Catena 147 (2016) 258–268

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Hyper-concentrated flow response to aeolian and fluvial interactions from a desert watershed upstream of the Yellow River

Zhijun Wang [a,b,c,*], Wanquan Ta [a]

[a] Cold and Arid Regions Environmental and Engineering Research Institute, Key Laboratory of Desert and Desertification, Chinese Academy of Sciences, 260 Donggang West Road, Lanzhou, Gansu Province, China
[b] School of Energy and Power Engineering, Lanzhou University of Technology, 287 Langongping Road, Lanzhou, Gansu Province, China
[c] University of Chinese Academy of Sciences, 19 Yuquan Road, Beijing, China

ARTICLE INFO

Article history:
Received 9 December 2015
Received in revised form 29 June 2016
Accepted 20 July 2016
Available online 25 July 2016

Keywords:
Aeolian and fluvial interactions
Aeolian process
Arid zone
Desert watershed
Hyper-concentrated flow

ABSTRACT

Aeolian and fluvial interactions (AFIs) are critical earth-surface processes in arid zones, especially in desert watersheds. The response of hyper-concentrated flows to seasonal alternate AFIs shows very high rates of sediment transport and has important environmental and ecological consequences from local to global scales. Here, we present the aeolian processes-induced hyper-concentrated (AHC) flows that occurred in the Sudalaer desert watershed upstream of the Yellow River, which primarily transport non-cohesive coarse aeolian sand (>0.08 mm) and show a peak suspended sediment concentration (SSC) of 1.1 to 1.4×10^6 mg l^{-3}. Our field study and theoretical analysis indicate that non-cohesive coarse aeolian sand downstream in the channel can be entrained from the bed and can be suspended in the turbulent flow by the significant runoff generated upstream with a SSC γ_0 value of 0.5×10^6 mg l^{-3}. Severe aeolian processes can provide an abundant coarse sediment supply in the channel, which, once entrained, can also trigger and promote the development of AHC flows. We define, for the first time, the ratio of the weight percentage of coarse sediment to fine sediment $C_{>0.08\ mm}/C_{<0.05\ mm}$ as the optimal grain size indicator (OGI) in suspended sediment, indicating that, as the fraction of coarse sediment increases, the significant runoff gradually changes to hyper-concentrated flows and reaches the peak SSC when OGI = 3.25. Due to the high frequency of sandstorms and the infrequency of rainstorms, most of the significant rainfall-induced runoff with a certain SSC γ_0 can develop into AHC flows and can substantially contribute to the total sediment yield, even leading to deleterious effects on the downstream river system and ecology. Compared with other desert watersheds in semiarid regions, we propose that a SSC γ_0 of 500 kg m^{-3} is the threshold criteria for the occurrence of AHC flows in the arid desert watersheds. Comprehensive governing of soil erosion in the upstream gully-dissected slopes is an essential and effective measure for controlling AHC flows.

1. Introduction

Aeolian and fluvial interactions are basic geomorphic processes that control sediment transport and yield while shaping the landscape in arid zones (Breshears et al., 2003; Bullard and Livingstone, 2002; Bullard and McTainsh, 2003; Field et al., 2009; Langford, 1989; Tooth, 2000). Evidence has demonstrated that many active aeolian dunes terminate at stream channels and deliver a large volume of aeolian sand into the channels (Bullard and McTainsh, 2003; Nanson et al., 1995; Smith and Smith, 1984; Ta et al., 2008; Thomas et al., 1997). These abrupt additions of non-cohesive sand to stream channels can lead to narrowing, aggrading and damming of the heavily aeolian sand-filled channels (Anderson and Anderson, 1990; Jones and Blakey, 1997; Marker, 1977; Mason et al., 1997; Teller and Lancaster, 1986), resulting in an incredible 40-fold increase in bed load (Smith and Smith, 1984) and high suspended sediment loads during channel flooding. Although the extent of aeolian sand transport has been recognised, aeolian and fluvial erosion have historically been studied separately. Furthermore, the lack of simultaneous observations and field data limit the direct quantitative understanding of aeolian and fluvial interactions. Ta et al. (2014) proposed, for the first time, the effect of the aeolian process and its contribution to hyper-concentrated flows both theoretically and physically. The three fundamental driving factors (i.e., the channel bed slope, the aeolian-fluvial climate factor and the aeolian-fluvial geomorphological factor) causing hyper-concentrated flows, as suggested by Ta et al. (2014) are of great importance for regulating the ecological stability of desert watersheds.

Abbreviations: AHC, aeolian processes-induced hyper-concentrated; AFI, aeolian and fluvial interactions; SDC, Sudalaer desert channel; C>0.08 mm/C<0.05 mm, the ratio of weight percentage of coarse sediment to fine sediment; OGI, optimal grain size indicator; SSC, suspended sediment concentration.

* Corresponding author at: Cold and Arid Regions Environmental and Engineering Research Institute, Key Laboratory of Desert and Desertification, Chinese Academy of Sciences, 260 Donggang West Road, Lanzhou, Gansu Province, China.
E-mail address: wzj1159@163.com (Z. Wang).

http://dx.doi.org/10.1016/j.catena.2016.07.033
0341-8162/

To understand these complicated processes in depth, we studied the Sudalaer desert watershed in the upstream area of the Yellow River in China, which is a typical watershed characterised by aeolian and fluvial interactions (AFIs). Our main objective is to further explain the mechanism and characteristics of aeolian processes-induced hyper-concentrated (AHC) flows based on the field observation of four flood events from August 2011 to July 2012 (23 August 2011, 18 July 2012, 19 July 2012 and 27 July 2012) that occurred in the study area to provide additional criteria for predicting AHC flow occurrence and to provide advice on controlling measures in arid and semiarid watersheds.

2. Study area

The Sudalaer desert watershed is an ephemeral desert channel located on the southern margin of the Hobq Desert in the Ordos plateau of China (Fig. 1b and c) and is one tributary of the Maobulang desert channel (Fig. 1b, T1). Composed of 32-km^2 gully-dissected slopes and 21-km^2 dune-covered slopes, the Sudalaer desert watershed has an area of approximately 59 km^2, with an 8-km-long aeolian sand-filled channel extending northeast by north that deviates approximately 38° with respect to the north direction, whose average channel slope is 0.0058. The gully-dissected slopes, distributed on the southeastern part of the upstream reach of the Sudalaer desert channel (SDC), are characterised by severe fluvial erosion and are the primary runoff-generating areas in the watershed, with widespread exposure of subsurface Cretaceous sandstone rocks. A low thickness of aeolian sand sheets covers parts of these gully-dissected slopes because of weak aeolian erosion. However, in the northwestern part of the downstream reach of the SDC, active sand dunes migrate southeasterly, which are dominated by aeolian processes, and terminate at the SDC. During the windy winter and spring seasons (December to May), large volumes of aeolian sand are delivered into the SDC, while in the rainy summer season, these aeolian sand deposits may be flushed downstream by rainfall-induced floods, consequently contributing to AHC flows.

As shown in Fig. 2, the left margin of the SDC is always covered with 2 to 10-m-high, active transverse aeolian dunes that migrate toward the downwind direction to the channel under the influence of W-, NW- and NNW- winds and deliver a large volume of aeolian sand into the channel. Occasionally, some channel sections are fully blocked by sand dunes during the windy seasons. This continuous and abundant sand input may constitute the significant contribution to the total fluvial sediment yield under certain hydraulic conditions. According to historical flooding records monitored by the Tugerige gauge station in the Maobulang desert channel from 1981 to 2010, rainfall-induced floods (>500 $m^3\ s^{-1}$) occurred once every 3 or 4 years (Ta et al., 2015). This suggests that as the tributary of the Maobulang desert channel, the SDC is likely to experience heavy rainfall with the same frequency. Thus, the sediment-laden floods (i.e., runoff) generated from the upstream rills or gullies always develop into AHC flows downstream by entraining aeolian sand sediment available in the channel. Some of these AHC flows merge into the Maobulang desert channel and deliver large volumes of sediment into the Yellow River, leading to the formation of cross-channel sand dams and resulting in catastrophic floods (Zhi and Shi, 2002).

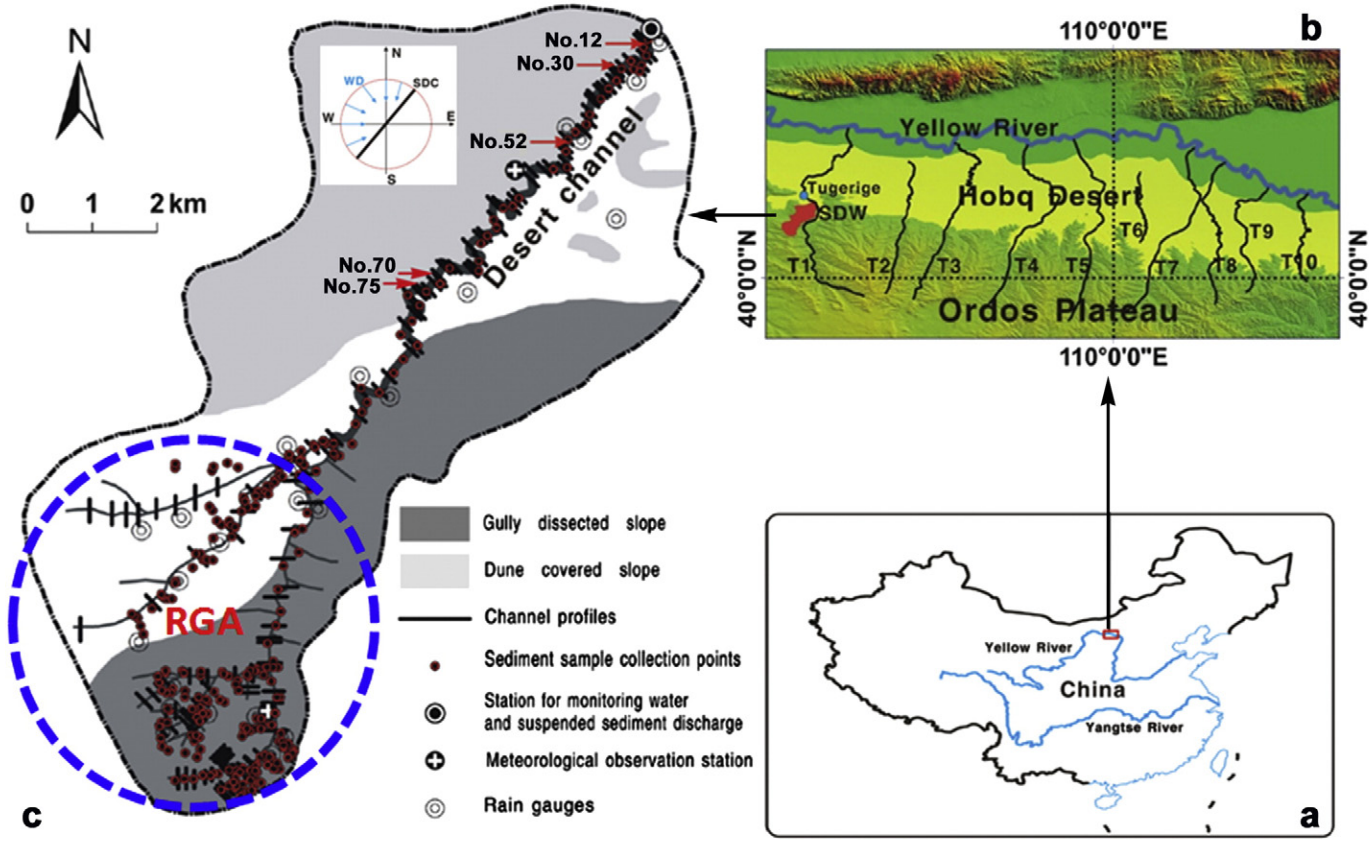

Fig. 1. Location of the Sudalaer desert watershed and the distribution of the sand-dune slopes, gully-dissected slopes and the desert channel: (a, b) Location of the Sudalaer desert watershed showing the juxtaposition of the Hobq Desert. T1–T10 are the ten ephemeral cross-desert tributaries flowing from south to north into the Yellow River. T1 denotes the Maobulang ephemeral desert channel to which the Sudalaer desert channel is a tributary. Tugerige is a gauge station. SDW is the Sudalaer desert watershed; (c) Plan view of the Sudalaer desert watershed showing asymmetrically distributed sand dunes and gully-dissected slopes, between which the white region is a transitional loess zone characterised by weak aeolian-fluvial erosion, of which 10–30% is covered with *Artemisia ordosica* Krasch shrubs, and the blue dashed circle shows the runoff-generating area (RGA). No. 12, No. 30 and No. 52 are examples of the surveyed profiles shown in Fig. 11, and No. 70 and No. 75 are the two profiles chosen for air flow measurement, as shown in Fig. 4. WD is the wind direction from which aeolian sand can be transported into the SDC.