WIND EROSION WITHIN A SIMPLE FIELD

J. E. Stout

ABSTRACT

Elementary analysis of the wind erosion process within a flat and uniform field is presented. A relationship is derived that describes the variation of the horizontal component of mass flux, f_x, downwind of a distinct field boundary. The derived functional relationship is then verified and completed through the use of field data. The generalized form of the equation contains two parameters, f_{mx} and b, that describe different aspects of the wind erosion process. The quantity f_{mx} is the maximum horizontal flux for a given height. The length scale b represents the distance at which f_x attains a value of 63.2% of f_{mx}. **KEYWORDS.** Wind erosion, Sediment transport, Windblown soil.

INTRODUCTION

Wind erosion is often limited to finite areas, such as bare agricultural fields, while the immediate surrounding surfaces remain stable. During strong winds, soil movement is initiated and generally increases with distance downwind of the dividing line between the stable and erodible surface. Chepil (1946) measured the increase in the mass flow rate of soil with distance downwind across an eroding surface. He found that the soil flow rate began with zero at the upwind edge of the eroding field, then approached different maximum values at different rates depending on the soil type and surface conditions.

The development of a theoretical description of field-scale variations of soil movement would provide valuable insight into the process of wind erosion. In the following pages an analysis is made of the horizontal variation of the flux of particles transported by wind across an eroding surface. Experimental evidence is then introduced to verify and complete the derived functional relationship.

THEORY

If the surface characteristics of an eroding field vary with distance in a very complex manner, then so will the mass transport rate. Consequently, the development of a simple analytical expression to describe the soil movement will be quite difficult. However, if consideration is limited to simple fields with flat and uniformly erodible surfaces then the problem becomes more amenable to analytical solution. Although this assumption might appear to greatly limit the application of the derived equation, it is actually quite common for agricultural fields to have fairly flat and uniform surfaces.

Imagine two level surfaces, S1 and S2, as shown in figure 1. Let the boundary between the two surfaces define the origin of our coordinate system and let a wind blow from S1 to S2. Both surfaces are assumed to have essentially the same aerodynamic roughness, so that the wind profile is not disturbed at the transition between the fields. The shear stress of the wind is assumed to exceed the threshold of S2 but not of S1.

CONSERVATION OF MASS EQUATION

The two-dimensional form of the conservation of mass equation may be expressed as:

$$\frac{\partial f_x}{\partial x} + \frac{\partial f_z}{\partial z} = 0 \qquad (1)$$

where

f_x = the horizontal component of mass flux,
f_z = the vertical component of mass flux.

Let $\xi = (-\partial f_z/\partial z)^{-1}$ and rewrite equation 1 as:

$$\xi \frac{\partial f_x}{\partial x} = 1 \qquad (2)$$

Taking the derivative of equation 2 with respect to x yields:

$$b \frac{\partial^2 f_x}{\partial x^2} + \frac{\partial f_x}{\partial x} = 0 \qquad (3)$$

where

$b = \xi / (\partial \xi / \partial x)$.

By rearranging equation 3, an equivalent expression for b

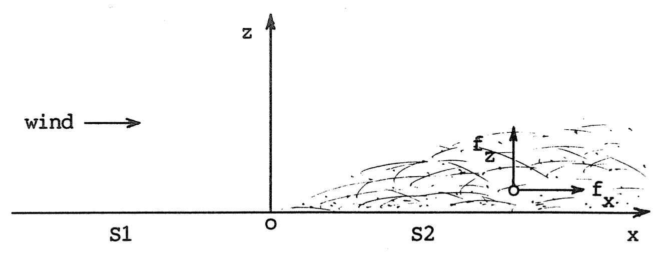

Figure 1–Definition sketch.

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The author is **J. E. Stout**, Wind Engineer, USDA-Agricultural Research Service, Big Spring, TX.

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may be expressed as:

$$b = -\frac{\partial f_x / \partial x}{\partial^2 f_x / \partial x^2} \qquad (4)$$

Stability of the Wind Erosion Process

To determine the spatial variation of b, we may invoke the concept of stability within the wind erosion system. Bagnold (1941) and Owen (1964) were the first to suggest that a self-balancing mechanism regulated the flow of windblown sand. More recently, this concept has been utilized in numerical models of saltation by Anderson and Haff (1988). The self-balancing concept suggests that the extraction of momentum from the surface wind by accelerating particles and the associated shear stress reduction are primarily responsible for limiting the growth of horizontal flux to a stable maximum value.

The concept of stability suggests a direct relationship between $\partial f_x/\partial x$ and $\partial^2 f_x/\partial x^2$. For example, if $\partial f_x/\partial x$ is positive, then this indicates an entrainment of additional particles into the flow. These additional particles extract additional momentum from the wind which reduces the ability of the wind to entrain more particles downwind. The reduction of entrainment leads to a negative $\partial^2 f_x/\partial x^2$.

Thus, the stability hypothesis suggests that the feedback from a non-zero $\partial f_x/\partial x$ results in a proportionally equal value of $\partial^2 f_x/\partial x^2$ but of opposite sign. If this assumption is correct, then the quantity b must always be positive and it should not vary horizontally.

Solution for b Varying Only with Height

Assuming b = b(z), equation 3 becomes:

$$\frac{\partial}{\partial x}\left(b \frac{\partial f_x}{\partial x} + f_x \right) = 0 \qquad (5)$$

or

$$b \frac{\partial f_x}{\partial x} + f_x = \text{constant} \qquad (6)$$

As $x \to \infty$ then f_x should approach the transport capacity, f_{mx}, associated with a given height and $\partial f_x/\partial x$ should reduce to zero. Therefore, the constant of integration is f_{mx} and equation 6 may be rewritten as:

$$b \frac{\partial f_x}{\partial x} + f_x - f_{mx} = 0 \qquad (7)$$

Another boundary condition involves the leading edge of the field. It has been assumed that the growth of flux begins at the field boundary, x = 0. This assumption limits the solution to the region of flow close to the surface.

With these boundary conditions, the solution of equation 7 is:

$$\frac{f_x}{f_{mx}} = 1 - e^{-x/b} \qquad (8)$$

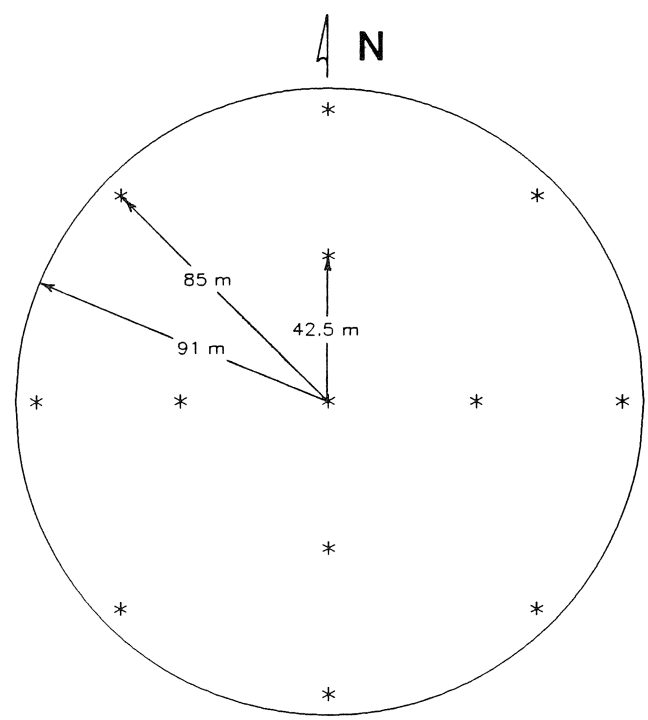

Figure 2–Arrangement of sampler clusters in the field.

Equation 8 describes the variation of the horizontal component of flux as a function of distance across an eroding surface. Both parameters, f_{mx} and b, may vary with height. The quantity f_{mx} is the maximum horizontal flux for a specific height. Note that the right side of equation 8 reduces to 0.632 when x = b. Therefore, b represents the distance at which f_x attains a value of 63.2% of f_{mx}.

Field Study

A field study was conducted within a flat bare circular field in Big Spring, Texas during March of 1988. The field set up is shown schematically in figure 2. Each star represents a cluster of three Fryrear (1986) type samplers such as that shown in figure 3. Each cluster measured flux at 0.15, 0.5, and 1.0 m height where the sampling height

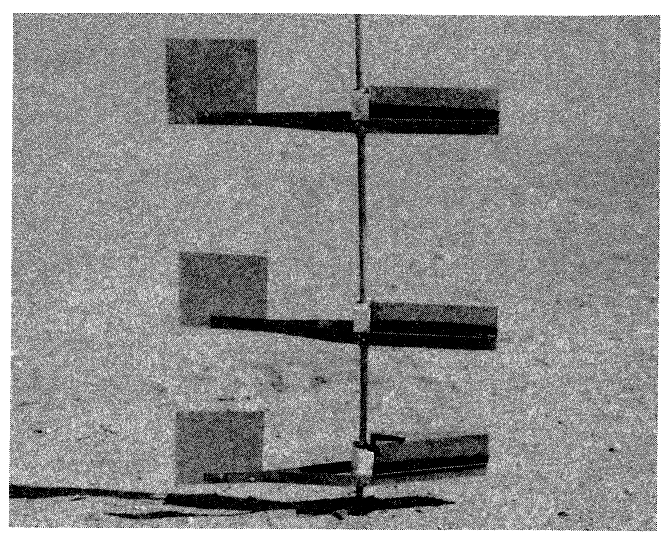
Figure 3–Cluster of samplers that measured the horizontal flux of windblown particles at heights of 0.15, 0.5, and 1.0 m.

was measured from the ground to the center of the inlet. The mass of material trapped by each sampler was divided by the sampler inlet area (50 mm tall by 20 mm wide) and the duration of the erosion event to determine the time average flux, f_x, at the given height of measurement. The duration of the erosion event was measured with a piezoelectric device, designed by Gillette and Stockton (1986). This instrument produced an electrical signal when it was hit by sand grains and thereby indicated when erosion was occurring.

Near the center of the field, the wind speed was measured by cup anemometers mounted at 0.3, 0.8, and 2.0 m above the ground. The boundary layer was found to follow a logarithmic wind profile with an aerodynamic roughness, z_o, of 0.0005 m.

Table 1 summarizes important information about the erosion events and Table 2 contains the full set of raw data.

Method of Data Analysis

A nonlinear regression routine that utilized the Gauss-Newton method was used to determine the parameters required to fit the data of Table 2 to equation 8 (SAS, 1985). For each height within each erosion event, a separate set of parameters, f_{mx} and b, were obtained. The results are shown in Table 3.

Some interesting patterns appeared in the calculated values of f_{mx} and b. As expected, f_{mx} decreased with height indicating that most of the movement occurred near the surface. The length scale b increased substantially with height. Therefore, flux nearer the surface reached a much larger value in a much shorter distance than flux at greater heights.

TABLE 1. Storm duration, wind direction, wind speed, and friction velocity for three erosion events in Big Spring, TX

Date	Storm duration	Wind dir	Wind speed @ 2 m	Friction velocity u_*
	h	deg	m/s	m/s
2 Mar 1988	3.9	340	9.37	0.46
7 Mar 1988	4.1	230	7.74	0.38
10 Mar 1988	5.9	225	8.37	0.41

TABLE 3. Parameters derived from nonlinear regression of field data

Date	Height	b	f_{mx}
	m	m	kg/(m^2-s)
2 Mar 1988	0.15	64.5	2.27 E-02
	0.50	103.5	1.77 E-03
	1.00	335.8	1.49 E-03
7 Mar 1988	0.15	31.1	9.88 E-03
	0.50	41.1	5.54 E-03
	1.00	56.9	2.44 E-04
10 Mar 1988	0.15	41.5	1.23 E-02
	0.50	63.8	7.30 E-04
	1.00	121.0	4.01 E-04

Comparison of Theoretical Equation to Field Data

The data of Table 2 were non-dimensionalized by the two parameters b and f_{mx} shown in Table 3. A plot of the scaled data is shown in figure 4. The flux data measured at different heights for all three data sets collapsed to a single dimensionless curve defined by equation 8.

Conclusions

Assuming the existence of a self-balancing mechanism that naturally controls the wind erosion process, an equation was derived that describes the variation of the horizontal component of flux with distance across a flat and uniformly erodible surface. Field experiments appear to confirm the results of the analysis.

The generalized form of the equation contains two parameters, f_{mx} and b. Horizontal flux measured at a fixed elevation was shown to grow with distance from zero to a maximum value, f_{mx}. The length scale b provided a measure of the growth rate of flux across the field. Small b values indicated rapid growth and large values indicated slow growth with distance. The length scale b, was shown to increase with height. Thus, the flux nearer the surface reached a larger value within a shorter distance than the flux at greater heights.

In the future a method for determining the quantities f_{mx} and b as a function of wind and surface conditions must be developed so that equation 8 may better predict the distribution of horizontal flux.

TABLE 2. Horizontal component of flux as a function of height, z, and distance from a nonerodible boundary, x, measured in Big Spring, TX, for 2, 7, and 10 March 1988

f_x in kg/(m^2–s) for 2 Mar 1988				f_x in kg/(m^2–s) for 7 Mar 1988				f_x in kg/(m^2–s) for 10 Mar 1988			
	Height, z				Height, z				Height, z		
x(m)	0.15 m	0.50 m	1.00 m	x(m)	0.15 m	0.50 m	1.00 m	x(m)	0.15 m	0.50 m	1.00 m
6	1.28E-3	0.60E-4	0.28E-4	6	1.48E-3	0.96E-4	0.32E-4	6	1.51E-3	1.17E-4	0.47E-4
7	1.03E-3	0.39E-4	0.23E-4	8	1.99E-3	1.09E-4	0.40E-4	8	1.59E-3	0.70E-4	0.24E-4
13	9.29E-3	3.33E-4	0.97E-4	9	3.85E-3	1.96E-4	0.79E-4	8	3.99E-3	2.01E-4	0.82E-4
15	5.08E-3	1.97E-4	0.40E-4	26	4.46E-3	3.10E-4	1.34E-4	33	4.11E-3	2.40E-4	0.92E-4
50	9.66E-3	5.42E-4	1.21E-4	41	7.81E-3	3.25E-4	1.25E-4	33	10.46E-3	3.36E-4	1.03E-4
67	9.81E-3	7.90E-4	2.63E-4	54	6.61E-3	3.86E-4	1.24E-4	56	6.92E-3	4.29E-4	1.31E-4
73	14.66E-3	7.90E-4	3.24E-4	58	9.75E-3	3.40E-4	1.25E-4	56	8.97E-3	3.77E-4	1.46E-4
84	12.16E-3	12.37E-4	4.29E-4	91	9.19E-3	5.40E-4	1.97E-4	91	9.76E-3	6.01E-4	2.26E-4
91	22.64E-3	10.60E-4	3.27E-4	112	9.87E-3	5.31E-4	2.06E-4	116	13.06E-3	6.05E-4	2.34E-4
96	25.92E-3	11.87E-4	3.69E-4	118	7.68E-3	4.83E-4	2.22E-4	116	13.57E-3	6.60E-4	2.53E-4
130	17.43E-3	11.24E-4	4.35E-4	119	12.61E-3	5.37E-4	2.07E-4	128	11.44E-3	6.13E-4	2.78E-4
161	20.75E-3	14.45E-4	5.46E-4	138	10.34E-3	4.62E-4	1.95E-4	128	12.77E-3	5.34E-4	2.30E-4
166	19.82E-3	13.81E-4	6.10E-4	175	8.33E-3	6.30E-4	2.66E-4	176	10.27E-3	7.33E-4	3.20E-4

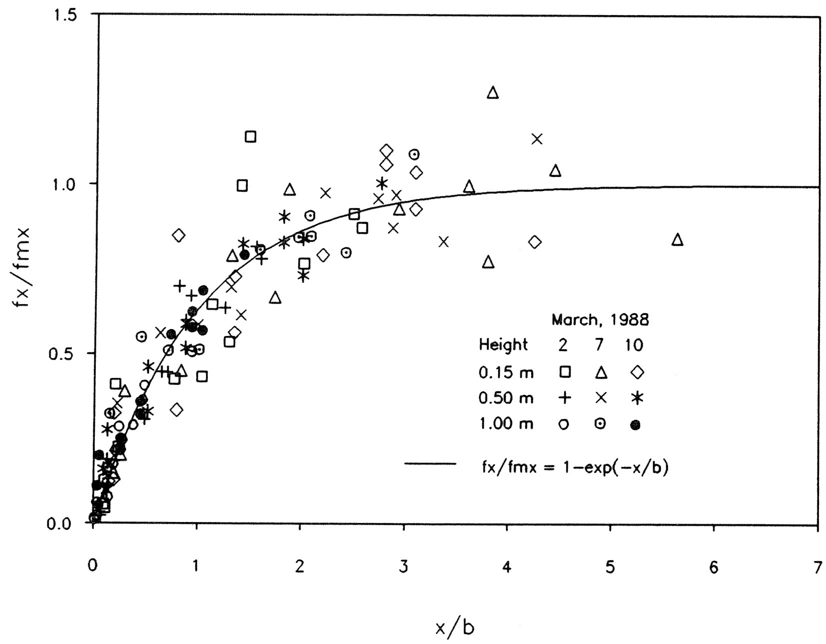

Figure 4–Horizontal distribution of normalized flux, $f_x/f_{mx} = 1 - e^{-x/b}$, compared to scaled field data measured at three heights during three separate wind erosion events in Big Spring, Texas.

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Symbols

b = characteristic horizontal length scale [L]

f_x = horizontal component of flux in the windward direction [$MT^{-1}L^{-2}$]

f_{mx} = maximum value of horizontal flux at a given height [$MT^{-1}L^{-2}$]

f_z = vertical component of flux [$MT^{-1}L^{-2}$]

u_* = friction or drag velocity [LT^{-1}]

x = horizontal coordinate [L]

z = vertical coordinate [L]

z_o = aerodynamic roughness [L]