Analysis of Wind Data Used for Predicting Soil Erosion

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INTRODUCTION

Analysis of meteorological data is a critical component in calculating soil losses from a field during wind erosion events. Although wind direction, precipitation and temperature have an effect, the basic parameter used to calculate soil loss is wind speed. In the United States, wind speed data are generally available from US National Weather Service (NWS) stations located at regional airports. However, most agricultural lands do not lie in proximity to NWS stations and wind speed data must be collected in situ, extrapolated or modeled using a weather generator. In cases where NWS data are available and appropriate for use, reported wind speeds are given as hourly averages. Wind speeds collected in situ usually are averaged over a shorter time scale of 10 to 15 minutes.

Much work has been done in developing climate models that are derived from historical meteorological data bases (Skidmore, 1986; Skidmore & Tatarko, 1990; Wagner et al., 1992) or are generated using stochastic weather models (Wilks, 1992; Katz, 1996). Recent research on climate change has also suggested that as precipitation decreases, both temperature and wind speed increase (Holliday, 1987; Stetler & Gaylord, 1996). Therefore, it is possible to use predicted changes in surface temperature, generated from stochastic weather models, to calculate potential changes in wind speed. This wind speed data can then be implemented in one of several currently available wind erosion models to calculate estimates of soil loss from fields due to eroding winds. However, most of the wind speed data determined from these methods are commonly given as hourly or daily averages. The question as to whether these wind speeds are representative remains unanswered.

In this paper, we attempt to illustrate potential differences in calculating wind energy, derived as a function of wind speed, using hourly and sub-hourly averages. The importance of this work is realized more fully if the soil loss calculations are being developed for a single storm event rather than for an annual average soil loss. These types of calculations are becoming more common in recent years because of national interest in air quality issues and the US EPA’s recent revision of the National Air Quality Standards (Wolff, 1996; U.S. EPA, 1997).

METHODS

We have collected meteorological data since 1993 at three intensively monitored wind erosion sites on the Columbia Plateau, Washington State (Stetler et al., 1994; Stetler & Saxton, 1996). Data collection occurred on a continuous basis between May and December and included wind speed (0.1, 0.75, 1.5, 3.0 and 5.0 m height), wind direction, ambient air temperature (0.1, 2.0 and 5.0 m height), humidity, precipitation and total and net solar radiation. All data were stored as hourly averages during non-erosive periods and 1 minute averages during erosion events.

An erosion event was defined, and the entire sampling grid was activated, by a 15 minute moving average 3.0 m wind speed that exceeded 6.35 ms^{-1}. This particular threshold wind speed was arrived at using two well-tested, empirical equations. Fluid threshold velocity, u^*_t, for initial movement of the average available grain size of erodible sand (0.05 cm diameter) was calculated using Bagnold's (1941) relation for dry, well-sorted sand:

$$u*_t = A\left(\frac{\sigma - \rho}{\rho} gd\right)^{0.5} \qquad (1)$$

where:

- σ = particle density, 2.65 gcm^{-3} for quartz grains
- ρ = air density, 1.22 x 10^{-3} gcm^{-3}
- g = acceleration due to gravity, 980 cms^{-2}
- d = mean particle diameter, 0.05 cm
- A = empirical coefficient of turbulence approximately equal to 0.1 for particle friction Reynolds number > 3.5.

The correlative threshold wind speed at 3.0m that relates to the fluid threshold was determined by substituting the result from Equation (1) as u* in the widely used form of the Prandtl equation, given again by Bagnold (1941), as:

$$U = 5.75u*\log\frac{z}{z_0} \qquad (2)$$

where:

- u* = (threshold) shear velocity, $u*_t$ = 32.62 cms^{-1}
- z_0 = surface roughness based on field data, 0.12 cm
- z = height for which calculated wind speed is required, 300 cm
- U = wind speed at height z.

The result from Equation (2) indicates the required wind speed at the specified height, z=3.0 m, for erosion of sediment on the surface to begin. Thus, once the15 minute moving average wind speed exceeded the 6.35 ms^{-1} threshold condition, the event was considered viable.

For the duration of the erosion event, the 3.0 m moving average wind speed was decreased to a 10 minute average with a minimum value of 5.75 ms^{-1}. When the minimum condition was satisfied the sampling grid shut down and meteorologic variables began again to be averaged on 1 hour increments. At the same time, the moving average wind speed was increased to a 15 minute average and monitoring for the next event was initiated using the 6.35 ms^{-1} wind speed criterion.

The minimum wind speed of 5.75 ms^{-1} was selected because data analyses showed that it was common for long tail-off periods of up to 10's of hours to occur at a wind speed slightly below the 5.75 ms^{-1} value. Field observation confirmed that in almost all cases, no sediment movement occurred during these periods.

Thus, each event was characterized by an unique set of wind speed data collected at 1 minute resolution that could be correlated to simultaneous quantitative soil erosion and dust emission values. In addition, field and soil conditions were characterized such that each event was further defined by an unique threshold wind speed at the 3.0 m height. This data set has provided an excellent opportunity to evaluate potential effects on soil loss calculations using hourly and sub-hourly averaged wind speed data collected during wind erosion events.

WIND CHARACTERISTICS

Approximately 145 wind erosion events have been recorded on the Columbia Plateau between May 1993 and December 1996. Detailed wind speed analysis has been performed on 114 of these erosion events since May 1994 that also have simultaneous soil loss data. Total erosion time for these 114 events was 177,220 minutes (2,953.7 hr). A logistic frequency distribution function was used to fit event duration and the event average and peak wind speed at 3.0 m. The results are shown in Figures 1 and 2. Average event duration, 3.0 m wind speed and 3.0 peak wind speed was 404 minutes (6.7 hr), 7.03 ms^{-1} and 11.8 ms^{-1}, respectively. These figures represent the total data base which was collected using the above defined guidelines for an event. However, there is a significant portion of the total data base where the 1 minute wind speed was below the threshold required to move the soil particles but the 10 minute moving average wind speed remained above the minimum value of 5.75 ms^{-1}. Thus, these data contain some portion of time (a majority in some cases) where the 1 minute wind conditions were not sufficient to erode soil.

A variable thickness of loess mantles the Columbia Plateau reaching depths of 75 m in the eastern regions known as the ‘Palouse’ (Busacca et al., 1992). Soils developed from the loess deposits are fine sandy loam and silt-loam. Owing to the fine-grained nature of these soils and the farming methods utilized, dry conditions that are maintained in the upper 10 cm of the soil profile place the soil in an extreme erodible state. Grain-size analysis indicate that approximately 50% of the soil is composed of grains < 50 μm in diameter (Stetler & Saxton, 1996). The viable saltation component (grain sizes > 150 μm) is only a few percent but varies from high to low to the NE. Measurements have indicated that at wind speeds between about 6.0 and 5.75 ms^{-1}, the saltation grains are no longer active. An appreciable number of included minutes where the wind speed was below this level would therefore, skew the analysis toward lower erodibility.

We believe that for accurate modeling of soil erosion to occur, only wind speed data at velocities above that required to erode the largest particles be used. Stetler and Saxton (1995) developed and used a numerical routine that identifies erosion minutes, termed ‘exceedance minutes’, where wind speed exceeded threshold wind speed

$$I = 1 \text{ if } (U > U_t) \qquad (3)$$

where U = 1 minute wind speed, U_t = threshold wind speed for the event, and I = 1 if the expression is true. ‘I’ was summed over the entire event record and was not dependent upon consecutive exceedance minutes. All wind speed measurements are reported as ms^{-1}.

The data base was evaluated using Equation (3) which resulted in a 65 % reduction from the total minutes data were acquired. Specifically, 62,478 minutes (1,041.3 hr) were identified as exceedance minutes where the 1 minute wind speed exceeded threshold wind speed required for soil to be eroded. We interpret this reduction in total erosion time as an indication of wind variability, i.e., significant wind speed fluctuations occur on a time scale which is most likely not represented or captured by long-term (hourly) averages.

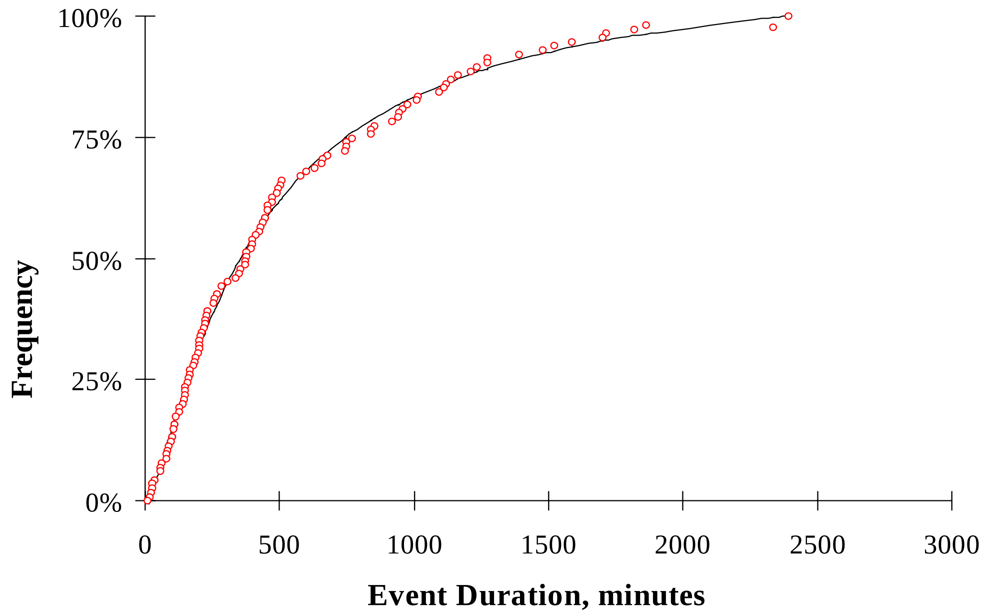

Figure 1 Frequency distribution of event duration for 114 wind erosion events from

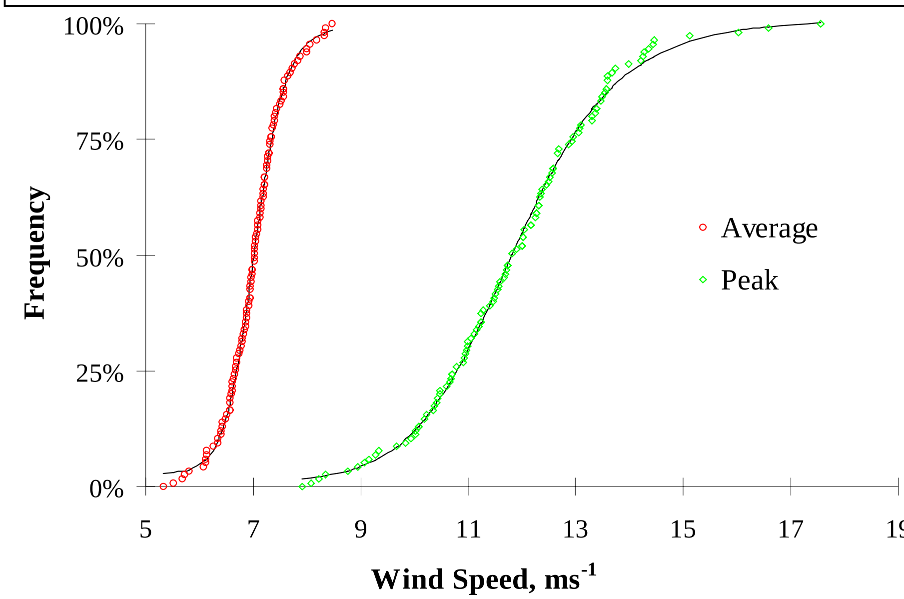

Figure 2 Frequency distribution of wind speeds and peak wind speeds at 3.0 m height for 114 wind erosion events from 1994-1996.

The erosive wind energy, $W*_e$, for each event was calculated for 3 time periods, 1, 15 and 60 minutes using the equation of Fryrear (1995) given as:

$$W*_e = U(U - U_t)^2 \qquad (4)$$

where, in our case, U = average wind speed for each 1, 15 and 60 minute ‘period’ and U_t = event threshold wind speed. Results using Equation 4 have units of m^3s^{-3} and are referred to as ‘erosion units’. Erosive wind energy is defined as the energy contained in a specific ‘period’ wind that is available for the transport of soil particles once threshold conditions have been exceeded. Given dry field conditions, $W*_e$ is most affected by the mean particle size of the soil, d, to which it is inversely related. As mean particle size increases, U_t will similarly increase as more wind speed is required to initiate the erosion process. An increase in U_t produces a smaller quantity under the radical in Equation (4) resulting in less available wind energy. In this way, particle size has a direct but inverse affect on wind energy. These data form the basis for all of the following analyses.

Frequency distributions for the 114 wind events are shown in Figure 2 and represents all data prior to treatment using equations 1 & 2. Overall, peak wind speeds increased at a greater rate than the average wind speeds, particularly for data in the 75 to 100% quartile. This suggests that for wind events characterized by a high average wind speed (>7.35 ms^{-1}, or above the 75% frequency), $W*_e$ calculated using an hourly average will most likely be less than that calculated using minute data since the energy contained in the extreme gusts will be missing from the former. If this hypothesis is correct, then it also implies that hourly averages which contain few total erosion minutes, and thus, a low hourly average wind speed, will most likely result in less calculated wind energy than if using minute data.

DATA ANALYSIS AND RESULTS

A subset consisting of 14 of the original 114 events were used to test the above hypothesis. Important parameters for these events are shown in Table 1. Equation (4) was used to evaluate $W*_e$ by performing a summation over 1, 15 and 60 minute periods resulting in an average period wind energy according to the following:

$$W*_e = \sum_{i=1}^{n} \frac{U_i(U_i - U_t)^2}{n} \qquad (5)$$

where i = i^{th} minute wind speed and *n* = number of minutes the wind speed was summed. When wind speed was below threshold, the result was set to zero and *n* remained unchanged. In this way, only those minutes which were in excess of threshold were included in the summation. Wind speed data for each of the 14 events were analyzed for 1, 15 and 60 minute averaging periods where the 1 minute values were used as the reference wind energy.

Table 1. Summary data for 14 analyzes wind events. Data in red are shown in Figure's 3-6.

Event Date	Total minutes	Exceedance minutes	U 3m ms^{-1}	$U_{t\text{-event}}$ ms^{-1}
5/23/96	2977	417	8.82	7.87
6/11/96	1565	480	9.81	8.54
6/26/96	**2103**	**187**	**9.34**	**8.79**
7/16/96	1613	184	9.01	8.54
7/19/96	1545	211	9.40	8.68
8/5/96	1194	575	8.01	6.98
9/17/96	1527	395	8.41	7.34
5/30/95	1940	179	9.93	8.89
6/12/95	1767	493	9.50	8.19
7/7/95	3896	1249	9.47	7.49
7/24/95	1736	722	8.29	7.26
7/31/95	1725	844	8.62	7.26
8/14/95	**3252**	**990**	**8.78**	**7.58**
8/31/95	3446	1658	8.15	7.33

Results from 2 wind events (6-26-96 and 8-14-95) using Equation (5) to average exceedance wind speed data over the 15 and 60 minute averaging periods are shown in Figure's 3, 4, 5 and 6. The 2 wind events used for these figure's span a time period from minimum erosion to the beginning of the most severe erosion on the Columbia Plateau. Field surface conditions also change significantly over the summer fallow season as tillage reduced surface roughness and residue cover. Therefore, wind erosion events which occur in late summer and early fall are often exacerbated compared to spring and early summer erosion events.

These figure's show that the 3.0 m erosive wind energies based on 15 minute averaging periods (Fig's 3, 5) are significantly correlated when compared to those based on a 60 minute average (Fig's 4, 6). Table 2 contains ratios between W^*_e based on 1 minute averages and W^*_e based on 15 and 60 minute averages for all 14 wind events analyzed. These ratios indicate the magnitude which 15 and 60 minute W^*_e values would have to be multiplied by to result in the same wind energy as when using 1 minute averages. In general, regardless of exceedance minutes, W^*_e based on 15 minute averages contain the least variance from the 1 minute average. W^*_e based on 60 minute averages fluctuate over a wide range and alone, are not good predictors of the energy contained in the wind. Figure 7 shows these ratios plotted as a function of exceedance minutes and indicates that as exceedance minutes increase, the ratios of the 1:15 and 1:60 minute averaging periods decrease. There is, however, a 3-fold difference between the rates of decrease. On the Columbia Plateau, an increase in wind speed is a common characteristic of an increase in event duration. Accompanied with the higher wind speed is the likely hood that the number of 15 minute averaging periods above threshold also increases. Therefore, the 1:15 ratio asymptotically approaches unity as a function of exceedance minutes and provides the highest correlation to 1 minute wind energies.

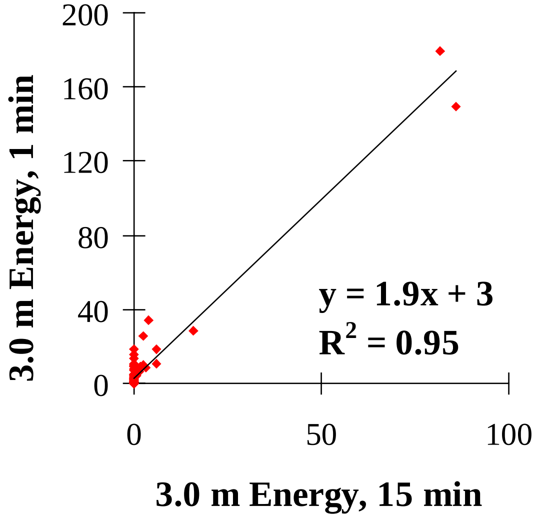

Figure 3. 1 minute vs. 15 minute wind energies for event of 6-23-96.

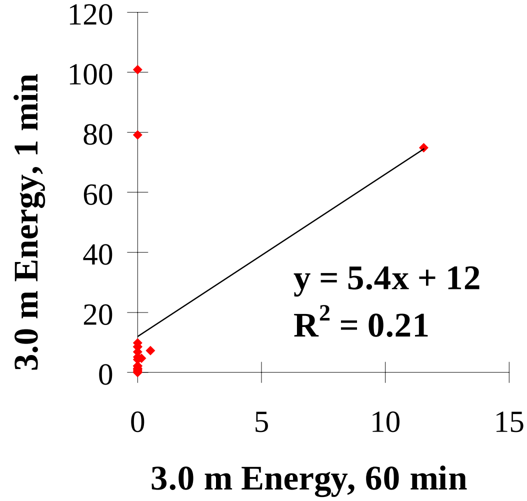

Figure 4. 1 minute vs. 60 minute wind energies for event of 6-23-96.

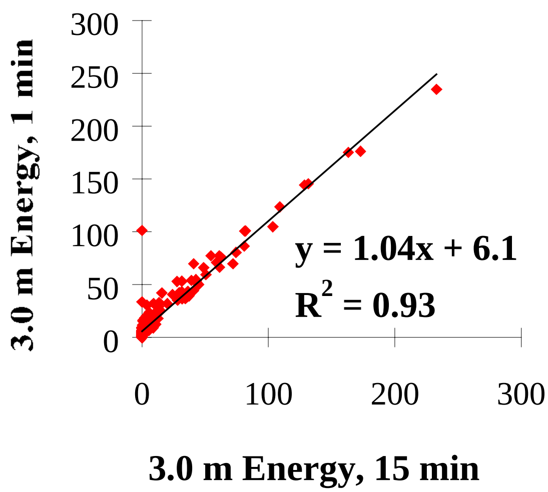

Figure 5. 1 minute vs. 15 minute wind energies for event of 8-14-95.

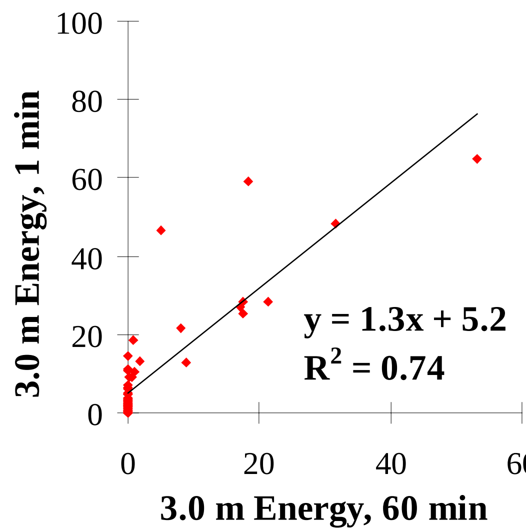

Figure 6. 1 minute vs. 60 minute wind energies for event of 8-14-95.

Calculated wind energy is also significantly affected by the total minutes in the averaging period where threshold conditions were exceeded. The frequency distribution of minutes above threshold for 15 and 60 minute averaging periods for a typical wind erosion event (8-14-95) is shown in Figure 8. Over the duration of this event there was a total of 188 periods from which a 15 minute average was calculated. By contrast, there was 49 hourly periods from which an hourly average was calculated. This figure shows the distribution of total exceedance minutes contained in each of the 15 and 60 minute averaging periods.

For example, 29% of the 15 minute averaging periods contained 15 exceedance minutes and 50% of the periods contained more than 11 exceedance minutes. The ratio between maximum (15 minutes out of 15 minutes exceeding threshold) and the 50% level is 1.4:1. Comparatively, 14% of the 60 minute averaging periods contained 60 exceedance minutes with 50% of the periods including 20 or more exceedance minutes for a ratio of 3:1. The smaller ratio for the 15 minute averaging periods suggests that there is a higher probability that a 15 minute period will contain a higher proportion of exceedance minutes than the larger, 60 minute averaging periods.

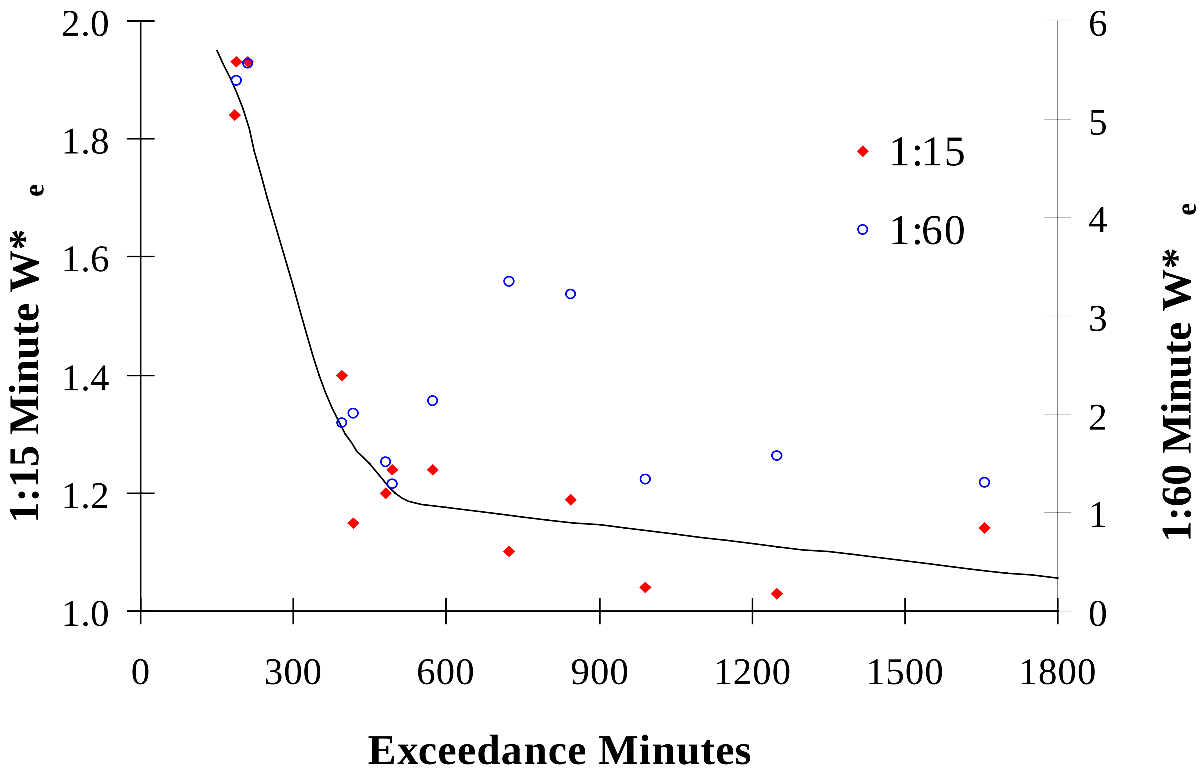

Figure 7. Comparison of ratios between 1:15 and 1:60 minute wind energies plotted as a function of exceedance minutes. Note the differences in scale. Curve is for 1:15 minute ratios.

This difference becomes more apparent when comparing the amount of calculable erodible wind energy contained within each of these averaging periods (Figure 9). A wide and mostly continuous spectrum of wind energy exists for the 15 minute data ranging from 1 to 240 erosion units. Frequency is below ~5% for all erosion units >5 but a significant amount of erosive power is shown to exist. Ninety percent of the energy exits at <60 erosion units. The 60 minute data appears very different and contains large gaps in the energy spectrum. A peak value of 55 occurs at a frequency of ~5%, which is 4 times less than the peak value using a 15 minute period. In this case, 90% of the energy exists below 30 erosion units.

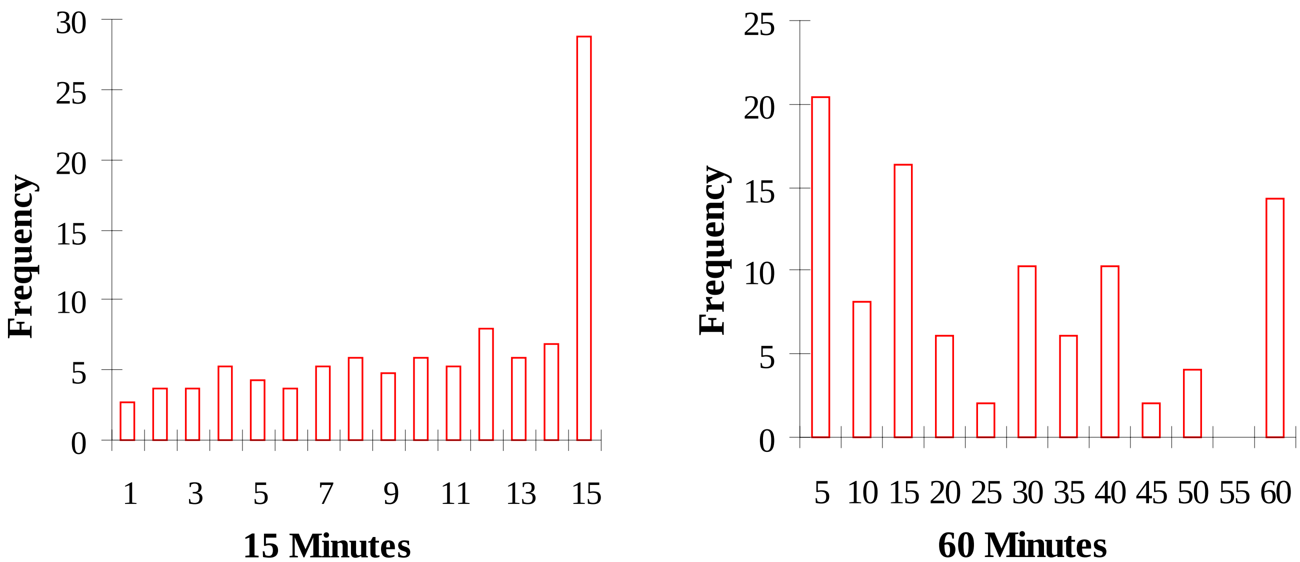

Figure 8. Frequency distribution of exceedance minutes for 15 minute (left) and 60 minute (right) averaging periods. Event of 8-14-95.

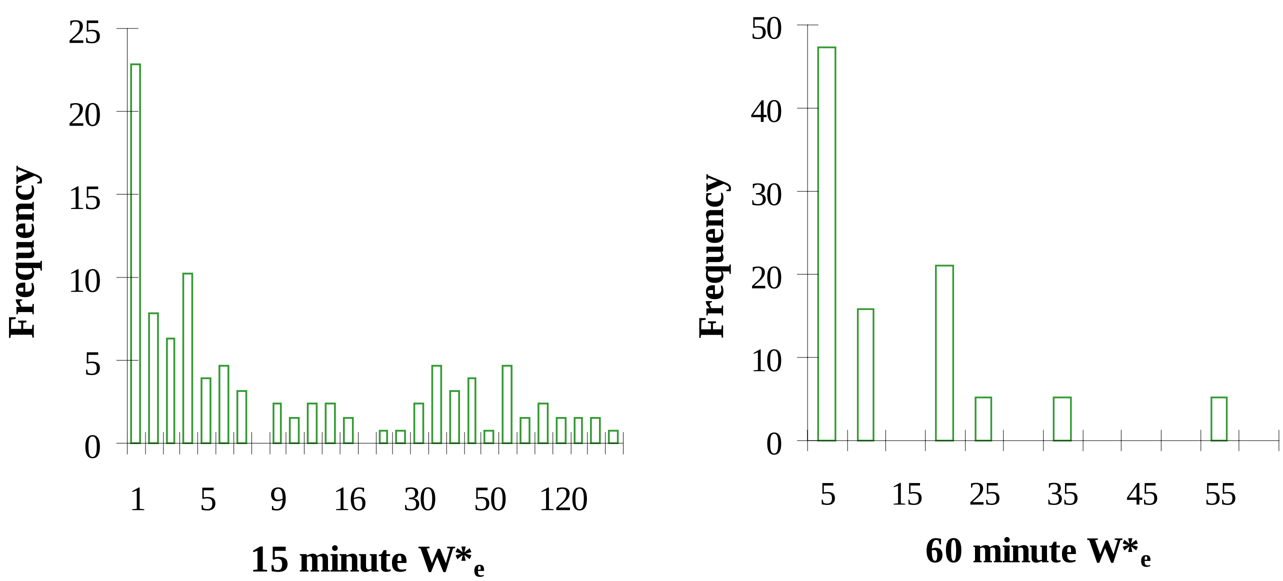

Figure 9. Frequency distribution of wind energy for exceedance minutes for event on 8-14-95. Left curve is 1:15 minute ratio and right is 1:60 minute ratio.

A measure of total calculable erosive wind energy can be determined by multiplying the frequency of occurrence by the erosion units. This results in a total of 2509 erosion units using the 15 minute averaging period compared to 1421 erosion units for the 60 minute averaging periods. The difference between the 2 values is the probable error in underestimating event wind power when using a 60 minute average wind speed. This ratio will vary from event to event depending on wind strength and duration, however, as shown in Table 2, will always favor the 15 minute averaging period. Using a 60 minute average wind speed, errors in W^*_e can be up to 250%.

Table 2. Ratios between 1 to 15 and 60 minute wind energies for wind speed and threshold wind speed.

Event Date:	U_t	
	1:15 min	1:60 min
5/23/96	1.15	2.01
6/11/96	1.2	1.51
6/26/96	**1.93**	**5.4**
7/16/96	1.84	455
7/19/96	1.93	5.57
8/5/96	1.24	2.14
9/17/96	1.4	1.91
6/12/95	1.24	1.3
7/7/95	1.03	1.58
7/24/95	1.1	3.35
7/31/95	1.19	3.22
8/14/95	**1.04**	**1.34**
8/31/95	1.14	1.31

SUMMARY

Analysis of wind speed data from 114 wind erosion events indicate that wind energy, calculated using 15 and 60 minute averaging periods (typical of readily available meteorological data) can vary greatly from wind energy calculated using a 1 minute wind speed. These analyses have indicated that the smaller the time scale over which wind speed data are acquired, the more likely the high energy fluctuations in wind speed will be represented in the calculated wind energy. These short-term fluctuations usually contain significant amounts of wind energy that are not adequately represented by long-term averages, such as hourly averages. For typical erosion events, a 15 minute average wind speed will provide reasonable estimates for wind energy and are superior to values calculated using an hourly averaged value. Based on the foregoing analysis, a conservative adjustment to hourly data of approximately +30% appears appropriate when the wind speeds is being used to estimate soil loss during a wind erosion event.

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