

Changes in sediment discharge in a sediment-rich region of the Yellow River from 1955 to 2010: implications for further soil erosion control

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Abstract: The well-documented decrease in the discharge of sediment into the Yellow River has attracted considerable attention in recent years. The present study analyzed the spatial and temporal variation of sediment yield based on data from 46 hydrological stations in the sediment-rich region of the Yellow River from 1955 to 2010. The results showed that since 1970 sediment yield in the region has clearly decreased at different rates in the 45 sub-areas controlled by hydrological stations. The decrease in sediment yield was closely related to the intensity and extent of soil erosion control measures and rainstorms that occurred in different periods and sub-areas. The average sediment delivery modulus (SDM) in the study area decreased from 7,767.4 t/(km²·a) in 1951–1969 to 980.5 t/(km²·a) in 2000–2010. Our study suggested that 65.5% of the study area with the SDM below 1,000 t/(km²·a) is still necessary to control soil deterioration caused by erosion, and soil erosion control measures should be further strengthened in the areas with the SDM above 1,000 t/(km²·a).

Keywords: sediment delivery modulus (SDM); Yellow River; hydrological station(s)-controlled sub-area; soil and water conservation

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Soil erosion from land areas is widespread and adversely affects all natural and human-managed ecosystems, including those used for agriculture and forestry (Pimentel and Kounang, 1998). Soil erosion is an increasing environmental problem globally, and the Chinese Loess Plateau is one of the regions with the most severe soil erosion in the world (Shi and Shao, 2000). Soil erosion on the Loess Plateau causes the loss of cropland onsite, the siltation of rivers and reservoirs offsite, and the potential flooding in the Yellow River Basin (Hessel et al., 2003; Liu et al., 2006).

Significant efforts have been made to combat soil erosion and environmental degradation on the Loess Plateau since the 1950s. As a result, the amount of sediment delivered to the Yellow River has decreased markedly since the early 1970s (Xu and Cheng, 2002). Focused on the decrease in sediment discharge to the

Yellow River, numerous investigations have been conducted to study the sediment reduction in tributaries and at station-controlled sub-areas in different periods (Sui et al., 2009), the sediment reduction benefits of soil-water conservation measures (Chen and Cai, 2006; Ran et al., 2008), and the contribution of climate change and human activities to sediment reduction in different tributaries of the Yellow River (Wang et al., 2007; Dai et al., 2009; Peng et al., 2010; Gao et al., 2011). These studies were performed with the data from several hydrological stations along the main-stream of the Yellow River or with only the data from the export stations of several typical tributaries. Furthermore, most previous studies primarily focused on a large regional scale and did not consider the sources of sediment in different tributaries and sub-areas in terms of the need for further soil erosion control

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and watershed management. However, the geographic and geomorphic conditions of the Yellow River Basin, even on the Loess Plateau, are highly heterogeneous, so the sediment yields from different areas differ substantially. The hydrological station(s)-controlled sub-area is the smallest sub-catchment that can provide sediment load measurement records from the Yellow River. The spatial variation in sediment discharge and the principal sediment sources can be illustrated in more detail at the scale of the hydrological station(s)-controlled sub-areas. Although our previous study has evaluated the variation in sediment yield on the Loess Plateau based on as many hydrological stations as possible at the scale of the hydrological station(s)-controlled sub-areas, the data used were only from years prior to 1990 (Jiao et al., 2002). Numerous soil and water conservation measures were applied between 1979 and 1997 due to government-sponsored conservation programs and environmental rehabilitation campaigns in the middle reaches of the Yellow River (Gao et al., 2011), and the national “Grain for Green” project was launched in 1999. The spatial distribution and temporal variation in sediment yield after 1990 therefore provide an important basis for understanding the effects of intensive soil erosion control measures on the decrease in sediment yield and the current status of sediment discharge, and also provide further bases for decision-making for soil and water conservation and watershed management.

Therefore, based on the data from 46 hydrological stations in the sediment-rich region between the Toudaoguai and Longmen hydrological stations region along the Yellow River, the objectives of this study were: (1) to analyze the spatiotemporal variation in sediment discharge from 1955 to 2010 at the scale of the hydrological station(s)-controlled sub-areas; (2) to discuss the decrease in sediment yield in different sub-areas and its related factors; and (3) to identify the sub-areas that require further control of soil erosion.

1 Study area and methods

1.1 Study area

The sediment-rich region of the Yellow River is located between the Toudaoguai and Longmen hydrological stations region along the Yellow River (Figs. 1 and 2). The mainstream of the Yellow River between Toudaoguai and Longmen (725 km long and 400–600

m wide) is located in the gorges of Shanxi and Shaanxi provinces, where the slopes are very steep and the gullies are narrow. There are 21 tributaries in this region with a catchment area larger than 1,000 km², and most of the tributaries develop in the loess hill and gully area. The area in the region between the Toudaoguai and Longmen stations only occupies 14.8% of the total area of the Yellow River Basin, but its sediment yield represented 69.0% of the total sediment discharge from the drainage area above Sanmenxia Station in Henan province in 1955–1969. Accordingly, this region is the critical area in the Yellow River Basin for soil and water conservation and ecological rehabilitation.

The soil in the study area is primarily developed from loess parent materials and the soil texture is silty loam. According to the USDA soil classification system, the contents of sand, clay and silt are 11.7%, 23.7% and 64.6%, respectively (Wang et al., 2009). The dominant vegetation is steppe, and the forest steppe shows a gradual transition to the typical steppe and the desert steppe from the southeast to the northwest. The mean annual precipitation is 300–600 mm, with 50% occurring from August to September. The area of rainstorms (>50 mm) is usually less than 20,000 km². Thus, the limited rainfall is spatially and temporally concentrated. This characteristic inhibits vegetation restoration but easily causes soil erosion (Jiao et al., 2002).

1.2 Data analysis

Annual sediment discharge records from 1955 to 2010 at 46 hydrological stations in the study area were obtained from the Yellow River Conservancy Commission (YRCC).

Based on the distribution of the 46 hydrological stations (1–46) and the DEM (25 m×25 m), we divided the study area into 45 sub-areas (S1–S45) monitored by hydrological stations using hydrology modeling in ArcGIS (Fig. 2).

The sediment yield for the hydrological station(s)-controlled sub-areas (S1–S45) was calculated as follows. (1) In a sub-area monitored by a single hydrological station in a tributary, the sediment yield was the observed value at the gauging station. (2) In a sub-area monitored by several hydrological stations in a tributary, the sediment yield was derived from the

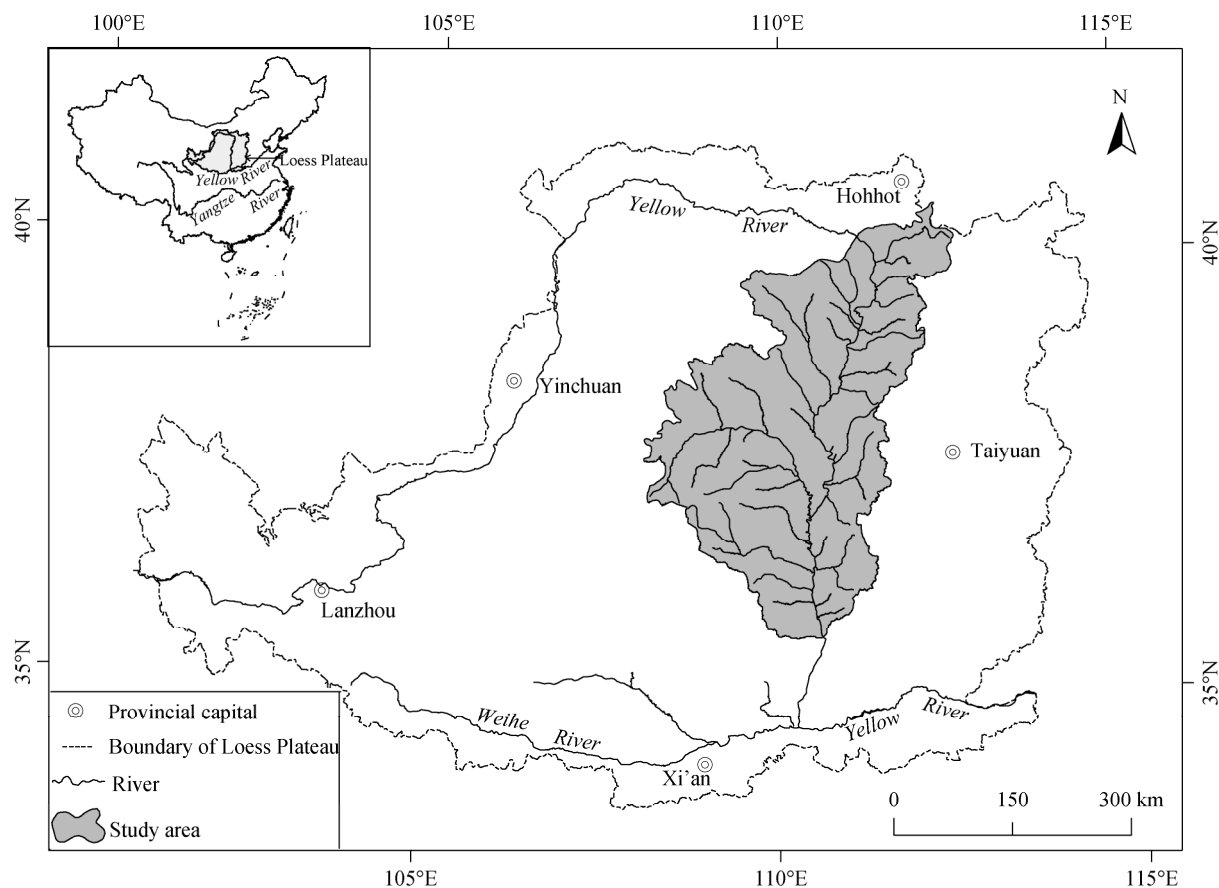


Fig. 1 The location of the sediment-rich region of the Yellow River in the Chinese Loess Plateau

lower and upper stations. (3) For the lower reaches of the tributaries not monitored by hydrological stations, the mainstream of the Yellow River within the study area was divided into several sub-areas according to the distribution of hydrological stations along the mainstream. The hydrological station(s)-controlled section was defined as the area controlled by tributary stations in the sub-area between two stations in the mainstream of the Yellow River, and the sediment yield was calculated as the amount of sediment at the lower station along the mainstream minus that at the upper station along the mainstream and the tributary stations in this sub-area. (4) If the calculated sediment yield within a particular hydrological station(s)-controlled sub-area was negative, it implied that the sediment was deposited in this sub-area.

The sediment delivery modulus (SDM ($t/(km^2 \cdot a)$), the amount of sediment transport per catchment area above one section of a river) of 45 sub-areas was obtained according to their sediment yields and catchment areas. The SDM was classified into intervals of <0 , $0-1,000$, $1,000-2,500$, $2,500-5,000$, $5,000-8,000$,

$8,000-15,000$ and $>15,000 t/(km^2 \cdot a)$ according to the classification criterion for the soil erosion modulus defined by the Ministry of Water Resources of the People's Republic of China (1997). A negative value of SDM implies that sediment was deposited in the corresponding sub-areas.

The pre-control period was considered to extend from 1950 to 1969, when soil and water conservation was in the stage of initial and scattered control on the Loess Plateau (Xu, 2003). Since the 1970s, a series of soil and water conservation measures including land terracing, tree and grass planting, and conservation tillage practices have been implemented, and numerous check dams have been built for sediment interception (Xu and Cheng, 2002). During the 1970s, land terracing was the dominant soil and water conservation measure aimed at solving the food shortage problem. In the 1980s, integrated management of small watersheds was implemented based on previous soil erosion control experience (Cai, 2001). Soil and water conservation in the 1990s, marked by the Law of the People's Republic of China on Water and Soil Con-

servation, aimed to prevent and control soil and water loss, and to protect and rationally utilize soil and water resources. Up to the 21st century, with the implementation of the “Grain for Green” project, soil erosion control focused on large-scale revegetation projects (McVicar et al., 2007; Zhou et al., 2009). Based on the progress of soil and water conservation on the Loess Plateau as described above, we divided the time period included in this study as follows: 1955–1969 (before soil erosion control), 1970–1979, 1980–1989, 1990–1999 and 2000–2010. The distribution maps of different classes of the SDM in these periods were

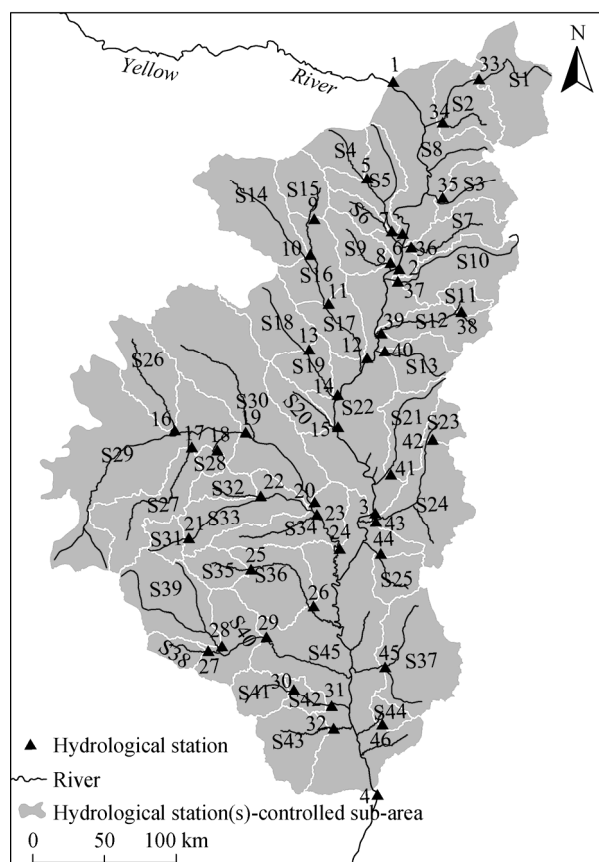


Fig. 2 The distribution of 46 hydrological stations (1–46) and 45 hydrological station(s)-controlled sub-areas (S1–S45) in the study area. 1–46 represent hydrological stations: 1, Toudaoguai; 2, Fugu; 3, Wubu; 4, Longmen; 5, Shagedu; 6, Huangfu; 7, Qingshui; 8, Gaoshiya; 9, Xinmiao; 10, Wangdaohengta; 11, Shenmu; 12, Wenjiachuan; 13, Gaojiabu; 14, Gaojiachuan; 15, Shenjiawan; 16, Hanjiamao; 17, Hengshan; 18, Dianshi; 19, Zhaoshiyao; 20, Dingjiagou; 21, Qingyangcha; 22, Lijiahe; 23, Suide; 24, Baijiachuan; 25, Zichang; 26, Yanchuan; 27, Zaoyuan; 28, Yan'an; 29, Ganguyi; 30, Linzhen; 31, Xinshihe; 32, Dacun; 33, Taipingyao; 34, Fangniugou; 35, Pianguan; 36, Jiuxian; 37, Xialiuqi; 38, Kelan; 39, Peijiachuan; 40, Bicun; 41, Linjiaping; 42, Gedong; 43, Houdacheng; 44, Peigou; 45, Daning; 46, Jixian. S1–S45 represent hydrological station(s)-controlled sub-areas.

visualized using the thematic map classification and rendering method from ArcGIS.

2 Results

2.1 Temporal variation in sediment yield

Figure 3 shows the annual variation of sediment yield in the sediment-rich area from 1951 to 2010. The annual sediment yield ranged from 0.11×10^8 (2008) to 21.37×10^8 t (1967), with a mean value of 6.08×10^8 t. The sediment yield was above the average value in 23 years and below the average value in 37 years. Of these 37 years, 31 years were between 1970 and 2010. Sediment yield showed a generally decreasing trend after 1970 and especially after 1980. Sediment yields in the 1970s, 1980s, 1990s and 2000s decreased by 25.3%, 63.0%, 53.2% and 87.4%, respectively, compared with 1951–1969. The mean SDM decreased from 7,767.4 t/(km²·a) before soil erosion control (1951–1969) to 980.5 t/(km²·a) after the implementation of the “Grain for Green” project (2000–2010).

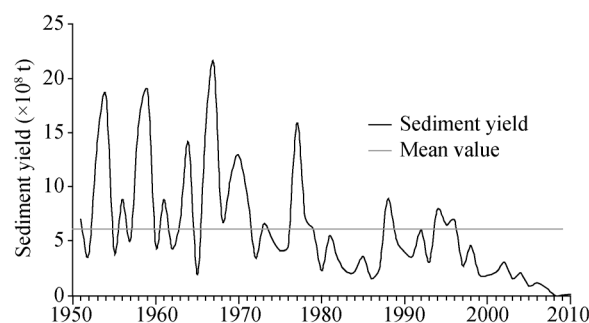


Fig. 3 The annual variation of sediment yield in the sediment-rich region from 1951 to 2010

2.2 Area variation of SDM

Table 1 shows the area variation of SDM for different periods. Before soil erosion control (1955–1969), the SDM was greater than 5,000 t/(km²·a) in 54.6% of the total area, between 2,500 and 5,000 t/(km²·a) in 30.0% of the total area and less than 1,000 t/(km²·a) in only 3.1% of the total area. The area with the SDM less than 2,500 t/(km²·a) clearly increased since 1970, although the area with the SDM ranging from 1,000 to 2,500 t/(km²·a) showed a decrease of 30.8% in 2000–2010. In contrast, the area with the SDM above 2,500 t/(km²·a) decreased. In 2000–2010, the SDM was greater than 5,000 t/(km²·a) in only 2.6% of the total area, between 2,500 and 5,000 t/(km²·a) in 23.4%

of the total area and less than 1,000 t/(km²·a) in 65.5% of the total area (for which the area with sediment deposited represented 26.8%). These results were almost the opposite of ones obtained for 1955–1969.

2.3 Sediment yield variation relative to SDM

The sediment yield variation relative to SDM in different periods is shown in Table 1. Before soil erosion control (1955–1969), the sediment yield from the area with the SDM of <2,500, 2,500–5,000 and >5,000 t/(km²·a) occupied 2.5%, 12.8% and 84.7% of the total yield, respectively. However, in 2000–2010, the sediment yield from the area with the SDM of <2,500, 2,500–5,000 and >5,000 t/(km²·a) represented 41.2% (of which the deposited sediment represented 19.3%), 47.6% and 11.3% of the total yield, respectively. Compared with 1955–1969, the sediment yield from the area with the SDM between 2,500–5,000 t/(km²·a) generally decreased by 52.0% and 59.3% in the 1970s and 1990s, respectively; the sediment yield from the area with the SDM between 5,000–8,000 and 8,000–15,000 t/(km²·a) generally decreased by 51.2% and 75.5% respectively in the 1980s, and 92.0% and 97.5% respectively in 2000–2010; and the sediment yield from the area with the SDM greater than 15,000 t/(km²·a) generally decreased by 89.6%–100.0% after 1980.

2.4 Spatial variation in sediment yield

Compared with 1955–1969, the period before soil erosion control, the SDM did not always decrease during the period of 1970–2010 in all sub-areas (Fig. 4). The SDM increased in S4, S6, S7, S9, S10, S14, S15, S16, S17, S29, S41 and S45 in 1970–1979, and in S41 and S45 in 1990–1999. However, the SDM of all sub-areas decreased in 1980–1989 and 2000–2010. In the 2000s, the sub-areas with the SDM less than 1,000 t/(km²·a) and greater than 5,000 t/(km²·a) occupied 65.5% (even including the sediment deposited in S8, S17 and S29) and 2.6% (only including S35 (SDM of 9,900 t/(km²·a)) and S33 (SDM of 5,850 t/(km²·a)), occupying 0.7% and 1.9% of the study area, respectively) of the total area, respectively, whereas the sub-areas with the SDM greater than 15,000 t/(km²·a) disappeared.

The SDM of these 45 sub-areas decreased to different levels after the three decades of soil erosion control. Results of the sub-areas with the SDM decreased to >1,000 t/(km²·a) in 2000–2010 showed that, the SDM of S45 decreased from 4,130 to 2,710 t/(km²·a), the SDM in the sub-areas of S38, S16, S22, S6, S25, S36, S39, S19, S32 and S31 decreased from 8,000–15,000 to 1,100–4,500 t/(km²·a), the SDM of S35 decreased from 14,900 to 9,890 t/(km²·a), the

Table 1 The area and yield variation of sediment delivery modulus (SDM) in different periods

SDM (t/(km ² ·a))	1955–1969	1970–1979	1980–1989	1990–1999	2000–2010
Percentage of the total study area (%)					
<0	0.0	0.0	0.0	17.9	26.8
0–1,000	3.1	20.2	17.7	15.8	38.7
1,000–2,500	12.3	26.9	46.6	21.4	8.5
2,500–5,000	30.0	11.1	17.5	10.6	23.4
5,000–8,000	20.1	18.0	10.6	17.4	1.9
8,000–15,000	23.8	18.7	6.7	15.7	0.7
>15,000	10.7	5.1	1.0	1.0	0.0
Sediment yield (×10 ⁴ t)					
<0	0.0	0.0	0.0	712.3	3,986.9
0–1,000	162.3	1,592.5	1,165.4	523.6	2,467.9
1,000–2,500	2,246.7	6,739.8	8,387.6	5,279.2	2,072.5
2,500–5,000	12,618.1	6,058.5	7,930.6	5,132.2	9,838.0
5,000–8,000	17,822.5	15,684.2	8,699.3	13,665.6	1,417.2
8,000–15,000	36,443.4	28,923.1	8,927.5	20,227.6	903.4
>15,000	29,043.7	16,279.9	2,110.6	3,025.9	0.0
Total	98,336.7	75,278.0	37,221.0	48,566.4	20,685.9

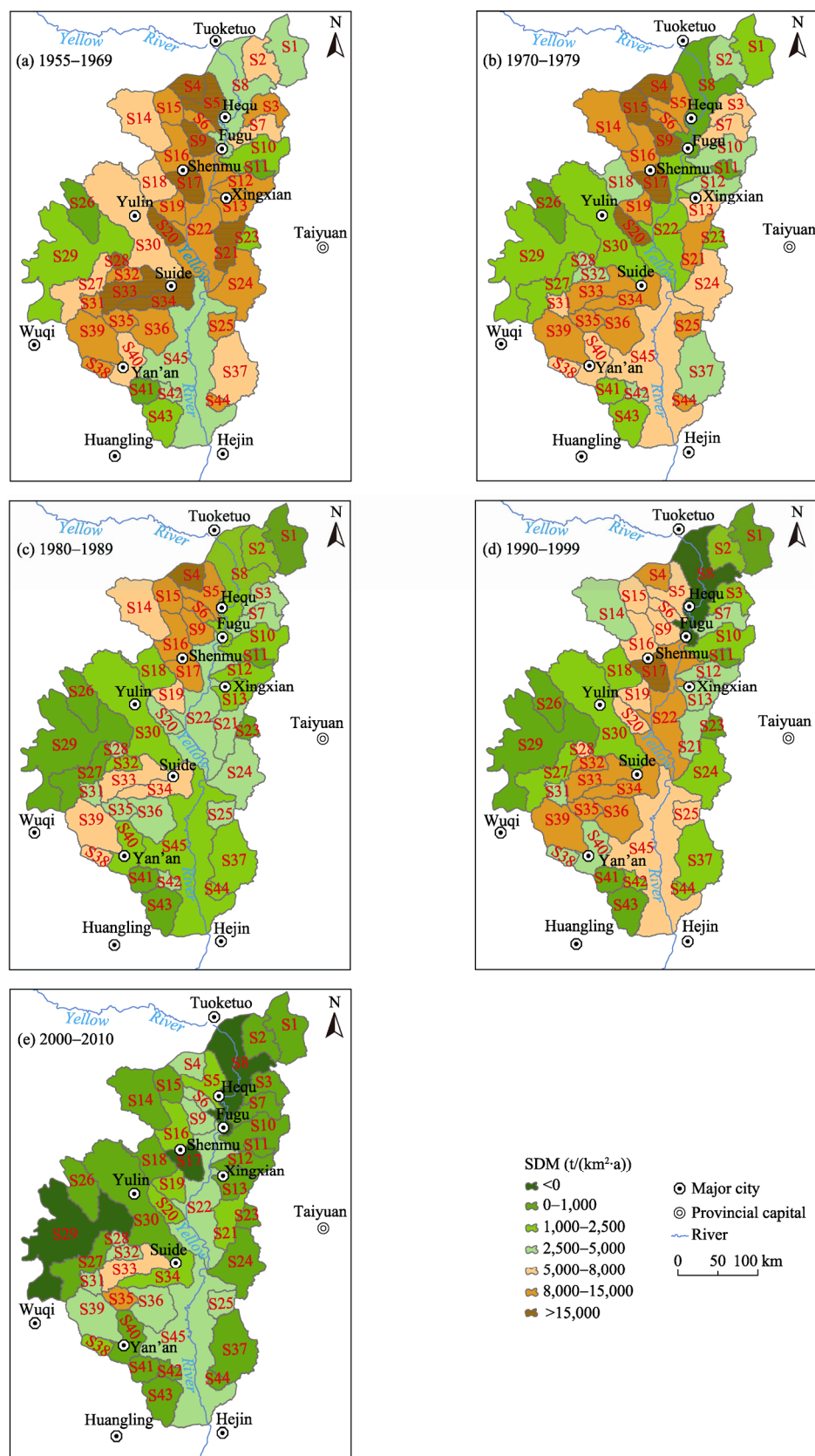


Fig. 4 The spatial variation of sediment delivery modulus (SDM) in different periods. (a), 1955–1969; (b), 1970–1979; (c), 1980–1989; (d), 1990–1999; (e), 2000–2010.

SDM of S4, S5, S9, S20, S21, S28 and S34 decreased from 15,300–25,800 to 1,700–3,300 $t/(km^2 \cdot a)$, and the SDM in S33 decreased from 15,300 to 5,850 $t/(km^2 \cdot a)$. In 1955–1969, the values of SDM between 1,000–2,500, 2,500–5,000, 5,000–8,000 and 8,000–15,000 $t/(km^2 \cdot a)$ were observed in the sub-areas of S10, S23, S29 and S43, the sub-areas of S1, S8 and S42, the sub-areas of S2, S7, S14, S18, S27, S30, S37 and S40, the sub-areas of S3, S12, S13, S15, S24 and S44, respectively. However, the SDM of all these sub-areas decreased below 1,000 $t/(km^2 \cdot a)$ in 2000–2010. Further, in 1955–1969, the SDM of S11, S26 and S41 with the SDM less than 1,000 $t/(km^2 \cdot a)$ decreased below 150 $t/(km^2 \cdot a)$, and the SDM of S17 decreased from 37,000 $t/(km^2 \cdot a)$ (the maximum value among the 45 sub-areas in 1955–1969) to the deposited state ($-270 t/(km^2 \cdot a)$).

3 Discussion

3.1 Effects of rainfall and human activities on SDM variation

In general, the decrease in sediment discharge by the rivers was strongly influenced by climate change and human activities (Walling and Fang, 2003; Chakrapani, 2005; Peng et al., 2010).

The climate is a factor primarily affecting sediment discharge because rainfall is the principal driver of soil erosion on the Loess Plateau. It has been shown that no statistically detectable increasing or decreasing trend in precipitation during the last five decades (1961–2010) was found in the Yellow River watershed (Fu et al., 2004; Gao et al., 2011; Wang et al., 2012a). However, soil erosion on the Loess Plateau was caused by a few rainstorms, and 70% of the intense soil erosion was caused by local rainstorms with short durations and high intensities (Wang and Jiao, 1996). It has also been reported that the greatest rates of runoff and soil loss were caused by intense but infrequent rainstorm events in southeastern France and northeastern Spain (Wainwright, 1996; Martínez-Casasnovas et al., 2005). Thus, soil erosion and sediment yield were strongly related to the occurrence of rainstorms. The SDM in the 45 sub-areas was clearly influenced by extreme rainstorms. For example, several heavy rainstorms occurred in the 1970s and severely damaged many check dams. Examples included the 408.7 mm rainstorm in the surroundings of the

Kuye and Lanyi rivers on 23 July 1971, the 112.5 mm rainstorm in Yanchuan county on 25 August 1973, the 50.7 and 108 mm rainstorms in Yanchang county in August 1975, the 225 mm/48 h rainstorm in Ansai and Zichang counties on 4–5 July 1977, the rainstorms in Shilou (356 mm) and Qingjian (294 mm) counties on 4–5 August 1977, and the rainstorms in Zichang, Qingjian and Zizhou counties (619 mm at the storm center) on 27 July 1978 (YRCC, 1993). Due to these heavy rainstorms, the SDM just decreased by below 20% in the sub-areas of S5, S13, S18, S19, S33, S35, S36, S40, S42, S43 and S44 while increased by 8.3%–110.9% in the sub-areas of S4, S6, S7, S9, S10, S14, S16, S17, S29, S41 and 45 in the above rainstorm areas in 1970–1979 compared with 1951–1969. In the 2000s, a heavy rainstorm of 168–254 mm/7 h and 39 mm occurred in the Zichang hydrological station-controlled sub-area (S35) on 4 July 2002 and on 27 July 2006 in the Huangfuchuan River (S4 and S5), respectively. The occurrence of these rainstorms could explain why the SDM of S35, S4 and S5 was still relatively high in 2000–2010. The SDM of these 45 sub-areas was closely related to the rainstorm center areas in the Toudaoguai and Longmen hydrological stations region (Wang and Jiao, 1996). The rainstorm characteristics (e.g. type, amount, intensity and area), rather than the annual precipitation, are the important factors that explain the contribution of rainfall to sediment yield.

Human activities have become crucial issues for soil and water loss on the Loess Plateau (Fu et al., 2004; Dai et al., 2009; Li and Wei, 2011). Peng et al. (2010) reported that human activities explained 80% of the sediment load decrease in the Huayuankou Station, whereas the remaining 20% was attributed to the decrease in precipitation above Huayuankou Station. Soil conservation practices reduced the mobilization of sediment in most areas of the Loess Plateau, typically representing about 75% of the observed decreases in annual sediment yield (Rustomji et al., 2008). The decrease of SDM in different sub-areas coincided well with the corresponding soil erosion control projects. For example, the Wuding (S26–S34), Sanchuan (S23 and S24) and Huangfuchuan (S4 and S5) rivers were the key national erosion control areas from 1983 to 2002, and the World Bank Loan Project has been implemented in the Hun (S1 and S2), Lanyi

(S11 and S12), Weifen (S13), Xinshui (S37), Zhu-jianchuan (S10), Xianchuan (S7), Pianguan (S3), Yan (S38, S39 and S40) and Jialu (S20) rivers since 1994 (Kang et al., 2002). The key tributary control project has been implemented in the Hun, Xianchuan, Kuye (S14–S17), Wuding and Xinshui rivers since 2001. The Huangfuchuan, Kuye, Guchanchuan (S9) and Tuwei (S18 and S19) rivers are always the key control rivers. As a result, the SDM of sub-areas in these rivers has decreased significantly. Sediment was deposited in S8 because the Wanjiazhai Reservoir and Tianqiao Hydropower Station are located there. The average annual amount of silt was 0.561×10^8 t in the Wanjiazhai Reservoir in 2000–2010 and 0.026×10^8 t in the Tianqiao Hydropower Station in 1977–2007.

3.2 Implications for further soil erosion control

According to the soil loss tolerance limit of $1,000 \text{ t}/(\text{km}^2 \cdot \text{a})$ on the Loess Plateau issued by the Ministry of Water Resources of the People's Republic of China (1997), the tolerable amount of soil loss from the Toudaoguai and Longmen hydrological stations region is $1.3 \times 10^8 \text{ t/a}$, whereas the sediment yield of the region was only $1.3 \times 10^8 \text{ t/a}$ in 2000–2010. However, these figures do not indicate that further soil erosion control is unnecessary in this region. The sediment delivery ratio has decreased rapidly to 0.3–0.4 in the Wuding River due to the large-scale erosion control measures implemented since the 1960s, whereas the sediment delivery ratio approaches 1 under natural conditions without human intervention (Xu and Sun, 2004). Many check dams have intercepted large amounts of sediment (Xu et al., 2004; Ran et al., 2008), but they cannot prevent soil erosion from the sources. Although the comprehensive practices have achieved remarkable progress on soil erosion control, it is still probable that soil loss will be extremely severe during heavy rainstorms (Fan and Xue, 2010). The severe soil erosion disaster during the “7.27” rainstorm in Jiaxian county in 2012 illustrated this conclusion (Wang et al., 2012b). Therefore, the mitigation of soil erosion from the sediment source in the study area will be a lengthy process.

Rainfall is a natural phenomenon that cannot be controlled by human intervention. Soil erosion control depends primarily on rational human activities in appropriate areas. The present status of different grades of the SDM and the corresponding temporal and spa-

tial distribution is highly important for the further soil erosion control in the sediment-rich region of the Loess Plateau and for the river management in the Yellow River Basin. Large-scale vegetation projects have been implemented for ecological restoration and soil erosion control up to the 21st century (Xu et al., 2006), and different hydrological years were also included in this period (Wang et al., 2012a). For these reasons, the sediment yield between 2000 and 2010 could be used to represent the present sediment status (Fig. 4e). Our results showed that in 2000–2010, the areas with the SDM of $>15,000$, $8,000$ – $15,000$, $5,000$ – $8,000$ and $2,500$ – $5,000 \text{ t}/(\text{km}^2 \cdot \text{a})$ decreased to 0, 913 (0.7%), 2,424 (1.9%) and $30,396 \text{ km}^2$ (23.4%), respectively. The areas with the SDM of $1,000$ – $2,500$ and 0 – $1,000 \text{ t}/(\text{km}^2 \cdot \text{a})$ increased to $10,998$ (8.5%) and $50,176 \text{ km}^2$ (38.7%), respectively. Furthermore, the area with sediment deposited was $34,747 \text{ km}^2$ (26.8%) (Table 1). Soil erosion control measures should therefore be further strengthened in the sub-areas with the SDM greater than $1,000 \text{ t}/(\text{km}^2 \cdot \text{a})$, especially the sub-areas with the SDM between $2,500$ – $5,000 \text{ t}/(\text{km}^2 \cdot \text{a})$. The sub-areas with the SDM less than $1,000 \text{ t}/(\text{km}^2 \cdot \text{a})$ still require soil erosion control measures to prevent these areas from deteriorating due to soil erosion. Proper and rational control measures and management strategies in these sub-areas need to be further explored based on the experience of soil erosion control in the sub-areas where sediment has been successfully reduced.

4 Conclusions

The sediment yield in the sediment-rich region of the Chinese Loess Plateau has demonstrably decreased, with different degrees of temporal and spatial variation among 45 hydrological station(s)-controlled sub-areas since 1970. The decreases of SDM in 45 sub-areas in different periods coincided well with the intensity and extent of soil erosion control measures implemented during the last 40 years in the study area. The decreases in SDM were also influenced by the rainstorms that occurred in different periods and sub-areas. Our study suggested that soil erosion control measures should be further implemented in 34.5% of the study area (S1–S3, S7, S8, S10–S15, S17, S18, S23, S24, S26, S27, S29, S30, S37 and S40–S44) with the SDM greater than $1,000 \text{ t}/(\text{km}^2 \cdot \text{a})$, and preventive

soil erosion control measures should be implemented in the other 65.5% of the study area (S4–S6, S9, S16, S19–S22, S25, S28, S31–S36, S38, S39 and S45) with the SDM less than 1,000 t/(km²·a). Proper and rational control measures and management methods in these different sub-areas need to be further explored and to focus on preventing soil erosion from the sediment source rather than from intercepting sediment, which poses potential risks to the watershed.

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