



Responses of the braided channel to reduced discharge and lateral inputs of aeolian sand in the Ulan Buh Desert Reach of the Upper Yellow River

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Abstract

The UlanBuh Desert reach belongs to the upper reaches of the Yellow River located in Inner Mongolia Autonomous Region (China), which has developed a sandy bed. This reach that flows across aeolian dunes field of the UlanBuh Desert has caused large lateral infusion of aeolian sands into riverbed, an abrupt addition of the bedload and a sharp channel widening, forming a typical braided channel. In addition to traditional driving factors such as discharge, suspended sediments and slope, here we also focus on the lateral infusion of aeolian sands into the Yellow River, which may have a significant impact on channel form. To further recognize the desert braided channel change, here based on a long-time series of field dataset from 1966 to 2013, results show that lateral infusion of aeolian sand is the same as discharge as a significant factor to channel form, which is mainly controlled by aeolian activity and discharge conditions. Before the early-1990s, higher discharge and greater intensity of aeolian activity caused a frequent lateral movement and large lateral inputs of aeolian sands into river; this reach showed an unsteady and wider braided channel with a higher braiding intensity. From the early-1990s to 2013, a reduced discharge that caused a decreasing lateral movement, coupled with the decreasing aeolian activity, have resulted in the main flow of the Yellow River far away from sand dunes, which led to a reduction in lateral inputs of aeolian sands. Thus, the braided channel of the UlanBuh Desert reach presented a shrinkage state, gradually changing from a wider and unsteady braided channel to a narrower and relative steady channel form.

Keywords The UlanBuh desert reach · Yellow River · Desert braided channel · Aeolian sand

Introduction

Braided channel form and its dynamics over time have been widely recognized by geomorphologists and sedimentologists in the past decades. The underlying causes of channel

braiding are complex, usually involving interactions of multiple factors, such as flow conditions, sediment characteristics, bank stability and slope (Bertoldi et al. 2009; Bridge 1993; Ferguson 1993; Knighton and Nanson 1993; Lane et al. 2010; Leopold 1963; Lewin and Brewer 2001; Nanson and Knighton 1996; Nanson et al. 1986; Parker 1976; Schumm 1985). Of which it is essential for channel braiding in alluvial rivers that abundant sediment loads are input into riverbed. (Schumm 1963, 1985; Smith and Smith 1984; Ta et al. 2014, 2015). Although there is increasing understanding on braiding processes over the past half century (Akhtar et al. 2011; Carson 1984; Ferguson 1993; Fredsoe 1978; Graf 1981; Miall 1977; Parker 1976; Rust 2010), few studies have focused on those rivers that flow across aeolian dunes field.

In semi-arid and arid areas, many active sand dune fields are intersected with perennial or ephemeral streams. Non-cohesive and unconsolidated aeolian sediments are easily eroded into channel by flood flow, which produce a great

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impact on river bed sediment texture and, in turn, on channel form in the desert river. For example, the William River in Canada is an outstanding example of channel widening and braiding in response to abrupt additions of sandy bedload caused by large lateral inputs of aeolian sand from both banks covered with aeolian dunes (Smith and Smith 1984). Limited studies on those braided rivers that flow across aeolian dune field have focused on and emphasized the role of large lateral inputs of aeolian sand in channel form evolution (Muhs and Holliday 1995; Smith and Smith 1984; Ta et al. 2013), and there is also rare field data to demonstrate interactions of this braided channel form with sand dunes.

The Ulan Buh Desert Reach of the Yellow River (China) has developed a large sandy-bed channel and flow across aeolian dunes of the Ulan Buh Desert, with large lateral inputs of aeolian sand, lots of central bars and frequent lateral movement, forming an unstable braided channel. Previous studies have shown that in this reach bed sediments are mainly composed of the coarser sands whose median grain size is greater than 0.08 mm. Based on elements and grain size distribution of the river bed sediments, it is confirmed that these bed loads are mainly supplied by the UlanBuh Desert (Jia and Wang 2011; Jia et al. 2011, 2013; Ta et al. 2011, 2013). According to Yang et al.'s estimation in 1978, lateral infusion of aeolian sand into the Yellow River was about 2000×10^8 t per year in the UlanBuh Desert reach (Yang 2005; Yang et al. 1987, 1988). Large infusion of aeolian sands can exert a great impact on the Yellow River and, for example, Ta et al. (2011) have revealed that large lateral infusion of aeolian sands have disrupted what would be smooth downstream trends in channel gradient and bed grain in this reach. Here, we have collected a long-term monitoring field dataset (from the year of 1966 to 2013) related with channel form in the Ulan Buh Desert Reach of the Upper Yellow River. This provides a good opportunity to enhance the current understanding of the braided channel of the large sand-bed river that flows across sand dunes. In addition to traditional driving factors for channel form change such as discharge and suspended sediments, here we also focus on lateral infusion of aeolian sands into the Yellow River.

Study area

The Ulan Buh Desert Reach is located in the ending reaches of the Upper Yellow River, starting at Shizuishan gauging station, ending at Bayangaole gauging station, with a total channel length of 138 km, of which only along 88 km from Wuhai to Bayangaole gauge the channel edge intersects sand dunes (Fig. 1). The study reach is characterized by very low gradient of 0.14‰, typical braided and wandering channel, large inputs of aeolian sand and high sediment load of well-known in the world. Also, this reach has no

tributaries and the mean annual rainfall ranges from 200 to 300 mm, belonging to the transition zones between semi-arid and arid region, with a potential evapotranspiration of 1000–2000 mm (Yao et al. 2011), which contribute little discharge to the Yellow River.

The Yellow River and aeolian dunes of UlanBuh Desert are intersected and interacted with each other in the study reach. The UlanBuh Desert, located along the left bank of the Yellow River, comprises an area of nearly 11,500 km² of active and partially inactive dunes. The Yellow River flows northwards through the UlanBuh dunes field at its east margin and the predominant winds of NW, W and WS transport large volumes of aeolian sand from the desert toward the river direction. Except for high suspended sediment load of well-known in the world, in the study reach, there are also ample bed loads supply caused by large lateral inputs of sand dunes in the UlanBuh Desert. Figure 2 shows an example of aeolian dunes intersected with the Yellow River at four locations along the left bank. It is confirmed that this Reach has developed a large sandy-bed of which bed loads consisted of the coarser sediments (> 0.08 mm) mainly sourced from the Ulan Buh Desert (Jia and Wang 2011; Jia et al. 2013; Yang et al. 1988).

In addition, there are many human activities widely in this area such as farming in floodplains, some engineering facilities for utilizing river resource such as reservoirs, levees and diversion engineering, which also play important roles in channel form (Ta et al. 2008) and have significant impacts on lateral infusion of aeolian sands directly or indirectly into riverbed and, in turn, on channel form.

Methods

To study the channel change in the past half century, we have collected a set data of channel cross-sections of total 20 (upstream from C1 to C23, except C8, C10 and C13) measured annually in April and October per year, lasting 48 years (from 1966 to 2013) in the Ulan Buh Desert reach, which are surveyed by Yellow River Engineering and Management Bureau of the Inner Mongolia Autonomous Region. In the Ulan Buh Desert reach, there are 23 cross-sections installed at this reach of 55 km-long upstream from Bayangaole gauging station, with intervals of about 2–5 km on average, and only 20 cross-sections have long-time series data (C8, C10 and C13 were only measured for several years) (Fig. 1). And these 20 cross-sections can provide detailed information on changes in channel morphology of this braided channel.

According to National Level 5 Measurement Specification (China), each cross-section, perpendicular to the main flow direction, was defined using two temporary benchmarks located on left and right bank respectively and measured from the right bank using an EPOCH RTK-GPS with an

Fig. 1 Location of the UlanBuh Desert Reach of the Yellow River and the spatial distribution of cross-sections

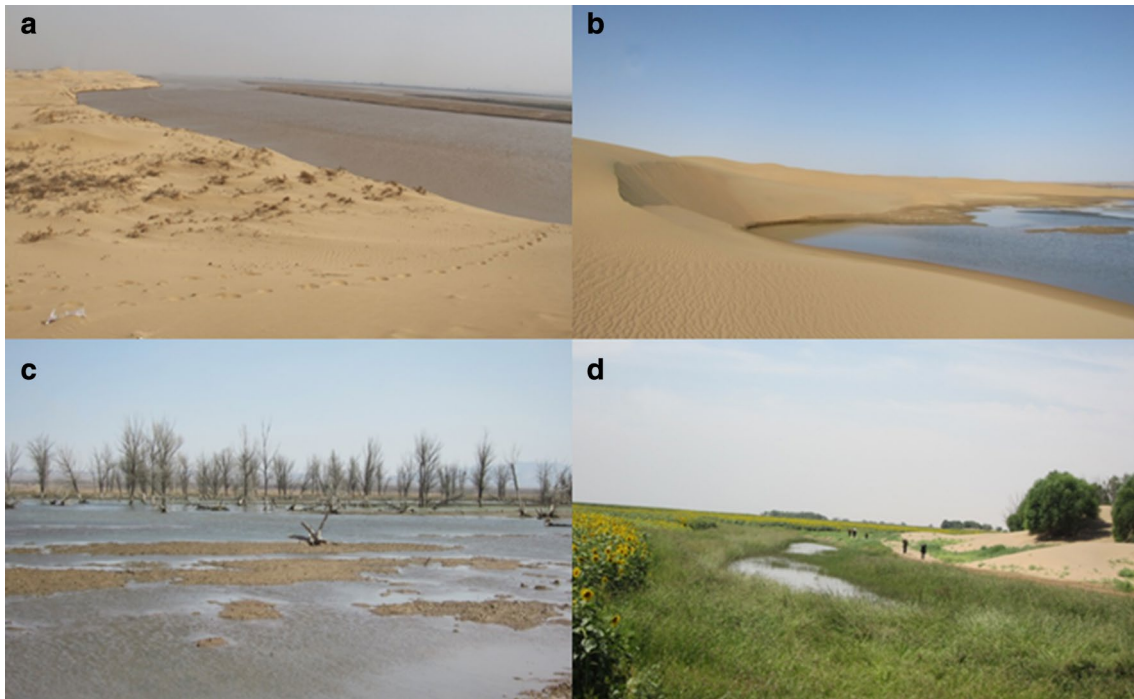
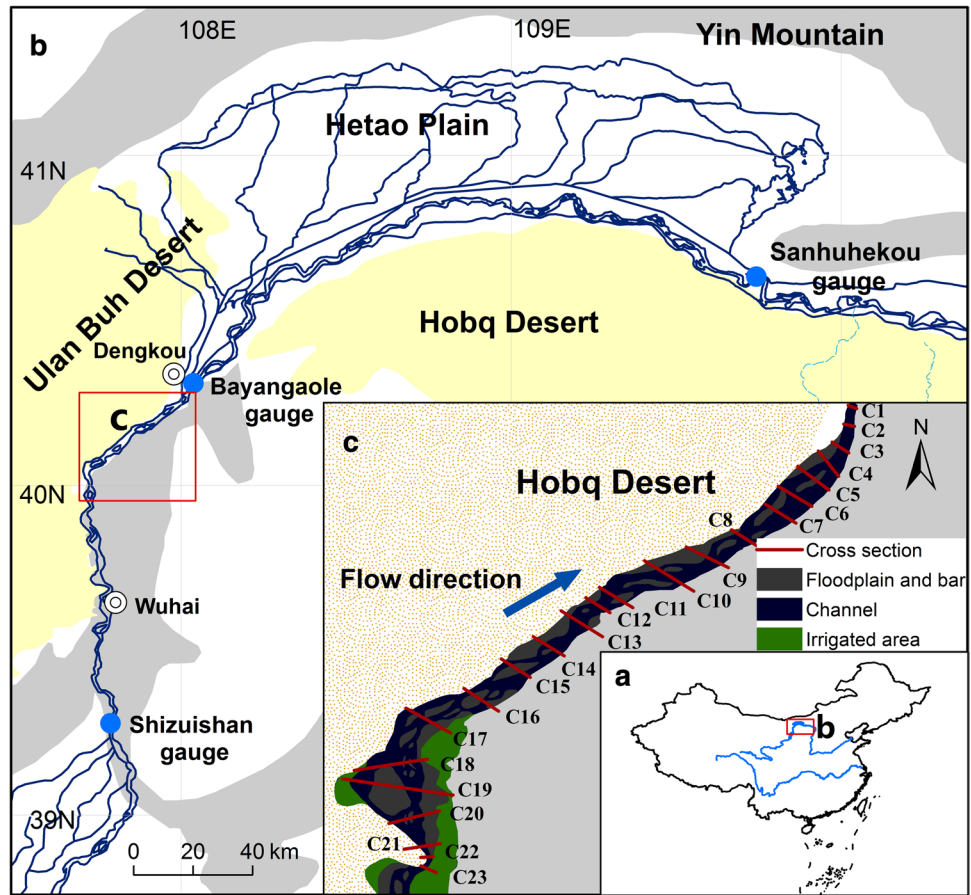


Fig. 2 **a, b** Examples of the left bank of the Yellow River covered with aeolian dunes and **c, d** of vegetation and planting on the floodplains

accuracy of $\pm(5\text{mm} + 1\text{ ppm})$, based on Beijing 1954 Coordinate of 6-degree projection with a central meridian of 108 degrees and 1956 National Elevation Datum (Yellow Sea Datum of China). In detail, floodplains, main channel, central-bars, anabranches, levees and ridges with a relative altitude more than 1 m were all measured and measuring points of each cross-section distributed as evenly as possible, with intervals of about 50 m on average in the channel and of about 100 m in the floodplains. Therefore, these cross-sections data accurately document channel form changes from 1966 to 2013. Meanwhile, to analyze causes for changes in channel form, we have also collected hydrological and meteorological data including monthly discharge and suspended sediment concentration at Shizuishan gauging station and Bayangaole station from 1966 to 2012, and wind direction and dust storm data at Dengkou County from 1956 to 2014.

Channel form can be described by varies index that are defined and extracted by many data sources (cross-sections, historical maps and satellite images), of which, however, cross-sections can present lateral riverbed state, which are more accurate than historical maps or satellite images that record channel planform. In this study, time series of the main variables according to monitoring cross sections of total 20, i.e., the mean active channel width and floodplain width, talweg elevation, channel number, and channel lateral movement rate, are analyzed. Here, width of the active channel refers to the width of bars and low-flow braided channels except for floodplain; and floodplain width refers to the length of other areas along the monitoring cross sections (Fig. 3). Talweg elevation is taken as the lowest point in the cross-sectional profile. In this study, 11 of the 20 cross sections are selected to calculate channel numbers, whose widths are larger than 2 km and for which the 48-year monitoring data are uninterrupted. The channel number refers to the number of braided channel with depth $> 1\text{ m}$ (Fig. 3), which can separate and convey water, suspended sediments

and bedload. Lateral channel movement rate is defined as the lateral shift distance of the main (deepest) talweg between successive surveying intervals.

Results

Channel width and floodplains change

Here, due to cross sections that were measured at floodplain margin, including floodplain and river bed, it can be representative of channel width. Based on the results extracted from 20 cross sections, channel width from 1966 to 2013 decreased slightly (Fig. 4b), with a maximum value of 2.60 km on average in 1968 and a minimum of 2.53 in 2013. However, active channel width from 1966 to 2013 showed a declining trend obviously on the whole and channel narrowing width was 0.3 km per 10a on average according to the linear regress result. Before the year of 1987, it maintained above 1.6 km on average; from 1986 to 1999, there was a rapid reduction, from 1.6 km down to 1 km on average; then from 2000 to 2013, a slight increase, but less than 1.1 km. On the contrary, floodplain width from 1966 to 2013 in turn increased (Fig. 4c), with 0.24 and 0.08 km increase per 10a on average in the left floodplain and right floodplain, respectively, of which obviously left floodplain width was larger than right floodplain mainly because of left bank composed by noncohesive and unconsolidated aeolian dunes and increased human activities on the left floodplains.

Braided intensity

Many ways or index can be used for indicating river braiding intensity (Brice 1960; Howard et al. 1970; Robertson-rintoul and Richards 1993; Rust 1977), of which number of channel and central bar are common braiding index applied

Fig. 3 Example of counting the channel number, and the active channel and floodplain width within a cross-section

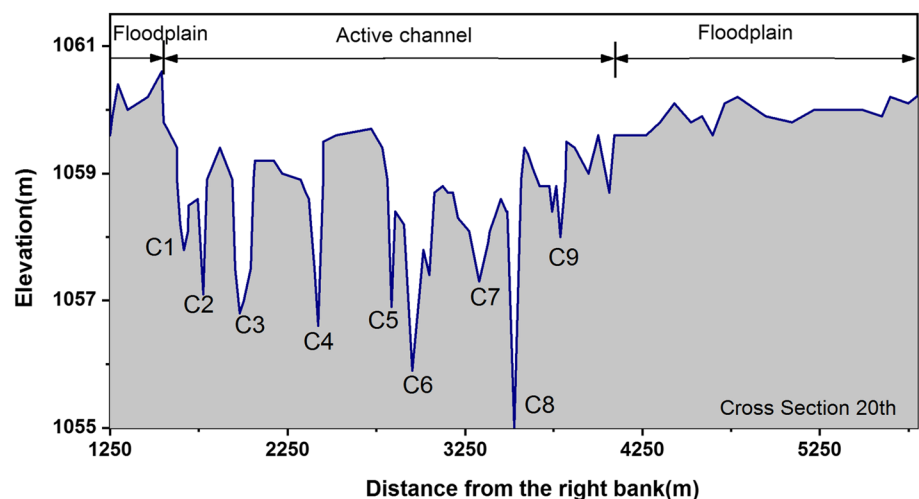
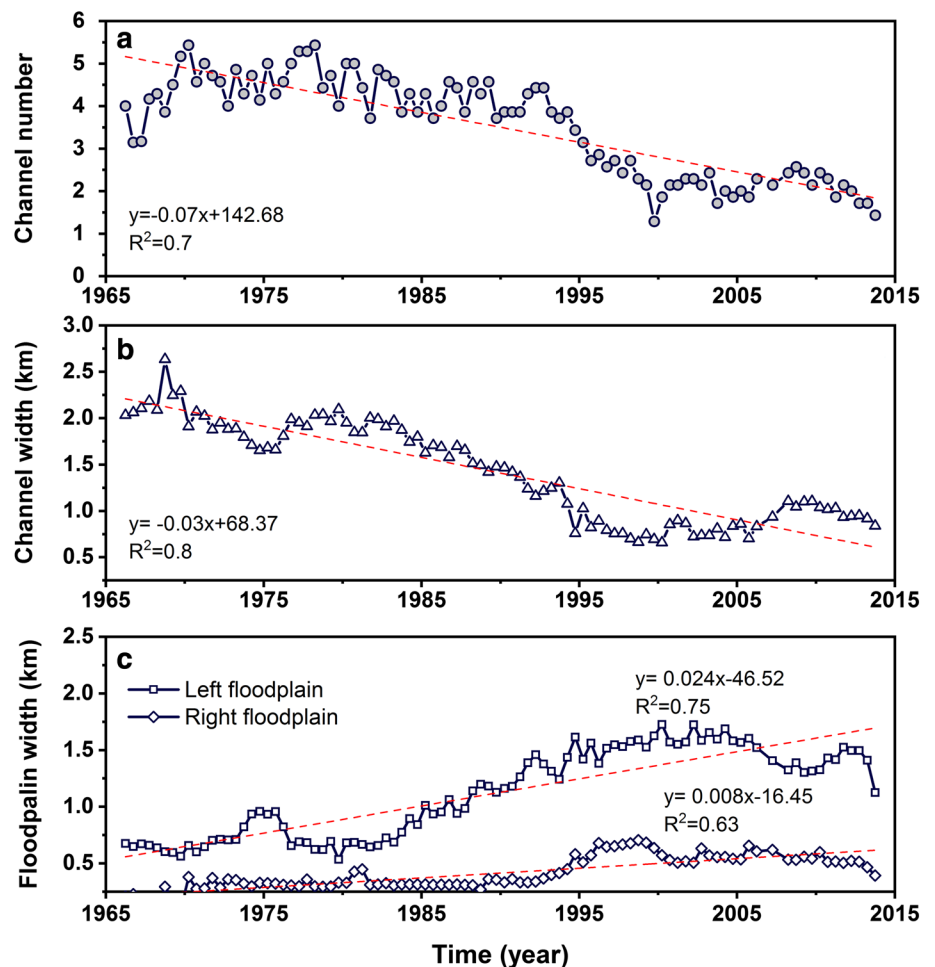


Fig. 4 **a** Changes of mean channel numbers, **b** active channel width, and **c** mean width of the floodplain and from 1966 to 2013



into the braided rivers. Here, we adopt channel number that reflects channel bed form more accurate based on cross sections. The results show that the braiding intensity presented a decreasing trend from the late-1960s to the early-2010s, with a decreasing rate in the braiding index of 0.7 per 10a based on the linear regress analysis (Fig. 4a). From the late-1960s to the early-1990s, the braiding index remained steady at a value between 3 and 5.5, about 4 on average, but then decreased rapidly in the late-1990s, attaining a value approaching 1.5 in 1999. Then from the 2000s to the early-2010s, the braiding index stabilized at a low level, with an averaging value of 2.

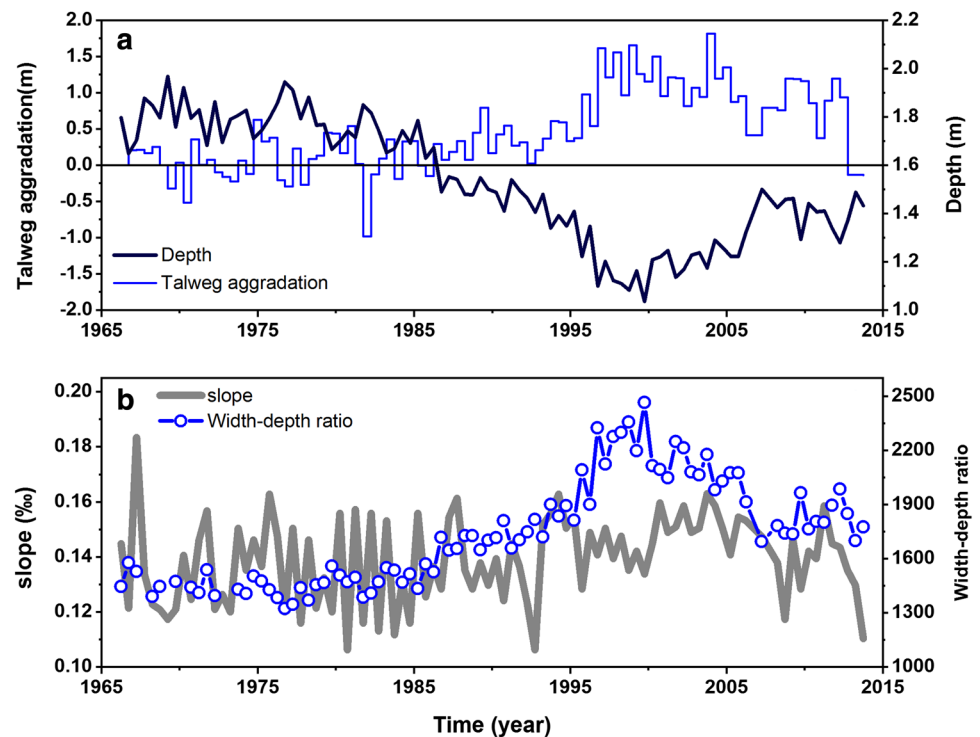
Talweg elevation and depth

Based on 20 cross sections, we compute changes in talweg elevation that indicates from 1966 to 2013 a slight aggradation state in the riverbed. Before the early-1990s, channel bed presented equilibrium between scouring and depositing; while from the early-1990s to 2012 channel bed showed an aggradation trend obviously, with a maximum value of 1.81 m. It should be noted that however, bed aggradation

was not continuous and showed a scouring state from 2012 to 2013, and rapidly recovered the level in 1966 primarily because of a high flood peak in 2012 which transported downstream large relative finer sediments of riverbed surface that were aggraded on the riverbed under the lower discharge period (Fig. 8).

Bed aggradation and floodplain expansion inevitably cause a reduction in depth and further an increase in width–depth ratio. The mean depth from 1966 to 1986 maintained above 1.6 m (1.5~2 m), a sharp decline from 1987 to 2000 with a minimum value of 1.1 m, after 2000 a slight recovery but with a maximum below 1.5 m. Furthermore, width–depth ratio experienced a rising trend on the whole from 1966 to 2013, before 1990 an averaging value of 1752.46, 2413.1 on average after 1990; especially from 1995 to 2005 width–depth with a maximum value of 2592.3 on average. Although channel bed talweg elevation showed an aggradation after 1993, channel bed longitudinal profile maintained a relative steady state during the period of 1966–2013 (Fig. 5), developing relative pseudo-equilibrium locally, and channel bed slope was averaging about 0.14‰ (0.1–0.18‰), close to that of the lower Yellow River.

Fig. 5 **a** Mean aggradation thickness of the thalweg relative to 1966 and **b** channel gradient change and mean width/depth from 1966 to 2013



However, bed slope fluctuated frequently from the year of 1966 to the late-1980s, then in recent 20 years maintaining a stable level with less frequent fluctuation (Fig. 5b).

Lateral channel movement

Lateral channel movement is an important indicator and condition of the development and evolution of the braided channel, which is usually linked with bank erosion, lateral inputs and sediments transportation and deposition. With the channel number decreased from 1966 to 2013, lateral movement distance per half year also shows a reduction (Fig. 6a). From 1966 to 1992, main channel shift towards left bank 474.26 m (1–2676 m) on average, towards right bank 439.54 m (1–3378 m); from 1993 to 2013 the main channel lateral movement rate declined, shift towards left bank 280.14 m (2–1772 m) and towards right bank 266.21 m (1–1836 m). Further, compared with the steady channel of the upper valley reach near Shizuishan gauging station or downstream near the Sanshenggong hydro project, main channel lateral movement distance per half year was higher, reaching up to 24-fold than the steady reaches. Figure 6b reveals that the larger the main channel lateral movement, the more braided channel number.

This trend in channel width, floodplains width and lateral movement rate we have revealed above agrees with the findings of Yao et al. (2011) who performed an analysis of bank erosion in the Ningxia–Inner Mongolia reaches (including the study reach) of the Yellow River from 1958 to 2008. His

results showed that before the early-1990s there is a higher annual average rate of bank erosion, however, from the early-1990s to the late-2000s an obvious reduction in bank erosion, which inevitable led to these results of decreasing lateral movement, narrowing channel and relatively increased floodplain width during the same period in this study.

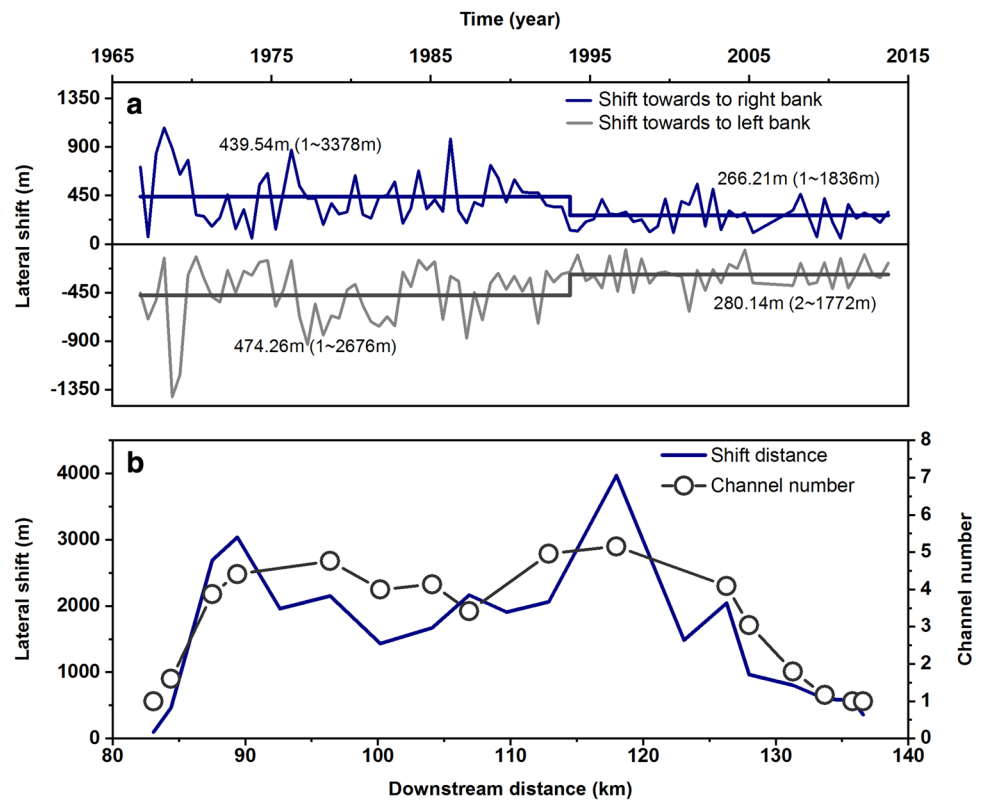
Discussions

For those rivers that flow across sand dunes, not only discharge, suspended sediments and boundaries have a significant impact on the channel form, but aeolian infusion may also play an important role in the channel form change. Many studies have proved that bed sediments were derived from the sand dunes of the left bank in the study reach, thus aeolian sand should be taken as a vital condition for the channel form change due to the lateral infusion of aeolian sands as an important component of the riverbed sediments. Here, we discuss these driving factors for the UlanBuh desert reach of the desert river in detail.

Decreasing blown-sand activity

In the study reach, aeolian dunes provide abundant coarse sediments for river bed. These abrupt additions of bedload that cannot be transported downstream are easily deposited into the river bed to cause braiding process (Smith and Smith 1984). Therefore, lateral inputs of aeolian sediments

Fig. 6 a Mean lateral movement distance per half year from 1966 to 2013 and **b** mean channel lateral shift distance each cross-section downstream from C23 to C1 and mean channel number each cross-section



have significant impacts on channel form in the desert river, thus the intensity of blown-sand activity is a key condition that controls the contributions of aeolian sands into the channel bed. Ta et al. (2011), Jia and Wang (2011) and Jia et al. (2013) have proved that in the UlanBuh desert reach, riverbed sediments were mainly supplied with aeolian sands of the left bank. Therefore, aeolian process that can influence lateral infusion of aeolian sand into the Yellow River, exert an important role in channel form change. Based on the meteorological data from 1956 to 2014, frequency of WN, W, and WS are dominant and the prevailing winds have moved active dunes directly to the channel edge (Figs. 2, 7). Dust storm days with visibility less than 1 km and between 1 and 10 km at Dengkou County from 1966 to 2014 both

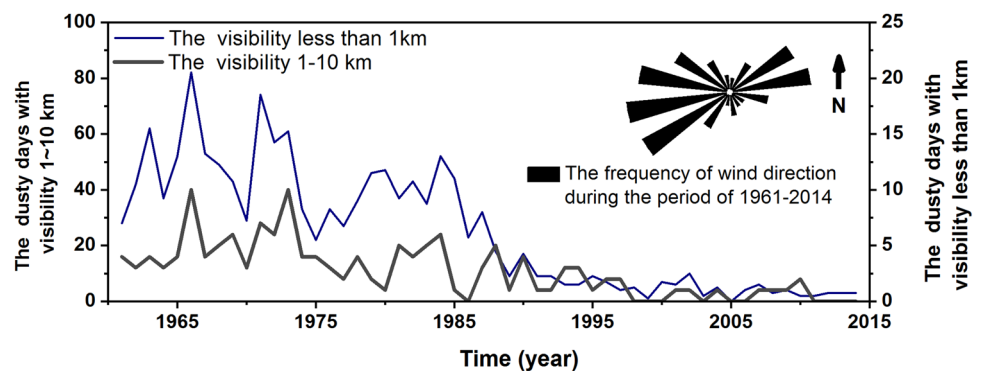
present a decreasing trend, especially a rapid reduction after 1987. Reduced dust storm days significantly have indicated a decreased intensity of windblown sand activity in the UlanBuh Desert. This shows that active dunes of the UlanBuh Desert move directly to the channel edge slowly, which weaken the process of the aeolian sands infused into riverbed.

Reduced discharge and increased SSC

Reduced discharge

Higher discharge and coefficient of variation (C_{vy}) are both beneficial to the braided channel developing. Annual runoff,

Fig. 7 The dust days within visibility less than 1 km and between 1 and 10 km, and the frequency of wind direction at Dengkou County from 1961 to 2014



monthly discharge and coefficient of variation from 1966 to 2012 all showed a decreasing trend at Shizuishan gauging station and meanwhile a declined channel braiding intensity correspond to it (Fig. 8). Before the year of 1990, monthly discharges over $2000 \text{ m}^3/\text{s}$ shows a higher frequency once every 2 years on average and during the period there is also a higher C_{vy} , which contributes to channel braiding (Bridge 1993; Lane et al. 2010; Leopold 1963; Nanson and Knighton 1996; Schumm 1985, 1963). Instead, from 1991 to 2012 a rapid reduction in discharges and C_{vy} , there is no 1 month of discharge over $1800 \text{ m}^3/\text{s}$ except for that in 2012. This is partly because of large reservoirs operation that can regulate spatial and temporal distribution of water resources for better utilization of water resources (Guo et al. 2014; Li et al. 2008), and partly because of reduced natural precipitation. Therefore, the decreasing discharges and C_{vy} lead to lateral movement rate and braiding intensity declining.

Increased SSC

In the study reach, suspended sediments are supplied by mainly upstream loess area, whose median grain size is less than 0.08 mm . With a reduction in discharge, however, suspended sediment concentration (SSC) from 1966 to 2012 showed an opposite trend. From 1966 to 1991 under high discharge condition monthly SSC were all below $10 \text{ kg}/\text{m}^3$, except a maximum value of $10.61 \text{ kg}/\text{m}^3$ in 1979; but under a low discharge from 1993 to 2000, a higher SSC above $10 \text{ kg}/\text{m}^3$ showed a higher frequency

with a maximum value of $15.44 \text{ kg}/\text{m}^3$ in 1997. After 2000, SSC recovered the level before 1991. This shows that SSC does not completely depend on discharge and this abrupt increase in SSC from 1993 to 2000 is mainly caused by the sediment sluicing of reservoir (Li et al. 1998; Lu 1987).

Since the early-1990s, low flow and increased SSC weakened the capacity of sediment transportation downstream which further led to an acceleration of the aggradation of suspended sediments into the small and shallow secondary-channels. Results of annual sediment discharge between Shizuishan and Bayangaole station show Bayangaole station present a reduction in annual sediment discharge than Shizuishan station from 1966 to 2013, especially from 1985 to 1995 reduced by $0.25 \times 10^8 \text{ t}$ on average per year (Fig. 9). Therefore, this reduction in sediment discharge can have a contribution to the decreasing braided channel number, which led to small and shallow channels deposited by sediments from upstream.

In addition, grain size of bedload on the river bed surface from 1964 to 2013 has also responded to the reduced discharge and decreasing lateral inputs of sands (Fig. 9c). From 1964 to late-1980s bedload had a median grain size of greater than 0.063 mm that is similar with aeolian sands. But bedload from the late-1980s to the middle-1990s showed a rapid fining, then after the middle-1990s bedload maintained a small median grain size, less than 0.08 mm . The rapid fining of the bed sediments in the Ulan Buh Desert channel of the Yellow River appears to

Fig. 8 **a** Mean monthly discharge and monthly SSC (suspended sediment concentration) and **b** annual runoff and the discharge' coefficient of variation (C_{vy}) monitored at Shizuishan gauging stations from 1965 to 2012

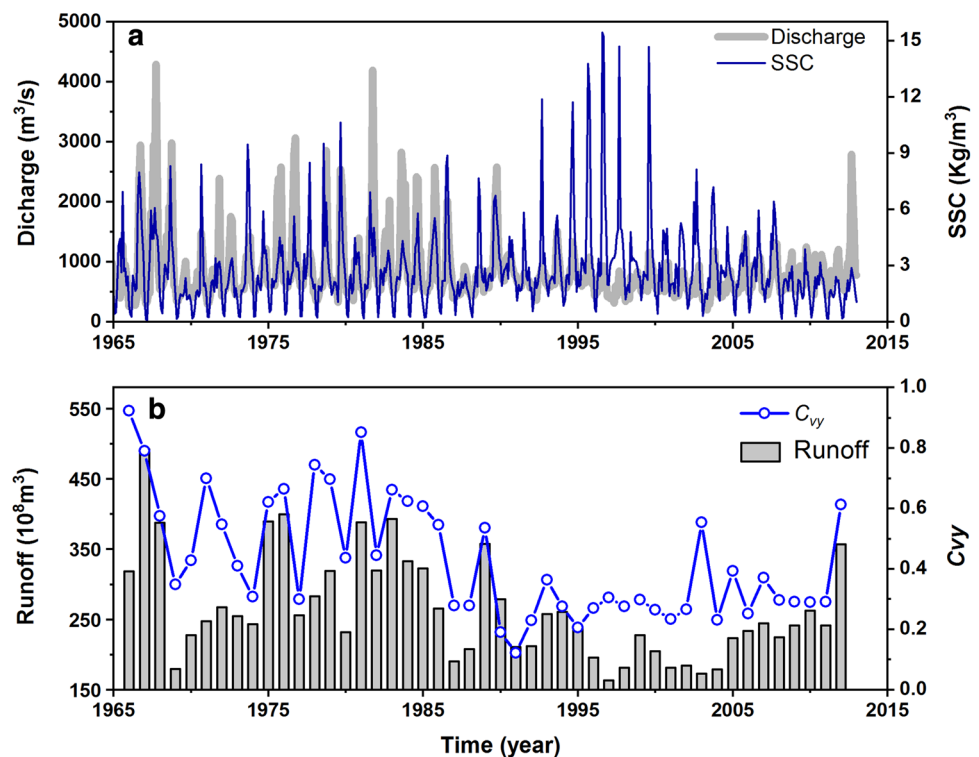
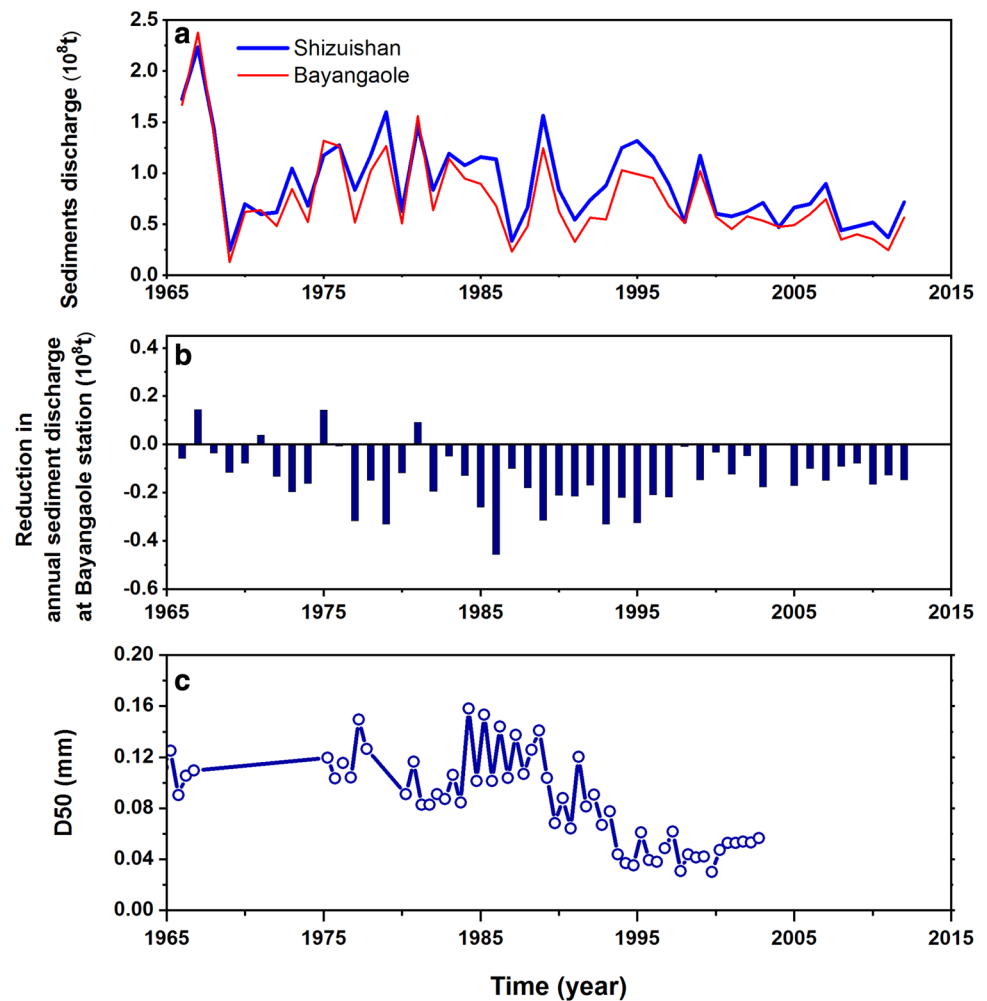


Fig. 9 **a** Annual sediment discharge monitored at Shizuishan and Bayangaole gauging station from 1965 to 2012 and **b** reduction in annual sediment discharge at Bayangaole station relative to Shizuishan station and **c** median grain size of bed surface sediment samples in 20 cross-sections from 1965 to 2003



be a response to the regulated low flows and high sediment releases associated with upstream reservoirs.

Based on the analyses of discharge and SSC above during the study period, the relationship between discharge and SSC presents two types that produce an opposite effect on channel form. From 1966 to 1991, low discharge, coupled with high SSC, caused large lateral inputs of aeolian sands and frequently lateral movement and promoted the braided channel developing; however from 1992 to 2000, low discharge accompanied by high SSC led to a declined lateral movement and made the main flow far away from aeolian dunes, causing channel shrinkage.

Impacts of human activities on channel form

For the UlanBuh Desert Reach of the Yellow River, human activities of reservoirs' construction and operation, farming in the floodplain and planting vegetation for aeolian dunes moving to these floodplains and building embankment also have exerted an important influence on channel geometry. First, reservoirs and dams constructed in the Upper Reach

of the Yellow River have changed spatial and temporal distribution of runoff, weakening the peak flood and decreasing discharge's coefficient of variation (Fig. 8). In addition, agricultural water demands are more than before decades, which speed reduction in runoff (Ta et al. 2008). Like above mentioned, increased suspended sediment supply in recent 20 year was mainly caused by Qingtongxia reservoir filling full that had to practice sediment ejection (Li et al. 1998; Lu 1987).

Then, farming on the floodplain, on one hand, whose crops can strengthen floodplain's steady and resistance to flow erosion, meanwhile (Carollo et al. 2002; Pollenbankhead and Simon 2009; Sandercock et al. 2007; Tsujimoto 1999), to some extent, also speed up the aggregation of suspended sediments on the floodplain; on the other hand, these farming works and planting artificial vegetation on the floodplain can effectively stop aeolian dunes moving to the Yellow River (Fig. 2c, d). In addition, levees have constructed along the left bank since the late-1990s, which can separate aeolian dunes with main flow of the Yellow River. Only small sections of the desert reach interact directly with

the sand dunes of the UlanBuh Desert and channel edge along 11 km of its 88 km directly contact to aeolian dunes, mostly separated by large floodplains nowadays. Based on 15 cross-sections, the distance between the main channel and sand dunes of the UlanBuh Desert is 2.267 km on average in 2013.

These factors mentioned above including discharge and SSC, blown-sand activity, and human activities have combined to reduce the coarser aeolian sediments supply and transport capacity and frequency of the lateral shift. These have led to the filling of small channels by suspended sediments and merging of central bars to expand the floodplain between the main channel and aeolian dunes. It should be noted that there is a time lag for the channel braiding intensity in responding to those driving factors because of complex interactions of these factors mentioned above, so the temporal variation of the driving factors and channel geometry have not shown a complete synchronous change.

Geomorphological effects of lateral inputs of aeolian sand

Except for the traditional conditions of controls on channel form such as water-sediments, slope and boundaries, bank covered with sand dunes has posed a new challenge to channel form in the desert river. Rules or experiences concluded from those rivers (Bertoldi et al. 2009; Ferguson 1993; Lane et al. 2010) that do not flow across sandy deserts, are not well applied into the desert rivers. Generally, aeolian sand can be classified into those problems of bank erosion; but considering the particularity of aeolian sand that rarely occurs in most rivers, we view it as a single vital driving factor in these rivers that flow across sand dunes.

The Ulan Buh Desert reach of the Yellow River has been defined as the upper reach of the Yellow River, however, with a low gradient, sandy bed, wide and shallow alluvial braided channel. Dunes-covered bank and lateral inputs of aeolian sand are both important controls on channel form in the study reach. Most field works have shown that this reach has developed a sandy-bed and bedload has a median size of greater than 0.08 mm mainly sourced from the Ulan Buh Desert. It has been confirmed that lateral inputs of aeolian sands from the Ulan Buh Desert into river bed can disrupt those phenomenon of what would be smooth downstream trends in mainstream bed elevation, channel gradient and bed grain size (Wang et al. 2015), which make this desert reach different from other upper reaches. First, noncohesive sand dunes on the bank provide a relative unstrained boundary for the channel lateral movement, which can be reflected by frequent lateral movement, extensive wide channel width, even above 10 km locally and large width–depth ratio more than 1000, up to 3000 s, abundant bedload supplied by sand dunes increase coarse sediments deposited on

riverbed and cause formation of a larger number of central bars and frequent lateral movement, further promote channel braiding. Some studies have shown that for those rivers that flow across sand dunes the stronger of blown-sand activity, the stronger the braiding process (Smith 1970; Smith and Smith 1984). However, in the UlanBuh Desert Reach from the early-1990s to 2013, due to small discharge and the main channel far away from sand dunes separated by large floodplains, there is a reduction in lateral inputs of sands infused into riverbed. Thus, if discharge of the Yellow River continues to maintain a low level, aeolian process play an opposite role in the channel form. The prevailing winds of NW, W and WS can move sand dunes expanding into floodplains, furthermore narrowing channel.

From the above analysis on variation of channel form and driving factors from 1966 to 2013 in the UlanBuh Desert reach, we can conclude that lateral inputs of blown sands have an important impact on channel form. And around the world, some aeolian dunes are intersected with perennial or ephemeral rivers, such as the sand dunes in Victoria valley in Antarctica (Bourke et al. 2009) and the sand dunes along the Colorado River corridor (Sankey et al. 2018; Sankey and Draut 2014), lateral infusion of aeolian sands into riverbed may have a profound effect to the channel form change in those desert rivers. Here, our results have provided a meaningful reference to understanding the braided channel form change of those desert rivers.

In the study area, under condition that high discharge from 1966 to the early-1990s and stronger blown activity intensity that caused large lateral inputs of sands, the study reach have developed a typical braided pattern. However, with a reduction in discharge and an increased distance between the main channel and sand dunes from the early-1990s to 2013, the braided channel has shown a shrinkage, and gradually changing from a wider and unsteady braided channel to a narrower and relative steady channel. If these conditions above mentioned continue to remain in the next few decades, the UlanBuh Desert reach may take a complete transformation of channel pattern, or towards a meandering channel, or towards a braided channel with islands.

Conclusions

In this paper, we present a large braided channel change over time in response to aeolian sand, flow conditions and human activities in the UlanBuh Desert reach and lateral infusion of aeolian sand is the same as discharge as a significant factor to channel form, which is mainly controlled by aeolian activity and discharge conditions. Based on cross sections, hydrological and meteorological data in the past 48 years (1966–2013), before the early-1990s, higher discharge and greater intensity of aeolian activity caused a frequent lateral

movement and large lateral inputs of aeolian sands into river; this reach showed an unsteady and wider braided channel with a higher braiding intensity. From the early-1990s to 2013, a reduced discharge that caused a decreasing lateral movement, coupled with the decreasing aeolian activity, have resulted in the main flow of the Yellow River far away from sand dunes, which led to a reduction in lateral inputs of aeolian sands. Thus, the braided channel of the UlanBuh Desert reach presented a shrinkage state, gradually changing from a wider and unsteady braided channel to a narrower and relative steady channel form.

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