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Grain size characteristics of a degraded Tugai riparian forest landscape between Taklamakan and Kuruktagh deserts in the eastern Tarim Basin, northwest China

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ABSTRACT

Grainsize is among the most important parameters in aeolian research as it controls the sediment mobilization and the mode of transport. Therefore, it is a critical parameter for instance in wind erosion modeling studies which are used to analyze sand and dust storms in the Tarim Basin, an important natural hazard in this region. Spatially explicit parameterization of grain size is difficult, as the texture of the topsoil is not homogeneous across a landscape. Thus, a geomorphological classification of a Tugai landscape in the eastern Tarim Basin is developed and a stratified analysis of the grain-size distributions and the corresponding threshold friction velocities is presented. The results show that transversal dunes have the coarsest sediment in this landscape, while vegetated patches within the alluvial plain of the Tarim River are characterized by the finest sediments. The other landform classes open space, channel, and nebkha have properties between these two landform types. It is concluded that the surface sediment of a Tugai landscape in the eastern Tarim Basin shows a considerable heterogeneity. The landform-based stratification for grain-size analysis is an appropriate solution for an assessment of sediment grains.

1. Introduction

Grainsize is one of the most important parameters in aeolian research. It controls the threshold wind speed for sediment entrainment, determines the mode of transport, and is a useful indicator when interpreting landform development (Bagnold, 1941; Greeley & Iversen, 1985; Shao, 2008). Meanwhile, the analysis of grainsize has become a standard procedure. Modern tools such as laser diffractometry and computer programs for the statistical analysis of grain-size distributions allow a fast and precise assessment (Blott & Pye, 2001; Varga et al., 2018). Meanwhile, automated analysis of grain shape by means of optical tomography also is possible (Joo et al., 2018; Szmańda & Witkowski, 2021). This could become beneficial for sediment transport studies as the (aeolian) mobilization and transport of sediment is dependent on the grain size and the grain shape (Shao, 2008). In addition, laser diffractometry based grain size measurements have a certain dependence on grain shape with a tendency to underestimate the fraction of plate shape grains in the clay fraction (Polakowski et al., 2014).

The importance of grainsize lead to a range of studies about the topsoil characteristics in the desert regions of Northwest China (Liu et al., 2014; Wang et al., 2003; Zhang & Dong, 2015; Zhang et al., 2015; Zhu & Yu, 2014). For the eastern Tarim Basin, however, no sound information is available up to now despite the fact that aeolian sediment movement is an important environmental issue for this region. For instance, drifting sand is a serious natural hazard for Highway G218 and the newly built Korla–Golmud Railway running along the lower reaches of the Tarim River and connecting Xinjiang with Inner China (Dong et al., 2004; Lei et al., 2008; Yang, 2017). The local indigenous vegetation — the so-called Tugai

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riparian forests — along the lower reaches of the Tarim River between two deserts (Taklamakan and Kuruktagh deserts) is considered to reduce these hazards. This sand drift hazard reduction is a widely used argument for the protection of the Tugai forests (Cyffka et al., 2021; Liu et al., 2016; Thevs et al., 2008).

Betz et al. (2015) suggested physical based modeling for assessing the fixation of sediment by the vegetation and argued that this might offer an indicator for the effectiveness of a restoration project in the lower Tarim River. However, when applying aeolian transport models beyond the plot scale, the spatially explicit parameterization is challenging as natural surfaces have a high degree of heterogeneity (Shao, 2008). Using landform information has been demonstrated as one promising option for coping with this issue.

For a continental to global scale, geomorphological mapping in combination with ground and remote sensing based observation of dust concentration has been used to establish a relation between characteristic landforms and their susceptibility towards dust emission (Baddock et al., 2016; Bullard et al., 2008, 2011; Zender, 2003). Basically, these approaches reflect the idea that different landforms are associated with different sedimentary properties. It is argued that this concept also is useful for a local to regional scale and the grain-size analysis of sediment from different geomorphological surfaces in a complex fluvial-aeolian landscape at the lower reaches of the Tarim River is presented. In the regional context of the current study, it is the goal to present grainsize distribution data to provide a reference for further research on aeolian sediment dynamics in the eastern Tarim Basin. Beyond the regional relevance, the suitability of landform based assessment of surface texture, e.g., for the parameterization of transport models is discussed as an approach which might be also of interest for other aeolian researchers.

2. Material and methods

2.1. Study area

The study area is located in the lower reaches of the Tarim River near the village of Arghan (Fig. 1a). The landscape is characterized by a wide alluvial plain formed by sedimentation of the Tarim River in the past. This alluvial plain is bordered by the Kuruktagh Desert in the east and the Taklamakan Desert in the west (Aishan et al., 2015; Ginau et al., 2013; Yusup et al., 2022). The climate is hyperarid with a precipitation below 15 mm (Fig. 1c). Under these harsh environmental conditions, the Tugai forests comprise the natural vegetation. This ecosystem depends solely on the water supply from the Tarim River. Consequently, the stand density and

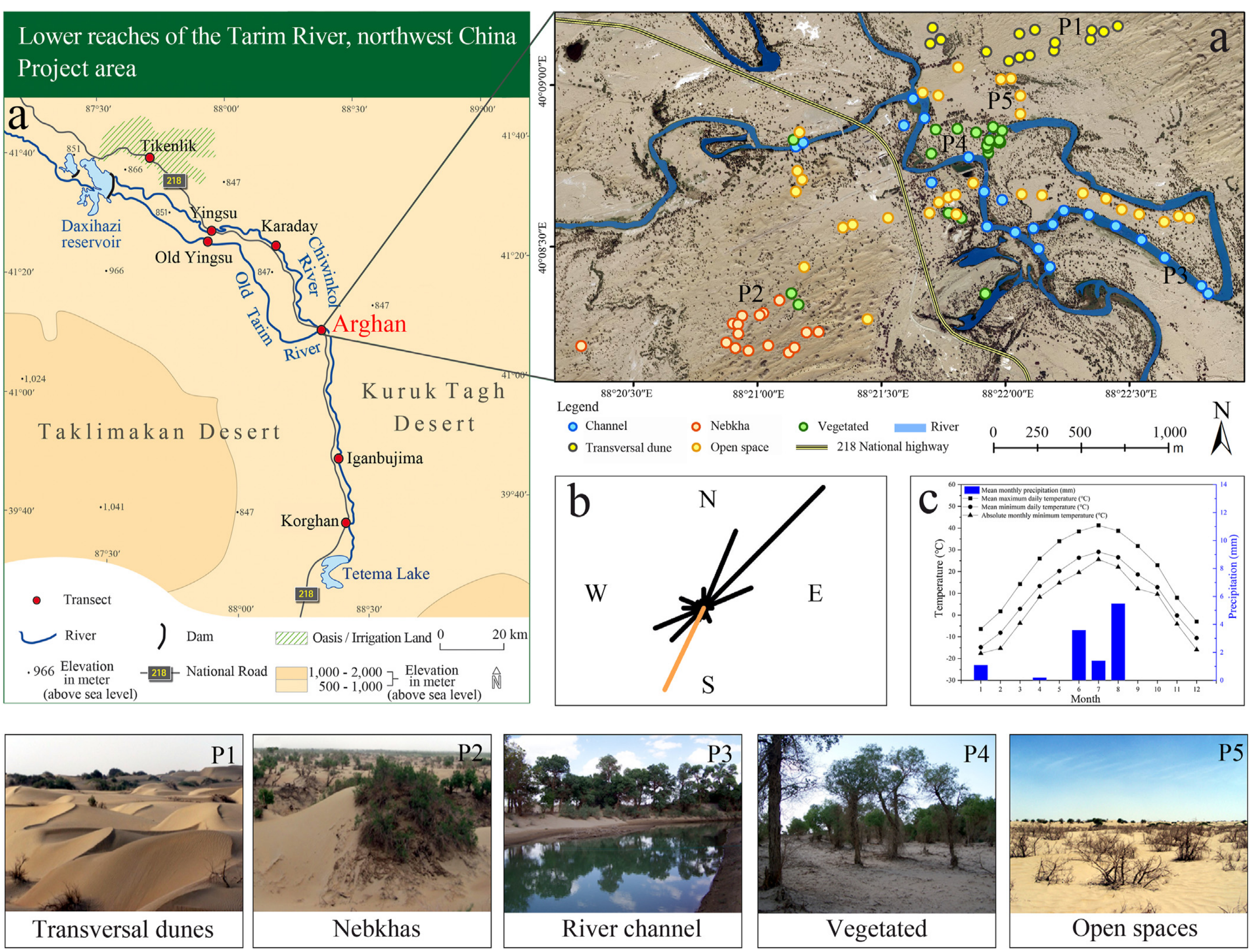

Fig. 1. Overview over the study area: (a) the location and the regional setting with the sampling locations; (b) the wind rose indicating the drift potentials and resultant drift direction; (c) the climate diagram for Arghan. The field photographs P1–P5 show examples of the different landform classes, the photo locations are indicated in the location map (a).

vegetation condition are decreasing with increasing distance from the water course (Aishan et al., 2013, 2014; Halik et al., 2019; Thevs et al., 2008; Yusup et al., 2023).

The soils in this setting are only poorly developed with low organic content. In general, they can be classified as arenosols according to the United Nations Food and Agriculture Organization (FAO) scheme (Ginau et al., 2013). The erodibility of these soils together with the arid climate and sufficiently strong northeasterly wind led to a high tendency towards aeolian sediment transport (Betz et al., 2015; Ginau et al., 2013). Main transport direction according to the sand rose (Fig. 1b) is from northeast to southwest.

2.2. Sampling and data analysis

Stratified soil sampling was applied in the current study using different landform types as strata. For the current study in the lower Tarim River the scheme proposed in Betz et al. (2015) was followed and the landform classes include transversal dunes, vegetated, open space, channel, and nebkha. The visual interpretation of a Quickbird image (60 cm resolution) was used to map these units for the entire study area of approximately 10 km^2. The mapping result was transformed in a raster-GIS format with a code for each landform class as a cell value. In a further step, the results of the grain-size analysis have been assigned to this coded raster. All in all, 108 samples have been collected from the topsoil (0–10 cm depth). For sampling the “channel” landform class, samples could be taken from the channel bed itself due to low flow conditions at the time of sampling. Then, the grain size was analyzed using a laser particle sizer (Microtrac S3500, USA). For the other landform classes, representative sites within the strata have been selected for taking the sediment samples. In the next step the grain size statistics have been calculated according to Blott and Pye (2001) for each sample using the geometric method of moments, the formulas are listed in Table 1. The verbal description of the distribution characteristics also is taken from Blott and Pye (2001), who modified them from Folk and Ward (1957) and Krumbein and Pettijohn (1938).

Beside the calculation of these descriptive statistical parameters of the grain-size distributions, theoretical distributions also were fitted for each strata. The log-normal distribution was used as it is a common choice for describing sediment (Marticorena et al., 1997; Shao, 2008). To enhance the fitting procedure, the dataset was aggregated to the widely used texture classes of the U.S. Department of Agriculture (USDA). This scheme has breaks at 5, 50, 100, 250, 500, 1000, and 2000 μm. A nonlinear least-squares technique then was used to estimate the parameters σ and D from Eq. (1) (with grain size d and probability function $p(d)$, where D is the mean and σ the standard deviation of the log-normal distribution).

$$p(d) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(\ln d - \ln D)^2}{2\sigma^2}\right) \tag{1}$$

To assign an accuracy measure of the fitted distribution, the mean absolute error (MAE) was determined for each landform class calculated from the residuals of the fitted distribution. Furthermore, the threshold friction velocities were estimated for each landform class based on the mean grain size. For this, we used the approach of Shao and Lu (2000) given in Eq. (2) was utilized.

$$u_{*t} = \sqrt{a_1 \frac{\rho_p}{\rho_a} g d + \frac{a_2}{\rho_a d}} \tag{2}$$

where d is the grain size, ρ_p the density of the sediment, ρ_a the air density, g the gravity acceleration, and a_1 and a_2 are empirical constants with 0.0123 and 0.0003, respectively. All calculations have been performed in R (R Core Team, 2015).

3. Results

3.1. Moments of the grain-size distribution

Figure 2 shows the moments of the distributions of all samples grouped by landform classes. From the boxplots, it is obvious that there are substantial differences between the sediment from the different landforms.

Channels have a fine composition with an average mean grain size of 80.65 μm. But they are only poorly to moderately well sorted with a median of 1.95 μm. However, the boxplot indicates that the degree of sorting varies a lot from sample to sample. Also of fine texture but with a better sorting of 1.67 μm are presented for the vegetated areas. Nebkhas have slightly coarser sediments (88.36 μm) than river channels. Their mean grain size is quite constant from sample to sample and can be classified as moderately well to moderately sorted. Open spaces show a big range of mean grain-size values from 68.96 μm to 181.72 μm. Their sorting also is heterogeneous with a span from 1.413 μm to 2.113 μm. With a mean of 127.96 μm, the dunes have much coarser sediment than the other landforms, vegetated areas have the finest composition (78.76 μm). Transversal dunes also show the best sorting, while vegetated areas are in a similar range as nebkhas and open spaces. All samples are fine skewed to symmetrical with channels and transversal dunes being likely to be more (fine) skewed than the other strata. Regarding the kurtosis, the samples from all landforms show a similar behavior, just the transversal dunes have a smaller kurtosis.

3.2. Fitting of theoretical distributions

Figure 3 shows the grain-size distributions of all samples grouped by the landform class. When having a look at the distribution curves, there are differences between the classes. While vegetated areas and transversal dunes show relative homogeneity in the distributions of the respective samples, the channel samples' distributions show considerable noise, also the peaks are not synchronous. Open spaces and nebkhas have distributions with two different behaviors. Some samples show a peak in the silt fraction, others have their peak in the sand fraction. The parameters of the fitted theoretical distributions show considerable differences (Table 2).

Nebkhas and open spaces show quite similar characteristics with means around 110 μm and standard deviations of 0.66 and 0.68 μm, respectively. River channels have a slightly smaller mean with a

Table 1
Equations for calculating the parameters of the grain size distribution using the geometric method of moments (Blott & Pye, 2001). f is the frequency of each class (%), m_m is the class-midpoint (μm), $\bar{x}$ is the mean grain size (μm), and σ is the sorting in the form of the standard deviation of the distribution (μm).

Mean grain-size	Sorting	Skewness	Kurtosis
$\bar{x} = \exp\frac{\sum f \ln m_m}{100}$	$\sigma = \exp\sqrt{\frac{\sum f(\ln m_m - \ln\bar{x})}{100}}$	$sk = \frac{f(\ln m_m - \ln\bar{x})^3}{100 \ln \sigma^3}$	$k = \frac{f(\ln m_m - \ln\bar{x})^4}{100 \ln \sigma^4}$

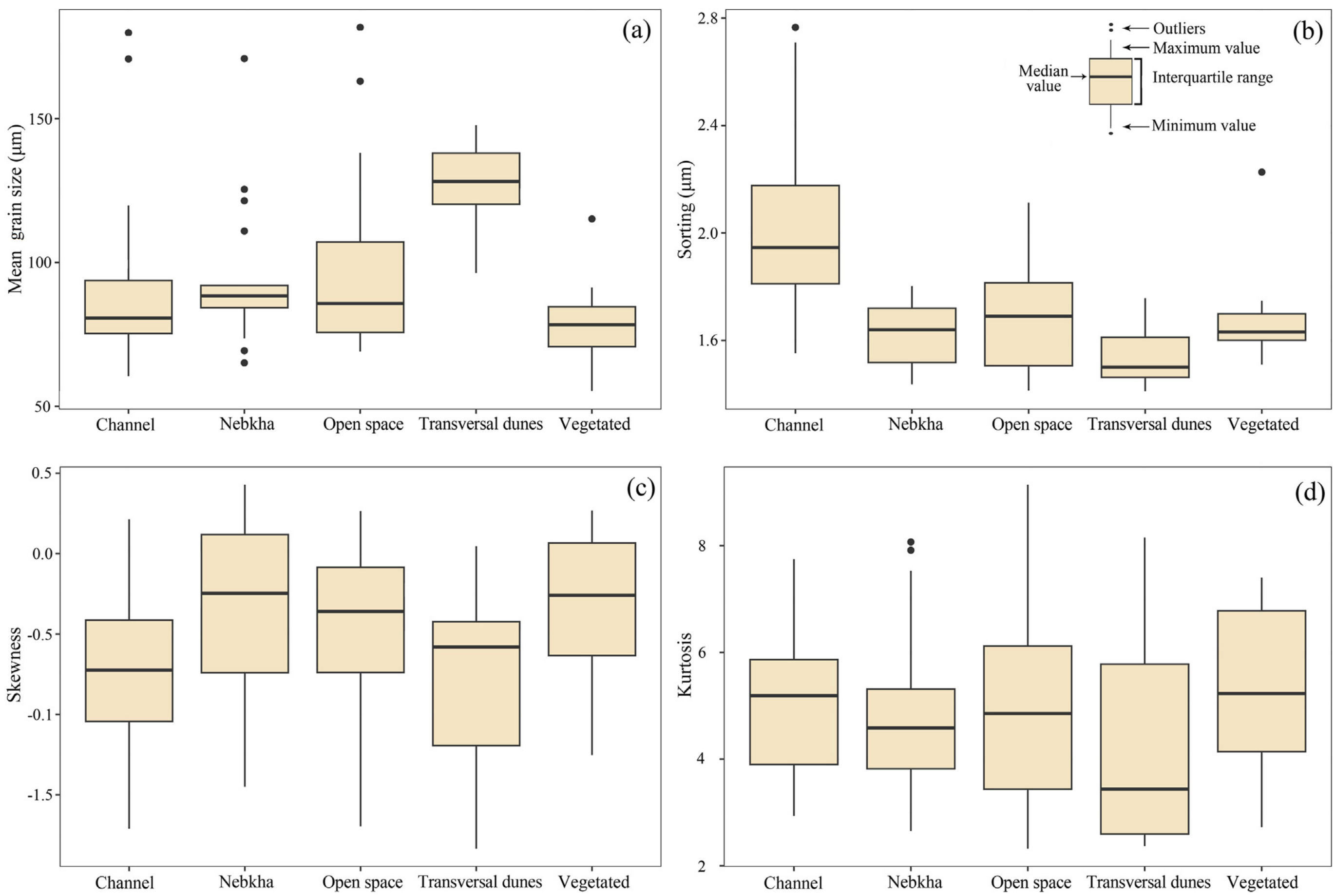

Fig. 2. Results of the grain-size distribution analysis: (a) mean grain size; (b) sorting; (c) skewness; and (d) kurtosis of the distributions.

bigger standard deviation. The extremes in the landscape in the lower Tarim River are the textures of the transversal dunes and the vegetated areas with a theoretical mean of the log-normal distribution of 145.97 and 90.13 μm, respectively. The uncertainty of the fitting reflected in the boundaries of the 95% confidence interval of the distribution parameters show similar ranges for all sampling units and is approximately 2 μm for the mean and 0.02 μm for the standard deviation. Thus, there is still some uncertainty in the values of the fitted distribution. Any application in further studies should consequently be accompanied with an ongoing accuracy assessment. In the current study, the MAE is used as a measure of the accuracy of the fitted sediment distribution, where this error measure indicates the difference between an actual percentage of a particular grain size in a sample and the percentage predicted by the theoretical distribution. The MAE is 2.53% for the channels, 2.8% for the nebkhas, 2.7% for the open spaces, 2.96% for the transversal dunes, and 2.75% for the vegetated surfaces.

3.3. Spatial distribution of landforms and threshold friction velocity

Figure 4 shows the result of the visual interpretation of the satellite images. All in all, an area of 10.15 km^2 has been mapped. The central part is characterized by the alluvial plain of the Tarim River basin. This section has an area of 6.51 km^2 (64.14%), 1.65 km^2 (16.25%) of this area is vegetated. Within this plain the Tarim River has several bends and oxbows. With an area of only 0.16 km^2, the area classified as river channel is relatively small and covers about 1.6 % of the entire study area. The northeast of the study area is dominated by transversal dunes (1.23 km^2, 12.18%). In the southwest, a vast area of 2.17 km^2 (21.38%) of nebkhas characterizes the landscape.

Using the median of all mean grain sizes for the different landform classes in Eq. (2), the (ideal) threshold friction velocity is obtained for each landform class (Fig. 5). Quite obvious is the difference between the coarse sediments of the transversal dunes in the northeast which have a high threshold friction velocity of 6.02 m/s. The lowest thresholds are found for the vegetated areas and river channels with 4.71 m/s and 4.78 m/s, respectively. The values for open space and nebkhas are in between (4.93 m/s and 5.00 m/s). The boxplots in Fig. 5 are included to give information about the heterogeneity of the ideal threshold friction velocities within each landform class. Here, open spaces show the biggest range followed by the channels. Transversal dunes and vegetated areas have a similar heterogeneity, the sediment of the nebkhas has relatively homogeneous characteristics regarding the threshold friction velocity. Please note, that this ideal threshold does not reflect the real behavior of the surface as only the grain size is considered and not further influences such as vegetation, crusts, or soil moisture. In addition, the relief of the landscape also influences the aeolian mobilization and transport of sediment.

4. Discussion

4.1. Potential sediment pathways

Interpreting the landforms and the associated sedimentary characteristics allows development of a conceptual idea about the sediment pathways across the Tugai landscape in the lower reaches

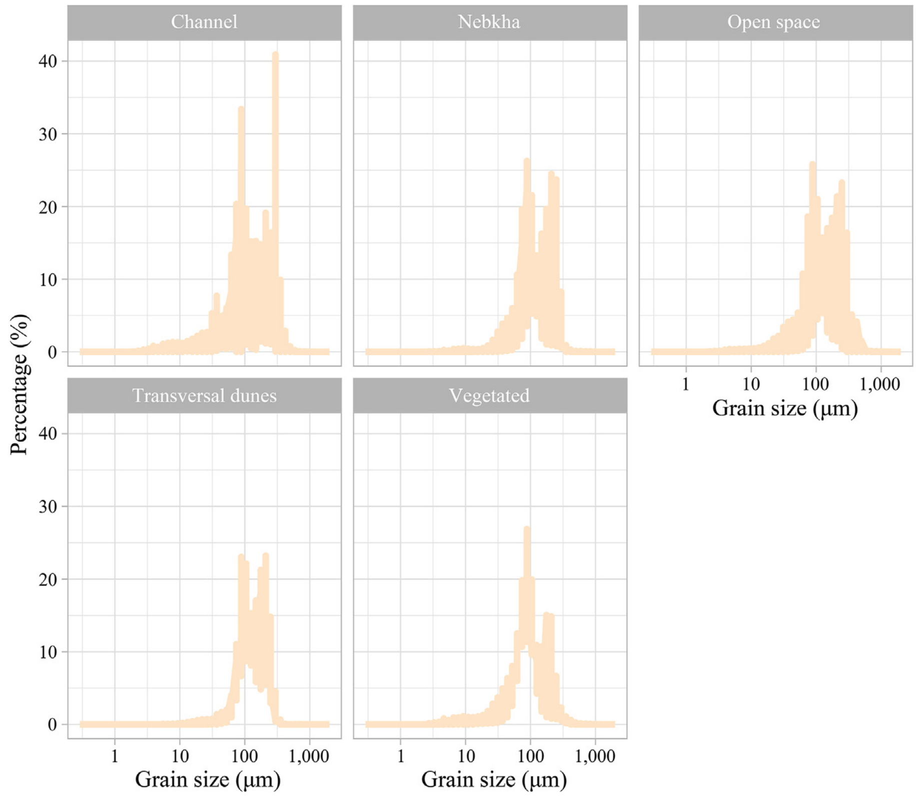

Fig. 3. The grain-size distribution curves for all soil samples from the different landform types.

of the Tarim River (Fig. 6). From the sorting of the grain-size distributions in combination with the field examination, one pure aeolian and one pure fluvial facies in the transversal dunes and in the river channels can be discriminated. The associated landforms and their characteristic topography can be clearly separated in the interpretation of the satellite images in the mapping process. Future work might also make use of digital elevation models (DEMs) which would allow an automated segmentation of channels and dunes, and, thus, the discrimination of the clearly aeolian and fluvial domains. However, at the date of the current study, no high resolution DEM was available for the area of interest and globally available DEMs like Shuttle Radar Topography Mission (SRTM) are not accurate enough for local scale landform mapping.

From the sediment characteristics, it becomes clear that there is an aeolian and a fluvial input to the sedimentary system of the Tugai landscape in the study area, and the other landforms will be influenced by the fluvial as well as the aeolian sediment. On the open spaces of the alluvial plain (i.e., areas without vegetation) the sediment shows heterogeneous characteristics with a wider range of mean grain sizes. This might reflect the fact that some areas are more influenced from the aeolian system and show an accumulation of wind-blown sand while other areas are eroded and show a surface built by the alluvial sediment from the Tarim River. Anyway, a sediment re-distribution can be assumed across the open spaces. Contrarily, vegetated areas show relatively homogeneous characteristics regarding mean grain size and sorting. Furthermore, the sediment texture is finer as in the other strata. This supports the assumption that vegetation has the ability to fix especially fine sediment which is not visible in the texture of open spaces anymore.

In the southwest of the study area, nebkhas have developed. They are formed by the trapping of aeolian sediment by vegetation. Thus, they are aeolian landforms, even if they are located on a relic floodplain as clearly indicated by abandoned channels. As the nebkhas are located in the direct downwind direction from the alluvial plain (Fig. 1b), one possible interpretation is that the nebkhas have been formed by the material deflated from the open spaces on the alluvial plains. This hypothesis also is supported by the fact that the moments of the grain size distributions of open spaces and nebkhas are similar. In summary, the sediment redistribution across the Tugai landscape in the current study are influenced by a fluvial and an aeolian sediment source, the main transport direction of the wind, as well as by a patchy vegetation structure. As a consequence a high degree of complexity of the landscape has to be considered in spatial analysis of ecological as well as geomorphological processes.

Table 2
Parameters of the fitted log-normal distributions. *D* is the mean and σ the standard deviation of the log-normal distribution (in µm).

Strata	*D* (µm)	σ (µm)	*D* [2.5%] (µm)	*D* [97.5%] (µm)	σ [2.5%] (µm)	σ [97.5%] (µm)
Channel	101.25	0.79	99.23	103.35	0.77	0.81
Nebkha	110.60	0.66	108.25	113.01	0.64	0.68
Open space	110.67	0.68	108.75	112.63	0.68	0.71
Transversal dunes	145.97	0.43	143.72	148.10	0.43	0.45
Vegetated	90.13	0.67	88.98	91.31	0.66	0.68

Note: the 2.5% and 97.5% bounds define the 95% confidence interval.

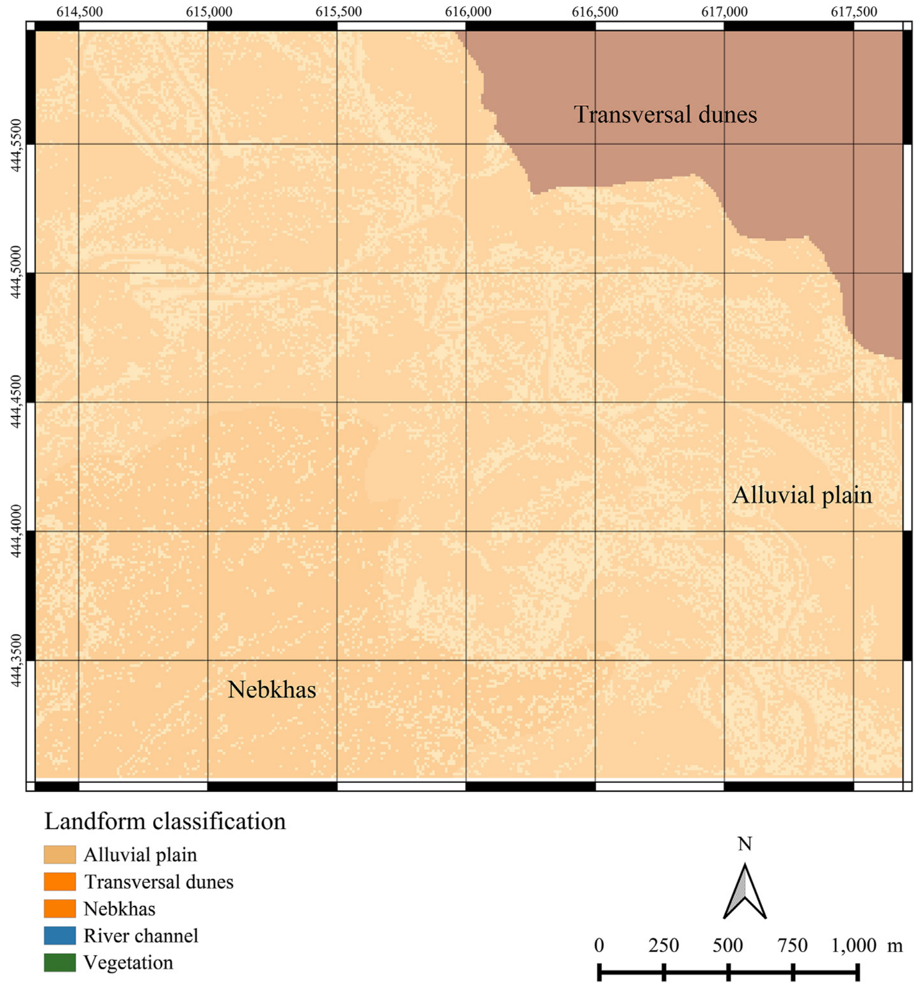

Fig. 4. Spatial distribution of landforms within the study area.

4.2. *Spatially explicit parameterization of ideal threshold friction velocity*

All physically based models for aeolian sediment transport require information about grain size to compute the threshold friction velocity. As sediment under field conditions is not composed of one single grain-size, the use of specific grain size distributions is one option (Shao, 2008). Linking the distribution parameters to clearly identifiable landforms is one promising way to cope with the issue of spatially explicit model parameterization. This approach follows the assumption that there is a link between the process forming a landform and the sedimentary characteristics. This assumption also is supported by the moments of the grain size distributions analyzed in the current study. For example, river channels have a smaller mean grain size and worse sorting than transversal dunes. Of course, in a real landscape, the threshold friction velocity does depend only on grain size. Soil moisture, vegetation, or topography can have a significant influence on threshold friction velocity. For modeling purposes, an "ideal" threshold friction velocity is estimated based on grain size only and then corrected for other factors by means of correction functions (Shao, 2008). In addition, the "ideal" value does not account for grain shape which influences the mobilization of wind as well (Polakowski et al., 2014; Shao, 2008). The threshold friction velocities presented in the current study represent only grain size characteristics forming the foundation for further processing.

On a continental to global scale, the research of Bullard et al. (2008) demonstrates already successfully the link of specific landforms to aeolian processes. Implicitly, these scholars link landforms to the surface characteristic "erodibility" even if dust concentrations above the surface were measured rather than erodibility directly (Baddock et al., 2016; Bullard et al., 2008). In the current study, this idea is transformed to a smaller scale. The mobilization of sediment rather than its transport across the landscape is the focus of the current study. As sediment mobilization is crucial, e.g., for the prediction of sand and dust storms, this focus is well justified. Nevertheless, investigating sediment pathways across a landscape along with the locations of mobilization are crucial for a comprehensive understanding of landform development and should be the subject of future studies. But instead of using dust concentrations as indicator for erodibility, grain size is used and a threshold friction velocity is calculated. The advantage of this approach is that it uses an objectively measurable property of the surface and allows the expression of erodibility in terms of the physically meaningful threshold friction velocity.

For the complex fluvial-aeolian landscape along the lower reaches of the Tarim River, there is a considerable heterogeneity within each landform class. For instance, the threshold friction velocity of the open spaces varies between 4.4 m/s and 7.2 m/s. As previously mentioned, the reason might be that open spaces can be eroding or accumulating. This raises the issue of scale dependency

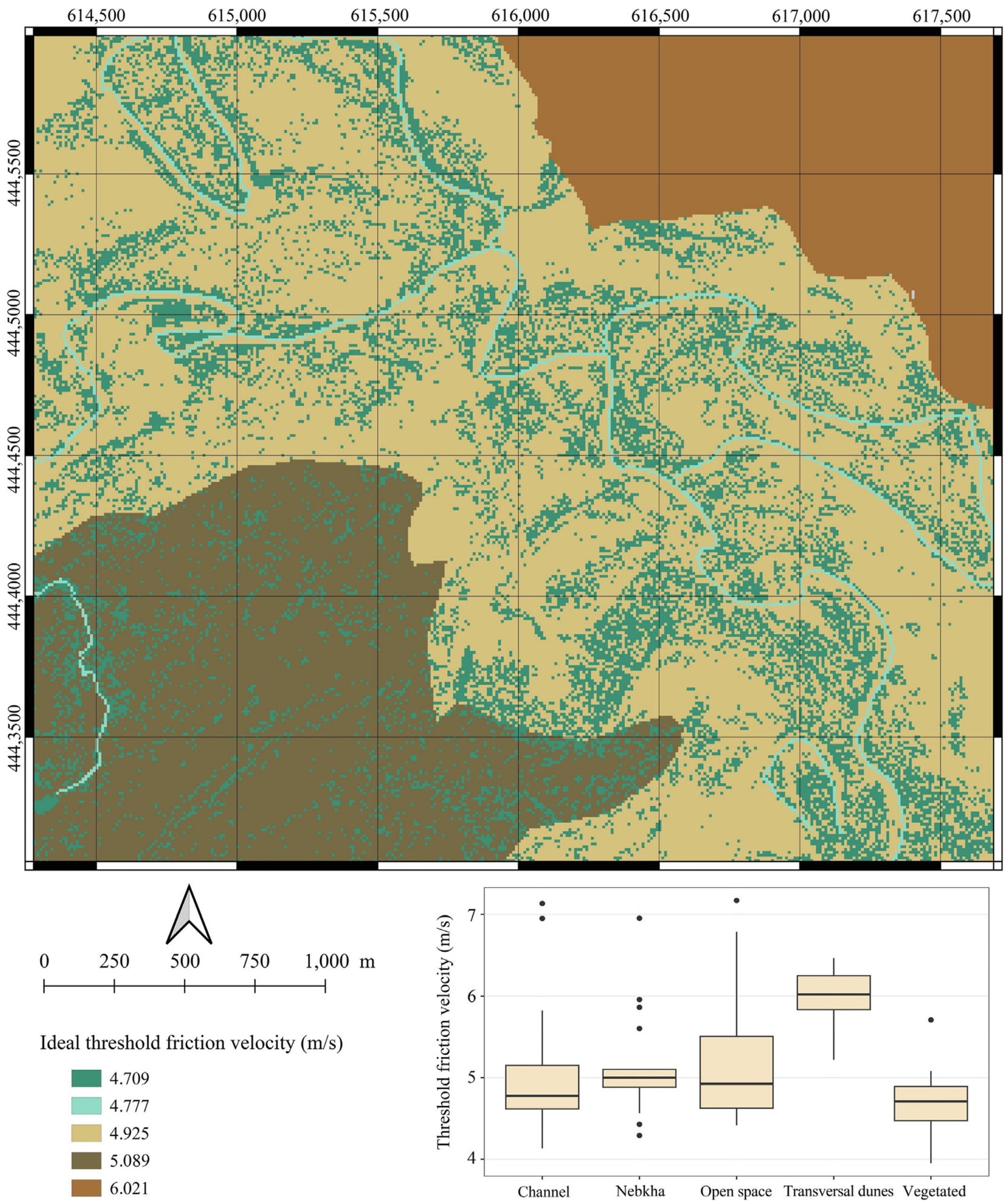

Fig. 5. Spatial distribution of the (ideal) threshold friction velocity estimated from Eq. (2) and the median of all computed threshold friction velocities for the respective landform. The boxplots illustrate the heterogeneity of the threshold friction velocity within a given landform type.

of the current approach. While for a local scale, such complexity might be included as the necessary input data can be derived from field mapping, for regional scales where terrain analysis, image interpretation, or remote sensing have to be applied for the mapping of landforms the difference between an eroding or accumulating bare surface probably is not detectable. The question how much of the real-world complexity to include in studies and models will always depend on the specific context of the application. The landform classification in the current case study is not claimed to be a general valid Rosetta Stone for all landscapes. In the end it will be necessary to discuss individual solutions for specific landscapes and specific applications.

5. Conclusions

The grain-size distributions of the different landforms in the Tugai landscape in the eastern Tarim River Basin show a considerable heterogeneity of the sediment characteristics. These characteristics are likely to arise from the complex interaction of fluvial and aeolian sediment input into the system, its redistribution across the landscape by wind and the trapping of sediment by vegetation. Despite this complexity, there is a clear linkage between the landform and the grain-size distribution. Thus, using landforms as templates for the characterization of sedimentary characteristics is a promising option for assessing information about grain size on

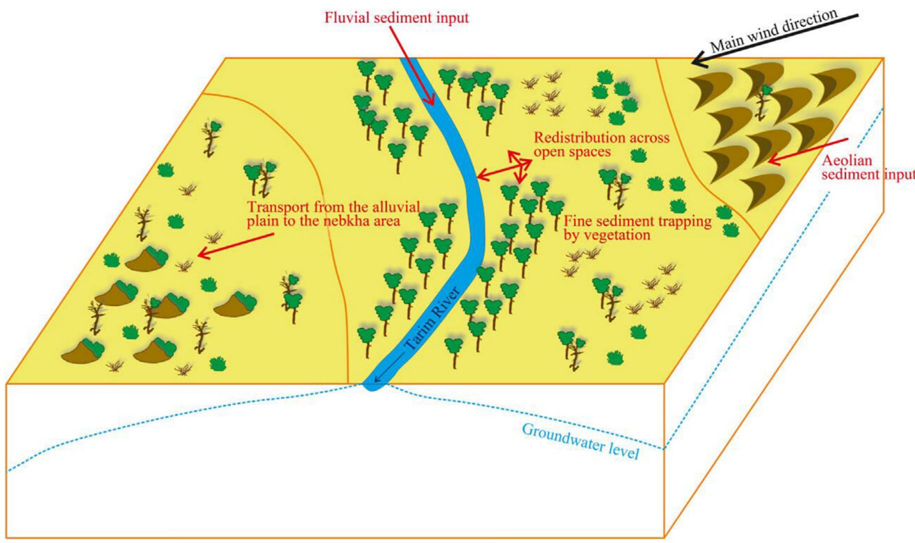

Fig. 6. Conceptual model of the sediment pathways across a Tugai landscape in the lower reaches of the Tarim River.

a local to regional scale. For instance, this approach demonstrate the estimation of the threshold friction velocity. Even though, the estimate still has to be corrected for the presence of vegetation or soil moisture, it is an important basis for identifying hotspots of sand and dust storms. In addition, sediment characteristics are a crucial input for models of aeolian sediment movement which can help predicting sand and dust storm hazards. For the case of the Tugai landscape in the eastern Tarim River Basin, there is a certain degree heterogeneity in the sediment within the different landform classes. This leads to uncertainties in the estimation of the grain-size distribution parameters and threshold friction velocities. Nevertheless, a landform-based approach is useful for objective aeolian transport model parameterization even if further effort is necessary for testing and improving it also in other environmental settings. The current study on grain size characteristics delivers a relevant foundation for studying sediment mobilization and transport by wind, but further research is needed to fully understand the complex fluvial-aeolian system of the lower reaches of the Tarim River.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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