Sediment Budgets 1 (Proceedings of symposium S1 held during the Seventh IAHS Scientific Assembly at
Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 291, 2005.

Investigations of the sediment budget of a reach of the Yellow River in the Loess Plateau

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Abstract Using sediment concentration (C_S) and discharge (Q) data measured at three gauging stations along the reach of the Yellow River in the Loess Plateau, this article focuses on high C_S levels during flood periods and low C_S levels under ice covered conditions. The results show that the annual maximum C_S is usually less than 30 kg m^{-3} during the flood season at the upstream Toudaoguai gauging station (TDGS). However, both maximum C_S and Q vary dramatically at the downstream Fugu gauging station (FGGS). The value of C_S under ice cover is very low compared to C_S during flood periods. For the same cumulative percentage undersize, the median grain size of the suspended load under ice cover is much coarser than that under open flow conditions, although Q during the period of ice cover is much less than that under open flow conditions. About 35% of the sediment eroded in the sub-watershed between TDGS and FGGS was produced from the HuangPuChuan watershed, which accounts for only 10% of its drainage area.

Key words flood seasons; HuangPuChuan sub-watershed; ice covered period; loess plateau; runoff depth; sediment concentration; Yellow River

INTRODUCTION

The Yellow River, with a total length of 5464 km, is the second largest river in China, draining an area of 795 000 km^2 with an erodible area of 454 000 km^2, including the Loess Plateau. The Loess Plateau, with a greatly varied and rolling surface, a relatively large topographic relief, a deep layer of loess, loose surface soils, fragmented land-forms, low vegetation density, and serious water-soil loss, is one of the main sources of floods and high suspended sediment concentrations (C_S). The mean annual sediment load downstream is 1.6 billion tonnes, with an average C_S of 35 kg m^{-3}. Every year, an average of 400 million tonnes of sediment are deposited within the lower reaches of the Yellow River, which results in aggradation of the river bed by 10 cm year^{-1}. The riverbed downstream is on average 4–7 m higher than the land outside the river, with a maximum of up to 13 m (CAHE, 1992). Every year, the sediment yield from the Loess Plateau totals between 200 and 30 000 t km^{-2} (Liu, 1985; Zhu *et al.*, 2004).

As shown in Fig. 1, Toudaoguai gauging station (TDGS), the Hequ gauging station (HQGS) and Fugu gauging station (FGGS) are located on the middle reach of the Yellow River. TDGS is the last gauging station on the upper reach of the Yellow River. Below this, the Yellow River flows approximately north to south through the middle reaches. The middle reaches of the Yellow River have an average slope of 8.4‰ (CAHE, 1992). This river reach is relatively straight, with a channel width of between 400 and 1000 m, and flows through the Loess Plateau region. Most of the

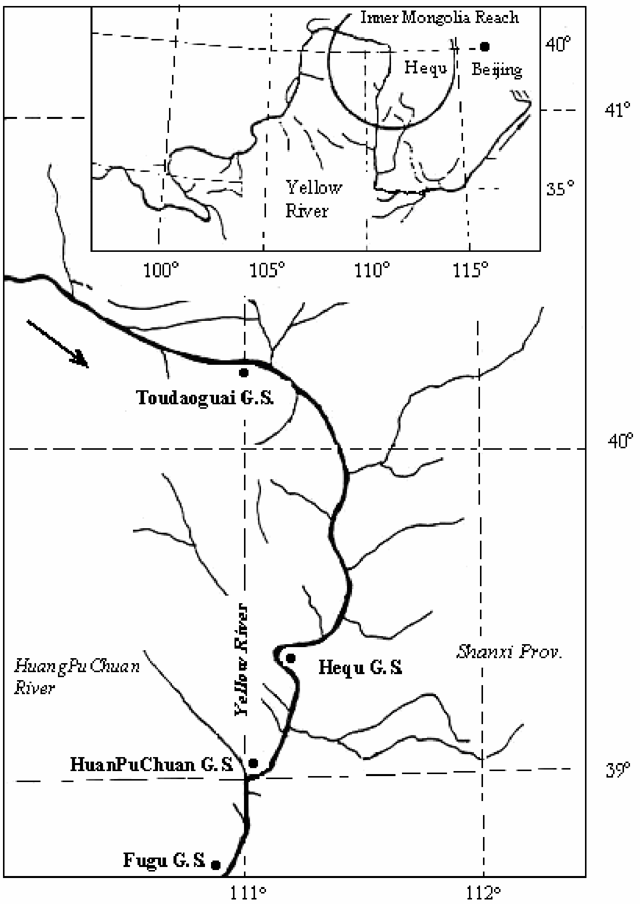

Fig. 1 Studied river reach of the Yellow River

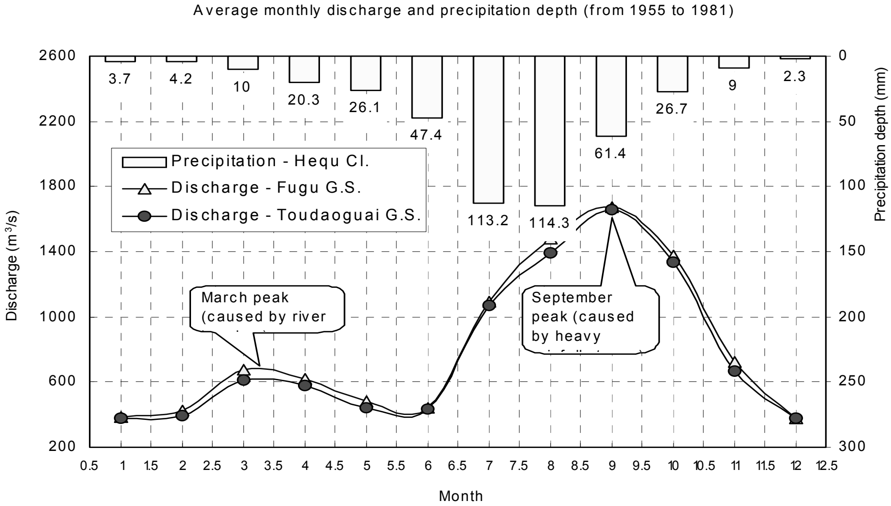

Fig. 2 Mean monthly discharge and precipitation (1955–1981).

sediment transported to the lower reaches of the Yellow River is mobilized from this region. The HuangPuChuan River is an important tributary of the Yellow River because of its high C_S.

The long-term measured precipitation at the Hequ climatic station between 1955 and 1981 shows that the mean annual precipitation is 438.3 mm. As shown in Fig. 2, the majority of the annual precipitation occurs in summer (between July and August) and accounts for over 50% of the total annual precipitation. Only about 2% of the annual precipitation falls between December and February.

RUNOFF CHARACTERISTICS

Discharge (*Q*) is an important variable affecting C_S in rivers. The C_S partially depends on *Q*, since an increase in *Q* generally leads to the increase in flow velocity in the main channel, hence increasing the turbulent energy required to keep material in suspension. Tables 1 and 2 summarize the *Q* and sediment data from 1955 to 1981 at TDGS and FGGS. During the four-month flood season (July–October), the water discharge accounts for 58% of the annual discharge. However, the corresponding sediment transport accounts for over 80% of the total annual sediment transport. Only about 15–19% of the total sediment load is transported during the eight-month non-flood season at TDGS and FGGS, respectively.

The average annual hydrographs at TDGS and FGGS are characterized by two peaks: the March and September peaks. Overall, the flow of the Yellow River within the river reach between TDGS and FGGS decreases to about two thirds, or ~400 $m^3 s^{-1}$ in late October or early November. The low precipitation in late autumn and early winter is an important reason for this reduction, as indicated by the decrease in monthly precipitation at this time shown in Fig. 2. In addition, freeze-up of the upstream river reach results in storage of some water in the channel upstream of the studied river reach. The water discharge peaks in March, typically exceeding 600 $m^3 s^{-1}$, even though the limited precipitation in February and March still falls as snow. The March peak is most likely caused by the release of water stored in the ice-covered/ jammed river reach during the ice break-up process within the upper Inner Mongolia reach and the study reach (Sui *et al.*, 2000, 2002). Subsequently, due to extraction of water for spring irrigation in this region and low precipitation amounts in spring, *Q* decreases again to about 400 $m^3 s^{-1}$. In early autumn, *Q* increases significantly, especially during the flood season between August and October, peaking in September. The September peak is clearly caused by heavy rainfalls during late summer and early autumn.

Figure 3 depicts the annual maximum *Q* and mean annual *Q* measured at TDGS and FGGS. The average annual *Q* at these two gauging stations are nearly identical, although the drainage area at FGGS is about 32 709 km^2 more than that at TDGS. However, the maximum *Q* at FGGS is much higher than that measured at TDGS. The characteristics of the sub-watersheds between TDGS and FGGS account for this increase. The sparse vegetation of the Loess region should significantly shorten the response time of the rainfall–runoff process, especially for heavy storms. This leads to a significant increase in maximum *Q*.

Runoff depth is a variable describing excess precipitation depth. The runoff depth reflects the impact of catchment characteristics such as soil type and vegetation cover on the rainfall–runoff process. Figure 4 shows the annual runoff depth at TDGS and FGGS. The values generally range from 50 to 90 mm. Compared with the average

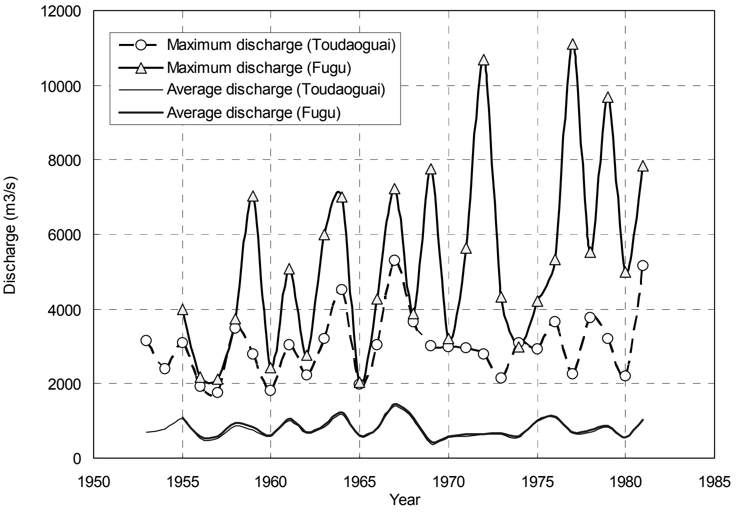

Fig. 3 Annual maximum, minimum and average discharge.

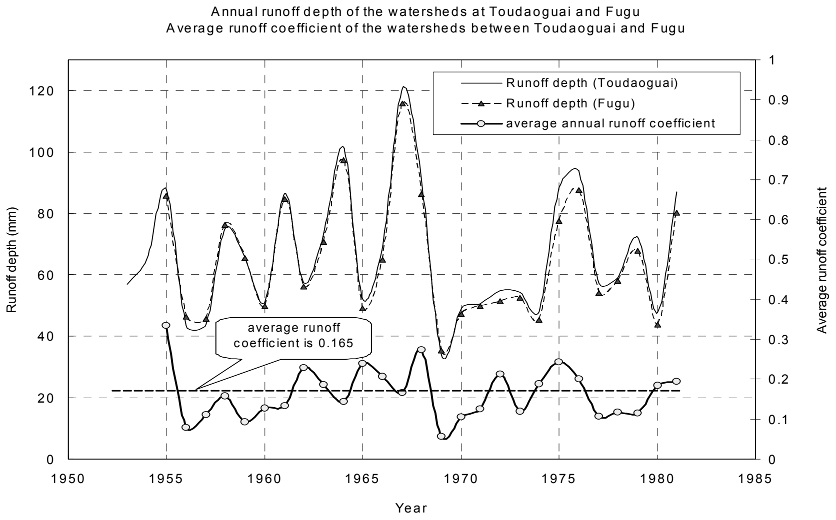

Fig. 4 Annual runoff depth and runoff coefficient of the watershed between TDGS and FGGS.

annual precipitation depth of 438.3 mm at Hequ climate station, over 80% of the precipitation is not able to contribute to runoff at the outlet of the watershed. Most of the precipitation is lost through infiltration and evapotranspiration. The average runoff coefficient between 1955 and 1981 was about 0.165. This fairly low runoff coefficient further demonstrates the impacts of the local loess soil on the rainfall–runoff process.

CHARACTERISTICS OF SEDIMENT TRANSPORT

The competence of sediment transport (the maximum grain size of sediment that can be carried) increases with flow velocity. The C_S is controlled by the turbulent energy of the fluid which is proportional to flow velocity. The C_S measured at these two gauging

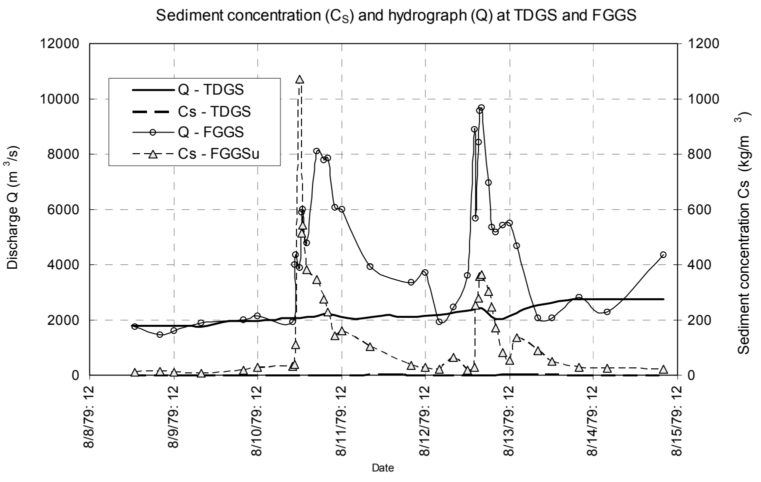

Fig. 5 Sediment concentration and hydrograph at TDGS and FGGS.

stations is usually greater than 5 kg m^{-3} but can reach substantially higher concentrations during flood events. As shown in Fig. 5, the C_S records at TDGS and FGGS are very different. The C_S reached values of 1070 kg m^{-3} on 11 August 1979 at FGGS (14.9 kg m^{-3} at TDGS). Generally, C_S is fairly low and does not change much at TDGS. However, C_S at FGGS may be over 1000 kg m^{-3} during flooding periods, and even less than 5 kg m^{-3} during drought periods. The easily detached sediment from the erodible upland Loess surfaces, in addition to the elevated Q during flood events, are likely reasons for the extremely high C_S values observed during the floods.

Table 1 shows the average C_S between 1954 and 1983 at TDGS was 5.84 kg m^{-3}. The average C_S during the flood season is about triple (8.04 kg m^{-3}) the equivalent value during months characterized by low flows (2.71 kg m^{-3}). Approximately 59% of the annual water Q occurs during the flood season but close to 81% of the annual suspended load is transported during this time. Only about 19% of the annual sediment suspended sediment load is transported during the eight-month non-flood season.

Table 2 shows the water and sediment data for FGGS, based on measurements made between 1954 and 1983. The average C_S during the flood season is about four times (17.50 kg m^{-3}) greater than during non-flood flows (4.18 kg m^{-3}). About 58% of the annual water Q occurs during the flood season, but over 85% of the annual suspended load is transported during this period. Only about 14.7% of sediment is transported during the eight-month non-flood season.

Table 3 shows the data for water and sediment transport based on the observations at the HuangPuChuan GS (gauging station on the HuangPuChuan River, a tributary that joins the Yellow River between HQGS and FGGS) for the period 1954–1983. The results show that most sediment transport and floods occur in July and August. Sometimes, as in the following examples, C_S exceeds 1000 kg m^{-3} (all units kg m^{-3}): 1210 (30/06/1979); 1260 (23/07/1979); 1220 (21/07/1981); 1020 (23/07/1981); 1140 (24/07/1981) and 1280 (06/08/1981) (Yellow River Conservancy Commission, 1985). The average C_S measured at HuangPuChuan GS was 312 kg m^{-3}. The average C_S during the flood season is over three times (371 kg m^{-3}) the Cs value during the eight-month non-flood season (100 kg m^{-3}). Approximately 80% of the annual water Q

Table 1 Water and sediment data for TDGS on the Yellow River (1954–1983).

	V_w	W_S	Q	C_S	% (yearly)		% (flood season)	
	(10^6 m^3)	(10^9 kg)	($m^3 s^{-1}$)	(kg m^{-3})	V_w	W_S	V_w	W_S
Flood season:								
July–Oct.	14660	118	1380	8.04	58.7	80.8		
July–Aug.	6810	57	1270	8.35			46.5	48.3
Sep–Oct.	7850	61	1490	7.79			53.5	51.7
Non-flood season:								
	10330	28	427	2.71	41.3	19.2		
Yearly	25500	146	793	5.84				

V_w = volume of water; W_S = mass of sediment transported; Q = discharge; C_S = sediment concentration.

Table 2 Water and sediment data for FGGS on the Yellow River (1954–1983).

	V_w	W_S	Q	C_S	% (yearly)		% (flood season)	
	(10^6 m^3)	(10^9 kg)	($m^3 s^{-1}$)	(kg m^{-3})	V_w	W_S	V_w	W_S
Flood season:								
July–Oct.	15230	266	1433	17.50	58.1	85.3		
July–Aug.	7170	178	1338	24.80			47.1	66.9
Sep–Oct.	8060	88	1529	10.90			52.9	33.1
Non-flood season:								
	11000	46	526	4.18	41.9	14.7		
Yearly	26230	312	832	11.90				

Table 3 Water and sediment data for HuangPuChuan GS on the Yellow River (1954–1983).

	V_w	W_S	Q	C_S	% (yearly)		% (flood season)	
	(10^6 m^3)	(10^9 kg)	($m^3 s^{-1}$)	(kg m^{-3})	V_w	W_S	V_w	W_S
Flood season:								
July–Oct.	146	54	13.7	371	78.4	93.1		
July–Aug.	116	49	21.6	426			79.5	90.7
Sep–Oct.	30	5	5.7	167			20.5	9.3
Non-flood season:								
	40	4	1.9	100	21.6	6.9		
Yearly	186	58	5.9	312				

occurs during the flood season, especially between July and August. On the other hand, over 93% of the annual suspended load is transported during this period. Less than 9% of the annual sediment load is transported during the non-flood season.

The differences evident between Tables 1 and 2 reflect the impact on sediment transport of the sub-watershed between these two gauging stations. The drainage area of the Yellow River is 364 732 km^2 upstream of TDGS, and 400 373 km^2 upstream of FGGS. The drainage area increment between these two gauging stations is 35 641 km^2. The main channel length of the HuangPuChuan River is 137 km with an average channel slope of 2.7‰. The drainage area of this branch river is 3246 km^2, and accounts only for 10% of the sub-watershed between TDGS and FGGS. As shown in

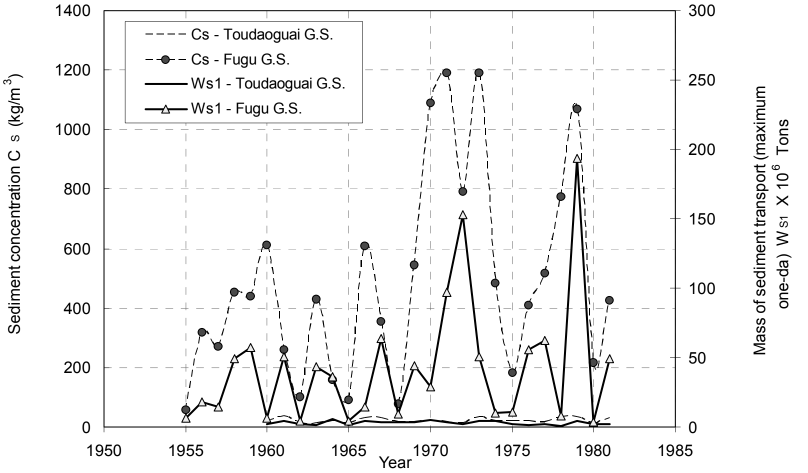

Fig. 6 Maximum instant sediment concentration and mass of maximum one-day sediment transport.

Tables 1 and 2, the annual net erosion between TDGS and FGGS is:

$$\Delta W_S = W_{S\text{-Fugu}} - W_{S\text{-Toudaoguai}} = (312 \times 10^9 - 146 \times 10^9)\ \text{kg} = 166 \times 10^6\ \text{t} \quad (1)$$

where W_s is the annual mass of sediment.

The mass of sediment transported at HuangPuChuan GS is:

$$W_{S\text{-HuangPuChuan}} = 58 \times 10^6\ \text{t} \quad (2)$$

Thus, about 35% of the sediment eroded in the sub-watershed between TDGS and FGGS was produced from the HuangPuChuan watershed which accounts for only 10% of the area of the sub-watershed between TDGS and FGGS (32 709 km^2).

Figure 6 provides information on the annual instantaneous maximum C_S at TDGS and FGGS, based on the sediment concentrations measured during flood periods between 1955 and 1981. The annual maximum C_S at TDGS does not change very much. It is usually less than 30 kg m^{-3} during flood seasons. However, both maximum C_S and Q vary markedly from year to year at FGGS. Localized heavy storms, especially those occurring in the HuangPuChuan sub-watershed, might be responsible for the significant change in Q. The easily erodible Loess Plateau accounts for the extremely high C_S of the Yellow River. Similarly, as shown in Fig. 6, the maximum one-day sediment transport at FGGS is much greater than that at TDGS, in addition to its significant fluctuation.

LOW C_S UNDER ICE-COVERED CONDITIONS AND ITS COARSENING

Under ice-covered conditions, the extra boundary added by the ice increases resistance to flow and leads to a completely different velocity profile under ice cover from that in open water conditions. The maximum flow velocity is reduced to approximately half that for the same water depth without ice cover, assuming that the riverbed and ice cover have similar roughness coefficients (Gogus & Tatinclaux, 1981). Thus, sediment movement under ice cover is more complex than that under open flow conditions.

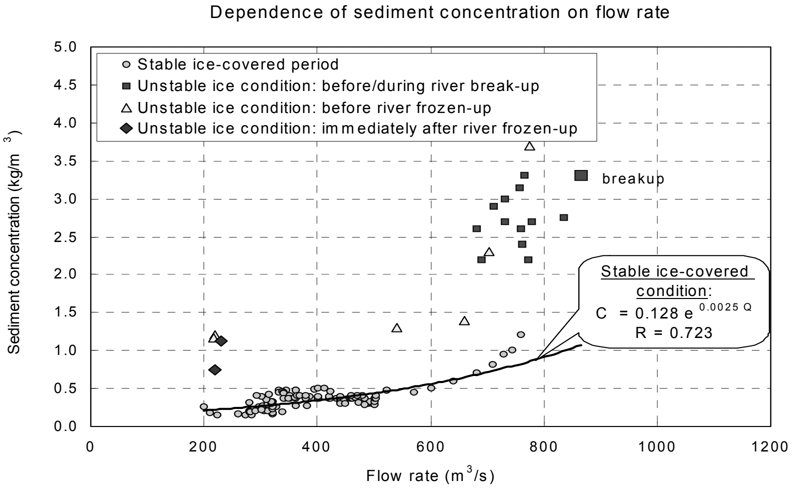

Fig. 7 Dependence of sediment concentration on discharge (ice-covered conditions).

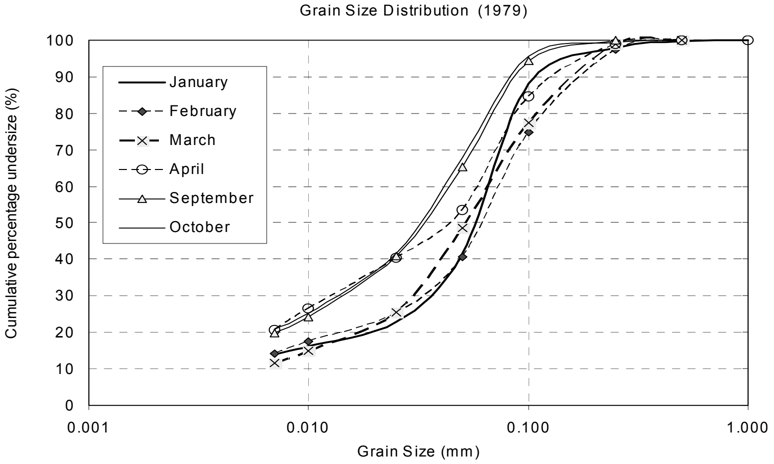

Fig. 8 Grain-size distribution of sediment concentration at the Hequ climatic station.

The C_S is much less for the ice-covered conditions than during the ice-free season, as shown in Fig. 7. The average C_S during the non-flood season is 2.71 kg m^{-3}. The C_S during the stable ice-covered period is only about 0.5 kg m^{-3}, much less than that under open water conditions. Also, C_S during stable ice-covered periods is much less than during unstable ice conditions. The impacts of ice blocks, such as riverbed ploughing, are important in accounting for the higher C_S values found under unstable ice conditions. The C_S during ice break-up periods may reach the level of C_S under open flow conditions, i.e. about 4.0 kg m^{-3}.

Interestingly, the grain size distribution of suspended sediment during the ice-covered period is different from that under open water conditions. For the same grain size cumulative percentage, as shown in Fig. 8, the median grain size diameter of the suspended load during the ice-covered period between late November and March, especially in January and February, is larger than that for open water conditions during the rest of the year, although Q during the winter period is less than that under open flow conditions. The following arguments can account for the low C_S and its coarsening under ice-covered conditions:

(a) The winter precipitation in this area falls as snow. The presence of snow cover reduces soil erosion on the Loess Plateau, which normally causes the high C_S of the Yellow River during flood seasons.
(b) During the stable ice-covered period, any soil eroded by wind should be intercepted by the ice cover, and cannot enter the water. This leads to a decrease in C_S under ice-covered conditions.
(c) In winter, the snow precipitation results in a significant decrease in surface runoff in the area between TDGS and FGGS. The tributary rivers in this ravine region become frozen during winter. Thus, the contribution of sediment to the main river by surface runoff decreases significantly.
(d) Decreased flow velocity under ice-covered conditions is another factor affecting the level of C_S. Because of the extra boundary added to flow by the ice cover/jam, the friction increases dramatically leading to a decrease in flow velocity and dynamic energy for sediment transport.
(e) Depletion of fine sediment supply from the riverbed and flood plain might be another reason for the low C_S and its coarsening under ice-covered conditions.
(f) During the ice break-up period, sediment intercepted by the ice cover and the sediment contained in ice will be released to the water. Together with increased exposure of riverbanks to erosion by an increased water level, C_S increases significantly.

CONCLUSIONS

This article discusses the behaviour of C_S along a reach of the Yellow River, located in the Loess Plateau. The mean annual Q at upstream TDGS and downstream FGGS are nearly identical. However, the maximum instantaneous Q at FGGS is much higher than that measured at TDGS. The annual runoff depths at TDGS and FGGS generally range from 50 to 90 mm. Based on the mean annual precipitation depth of 438.3 mm at the Hequ climatic station, over 80% of precipitation falling in this watershed does not contribute to runoff. The level of C_S at FGGS is much higher than that at TDGS, although the annual runoff depths at these two gauging station are nearly identical. The annual maximum C_S is usually less than 30 kg m^{-3} during the flood season at TDGS. However, both maximum C_S and Q vary markedly at FGGS. The sparse vegetation cover and local heavy storms, especially those occurring in the HuangPuChuan sub-watershed, might be responsible for the high instantaneous maximum Q. The easily erodible loess between these two gauging stations provides the main reasons for the extremely high C_S. The value of C_S under ice-covered flow is fairly low compared to C_S in summer. For the same cumulative percentage undersize, the median grain size of suspended load under ice cover is much coarser than that under open flow conditions. Overall, about 35% of the sediment eroded in the sub-watershed between TDGS and FGGS was produced from the HuangPuChuan watershed, which accounts only 10% of its drainage area.

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