A Discussion of Mathematical Models Used to Simulate the Vertical Mass Flux Profile of the Mega-Dune

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Abstract. The research of the sand transport profile is significant for the calculation of sediment transport rates and the improvement of previous models. However, there are few suitable mathematical models to simulate the “stratification pattern” of the vertical mass flux profile in sandy lands. The present study measured the sand flux vertical distribution within 30cm height with 2cm division at the windward slope and the top of the mega dune in the hinterland of Badain Jaran Desert in winter and used the method of function fitting to analyze the flux density profiles above each observation site. The results show that: (1) The sand-drift activity at each site of the mega-dune is in the erosional state. (2) Low temperature and snow cover have little effect on the vertical mass flux profile. (3) The slope is the key factor to affect the vertical mass flux profile. It is significant in the middle and upper-middle of the windward slope, the sediment transport rate decreases exponentially with the increase of the height. At the top of the slope, the sediment transport rate increases at the beginning and then decreases with the increase of the height, which is an Extreme function distribution. The present study use suitable mathematical models to simulate the stratification pattern of the sand transport profile in sandy lands, explains the physical significance of each fitting coefficients in the function, discusses the effect of the slope on the vertical mass flux profile, and provides theoretical support for the practice of sand-control.

1. Introduction
The distribution of aeolian sand mass flux versus height is a considerable topic in the sand transport research[1], which is essential for the estimation of sediment transport rates and the improvement of previous models. It also has effects on the vertical profile of the wind velocities, the sediment transport rate, and the geographic process for soil corrision and dust storm formation[2]. Studying the vertical mass flux profile can provide theoretical guidance for the practice of sand control[3].

A lot of attempts have been made to the vertical distribution of the transported sand on sandy land. The research methods mainly include field observation[4], wind tunnel experiments[5] and numerical simulations[6]. Field observation is extremely important in the study of the vertical mass flux profile [7]. For the wind tunnel test, because of the scant length of the wind tunnel, the sediment transport rate has not reached saturation, making the calculation results of different wind tunnels lack comparability. The quantitative research of numerical simulations is mostly empirical, lacking a reasonable physical explanation, and its popularization and application are greatly restricted.

The field observation areas are mainly concentrated in the Tengger Desert[8], Kumtag Desert[9], Gurbantunggut Desert[10], etc. However, the predecessors did not observe the vertical mass flux profile in the hinterland of the Badain Jaran Desert. The observation time at other observation sites was mostly concentrated from April to May in the spring, while there were few observations conducted in winter. Through the fitting analysis of field observation data, the sediment transport rate decays exponentially with the increase of height, which is proved by most field observations [11]. Besides, affected by factors...
such as the nature of the underlying surface, it can also be expressed as the power function[12] and logarithmic function[11].

However, there is another mode of the mass flux distribution called "stratification model", the distribution of mass flux is divided into three layers: the sediment transport rate increases with the height of the lower layer, reaches the maximum in the middle layer, and decreases monotonously in the uppermost layer[13]. However, this study is only a simple representation of the sand transport profile and does not use a mathematical model to simulate it. Zhang et al.[14] conducted field observations on various underlying surfaces in northwestern China, and pointed out that the trend of sediment transport rate with height is related to the average particle size: above the surface with finer particle size, the sediment transport rate can be indicated as an exponential function; on the surface with coarse particles, the sediment transport rate with height can be indicated as a Gaussian function, and the height of the inflection point at which the sediment transport rate reaches the maximum is also related to the average particle size. Han et al.[15] observed the vertical mass flux profile within the height of 0-100cm in the barchan dune and pointed out that the vertical mass flux profile in each site of the barchan dune was affected by the surrounding microtopography. At the bottom of the windward slope, the "stratification pattern" appeared, but no fitting was performed. Sun et al.[16] pointed out that the particle velocity and lift-off angle vary with the slope, and the slope of dunes greatly affects the transportation of sand particles. Liu et al. [17] pointed out that the amount of sediment at the brink of barchans driven by the reverse winds increases first and then begins to decrease monotonously, which is a double Gaussian function, but the function form is more complicated, and the physical significance of the fitting coefficients need to be studied further.

Because of the researches mentioned above, the present study chooses the hinterland of the Badain Jaran Desert as the experimental area and conducts observations in late December. Under the field observation results, the exponential function and the Extreme function are used for fitting, which is efficient and concise. Compared with previous studies[13-15], this research achieves a quantitative description of the stratification model, the physical significance of the coefficients in the function and the influence of the slope on the vertical mass flux profile are discussed. These results can provide a reference for the theory and practice of aeolian research, especially in the fields of sand control and desertification control, for example, the height of sand control facilities is determined according to the flux density profiles simulated by this model.

2. Materials and Methods

2.1 Study Area

The Badain Jaran Desert is located in Alxa Right Banner, Alxa League, Inner Mongolia Autonomous Region, 39°30′~42°N, 100°~103°E. With an area of 49,200 square kilometers, it is the second-largest mobile desert in China. The mega dunes of the Badain Jaran Desert are widely spread with an average height of 200-300 meters, and the highest can reach over 400 meters. The lakes in the desert are widely distributed, with more than 100 lakes of varying sizes. The Badain Jaran Desert is on the path of sandstorms in China, providing a rich source of sand for aeolian processes which have a huge impact on the social economy and people's lives in the downstream areas.

The study area is located in the hinterland of the Badain Jaran Desert (Figure 1). The observation site is located in the mega-dune on the east side of Shuanghaizi. The lowest elevation of the bottom of the mega-dune is 1198m, the highest elevation of the top of the mega-dune is 1496m, the altitude difference is 298m, and the top of the mega-dune is about 1600m from Shuanghaizi. The slope of the windward slope gradually increases from the bottom to the top of the slope. The slope is about 5°~7° at the bottom of the windward slope, 9°~11° at the middle of the windward slope, and 15°~17° at the top of the slope, and varies greatly under different microtopography. Three observation sites are set up at the middle, upper-middle, and top of the windward slope of the mega-dune to observe the aeolian sand flux. Observation site 1 is located in the middle of the windward slope, with geographic coordinates of 102°20′20.92″E, 39°43′49.98″N. Observation site 2 is located in the upper-middle of the windward slope, with geographic coordinates of 102°20′22.36″E, 39°43′27.40″N. Observation site 3 is located at the top
of the slope, with geographic coordinates of 102°20′45.05″E, 39°43′29.88″N. The slopes of the observation sites are quite different. The slopes of observation site 1 and observation site 2 are relatively small, and the terrain is relatively gentle; the slope of observation site 3 is relatively large, and the terrain is undulating. Observation site 1 was covered with snow during the measurement, while observation site 2 and observation site 3 were not covered by snow. These 3 observation sites can show the similarities and differences of the sand transport profile at different sites and slopes of the mega-dune.

**Figure 1.** Schematic map of the studied area and observation site.

### 2.2 Research Methods

The observation time is December 2019. To facilitate the study of the variation of sediment transport rate with height, windy days are selected for observation, and the sediment transport rate at three observation sites within a height range of 0–30 cm is collected and measured. The WITSEG sampler is selected as the instrument for measuring the blown sand flux, which was developed and improved based on the Bagnold sampler by the Northwest Institute of Eco-Environment and Resources [18]. The sampler is mainly composed of four main components: a wedge-shaped leading edge, a removable side cover, a support, and 15 sand chambers. The sampler is 450mm high, 170mm wide and 33mm thick. There are 15 nozzle orifices in general connecting to 15 sand chambers. Each orifice is an area of 200mm², 20mm high and 10mm wide. The leading edge and a sidecover are removable for easy disassembly after measurement. After testing, the sampling efficiency of the sand sampler reaches 91%[18], and it is a reliable tool for the study of vertical mass flux profile. During the experiment, the sampler was flush with the ground and the direction of the sampler was parallel to the main wind direction. The collected sand particles are weighed with FA1204 electronic analytical balance, with an accuracy of 0.0001g and a linear error within ±0.0005g. The wind speed is measured by the DEM6 hand-held anemometer, and
the height above the ground is maintained at 1.5m during measurement, the wind direction is read according to the pointer of the wind direction sensor, and the displayed wind speed parameter is adjusted to the "average wind speed" file. Two sets of WITTSRG sampler are set up at each observation site, and the measurement time is 30 minutes. The amount of transporting sand is the average value measured by two sets of sand sampler. The wind speed is recorded every 1 minute, 30 times in general. After the measurement, the wind speed is the average of 30 times. Samples were taken at each observation site, and the samples were tested for particle size using the Malvern Mastersizer2000 Laser Particle Size Analyzer.

Use the following formula to calculate the sediment transport rate $Q$:

$$Q = \frac{W}{L \Delta T}$$  \hspace{1cm} (1)$$

where $Q$ is sediment transport rate (g·cm^-1·h^-1), $W$ is the amount of transporting sand (g), $L$ is the width of the sand inlet (cm), and $\Delta T$ is time (h).

Use the following formula to calculate the index of the sand stream $S$ to judge the directionality of the wind erosion process[19].

$$S = \frac{Q_{\text{max}}}{\bar{Q}}$$  \hspace{1cm} (2)$$

where $Q_{\text{max}}$ is the amount of transporting sand at 0–1 cm height (g) and $\bar{Q}$ is the average amount of transporting sand at 0-10cm height (g).

Under the sandy lands, the threshold of $S$ is 3.8. When the value of $S$ is greater than the threshold, it indicates that the wind-blown sand activity is in the deposition process, otherwise in the erosion process.

Use the following formula to calculate the characteristic values of the sand flux profile $\lambda$ to express the structural characteristics of sand flow[20].

$$\lambda = \frac{Q_{0-10}}{Q_{0-1}}$$  \hspace{1cm} (3)$$

where $Q_{0-1}$ is the amount of transporting sand at 0–1 cm height (g·min^-1), $Q_{2-10}$ is the amount of transporting sand at 2-10cm height (g·min^-1).

When the $\lambda$ value is close to 1, it means that there is no erosion or deposition; when $\lambda <1$, it indicates that the deposition is dominant; when $\lambda >1$, it indicates that erosion is prone to occur.

Use OriginPro9.0 to fit and analyze the trend between the sand transport rate and the height at the observation site, and draw the graph.

3. Results and Analysis

The fitting effect between the sediment transport rate $Q$ at different heights and the height $h$ of the three observation sites is good (Table 1 and Figure 2). The image of the sand transport rate $Q$ at different heights and the height $h$ at the three observation sites are shown in Figure 2.
Table 1. Coupling relation between sediment transport rate and height and the measured values of parameters at three observation sites.

| Observation site | Average wind velocity | Wind direction | Equation | $R^2$ | $S$ | $\lambda$ |
|------------------|-----------------------|----------------|----------|-------|-----|--------|
| 1                | $6.64 \text{ m} \cdot \text{s}^{-1}$ | N              | $Q = 3.967 e^{-0.2558h}$ | 0.975 | 8   | 2.13   |
|                  |                       |                | $Q = 3.175h$ | 0.860 | 6   | 2.67   |
| 2                | $6.28 \text{ m} \cdot \text{s}^{-1}$ | N              | $Q = 2.289e^{-0.173h}$ | 0.976 | 3   | 1.90   |
|                  |                       |                | $Q = 2.138h$ | 0.927 | 9   | 3.25   |
| 3                | $6.42 \text{ m} \cdot \text{s}^{-1}$ | N              | $Q = 0.275 + 2.477e^{-\left(e^{-\left(h-17.323\right)/2.655} - h-17.323\right)}$ | 0.965 | 1   | 1.14   |

Figure 2. Coupling relation between sediment transport rate and height.

Observation site 1 is located in the middle of the windward slope of mega-dune on the east side of Shuanghaizi, with a small slope. The amount of transporting sand within $0 \sim 2\text{ cm}$ and $0 \sim 10\text{ cm}$ respectively accounted for 38.2% and 89.5% of the general sand transport amount within the height of $0 \sim 30\text{ cm}$. The sediment transport rate shows a downward trend as the height increases. In the range of $0-10\text{ cm}$, the sand transport rate decreases rapidly with the height, while in the range of $10-30\text{ cm}$, the changing trend of the sediment transport rate with the height is relatively gentle. By fitting the sediment transport rate and height, it is found that the exponential function has the best fitting effect, and the function expression is:

$$Q=a e^{bh}$$

where $a$ and $b$ are fitting coefficients. The coefficient $a$ is a function of the transmission rate, and it increases with the increase of the transmission rate; the coefficient $b$ represents the relative attenuation rate of the flux density, and the larger the $b$, the slower the attenuation of the flux density with height[7]. Besides, the fitting effect of the power function is slightly worse than that of the exponential function, so the exponential function is used to describe the relationship between the sediment transport rate $Q$ of observation site 1 and the height $h$. The particle size of observation site 1 is comprised of very fine sand (0.28%), fine sand (43.77%), medium sand (51.32%), and coarse sand (4.63%). The average particle size ($M_z$) is $1.916 \Phi$.

Observation site 2 is located in the upper-middle of the windward slope, with small slope and relatively gentle terrain. The amount of transporting sand within $0 \sim 2\text{ cm}$ and $0 \sim 10\text{ cm}$ respectively accounted for 28% and 73.7% of general sand transport amount within the height range of $0 \sim 30\text{ cm}$, which is lower than that of observation site 1. By fitting the sand transport rate at different heights of observation site 2, it is concluded that the exponential function has the best fitting effect, followed by the power function, which is the same as observation site 1, therefore, an exponential function is used to describe the relationship between the sediment transport rate $Q$ and the height $h$ at observation site 2. The particle size of observation site 2 is comprised of very fine sand (1.42%), fine sand (39.37%), medium...
sand (49.51%), and coarse sand (9.7%). The average particle size \((M_z)\) is 2.019\(\Phi\).

Comparing the exponential function fitting formulas between observation site 1 and observation site 2, it is found that the value of coefficient \(a\) of observation site 1 is greater than that of observation site 2, while the value of coefficient \(b\) of observation site 1 is smaller than that of observation site 2. The numerical value indicates that the sediment transport rate in the middle of the windward slope of the mega-dune is larger than that in the upper-middle of the windward slope, and the sediment transport rate \(Q\) decreases faster with the increase of the height \(h\).

Observation site 3 is located at the top of mega-dune on the east side of Shuanghaizi, with a relatively large slope and obvious topography. The vertical mass flux profile is quite different from the observation site 1 and observation site 2. The sediment transport rate at different heights increases first and then decreases, and reaches the maximum at a certain height, which is a typical peak function. The amount of transporting sand within 0~2cm and 0~10cm only accounted for 2.1% and 9.1% of the general sand transport amount within the height range of 0~30cm; most of the amount of transporting sand concentrated within the height range of 12~26cm, accounted for 81.8% of the general sand transport amount; the amount of transporting sand reaches the maximum at the height of 16-20cm, accounting for 41.3% of the general sand transport amount; The sediment transport rate in the height range of 20~30cm is roughly the same as that in the height range of 12~14cm, and it is 3 to 4 times that of the height range of 0~12cm. In terms of changing trends, the amount of transporting sand in the 0-12cm height remains unchanged, and then increases rapidly within the height range of 12-18cm, and reaches the maximum at a height of 20cm. The sediment transport rate in the range of 20cm~30cm decreases with the increase of height, but its descending rate is slower than the rising rate of the height range of 12~18cm. Aiming at the situation where the sediment transport rate first increases and then decreases with the increase of height, a peak appears, and the two sides of the peak are asymmetrical, the Extreme function is used for fitting. The Extreme function is a special form of the Gumbe distribution, and the function expression is as follows:

\[
Q = y_0 + Ae^{-\left(\frac{h-x_c}{w}\right)^{-\frac{1}{w}}}
\]

where \(y_0, A, x_c\) and \(w\) are fitting coefficients.

In this extreme function, \(y_0\) is the initial value, representing the minimum value of the sediment transport rate within the height range of 0 to 30 cm; \(x_c\) is the center, representing the abscissa of the peak point; \(A\) is the amplitude, representing the ordinate of the peak point; \(w\) is the width of the peak. Through fitting, get \(R^2 = 0.9651\), and the fitting effect is good. Among the various coefficients, \(y_0 = 0.275\), the minimum sediment transport rate of each height from 0 to 30 cm is 0.185 g·cm\(^{-1}\)·h\(^{-1}\), which is approximately equal; \(x_c = 17.323\), the height of the inflection point at which the sediment transport rate reaches the maximum is at 16 cm to 20 cm, \(x_c\) is in this range; \(A = 2.477\), the maximum value of sediment transport rate \(Q\) is 2.701 g·cm\(^{-1}\)·h\(^{-1}\), which is approximately equal; \(w = 2.655\), which is approximately equal to the height range where the sediment transport rate \(Q\) is greater than 2.5 g·cm\(^{-1}\)·h\(^{-1}\). Each coefficient of the Extreme function has a certain physical meaning. The particle size of observation site 3 is comprised of very fine sand (0.62%), fine sand (41.25%), medium sand (50.41%), and coarse sand (7.72%). The average particle size \((M_z)\) is 1.968\(\Phi\).

The composition and the average particle size of sand particles at each observation site are similar. Moreover, the index of the sand stream \(S\) of the three observation sites are all less than 3.8, and the characteristic values \(\lambda\) are all greater than 1, indicating that the sand-drift activity at each location of the mega-dune at the three observation sites are mainly in erosion state, and the airflow still has a large carrying capacity. Comparing the index of the sand stream \(S\) and the characteristic values \(\lambda\) of the three observation sites, it can be seen that the index of the sand stream \(S\) decreases from observation.
site 1 to observation site 3, while the characteristic values $\lambda$ increase sequentially, indicating that the erosion of wind-sand flow gradually increases from the middle of the windward slope to the top.

4. Discussion
The "stratification pattern" is a reflection of the erosion state of wind-sand flow[9]. In this study, the characteristic values of the sand flux profile $\lambda$ of each location of the mega-dune are greater than 1, and the index of the sand stream $S$ is less than 3.8. The near-surface wind-sand erosion at the top of the slope reaches the strongest, and a "stratification pattern" appears, which reflects that the wind-sand flow at the windward slope and the top of the mega-dune are unsaturated.

The sand particles on the windward slope rise at a certain angle after reaching the top of the slope. The lift-off angle is related to the slope at the top of the slope. The greater the slope, the greater the lift-off angle of the sand particles, and the more sand particles will be blown up in the air at a certain height instead of being close to the ground, so that the sediment transport rate increases first and then decreases with height, and a peak occurs[13]. In the present study, the distance between each observation site is relatively short, and the particle composition and average particle size of the sand particles at each observation site are similar. Observation site 1 and observation site 2 are located at a position with a small slope, and the lift-off of sand particles is not obvious, the sediment transport rate is an exponential function of height. The slope of observation site 3 is relatively large, and it can be observed that the sand particles lift off, and the sediment transport rate increases first and then decreases with height, which is an Extreme function distribution. Therefore, when the mean particle size of the sand particles is approximately the same, the slope has a greater impact on the vertical mass flux profile. Besides, the slope has a significant impact on airflow direction, turbulence intensity and flow exuberance[20], which will interfere with the sand sampler, change the sand collection rate, and increase the error in the experiment process[20]. The desert in reality is composed of complex microtopography, and different microtopography has diverse effects on the vertical flux profile.

The field observation was conducted in late December, and the temperature was low in winter. The lower the temperature is, the greater the threshold wind velocity of sands is, and the sediment transport rate at low temperatures is lower than that at higher underlying surface temperatures. According to the observation results of observation site 1 and observation site 2, the trend between the sand transport rate and height has not changed. It can be inferred that the low temperature has little influence on the characteristics of the vertical mass flux profile where the slope is small.

During the observation, observation site 1 was covered with snow, and observation site 2 and observation site 3 were not covered by snow. The mechanical properties of sand particles and natural snow are quite different, which makes their characteristics different when they collide with the underlying surface. When the snow particles leave the underlying surface with the wind, drifting-snow is formed. During the formation of drifting-snow, the sublimation of snow particles will change the air humidity and temperature near the surface, which in turn will affect the sediment transport rate. The relationship between the sediment transport rate of observation site 1 and the height has not changed. Therefore, the snow cover has little influence on the characteristics of the vertical mass flux profile where the slope is small. However, the effect of snow cover on the features of wind-sand flow such as the general sand transport amount needs further study, which is the focus of subsequent research.

5. Conclusion
This study measured the sand flux vertical distribution within 30cm height with 2cm division at the windward slope and the top of mega dune in the hinterland of Badain Jaran Desert in winter, and used the method of function fitting to analyze the vertical mass flux profile at each observation site, and draw the following conclusions:

(1) The particle composition and the average particle size at different sites of the mega dune in the hinterland of the Badain Jaran Desert are similar. The index of the sand stream $S$ of the three observation sites are all less than 3.8, and the characteristic values $\lambda$ are all greater than 1, indicating that the sand-drift activity at each location of the mega-dune is mainly in erosion state.

(2) The sediment transport rate in the upper-middle and middle of the mega-dune is an exponential
function with height, and most of the amount of transporting sand is concentrated in the range of 0-10cm height, accounting for more than 70% of the general sand transport amount. In the range of 0～10cm, the sediment transport rate decreases rapidly with height, while in the range of 10～30cm, the changing trend of sediment transport rate with height is relatively gentle.

(3) At the top of the slope with a large slope, the sediment transport rate first increases and then decreases with the height. Most of the amount of transporting sand is concentrated in the range of 12～26cm height, accounting for 81.8% of the general sand transport amount; the amount of transporting sand reaches the maximum in the height range of 16-20cm, accounting for 41.3% of the general sand transport amount, which is an Extreme function distribution. By comparing the changing trend of sediment transport rate at different observation sites, it is shown that slope is a key factor affecting the vertical mass flux profile.

(4) Under the conditions of low temperature and snow-covered desert environment, the wind-sand flow in the middle of the windward slope is accompanied by drifting-snow, but the trend between the sand transport rate and height has not changed, indicating that low temperature and snow cover have little effect on the changing trend of sediment transport rate $Q$ with height where the slope is small.

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