88-2560

WIND EROSION: FIELD MEASUREMENT AND ANALYSIS

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ABSTRACT

Wind erosion researchers need field equipment and techniques for ascertaining threshold wind velocities and the amount and vertical distribution of the eroded soil particles. To detect moving soil particles and field erosion, sensors and soil samplers to measure surface creep and airborne particles have been developed. A power expression will describe the variation in amounts of suspended material to a 2-m height. The quantity of material (f) and height of material (y) within the saltation zone can be explained by the expression $f = fo(1-y/\sigma)^{\beta}$ where "fo" is surface creep, σ is height below which 50% of the total mass flow occurs in the saltation process, and β is the slope of the line. With this equipment and the analytical techniques described, the wind erosion process can be studied in the field, and the effectiveness of wind erosion control systems can be evaluated.

KEYWORDS. Soil, Wind erosion, Measurement, Sensors.

INTRODUCTION

The movement of soil particles by wind influences and limits man's utilization of agricultural regions of the world. In addition, wind erosion contributes significant quantities of soil material to the atmosphere.

Wind erosion and wind-transported loose soil material have affected mankind for centuries. The loss of eroded material degrades the source areas, deteriorates the atmosphere in the transport area, and impacts citizenry throughout the depositional area, even though the source and depositional areas may be thousands of miles apart. Research on wind erosion processes was initiated by Bagnold (1943) and Chepil and Milne (1939). Laboratory wind-tunnels were used to identify the basic physical processes in the transport of loose sand or soil material by wind. This research serves as the foundation for understanding wind erosion processes even today and culminated in the first erosion equation (WEQ) (Woodruff and Siddoway, 1965); however, field verification of their laboratory-derived relationships was not possible at the time because satisfactory field erosion measuring equipment was not available.

Rough estimates of the long-term trend of erosion can be obtained by using a grid of reference points (Gibbens et al., 1983) or observing depth of root exposure (Chepil, 1960). However, these observations provide little detailed information about wind erosion processes. Thus, to investigate processes, measurements encompassing a single storm are needed. Such field investigations generally require three groups of instrumentation—those for measuring the meteorological variables, those for measuring the soil flux, and those for measuring surface soil properties.

Soil surface properties include temporal properties, which control soil erodibility, and intrinsic properties, which combined with the climate and management, give rise to the temporal soil state. The temporal soil properties include the size distribution and mechanical stability of soil aggregates, the depth, coverage, stability, and loose saltation-size particles on the crust, surface roughness, and surface wetness. Initial work on measurement methodology for the temporal properties has been discussed by Zobeck (1988), Zobeck (1989), McKenna-Neuman and Nickling (1989), Boyd, Skidmore, and Thompson (1983), and Hagen, Skidmore, and Fryrear (1987). Measurement methodology for the intrinsic properties is reported by Klute (1986). Thus, measurement of soil properties will not be considered further in this report.

During wind erosion, soil is transported in various modes, and the transport mode for a particular size particle is controlled by windspeed. To understand the conditions responsible for soil erosion by wind, it is essential that good meteorological measurements be collected. Those traditionally collected in connection with this study will be listed under field instrumentation.

In the wind erosion process, eroded particles move in creep, saltation, or suspension. Creep particles roll along the ground and have a diameter of 1 to 2 mm. Saltating particles have a diameter of 0.1 to 1.0 mm, and depending on surface roughness, particle size, distribution, and wind speed, move in a series of short hops at heights generally below 1 m. The suspended particles range from <0.001 to 0.1 mm in diameter and are subject to long-range transport.

Because specific transport modes interact with the various erosion processes, field instruments must be designed to provide samples of eroding soil in the separate transport modes. The creep component of the soil flux can be sampled using an exposed horizontal slot or circular opening which leads to a buried container. If a slot is used, it must rotate, so it remains normal to the wind direction. The important consideration is to avoid surface perturberances which prevent the sampler from collecting a representative sample of the moving soil. A small fraction of saltation and suspension flux is also trapped by creep samplers, but this can be estimated by sieving the trapped sample.

Article was submitted for publication in August 1990; reviewed and approved for publication by the Soil and Water Div. of ASAE in November 1990. Presented as ASAE Paper No. 88-2560.

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The objectives of this article are to describe the newly developed field wind erosion measuring equipment needed to validate new models of vertical distribution and horizontal movement of eroded material, and to describe analytical procedures used in analyzing the results. These measurements are needed to test the processed-based technology that, when actual physical processes are quantified, will replace the empirically based WEQ (Hagen, 1988; Hagen, Zobeck, and Fryrear, 1989).0

FIELD INSTRUMENTATION

The vertical slot sampler designed by Bagnold (1943) was the first instrument for collecting eroded sand in the field, but it did not adjust to changes in wind direction. Bagnold's sampler was modified by Chepil (1957) to rotate, but the modified sampler was not well suited for highly erodible soils. Vented vertical samplers (Merva and Peterson, 1983; Fryberger et al., 1979) all rotated into the wind, but had a metal edge that moved over the soil surface. Fryrear (1986) recognized the problems of a metal edge sliding over the eroding soil surface and developed a sampler for collecting airborne material above the soil surface. The sampler is called a BSNE wind erosion sampler. The BSNE does not contact the soil surface and was the first of a family of wind-aspirated samplers to permit the accurate sampling of eroded material. The BSNE samplers provided the first extensive field data on the distribution of airborne material from a height of 0.05 m to a height of 6 m across eroding fields, but the BSNE does not measure surface creep or saltation flow below 0.05 m. The performance and efficiencies of the BSNE cannot be compared with previous samplers because sampling efficiencies were not reported. For the BSNE, the efficiency averaged over 89% for washed sand or sieved soil (sieved to remove all aggregates larger than 250 mm) and wind velocities of 10.4 to 15.7 m/s.

Stout (1989) developed a surface creep and saltation sampler for collecting eroded material from the soil surface to a height of 0.2 m. Stout's sampler is extremely accurate (98% efficient in wind tunnel tests), and the rotating portion does not contact the soil surface. The sampler is rugged and has successfully operated in extremely erodible soils, provided the sampler is lowered as the surrounding soil surface erodes. The combination of the BSNE and the Stout sampler permits the measurement of the eroding flux from the soil surface to a height of at least 6 m. For most studies; however, the BSNE samplers are located below a height of 1 m.

To provide more detail in the vertical distribution, Dr. Earl Vories reduced the height of the opening of the BSNE sampler from 50 mm to 10 mm. This permits sampling at a height of 40 mm above the soil surface, and at vertical intervals of 40 mm. Examples of data collected with the BSNE, Stout's, and Vories' samplers are listed in Tables 1 and 2.

Most wind erosion models require an accurate estimate of the threshold conditions within a field. With the piezoelectric quartz crystal sensor developed by Gillette and Stockton (1986), it is possible to determine the exact moment soil movement begins (threshold) by counting the number of particles being transported by wind. In addition to the number of particles, the kinetic energy of the particles being transported by the wind can be computed. This sensor, called SENSIT, also permits the research engineer to accurately determine the duration of wind eroding events, and when coupled with wind direction sensors, the direction of eroded material.

FIELD EQUIPMENT INSTALLATION

In the first field installation, the samplers were placed equidistant in three transects across a 7-ha rectangular field. As the wind direction changed, the horizontal distance sampled by the samplers also changed, making it

TABLE 1. Field sampler data for storm date 11 March 1988

		Flux at 4 heights							
Cluster	DPS	0.15	0.50	1.0	2.0	fo creep	Q_t	σ	β
	(m)	(kg/m^2)					(kg/m)	(m)	
A	33	158.4	5.67	1.82	0.56	5413	186	0.093	- 3.7
B	128	252.0	16.02	5.86	2.14	7547	260	0.062	- 2.8
C	176	337.9	17.42	7.56	3.08	9333	347	0.078	- 3.1
D	128	308.7	16.66	6.42	2.82	8747	328	0.075	- 3.0
E	33	180.1	8.53	2.91	0.89	5938	173	0.101	- 3.4
F	8	41.9	1.92	0.58	0.18	2080	58	0.059	- 3.1
G	6	4.51	0.30	0.16	0.08	420	8	0.026	- 2.4
H	8	10.19	0.56	0.23	0.12	753	17	0.038	- 2.7
I	81	188.4	9.15	2.64	0.37	633	212	0.076	- 3.2
J	134	290.6	15.27	5.51	2.37	8373	303	0.076	- 3.1
K	81	223.3	9.88	3.48	1.17	6927	253	0.084	- 3.3
L	49	77.0	4.25	0.99	0.31	3220	97	0.057	- 2.9
M	91	218.2	11.19	3.53	1.16	6813	240	0.074	- 3.1

* fo = 141.87 (x @ 0.15) $^{0.719}$.

† Q_t = mass flux at each cluster.

TABLE 2. Modified BSNE sampler located close to cluster "J" on 11 March 1988*

Height (mm)	Sample collected (kg/m^2)
53	1689
83	964
115	580
145	367
176	250
210	162
246	107
279	83
312	58
344	45

* Sampler collects aliquotes of airborne material.

difficult to compare erosion results for varying wind directions.

The second year, a circular pattern was utilized (fig. 1) (Fryrear et al., 1988). This permitted field erosion data collection regardless of the wind direction and provided a range of field lengths with a minimum number of sampler locations. If the soil surface is smooth, the meteorological instrument tower can be located anywhere on the downwind edge of the field to obtain wind profile information. If the soil is ridged, the tower should be located in the center of the field to insure that the wind will pass over the same surface conditions regardless of wind direction (excluding the 60° wind shadow when the tower is upwind of the velocity sensors). The anemometers and direction sensor outputs are used to evaluate wind shear stress. The remainder parameter outputs are used in the plant growth and hydrology models.

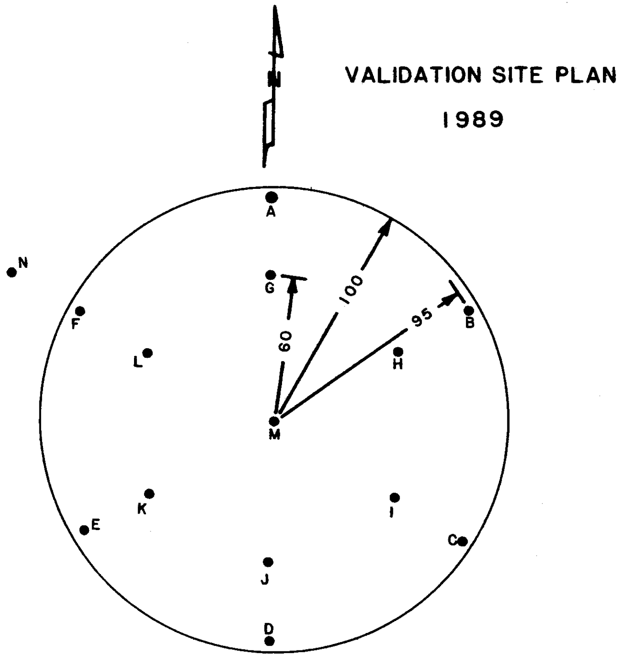

Figure 1–Plan of cluster locations for validation test sites in Scobey, MT; Sidney, NE; Akron, CO; Big Spring, TX; Crookston, MN; Elkhart, KS; and Crown Point, IN.

For a typical field with a well-defined noneroding boundary, the following equipment and instruments are used:

One Meteorological Tower Instrumented With Following:

4 × anemometers, 0.20, 0.50, 1.0, and 2.0 m
2 × air temperatures, 0.20 and 2.0 m
1 × solar radiation sensor
1 × soil temperature sensor, 0.02
1 × wind direction sensor, 2.5
1 × tipping bucket rain-gauge
1 × relative humidity sensor
1 × data logger with sufficient memory to sample all parameters every minute for two weeks

Erosion Samplers:

14 × clusters of erosion samplers with samplers at 0.05, 0.10, 0.20, 0.5, and 1.0 m above the soil surface (aerial locations illustrated in fig. 1)
1 × surface creep sampler (0 to 0.003 m height, 0.005 m wide opening) with a saltation sampler (0.003 to 0.2 m height by 0.005 m wide)
1 × weighing BSNE sampler at 0.20 m height
1 × SENSIT at 0.02 m height

This array and selection of samplers enables one technician to service a site.

To test the efficiency of multiple wind strips or shelterbelts, the erosion samplers should be located the same distance upwind from each wind strip. To test the efficiency of a single shelterbelt, several samplers can be located in a line transect downwind from the shelterbelt parallel with the wind. Each field will present unique installation problems, depending on the objectives of the research.

After every dust storm, all samplers should be emptied, the contents transferred to metal tins, and the field conditions recorded. Field conditions of interest include: aggregate size distribution of the surface soil; soil roughness, if the roughness has changed due to rainfall or erosion since the last measurement; the quantity and orientation of surface residues; the status of any growing vegetation; the presence of non-erodible clods or rocks; and if a crust is present, the percentage of the crusted soil that is covered with loose material.

DATA ANALYSIS

VERTICAL DISTRIBUTION

After the erosion samples have been dried and weighed, the vertical profiles can be determined using the sample weights and the heights of the samplers at each cluster. The equation or equations used to describe the vertical profile can be integrated to determine total mass moving past that cluster. A power expression of the mass data accurately described the suspended portion of the flow, but a plot of the residuals revealed that the power expression was not satisfactory for saltation and surface creep below about 0.3 m. Since the majority of eroded material moves below a height of 0.3 m, (fig. 2), it is important to accurately describe the concentration from the soil surface to a height of 0.3 m. Using empirical solutions, the distribution for one storm or one cluster may be described, but the same coefficients may not fit another cluster or the next storm.

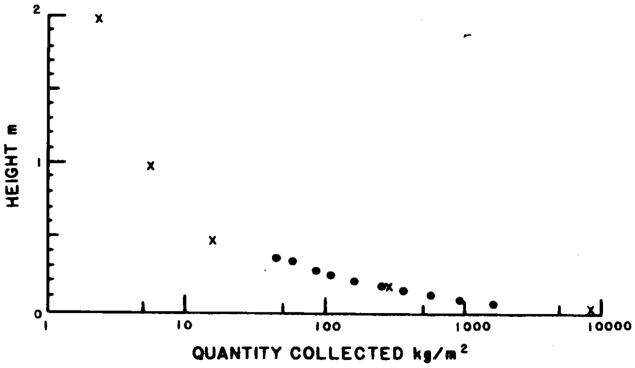

Figure 2–Vertical mass for cluster "J", 11 March 1988. Quantity collected is on log scale. Data From Modified BSNE "Vories" samplers are circles, the x are from cluster "J".

To accurately describe the vertical distribution, the physical process of material transport by wind must be understood. Stout (1990a) derived a theoretical expression for saltation flow:

$$f = fo\left(1+\frac{y}{\sigma}\right)^{\beta} \qquad (1)$$

where
f = Soil mass at height y, kg/m^2,
fo = Soil mass moving immediately above the soil surface at a height interval of 0 to 3 mm, kg/m^2,
y = Height above soil surface, m,
σ = Height below which 50% of total mass flow in saltation occurs, for $\beta = -2$, m,
β = Dimensionless power term describing slope of relationship in figure 2.

This expression corrects the problems of the mass in the power term approaching infinity at the soil surface. To solve equation 1, a surface creep sample is required. A computerized "Best Fit" program can be used to determine σ, β, and "fo" , but a small difference in "fo" can make a major difference in total soil mass.

Using equation 1, it is possible to quantify changes in soil mass due to changes in size distribution of eroded material or changes in composition of the material. The parameters in equation 1 change with changes in field surface conditions. For example, in the spring of 1988 non-eroding aggregates gradually broke down, and σ increased, indicating an increase in concentration of fine material. This same phenomenon was observed in 1984 (Fryrear, 1986). An increasing σ will also reflect an increase in concentration of material in suspension. The suspension component is subject to long distant transport and represents a loss of soil from the source area.

The movement of wind over the soil surface is an extremely complex process difficult to model and measure. It's not surprising that the field erosion data exhibits considerable variability. In Table 1, data collected from a dust storm on 11 March 1988 are listed and portions illustrated in figures 2 to 4. Since wind erosion is primarily a soil surface phenomenon, any small variations due to soil texture, surface roughness, soil crust, or elevation will change the mass of soil being transported by wind. Measuring this change in mass will verify or challenge previous erosion models or descriptions of the physical processes involved in describing wind erosion.

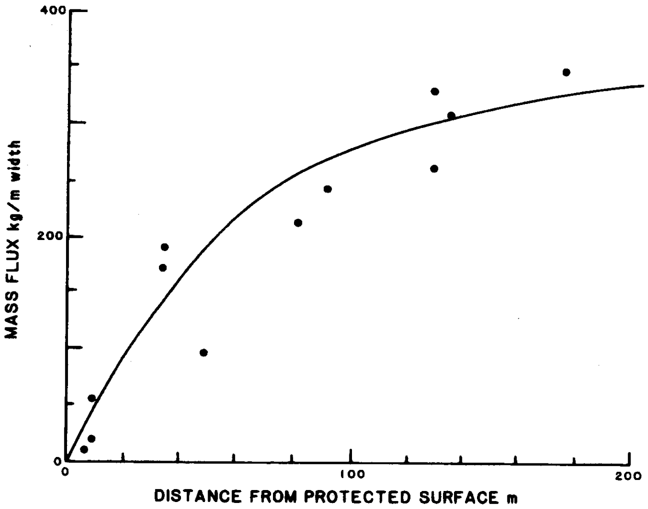

Figure 3–Total mass at various distances from a nonerodible surface for 11 March 1988, storm at Big Spring, TX.

For the storm on 11 March 1988, the field was smooth, and there was an abundance of saltation-size material present on the surface during the storm. Nevertheless, the parameters describing the saltation profiles, σ and β, varied over the field. A graph of a vertical profile of the cumulative horizontal flux from a cluster is illustrated in figure 2. Note that the bulk of the eroded soil is carried very close to the soil surface. For fields with gradients in surface condition, it may be desirable to add additional saltation/creep samplers to fully characterize the flux.

Integrating the profiles of erosion flux permits calculation of total flux past a point during a storm. By separating the various transport modes, one can use the data to infer the upwind behavior of the various erosion processes. For example, for a given saltation flux, the suspension component can vary by orders of magnitude (Gillette, Blifford, and Fenster, 1972). This reflects the ability of various soils to produce suspension-size material during erosion. However, the abrasion of surface

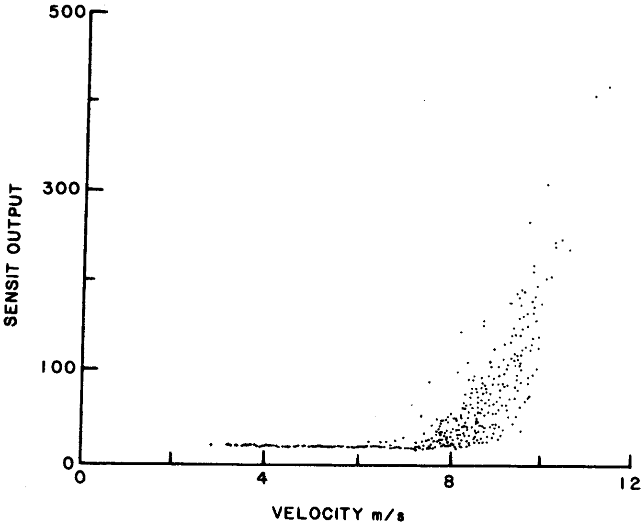

Figure 4–SENSIT output for a smooth, bare, fine, sandy-loam soil surface for various wind velocities on the 11 March 1988 storm.

aggregates and crust depends directly on the flux of saltation-size particles (Hagen, 1984b). Thus, proper division among the transport modes is essential to model abrasion. In some soils, because of the fragile nature of non-erodible material, suspension-size particles will result with little abrasive action from the moving material. Chepil (1945) described these soils as "non-abrasive".

HORIZONTAL DISTRIBUTION

Once the total mass moving in a vertical plane at each cluster location has been modeled, the horizontal distribution across an eroding surface can be determined. This data is needed to verify expressions of the erosion process, to plan wind erosion control systems, and for identifying depositional areas within the field.

As field length increases, the mass flux increases until the transport capacity of the wind has been reached. The rate that erosion increases across an erodible surface is also a function of the surface conditions and the texture of the soil (Chepil, 1959). Chepil developed empirical relationships that included the aggregate size distribution of the surface, but other parameters that influence mass movement such as crop residues or soil roughness are separate factors in the wind erosion equation. Stout (1990b) derived an expression for the change in total mass moving in saltation or surface creep for increasing distances across an eroding field downwind from a nonerodible surface:

$$Q = Qmx\left(1 - e^{\frac{-x}{B}}\right) \qquad (2)$$

where

Q = total mass at x, kg/m-width,
Qmx = Maximum mass transportable by this wind over this field surface, kg/m-width,
x = Distance downwind from nonerodible surface, m,
B or a = Expression of erodibility of soil surface, m.

In this equation, the erodibility term "B" is a combination of all the factors that modify the wind profile or the abrasive resistance of the surface. For an erodible surface downwind from wind barriers, or for nonerodible surfaces, the X/B term in equation 2 is replaced with $x^2/2a^2$. This will produce an S-shaped curve where erosion gradually increases as the wind profile adjusts to the erodible surface. If the mass flux is an integrated value from equation 1, then the erodibility "B" or "a" can be interpreted as an entrainment coefficient for loose saltation-size material which acts to satisfy the transport capacity of the wind (Stout, 1990b). If the mass flux includes the suspended material, the "B" or "a" value represents an equilibrium state between the total emission from the surface and the transport capacity of the fluid. A computerized "Best Fit" program can be used to determine Q max and B, or a. An alternate method would be to estimate Q max from an "eyeball" curve (fig. 3), then multiply Q max by 0.632 to determine Q at the point where x equals B. For the 11 March 1988 storm, the maximum mass flux is 374 kg/m-width and the "B" value is 81 m.

As additional data becomes available, it should be possible to adjust the horizontal mass predictions according to changing soil erodibility across an entire field. This may remove some of the variability in the horizontal mass results.

EROSION THRESHOLD

The SENSIT detects particle impacts, so the threshold windspeed velocity for a surface can be determined. The results show considerable scatter about the threshold level and indicate a few particles move well before general particle movement begins (fig. 4). This occurs because a few particles are perched in exposed positions and move at velocities that will be called the static threshold velocity. For descriptive purposes, the static threshold will be defined as the velocity required to initiate particle movement by wind. With the static threshold, the dislodged particle may move a few millimeters before moving behind a nonerodible particle or into a sheltered area. When the particle is trapped in protected zones, their movement may not continue until a higher level of shear stress is generated by an increase in wind velocity. Essentially, particle movement will stop until the velocity is increased. Bagnold (1943) suggested the wind speed at which sand movement starts, due to the direct pressure of the fluid only, be called fluid threshold. The definition is similar, but Bagnold was working with uniform-size sand in the wind tunnel, and the static threshold is for a much more complex surface where dislodged particles can easily move into protected areas. Bagnold (1943) defined the velocity at which sand movement is continuous along the downwind surface as impact threshold which is about 80% of the static value. Since static refers to bodies at rest and dynamics to bodies in motion, the threshold at which particle movement will be sustained will be called the dynamic threshold. At the dynamic threshold, particle movement never stops until all the erodible particles have been removed or the velocity decreases below the dynamic threshold. For soils that have been eroding, and then erosion stops, the static and dynamic thresholds may be nearly identical. The velocities in figure 4 vary considerably more than 80% between static and dynamic conditions. Part of the increased variability may be due to the more complex field surface than Bagnolds's wind tunnel, and part due to the natural wind conditions compared to laboratory wind tunnel conditions. For modeling purposes, it is essential that both static and dynamic thresholds be described for any surface. The process is very dynamic and in reality will involve many factors that describe the position and stability of each particle on the surface. This may be partially caused by the separation of the SENSIT and the anemometers, because the same wind gust cannot always affect both simultaneously or may reflect the variation due to micro changes in the soil erodibility.

CONCLUSIONS

Accurate, reliable, and rugged field wind erosion measuring equipment has been developed within the last five years. The measuring equipment can be used to determine eroded soil mass on 10-min time increments, the instant wind threshold conditions have been exceeded, the total mass eroded from a single storm event, and the total mass eroded for an entire year. Procedures for summarizing field data were developed and tested using actual data. An expression, $f = fo\ (1 + y/\sigma)^{\beta}$, describes the vertical distribution of material moving in saltation and surface creep. With this expression, the soil flux decreases as the height increases and produces a maximum flux at the soil surface. The vertical mass of suspended material can be modeled with a power expression. The model can be integrated between specific heights to compute total soil movement, and the total mass can then be determined by adding the saltation/creep and suspension flows. The horizontal distribution across eroding soil surfaces can be described with the formula $Q = Qmx(1 - e^{-x/B})$. Research is underway to describe the B coefficient from various soil and crop conditions.

A piezoelectric quartz sensor (SENSIT) that counts eroded particles profiles valuable information on the threshold velocities for a given field condition and the duration of a storm. Changing soil erodibility, crop residues, or surface roughness will influence both the static and dynamic threshold velocities. The SENSIT is the first field instrument capable of providing this essential information.

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