Ratios of Erosive Wind Energies on Dry Days and All Days in the Western United States

L. J. Hagen

Abstract. *Simulated wind speeds and precipitation events from stochastic weather generators often are not correlated. This study was undertaken to determine (1) if wet and dry day distributions of hourly wind speeds were different, and (2) if different, would using distributions for all days cause errors in predictions of erosive wind energy and wind erosion on dry days. Hourly weather data were obtained from the National Climatic Data Center SAMSON data set at 46 stations in the western U.S. Wind speeds were sorted into 25 classes and a calm class (0 to 0.5 m s^{-1}). After removal of calm periods, distributions were created for all days, dry days, and wet days. The wet days comprised wind speeds from the initial hour of precipitation and the 23 succeeding hours. Among 552 pairs of wet-day and dry-day cumulative monthly wind speed distributions, 87% of the distributions were significantly different (0.10 level or less based on a Kolmogorov-Smirnov test). To determine the importance of these differences, monthly ratios of erosive wind energy were calculated from dry-day and all-day distributions. Over much of the area, the erosive wind energy was lower on dry days than on all days. The eastern Great Plains and eastern Washington had the lowest ratios. Hence, use of an all-day wind speed distribution at these locations likely overestimates potential soil loss from wind erosion. Limited wind erosion simulations using the WEPS model tended to support this conclusion. In contrast, a few of the low-precipitation areas in the west had ratios that were consistently greater than 1. In summary, accuracy of predicted wind erosion from physically based models can be modestly improved by accounting for differences in wind speed distributions on wet and dry days.*

Keywords. *Erosive wind energy, Probability, Rain, Wind erosion, Wind speed.*

Many applications require accurate stochastic simulation of wind speeds, but there has been little research to determine if the wind speed distributions on wet and dry days are similar. Weather simulation models such as CLIGEN (Nicks et al., 1995) are used as drivers for both wind and water erosion models. The CLIGEN model simulates sequences of wet and dry days, but the simulated wind speeds and precipitation are assumed to be random, uncorrelated variables. A similar assumption was made in developing the hourly wind speed simulator (Van Donk et al., 2005) used for the WEPS wind erosion model (Wagner, 1996). Other applications for wind speed simulations include assessments of available wind power (Bryukhan and Diab, 1993), extreme winds for building codes (Cook et al., 2003), and sand drift potential (Fryberger, 1978).

Significant differences in wind speed distributions on wet and dry days could cause errors in simulating soil loss. The drying of the soil surface is a multi-phase process, which is first limited by available energy and later limited by available moisture (Idso et al., 1974; Durar et al., 1995). The duration of surface wetness sufficient to impede wind erosion generally extends beyond the time of the precipitation, particularly during low evaporation periods in fall, winter, and spring. Soil surface wetness greatly reduces wind erosion because it increases the threshold speeds at which erosion is initiated (Chepil, 1956; Saleh and Fryrear, 1995). The threshold begins to increase linearly when surface moisture content exceeds about 25% of that at 1.5 MPa tension. In sand, a sharp curvilinear increase in threshold occurs as surface moisture tension decreases to less than about 0.4 MPa (McKenna-Neuman and Nickling, 1989).

Effects of high wind speeds during rainfall events may also need to be included in future models that predict water erosion. Recent simulations show that rainfall accompanied by high wind speeds significantly enhances soil detachment, particularly on hills (Choi, 2002).

Some data currently show that the winds on wet and dry days may differ. For example, both the January average and annual average wind speeds in the contiguous U.S. during hours with snowfall or rainfall exceed the averages for all hours (Groisman and Baker, 2002). The major objectives of this study were to determine (1) if wet and dry day distributions of hourly wind speeds were different, and (2) if different, would using distributions for all days cause errors in predictions of erosive wind energy and wind erosion on dry days.

Materials and Methods

Weather data from 46 observation stations in the western U.S. were analyzed. All the data were taken from the SAM-

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The author is **Lawrence J. Hagen, ASABE Member Engineer,** Agricultural Engineer, USDA-ARS Grain Marketing and Production Research Center, 1515 College Ave, Manhattan, Kansas 66502; phone: 785-537-5545; fax: 785-537-5507; e-mail: hagen@weru.ksu.edu.

SON data set (NOAA, 1993), which contains hourly weather data spanning 1961 through 1990. The data set contains some gaps, but more than ten years of data were available for each of the selected stations. Both anemometer heights and locations varied over the years, so only ratios of the data for wet and dry days are used in this article.

Hourly wind speeds for each station were sorted, according to the frequency with which the wind speeds occurred, into a series of 25 wind speed classes and a calm class for each month, as illustrated in table 1. The methodology is similar to that used by van Donk et al. (2005). Frequencies of occurrence of all available wind speeds were placed in classes of an all-day distribution. To represent samples of wind speeds when wind erosion would likely be limited by wet soil, wind speed frequencies coinciding with the first hour of precipitation along with the 23 succeeding hours were placed in wet-day distribution classes. After 24 hours from the initial precipitation, the next hour of precipitation initiated sampling for another wet-day. Dry-day frequency distributions were obtained by subtracting the frequencies in the wet-day classes from those in the all-day classes.

After the calm wind speed data class (0 to 0.5 m s^{-1}) was removed, the cumulative frequency distributions of the remaining 25 classes were calculated for each month at each station. To determine if the dry-day and wet-day distributions were significantly different, a distribution-free Kolmogorov-Smirnov test (Hollander and Wolfe, 1999) was applied to each monthly pair of cumulative distributions at each station.

If the wet-day and dry-day distributions of wind speeds were different, we wanted to investigate the potential impact of using the dry-day distributions compared with the all-day distributions on estimated erosive wind energy. This was accomplished by taking the ratio (R_t) of erosive wind energies of the dry-day to all-day distributions as:

$$R_t = \frac{\sum_{1}^{n} U_i^2 (U_i - U_t)(f_{i\_dry})}{\sum_{1}^{n} U_i^2 (U_i - U_t)(f_{i\_all})} \qquad (1)$$

where

U_i = wind speed at center of the ith class (m s^{-1})
U_t = erosion threshold wind speed (m s^{-1})
f_{i_dry} = frequency of the wind speeds in the ith dry-day class
f_{i_all} = frequency of the wind speeds in the ith all-day class
n = number of wind speed classes (25).

Table 1. Wind speeds sorted into 25 classes and a calm class.

Class	Wind Speeds (m s^{-1}) Lower	Central	Upper
0 (calm)	0	0.25	0.5
1	>0.5	1	1.5
2	>1.5	2	2.5
3	>2.5	3	3.5
⋮	⋮	⋮	⋮
17	>16.5	17	17.5
18	>17.5	18	18.5
19	>18.5	19	19.5
20	>19.5	20	20.5
21	>20.5	21	25.5
22	>25.5	23	30.5
23	>30.5	28	35.5
24	>35.5	38	40.5
25	>40.5	43	50.0

Threshold wind speeds of 8.5, 10.5, 12.5, and 14.5 m s^{-1} that coincide with class boundaries were used in the analyses to represent field susceptibilities to wind erosion, ranging from high to low. At these four wind speed thresholds, surface grain diameters less than 0.62, 0.97, 1.32, and 1.78 mm, respectively, would be susceptible to deflation from a sandy soil with an aerodynamic roughness of about 2 mm (Bagnold, 1941). Both monthly and seasonal values of R_t were calculated. The seasonal values of R_t were then plotted for wind speed thresholds of 8.5 and 12.5 m s^{-1} to illustrate the spatial variation in R_t on a seasonal basis in the western U.S. Isolines on the plots were estimated using automated software kriging techniques (Golden Software, 2002).

Finally, predicted ratios of monthly dry-day to all-day soil losses were obtained from the WEPS erosion model (Wagner, 1996) using the dry-day and all-day wind speed distributions. The ratios were calculated for flat fields 800 × 800 m in size during selected months when wind erosion is often observed on fields without vegetation. Loamy fine sand and silt loam soil textures were selected to represent two levels of inherent soil erodibility in the simulations. Initial soil conditions as supplied by the WEPS model for these soil textures were used in the simulations. We assumed that no erosion occurred on wet days.

Results And Discussion

A total of 552 wet-day:dry-day pairs of cumulative wind speed distributions were developed by using 12 monthly data sets from 46 observation stations. According to the Kolmogorov-Smirnov test, 84% of the wet-day and dry-day distribution pairs were significantly different (0.05 level). An additional 3.3% were different at the 0.10 significance level (table 2). Four months, May through August, had 61% (i.e., 42 pairs) of the distribution pairs that were not significantly different. These also tended to be the months with low erosive wind energies (data not shown). The rest of the pairs that were not different were scattered throughout the other eight months.

The preceding results demonstrate that the wind speed distributions on wet and dry days are usually significantly different. But many of the maximum differences between the distributions occurred at wind speeds below the erosion threshold. Further testing of the distributions was then undertaken to determine if the observed differences caused overestimates or underestimates of simulated erosive wind energies. The largest errors in simulated erosion presumably would occur if the erosive wind energies simulated on dry days were larger or smaller than those from the all-day distributions that are generally used in erosion simulations. To determine the potential impact on simulated erosion, the ratios (R_t) of dry-day to all-day erosive wind energies were calculated from these pairs of frequency distributions.

Over most of the western U.S., there were regional and seasonal patterns in the R_t when using an U_t of 8.5 m s^{-1} to represent soil conditions that are the most susceptible to wind erosion (fig. 1). The largest impact from using the all-day

Table 2. Comparison of hourly wind speed distributions on wet and dry days.[a]

State	Station	Winter			Spring			Summer			Fall		
		Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
Arizona	Phoenix	*	*	*	*	*	0	*	0	*	*	*	*
	Tucson	*	a	a	*	*	0	0	*	0	*	*	*
Colorado	Colorado Springs	*	*	*	*	0	*	*	*	*	a	0	*
	Grand Junction	*	*	*	0	*	*	0	0	*	*	*	*
	Pueblo	*	0	0	*	*	0	*	*	0	0	*	*
Idaho	Boise	*	*	*	*	*	*	0	*	0	*	*	*
	Pocatello	*	*	*	*	*	*	*	*	0	*	*	*
	Dodge City	*	*	*	*	*	0	*	*	*	*	*	*
Kansas	Goodland	*	*	*	*	*	*	a	*	*	*	*	*
	Topeka	*	*	*	*	*	*	*	*	*	*	*	*
	Wichita	*	*	*	*	*	*	*	*	*	0	*	*
Montana	Cut Bank	*	*	*	*	*	0	a	0	*	0	*	*
	Glasgow	*	*	*	*	*	*	*	*	*	0	*	*
	Great Falls	*	*	*	*	*	*	*	*	*	*	*	*
	Miles City	0	*	0	*	*	*	*	0	0	*	*	*
North Dakota	Bismarck	*	*	*	*	*	*	*	*	*	*	*	*
	Fargo	*	*	*	*	*	*	*	0	*	*	*	*
Nebraska	Grand Island	*	*	*	*	*	0	*	*	*	*	*	*
	Norfolk	*	*	*	*	*	a	*	*	*	*	*	*
	North Platte	*	*	*	*	*	*	*	*	*	*	*	*
	Omaha	*	*	*	*	*	*	*	*	*	*	*	*
	Scottsbluff	*	*	*	*	*	*	0	*	*	*	*	*
New Mexico	Albuquerque	*	*	*	*	0	0	*	0	0	*	*	*
Nevada	Elko	*	*	*	*	*	*	a	0	a	*	*	*
	Las Vegas	*	*	*	*	*	*	*	*	*	*	0	*
	Reno	*	*	*	*	*	*	*	*	*	*	*	*
	Winnemucca	*	*	*	*	*	0	*	0	0	*	*	*
Oklahoma	Oklahoma City	*	*	*	*	a	0	*	*	0	*	*	*
	Tulsa	*	*	*	*	*	0	*	*	*	a	*	*
Oregon	Burns	0	*	*	*	0	0	0	a	*	0	0	*
	Pendleton	*	*	*	*	*	*	0	0	*	*	*	*
South Dakota	Huron	*	*	*	*	*	*	*	*	*	*	a	*
	Sioux Falls	*	*	*	*	*	*	*	*	0	*	*	*
Texas	Abilene	*	*	*	0	*	*	*	*	*	*	0	0
	Amarillo	*	*	*	*	*	*	*	*	*	*	*	*
	El Paso	*	*	*	*	0	0	*	*	a	*	*	*
	Lubbock	*	*	*	*	*	*	*	*	*	0	*	*
	Midland	*	*	*	*	*	*	*	*	0	*	*	*
Utah	Salt Lake City	*	*	*	0	*	a	*	*	0	a	*	*
Washington	Spokane	*	*	*	*	*	*	*	*	*	*	*	*
	Yakima	*	*	*	*	*	*	*	0	*	*	*	*
Wyoming	Casper	*	*	*	*	*	*	*	a	a	*	*	*
	Cheyenne	*	*	*	*	*	*	a	0	*	*	*	*
	Lander	*	*	*	*	*	*	*	*	*	*	*	*
	Rock Springs	0	0	*	*	0	*	*	0	0	*	*	0
	Sheridan												

[a] Based on Kolmogorov-Smirnov tests of wind speed distributions in each month, all wet-day and dry-day distribution pairs are: * = different at the 0.05 level, a = different at the 0.1 level, and 0 = not different.

distribution (i.e., smallest R_t) occurred in the northeastern portion of the Great Plains, whereas the impact was somewhat less in the southern plains. There was also a large effect in eastern Washington. Deviations from an R_t of 1 were generally smallest in the summer. At a few stations in areas with low precipitation, seasonal R_t values were greater than 1. At those stations, high wind speeds may precede the precipitation events or occur at other times.

Highly erodible soils have may have threshold wind speeds of less than 8 m s^{-1} measured at a 10 m height (Bagnold, 1941). These wind speeds occur frequently, so most of the year, soils are usually managed to be at least moderately resistant to wind erosion, with wind speed thresholds of 12.5 m s^{-1} or more. At this increased threshold wind speed, the spatial patterns of R_t during various seasons remained similar to those observed with the 8.5 m s^{-1} wind speed threshold (fig. 2). However, the magnitude of R_t decreased markedly in many areas; hence, the likely overestimation of simulated wind erosion should also increase when using an all-day distribution.

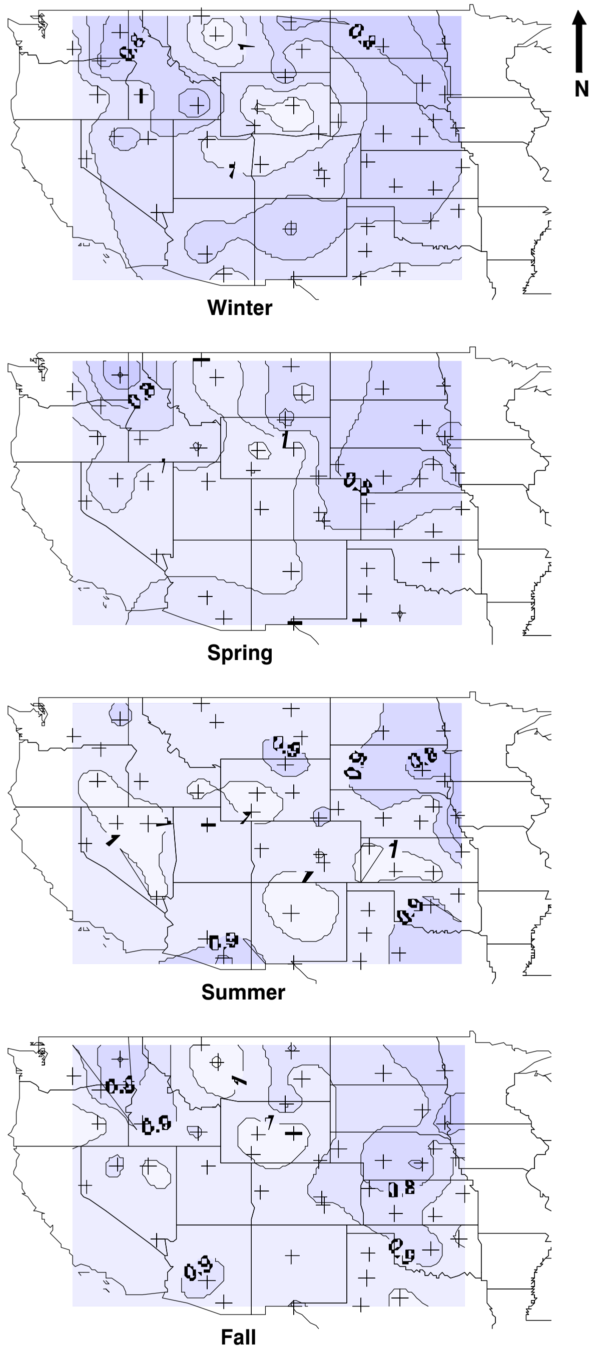

Figure 1. Seasonal erosive wind energy ratios (dry days / all days) of hourly wind speeds with an erosion threshold of 8.5 m s^{-1} in the western U.S. (crosses denote station locations).

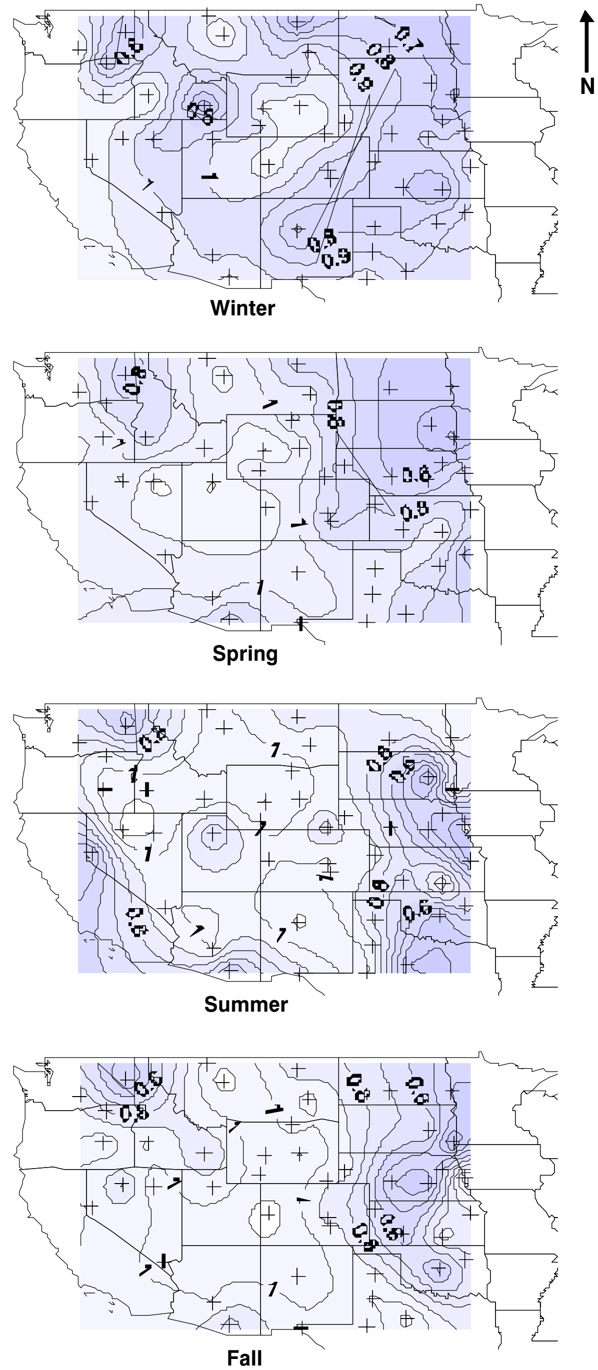

Figure 2. Seasonal erosive wind energy ratios (dry days / all days) of hourly wind speeds with an erosion threshold of 12.5 m s^{-1} in the western U.S. (crosses denote station locations).

The seasonal plots of R_t provide an overview of their general spatial variation, but the monthly results often illustrate that the range in the R_t can be larger than the seasonal averages. For example, by using U_t of 12.5 m s^{-1}, the monthly R_t ranged from 0.23 to 1.13 at Fargo, North Dakota (fig. 3) and from 0.09 to 1.17 at Spokane, Washington (fig. 4). At both locations, R_t in fall, winter, and spring suggest that using all-days distributions could significantly overestimate soil loss by wind erosion during periods without snow cover.

At Yakima, Washington, R_t ranged from 0.43 to 1.3, but overall the seasonal effects appear small, and using the all-day distributions may lead to a slight underestimation of simulated erosion (fig. 5). Hence, between Spokane and Yakima there seems to be a steep reduction in the likelihood of overestimating erosion by using the all-day distribution.

At Dodge City, Kansas, R_t values are generally less than 1, except in August. Hence, erosion would likely be overestimated to various degrees with the all-day distribution, depending on the erosion threshold condition of the surface (fig. 6). At Lubbock, Texas, R_t values are less than 1 during January, February, and March, but may exceed 1 in September, October, and December (fig. 7).

In general, ratios of selected monthly dry-day to all-day soil loss predicted using the WEPS model for the stations de–

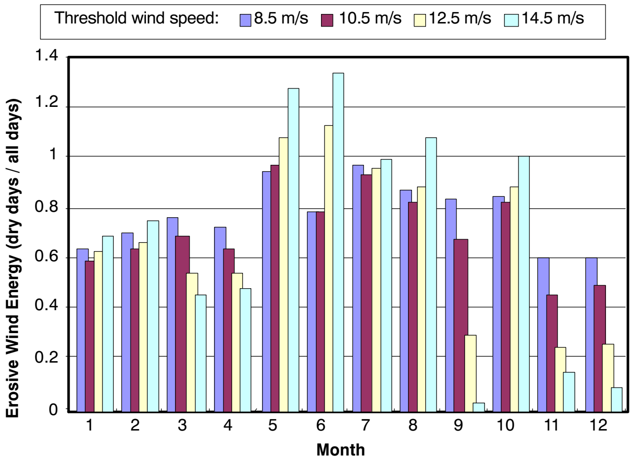

Figure 3. Monthly wind energy in hourly wind speed distributions of dry days divided by all days for various erosion threshold wind speeds at Fargo, North Dakota.

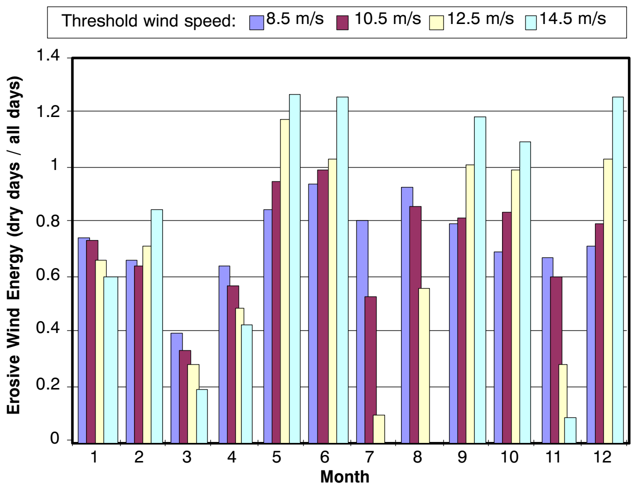

Figure 4. Monthly wind energy in hourly wind speed distributions of dry days divided by all days for various erosion threshold wind speeds at Spokane, Washington.

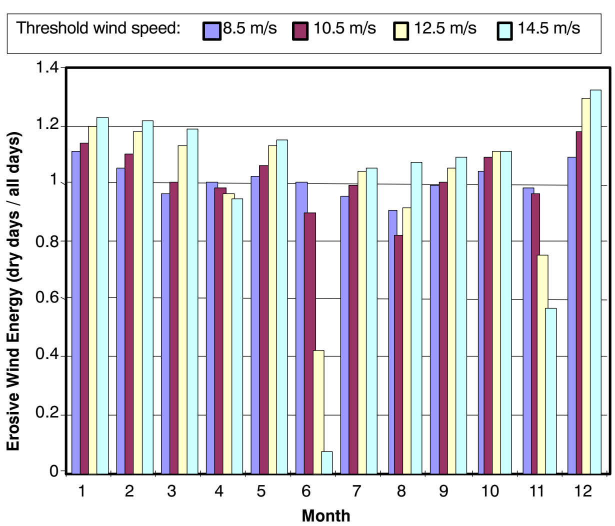

Figure 5. Monthly wind energy in hourly wind speed distributions of dry days divided by all days for various erosion threshold wind speeds at Yakima, Washington.

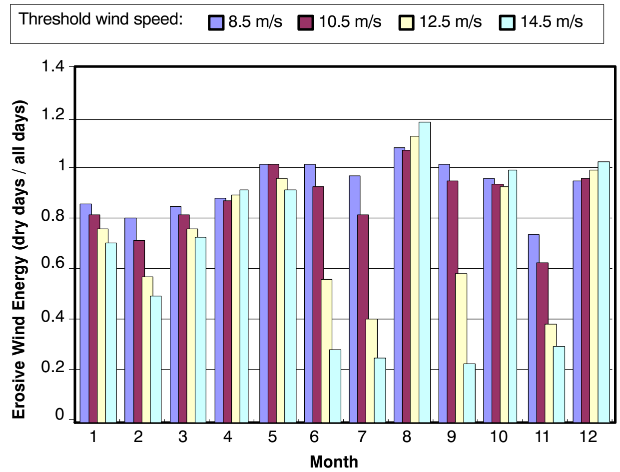

Figure 6. Monthly wind energy in hourly wind speed distributions of dry days divided by all days for various erosion threshold wind speeds at Dodge City, Kansas.

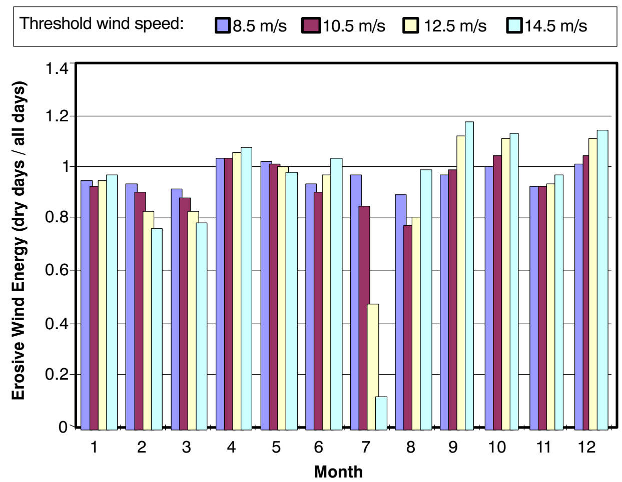

Figure 7. Monthly erosive wind energy in hourly wind speed distributions of dry days divided by all days for various erosion threshold wind speeds at Lubbock, Texas.

picted in figures 3 through 7 tended to follow the trends in erosive energy ratios (table 3). Two minor exceptions in the data trend appear to be the soil loss ratios at Dodge City in April on the silt loam soil and at Lubbock in April on the loamy fine sand soil. These exceptions may be caused by interactions between the updating of surface conditions by WEPS during erosive events and the wind speed distributions.

Whether the impact of using the all-days distribution in long-term simulated wind erosion is positive or negative will depend on the distribution of months in which the soil is vulnerable to wind erosion. The variability in R_t among stations supports the conclusion of Schoof and Robeson (2003) that station-specific parameters are needed for applications that require proper simulation of variable relationships.

Table 3. Predicted ratios of monthly dry-day to all-day soil losses obtained from the WEPS erosion model using dry-day and all-day wind speed distributions on 800 × 800 m, bare fields with two different soil textures.

Station	Month	Soil Texture	Soil Loss Ratio
Fargo, North Dakota	April	Loamy fine sand	0.78
		Silt loam	0.84
	May	Loamy fine sand	0.95
		Silt loam	0.95
Spokane, Washington	September	Loamy fine sand	0.81
		Silt loam	0.0[a]
	October	Loamy fine sand	0.75
		Silt loam	0.0[a]
Yakima, Washington	September	Loamy fine sand	0.99
		Silt loam	0.97
	October	Loamy fine sand	1.08
		Silt loam	1.22
Dodge City, Kansas	March	Loamy fine sand	0.87
		Silt loam	0.61
	April	Loamy fine sand	0.97
		Silt loam	1.04
Lubbock, Texas	March	Loamy fine sand	0.99
		Silt loam	0.92
	April	Loamy fine sand	0.88
		Silt loam	1.07

[a] Maximum wind speeds on dry days at Spokane were below the erosion threshold for the silt loam soil, so no erosion was predicted.

CONCLUSIONS

Analysis of hourly wind speed and precipitation data taken from the NCDC SAMSON data set at 46 selected observation stations in the western U.S. yielded 552 pairs of wet-day and dry-day cumulative monthly wind speed distributions. Comparison of the wet-day and dry-day distributions showed that 87% were significantly different (0.10 level or less). Hence, the utility of time series produced by stochastic wind speed generators for use wind erosion prediction can likely be improved by accounting for correlations between local wind speed and precipitation events.

Further tests showed that monthly ratios of dry-day to all-day erosive wind energies differed among months, stations, and erosion threshold wind speeds. However, over much of the western U.S., the erosive wind energy was lower on dry days than on wet days. The eastern Great Plains and eastern Washington near Spokane had the lowest ratios. Hence, use of an all-day wind speed distribution in these locations likely overestimates potential soil loss from wind erosion. Limited simulation of soil loss using the WEPS model with dry-day and all-day wind speed distributions tends to support the preceding conclusion. In contrast, a few of the low-precipitation areas in the west had ratios that were consistently greater than 1. Thus, at many locations, accuracy of physically based wind erosion simulation models could be modestly improved by accounting for differences in wind speed distributions on wet days and dry days.

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