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# Distinct Aeolian-fluvial Interbedded Landscapes in Three Watersheds of the Northern China

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**Abstract:** Due to the complex dynamic of aeolian and fluvial interacted processes behind the landform development, most of previous works started from classifying the types of landscape characterized by various aeolian and fluvial features. Such classifications are usually generalized based on large geomorphic data set abstracted from satellite images without field verification and dynamic field data. In this study, we identified river banks in deserts as a unique geographical unit dominated by aeolian-fluvial processes. Three distinct locations have been identified as representative study cases, which are in the Keriya River Basin in the west, the Mu Bulag River Basin in the middle and the Xar Moron River Basin in the east of the northern China. The aeolian-fluvial interaction types were quantified based on site observation and measurement, topographic mapping and remote-sensing image analysis. Dimensional morphological relationship between river channel and adjacent sand dunes areas were explored. We concluded that different channels are often associated with different distributions of riparian dunes. The quantitative data enabled us to distinguish statistically four different types of landscape in aeolian-fluvial dominant environment, namely riverside dunes-straight channel, symmetrical interleaving dunes-meandering channel, river-island dunes- braiding channel, and grid-like dunes-anastomosing channel, aiming to provide compensational information to current aeolian-fluvial interaction studies. The angle of interaction between aeolian and fluvial systems, the windward and leeward sites of the bank, vegetation coverage and underlying landform determines the distribution, morphology, scale and direction of extension of the riparian dunes. The results of the work study can provide a reference for study of aeolian-fluvial interactions at different spatial scales in arid region.

**Keywords:** Sand dune-channel; aeolian-fluvial interaction; spatial distribution pattern; type classification; northern China

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## 1 Introduction

Aeolian-fluvial interactions have important impacts on the spatial and temporal evolution of the vast arid and semi-arid landscapes of Earth (Tooth, 2008). The most prominent physical manifestation of flowing water and wind forces in desert areas is the formation of dunes distributed on both sides of riverbanks. Such landforms are formed through aeolian-fluvial interactions and often feature temporal inheritance and spatial superposition. It is generally accepted that desert rivers control the distribution of desert sand by providing material sources and

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sites (Bullard and Livingstone, 2002; Yan et al., 2015), whereas, in turn, the distribution of sand and wind-driven sand erosion affect river channel development and sediment transport (Draut, 2002; Pan et al., 2015). Dune migration towards a river can lead to the additional input of sand into a river, with knock-on effects including the blockage of channels and even river channel diversion, thereby acting as a driver of fluvial system evolution (Tooth and Nanson, 2011). Such phenomena suggest that riverbanks in deserts worldwide are unique geographical units. However, riverside aeolian landforms and their interactions with river channels have attracted relatively little attention, with a few studies having explored the characteristics of meandering channels in deserts from the perspective of river geomorphology (Pan et al., 2015).

River valleys in arid regions represent a unique zone type which is affected strongly by aeolian-fluvial interaction. Riverside dunes are often located in these environments (Li et al., 1999). The complex landform of channels and riverside dunes is the result of not only aeolian-fluvial interactions, but also dynamic environmental changes between aeolian and fluvial systems. Therefore, the investigation of such aeolian landforms in arid areas is of great value, and related studies have increased in recent years (Li and Yan, 2014; Liu and Coulthard, 2015; Han et al., 2016). It is widely accepted that there are different types of interactions between channels and dunes (Al-Masrahy and Mountney, 2015; Liu and Coulthard, 2015), and dunes located on both sides of river channels show different development patterns under the influence of river flow (Han et al., 2016; Guan et al., 2017). Most privious studies have been qualitative due to lacking of regional long-term morphological monitoring and dynamic observation data, and to date, no consensus has been reached on the classification of interactions between channels and dunes, and the mechanisms responsible for the development of riverside dunes remain poorly understood. Four variables were analyzed to explore possible relationships between fluvial and aeolian systems, including dune type, channel pattern, meeting angle (prevailing wind water flow) and interaction types to describe different geomorphology types of aeolian-fluvial interaction based on the methods of site observation and measurement, topographic mapping and remote-sensing image analysis on the scale of channel-sand dune. The purpose of this study is to quantitatively interpret and distinct aeolian-fluvial interbedded landscapes in three watersheds of the northern China. The results of the present study will provide a reference for study of aeolian-fluvial interactions at different spatial scales.

## 2 Study Area

The current study selected three typical drainage basins from the northern China, including the Keriya, Mu Bulag and Xar Moron River Basins in the Taklimakan, Hobq and Horqin Sand Land desert areas in the west, central region and east of China, respectively (Fig. 1).

The Keriya River originates from the northern slope of Mount Wushitengge, the main peak of the Kunlun Mountains, following which it flows into the hinterland of the Taklimakan Desert to the north, running through the southern edge of the desert. The river has a total length of 860 km, including 90 km of ancient channel, and drains an area of $3.95 \times 10^4$ km$^2$. The average annual precipitation and temperature of the Keriya River Basin is 44.7 mm and 11.6°C, respectively. The basin falls within a continental climate zone in which wind mainly blows from the northwest and northeast, with an average wind speed of 1.90 m/s and a maximum wind speed exceeding 30.0 m/s, with wind prevailing from February to June (Yang et al., 2002). The Keriya River experiences floods due to seasonal snow meltwater and rainstorms, with the flood seasons extending from June to September and this period accounting for 74% of the annual discharge volume. Most of the sediment transport in the river occurs during the flood season from April to September.

The Mu Bulag River is a first-level tributary of the Yellow River, and the middle and lower reaches of the river run through the Hobq Desert. The mainstem of the Mu Bulag River extends for 111 km, and the river drains an area of $1.3 \times 10^3$ km$^2$. The river basin falls within a semi-arid grassland climate zone, with an average annual rainfall and temperature of 241.1 mm and 5.9°C, respectively. The predominant wind direction is northwest, and the wind force level varies between 5–8. The average annual wind speed is 4.5 m/s, with a maximum wind speed of 28.7 m/s. The annual number of strong wind days (force level > 8) is 28, and they are mainly concentrated during spring and autumn, and result in sandstorms in this area (Wu et al., 2011). River channels in this desert were formed from temporary floods. Flood events occur frequently during June and September as a result of heavy rains, and the floods mobilize large volumes of sediment (Xu, 2014). The maximum peak discharge of the river is often observed during this period, resulting in both high river flow and sediment concentration, with flow and sediment over this period accounting for 74.0% and 94.3% of the annual totals, respectively.

The Xar Moron River is a tributary of the upper reaches of the West Liao River. The river has a total length of 380 km and drains an area of $3.2 \times 10^4$ $km^2$. The river flows through the Hunshadake Sandy Land in the west and crosses the Horqin Sand Land in the east. The river basin falls within a temperate and semi-humid climate zone, with an average annual precipitation and temperature of 300–500 mm and 5°C–7°C, respectively. The flood season occurs over summer, with 70% of annual precipitation falling during this period, contributing 62%–90% of the annual sediment output, with the maximums of flow and sediment output observed during July. The annual average wind speed of the desert ranges between 3.5–4.5 m/s, and the desert experiences ~22.4 d of strong wind (> 17.2 m/s), with these days concentrated over spring (from March to May). The wind blows mainly from the northwest, including during the maximum wind speed events (Han et al., 2007).

In the present study, we selected different reaches of the rivers to analyze the landforms of the rivers and the dunes on bank. For example, downstream of Keriya River; upstream, middlestream and downstream of Mu Bulag River; upper and middle reaches of Xar Moron River (Fig. 1) of the three rivers (or tributaries). As shown in Fig. 1, four sites in each drainage basin were further selected and marked.

## 3 Materials and Methods

The present study classified channels based on sinuosity (S) and braiding (B) parameters according to Rust (1978). This approach divides channel types into four categories: 1) straight (S < 1.5, B < 1); 2) meandering (S > 1.5, B < 1); 3) braiding (S < 1.5, B > 1), and; 4) anastomosing (S > 1.5, B > 1). The present study mainly explored straight single, highly sinuous meandering, and highly sinuous anastomosing multi-chan-

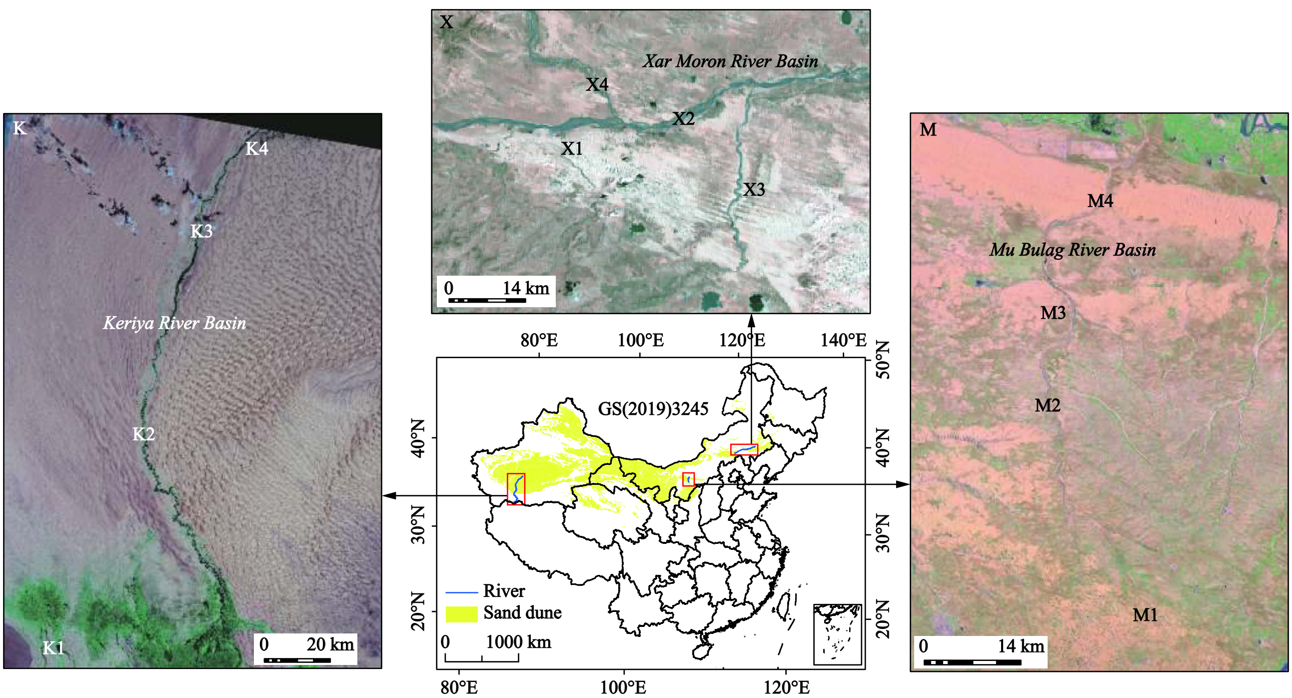


**Fig. 1** Illustration of study sites for three river basins in the northern China (K. Keriya River Basin; M. Mu Bulag River Basin; X. Xar Moron River Basin). Specific sites in each drainage basin were labelled as: K1 to K4 along Keriya River Basin, M1 to M4 along the Mu Bulag River Basin and X1 to X4 along Xar Moron River Basin (The dataset is provided by National Cryosphere Desert Data Center, http://www.ncdc.ac.cn)

nels with interaction with sand dunes on the riverbanks.

Remote sensing images were used to interpret the geomorphic patterns of the study sites. Landsat 8 Operational Land Imager (OLI) data captured in August, 2013 for the three drainage basins were downloaded from the Earth Explorer (United States Geological Survey, USGS, http://glovis.usgs.gov/). Processing of the images included correction for radiation, geometric correction, false color composite rendering (7, 4, 2 waveband), image mosaic processing and enhancement. These images were further calibrated and registered together with 1∶50 000 topographic maps of the three drainage basins to form the dataset essential for further analysis.

Human-computer interactive interpretation was conducted to identify the current distributions of channels and dunes in different sections of the three drainage basins. Additional information on the landscape elements were obtained based on ground surveys, literature and expert experience, such as the area size and perimeter.

In addition, dunes were divided into three categories: 1) source-bordering dunes (SBD); 2) transitional dunes, and; 3) regional dunes. The source-bordering dunes were mostly distributed in the open areas of floodplains or low terraces (Nanson et al., 1995), usually along the downwind side of floodplains or river valleys. This type of dune situated adjacent to the riverbank beach is characterized by an off-white color, different from the relatively dark red dunes seen on the terraces (Twidale and Wopfner, 1990; Bullard and Nash, 1998; Han et al., 2015). The regional dunes (RD) are dark red dunes situated on the terraces and are widely distributed in the region (Han et al., 2007; 2015). The color of transitional dunes (TD) is between off-white and dark red, usually exhibiting a light-yellow hue. The distribution and color features of each type of dune were characterized based on the differences in colors and information obtained from the geomorphologic map of wind-driven sand erosion and high-resolution images from Google Earth, and revised by field investigation. In contrast to dune patches, the spectral characteristics of ground objects for channels were more obvious, and were therefore initially automatically interpreted. However, the spectral characteristics of ground objects were weak for some of dry or ancient channels, and visual interpretation was used to obtain more information on the spectral characteristics of these channels.

Precipitation and temperature data during 1960–2010 at Yutian Station of the Keriya River Basin, Hanggin Banner Station of the Mu Bulag River Basin, Daban Station of the Xar Moron River Basin from the National Meteorological Information Centre of China of the China Meteorological Administration (http://www.nmic.gov.cn).

## 4 Results

### 4.1 Spatial patterns of channels and dunes

Table 1 shows a summary of the channel morphological parameters for every site investigated (locations of sites are illustrated in Fig. 1). The different drainage basins showed distinct dune distributions.

#### *4.1.1 Spatial patterns of channels and dunes in the Keriya River Basin*

TheuppertributarysectionofdownstreamintheKeriyaRiver (Fig. 2-K1) is slightly curved, with a bending coefficient of 1.21. The river flows against the prevailing wind direction, with an obtuse angle between the flow and wind direction. The SBD form a narrow distribution range and are mainly located along the convex bank (west bank) of the river. The dunes are positioned in a long and narrow belt, with the width of the adjacent channel varying from 40 m to over 100 m. The SBD along the ancient channels on the east bank are situated close to RD and develop and extend in a zonal pattern.

**Table 1** Morphological parameters of channels of different river reaches for three river basins of the northern China

| Drainage basin | Sites | Channel length / km | Linear distance / km | Sinuosity |
|---|---|---|---|---|
| Keriya River | K1 | 3.132 | 2.577 | 1.215 |
| | K2 | 22.726 | 10.597 | 2.145 |
| | K3 | 22.728 | 19.511 | 1.165 |
| | K4 | 18.672 | 11.049 | 1.690 |
| Mu Bulag River | M1 | 12.632 | 7.340 | 1.721 |
| | M2 | 10.706 | 9.097 | 1.177 |
| | M3 | 4.664 | 3.514 | 1.327 |
| | M4 | 5.213 | 4.409 | 1.182 |
| Xar Moron River | X1 | 9.154 | 4.370 | 2.095 |
| | X2 | 7.255 | 5.216 | 1.391 |
| | X3 | 8.695 | 5.628 | 1.545 |
| | X4 | 12.412 | 11.224 | 1.106 |

Note: location of sites are illustrated in Fig. 1

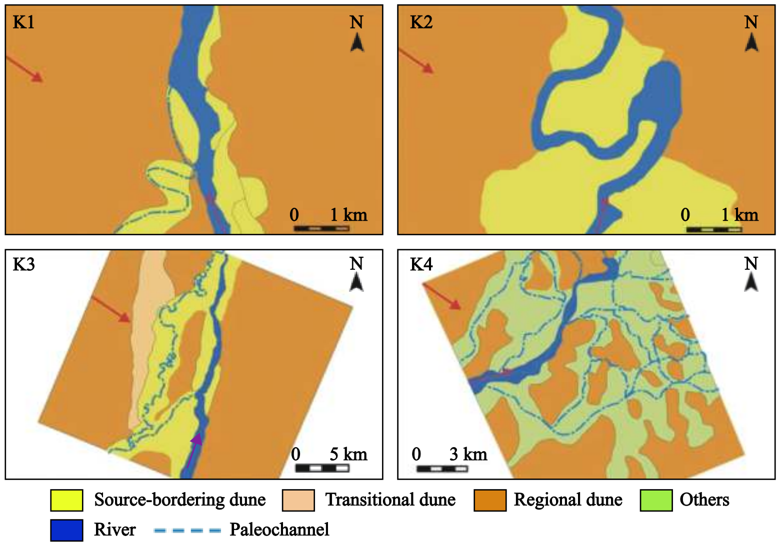


**Fig. 2** Distribution pattern of sand dunes and channels in four sites (K1–K4) of Keriya River Basin, the northern China. Red arrow denotes the direction of the prevailing wind; purple arrow denotes the direction of water flow

The sinuosity of the channel is high in the middle and upper sections of the downstream in the Keriya River (Fig. 2-K2), with a bending coefficient of 2.15. The channel pattern changes greatly with distance, with the signs of river oscillation clearly visible. However, the amplitude of oscillation is low, which might be related to the blocking of high mobile dunes on both sides. Convex banks are distributed symmetrically on both sides of the river along with the SBD. However, the SBD on the east bank are larger than those on the west bank, with the former continuously extending to the terraces under the action of the westerly wind, forming a banding mosaic distribution of SBD, TD and RD. The concave bank is mostly covered by RD that are situated near to the channels. It is possible for the RD to migrate and fill the riverbed during the windy seasons. Single barchan or barchanoid dunes can occasionally form on the riverbed, and are eroded by runoff during the rainy season.

The swing amplitude of the river is large in middle and lower sections of the downstream in the Keriya River (Fig. 2-K3). The west bank shows some obvious traces of ancient channels with a high curvature, located 1–3 km away from the modern channels. This migration may have resulted from the eastward-moving dunes forcing the river to divert eastward (Guan et al., 2017). The modern channels are relatively straight, with a bending coefficient of 1.17. The flow of the river is also in an opposite direction to the prevailing wind, thereby forming an obtuse angle between the flow and wind direction. The types of dunes distributed along the modern and ancient channels are slightly different, with the former showing patched SBD mainly located on the convex banks, whereas RD occupy the concave banks, and a belt of SBD have colonized both sides of the banks of the latter, gradually being replaced by TD and RD with increasing distance to the channel.

The water flow is diffused in the tail section of the river (Fig. 2-K4), and the tributaries connect with each other to form a grid-like pattern. The curvature of the channel is large, with an average bending coefficient of 1.55. The river spreads into the interdune areas among the ranges of dunes, resulting in the distribution of RD on the floodplains having a grid-like form with relatively good vegetation cover. Some SBD surround the riverbanks in a stripe form due to a lack of development space.

#### *4.1.2 Spatial patterns of channels and dunes in the Mu Bulag River Basin*

The source of the Mu Bulag River is the basin of an ancient lake in which scattered sandy lands can be seen (Fig. 3-M1). The ancient channels of the river can be clearly observed and are intertwined and densely distributed. The scattered distribution of pools and small lakes is surrounded by a sand sheet, and the river meanders in the hilly lowlands, with an average bend coefficient of 1.73. The abundant water resources and good vegetation near the river has resulted in the regional mobile dunes being distributed in patches on the beaches. Most of the dunes are composed of loose sediments originat-

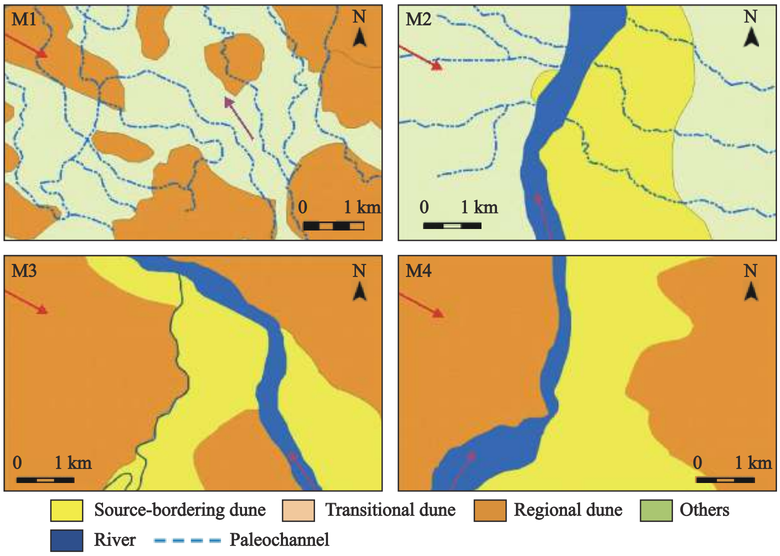


**Fig. 3** Distribution pattern of sand dunes and channels in four sites (M1–M4) of Mu Bulag River Basin, the northern China. Red arrow denotes the direction of prevailing wind; purple arrow denotes the direction of water flow

ing from ancient lake basins, and these sediments were deposited during the Quaternary period, with few materials provided by modern channels. The SBD are distributed in the dry channels along the tributaries in an elongated shape, with a width of only 12 m. The upstream section comprises a gully-river valley system (Fig. 3-M2). The river valley is steep, the river channel is relatively straight, and deep gullies are presented asymmetrically on each bank. The river flows almost perpendicular to the prevailing wind. The convex bank on the east side of the river is covered with loose sediments carried by the river mainstem and gullies. SBD have developed in large quantities due to the abundant sand sources and wide floodplains, and are distributed along the banks in a schistose structure. The tributaries of the river along the west bank are relatively short, and are characterized by eroded concave banks and steep river valleys. The tributaries carry large quantities of sands into the riverbed, which impedes the development of SBD.

The bending coefficient of the river in the middlestream and downstream (Fig. 3-M3) is 1.33. The river flows in a direction opposite to that of the prevailing wind. Sediment accumulates along the east bank, which contributes to the development of SBD in the downwind side and the pushing of dunes toward the terraces near the RD. Similar to the patterns exhibited at Fig. 2-K3 on the Keriya River, the RD occupy the concave bank and tend to invade the channels. However, a large quantity of sediment was deposited at the entrances of tributaries, thereby favoring the formation of SBD in the joint areas between streams. The flow directions of the tributaries are mainly perpendicular to the prevailing wind direction, and the dunes on the north bank are situated close to the channels. The SBD on the south bank are distributed along the river in a strip shape and are connected to the dunes in the terrace area.

The downstream dry channels of the river run across a mobile sandy area (Fig. 3-M4), with a bending coefficient of 1.18. The direction of river flow is mainly opposite to the prevailing wind direction. High RD encroach on the channels on the west bank. The high mobile dunes migrate towards the riverbed during the windy season under the action of the westerly wind, and projections of dunes are often seen on the channel beds. The dunes are washed away by floods during the wet season, and the floods also transport a large quantity of sands into the river. This results in sands being relocated to the next convex bank, thereby providing a source for the development of new SBD.

#### *4.1.3 Spatial pattern of channels and dunes in the Xar Moron River basin*

The upstream of the Xar Moron River are highly branched, with the river system taking on a shape similar to a lotus root, with branches extending in various directions. The flow of the river is smooth, and flow occurs along a single channel. The riverbed changes rapidly in the wide sections, with flow directions becoming inconsistent, thereby forming anastomosing channels. However, relatively stable dune patterns occur on both sides of the channel. The north bank is covered with fixed ancient dunes, whereas the south bank is covered with mobile dunes, among which there are stronger interactions between the modern mobile sands and channels on the south bank (Han and Zhang, 2001; Qin et al., 2010). Traces of the ancient rivers are faintly visible in the mobile sand area on the south bank, which indicate that the river crossed the mobile sand area at some point, following which it flowed into the river mainstem from south to north. Stable flow remains in only a few channels. As shown in Fig. 4-X1, the Zhangfang River tributary takes on a meandering shape. The curvature of the channel is large, with a bending coefficient of 2.10. The direction of flow of the river forms an obtuse angle with the prevailing wind direction. Part of the river is buried by RD when passing through the mobile sand area, during which the fluvial process is weak, thereby impeding the development of SBD. RD are presented along edges of both banks.

The banks of the downstream Xiangshui River tributary (Fig. 4-X3) are covered by fixed and semi-fixed dunes. The states of the channel and dunes located along the banks of the river are relatively stable. The river shows stable discharge and is highly sinuous, with a bending coefficient of 1.45. The flow of the river is almost opposite to the prevailing wind direction. Ancient channels are evident on the right bank of the river, indicating that the river once flowed eastward to the present position. The west side of the ancient channels is covered with RD, which again are located close to the channels. SBD have developed along the east side of the modern channels, taking on a stripe shape and continuously extending to the terraces under the action of wind. These SBD are transformed into RD on the terraces. In

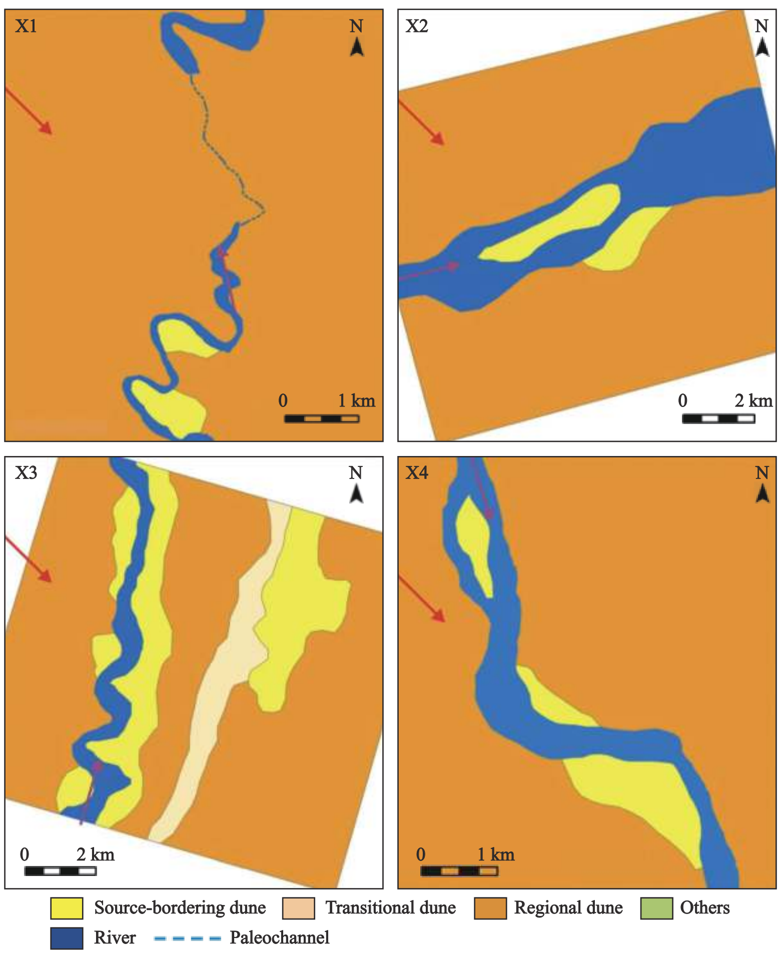


**Fig. 4** Distribution pattern of sand dunes and channels in four sites (X1–X4) of Xar Moron River Basin, the northern China. Red arrow denotes the direction of prevailing wind; purple arrow denotes the direction of water flow

contrast, the SBD on the west of the river are distributed in discontinuous patches on the convex banks.

The tributary on the northern bank (Chaganmulun River) is perennial (Fig. 4-X4). The channel forms into an anastomosing type, with a bending coefficient of 1.31. The river flows in line with the prevailing wind direction, thereby forming an acute interaction angle. SBD are under development in the central bars between anastomosing channels as well as in the narrow parts of channels or the highly curved convex banks, and the area of developing SBD on the east bank exceeds that on the west bank. The terrain became flat and water flow is dispersed along the downstream of the river (Fig. 4-X2), thereby forming a 'river island' type distribution of SBD between two larger streams. The large-scale SBD between the modern channels and the ancient channels are distributed in a schistose structure.

### 4.2 Distinct spatial patterns of channels and dunes

Four distinct landscapes were identified based on the spatial combination of the source-bordering dunes, which are directly influenced by fluvial system, and channel morphologies:

#### *4.2.1 Symmetrical interleaving dunes-meandering channel*

Most rivers in extremely arid deserts are highly curved due to the lack of vegetation (Santos et al., 2019). Dunes were usually formed through aeolian processes under conditions of absent or sparse vegetation. Most meandering rivers are intricately linked to the major drainage systems within desert. The river channel stabilization mechanisms in the absence of vegetation include the cohesion provided by fine sediments and salts and the constant sediment input from aeolian dunes. In particular, inland river basins are more likely to preserve the meandering channel sediments under conditions of absent or sparse vegetation. The geomorphologic features of these basins are characterized by narrow, single and meandering channels. Aeolian-fluvial interactions result in the meandering of rivers in the desert with a bending coefficient exceeding 1.5, with the river developing convex and concave banks and deep troughs. Sediment often accumulates along the convex banks of the river, and barchans and barchanoid dunes evolve on the broad floodplains on the windward bank of the river. The dunes continuously extend toward the terraces under a condition of sufficient sediment supply, and join the RD, forming SBD, TD and RD patterns.

Sand on the terrace is blown into the river on the concave riverbank due to the movement and erosion of the flowing water, particularly if the sand is situated leeward of the prevailing wind direction. This results in the encroachment of dunes towards the river, forming RD close to the river. Consequently, the concave and convex banks of highly curved channels in extremely arid areas are interlaced, and the dunes on both sides are distributed in a symmetric pattern, forming a 'casting' spatial distribution, as shown in Fig. 5a. The middle reaches of the Keriya River (Fig. 2-K2) show a similar distribution pattern.

#### *4.2.2 Riverside dunes-straight channel*

Since rivers are mostly ephemeral in semi-arid areas,

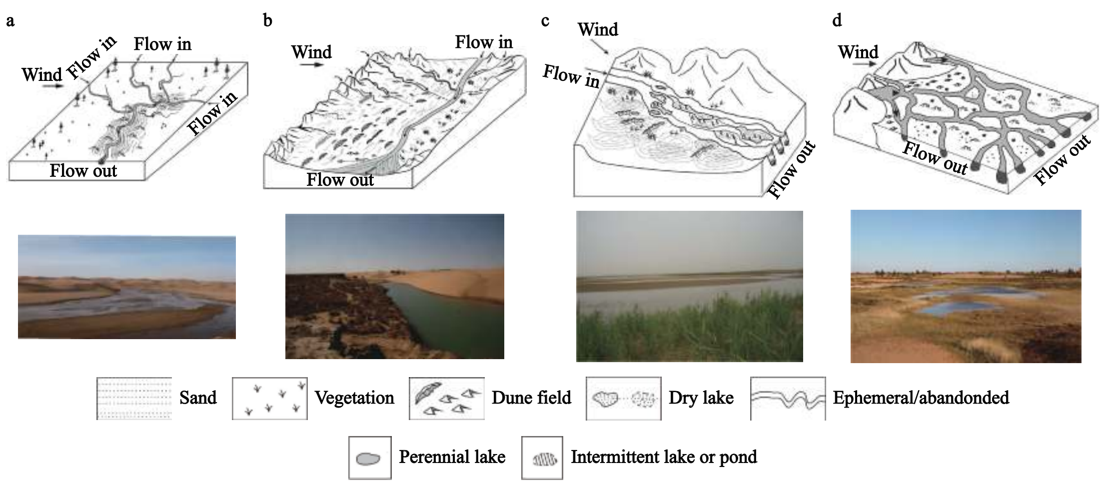


**Fig. 5** Four distribution patterns and corresponding pictures. a. type I: symmetrical interleaving dune-meandering channel; b. type II: riverside dune-straight channel; c. type III: river island dune-braiding channel; d. type IV: grid-like dune-anastomosing channel

straight channels are a temporary form of alluvial rivers that exist under certain conditions or during certain development processes (Ni and Wang, 2000). The formation of this kind of channel is generally closely related to vegetation development in the riparian zone, with higher development of vegetation facilitating the formation of a straighter channel (Begin, 1981; Ni and Wang, 2000). Straight channels are generally characterized by a wide area on the windward bank in which sand from the riverbed accumulates to form barchan or barchanoid dunes under the action of wind. Dunes tend to not develop on the other side of the channel. This spatial pattern of dunes along straight channels suggests that dunes are unable to pass through the channels, as shown in Fig. 5b. For example, the middle section (Fig. 3-M2) and the downstream section (Fig. 3-M4) of Mu Bulag River can be regarded as examples of this type of spatial distribution.

#### *4.2.3 River-island dunes-braiding channel*

The plane form of this type of interaction shows an alternating distribution of single and multiple channels (Wang, 2002). The velocity of water flow in the channel decreases considerably and a large quantity of sediment is deposited at the point at which the single channel branches into multiple channels, resulting in the formation of central bars in between the channels. Sand from the source of the central bar take on an embryonic form of barchanoid dunes under wind action (Zhou et al., 2014). The morphology and direction of extension of near-source dunes are likewise different due to differences in the directions of river flow and prevailing wind. Portions of the sand can be carried away by river flow during flood events, resulting in a change in the morphology and scale of the dunes. Certain quantities of sediment are deposited during drought periods, and these two processes form a reciprocating cycle. Therefore, the near-source dunes occur at a smaller scale and are transient. Large dunes or dune ranges develop unless river flow is modified and river avulsion occurs due to the continuous supply of sand and abandonment of the original river channel, such as has occurred along the lower reaches (Fig. 4-X2 and Fig. 5c) and branches (Fig. 4-X4) of the Xar Moron River.

#### *4.2.4 Grid-like dune-anastomosing channel*

An anastomosing river is a stable multichannel system composed of small, moderately curved, interconnected channels separated by interfluves (Wang et al., 2002). This category of river usually develops in semi-humid regions. The interfluve of an anastomosing river is formed through the cutting of a river through a continuous floodplain, and the size of the interfluve greatly exceeds the size of the channel (Nicholas and Andrew, 2013). This type of channel is generally formed at the source of rivers and deltas in deserts at the points in which the channels converge and channels form radial patterns, respectively. The rivers meander along the interdune areas, forming an interweaving pattern of sand dunes, rivers and lakes. As is shown in Fig. 5d, SBD are distributed on the edge of the channels in a narrow annular form due to limited development space. Vegetation grows well due to the abundant water source in the interdental lowland, resulting in large areas of SBD being fixed by vegetation, forming vegetated dunes. The intertwined distribution of vegetated dunes and channels are relatively stable due to a stable source of sand and a stable channel system. For example, the source section of the Mu Bulag River (Fig. 3-M1) and the tail section of the Kerry River (Fig. 2-K4) have a similar geomorphological pattern.

## 5 Discussion

### 5.1 Influence of the climate on the spatial patterns of channels and dunes

Geological structure and climate are important factors influencing the morphologies of watershed systems. Different climatic conditions in desert systems form various interlinked watershed systems and dune landforms (Yan et al., 2015). As shown in Fig. 6, the annual precipitation of the Keriya, Mu Bulag and Xar Moron river basins increased from an average of 10 mm/yr to over 400 mm/yr, and precipitation in these basins has shown an increasing trend in the last 50 yr. Seasonal variation in precipitation in these basins is characterized by higher precipitation during summer and autumn, and less precipitation during winter. The rainy season is particularly pronounced and short-lived in Mu Bulag River Basin. Such climatic conditions affect the wind-driven sand erosion of the drainage basins of the three rivers. Although the wind-driven sand erosion in the arid areas of the Keriya River Basin is relatively strong, this river experiences relatively weak fluviation, which has resulted channel diversion. Abandoned channels exist along the west bank of the modern channels of the Keriya River Basin, and the highly curved channels of

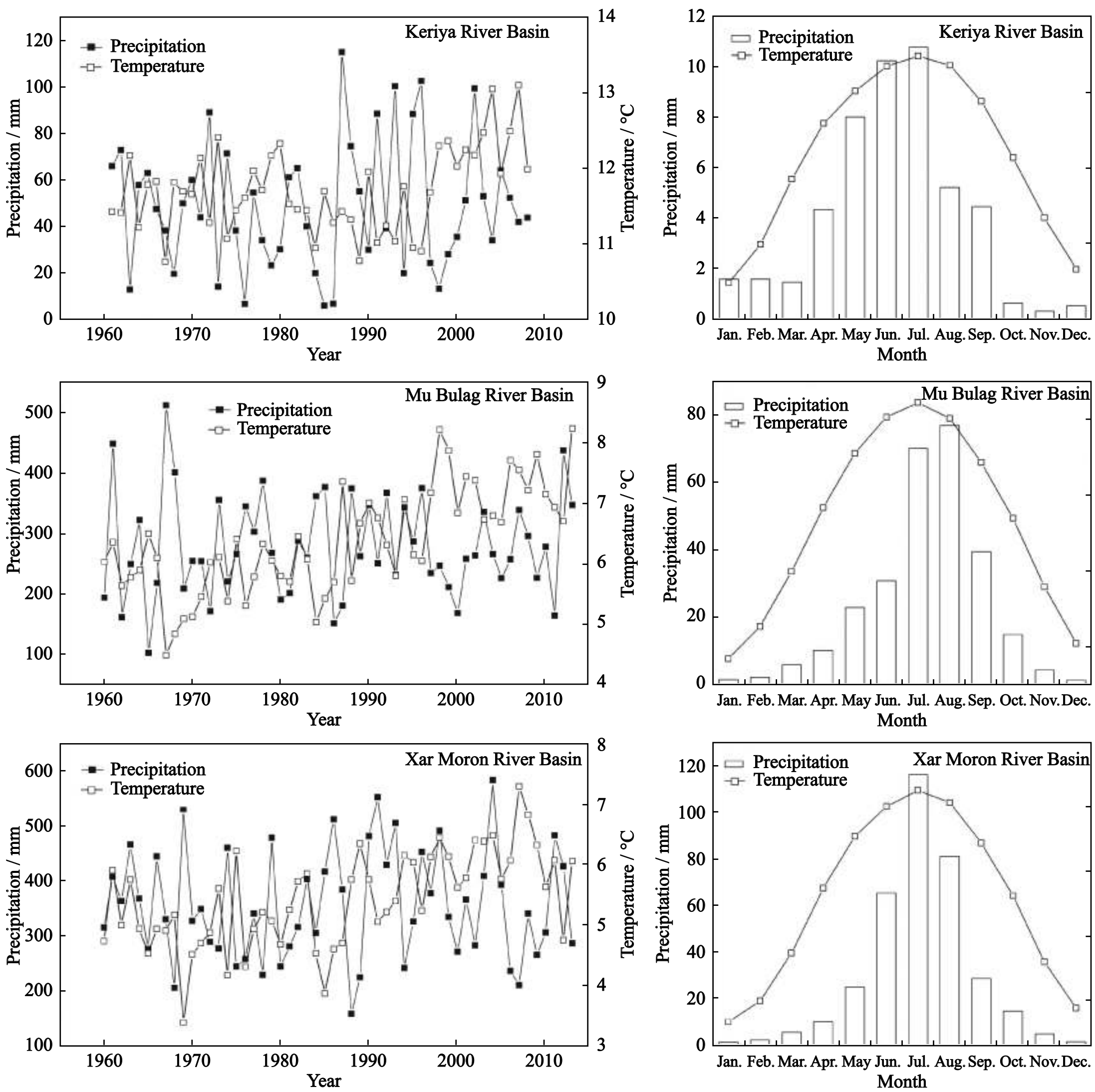


**Fig. 6** The average annual and monthly temperature and precipitation of three drainage basins in the northern China.

the river run through mobile sand areas. Relatively strong fluviation occurs in the semi-humid areas of the Xar Moron River Basin in contrast to the weak wind-driven sand erosion. Patchy distributions of fixed and semi-fixed dunes exist on both sides of the river channels and at the junctions of different tributaries, forming anostomosing channels; the Mu Bulag River Basin experiences ephemeral flow in semi-arid areas, with channels experiencing water flow only over the rainy season. Most channels of the Mu Bulag River Basin are straight, and dunes are distributed along the windward banks or river junctions.

### 5.2 Influence of fluvial morphology on the spatial patterns of channels and dunes

It is widely accepted that differences in fluvial morphology and in the spatial distributions of dunes exist in different parts of a river. For example, river channels in the upstream of the Keriya River are relatively straight, and patchy distributions of near-source dunes have developed. In contrast, the channels in the lower reaches of the Keriya River have developed large bends, and a mosaic distribution of near-source dunes dominate due to space restrictions. Modern river channels and ancient river channels crisscross in the tail-end region of the downstream of the Keriya River Basin, with the development of high and large dunes. The spatial distribution of dunes in upstreams of the Mu Bulag River are similar to those at the tail-end of the downstream of the Keriya River, with dunes located close to the river channels in both regions. The river channels in the upstream, middlestream and downstream of the Xar Moron River have a torose-shaped distribution. Dunes have developed along the branching channels in the broad valley areas of the Xar Moron River basin, whereas there are patchy distributions of near-source and point-bar dunes in the narrow and fast-flowing regions of the river.

### 5.3 Influence of angle between the prevailing wind direction and river water flow on the spatial patterns of channels and dunes

Within each river basin, various dune distribution patterns exist due to the presence of different types of riverbank and different angles of interaction between the aeolian and fluvial systems, as well as other factors. RD generally occur along the concave banks close to the channels, whereas SBD occur along the convex banks, with the scale of SBD larger along the leeward bank than along the windward bank. The dunes found on the convex banks are prone to collapse, thereby forming debris which slide and roll into the riverbeds. Dunes on the windward bank show continual wind-driven extension to the riverbed. The angles of interaction between the aeolian and fluvial systems can significantly affect the development of dunes and the mechanisms under which sand is blown into the river. Airflow dominates the morphology of the dunes when the direction of airflow is parallel to that of flow. However, this condition is not conducive to sand entering the river channel. Airflow has a higher influence on the direction of dune extension when the angle of interaction between airflow and the river flow is perpendicular, with this condition pushing the migrating dunes towards either the valley or the terraces, and resulting in changes to the channel.

## 6 Conclusions

The present study examined three typical drainage basins located in distinct climatic zones of the northern China in which various patterns of aeolian-fluvial interaction landforms are presented. The quantitative analysis of each type of interaction conducted in this study has not only demonstrated how the landforms can be differentiated, but also the dynamic processes responsible for the observed phenomena. The results of the present study can provide a reference for separated study of aeolian landform and fluvial landform in arid areas.

Due to the different channels such as meandering channel, straight channel and anabranches channel, it formed different distribution patterns of riparian dunes. The distribution patterns of dunes and rivers observed in this study were named as: 1) symmetrical interleaving dunes-meandering channel, 2) riverside dunes-straight channel, 3) river-island dunes-braiding channel, and 4) grid-like dunes-anastomosing channel. These types will be compensational observations in addition to previous classification systems of aeolian-fluvial interactions.

Different channels are often associated with different distribution patterns of riparian dunes. In addition to geological structure, climate and the source of sand are also dominant factors that affected the later development morphology of channels, which can affect the development of morphology of river and sand dunes. For different reaches in a river, the angle between the directions of water flow and the wind, the windward and leeward sites of the bank, vegetation coverage and underlying landform determines the distribution, morphology, and scale and extension direction of the riparian dunes. Generally, the floodplains were greatly affected by rivers and they develop into source-bordering dunes, most of which were crescent-shaped dunes. A majority of dunes on the high terraces were regional dunes, which consisted of composite ridge-shaped dunes, dune chains and sand hills.

## References

Al-Masrahy M A, Mountney N P, 2015. A classification scheme for fluvial-aeolian system interaction in desert-margin settings. *Aeolian Research*, 217: 67–88. doi: 10.1016/j.aeolia.2015.01.010

Begin Z B, 1981. The relationship between flow-shear stress and stream pattern. *Journal of Hydrology*, 52(3–4): 307–319. doi: 10.1016/0022-1694(81)90177-3

Bullard J E, Livingstone I, 2002. Interactions between aeolian and fluvial systems in dryland environments. *Area*, 34(1): 8–16. doi: 10.1111/1475-4762.00052

Bullard J E, Nash D J, 1998. Linear dune pattern variability in the vicinity of dry valleys in the southwest Kalahari. *Geomorphology*, 23(1): 35–54. doi: 10.1016/S0169-555X(97)00090-1

Guan C, Hasi E, Zhang P et al., 2017. Parabolic dune development modes according to shape at the southern fringes of the Hobq Desert, Inner Mongolia, China. *Geomorphology*, 295: 645–655. doi: 10.1016/j.geomorph.2017.08.009

Draut A E, 2002. Effects of river regulation on aeolian landscapes, Colorado River, southwestern USA. *Journal of Geophysical Research: Earth Surface*, 117(F2): F02022. doi:

10.1029/2011JF002329

Han G, Zhang G F, Dong Y X, 2007. A model for the active origin and development of source-bordering dunefields on a semiarid fluvial plain: a case study from the Xiliaohe Plain, Northeast China. *Geomorphology*, 86(3–4): 512–524. doi: 10.1016/j.geomorph.2006.10.010

Han G, Zhang G F, You Li et al., 2015. A mechanism for the origin and development of the large-scale dunefield on the right flank of the lower reach of Laoha River, Northeast China. *Sciences in Cold and Arid Regions*, 7(1): 29–39. doi: 10.3724/SP.J.1226.2015.00029

Han G, Zhang G F, You Li et al., 2016. Deflated rims along the Xiangshui River on the Xiliaohe Plain, Northeast China: a case of active fluvial-aeolian interactions. *Geomorphology*, 257: 47–56. doi: 10.1016/j.geomorph.2015.12.025

Han Guang, Zhang Guifang, 2001. Effects of river evolution on formation and development of Horqin sandy land. *Journal of Desert Research*, 21(2): 129–134. (in Chinese)

Li S, Dong G R, Shen J Y et al., 1999. Formation mechanism and development pattern of aeolian sand landform in Yarlung Zangbo River valley. *Science in China Series D: Earth Sciences*, 42(3): 272–284. doi: 10.1007/BF02878964

Li Xiaomei, Yan Ping, 2014. Landscape pattern characteristics of deserts and rivers in Northern China. *Progress in Geography*, 33(9): 1198–1208. (in Chinese)

Liu B L, Coulthard T J, 2015. Mapping the interactions between rivers and sand dunes: implications for fluvial and aeolian geomorphology. *Geomorphology*, 231: 246–257. doi: 10.1016/j.geomorph.2014.12.011

Nanson G C, Chen X Y, Price D M, 1995. Aeolian and fluvial evidence of changing climate and wind patterns during the past 100 ka in the western Simpson Desert, Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 113(1): 87–102. doi: 10.1016/0031-0182(95)00064-S

Ni Jinren, Wang Suiji, 2000. On straight river. *Journal of Hydraulic Engineering*, 31(12): 14–20. (in Chinese)

Nicholas F, Andrew P, 2013. Modelling the continuum of river channel patterns. *Earth Surface Processes and Landforms*, 38(10): 1187–1196. doi: 10.1002/esp.3431

Pan B T, Guan Q Y, Liu Z B et al., 2015. Analysis of channel evolution characteristics in the Hobq Desert reach of the Yellow River (1962-2000). *Global and Planetary Change*, 135: 148–158. doi: 10.1016/j.gloplacha.2015.10.015

Qin Xiaoguang, Liu Jiaqi, Qiu Shanwen et al., 2010. Development and evolution of Horqin sandy land and ancient hydrological networks. *Quaternary Sciences*, 31(1): 80–95. (in Chinese)

Rust B R, 1978. A classification of alluvial channel systems. In: Miall A D (ed). *Fluvial Sedimentology*. Calgary: Canadian Society of Petroleum Geologists Memoir, 187–198.

Santos M G M, Hartley A J, Mountney N P et al., 2019. Meandering rivers in modern desert basins: implications for channel planform controls and prevegetation rivers. *Sedimentary Geology*, 385: 1–14. doi: 10.1016/j.sedgeo.2019.03.011

Tooth S, 2008. Arid geomorphology: recent progress from an Earth System Science perspective. *Progress in Physical Geography: Earth and Environment*, 32(1): 81–101. doi: 10.1177/0309133308089500

Tooth S, Nanson G C, 2011. Distinctiveness and diversity of arid zone river systems. In: Thomas D S G (ed). *Arid Zone Geomorphology: Process, Form and Change in Drylands*. 3rd ed. New York: John Wiley & Sons, 269–300.

Twidale C R, Wopfner H, 1990. Dune fields. In: Tyler M J, Twidale C R, Davies M et al. (eds). *Natural History of the North East Deserts*. Northfield: Royal Society of South Australia, 45–60.

Wang Suiji, 2002. Comparison of formation model and channel stability between two different sorts of multiple channel river patterns. *Acta Geoscientia Sinica*, 23(1): 89–93. (in Chinese)

Wang Suiji, Xie Xiaoping, Chen Dongsheng, 2002. The Progress in the Research of Anastomosing River. *Progress in Geography*, 21(5): 440–449. (in Chinese)

Wu Xiufeng, 2011. Analysis on the influence of climatic change on ecological environment in Ordos area. *Meteorology Journal of Inner Mongolia*, 6: 56–59. (in Chinese)

Xu Jiongxin, 2014. Temporal and spatial variations in erosion and sediment yield and the cause in the ten small tributaries to the Inner Mongolia reach of the Yellow River. *Journal of Desert Research*, 34(6): 1641–1649. (in Chinese)

Yan P, Li X M, Ma Y F et al., 2015. Morphological characteristics of interactions between deserts and rivers in northern China. *Aeolian Research*, 19: 225–233. doi: 10.1016/j.aeolia.2015.01.005

Yang X P, Zhu Z D, Jaekel D et al., 2002. Late Quaternary palaeoenvironment change and landscape evolution along the Keriya River, Xinjiang, China: the relationship between high mountain glaciation and landscape evolution in foreland desert regions. *Quaternary International*, 97–98: 155–166. doi: 10.1016/S1040-6182(02)00061-7

Zhou N, Zhang C L, Wu X X et al., 2014. The geomorphology and evolution of aeolian landforms within a river valley in a semi-humid environment: a case study from Mainling Valley, Qinghai-Tibet Plateau. *Geomorphology*, 224: 27–38. doi: 10.1016/j.geomorph.2014.07.012