



Design and Characterization of a Wind Tunnel for Wind Erosion Research

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Abstract—Wind tunnels are indispensable tools for the controlled analysis of wind-induced soil erosion, sediment transport and deposition, especially given the complexities of direct field observation. This research focused on the design and in-depth characterization of a new wind tunnel facility established at Erciyes University, specifically designed to simulate wind erosion mechanisms in fragile light-textured soils. Constructed of aluminum composite, the tunnel features a 5 m test section, a raised platform for easy access, and an axial fan capable of generating variable wind conditions. Wind speed profiles were meticulously measured at 5, 7 and 9 m/s using pitot-type anemometer at various longitudinal positions. Reynolds numbers were well above 200,000, clearly confirming a fully turbulent flow regime, while Froude numbers remained consistently below 7.64, indicating subcritical flow. The thickness of the developing boundary layer was observed to vary between 0.10 and 0.24 m, corresponding to shear velocities between 0.146 and 0.504 m/s. The spatial variability of the wind flow along the test section was effectively visualized using kriging interpolation. These comprehensive experimental results highlight the ability of the wind tunnel to mimic natural wind erosion scenarios effectively and to provide important quantitative data sets for the improvement and validation of soil erosion prediction models. As a result, this advanced wind tunnel is well positioned to facilitate future in-depth investigations of aeolian processes and the further development of predictive modelling frameworks, thereby providing valuable insights for mitigating land degradation and informing sustainable environmental management practices in vulnerable regions.

Keywords: Turbulent air-flow, soil erosion, aeolian research.

1. Introduction

Wind erosion is a widespread environmental challenge, particularly in arid and semi-arid regions, where it leads to soil degradation, loss of agricultural productivity and disruption of ecosystems. Accurate estimates of sediment transport are essential for understanding erosion dynamics and developing effective management strategies. However, direct field measurements of wind-induced soil loss are hampered by variable conditions and methodological limitations (Kaplan et al., 2020, 2024; Uzun et al., 2022).

Wind tunnels provide a solution by allowing controlled simulation of aeolian processes. Advances in wind tunnel design—both portable and stationary—have expanded the possibilities for studying wind-induced soil erosion, sediment transport and deposition (Basaran et al., 2011; Cornelis & Gabriels, 2003; Gabriels et al., 1997; Youssef et al., 2012). The incorporation of devices such as screens, honeycombs, and pitot-type anemometer has improved the reliability and accuracy of wind velocity and sediment flux measurements (Dong et al., 2007; Tominaga et al., 2018). Previous studies have highlighted the importance of tunnel geometry, flow uniformity, and innovative measurement techniques to improve experimental results.

Recent advances in wind tunnel technology have significantly enhanced the research on wind erosion dynamics and sediment transport processes. Substantial progress has been made in evaluating the erodibility of field surfaces since the invention of a portable wind tunnel and dust collection system (Zingg, 1951). Pietersma et al. (1996) advanced the development of wind tunnel design, specifically designed for studying soil erosion and fugitive dust. This improved researchers' capacity to conduct

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controlled experiments in various situations (Carman et al., 2016; Goossens, 1988; Goossens & Offer, 1997; Leys & Raupach, 1991; Nickling & Gillies, 1993; Zingg, 1951). Empirical studies comparing different tunnel cross-sections have shown that a rectangular shape more effectively achieves air flow uniformity within the test section (Raupach & Leys, 1990). Maurer et al. (2006) enhanced this concept by creating a portable wind tunnel with a rectangular shape, thereby improving the accuracy of wind tunnel simulations. Wind tunnels are crucial in preparing airflow for wind erosion experiments by including devices such as screens, honeycombs and spires to ensure flow homogeneity, reduce turbulence and improve boundary layer depth (Erci et al., 2021).

Recent technological developments in wind tunnels have facilitated more precise assessment of sand erosion and deposition processes. Scaling laws in small-scale wind tunnel simulations were emphasized by demonstrating the influence of the Froude number on particle transport in aeolian processes (James, 2020). Wind tunnel experiments have been widely used to investigate different elements of aeolian processes in various environments (Mina et al., 2022; Rezaei et al., 2022). The studies have provided valuable information on the average speed of fluid flow behind porous barriers, the impact of moisture on the movement of sediment and the influence of vegetation on the patterns of wind-driven sediment movement (Dong et al., 2007; Han et al., 2011; Miri et al., 2019, 2021).

Moreover, wind tunnel experiments have tackled important issues in the study of wind-driven erosion, such as limitations on the movement of sand particles (Owen & Gillette, 1985), uncertainties in measuring the amount of sand transported by wind (Poortinga et al., 2014) and evaluations of the effectiveness of erosion control methods (Marzen et al., 2016; Wang et al., 2019; Yu et al., 2020). Additionally, the use of wind tunnel models has been essential in investigating the prevalence of dust deposition in desert conditions (Goossens & Offer, 1997; McKenna Neuman and Bédard 2015).

The development of the new wind tunnel was motivated by the growing need for controlled experimental facilities capable of reproducing near-surface airflow and sediment transport processes

under realistic conditions. In many regions, including areas actively studying wind erosion, research has mainly relied on field measurements and numerical modeling, while experimental simulation capacities have remained limited (Farrell et al., 2024). The present tunnel bridges this methodological gap by enabling reproducible experiments that link field observations and model validation (Rezaei et al., 2022; Zhao et al., 2022).

Globally, such controlled wind tunnel systems play an essential role in advancing the understanding of aeolian processes and refining erosion prediction models under changing climatic conditions (Ma et al., 2021; Zucca et al., 2022). The new facility introduces a flexible, digitally controlled design optimized for surface-layer flow characterization and soil–wind interactions, integrating high-precision airflow regulation and visual monitoring similar to those adopted in modern boundary layer facilities.

Despite significant progress, optimizing and validating wind tunnels for various soil and environmental conditions remains an ongoing challenge. The present study addresses this gap by designing and characterizing a new wind tunnel, focusing on a detailed assessment of wind flow characteristics at different velocities and locations within the tunnel. This research was funded by the Scientific Research Projects Department of Erciyes University (Grant number FBA-11-3628) and was conducted to determine wind flow characteristics of a newly designed wind tunnel to be used in wind erosion studies at three different wind velocities and different distances from the test section of the tunnel. Present outcomes will be used to improve the wind tunnel further and as reference materials for the other theoretical studies to be carried out in wind tunnels.

2. Material and Method

2.1. Materials

The wind tunnel used in this study has been designed and built to study wind erosion dynamics and flow of sediment flux. There are some important things to be mentioned about this new tunnel. It extended beyond 5.0 m long in the longitudinal

direction and included benches that protruded 0.9 m from the floor area, enabling experimental arrangements and instrument layout. The inlet size of the rectangular tunnel was 0.8×0.9 m, and the bed slope was set to 1%, which is typical for wind tunnel experiments. One side of the tunnel was made of transparent plastic reinforced with aluminum composite profiles so that it would be possible to monitor the experiment visually and assess the air flow in an obvious manner (Fig. 1). To minimize friction within the tunnel and ensure smooth airflow, special attention was given to reducing frictional effects, as recommended by previous studies (Tominaga et al., 2018). A protective screen measuring 25×25 mm was also added at the tunnel entrance to ensure a uniform wind profile and to prevent possible accidents, a safety measure in line with standard wind tunnel procedures (Dong et al., 2007).

A high-performance axial fan was used to simulate wind erosion conditions in the wind tunnel. An axial fan with an 11.20 m diameter was used due to its high efficiency and ability to produce large volumes of air flow. The axial fan generates air flow rates of $60,000 \text{ m}^3/\text{h}$ at pressures from 20 to 200 Pa, which supplies the necessary air velocity to replicate wind erosion processes effectively. A 7.5-KW-powered fan, running at 950 rpm, provided uninterrupted and easily controlled airflow across 90% of the experimental runs, ensuring that results could be

reproduced reliably. Accurate control of flow speed inside the system was necessary for the accurate performance of experiments and for creating appropriate erosion conditions. This was enabled with the help of the most modern digital speed control panel. This panel enabled the researchers to precisely control the speed of the axial fan so wind velocities could be customized to parameters necessary for the individual tests. By manipulating wind velocity, the researchers could simulate everything from gentle erosive winds to more forceful gusts, understanding how eolian (wind-driven) erosion works under different wind velocities. The reference velocities of 5, 7, and 9 m s^{-1} correspond to moderate to strong winds typically observed in semi-arid regions of Central Anatolia during erosive events. The digital control system ensured stable velocity output with $\pm 0.05 \text{ m/s}$ deviation, enabling realistic and repeatable wind simulation. By maintaining subcritical flow ($Fr < 10$) and fully turbulent conditions, the tunnel reproduced near-surface aerodynamic behavior representative of natural wind erosion events.

Recent advances in wind tunnel technology have enhanced the precision and flexibility of aeolian research. In the present setup, the combination of an axial fan and digital speed control allowed accurate adjustment of airflow parameters and simulation of different wind velocities for evaluating sediment transport, erosion intensity, and surface morphology

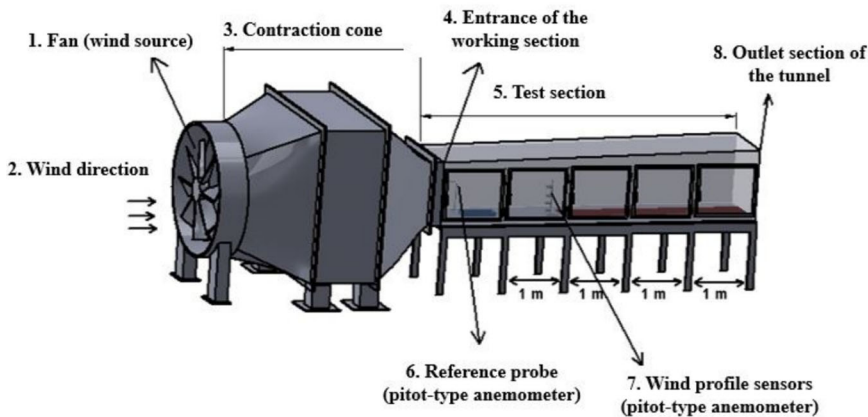


Figure 1
Tunnel test section and acceleration cone

(Giménez et al., 2019; Yan et al., 2022). Similar high-precision control systems have been implemented in modern boundary layer facilities such as the TJ-3 Wind Tunnel at Tongji University, which reproduces atmospheric wind fields with variable turbulence intensities (Gao et al., 2012; Huang et al., 2019). While the TJ-3 facility is primarily used for aerodynamic and structural testing, the present tunnel focuses on near-surface airflows relevant to soil erosion dynamics. These improvements reflect the ongoing trend toward integrating digital control and monitoring systems in wind erosion research (Mao et al., 2022; Rostami et al., 2025; Wang et al., 2023).

2.2. Methods

2.2.1 Tunnel Wind Flow Characteristics

The air flow condition of the wind tunnel was rigorously researched to simulate the natural wind flow. The wind speeds of 5, 7, and 9 m/s acted as the speeds of reference to analyze the wind profile and the velocity distribution in the tunnel. Two pitot-probe anemometers (Testo 0635 2145) were used to measure the logarithmic wind profile and another anemometer as reference to calibrate the wind velocity in the tunnel. Wind velocity, flow rate and temperature data were recorded at 1-s intervals and read in real-time to a computer interface to monitor wind velocities during the experiment (Fig. 2).

A reference pitot-type anemometer was placed at coordinates of $x = 0.56$ m, $y = 0.30$ m and $z = 0.41$ m at the tunnel entrance. All coordinate measurements were referenced to the tunnel inlet plane, where the origin ($x_o = 0$, $y_o = 0$, $z_o = 0$) corresponds to the central axis at the floor level of the test section. The differences between the measurements for the reference Pitot-type anemometer and the two additional probes were negligible and therefore omitted. Correction coefficients were applied to maintain consistency and minimize device-to-device variation. The function of these correction coefficients, shown in Fig. 3, validates the calibration of the anemometers and ensures that all recorded wind velocity data were standardized and comparable. This step was crucial for improving the

reliability and accuracy of the experimental results. The airflow was fully turbulent according to the calculated Reynolds numbers ($> 2 \times 10^5$). Temperature and pressure conditions inside the tunnel were recorded simultaneously using built-in sensors of the pitot-type anemometer system to ensure air density corrections. Boundary effects were minimized by using smooth aluminum-composite sidewalls and maintaining a slight 1% floor slope to promote uniform flow acceleration. The measured Reynolds numbers ($> 2 \times 10^5$) and subcritical Froude numbers ($Fr < 8$) confirmed dynamic similarity with natural aeolian flow regimes. The boundary layer thickness (0.10–0.24 m) observed along the test section indicates that the flow development was consistent with theoretical expectations for open-channel turbulent flow, validating the similarity scaling adopted in this design.

2.2.2 Spatial Wind Distribution Pattern

For the present wind tunnel, uniform flow distribution is necessary for optimizing its performance for wind erosion studies and flow analysis. The ultimate goal in present wind tunnel construction is the union of such intensive design considerations and engineering techniques. Geostatistical techniques were employed to investigate wind velocities' temporal and spatial distributions at 5, 7 and 9 m/s. In order to collect the wind data across the entire tunnel cross-section, pitot-type anemometers were placed at distances of h_1 (1.0 m), h_2 (2.0 m), h_3 (3.0 m), and h_4 (4.0 m) from the tunnel inlet, hereafter referred to as h_1 , h_2 , h_3 , and h_4 , respectively. A Pitot-type anemometer was used to evaluate wind distribution and flow characteristics at 176 separate points. Thereafter, variogram graphs were constructed using Eq. (1), allowing for all property spatial variability and uniformity in the wind flow distributions to be closely assessed:

$$\gamma^*(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \quad (1)$$

In the equation; $z(x_i)$ is the total dust flow measured and modeled at point x_i ; $N(h)$ is the number of sampling points at distance h (Webster & Oliver, 2007).

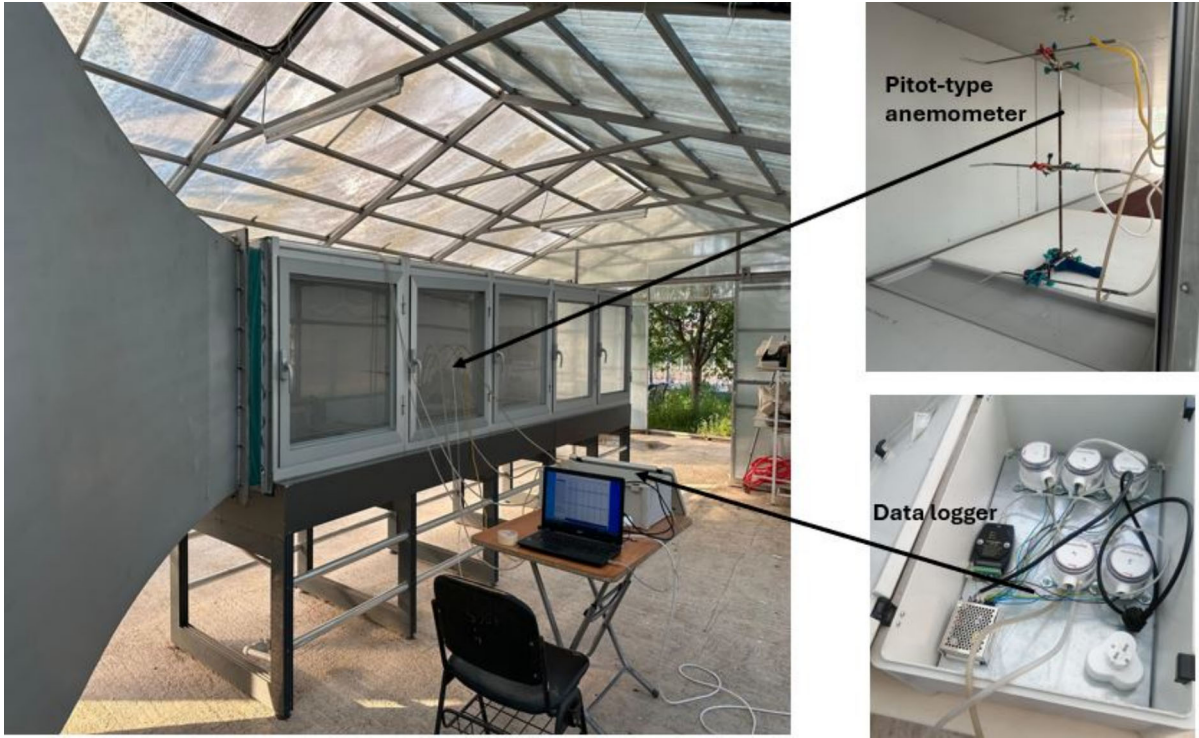


Figure 2
Wind tunnel measurement design

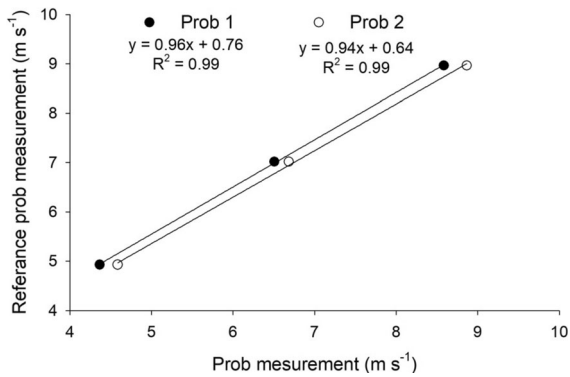


Figure 3
Correction factors for reference pitot-type anemometer measurements

The cross-validation method was used to identify the proper variogram model. Kriging maps were developed using models and parameters from the variograms to map out wind distributions throughout the tunnel. GS + 10 geostatistical software was used

for geostatistical analysis and was used for the comprehensive assessment of wind flow characteristics and spatial distribution.

2.2.3 Reynolds Number

The Reynolds number quantifies the relative significance of inertial forces to viscous forces, distinguishing between laminar and turbulent flow regimes Eq. (2);

$$Re = \frac{u * L}{\nu} \quad (2)$$

In the equation; Re : Reynolds number, u : flow rate (m/s), L : characteristic length = $\frac{1}{2} * (\text{tunnel width} + \text{tunnel height})$ (m), ν : kinematic viscosity (m²/s).

A Reynolds number exceeding approximately 2000 indicates turbulent flow conditions, essential for realistic wind erosion simulations.

2.2.4 Froude Numbers

The Froude number describes the balance between inertial and gravitational forces, providing insight into flow regime and sediment transport dynamics equation (3);

$$Fr = \frac{u^2}{g * H} \quad (3)$$

In the equation; Fr : Froude number, u : flow rate (m/s), H : tunnel height (m), g : gravitational acceleration (m/s^2).

Froude numbers below 10 are characteristic of subcritical flow, promoting stable and homogeneous wind profiles for experimental assessment. Both Re and Fr were calculated at all measurement points to ensure experimental conditions accurately replicated natural aeolian processes.

3. Results and Discussion

3.1. Descriptive Statistics for Wind Measurements

Table 1 presents average wind velocities ($\bar{U}$) for experimental wind velocities of 5, 7, and 9 m/s at 1.0, 2.0, 3.0 and 4.0 m away from the tunnel inlet. The average wind speeds clearly increased with increasing experimental wind speeds and decreasing distance from the tunnel inlet. The average wind velocities in the least wind speed (5 m/s) ranged from

2.31 m/s at the distance of 4.0 m to 4.43 m/s at the distance of 1.0 m. At maximum wind speed of 9 m/s, average velocities also span from 6.40 m/s at the center of the chamber to 8.39 m/s towards the chamber walls. This trend implies that the wind tunnel can deliver higher velocities closer to the inlet, as this point corresponds to where the flow loses the least energy. Since these values tell about the variability in the wind velocities for a given distance and wind velocity, the coefficients of variation can be used as good metrics. In these cases, the explanation could be found that the known higher CVs have appeared at the region compacted further from the tunnel inlet, suggesting that the wind velocities are becoming dispersed further away as the wind flow passes through the tunnel. Those fluctuations could have been due to obstacles-induced turbulence or boundary-layer effects along the tunnel walls. Based on the measured wind velocities and the specifications of the wind tunnel design, it can be established that the wind tunnel can generate controllable and uniform flows. Overall, the measured velocities are within reasonable agreement with the expected values calculated based on the tunnel design, ensuring that the desired flow characteristics are represented within the achieved velocities (Maniaci et al., 2016). These wind flow characteristics are important for understanding wind erosion processes (Ariyasena et al., 2024). By producing uniform and controllable wind speeds at variable distances,

Table 1

Descriptive statistics of wind measurements at different velocities and heights

Distance (m)	U (m/s)	Min U (m/s)	Max U (m/s)	Mean velocity (m/s)	SD	V	(CV) (%)	S	K
h_1	5	0.7	6.9	4.43	1.36	1.83	31	− 1.08	1.1
	7	0.8	8.9	6.46	1.24	1.54	19	− 1.3	3.89
	9	2.8	10.9	8.39	1.21	1.45	14	− 0.85	2.52
h_2	5	0.7	5.6	4.00	1.02	1.04	26	− 1.39	2.1
	7	0.8	7.4	5.96	0.93	0.85	16	− 2.18	8.53
	9	3.9	9.2	7.82	0.84	0.7	11	− 1.17	3.09
h_3	5	0.6	5.4	3.21	1.37	1.86	43	− 0.66	− 0.8
	7	0.6	7.1	5.30	1.21	1.46	23	− 1.48	2.57
	9	3.2	8.9	7.18	1.01	1.01	14	− 1.15	1.59
h_4	5	0.7	4.3	2.31	1.08	1.17	47	− 0.19	− 1.3
	7	0.8	5.9	4.48	1.16	1.34	25.87	− 1.68	2.46
	9	1.2	7.7	6.40	0.95	0.91	14.83	− 1.88	5.25

SD standard deviation, V variance, CV coefficient of variation, S skewness, K kurtosis; $h_1 = 1.0$ m, $h_2 = 2.0$ m, $h_3 = 3.0$ m, and $h_4 = 4.0$ m distances from the tunnel inlet

researchers have a more accurate method by which to study sediment transport, erosion rates, and deposition profiles (Strong et al., 2016). The uniformity or variability in wind velocities is critical for simulating real-world wind erosion situations in an accurate manner and for implementing successful erosion control techniques. However, there are limitations and uncertainties related to the measurements of wind velocity performed in the wind tunnel, despite the great attention that was paid to its measurements. Instrumentation accuracy, turbulence effects, and boundary layer interaction may introduce uncertainties in the results. Future research could lead to strategies to mitigate these limitations to increase the reliability of wind tunnel experiments for wind erosion studies.

The wind velocity data confirm that the newly designed wind tunnel effectively produces a digitally controlled airflow suitable for investigating wind erosion processes. This work enhances the understanding of spatial and temporal variations in airflow within the test section and provides valuable insights into the relationship between wind speed and airflow dynamics under controlled laboratory conditions. These findings establish a solid foundation for future studies on sediment transport, erosion rates, and mitigation strategies using this facility.

Table 2
Reynolds and Froude numbers for test conditions

Range	U (m/s)	Re	Fr
h_1	5	268,354	2.13
	7	391,363	4.52
	9	508,808	7.64
h_2	5	247,243	1.72
	7	368,321	3.81
	9	483,434	6.57
h_3	5	203,414	1.08
	7	335,875	2.95
	9	455,704	5.43
h_4	5	250,797	0.55
	7	292,183	2.07
	9	417,488	4.22

Re Reynolds number, Fr Froude number; $h_1 = 1.0$ m, $h_2 = 2.0$ m, $h_3 = 3.0$ m, and $h_4 = 4.0$ m, distances from the tunnel inlet;

3.2. Tunnel Wind Flow Characteristics

Table 2 summarizes the Reynolds (Re) and Froude (Fr) numbers computed for the reference wind velocities of 5, 7, and 9 m/s at different distances scaled from the tunnel inlet. Reynolds numbers were greater than 200,000 for all measurement points and wind velocities, showing that the flow in the wind tunnel was turbulent. It is worth noticing that this unsteady flow is in line with Bognold's (1973) results that Reynolds numbers greater than 1400 indicate turbulent flows.

Throughout the various distances and wind velocities, the Froude numbers calculated were always below 7.64, suggesting flow in subcritical behavior. Froude number ($Fr < 20$, Owen & Gillette, 1985; $Fr < 10$, White & Mounla, 1991) indicates the quality of airflow in wind tunnels. The Froude numbers recorded in the current study satisfy these criteria, indicating that the airflow in the wind tunnel allows for quality testing. Differences between the lowest and highest wind velocities were far more evident for the surfaces with roughness elements placed over the tunnel base. The presence of these roughness elements can significantly affect how the wind moves within the tunnel; hence, the turbulent behavior of the flow is retained. Gabriels et al. (1997) also noted similar observations and observed turbulent airflow in wind tunnel tests.

In comparison, the Reynolds number calculated against that of Fister et al. (2012) highlights similarities in the turbulent flow characteristics. The trend can be attributed to differences in the designs of the wind tunnels and experimental setups. However, it indicates of turbulence at the reported Reynolds numbers for each study, suggesting that the current wind tunnel design is robust. This phenomenon observed in the wind tunnel has significant implications for wind tunnel research, particularly when conducting aeolian process and erosion experiments. Through turbulent airflow, sediment particles become suspended and transported, allowing researchers to study sediment transport processes and erosion rates more accurately. Flow effects should be considered during testing for valid experimental results in a wind/water tunnel. Present Reynolds and Froude numbers confirmed the wind tunnel's ability to

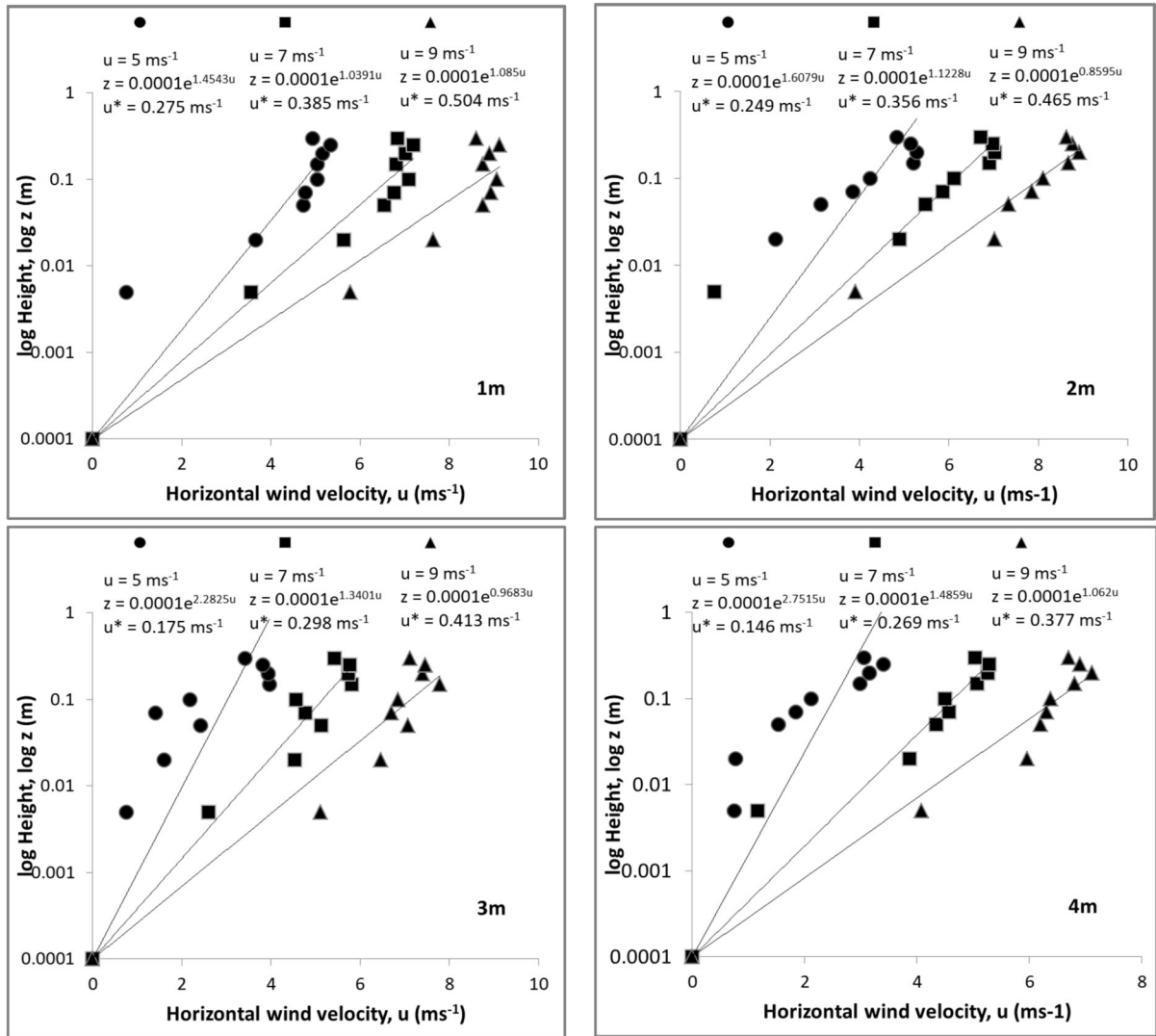


Figure 4

Logarithmic wind profiles generated at 5, 7 and 9 m/s wind velocities and h_1 , h_2 , h_3 and h_4 distances from the tunnel inlet

Table 3

Calculated shear velocities at different wind speeds and heights

U (m/s)	U* (m/s)			
	h_1	h_2	h_3	h_4
5	0.275	0.249	0.175	0.146
7	0.385	0.356	0.298	0.269
10	0.504	0.465	0.413	0.377

$h_1 = 1.0$ m, $h_2 = 2.0$ m, $h_3 = 3.0$ m, and $h_4 = 4.0$ m, distances from the tunnel inlet

produce actual field conditions for aeolian processes and erosional mechanics. Roughness elements influenced by wind profile and flow parameters were similar to those found in the literature, allowing wind tunnel validation as a research material for wind erosion (Ariyasena et al., 2024; Miri et al., 2019; Rezaei et al., 2022).

Figure 4 displays logarithmic profiles at wind speeds of 5, 7, and 9 m s⁻¹ and at 1.0, 2.0, 3.0, and 4.0 m from the tunnel inlet. The shear velocities (u) are listed in Table 3. To ensure that the roughness

at the base of the tunnel was kept at a minimum level, an aerodynamic roughness height of 0.0001 m was assumed according to the methodology of Erpul et al. (2004). Most notable was the reduction of u values with increased distance from the tunnel inlet caused by the stagnant pressure built up through the tunnel test section. For example, at distance of h_1 from the inlet with wind velocities of 5, 7 and 9 m/s, u^* values were 0.275, 0.385 and 0.504 m/s respectively. These values sharply decreased by around 40% at distance h_4 ; they were 0.146, 0.269, and 0.377 m/s for wind velocities of 5, 7 and 9 m/s respectively. In addition, at each measurement point, u^* values drastically increased as the wind velocities increased, as evidenced by the positive correlation between wind speed and shear velocity. This observation concurs with the work done by Gabriels et al. (1997), which reported the u^* value of 0.25 m/s for a closed-system wind tunnel at Gent University Eremology Center. The derived wind profiles in terms of logarithmic function and shear velocities from the wind tunnel experiments expose a real aerodynamic momentum transfer features within the wind tunnel. Overall, the shear velocity trends observed were simply affected by the wind speeds and the distance from the tunnel inlet, however, particularly about wind tunnel experiments to mimic aeolian processes and erosion dynamics.

The Boundary Layer Thickness (δ) is an important parameter when working with wind tunnels as it helps understand the dimensions of the boundary layer over a flat plate and its dependence on wind speed as well as distance from the wind tunnel inlet. The δ values measured at different wind speeds and

distances from the tunnel inlet are presented in Table 4. The δ values fell in a range of 0.10–0.24 for different boundary layer conditions measured in the tunnel. As anticipated, δ values were seen to increase in the post-jet section of the tunnel, according to the airflow direction. In addition, the δ increased with higher reference wind velocities, indicating a linear correlation between the reference wind speed and boundary layer thickness. In the special conditions of a wind tunnel, Gabriels et al. (1997) stipulated that $0.15 < \delta < 0.25$ m was appropriate for $V_{\text{ref}} = 6.4$ m/s. This range, albeit with some variability, is in line with the present δ parameters. Additionally, Maurer et al. (2006) reported a δ value of 0.45 m for a portable wind tunnel. In case of flow through wind tunnel, determination of boundary layer thickness helps to understand the flow behavior within wind tunnel and the flow behavior around an object in a flow field at different wind conditions. The trends observed in δ values reveal the necessity of considering the effects associated with the boundary layer in wind tunnel tests, as these can affect aerodynamic results and the reliability of simulation studies.

3.3. Geostatistical Analysis for Wind Measurements

The variogram models of different wind speed measurements are shown in Figs. 5, 6 and 7 and the variogram parameters are presented in Table 5. The measured points of h_3 and h_4 at wind velocity 5 m/s were modeled with an exponential model. Nugget effects varied according to wind velocity and distance. So, as the pitot-type anemometers were very sensitive, nugget effects may have originated from the high turbulence created within the tunnel and also cyclone type wind flow caused by the axial fans. Such a case showed that the filter system used to eliminate turbulence inside the tunnel was ineffective. The nugget effect was minimum at 9 and 5 m/s wind speeds at h_1 and h_4 distances with $C_o = 0.001$, whereas the nugget effect was maximum at 7 m/s at h_4 distance ($C_o = 0.8$).

Geostatistical analyses were applied to assess the spatial variability of the wind erosion measurements. The variogram models, in conjunction with variogram parameters (Table 5) further describe the complex behavior of the wind field in the tunnel.

Table 4

Boundary layer thickness at different wind velocities and heights

U (m/s)	The boundary layer thickness (δ)			
	h_1	h_2	h_3	h_4
5	0.10	0.15	0.20	0.22
7	0.10	0.17	0.20	0.23
9	0.10	0.20	0.22	0.24

$h_1 = 1.0$ m, $h_2 = 2.0$ m, $h_3 = 3.0$ m, and $h_4 = 4.0$ m, distances from the tunnel inlet

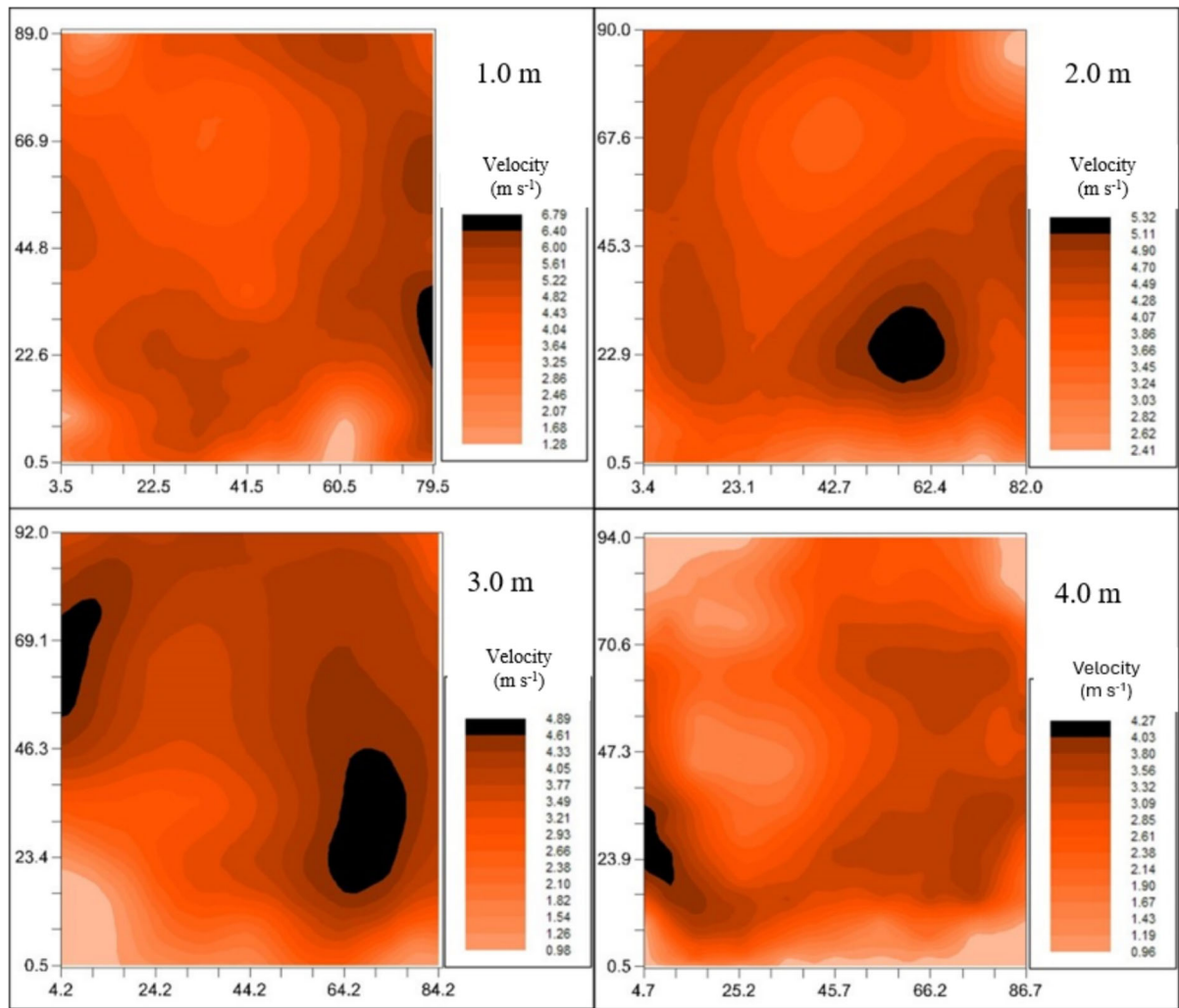


Figure 5

Spatial wind distribution pattern for 5 m/s reference wind velocity measured at four distances from the tunnel inlet (1.0–4.0 m, corresponding to h_1 – h_4)

This is particularly evident, for example, at a wind speed of 5 m/s where h_3 and h_4 show a distinctly opposing trend due to the heterogeneous nature of wind. The differences in nugget effects across wind velocities and distances suggested heterogeneous turbulence patterns within the environment of the tunnel. This effect was likely amplified due to the sensitivity of the pitot-type anemometer, combined with cyclone-type wind flow created by the axial fans. Importantly, the minimum nugget effect ($C_o = 0.001$) was observed for distances h_1 and h_4 at wind

speeds of 9 and 5 m/s, respectively while the maximum nugget effect ($C_o = 0.8$) was recorded at 7 m/s at distance h_4 . These findings offer important insights into the complex interaction between wind dynamics and the sensitivity of measurement points, helping with future improvement of experimental strategies within wind tunnels.

Variogram Parameters (Table 5) show differences in trends concerning spatial variability of wind erosion measurements due to wind velocity and measurement locations through test section.

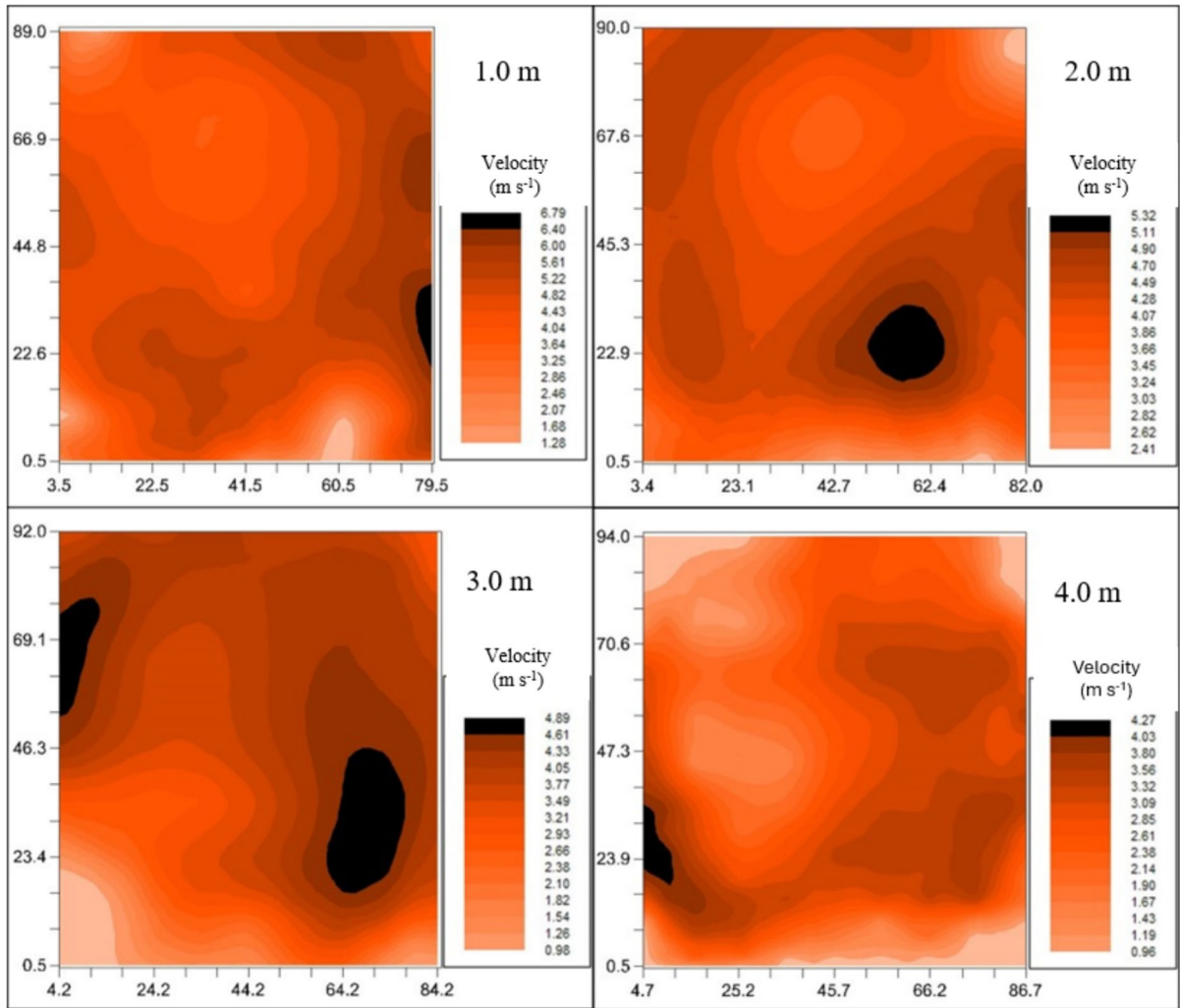


Figure 6

Spatial wind distribution pattern for 7 m/s reference wind velocity measured at four distances from the tunnel inlet (1.0–4.0 m, corresponding to h_1 – h_4)

At a wind velocity of 5 m/s:

- At 1.0 m distance, the nugget effect (C_o) was relatively low as 0.200, indicating a moderate level of spatial dependence in wind erosion measurements at this distance. The sill ($C_o + C$) value of 1.75 suggests that there is still substantial variability beyond the nugget effect.
- At 2.0 m distance, a similar pattern was observed with a slightly lower nugget effect of 0.005, indicating a stronger spatial dependence compared to the previous distance. The sill value remains

relatively high as 1.6, suggesting significant variability beyond the nugget effect.

- At 3.0 m distance, an exponential model was observed with a nugget effect of 0.099, indicating a relatively weak spatial dependence in wind erosion measurements at this distance. The sill value of 1.46 suggests that there is still considerable variability present beyond the nugget effect.
- At 4.0 m distance, the nugget effect increased substantially to 0.6, indicating a weaker spatial dependence compared to closer distances. The sill

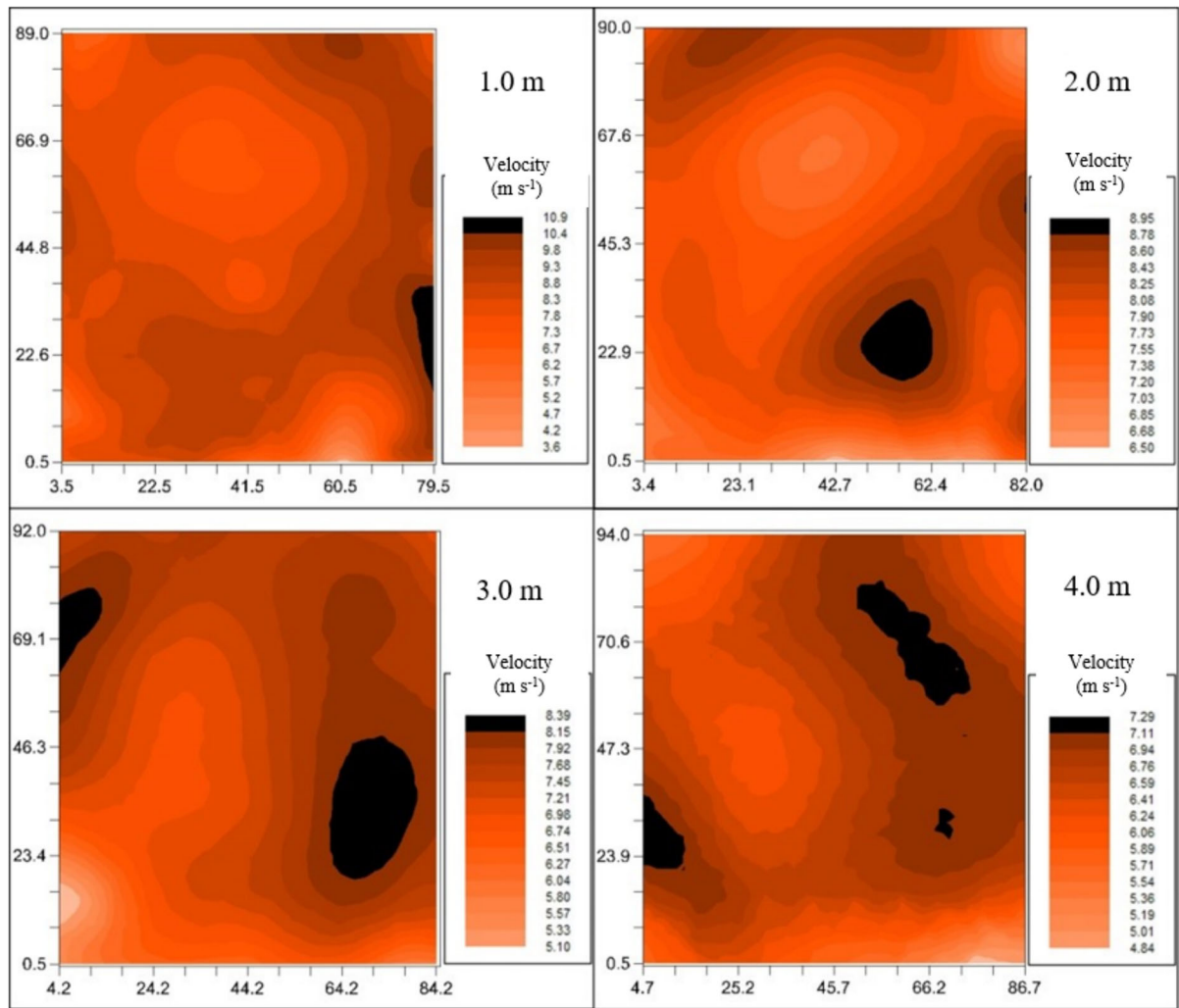


Figure 7

Spatial wind distribution pattern for 9 m/s reference wind velocity measured at four distances from the tunnel inlet (1.0–4.0 m, corresponding to h_1 – h_4)

value of 1.05 suggests that there is still considerable variability beyond the nugget effect.

At a wind velocity of 7 m/s:

- The patterns observed at different distances were generally consistent with those observed at 5 m/s, with variations in nugget effects and sill values reflecting changes in spatial dependence and variability.
- Notably, at 3.0 m distance, the nugget effect increased to 0.51, indicating a stronger spatial dependence compared to the same distance at 5 m/s.

s. The sill value also increased significantly to 3.04, suggesting greater variability beyond the nugget effect.

At a wind velocity of 9 m/s:

- Similar trends in nugget effects and sill values were observed compared to the previous wind velocities, with variations reflecting spatial dependence and variability changes.
- At 3.0 m distance, the nugget effect decreased to 0.36, indicating a weaker spatial dependence than the same distance at 7 m/s. However, the sill value

Table 5

Fitted variogram parameters

Distance (m)	U (m/s)	Model	Nugget effect (C_o)	Sill ($C_o + C$)	$C_o/C_o + C$ (%)	Range (m)
1.0	5	Spherical	0.200	1.75	11	0.24
	7	Spherical	0.005	1.6	0.3	0.24
	9	Spherical	0.001	1.5	0.06	0.24
2.0	5	Spherical	0.6	1.05	57	0.33
	7	Spherical	0.45	0.98	45	0.36
	9	Spherical	0.38	0.8	48	0.39
3.0	5	Exponential	0.099	1.46	7	2.10
	7	Spherical	0.51	3.04	16	2.00
	9	Spherical	0.36	2.15	16	2.10
4.0	5	Exponential	0.001	1.25	0.08	0.14
	7	Spherical	0.8	2.18	36	2.10
	9	Spherical	0.7	1.35	51	2.10

$h_1 = 1.0$ m, $h_2 = 2.0$ m, $h_3 = 3.0$ m, and $h_4 = 4.0$ m, distances from the tunnel inlet

remains relatively high at 2.15, suggesting significant variability beyond the nugget effect.

The results obtained from fitted models are important for explaining the spatial structure of wind erosion measurements taken from the wind tunnel's test section, which exhibit differing levels of spatial dependence and spatial variability across different wind velocities and measurement points. The implications of these results for future wind erosion experiments can guide the design and implementation of such experiments to yield more accurate and reliable information about the dynamics of wind erosion. By performing a variogram analysis, nugget effect and sill values were obtained. The distance at which variance is maximized represents the spatial correlation of wind velocities at some distances. The closest minimum distance-dependent likelihood distance was observed at h_4 measurement point with a wind velocity of 5 m/s and with a distance of 0.14 m. In contrast, maximum likelihood distance was found for almost all wind velocities for h_3 and h_4 points as 2.10 m. The maximum likelihood distances from different wind velocities and different measurement distances are estimates of how much wind velocities are spatially correlated. At all points along the tunnel for every wind velocity, these maximum likelihood distances were comparable, indicating that sediment samples collected at any point will likely yield accurate representations. Nonetheless, a maximum likelihood distance of 14 m was observed for a wind velocity of 5 m/s at 4 m away, which merits

attention. This underscores the necessity to consider spatial correlations in the wind velocities when interpreting sediment measurements, particularly at larger distances from the tunnel inlet. Additionally, the nugget effect to sill value ratio ($C_o/C_o + C$) offers further understanding of wind velocity dependency levels at various measurement locations. It was a medium level of dependence for the h_2 measurement point at all the wind velocities and a strong dependence for the other measurement points. These results demonstrate the nuanced relationship between wind velocities and spatial dependence in the tunnel environment and the need for incorporating this inter-relationship and developing better methods for wind erosion research and analysis.

3.3.1 Tunnel Inside Wind Velocity Distribution Pattern

Kriging maps, a type of geostatistical interpolation, were created to analyze wind distribution trends at three wind velocities (5, 7, and 9 m/s) and at a variable distance from the measurement layer (h_1 , h_2 , h_3 , and h_4). The maps, shown in Figs. 5, 6, and 7, provide a comprehensive view of the variation in wind speeds at different locations in the tunnel. A closer look at the Kriging maps for the reference wind velocities at h_1 indicates that there will be negligible differences in the pattern of wind velocities across the map. Notably, as the wind velocities increase, observable variations in the pattern of

distributions occur from inlet to the outlet of the tunnel. Although these differences would not affect measurements made with passive or active traps, the observed differences in wind profiles at different locations demonstrate the importance of placing measurement points strategically. More detailed analysis of the Kriging maps representing each reference wind velocity and measuring point indicates varying profiles of wind generation from open tunnel base and distribution. For approximating natural conditions in the tunnel, cubic roughness elements of size $7 \times 7 \times 7$ cm were installed in two rows within the test section. As evidenced from the Kriging maps, these elements easily establish a boundary layer in roughly 0.25 cm from the tunnel base.

4. Discussion

To interpret these findings, first, aerodynamic principles that govern experiments in a wind tunnel must be considered. The roughness elements, cubes, create a boundary layer through which air must pass, allowing the wind to simulate natural conditions in the tunnel. Tracking the air quality in a laboratory and contributing to relatively controlled experiments provides a solid foundation for ensuring the accuracy and reliability of experimental results by mimicking the real boundary layer of realistic scenarios.

Although this study focused on characterizing the airflow and turbulence regime of the new wind tunnel, the facility was designed to accommodate future measurements of sediment transport and deposition. The test section allows the installation of various sediment traps and surface trays to quantify saltation and suspension fluxes under controlled wind conditions. These measurement systems will be integrated in subsequent experiments to establish a complete mass-balance of erosion and deposition processes.

The newly designed wind tunnel demonstrated flow stability and turbulence characteristics comparable to those reported in other experimental facilities simulating boundary-layer wind fields (Dentoni et al., 2020; Rostami et al., 2025). Similar to the findings of Zhang et al. (2023), the spatial variation of wind speed along the test section highlights the importance

of flow conditioning and inlet design for reproducing realistic shear stress distributions. The results confirm that roughness elements can effectively initiate a boundary layer with predictable turbulence, supporting comparable conclusions to those drawn by Erci et al. (2021) under turbulent flow conditions. Unlike small-scale devices such as PI-SWERL used for emission potential studies (Leitão et al., 2025; Vos et al., 2021), the present tunnel provides a more comprehensive simulation of sediment transport, enabling control over both erosive and depositional dynamics. Minor deviations from other tunnels, such as the flow-sand two-phase studies of Zhao et al. (2025), may be attributed to differences in cross-sectional geometry and fan control systems. Overall, the results validate the tunnel's capability to replicate near-surface wind-soil interactions, thereby contributing to ongoing advancements in wind tunnel design and experimental aeolian research. To sum up, discussing wind distribution patterns in the wind tunnel gives an overview of the complex interaction of the wind velocities, the measurement distances and the boundary layer. This means that, through applying geostatistical techniques built on the foundation of aerodynamic principles, scientists can synthetically replicate natural wind conditions and extrapolate practical conclusions from wind tunnel experiments.

5. Conclusion

Through the successful design and characterization of a new wind tunnel for wind erosion research, this study has made it possible to accurately simulate and analyze aeolian processes in a controlled laboratory environment. The following are the paper's primary conclusions:

- (i) At all tested wind speeds, the tunnel continuously produced turbulent flow with Reynolds numbers above 200,000.
- (ii) Shear velocities (0.146–0.504 m/s) and boundary layer thickness measurements (0.10–0.24 m) agreed with theoretical predictions and values reported in the literature.

(iii) Kriging was used to map the spatial variability in wind velocity to facilitate optimal pitot-type anemometer placement and tunnel operation. A pitot-type anemometer and digital data logger were incorporated into the measurement system to ensure accurate and repeatable results.

In order to conduct thorough aeolian studies, future research should focus on incorporating more turbulence management devices, evaluating different surface roughness components, and using the tunnel on a broader variety of soil textures and sediment traps, including the future integration of honeycomb and screen flow conditioners to further improve air-flow uniformity within the test section.

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Data Availability

No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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