Post-Transport Aeolian Sand Imprints in the Wide Valley Wind-Erosion Region of the Middle and Lower Yarlung Tsangpo River

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Abstract

The wide-valley wind erosion area in the middle and lower reaches of the Yarlung Tsangpo River is one of the most active aeolian sand regions on the Qinghai-Tibet Plateau. In-depth investigation of sand entrainment patterns across different underlying surfaces during the aeolian sand season in the basin' s wide-valley area holds significant importance for windbreak, sand fixation, and ecological environment sustainability. This study selected four typical underlying surfaces in the Nyingchi section of the middle and lower reaches of the Yarlung Tsangpo River basin, and systematically revealed aeolian sand transport characteristics of different underlying surfaces through synchronous observations with gradient anemometers and multi-channel sand collectors. The results indicate that: (1) Under the influence of surface vegetation, the near-surface wind speed profile follows a logarithmic function, but parameters differ significantly. (2) Sediment particle size demonstrates spatial heterogeneity; the silt content in floodplain mobile sandy land (25.6%) substantially exceeds that of other underlying surfaces, while riverbank mobile sandy land is predominantly composed of fine-medium sand particles (accounting for 83.4%). (3) The sand transport process exhibits pronounced underlying surface dependency, and the aeolian sand flow structure follows a composite exponential-power function model. (4) The unit area sand transport rates during the aeolian sand season rank as follows: riverbank sandy land (96.16 t·d-1) > piedmont sandy land (77.65 t·d-1) > floodplain sandy land (69.87 t · d-1) > sparse forest land (5.23 t · d-1).

Full Text

Preamble

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Characteristics of Wind-Blown Sand Transport in the Wide Valley Wind Erosion Area of the Middle and Lower Reaches of the Yarlung Zangbo River

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Abstract: The wide valley wind erosion area in the middle and lower reaches of the Yarlung Zangbo River is one of the regions with the most frequent wind-sand activities on the Qinghai-Xizang Plateau. Investigating the sand emission patterns across different underlying surfaces during the wind-sand season is crucial for windbreak and sand fixation efforts and the sustainable development of the ecological environment. This study selected four typical underlying surfaces in the Linzhi section of the middle and lower Yarlung Zangbo River Basin. Based on synchronous observations using gradient anemometers and multi-channel sand collectors, the characteristics of wind-sand transport across different underlying surfaces were systematically revealed. The results show that: (1) Sediment particle size exhibits spatial differentiation, with the silt fraction in river beach mobile sand land (37.93%) being significantly higher than other underlying surfaces, while riparian mobile sand land is dominated by fine to medium sand (83.49%). (2) Affected by surface vegetation, the near-surface wind speed profile conforms to a logarithmic function but with significantly different parameters. (3) The sand transport process shows significant dependence on underlying surface type, and the wind-sand flow structure conforms to an exponential-power function composite model. (4) The ranking of sand transport per unit area during the wind-sand season is: riparian sand land (96.16 $t \cdot d^{-1}$) > foothill sand land (77.65 $t \cdot d^{-1}$) > river beach sand land (69.87 $t \cdot d^{-1}$) > sparse forest semi-mobile sand land (5.23 $t \cdot d^{-1}$).

Keywords: Yarlung Zangbo River; wind speed profile; wind-sand flow structure; sand transport flux

Introduction

The Qinghai-Xizang Plateau is a sensitive region responding to climate change. Its aeolian landforms have formed under long-term natural conditions and human intervention, widely distributed in river valleys, intermontane basins, and piedmont alluvial zones, characterized by large area, wide distribution, and severe hazards. The wide valley section of the Yarlung Zangbo River is one of the areas with the most intense wind-sand activities on the plateau, providing material sources and dynamic mechanisms for desertification formation. Air movement over underlying surfaces provides kinetic energy for surface sediments, forming wind-sand flow. As a key indicator of wind-sand flow, sand transport quantity constitutes a primary research focus in aeolian geomorphology, desertification, and sand control studies. The varying sand content and particle size at different heights in the wind-sand flow structure can explain sediment transport patterns and further determine wind-sand activity environments, desertification degree, and sedimentary environment evolution processes. In addition to wind erosion modulus, sand transport quantity can also reflect wind erosion intensity and, to some extent, better reflects the essence of wind erosion.

Affected by high altitude and low pressure, research on wind-sand movement on the Qinghai-Xizang Plateau has mainly focused on aerodynamic parameters and characteristics of typical underlying surfaces, climbing dune grain size differentiation, and mobile patterns, as well as sand transport characteristics across different surface types. Previous studies have concentrated on the middle and upper reaches of the Yarlung Zangbo River, while research on wind-sand transport in the middle and lower river valley areas remains almost blank. Surface radiation characteristics significantly influence surface temperature changes, altering the turbulent heat exchange pattern between sandy surfaces and near-surface atmosphere, thereby affecting regional sand emission mechanisms. Investigating near-surface sand-driving wind characteristics can help understand the dynamic conditions for regional aeolian landform formation and provide theoretical foundations for sand control system design and wind-sand movement research.

Therefore, this study focused on the winter-spring wind-sand season in the Linzhi section of the middle and lower Yarlung Zangbo River, establishing four field observation sites on river beach mobile sand land, riparian mobile sand land, foothill mobile sand land, and sparse forest semi-mobile sand land. Through field observations of surface sand transport quantity and wind speed at different heights, combined with comprehensive analysis of surface sediment particle size (0–2 cm), the wind-sand transport characteristics were systematically revealed to provide theoretical support for studying wind-sand activity intensity and patterns across different underlying surface types in plateau river valleys. These findings also offer important reference value for optimizing existing sand control measures in the study area.

1.1 Study Area Overview

The study area is located in the Linzhi section of the middle and lower Yarlung Zangbo River (hereinafter referred to as the Yarlung Zangbo River), representing the most typical river wide valley region in the basin [Figure 1: see original paper]. Dunes in this area account for 85% of the total regional dune area. The region belongs to a plateau temperate monsoon semi-humid to semi-arid climate transition zone, with an average annual temperature of 7.2–15.8°C, high potential evapotranspiration, and seasonal water shortage. During winter and spring (November to May), strong westerly winds prevail, with local sandstorms occurring frequently. The westerly jet stream and valley wind circulation generate valley winds with speeds reaching 4.7 $m \cdot s^{-1}$ in the Yarlung Zangbo River valley. During winter and spring, decreasing river water levels expose large areas of river beaches and mid-channel bars, which, combined with enhanced thermal turbulence, create a high-frequency sand transport window from 14:00 to 18:00 daily.

1.2 Methods

1.2.1 Field Observations

Based on the systematic classification principles of aeolian geomorphology, four observation sites were established in the wide valley area of the middle and lower Yarlung Zangbo River: river beach mobile sand land, riparian mobile sand land, foothill mobile sand land, and sparse forest semi-mobile sand land . In-situ observations of wind-sand dynamic processes were conducted using gradient anemometers (0–200 cm vertical gradient) and multi-channel rotating sand collectors (0–50 cm stratified) for synchronous wind speed monitoring. Field observations covered the typical wind-sand season (spring, March–May), with continuous observations conducted daily during the period of strongest thermal turbulence (14:00–20:00).

Wind speed and direction were measured using gradient anemometers installed approximately 2 m from the sand collectors, with observation heights of 20 cm, 50 cm, 100 cm, 150 cm, and 200 cm. Data recording frequency was 1 min, with a wind speed range of 0–30 $m \cdot s^{-1}$ and accuracy of 0.1 $m \cdot s^{-1}$. Sand transport quantity was measured using multi-channel rotating sand collectors with a total height of 50 cm and 10 collection layers, each with a 10 mm × 20 mm inlet. Collection began when surface sand movement was observed, and collected sand was weighed using an electronic balance with 0.01 g precision. Simultaneously, surface sediment samples (0–2 cm depth) were collected within a 10 cm × 10 cm area around the sand collectors for particle size analysis.

1.2.2 Wind Speed Profile Analysis

Through data integration and screening, combined with literature review and field verification, the sand-driving wind speed in the study area was determined to be approximately 4.7 ± 0.3 $m \cdot s^{-1}$ (at 200 cm height). Considering wind pulsation and compatibility with the multi-channel sand collectors, data with wind speeds greater than 4 $m \cdot s^{-1}$ were selected for analysis. Previous studies suggest that near-surface air belongs to neutral stratification at higher wind speeds. This study used the gradient Richardson number (Ri) for determination, calculating the potential temperature gradient $\Delta\ /\Delta z = 0.008\ K \cdot m^{-1}$ and wind speed gradient $\Delta u/\Delta z = 0.004\ s^{-1}$ between 0.2 m and 0.5 m heights, yielding Ri = 0.004. According to meteorological standards, $|Ri| < 0.01$ indicates neutral stratification. Observation data were synchronized with clock error less than 0.1 s.

The relationship between wind speed and height was fitted using the least squares method in Origin software according to the following formula, with the coefficient of determination (R^2) introduced to evaluate goodness of fit:

$$u_z = a\ln(z) + b$$

where a and b are fitting coefficients; z is height above ground (cm); and u_z is wind speed at height z ($m \cdot s^{-1}$).

1.2.3 Particle Size Analysis

Surface sediment samples (10 cm × 10 cm, 0-2 cm depth) were collected from each site for particle size analysis, totaling 12 samples. Particle size testing was completed at the Key Laboratory of Soil and Water Conservation, Beijing Forestry University, using a Mastersizer-3000 laser particle size analyzer (Malvern, UK) with a measurement range of 0.01-3500 m.

1.2.4 Wind-Sand Flow Structure Analysis

Based on data collected by the multi-channel rotating sand collector, sand transport flux at each site was calculated using:

$$q(z) = \frac{m(z)}{A \cdot t}$$

where $q(z)$ is sand transport flux at height z ($g \cdot cm^{-2} \cdot min^{-1}$); $m(z)$ is sand mass collected at height z (g); A is the collector inlet area (cm^2); and t is sampling time (min).

Current research on wind-sand flow structure remains controversial, but generally agrees that it can be expressed by power, logarithmic, exponential, or composite functions. Following previous studies, to offset near-surface turbulence effects, piecewise fitting was performed for 0–20 cm and 20–50 cm ranges in Matlab software. The fitting models are:

$$q(z) = cz^{-d} \quad (0\text{ cm} \le z < 20\text{ cm})$$

$$q(z) = ez^{-f} \quad (20\text{ cm} \le z < 50\text{ cm})$$

where c, d, e, and f are fitting coefficients.

1.2.5 Wind-Blown Sand Transport Estimation

Based on British physicist Bagnold' s transport equation and considering the collector inlet width, plot length in the wind direction, and plot width perpendicular to wind direction, the sand transport quantity per unit time for different underlying surfaces was estimated:

$$Q(z) = q \cdot t \cdot D \cdot L$$

where $Q(z)$ is total sand transport quantity ($\mathrm{t \cdot d^{-1}}$); q is sand transport flux ($\mathrm{g \cdot cm^{-2} \cdot min^{-1}}$); D is plot width perpendicular to wind direction (m); L is plot length in wind direction (m); and t is single experiment duration (min).

Different transport modes across underlying surfaces were distinguished by combining stratified sand collection with laser particle size analysis. According to previous studies: creep occurs in the 20–50 cm layer with particle size >0.5 mm; saltation occurs in the 1–20 cm layer with particle size 0.1–0.5 mm; and suspension occurs in the 0–1 cm layer with particle size <0.1 mm.

2.1 Wind Regime and Wind Speed Profile Characteristics

Comprehensive statistical analysis of wind direction data at observation points (Table 2), combined with field measurements, determined the sand-driving wind speed as 4.7 ± 0.3 $\mathrm{m \cdot s^{-1}}$ (at 200 cm height), with multi-directional composite characteristics. Northerly winds (NNE) accounted for 73.33% at river beach sites, while the other three underlying surfaces were dominated by easterly winds (90.33%) and northerly winds (56.7%). Maximum wind speeds at 200 cm height were recorded at foothill mobile sand land (14.0 $\mathrm{m \cdot s^{-1}}$), followed by riparian mobile sand land (13.6 $\mathrm{m \cdot s^{-1}}$), river beach mobile sand land (11.5 $\mathrm{m \cdot s^{-1}}$), and sparse forest semi-mobile sand land (6.8 $\mathrm{m \cdot s^{-1}}$). Wind speed attenuation rate positively correlated with initial wind speed; for example, at foothill mobile sand land, attenuation reached 77.86% at 14.0 $\mathrm{m \cdot s^{-1}}$ but decreased to 41.67% at 5.6 $\mathrm{m \cdot s^{-1}}$.

All underlying surfaces showed near-surface wind speed distributions conforming to the logarithmic model $U_z = a\ln(z) + b$ ($R^2 > 0.90$), but with significant spatial differentiation in parameters a and b (Table 3). Sparse forest semi-mobile sand land, with vegetation height of 150 cm and coverage of 5%–10%, exhibited the maximum a value (1.5 ± 0.3 $\mathrm{m^{-1}}$) at 6.5 $\mathrm{m \cdot s^{-1}}$, significantly higher than mobile sand lands. River beach and foothill mobile sand lands, essentially without vegetation cover, showed similar a values, demonstrating that differences in wind profile coefficients result from varying underlying surface properties.

2.2 Underlying Surface Sediment Characteristics

Particle size composition reflects the percentage content of different grain size fractions in sediments, closely related to wind-sand transport and accumulation processes, and reveals three different transport modes. Results show that mobile sand lands are dominated by fine and very fine sand fractions (Figure 4). The river beach mobile sand land had the highest silt content at 37.93%, while riparian mobile sand land was dominated by fine to medium sand (83.49%). Clay and coarse sand contents were relatively low across all surfaces, with riparian mobile sand land showing the highest coarse sand content (50.56%) and river beach mobile sand land the highest clay content (2.71%).

From a transport mechanism perspective, riparian and foothill mobile sand lands primarily experienced creep and saltation. River beach mobile sand land, dominated by silt fractions, mainly experienced suspension. Sparse forest semi-mobile sand land, with medium sand as the dominant fraction, showed greater potential for creep near the surface.

2.3 Wind-Sand Flow Structure and Transport Estimation

Observations revealed significant spatial heterogeneity in the vertical structure of wind-sand flow across different underlying surfaces (Figure 5). Based on exponential-power function composite modeling, the fitting results ($R^2 > 0.90$) revealed sand transport flux distribution characteristics with height. At 6 $m \cdot s^{-1}$, riparian mobile sand land showed maximum flux in the near-surface layer (0–1 cm) at 20.92 $g \cdot cm^{-2} \cdot min^{-1}$, indicating creep dominance. Sparse forest semi-mobile sand land, due to vegetation obstruction, showed only 3.18 $g \cdot cm^{-2} \cdot min^{-1}$ flux, with the highest fitting degree ($R^2 = 0.96$).

Fitting coefficients c, d, e, and f were positively correlated with wind speed growth. Within the 0–20 cm range, the e value for river beach mobile sand land increased from 1.24 at 6 $m \cdot s^{-1}$ to 8 at 8 $m \cdot s^{-1}$, while the increment for d and f was relatively small. The vertical distribution of sand transport quantity across different heights (Figure 6) differed from plain areas, showing a decreasing trend with height. The 0–10 cm near-surface layer dominated, accounting for 79.05% on average, decreasing sharply to 1.75% above 40 cm.

Vertical transport characteristics varied significantly across underlying surfaces. Riparian mobile sand land showed the highest near-surface (0–10 cm) transport proportion at 91.45%, significantly higher than river beach mobile sand land (63.91%). Sparse forest semi-mobile sand land exhibited the most dramatic decrease at 20 cm, with the largest attenuation amplitude among all surfaces. Foothill sand land showed a unique vertical distribution pattern with transport across all height layers, but with proportions below river beach land above 20–30 cm.

Different transport modes showed typical differentiation. Riparian mobile sand land was dominated by creep (87.95 $t \cdot d^{-1}$), far exceeding sparse forest land (46.36 $t \cdot d^{-1}$). Foothill sand land showed dual dominance of creep (46.36 $t \cdot d^{-1}$) and saltation (22.75 $t \cdot d^{-1}$). River beach mobile sand land exhibited significantly higher suspension transport, with fine particles (2–50 m) reaching 4.72 $t \cdot d^{-1}$, much higher than the average of other surfaces (0.32 ± 0.15 $t \cdot$

d^{-1}), explaining the high incidence of dust weather in the Yarlung Zangbo valley. Notably, sparse forest semi-mobile sand land, with increased vegetation coverage, saw total transport decrease sharply to 5.23 $t \cdot d^{-1}$, a 94.56% reduction compared to bare sand land.

3 Discussion

3.1 Effects of Underlying Surface Vegetation on Near-Surface Wind Speed

Vegetation coverage is a primary factor affecting wind-sand movement, significantly reducing surrounding wind speeds and obstructing dust transport. During the observation period, the most pronounced wind speed reduction occurred at sparse forest semi-mobile sand land, consistent with Bai et al.' s conclusion that vegetation coverage is a critical factor affecting wind-sand movement under the same wind speed conditions. The significant wind speed decrease within the forest contrasted sharply with other surfaces. Zhang et al. attributed this difference to flexible vegetation' s ability to consume near-surface airflow energy through structural and morphological changes, reducing energy reaching the surface and thereby increasing near-surface wind speed reduction, which quickly decreases wind speed to the threshold velocity. At low wind speeds in sparse forest semi-mobile sand land, this phenomenon was particularly evident, with a reduction reaching 91.43%.

This study reveals that sparse forest semi-mobile sand land in the middle and lower Yarlung Zangbo River valley shows significantly higher wind speed attenuation effects under low wind speed conditions compared to mobile sand lands, which may be related to vegetation morphological specificity and coupling with local turbulence during the wind-sand season. Notably, foothill mobile sand land maintained a 77.86% reduction even at high wind speeds, contrasting sharply with riparian bare sand land (41.67% reduction). This phenomenon contradicts the traditional understanding that mobile sand lands have no significant windbreak effect, possibly due to local circulation suppression effects in the dune-forest transition zone.

3.2 Sand Particle Movement and Wind-Sand Flow Structure

Sand particles in wind-sand flow move forward through suspension, saltation, and creep depending on wind force, particle size, and mass. Analyzing sand grain size characteristics and differentiation helps identify surface sand material sources and explore wind-sand flow movement mechanisms. Sun et al. found that the average sediment particle diameter was around 0.08 mm, with particles smaller than 0.1 mm showing a power function increase in relative content with height, while particles larger than 0.08 mm showed decreased relative content with height. Wind-sand flow concentrates within a certain height above the surface during transport. Regardless of wind speed changes, height and wind speed show a linear relationship, while sand content decreases rapidly with height. Ding et al. concluded that height and sand transport rate follow a power function relationship, with transport concentrated in 0–20 cm. Zhang et al. showed that over 63.97%–91.35% of sand transport concentrates within 0–30 cm of the surface.

Based on extensive field data, this study shows that wind-sand flow primarily concentrates within the 0–30 cm height range, with transport quantity accounting for 90.96% of total transport within $ $20 cm, more concentrated than Zhang et al.' s findings, and consistent with Wu' s conclusion that sand content mainly concentrates in 0–30 cm. This difference may stem from low-pressure, high-frequency turbulence in plateau valley areas shortening sand particle trajectories, causing transport to concentrate near the surface. Different underlying surfaces show varying function fittings due to differences in surface sediments and vegetation coverage, consistent with Yang et al.' s finding that different underlying surfaces have different wind-sand flow structures and fitting functions, attributable to varying surface sediment particle sizes.

3.3 Wind-Blown Sand Transport Estimation

Sand transport quantity represents the total amount of sand material moving per unit time and area during wind-sand movement, better reflecting wind erosion essence than wind erosion modulus. Regarding transport estimation, Bagnold' s equation is derived from sand particle saltation characteristics and trajectory equations based on momentum theorem. Zhao et al. revised the formula for estimating sand transport in the central Taklamakan Desert based on measured data: $Q = 2.284 \times 10^{-4} v^{3t}$. Li et al. calculated sand flux using $Q = q \times L \times 10^3 \times \sin\theta$, introducing the angle between wind direction and river direction for more precise estimation of sand entering the Yellow River. Shao et al. estimated regional potential wind-sand transport quantity as the product of sand transport flux and effective transport width. Zhao et al. used fitted functions ($Q = q(v) \times d \times t$) to estimate total wind-sand transport across different underlying surfaces and ArcGIS software to estimate dune volume, then calculated dune advance sand quantity using soil bulk density.

This study' s collector-plot coupling model effectively solves tool disconnection issues and the generalization deficiency of saltation length. The model directly uses the stepped collector' s stratified inlet area and sampling time as input parameters, eliminating extrapolation errors from traditional model-tool mismatches. Compared with Zhao et al.' s ArcGIS-based dune volume estimation, this model significantly improves computational efficiency, providing a standardized solution for rapid estimation of wind-sand transport quantity across complex underlying surfaces.

3.4 Sand Control Strategies and Recommendations

Wind-sand transport in typical mobile sand surfaces of the middle and lower Yarlung Zangbo River valley shows obvious spatiotemporal variation characteristics, requiring different sand control measures for different surfaces. For example, river beach mobile sand land, widely distributed at river channel shifts in the study area, becomes extensively exposed during low water periods, providing abundant sand sources and generating large amounts of suspension transport, making it a primary dust emission zone. Sand control measures should combine mechanical and biological methods, with vegetation restoration as the main approach.

For riparian mobile sand land where transport occurs mainly through creep and saltation, low-density vegetation and gravel cover measures should be promoted, along with establishing low-density shelterbelts with strong windbreak effects. For foothill mobile sand land, the main wind deposition area with gradually expanding range, enhanced protection measures should be implemented, establishing dune activation monitoring and early warning systems based on sand-driving wind speed thresholds. For sparse forest semi-mobile sand land, protective measures should maintain existing vegetation while appropriately increasing shrub density to enhance surface stability.

4 Conclusions

Based on field observation data from different underlying surfaces during the wind-sand season in the middle and lower Yarlung Zangbo River Basin, this study systematically revealed the driving mechanisms of wind-sand activities and sand emission patterns in wide valley areas. The main conclusions are:

(1) In the wide valley wind erosion area of the Yarlung Zangbo River, near-surface wind speed reduction in sparse forest semi-mobile sand land is greater than in mobile sand lands, demonstrating vegetation' s role in weakening near-surface wind speed and thereby reducing soil wind erosion.

(2) Different underlying surface types affect sand particle transport modes through grain size sorting and threshold wind speed differences. Riparian mobile sand land, with larger surface particle sizes, mainly experiences creep and saltation. River beach land has significantly higher silt and clay content than mobile sand lands and foothill sand lands, experiencing large amounts of suspension transport with higher and farther transport characteristics in addition to saltation and creep.

(3) The wind-sand flow structure in the Yarlung Zangbo River area can be expressed by piecewise exponential and power functions, with fitting coefficients closely related to wind speed and sand content.

(4) Different windbreak and sand fixation measures should be formulated according to sand transport quantity and movement modes across different underlying surfaces.

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Note: Figure translations are in progress. See original paper for figures.