Increasing effect of aeolian sediment transport on riverbed evolution under decreased flow conditions in the alluvial desert reach of the Upper Yellow River

Abstract

Aim: In this study, an essential role of bed-material load mainly composed of coarse aeolian sand rather than that of wash-load originating from tributaries of the Loess Plateau in the development of channel morphology in response to decreased flows in the alluvial desert reach of the Yellow River is outlined.

Methodology: Two sediment cores were drilled in the channel beds of the upstream braided stretch (Shizuishan-Sanhuhekou) and the downstream meandering stretch (Sanhuhekou-Toudaoguai), respectively.

Results: The following coarse sediment identification of bed material, grain size distributions (GSDs) in suspension and channel geometry measurement indicated that aeolian and fluvial interactions in our study reach trigger and lead to channel aggradation and lateral migration following the operation of the upstream large reservoirs. In response to the decreased flows in recent 30 decades since 1986, the wash-load proportion of both the braided and the meandering channel increased from 82.98% to 91.09% on average, with the bed material-load proportion decreased from 12.26% to 7.22%, showing an evident tendency of getting finer and channel aggradation. The coarse sediment (0.08-0.25 mm), although only a small fraction of 10% on average, is active in suspension as bed material-load or in saltation as bed-load, indicating that the study channel should be transitional channel or transitional to labile, with the calculated river competence indicator t* as 0.92-2.5. In addition, the primary river stability indicator (K) adapted to the two stretches was proposed and calculated by introducing D50 and bank-full discharge instead of maximum discharge. The calculated values showed that the meandering channel (K=0.647) is more stable than the braided channel (K=0.238), which is of primary guiding significance for alluvial river stability prediction.

Interpretation: Deterioration in runoff-sediment relations is increasingly threatening the health of the upper Yellow River. Accordingly, with the decline of the sediment trapping ability of existing reservoirs in the future, erosion rates will increasingly affect the fluvial sediment characteristics and even the channel morphology development.

Key words: Aeolian sand, Alluvial geomorphology, Bed material, Channel stability, Yellow River

Citation: Wang, Z. and W. Ta: Increasing effect of aeolian sediment transport on riverbed evolution under decreased flow conditions in the alluvial desert reach of the Upper Yellow River. J. Environ. Biol., 40, 536-547 (2019).
Introduction

Purely individual alluvial channels are classified into two patterns: single-thread pattern and multi-thread pattern, of which straight and meandering are representative of the former, while braided belongs to the latter (Lepold and Wolman, 1957). Perennial rivers with greater channel scale always show various channel patterns in different reaches depending on the part of fluvial system that is under consideration (Schumm, 1985; Khattak et al., 2018).

It has long been recognized that alluvial channels are self-formed in the sediments that they have transported and deposited and the transitions between different channel patterns are gradual (Bridge, 1985; Carson, 1984; David Knighton and Nanson, 1993; Ferguson, 1987; Ul-Haq et al., 2018). Morphological style is determined chiefly by the quantity and caliber of sediment delivered to the channel (Church, 2006; Qiao, 2018) and even the dynamic variation of the relations between runoff and sediment. S.A. Survey and Schumm (1963) proposed a classification that subdivided alluvial rivers into three categories on the basis of the dominant mode of sediment transport and gave some characteristics of the channels associated with each (i.e., threshold channel with bed load dominance, transitional channel with mixed load dominance and labile channel with suspended load dominance, respectively), which established a basis to seek the origins of alluvial channel morphology while laying emphasis on the competence of the river to move sediment (i.e., the power of the river) and assigning appropriate prominence to the important role of bed material-load (Fig. 1) other than that of wash-load in shaping alluvial channel geometry and morphology. Nevertheless, most studies still focused their attention on the suspended sediment transport, especially wash-load transport, rather than total sediment transport just because the magnitude of throughput wash-load dwarfs that of the bed material-load and bed-load, and perhaps because of the difficulty in measuring the bed materials.

Numerous studies have reported that low flow regulation may trigger channel changes such as channel degradation, channel aggradation, or channel metamorphosis at different temporal and spatial scales (Brookes, 1995; Downs and Gregory, 2004; Emmett, 1974; Grams and Schmidt, 2002; Gregory, 2006; Gregory and Park, 1974; Hooke, 1997; Knox, 1977; Petts, 1979, 1980; Schumm, 1969; Williams and Gordon, 1984). Even in arid desert regions, potential input of aeolian sand can also play an important role in river channel changes (Ta et al., 2008; Kassim et al., 2018). However, adequate field evidence to confirm the effect of decreased flow and aeolian processes on the long-term pattern between sediment and alluvial channel morphology is lacking. The Yellow River provides an opportunity to study this complex processes.

The Yellow River is regarded as the second largest river in the world in terms of sediment load, with the upper reach shows typical runoff-sediment mismatch. The sediment primarily contains silt and clay (i.e., wash-load; <0.063 mm (Asselman, 2000; Sultana et al., 2018) originating from tributaries of the Loess Plateau, whereas the primary runoff is generated from upstream rock mountains (Fig. 2a). Most of the wash-load has been discovered in suspension for a long distance in the main stream of the Yellow River, with only a small fraction of it deposited on bar tops and floodplain surfaces due to shallow water. In addition, the alluvial reach of the upper Yellow River through the Kubq Desert deposits an approximately 1000-2400 m thickness of coarse sediment layer (Yang, 2002), the surface layer of which may be entrained by strong turbulent flows and consequently contribute to bed-load saltation or bed-material load (coarse aeolian sand with a median grain size of 0.08mm (Ta, et al., 2011; Kibria et al., 2018) in suspension. The same is the upstream reach flowing through the Ulan Buh Desert with a 1-3 m thickness of coarse sediment layer apt to move (Ta et al., 2015). In recent 60 years, the runoff-sediment relations of the Yellow River experienced dramatic changes due to both regional climate change and human activities (i.e., construction and operation of the large reservoirs), resulting in great changes in channel geometry and morphology. Accordingly, the sand-bed reach mentioned above shows more and more obvious meandering and braided channel patterns (Yao et al., 2013). Although this fluvial process affects increasingly the structure and the function of the Yellow River ecosystems, The apparent lack of relation between bed-material load and river morphology in response to low flow regulation on a larger temporal and spatial scale has so far posed a major obstacle to the knowledge of river bed evolution.

Previous studies indicated that tributaries in the Loess Plateau in the upper basin of the Yellow River, such as the Huangshui, Taohu and Qingshui Rivers (Fig. 2a) supplied sediments which led to the aggradation of the Ulan Buh and Kubq Deserts channel due to low flow regulation of the upstream reservoirs (Wang et al., 1998; Zhao et al., 1999). However, according to the analysis in this paper, if there is no input of aeolian sands from the Ulan Buh and Kubq Deserts, the channel should be a degradation channel rather than an aggradation channel. This inconsistency prompted a much closer look at the relationship between the channel aggradation and aeolian sand input.

In this study, we provided a long-term evidence of sediment transport and alluvial channel morphological characteristics in response to decreased flows and made attempts to analyze quantitatively the significance of the bed material transport in shaping channel morphology while explaining the alluvial channel stability and adjusting mechanism in the sand-bed reach of the upper Yellow River.

River stability related to channel morphology: It has long been recognized by both geomorphologists and sedimentologists
It is not difficult to find that Eq. (1a) also indicates the qualitative statement of the principal governing conditions of alluvial channel pattern, hence the fluvial sediment transport function as:

$$\frac{Q}{Q_o} = f\left[\frac{pghS}{g(p - p_s)D_{50}}\right]$$

where $g$ is the acceleration of gravity, the term on the left is the average concentration of bed material sediment transport, which we can define as the inflow bed material coefficient here, and the term in brackets is conventionally notated by $t^*$ and is precisely the Shields number, hence suggests the competence of the river (Lane, 1955; Shields, 1936).

In summary, river channel, including alluvial channel, always adjusts and develops itself toward stability and balance, and the self-adjusting process of alluvial channel shows significant contrasts between the input of bed material-load content and the competence of the river channel. Generally speaking, if the imposed sediment concentration is greater than can be entrained on the available gradient, the channel should deposit the rest of load and would ultimately lead to channel aggradation and braid; on the contrary, however, if the imposed sediment concentration is less than can be entrained, the channel will adjust to bring up to the equilibrium state again.
The Yellow River flows through the Yinchuan-Hetao plain and develops a typical sand-bed stream channel, of which the stretch between Shizuishan to Sanhuhekou gauge station is a braided channel of 353 km with an average gradient of $1.44 \times 10^{-4}$, and the stretch between Sanhuhekou to Toudaoguai gauge station is a meandering one of 310.5 km with an average gradient of $1.03 \times 10^{-4}$ (Fig. 2). Along the two desert reaches, the banks are primarily composed of aeolian sands and loams without any effective vegetation stabilization. It has long been observed and generally accepted that aeolian sand inputs from the Ulan Buh Desert and sand-bank erosion from the Kubq Desert occurred in the upstream braided channel as well as hyper-concentrated flows from the ten tributaries (T1-T10, Fig. 2b) crossing the Kubq Desert in the downstream meandering channel are three major coarse sand origins delivered to the stream channel (Ta et al., 2008, 2011, 2013) (Fig. 3).

Following the operation of upstream large reservoirs such as Longyangxia and Lujiaxia reservoirs (Fig. 2a) in recent 60 years, the meandering desert reach (Sanhuhekou-Toudaoguai) has experienced its dramatically decreasing trend for the flow discharge. Moreover, the abrupt sediment supply (Table 1) delivered by the hyper-concentrated flows from the ten tributaries have made the runoff-sediment relation deteriorated. As a consequence, the river channel pattern changes in this study reach primarily depends on its tributary confluences rather than on the upstream sediment supply alone.

The upper (U), middle (M) and lower reaches of the Yellow River are divided by white lines. The upper reach is further subdivided into the Plateau (rock mountains) portion and the alluvial platform portion where our study area is located by the Qingtongxia reservoir (the yellow pentagram with black border). The green dots with black borders are gauge stations (Shi is Shizuishan station; Bay is Bayangaohe station; San is Sanhuhekou station; Tou is Toudaoguai station) and the white dots with balck borders are sampling sites of the drilling cores marked with numbers 1 and 2. The drainage area of the Yellow River is highlighted by the thick, black, dashed contour. (b) Location of the Kubq desert reach of the Yellow River, showing the distribution of 113 cross-section profiles and the ten cross-desert ephemeral tributaries (T1-T10). No. 22 is the typical cross-section in upstream braided channel, No. 65 is the typical cross-section in downstream meandering channel.

To understand the channel changes in the Kubq Desert reach in response to flood control issues, the Yellow River Conservancy Commission of China (YRCC) has installed 113 monumented channel cross-sections at approximately 5 km intervals along the stream channel since 1962. These profiles were surveyed in 1962, 1982 and 1991 by the YRCC and were resurveyed by Inner Mongolia Water Conservancy and Hydropower Survey and Design Institute of China in 2000. We used the profile data to determine the channel geometry changes in different periods with respect to the severe bank erosion and channel fill. For seeking the internal relations between channel pattern and sediment characteristics, we also analyzed the full-time monitored data of suspended sediment load and its grain size distribution (GSD) measured by YRCC at the input controlling gauge station: Shizuishan and the output controlling gauge station: Toudaoguai of our study area from 1950 to 2014, to distinguish between wash-load and bed material-load, among which the primary data from 2011 to 2014 was cited from the river sediment bulletin issued by the Ministry of Water Resources of the People's Republic of China (http://www.mwr.gov.cn/). In addition, we also drilled two sediment cores in the channel bed (Fig. 2a). The first (No. 1) was about 60 km upstream of the Bayangaohe gauge station and the sample was taken in sand bars that were exposed during periods of low flow near the channel centerline. The second (No. 2) was on the sand bar in the mouth of the Xiliu

<table>
<thead>
<tr>
<th>Tributaries</th>
<th>Length (km)</th>
<th>Drainage area (km²)</th>
<th>Average annual runoff (10⁶ m³)</th>
<th>Average annual sediment load (10⁶ t)</th>
<th>Modulus of sediment yield (t km⁻² yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1: Maobula</td>
<td>110.9</td>
<td>1261</td>
<td>901</td>
<td>331</td>
<td>2620</td>
</tr>
<tr>
<td>T2: Burigasetai</td>
<td>73.8</td>
<td>545.9</td>
<td>430</td>
<td>158</td>
<td>2890</td>
</tr>
<tr>
<td>T3: Heilai</td>
<td>89.2</td>
<td>943.8</td>
<td>998</td>
<td>367</td>
<td>3890</td>
</tr>
<tr>
<td>T4: Xilu</td>
<td>106.6</td>
<td>1193.8</td>
<td>3220</td>
<td>481</td>
<td>4030</td>
</tr>
<tr>
<td>T5: Hantai</td>
<td>90.4</td>
<td>874.7</td>
<td>1880</td>
<td>274</td>
<td>3130</td>
</tr>
<tr>
<td>T6: Haoqing</td>
<td>34.2</td>
<td>213.3</td>
<td>335</td>
<td>84</td>
<td>3940</td>
</tr>
<tr>
<td>T7: Hashila</td>
<td>92.4</td>
<td>1088.6</td>
<td>3510</td>
<td>524</td>
<td>4810</td>
</tr>
<tr>
<td>T8: Muhar</td>
<td>77.2</td>
<td>406.7</td>
<td>669</td>
<td>117</td>
<td>4350</td>
</tr>
<tr>
<td>T9: Dongjilu</td>
<td>75.4</td>
<td>451.2</td>
<td>669</td>
<td>167</td>
<td>3700</td>
</tr>
<tr>
<td>T10: Husaitai</td>
<td>65</td>
<td>406</td>
<td>590</td>
<td>148</td>
<td>3650</td>
</tr>
</tbody>
</table>
tributary (T4, Fig. 2b). Both the two cores are 3-m-deep and we obtained the samples by inserting iron pipes (4-m-long and 5 cm in diameter) vertically into the beds. The pipes were hammered into the bed using a trestle for support. The samples were dried and sieved to measure the coarse grain size distribution and were analyzed by the Malvern Master Size 2000 for the GSD of the finer portions (<0.063 mm). The analysis focused on their different layers with a 50-cm thickness. Assuming that the GSD by volume approximates the GSD by weight for the fines (<0.063 mm), we used full phi grain-sized classes for particles less than 0.5 mm to calculate the $D_n$. Then, using GSD data for the separated samples, we calculated the depth-averaged $D_n$ of each sediment core. Moreover, analysis using a JSM-5600LV scanning electron microscope (SEM) combined with macroelement oxide content analysis were carried out to determine the origin of bed material.

Results and Discussion

Our fluvial sediment analysis on the meandering channel stretch between Sanhuhekou and Toudaoguai station indicates that the annual suspended sediment load decreased by approximately 40% (Fig. 4) compared with that of natural channel state before 1968 due to the operation of the Qingtongxia (1967) and Liujiaxia (1968) reservoirs. Because the two reservoirs have large storage capacities ($5.7 \times 10^8$ m$^3$ and $57 \times 10^8$ m$^3$, respectively), they can store large amounts of water and trap
most of the sediment yielding from upstream. In addition, the flow discharge experienced an obvious decreasing tendency since the operation of the Longyangxia reservoir in 1986, and the annual flow discharge decreased by 35% compared with that of before 1986, thus the period from then on experienced a typical decreased flows period (Fig. 5). Following the operation of this reservoir, the flow regime of the upstream reaches became completely regulated due to the very large storage capacity (247×10^3 m^3) for storing large amounts of water and with drawing for irrigation. Moreover, the suspended sediment load at Toudaoguai station is lower than that of Sanhuhekou station since 1986 (Fig. 4), concealing a complicated and significant fluvial sedimentation process i.e. the hyper-concentrated flows from the ten tributaries crossing the Kubq Desert, which, on average, delivers about 0.2×10^6 t yr^-1 coarser sand sediment to the stream channel of the Yellow River (Ta et al., 2013).

For instance, on July 21, 1989, a mudflow event occurred at the ten cross-desert ephemeral tributaries (T1-T10), with the peak sediment concentration reaching as high as 1600 kg m^-3, which delivered about 1.13×10^6 t of sediment to the Yellow River (Zhi and Shi, 2002). These disastrous mudflows processes combined with the decreased flows gradually led to severe channel aggradation and migration (Fig. 6a), and consequently

**Fig. 3**: Photographs of three major coarse sand origins delivered to the stream channel. (a) aeolian sand input; (b) sand-bank erosion; (c) hyper-concentrated mudflows.

**Table 2**: Channel section profile characteristics of Sanhuhekou station in representative years

<table>
<thead>
<tr>
<th>Time</th>
<th>Beach lip elevation (m)</th>
<th>Flow area A (m^2)</th>
<th>Width B (m)</th>
<th>Depth H (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965.6.1</td>
<td>1020.26</td>
<td>1293</td>
<td>402</td>
<td>3.21</td>
<td>(Wu et al., 2010)</td>
</tr>
<tr>
<td>1972.6.15</td>
<td>1020.06</td>
<td>1473</td>
<td>446</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>1986.5.10</td>
<td>1019.54</td>
<td>1435</td>
<td>397</td>
<td>3.62</td>
<td></td>
</tr>
<tr>
<td>2004.4.4</td>
<td>1019.5</td>
<td>678</td>
<td>278</td>
<td>2.44</td>
<td></td>
</tr>
<tr>
<td>2005.4.4</td>
<td>1019.84</td>
<td>860</td>
<td>310</td>
<td>2.77</td>
<td></td>
</tr>
</tbody>
</table>
contributed to the development of channel meandering. The channel section profile characteristics of Sanhuhekou station shows the striking changing process (Table 2). Further profile survey results indicate that the desert reach is unsteady and experienced a striking characteristics of lateral channel migration and deposition. As shown in Fig. 6b, the severe sand-bank erosion and failure results in a large amount of coarse aeolian sand delivered into the channel, with a total lateral channel erosion rate of $0.6-0.67 \times 10^4 \text{ t yr}^{-1}$ in response to the decrease in flow (Ta et al., 2013), which leads to the mismatch of the river competence with sediment concentration and to the development and exposure of sand bars, and ultimately results in the river braided.

Although these large volumes of aeolian sands are coarser than the suspended sediments in the river system and once delivered into the main stream of the Yellow River, may develop as a coarse sediment layer on the channel bed, they may be entrained by strong turbulent flows and consequently contribute to bed-load saltation or bed-material load suspension due to the high flow releases from upstream reservoirs.

To validate this hypothesis, we compiled and analyzed the monitored data related to the GSDs of the annual suspended-load in our study area. Our findings indicate that, on average, nearly 86% of the total suspended sediment-load is wash-load (silt and clay, $<0.063 \text{mm}$) (Fig. 7), with the average value of 83.8% in the input site: Shizuishan station and that of 87.6% in the output site: Toudaoguai station. Moreover, the proportion of wash-load to suspended-load increased by 11% in the recent six decades in both the two stations, exhibiting an evident tendency of getting finer in response to the decreased flows. Although the abundant wash-load substantially inflates the suspended fraction, it
appears that a population of coarse sand grains with the size of 0.1-0.25mm, although only a small fraction of 10% on average, are also active in suspension as bed material-load or in saltation as bed-load, which are of great importance in shaping the channel morphology. As shown in Fig. 7a and b, the bed material-load fraction decreased from 16.07% to 9.15% in Shizuishan station and from 8.45% to 5.29% in Toudaoguai station since 1986, indicating a sediment deposition process and contributing to the development of the related channel morphology.

Analysis of the two drilling samples collected from two typical channel sections indicates that on average, 82.47% and 64.56% of the channel bed sediments are composed of the coarse sand (>0.08mm) (Table 3), with the $D_{50}$ to be 0.12 mm and 0.2 mm in the braided channel stretch and the meandering channel stretch, respectively. Our results also demonstrated that an average 30% of particles finer than 0.063 mm are found among the surface sediment layer, which should be the result of high fine sediment releases from the upstream reservoirs. The SEM analysis of the surface microstructures of the coarse sand particles shows that most of the coarse sand particles are identified as chipped depressions and oval-shaped particles (Fig. 8), which agrees well with the aeolian samples collected in the slip face of barchans or barchanoids and in the crest of foredunes, further indicating that the coarse sediment are aeolian sands.

The hyper-concentrated mudflows events delivering large volumes of coarse sediment to the main stream of the Yellow River appear to be the main reason for bed material getting coarser, because an approximately 30% of coarse particles named Cretaceous sandstone rocks (Fig. 9) are identified apart from the coarse aeolian sand particles in the No.2 drilling sample. These Cretaceous sandstone rocks are originating from the upstream gullies of the ten tributaries, where the significant runoff generating area is located (Ta et al., 2015; Wang and Ta, 2016). The chemical components of channel drilling samples agree well with those of desert surface ones, which also demonstrates that the bed material-load in suspension is originating from the local deserts (Fig. 10). Hence, the bed material in our study area is active in moving as suspension and saltation. In other words, the sediment transport regime in the alluvial desert reach of the Yellow River should be mixed load under the dominance of suspension.

In addition, the mineral content of each samples also agrees well. The main light minerals are quartz, feldspar, carbonate and so on, with the contents of quartz and feldspar account for 80% of the total. The contents of heavy mineral account for 2% merely. As the density of the bed material is the weighted mean of the densities of each mineral, we calculated the value: $r = 2.68$ g cm$^{-3}$, thus the $t^*$ and the primary river stability indicator of the two channel stretches according to Eqs. (1b) and (3) are shown in Table 4.

Our findings outline an essential role of bed-material load originating from coarse aeolian sand in the development of channel morphology in response to decreased flows in the alluvial

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**Table 3**: Results of the sieving and SEM analysis of the drilling samples.

<table>
<thead>
<tr>
<th>Drilling core</th>
<th>Propotion of coarse aeolian sand (%) in the different layers (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-50</td>
</tr>
<tr>
<td>No. 1</td>
<td>83.92</td>
</tr>
<tr>
<td>No. 2</td>
<td>62.47</td>
</tr>
</tbody>
</table>
Qingtongxia reservoir (1967) from 1960 to 1968, the stretch from Baygaole to Sanhuhekou station exhibited channel scour and that from Sanhuhekou to Toudaoguai station showed channel deposition (-0.0247×10^8 t yr^-1 in total, "-" represents scour). Then, from the operation of the Liujiaxia reservoir (1968) to the operation of the Longyangxia reservoir (1986), it showed a small amount of deposition (0.0346×10^8 t yr^-1 in total), however, a continuous deposition occurred from 1987 to 2010 (0.7814×10^8 t yr^-1 in total), although there were slight scour in the stretch between Bayangaole and Sanhuhekou station (Fig. 11). The desert reach of the Yellow River. This process of aeolian-fluvial interaction in our study reach is unique, and in particular, triggers and leads to the channel aggradation and lateral migration following the operation of the upstream large reservoirs. The annual sediment erosion and deposition from 1952-2010 calculated by the sediment transport equilibrium method suggested by Wu et al. (2015) indicated that in the natural channel state from 1952-1959, the input sediment load was large, and the two channel stretch in our study area both showed fluvial deposition (0.7135×10^8 t yr^-1 in total); with the operation of the Sanshenggong and Yanguoxia reservoir (1961) as well as the Qingtongxia reservoir (1967) from 1960 to 1968, the stretch from Baygaole to Sanhuhekou station exhibited channel scour and that from Sanhuhekou to Toudaoguai station showed channel deposition (-0.0247×10^8 t yr^-1 in total, "-" represents scour).

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As far as the calculation of the river stability indicator is concerned, here, for simplicity, we used the averaged expressions for the channel gradient, water depth, and grain diameter and assumed that the water density is constant, not including here the influence of the sediment concentration which could be relevant as, for instance, Yang and Simões (2005) and Yang et al., (2014) indicated. Compared with the related studies focused on flood dynamics and the movement of water and sediment particles of the Yellow River (Chen et al., 2015), our results may be lacking of accuracy for the description of such a complex river, the value of the river stability indicator \(K\) we calculated, however, should be of primary guiding significance for alluvial river stability prediction.

In this study, the wash-load and bed material-load in suspension were distinguished for the first time for laying emphasis on the role of bed material in shaping channel morphology of the alluvial desert reach in the Yellow River. Our results indicates that, in response to the decreased flows in recent 30 decades (decreased by 35% since 1986), the wash-load content of both the upstream braided channel stretch and deposition between Bayangaole to Toudaoguai station are consistent with the value calculated by the means of cross-section measurement using the profile data and the method provided by Kasai et al. (2004) (Fig. 12). Deterioration in runoff-sediment relations is increasingly threatening the health of the upper Yellow River.

According to the analysis by Yao et al. (2013) using landsat images and topographic maps, the channel sinuosity of the whole sand-bed reach of the upper Yellow River form Shizuishan to Toudaoguai varied between 1.34 and 1.45 during the period of 1958-2008. The decreased flows and reduced sediment transport under the influence of the large flood control issues, as well as the severe noncohesive sand bank erosion and hyper-concentrated mudflows input have been undoubtedly accelerating the self-forming process of the available alluvial channel. Therefore, with the decline of the sediment trapping ability of existing reservoirs in the future, erosion rates will increasingly affect the fluvial sediment characteristics and even the channel morphology development.

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Table 4: Primary river stability indicators of two channel stretches of Yellow River

<table>
<thead>
<tr>
<th>Channel stretch</th>
<th>Mean depth (m)</th>
<th>Mean gradient (S (‰))</th>
<th>Bed material diameter (D_m (mm))</th>
<th>Stability indicator (K)</th>
<th>(T^*)</th>
<th>Channel pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shi-San (braided)</td>
<td>3.5</td>
<td>0.144</td>
<td>0.12</td>
<td>0.238</td>
<td>2.50</td>
<td>Transitional (Schumm, 1985; Survey and Schumm, 1963)</td>
</tr>
<tr>
<td>San-Tou (Meandering)</td>
<td>3</td>
<td>0.103</td>
<td>0.20</td>
<td>0.647</td>
<td>0.92</td>
<td>Survey and Schumm, 1963</td>
</tr>
</tbody>
</table>

*The larger the \(K\) is, the more stable the river channel should be.* According to Survey and Schumm (1963), Shi-San channel may be labile channel, our field study and analysis suggest that it should be transitional channel or transitional-labile; As the discharge in the study reach varies between about 500 m³ s⁻¹ in Winter and Spring to peak values of about 2000 m³ s⁻¹ in Summer, and the mean bankfull discharge is about 1000 m³ s⁻¹ (Schuurman, 2018), the Chézy formula was used to estimate the water depth for the corresponding discharge, of which the water surface levels along the Yellow River were monitored with river level gauges by the YRCC.
(Shizuishan-Sanhuhekou) and the downstream meandering channel stretch (Sanhuhekou-Toudaoguai) increased from 82.98% to 91.09% on average, with the bed material-load content decreased from 12.26% to 7.22%, showing an evident tendency of getting finer and the related channel aggradation ($0.7814\times10^3$ t yr$^{-1}$ of sediment deposition from 1987 to 2010). The severe noncohesive sand bank erosion and hyper-concentrated mudflows input have been undoubtedly accelerating the self-forming process of the available alluvial channel. Moreover, the medium and coarse sediment (0.08-0.25mm, appropriately), although only a small fraction of 10% on average, are active in suspension as bed material-load or in salitation as bed-load, which indicates that the study channel reach should be transitional channel or transitional to lable, with the calculated river competence indicator $t^*$ to be 0.92-2.5. In addition, the primary river stability indicator ($K$) adapted to the two channel stretches were proposed and calculated by introducing the $D_0$ and bank-full discharge instead of Maximum discharge. The calculated values shows that the meandering channel ($K = 0.647$) is more stable than the braided channel ($K = 0.238$), which is of primary guiding significance for alluvial river stability prediction. Our quantitative analysis also indicates that deterioration in runoff-sediment relations is increasingly threatening the health of the upper Yellow River. Accordingly, with the decline of the sediment trapping ability of existing reservoirs in the future, erosion rates will increasingly affect the fluvial sediment characteristics and even the channel morphology development.

Acknowledgments

This work was supported by the Natural Science Foundation of China (No. 51269009) and the National Basic Research Program of China (No. 2011CB403302) and the West Light Talents Foundation of Chinese Academy of Sciences (29Y329971) “Transport Mechanism of coarse sediment in desert watershed in arid zones-a case of Ningxia-Inner Mongolia Reach of Yellow River” (2012).

References

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