2014	6	3.55
MH4#	1980–2014	35	0.32

an accuracy of ±1 cm. First, we scanned the topography map (1:10,000) of 1981 and vectorized the scope of Manhonggou dams-controlled watershed in ARCGIS 10.1 (Esri China Information Technology Co. Ltd., Beijing, China). Second, the vectorization of topography map was used to produce the digital elevation model. Then, the silt area of check dams at different elevations was obtained by using the Surface Area command of "3D Analyst Tools" in the ARCGIS 10.1 based on the digital elevation model. Finally, the sediment volume was calculated as follows:

$$V = \frac{\left(S + S' + \sqrt{S * S'}\right) * h}{3} \quad (1)$$

Where: V is the sediment volume, (m^3); S and S' are the upper and lower silt area, that is the area surrounded respectively by the two adjacent elevations, (m^2); h is the elevation difference, that is 1 m (Wei *et al.*, 2006). Thus, the capacity curve of check dams could be established by with the cumulative capacity that was obtained through the accumulation of volume (V) as the ordinate and the elevation as the abscissa (Figure 2).

Field Sampling and Flood Couplets Interpretation

Sediment samples were collected in the catchment using drilling machine in May 2014 (Figure 3a). Totally 11-hole soil cores were distributed along the check dams from downstream to upstream, with the drilling depth in between 10.37 m to 17.28 m. In dam MH1#, MH2#, MH3# and MH4#, there were 3, 5, 1 and 2– holes of sediment deposition cores, respectively. Here, it should be stated that it contained water in the front and had road and trees in the middle of the dam MH3#, and the deposition sequence was confused, so it was not used in the analysis of this study.

The corresponding flood couplets can be dated according to thickness of deposition layers, distribution of sediment particle size and historical rainfall events. First of all, the profiles were sectioned carefully to reflect the flood couplets in the check dams according to the deposition characteristics (Figure 4a). The boundaries of the couplets could be easily identified owing to the sediment deposition behind the check dams had obvious layers and the top layer was fine while the bottom layer was coarse in a couplet (Figure 3b; Li & Wei, 2011; Zhang *et al.*, 2006).

Next, the sediment particle size distribution was determined. As the thickness of a couplet ranged from a few centimetres to hundreds of centimetres, we divided it into three samples usually, while some couplets were divided into two or four samples. In total, 452, 1,016 and 374 sediment samples were collected from the profile of the dam MH1#, MH2# and MH4#, respectively. All of the sediment samples were air-dried, and the rhizomes or gravels were removed, and then the samples were crushed and passed through a 2-mm mesh sieve. The particle size distribution of sediment samples was analysed by using a Mastersizer 2000 laser particle size analyser (Malvern Instruments, Malvern, England) with the measurement interval of sizes ranging from 0.02 to 2,000 μm. In general,

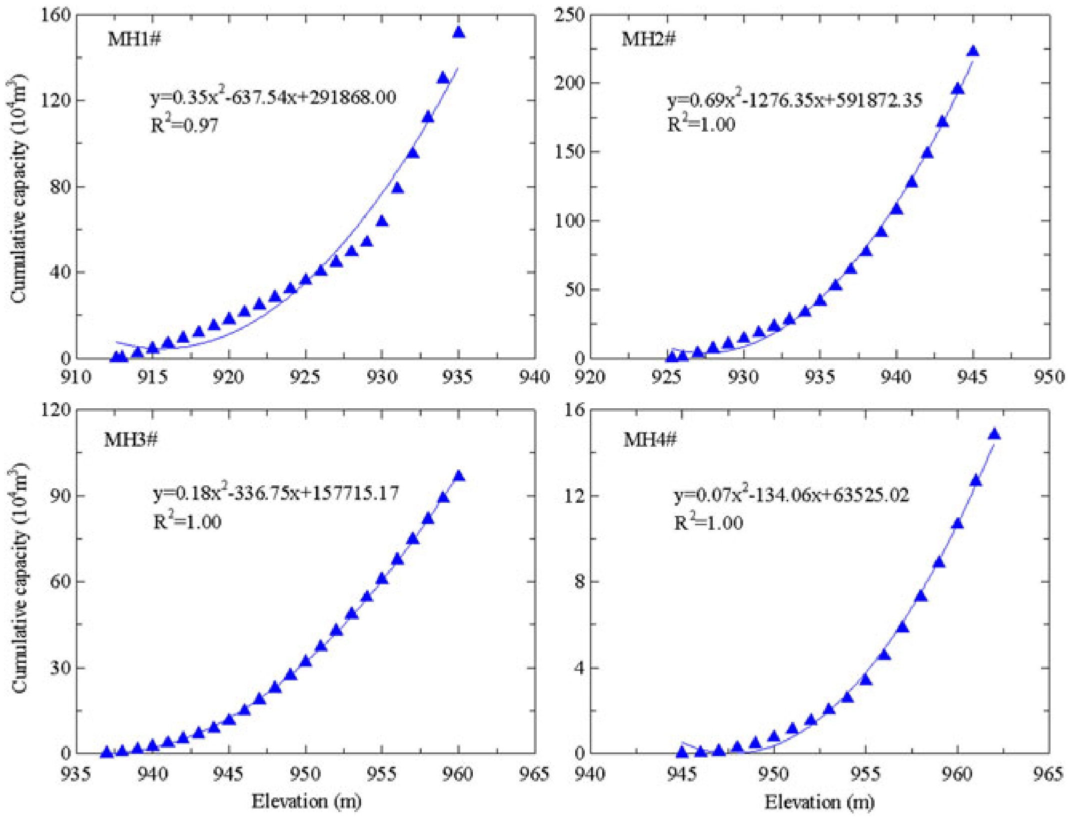


Figure 2. Capacity curve of check dams in the Manhonggou watershed.

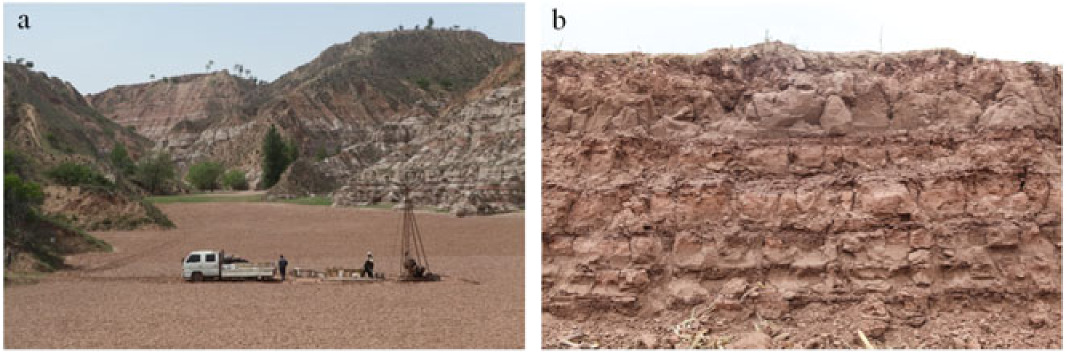
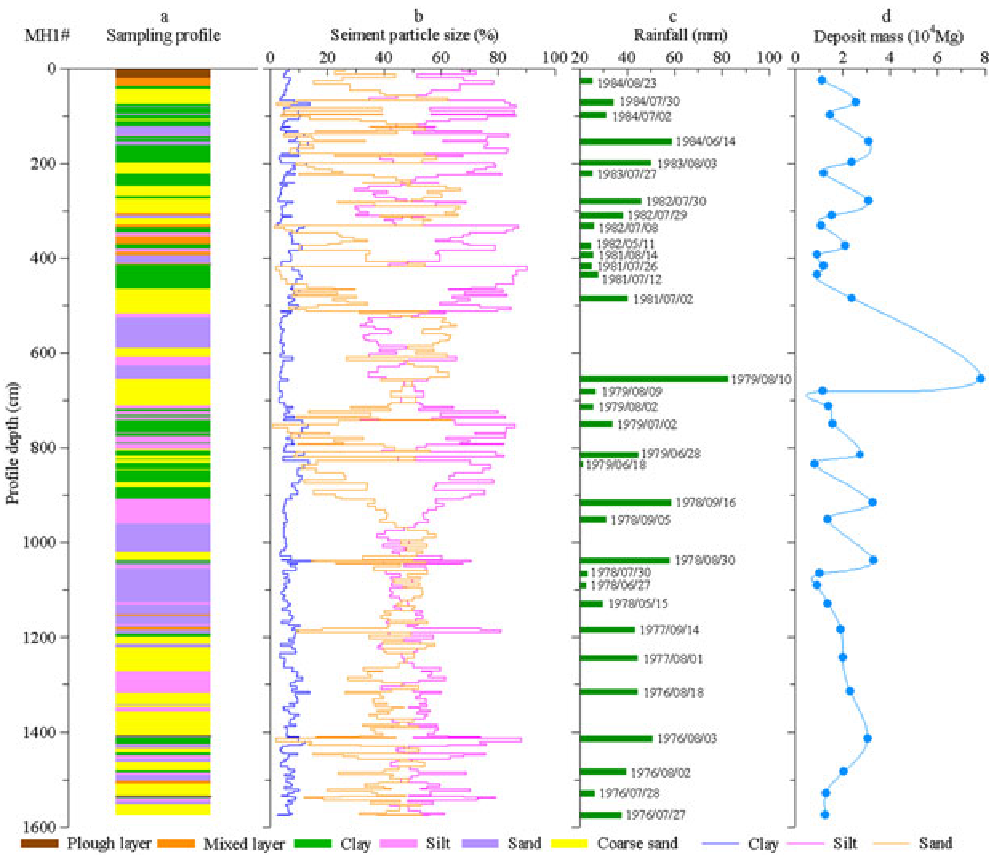


Figure 3. Photos of field sampling and sediment profile in a check dam of the Manhonggou watershed. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

soil particle size distribution was focused on silt and sand fractions, and silt content accounted for more than 50% of the sediments in the three check dams of Manhonggou watershed. In terms of single check dam, the percentage of clay and silt fractions has the same changing trend, while the sand content just the opposite from the top to the bottom in the depth profile. For three check dams, the silt sediment fraction decreasing gradually and the sand content gradually increasing from upstream (dam MH4#) to downstream (dam MH1#; Figure 4b). Meanwhile, a soil cylinder with a volume of 100 cm^3 was used for sampling to measure the soil bulk density for obtaining the sediment yield.

Then, according to the definition of the erosive rainfall event as one with rainfall amount ≥12 mm in the Chinese Loess Plateau (Xie *et al.*, 2000), we selected all rainfall events with daily precipitation greater than 12 mm at the Shagedu station from 1976 to 2009 based on the dates when the check dams was built and used. Owing to the larger rainstorm could result in more sediment deposited behind the check dams and vice versa (Li & Wei, 2011), the 33, 60, and 55 couplets were corresponded to individual flood events in the dam MH1# from 1976 to 1984, the dam MH2# from 1985 to 2007, and the dam MH4# from 1981 to 2009 by careful interpretation of the rainfall data from 1976 to 2009, respectively (Figure 4c).



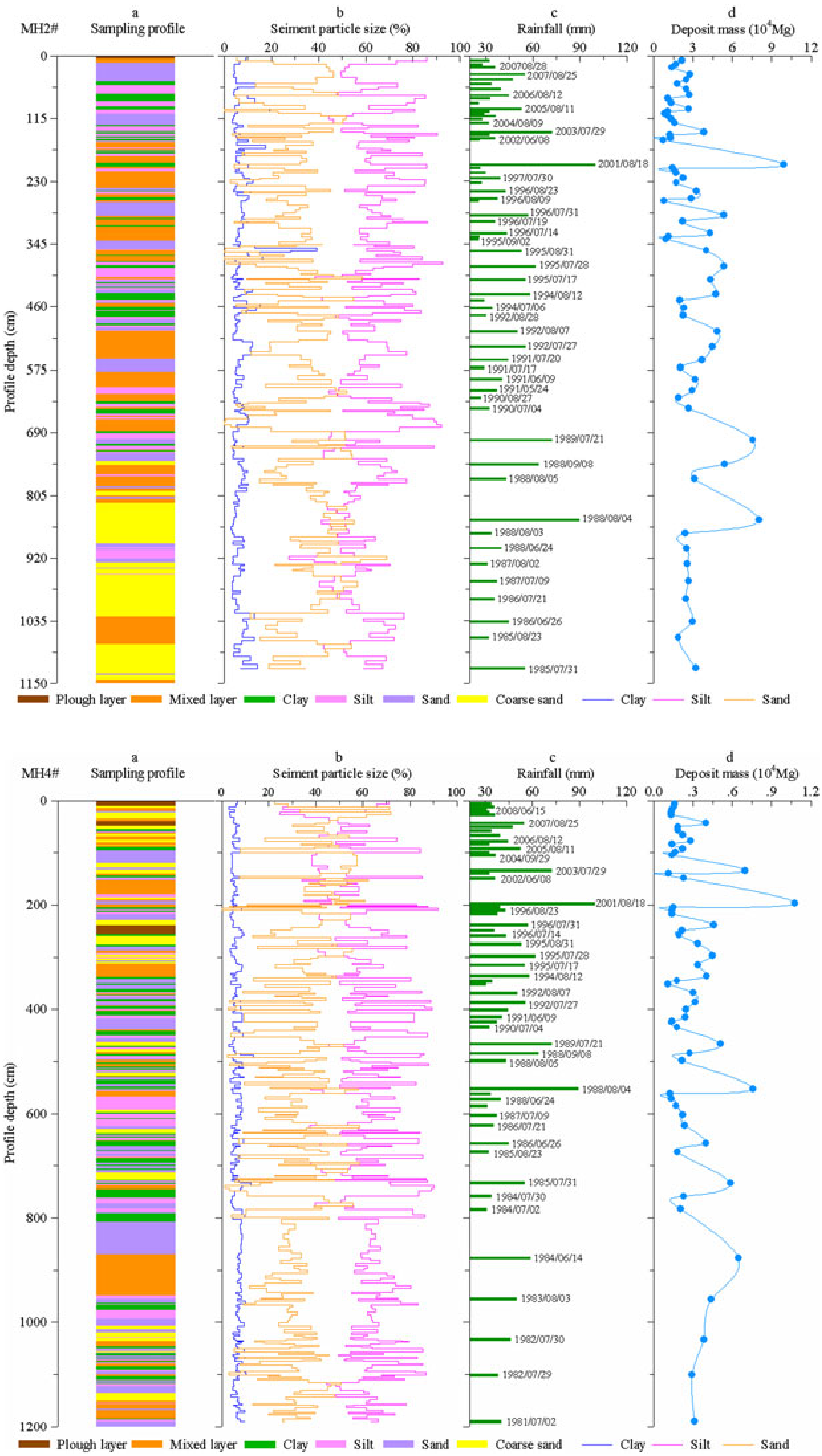


Figure 4. Corresponding relationship between sediment particle size, historical rainfall events and deposit mass in dam MH1#, MH2# and MH4#. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Estimation of Sediment Deposit Amount

On the basis of the capacity curve, the soil bulk density and the thickness of couplets, we applied the following formula to estimate the sediment deposit mass in dam MH1#, MH2# and MH4# (Figure 4d).

$$W_i = V_i \times \rho_i \quad i = 1,\ 2 \ldots n,$$
$$n = 33, 60 \text{ and } 55 \text{ of MH1 \#, MH2 \# and MH4 \#} \tag{2}$$

$$W = \sum_{i=1}^{n} W_i \tag{3}$$

Where: W_i is the sediment deposit mass of the couplet i, (Mg); V_i is the volume of the couplet i, (m^3); ρ_i is the soil bulk density of the couplet i, ($Mg\,m^{-3}$); and W is the total sediment deposit mass of a check dam, (Mg).

Sediment Yield Deduction

The total deposit volume and deposit mass of check dams in the Manhonggou watershed were shown in Table II. The annual deposit mass of dam MH1#, MH2# and MH4# is accumulated by the sediment deposit mass of all the couplets in the same year, while the annual deposit mass of Manhonggou watershed derived from the average of annual deposit mass in dam MH1#, MH2# and MH4#.

At the runoff event scale, the specific sediment yield were obtained through the sediment deposit mass of the couplets dividing by its controlled watershed area. At the annual scale, the annual sediment yield were determined through the annual deposit mass of dam MH1#, MH2# and MH4# dividing by its controlled watershed area, respectively. At the watershed scale, the annual sediment yield of Manhonggou watershed was got from the average of annual sediment yield of dam MH1#, MH2# and MH4# controlled watersheds.

In addition, the sediment deposition in dams represents the majority of total amount of erosion within the watershed because the sediment deposition along the way before reaching the dams and sediment transport by the spillway of check dams.

Table II. Total deposit volume and deposit mass of check dams in the Manhonggou watershed

Dam	Sampling cores	Deposit volume ($10^4\,m^3$)	Deposit mass (10^4 Mg)
MH1#	MH1D1	45.0	40.9
	MH1D2	64.1	66.4
	MH1D3	84.1	97.1
MH2#	MH2D1	106.3	96.2
	MH2D2	118.9	138.2
	MH2D3	138.8	127.2
	MH2D4	112.6	99.5
	MH2D5	132.3	161.7
MH4#	MH4D1	7.0	7.7
	MH4D2	8.4	9.3

RESULTS

Sediment Yield at the Runoff Event Scale

In dam MH1#, the rainstorm events for 33 couplets were identified by careful interpretation of the rainfall data from 1976 to 1984 (Figure 5). There were 1 and 32 runoff events with the specific sediment yield greater than 10,000 Mg km^{-2} and 1,000–5,000 Mg km^{-2}, respectively. The largest single-day rainfall was 82.5 mm on 10 August 1979, corresponded to the highest specific sediment yield for runoff event of 11,527.9 Mg km^{-2}. The lowest specific sediment yield was 1,188.5 Mg km^{-2}, corresponded to the smallest single-day rainfall was 21.1 mm on 18 June 1979.

In total, 60 flood couplets were identified from 1985 to 2007 in dam MH2# (Figure 5). There were 3, 17 and 40 runoff events with the specific sediment yield greater than 10,000 Mg km^{-2}, 5,000–10,000 Mg km^{-2}, and 1,000–5,000 Mg km^{-2}, respectively. The specific sediment yield for flood events varied from 1,278.6 Mg km^{-2} to 17,136.7 Mg km^{-2}, corresponded to the daily rainfalls from 25.8 to 99.6 mm.

In dam MH4#, the 55 flood couplets during the period from 1981 to 2009 were identified (Figure 5). There were 4, 11, 25 and 15 runoff events with the specific sediment yield greater than 20,000 Mg km^{-2}, 10,000–20,000 Mg km^{-2}, 5,000–10,000 Mg km^{-2} and 1,000–5,000 Mg km^{-2}, respectively. The daily rainfalls ranged from 30.3 to 99.6 mm, corresponded to the specific sediment yield of 3,395.9 Mg km^{-2} and 33,698.5 Mg km^{-2}.

Moreover, the rainstorms and the high specific sediment yield behind the check dams are synchronous generally. In the erosive rainfall events with rainfall amount ≥12 mm, there was soil erosion but no sediment transported to the dams for some smaller rainfall events. In this study, the minimum rainfall for sediment deposited in the dams was greater than 20 mm. There was fairly good linear regression relationship between specific sediment yield and rainfall at the runoff events scale in dam MH1#, MH2# and MH4#; the R^2 values were 0.82, 0.86 and 0.82, respectively (Figure 5).

Sediment Yield at the Annual Scale

Figure 6 was the annual sediment yield, the corresponding rainfall and correlation at the annual scale in dam MH1#, MH2# and MH4#. The annual sediment yield ranged from almost no sediment load to 22,821.2 Mg km^{-2} with an average of 10,728.6 Mg (km$^2 \cdot$ a)$^{-1}$ during the period of 1976–1984 in dam MH1#, and the maximum annual sediment yield occurred in 1979. However, there was no corresponding couplet in 1980 because there was only three erosive rainfalls in this year, and the total erosive rainfall was only 54.1 mm with two individual events less than 20 mm. In dam MH2#, the annual average sediment yield was 12,662.9 Mg (km$^2 \cdot$ a)$^{-1}$ during the period from 1985 to 2007, and the maximum annual sediment yield of 42,647.1 Mg km^{-2} appeared in 1994. The years of 1993 and 1999 were no corresponding couplets, and the majority of the erosive rainfalls were less than 20 mm. In dam MH4#, the annual average sediment yield was 16,753.3 Mg (km$^2 \cdot$ a)$^{-1}$ during the period

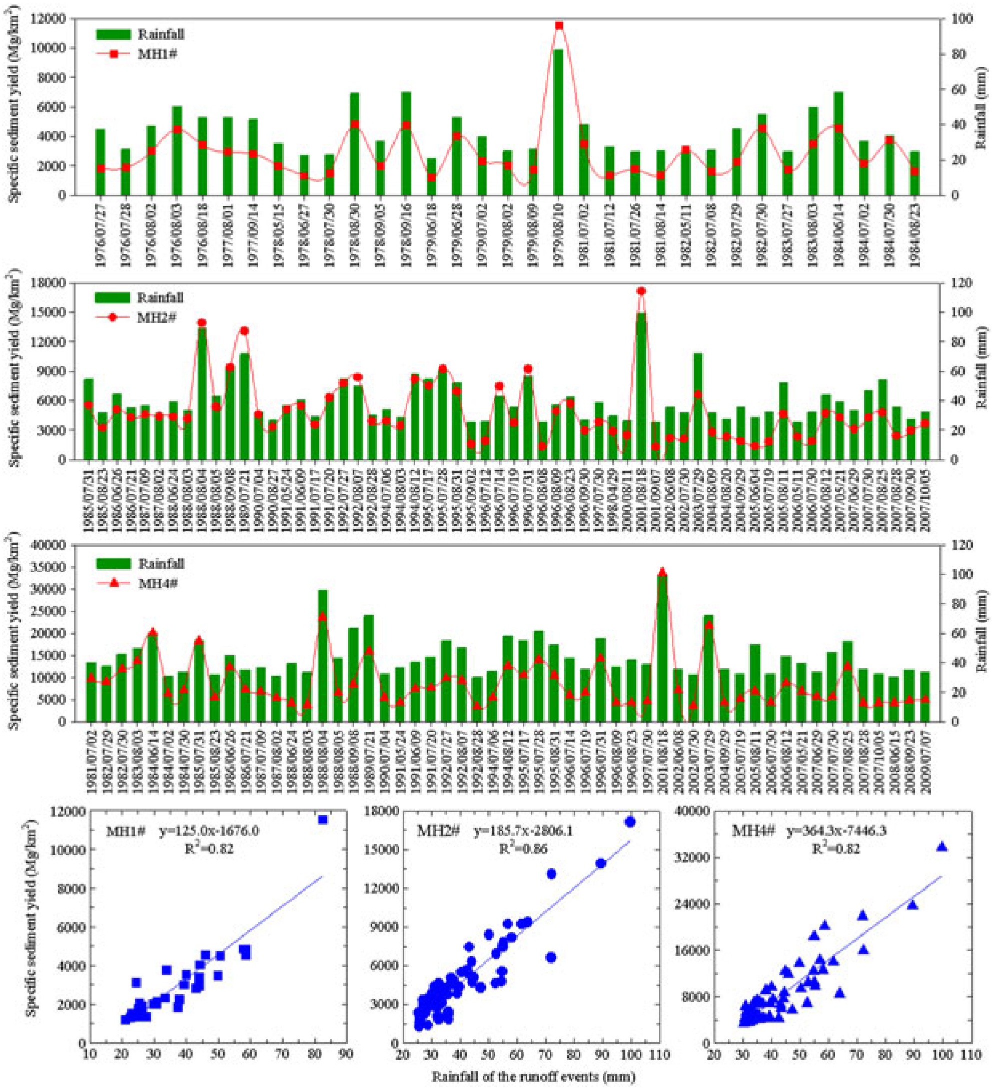


Figure 5. Specific sediment yield, the corresponding rainfall and their correlation at the runoff event scale in dam MH1#, MH2# and MH4#. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

from 1981 to 2009. The maximum annual sediment yield of 46,888.4 Mg km^{-2} occurred in 1988. The years of 1993, 1998, 1999 and 2000 were no corresponding couplets for a large proportion of the erosive rainfalls less than 20 mm. The erosive rainfalls in 1979, 1994 and 1988 were abundant and were 288.4, 352.1 and 337.0 mm, respectively. The relationship between annual sediment yield and annual rainfall of sediment transported into dams has a high correlation at the annual scale in dam MH1#, MH2# and MH4# ($R^2 = 0.92$, 0.90 and 0.81, respectively).

Sediment Yield at the Watershed Scale

For the whole Manhonggou watershed, the annual sediment yield and the corresponding annual and erosive rainfall from 1976 to 2009 was shown in Figure 7. The annual sediment yield showed a decreasing trend and the annual average sediment yield was 14,011.1 Mg (km$^2 \cdot$ a)$^{-1}$ from 1976 to 2009. The maximum annual sediment yield occurred in 1988, was 42,034.2 Mg km^{-2}, corresponded to the annual and erosive rainfall of 515.4 and 337 mm, respectively. A total of 322 erosive rainfall events occurred in the Manhonggou watershed during from 1976 to 2009 on average 9.5 times a year, while the year of 1988 occurred 12 events. No corresponding deposition layer was found in 1980, 1993 and 1999, next was 2,456.8 Mg km^{-2} occurred in 2000 with only four erosive rainfall events, and corresponded to the annual and erosive rainfall were 265.2 mm and 115.9 mm, respectively. There was a good correlation between the annual sediment yield and annual rainfall of sediment transported into watershed with a relatively high correlation coefficient of 0.76 in the Manhonggou watershed.

DISCUSSION

Sediment Yield Deduction by Rainfall Events Dating

Soil erosion dynamics in semiarid environment is characterised by high magnitude, low frequency rainstorms that produce runoff with high sediment concentration (Polyakov *et al.*, 2014). In the semi-arid loess hilly area of

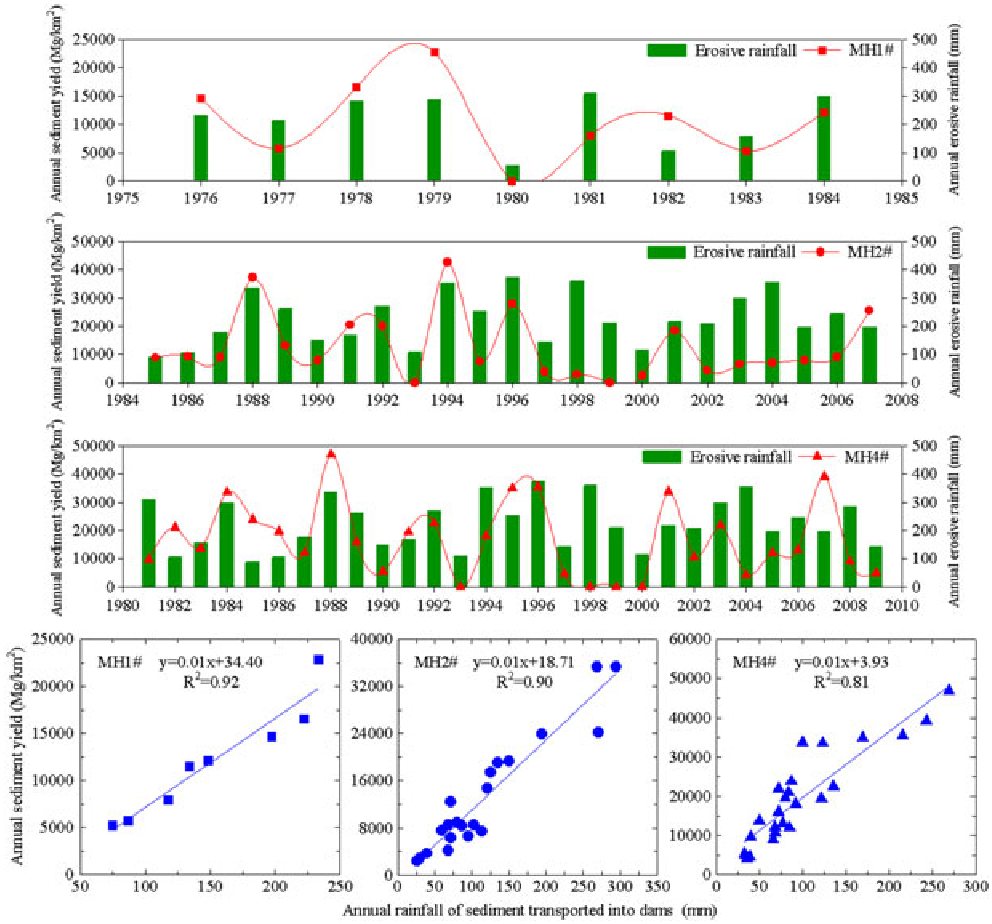


Figure 6. Annual sediment yield, the corresponding rainfall and their correlation at the annual scale in dam MH1#, MH2# and MH4#. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

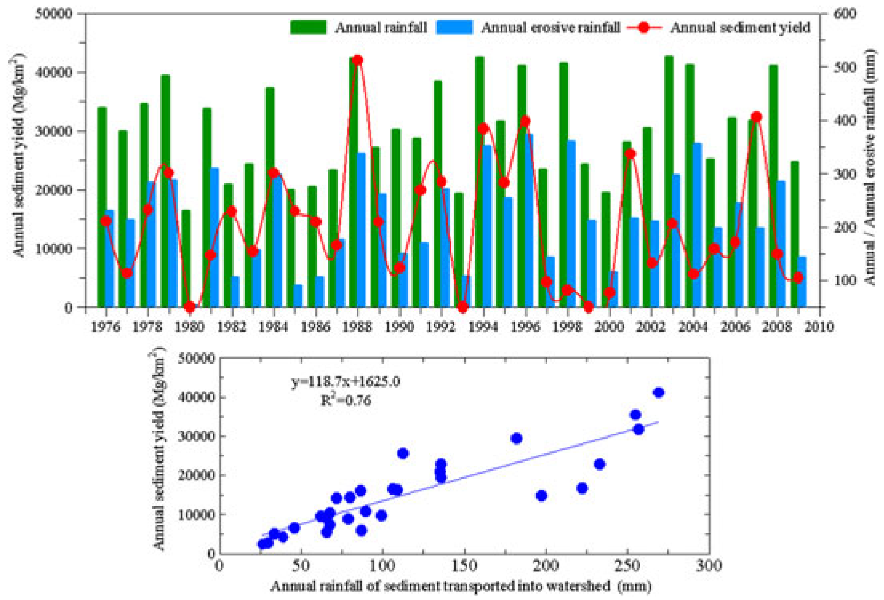


Figure 7. Annual sediment yield, the corresponding annual and annual erosive rainfall and their correlation from 1976 to 2009 in the Manhonggou watershed. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

China, the rainfall events with such features as high intensity, short duration and high frequency could cause the greatest proportion of runoff and soil loss (Wei *et al.*, 2007). Wang & Jiao (1996) also reported soil erosion is caused by few rainstorms and 70% of intense soil erosion was caused by local rainstorms with short duration and high intensity on the Loess Plateau. In southeastern France and North East Spain, the greatest runoff and soil loss rates were also caused by intense but infrequent storm events (Martínez-Casasnovas *et al.*, 2005; Wainwright, 1996). Zema *et al.* (2012) applied the Annualized Agricultural Non-point Source model to simulate the runoff, peak flow and sediment yield at the event scale in the Ganspoel watershed of Belgium, where high intensity rainfall events occurred mainly in spring and summer and such thunderstorms might reach peak rainfall intensities. Furthermore, Vandaele & Poesen (1995) indicated that 50% and 61% of total sediment in the Hammeveld and Ganspoel catchments of Belgium could be attributed to only three rainfall events in the period 1989–1992, respectively. The short but intense rainfall events prompted high suspended sediment concentrations in Mediterranean catchments of the northeast Iberian Peninsula, but the maximum suspended sediment concentrations were positively correlated with the magnitude of the floods (Tuset *et al.*, 2016). There were significant correlations between rainfall intensity in the sediment source areas, sediment storage and sediment yield in a highly erodible Mediterranean catchment (Buendia *et al.*, 2016). In the Chinese Loess Plateau, it showed that there was strong positive relationship between precipitation and erosion (Cheng *et al.*, 2016). Meanwhile, Zhao *et al.* (2015a) indicated that the relationship between sediment yield and rainfall at the runoff event scale had a relatively good correlation in a small watershed of Huangfuchuan tributary. In addition, the correlation between annual rainfall and sediment load had a power function from 1955 to 1979 in the Huangfuchuan tributary where our study area is located (Zhao *et al.*, 2013). Furthermore, Zhang *et al.* (2006) investigated the relationship between annual specific sediment yields and annual rainfall was a relatively good linear relationship in a small dam-controlled watershed of the Yanhe River in the middle reaches of Yellow River. Moreover, Li *et al.* (2016b) investigated that the layered sediment volume was closely related to the rainfall erosivity and the maximum rainfall intensity over 30 min in four typical check dams in the Wudinghe River watershed of the north-central Loess Plateau. There was the similar research in semi-arid Tunisia; Bouchnak *et al.* (2009) found out the relationship between head-cut sediment yield and annual rainfall for both gentle and steep slope catchments had high correlation. When the erosive rainfall-runoff event occurred, the sediments would be retained behind the check dams (Wang *et al.*, 2014). As a result, we can reconstruct the process of soil erosion in the small watershed by analysing the relationship between the sediment deposition amount behind the check dams and the historical rainfall events. And it was a feasible method to apply the rainstorm events dating to determine the sediment yield in the small and ungauged watershed compared with the ^{137}Cs dating with the expensive test cost.

The related researches of sediment deposition for check dams in small watersheds on the North Loess Plateau were shown in Table III. The annual erosion modulus was 10,839.1 Mg $(km^2 \cdot a)^{-1}$ and 10,371.0 Mg $(km^2 \cdot a)^{-1}$ at Wangmaogou and Weijiata watersheds (Xue *et al.*, 2011; Ye *et al.*, 2006), which was relatively close to the annual sediment yield of 10,728.6 Mg $(km^2 \cdot a)^{-1}$ in dam MH1#. In dam MH2#, the annual average sediment yield of 12,662.9 Mg $(km^2 \cdot a)^{-1}$ was near to the annual erosion modulus of 12,702.0 Mg $(km^2 \cdot a)^{-1}$, 12,530.0 Mg $(km^2 \cdot a)^{-1}$ at Guandigou and Beitagou watersheds (Li *et al.*, 2008; Liu *et al.*, 2015b). The annual erosion modulus was 16,931.0 Mg $(km^2 \cdot a)^{-1}$, 16,812.0 Mg $(km^2 \cdot a)^{-1}$ and 16,563.0 Mg $(km^2 \cdot a)^{-1}$ at Fenglimao, Huangcaoliang and Shimiao watersheds (Liu *et al.*, 2015a), which was basically close to the annual sediment yield of 16,753.3 Mg $(km^2 \cdot a)^{-1}$ in dam MH4#. However, the annual sediment yield was 14,011.1 Mg $(km^2 \cdot a)^{-1}$ at the watershed scale, which was roughly the same as the annual erosion modulus of 13,440.0 Mg $(km^2 \cdot a)^{-1}$ and 13,577.0 Mg $(km^2 \cdot a)^{-1}$ at Guandigou and Longtou watersheds (Li *et al.*, 2008; Liu *et al.*, 2015a). Therefore, the results were credible by using capacity curves and historical rainfall events to estimate the sediment yield in Manhonggou watershed on the North Loess Plateau.

Influence of Underlying Surface on Sediment Yield

Topography, geology, soil type, vegetation and land use all affected the sediment yield of a small watershed. Molina *et al.* (2008) showed that sediment yield decreased exponentially with an increasing vegetation cover in a central Andean mountain area, the lithology also influenced the catchment sediment yield significantly and explained an additional 23% of the observed variance in specific sediment

Table III. Related researches of sediment deposition for check dams in small watersheds on the North Loess Plateau

Study area	Small watershed	Operation period	Dam-controlled area (km^2)	Total deposit mass (Mg)	Annual erosion modulus [Mg $(km^2 \cdot a)^{-1}$]	Reference
Suide	Guandigou	1979–1987	0.045	5,095.2	12,702.0	Li *et al.* (2008)
Suide	Guandigou	1964–1978	0.045	8,386.3	13,440.0	
Suide	Wangmaogou	1957–1990	0.181	6,6703.6	10,839.1	Xue *et al.* (2011)
Zhungeer	Weijiata	early 70s	4.016	458,165.6	10,371.0	Ye *et al.* (2006)
Hengshan	Longtou	2005–2012	5.500	597,388.0	13,577.0	Liu *et al.* (2015a)
Hengshan	Fenglimao	2005–2012	3.600	487,612.8	16,931.0	Liu *et al.* (2015b)
Hengshan	Huangcaoliang	2006–2012	3.150	370,704.6	16,812.0	
Hengshan	Shimiao	2006–2012	3.860	447,532.3	16,563.0	
Suide	Beitagou	1977–1998	0.197	54,305.0	12,530.0	

yield. Grassland showed the highest values in soil quality properties, and soil loss was reduced by 70% on slopes with the grass compared with bare slopes in water–wind crisscrossed erosion regions of the Loess Plateau (Zhao *et al.*, 2016a; Zhao *et al.*, 2015b). The land use changes alone reduced sediment yield up to 14%, but in combination with check dams, the reduction in sediment yield reached 44 ± 6% in southeast of Spain (Quiñonero-Rubio *et al.*, 2016). Shi *et al.* (2014) revealed that the land use composition and land use pattern exerted the largest effects on the specific sediment yield and explained 65.2% of the variation in the specific sediment yield in Danjiangkou Reservoir area of central China. While in Chinese Loess Plateau, the watershed shape parameters and relief parameters were the major factors that affected sediment yield, in which the plan curvature and the highest order channel length primarily controlled the sediment yield (Zhang *et al.*, 2015). In the Huangfuchuan watershed on the North Loess Plateau, the land use changes between 1980 and 2005 decreased 40.6% of the sediment yield, when in combination with the check dam construction in 2006 reduced the sediment yield by approximately 80% (Zhao *et al.*, 2016b; Zuo *et al.*, 2016)

Check dams in gully were effective measures decreasing sediment yield in catchments, and the relief of the gullies was changed after the check dams constructed, including the stream channel wider and flatter, the base level of the controlled watershed raised, gully and headward erosions alleviated and sediment yield and deposition downstream reduced in small watersheds (Castillo *et al.*, 2007; Liu, 1992; Wang *et al.*, 2011; Xu *et al.*, 2006). However, check dams had great influence on controlling sediment yield in the short term by mainly intercepting sediment from the upper area; land use changes were sustained sediment reduction measures to control soil erosion at the source (Boix-Fayos *et al.*, 2008; Quiñonero-Rubio *et al.*, 2016).

In this study, the annual average sediment yield was 14,938.4 Mg $(km^2 \cdot a)^{-1}$ in the 1970s, 15,526.1 Mg $(km^2 \cdot a)^{-1}$ in the 1980s, 13,830.7 Mg $(km^2 \cdot a)^{-1}$ in the 1990s and 12,305.7 Mg $(km^2 \cdot a)^{-1}$ in the 21st century at the Manhonggou dams-controlled watershed. The land use types in 1978, 1990, 2000 and 2006 were shown in Figure 8. Grass land was the most common land use type in the Manhonggou watershed, accounting for more than 65%. Likewise, Zuo *et al.* (2016) reported similar results that grassland is the most common evenly distributed land use type in the in the Huangfuchuan watershed from 1980 and 2005. Forest land decreased and others (including dam land, stream channel and unused land) increased gradually, the cultivated land area in 1990 was 55 times that of 1978 in the Manhonggou watershed. Zhao *et al.* (2015a) indicated that the bare and weathered *pisha* rock in the steep gullies was the main source of sediment, which contributed approximately 92.8% of the sediment yield on average of the small watershed in Huangfuchuan tributary. Hence, land use changes and weathered sandstone were the main influence factors for the increase of the sediment yield in the 1980s in our study area. Thus, the application of both land use changes and check dams to control catchment sediment yield was necessary for the aims of sustainable watershed management strategy in this area.

Influence of Check Dams on the Sediment in Downstream

The runoff–sediment relationship is important to understand the soil erosion and land degradation processes in severe eroded areas (Gao *et al.*, 2016; Tian *et al.*, 2016; Zhao *et al.*, 2016c). Check dams had a regulation effect on runoff and a retention effect on sediment. The check dams decreased the number of runoff events generated by small rainstorms by 60% in southern Arizona (Polyakov *et al.*, 2014). Compared with the case of no check dams, the surface runoff was decreased by 60% in a small dam controlled

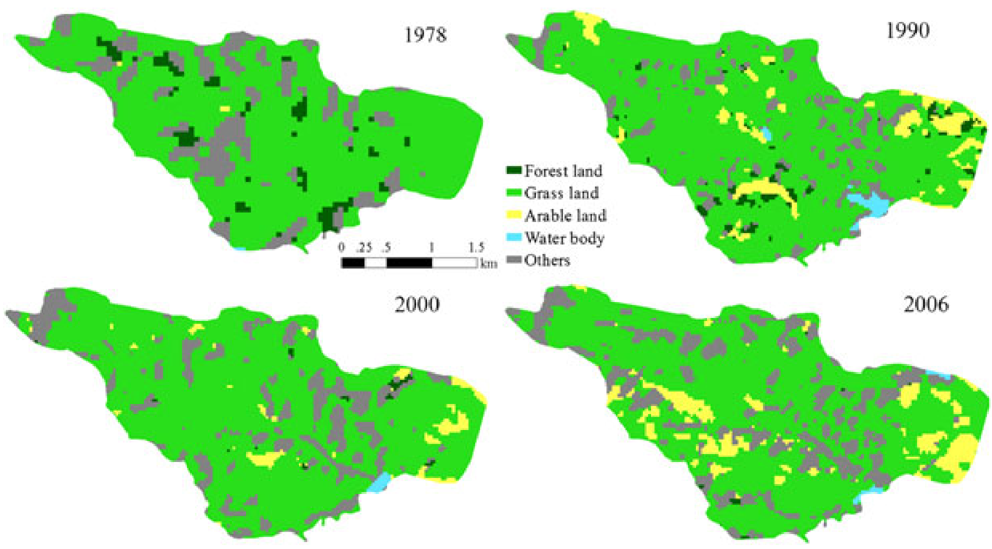


Figure 8. Land use types of the Manhonggou watershed in 1978, 1990, 2000 and 2006. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

watershed of the northern Loess Plateau (Huang *et al.*, 2013). The annual runoff was reduced by less than 14.3%, while the sediment was intercepted up to 85.5% owing to the check dams in the Yanhe watershed (Xu *et al.*, 2013). From 1970 to 1996, the sediment mass was reduced 57.8% by check dams in the Huangfuchuan watershed, while sediment reduction in the Hekouzhen–Longmen section by check dams accounted for 64.7% of the total sediment reduction from all soil and water conservation measures (Ran *et al.*, 2008; Ran *et al.*, 2004). In order to better understand the impacts of check dams on runoff and sediment load in the Huangfuchuan watershed, Tian *et al.* (2013) concluded that the magnitude of daily flow generally decreased during the changing period (1980–2010) compared with the referenced period (1955–1979), and the percentage of daily sediment delivery ratio is nearly 60% in the referenced period but reduced to 32.6% during the changing period. By using the erosion model WATEM–SEDEM simulation, the results showed that in a scenario without land use changes but with check dams, approximately 77% of the sediment yield was retained behind the check dams in the Rogativa catchment of SE Spain (Boix-Fayos *et al.*, 2008). In the hilly–gully region of the Chinese Loess Plateau, check dams reduced runoff and suspended sediment concentration, also significantly influenced the relationship between runoff and sediment delivery (Yan *et al.*, 2015). Moreover, check dams were one of the most dominant forms of human impact on fluvial systems and had considerably reduced stream bed slope, which caused a disruption in connectivity and diminished the sediment transport capacity of the rivers (Díaz *et al.*, 2014; Poeppl *et al.*, 2015). Other man–made pathways (terrace embankments, roads, fish-scale pits and tracks), topographic factors, soil moisture, soil components and vegetation also had a major influence on sediment connectivity and the frequency of water and sediment fluxes (Cao *et al.*, 2015; Li *et al.*, 2016a; Marchamalo *et al.*, 2016; Masselink *et al.*, 2016; Yu *et al.*, 2016).

In general, the effect of check dams retention for sediment yield had major implication for flood control and sediment delivery into the main rivers and reservoirs downstream (Castillo *et al.*, 2007). Mekonnen *et al.* (2015) also showed that the sediment storage dams have already trapped large amounts of sediment at the outlets of subcatchments and subsequently reduced sediment movement to downstream water bodies in northwest Ethiopia. Since 1950s, check dams were the most effective engineering measure to rapidly reduce the amount of coarse sediment and prevented sediments from entering into the Yellow River at a rate about 3–5 million Mg each year, and they had intercepted 28 billion Mg sediments in the Loess Plateau (Ran *et al.*, 2008; Wang *et al.*, 2011). Among all other soil and water conservation measures, check dams had already retained the largest amount of sediments, and the dam lands had brought high crop yields because of the plentiful moisture and nutrients during soil and water loss from on hillslopes (Xu *et al.*, 2006). This indicated that check dams not only decreased catchment sediment yield, but also promoted the transformation of conventional farming patterns to some extent. However, check dams had a certain service life depending on their size and did not an unlimited capacity to intercept sediment in small watershed, and more check dams did not always result in a proportional reduction of sediment yield (Quiñonero-Rubio *et al.*, 2016). As a result, to optimise check dams distribution in gullies was crucial to decrease sediment yield and control soil erosion in specific erosion areas. The best management practices are required for planning, construction, use and maintenance of check dams to protect water and soil resources especially in developing countries agricultures.

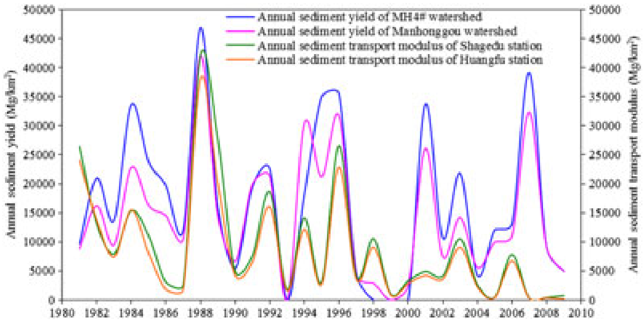


Figure 9. Variation of annual sediment yield and annual sediment transport modulus in the Huangfuchuan watershed. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

In this study, the annual average sediment yield in dam MH4# ($0.32\,km^2$) and Manhonggou watershed ($6.78\,km^2$) were $16{,}753.3\,Mg\,(km^2\cdot a)^{-1}$ and $14{,}366.4\,Mg\,(km^2\cdot a)^{-1}$, while the annual average sediment transport modulus at Shagedu ($1{,}351\,km^2$) and Huangfu ($3{,}199\,km^2$) hydrological stations were $9{,}561.2\,Mg\,(km^2\cdot a)^{-1}$ and $8{,}289.3\,Mg\,(km^2\cdot a)^{-1}$ from 1981 to 2009, respectively (Figure 9). It showed that a large amount of sediment (42.3–50.5%) was intercepted gradually along the way from small watershed to river channel.

CONCLUSIONS

In our study, we estimated the sediment yield in Manhonggou dams–controlled watershed on the North Loess Plateau based on flood couplets interpretation and the check dams capacity curve. In the dam MH1# from 1976 to 1984, the dam MH2# from 1985 to 2007 and the dam MH4# from 1981 to 2009, the 33, 60 and 55 couplets were corresponded to individual runoff events in by careful interpretation of the rainfall data from 1976 to 2009 at the Shagedu station, respectively. The minimum rainfall for sediment deposited in the dams was greater than 20 mm in this watershed. The specific sediment yield for flood events varied from $11{,}88.5\,Mg\,km^{-2}$ to $11{,}527.9\,Mg\,km^{-2}$ in dam MH1#, $1{,}278.6\,Mg\,km^{-2}$ to $17{,}136.7\,Mg\,km^{-2}$ in dam MH2# and $3{,}395.9\,Mg\,km^{-2}$ to $33{,}698.5\,Mg\,km^{-2}$ in dam MH4#, respectively. The annual average sediment yield of the dam MH1#, MH2# and MH4# were $10{,}728.6\,Mg\,(km^2\cdot a)^{-1}$, $12{,}662.9\,Mg\,(km^2\cdot a)^{-1}$ and $16{,}753.3\,Mg\,(km^2\cdot a)^{-1}$, respectively. For the whole watershed, the annual sediment yield showed a decreasing trend, and the annual average sediment yield was 14,011.1 Mg $(km^2 \cdot a)^{-1}$ from 1976 to 2009. The maximum annual sediment yield was 42,034.2 Mg km^{-2} in 1988, corresponded to the annual and erosive rainfall were 515.4 and 337 mm, respectively. It showed that a large amount of sediment (42.3–50.5%) was intercepted gradually along the way from small watershed to river channel.

The results of our study indicated that the capacity curve and rainstorm event dating was a feasible method for sediment yield estimation in the small watershed. This research method can increase the knowledge about sediment analysis, suggesting the best management practices devoted to protect water and soil resources especially in developing countries agricultures. The sediments deposited behind the check dams were helpful for understanding the soil erosion evolution of ungauged and dam-controlled watersheds and providing the references to plan of soil and water conservation measures and watershed management on the North Loess Plateau.

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