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 landforms, 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
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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 \(~400\ \text{m}^3\ \text{s}^{-1}\) 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 \(600\ \text{m}^3\ \text{s}^{-1}\), 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 \(400\ \text{m}^3\ \text{s}^{-1}\). 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 \(32\ 709\ \text{km}^2\) 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
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
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 $C_S$ value during the eight-month non-flood season (100 kg m$^{-3}$). Approximately 80% of the annual water $Q$
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Table 1 Water and sediment data for TDGS on the Yellow River (1954–1983).

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

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

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

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

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

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

where $W_S$ is the annual mass of sediment.

The mass of sediment transported at HuangPuChuan GS is:

$$W_S^{\text{HuangPuChuan}} = 58 \times 10^6 \text{ t}$$  \hspace{1cm} (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 km²).

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.
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Dependence of sediment concentration on flow rate

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

Grain Size Distribution (1979)

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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