

Potential of wind erosion and dust emission in an arid zone of northern Mexico: A simple assessment method

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ABSTRACT: Wind erosion is the main problem that arid lands in northern Mexico are facing. Quantification of this phenomenon is crucial for planning purposes and to scale its impact. The challenge is to assess the problem under limited availability of climatic information. This study aimed to identify potential areas of dust emissions in an arid zone of Northern Mexico. Wind direction and intensity were characterized through a robust index that involves rainfall and evaporation as well as the climatic factor of the general wind erosion equation. A method for assessing the likelihood of dust emission associated with wind erosion was applied. Data from twelve weather stations within the region of the study was analyzed. The variables considered were wind velocity and direction, temperature, and precipitation. A wind rose of wind direction and intensity was obtained. Results showed that the Thornthwaite's method for computing the Soil Moisture Index (SMI) is a good approach when computing the climatic factor C of the general function of the potential average annual soil loss. Given the lack of local evaporation data, the precipitation-evaporation ratio ($\frac{P}{E}$) for each weather station was computed as an intermediate step towards the computation of C. Three of the analyzed climatic stations had intermediate C values (36-71 %) in the scale of wind erosion climatic factor. The wind velocities registered in these climatic stations ranged from 15 to 30 km h⁻¹. The magnitude-frequency analysis of the $\frac{P}{E}$ parameter for the stations showed the differences in rainfall and evaporation regimes. Dust pollution prone areas were identified, showing areas where conservation strategies should be directed.

Keywords: air quality, suspended particles, soil loss, arid lands.

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INTRODUCTION

Dust storms originate from the uplift of dust into the atmosphere resulting from the complex interaction of moving airflows and soil particles on the ground (Gherboudj et al., 2017). Their frequency has been on the rise during the last decade, and forecasts suggest that their incidence will increase as a response to climate change and anthropogenic activities (Schweitzer et al., 2018). When the ground is covered by vegetation, it provides a barrier to uplift soil particles, reducing wind erosion and the quantity of dust emitted. However, in arid and semi-arid regions (drylands), native vegetation is scarce, affecting the type and amount of particles carried into the atmosphere. Considering its long transportation distance and harmful effects, sandstorms (or dust storms in other regions) are classified as international weather disasters (Luo et al., 2016). As expressed by interviewed people during the study conducted by Sacchi et al. (2017) in South America: *“The disadvantage of agriculture is the lack of vegetation. Sometimes we have strong winds, and nothing protects us and a lot of dust comes, a lot!”*. Among the effects of dust storms are loss of soil, organic matter, and nutrients, which decrease agricultural productivity, damage to young crop plants, reduced visibility, which affects aircraft and road transportation, and effects on human health (Gerivani et al., 2011).

In the United States, mapping spatial and temporal patterns of wind erosion has been prioritized by the National Wind Erosion Research Network for building an understanding of wind erosion processes at management-relevant scales (Webb et al., 2014). Awareness of climate hazards in drylands is also important because of the extent and population living in these regions. In Mexico, drylands cover about 69 % of the total territory. One of the areas of interest due to the severity and frequency of dust storms, as well as the impact on population is the “Comarca Lagunera”, which can be translated as “*region of lagoons*”. Ironically, there are no lagoons left, but only drylands as the two main lagoons (Mayrán and Viesca) of the initial 13 vanished after the construction of a dam in the 1940s. The characteristics of winds in the region obey more to topographic and orographic conditions rather than a general wind classification. In this way, prevailing winds from the south have a physical barrier in the Sierra de Jimulco and the Carolina’s mountains. Towards the northwest, the physical barrier is the Del Rosario Mountains. These, along with Las Delicias and Tlahualilo mountains, force the winds to bend towards the northwest of the region passing over the cities of Torreón, Gomez Palacio, and Lerdo which have a combined population of about 1.04 million people (Conapo, 2018). These cities constitute a potential area of dust deposition and associated pollution. The amount and type of pollutants adhered to dust particles are yet to be determined. Nevertheless, some monitoring stations in Torreón (population 700,000 approximately) reported that during 2016 PM₁₀ particles concentration was above the federal regulation of 180 and 76 µg m⁻³ for 24 h and annually, respectively (Sinaica, 2016). These small particles found in dust and smoke can get into the throat and lungs (Environment Protection Authority Victoria, 2019) and have a negative impact on human health.

Dust source studies in downwind cities could provide critical information for government policymaking in dust storms damage control and identify the parental material of the entrained dust for further assessment of its impacts (Yan et al., 2015). Plans to cope with hazards in drylands should contain three basic components: monitoring and early warning, risk assessment, and mitigation and response strategies (Middleton and Sternberg, 2013). However, the spatial and temporal distribution of wind currents and dust storms, as well as their intensity, remains undocumented to date in Mexico. Consequently, land management and mitigation strategies, as well as early warnings to prevent people to take measures, cannot be implemented if the extent of the phenomenon is unknown.

Compared to experimental measurements, numerical modeling is a more economical solution but is limited by computing capability and some technical problems (Luo et al., 2016). Sophisticated models such as the Weather Research and Forecasting with Chemistry

(WRF/Chem) have been used to simulate dust storm events over East Asia (Cheng and Zhao, 2013). Even though comparisons between model simulations and observation data revealed that the model reasonably reproduced the spatial distribution of surface dust concentration, the simulated total dust budgets differed significantly among schemes, and the uncertainty varied among regions. Therefore, region-specific models may still be needed. Also, in Europe, a study by Chervenkov and Jajobs (2011) implemented the EURAD model for understanding the processes involved in dust storms. When sufficient data are available, the incorporation of a probability distribution function for surface wind in distributed parameter modeling approaches is a suitable way to account for wind variability due to dry and moist convection (Foroutan and Pleim, 2017). Due to the lack of field infrastructure for the assessment of wind erosion in Mexico, simple indirect methods are used for obtaining the parameters that define this process. In this way, the climatic factor C of the functional relationship of wind erosion is computed based on wind velocity and soil moisture content. The objectives of this study were: 1) to identify the potential main source areas of dust storms in an arid zone of northern Mexico; 2) to develop a regional wind rose showing the direction and velocity of predominant winds; and 3) to determine the rainfall evaporation ratio ($\frac{P}{E}$) and the climatic factor C of the wind erosion equation as indicators of the potentiality of the region for being eroded by the wind as a precursor of dust pollution to the cities.

MATERIALS AND METHODS

Study Area

There are 18.12 million hectares affected by wind erosion in Mexico (SNIARN, 2019). In the northern part of the country, within the states of Coahuila and Durango, lies the Comarca Lagunera (24° 44' N and 102° 40' W) at an average elevation of 1,120 m a.s.l. (Figure 1). It encompasses 16 counties from the states of Coahuila and Durango and covers an area of approximately 48,770 km² (Inegi, 2016a,b). The estimated total population of this important economical region is about 1.6 million inhabitants, being the major cities Torreón, Matamoros, San Pedro, Gómez Palacio, and Lerdo, which account for 87 % of the population (Inegi, 2017a,b). In this region, 13.8 % of the area of the state of Coahuila and 17.9 % of the area of Durango are affected by wind erosion with an estimated annual soil loss of 200 Mg ha⁻¹ yr⁻¹ (Inegi, 2017a,b).

The location of the climatic stations shown in figure 1 depicts the representativeness of the weather conditions within the study area. The climate in the region is dry (arid) to semi-dry (semi-arid) with summer rains, which, according to Koppen's classifications system, corresponds to BWs and BSw (Garcia, 2004). The average annual temperature is 20 °C, but it reaches a maximum of 42 °C and a minimum of -7 °C; average annual rainfall is 220 mm (Miranda, 2008). The predominant vegetation is scarce and consists mainly of desert-type species such as cactus, bushes, shrubs, and other drought-tolerant native plants. However, there are also extensive cultivated areas (e.g., corn, sorghum, and alfalfa) used mainly for forage production (Sanchez et al., 2015). Soil types and vegetation characteristics of the study region are shown in table 1.

Source of data

Within the study area, twelve automated weather stations were selected and geo-referenced (Table 2). Time data series were drawn from the National Laboratory of Remote Sensing of the National Institute for Forestry Agriculture and Livestock Research of Mexico (Inifap, 2018). At the weather stations, wind velocity is recorded on an hourly basis. Wind information was processed for the period 2006-2017, but as shown in table 2, not all the weather stations had the same length of records. Maximum, minimum, and average values of wind direction and velocity for each station were recorded. Table 3 shows the

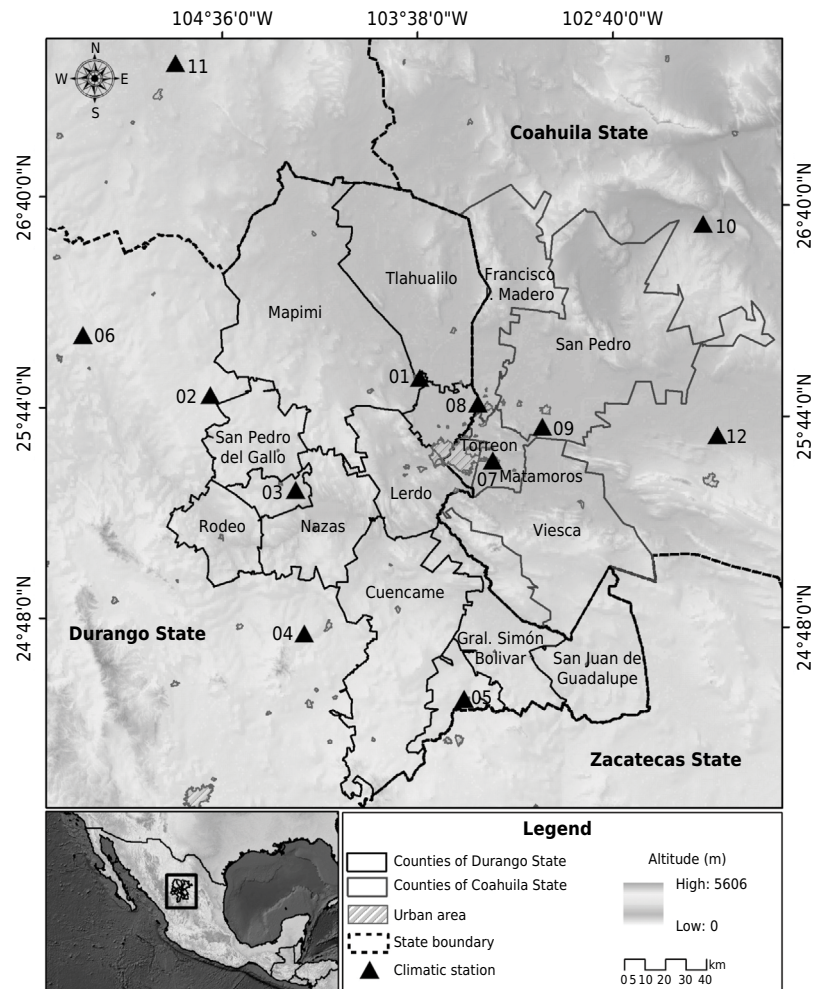


Figure 1. Study area and location of weather stations. Numbers correspond to names listed in table 2.

Table 1. Soil type and vegetation within the study area

ID	Name	Soil type	Primary Vegetation ⁽¹⁾
01	Uruza	Calcisol ⁽²⁾	Irrigated agriculture
02	Agua Nueva	Leptosol	Native grassland
03	La Purisima	Calcisol	Rain fed agriculture
04	Peñon Blanco	Chernozem	Native grassland
05	Santa Clara	Kastanozem	Irrigated agriculture/Grassland
06	Puerta de Cabrera	Phaeozem	Native grassland/Rain fed agriculture
07	Matamoros	Cambisol	Irrigated agriculture
08	El Porvenir	Vertisol	Irrigated agriculture
09	San Pedro	Phaeozem	Irrigated agriculture
10	Tanque Nuevo	Solonchak	Irrigated agriculture/Rosethopile desert scrub
11	Jimenez	Calcisol	Irrigated agriculture
12	Parras	Regosol	Xerophilous vegetation/Rain fed agriculture

⁽¹⁾ Vegetation near the weather station (visual verification visited sites and from maps). Source: Inegi (2019).

⁽²⁾ IUSS Working Group WRB (2015).

main characteristics of wind for the weather stations considered in the study. Suspicious data (outliers) were recalculated considering the statistical parameters of the time series recorded. For instance, to check on the reliability of high wind speeds, a suspicious value (outlier) of the variable was compared with the nearest weather station to see if the

Table 2. Location and characteristics of the weather stations

ID	Name	Latitude	Longitude	Elevation	Length of data	AAP	AAT
				m	year	mm	°C
01	Uruza	25° 53' 34"	103° 36' 11"	1115	2009-2013	145.2	21.0
02	Agua Nueva	25° 48' 17"	104° 37' 39"	1935	2010-2017	397.4	17.7
03	La Purisima	25° 23' 21"	104° 12' 05"	1409	2007-2017	371.8	19.5
04	Peñón Blanco	24° 45' 15"	104° 08' 55"	1970	2007-2017	517.7	18.3
05	Santa Clara	24° 28' 27"	103° 22' 17"	1814	2007-2017	443.5	17.6
06	Puerta de Cabrera	26° 03' 26"	105° 15' 19"	1905	2007-2017	439.9	15.9
07	Matamoros	25° 31' 57"	103° 14' 36"	1116	2006-2017	209.3	22.0
08	El Porvenir	25° 46' 58"	103° 19' 06"	1111	2006-2013	188.7	21.1
09	San Pedro	25° 41' 02"	103° 00' 03"	1102	2006-2013	298.0	21.0
10	Tanque Nuevo	26° 34' 60"	102° 13' 08"	822	2008-2012	118.8	21.7
11	Jimenez	27° 16' 11"	104° 49' 39"	1343	2012-2017	324.6	18.5
12	Parras	25° 38' 50"	102° 08' 52"	1197	2006-2017	185.8	20.9

AAP: Annual Average Precipitation. AAT: Annual Average Temperature.

Table 3. Statistical parameters for wind in the study area

ID	Name	Wind velocity				Wind velocity direction		
		Max	Min	Avg	SD	Avg	SD	Prevailing direction from
		km h ⁻¹				degrees Azimut		
01	Uruza	68.2	0.2	13.0	7.6	183.1	126.9	SW
02	Agua Nueva	74.9	0.2	25.8	10.1	134.8	97.2	SE
03	La Purisima	50.3	0.0	14.8	7.5	183.4	115.0	SW
04	Peñón Blanco	75.0	0.8	19.4	10.5	181.1	113.0	SE
05	Santa Clara	64.0	0.1	12.4	10.1	159.0	120.9	SE
06	Puerta de Cabrera	61.7	0.0	20.7	8.1	158.8	104.2	SE
07	Matamoros	39.0	0.0	10.7	6.4	148.1	111.4	SE
08	El Porvenir	42.6	0.0	8.3	8.7	133.0	97.1	SE
09	San Pedro	44.4	0.0	16.2	7.1	109.8	96.3	SE
10	Tanque Nuevo	18.5	0.0	18.5	7.5	128.7	85.7	SE
11	Jimenez	67.1	2.0	14.3	5.6	178.2	87.9	SE
12	Parras	75.0	0.2	19.7	8.0	138.5	79.6	SE

Max: maximum. Min: minimum. Avg: average. SD: standard deviation.

wind event was also recorded on that day. If not, the mean and the standard deviation of the series were considered to make the appropriate correction.

Wind erosive power

For computing potential dust emission in areas with scarce or no vegetation, it is desirable to account for wind erosion. Wind erosion equations have been developed since the early 1960s and have evolved depending on the algorithms to account for different variables. In the Woodruff and Siddoway's model (Woodruff and Siddoway, 1965), degradation of soil by wind is accounted for in the general functional relationship between the dependent variable, E , the potential average annual soil loss in tons hectare⁻¹ yr⁻¹ (or tons acre⁻¹ yr⁻¹), and a series of correlated variables as shown in equation 1:

$$E = f(I, C, K, L, V) \quad \text{Eq. 1}$$

in which I is the soil erodibility index, which represents the potentiality of soil without slope, no cover, unattached, and non-crusted, for being eroded. The value of this variable increases as the percentage of soil fractions greater than 0.84 mm in diameter decreases. The highest value is $765 \text{ ton ha}^{-1} \text{ yr}^{-1}$ ($310 \text{ Mg acre}^{-1} \text{ yr}^{-1}$) for a soil having 1 % of very fine, fine, medium or coarse sand, and the lowest value is $93 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ($38 \text{ Mg acre}^{-1} \text{ yr}^{-1}$) for a soil having 50 % of particles greater than 0.84 mm in diameter. The C factor in equation 1 measures the erosive potentiality of the wind and considers the soil moisture of the site of interest. The soil surface moisture varies directly with precipitation and inversely with the square of temperature. Soil surface moisture levels are not readily available for most areas; therefore, the Thornthwaite's precipitation-evaporation index is used as a proxy (Chepil et al., 1962). The parameter K is the ridge roughness factor, which is a measure of the effect of ridges formed by tillage and planting implements on wind erosion; L is the unsheltered distance across an erodible field, measured along the prevailing wind erosion direction; and V is the vegetative cover factor which accounts for the type, amount, and orientation of growing plants or plant residues on the soil surface (Woodruff and Siddoway, 1965).

For the purpose of this paper, the research was focused on the climatic factor C (Equation 2) aiming to detect potential sites for wind erosion and dust emissions. The rate of soil movement varies directly as the cube of wind velocity (V) and inversely as approximately the square of effective moisture (i.e., moisture held by the soil particles against a given tension exerted by forces of evaporation acting on the soil particles).

$$C = 100 \left[\frac{V^3}{(P - E)^2} \right] M \quad \text{Eq. 2}$$

in which P is the amount of precipitation (inches) and E is the amount of evaporation (inches). The PeE variable is known as the *Soil Moisture Index* described by Thornthwaite (1931) and is the sum of the monthly amounts of $\frac{P}{E}$ through the year (Equation 3). The M factor of equation 2 is the annual average of $\left[\frac{V^3}{(PeE)^2} \right]$ for Garden City Kansas, a city located in the Great Plains of the United States where the model was developed.

$$PeE = \sum_{m=1}^n \left(\frac{P}{E} \right) \quad \text{Eq. 3}$$

in which n is the number of months considered in the computation of the PeE index. As mentioned, to obtain values of C , equation 3 was applied in a monthly way for the months of maximum wind velocities within the study area. According to the Thornthwaite's method, the total annual precipitation divided by the total evaporation is called the $\frac{P}{E}$ quotient. The sum of the twelve monthly $\frac{P}{E}$ ratios is called the PeE index. The M parameter was obtained yearly for each weather station considered in the study. Maximum wind velocities were considered for obtaining C values with their corresponding probabilities of occurrence. Wind velocity data from the weather stations used in this research are set at 2.0 m above the soil surface. However, wind speed varies with height, according to a power-law. Therefore, according to the Thornthwaite's method, the velocity must be corrected to 10 m high (Table 2). The power-law equation is a simple yet useful model of the vertical wind profile; its general form is shown in equation 4 (Spera and Richards, 1979; Lim, 2012).

$$\frac{\overline{V}_z}{V_{z10}} = \left[\frac{Z}{Z_{10}} \right]^\alpha \quad \text{Eq. 4}$$

in which \overline{V}_z is the mean wind speed (m s^{-1}) at height Z at the study site; V_{z10} is the wind velocity at a height of 10 m; and α is an empirical exponent that depends on the surface roughness, stability, and temperature gradient. For the conditions in the region of study, $\alpha = 0.14$, which corresponds to open terrain with scattered obstacles generally less than

10 m high (Usepa, 2000). Given the lack of data for evaporation (pan evaporation) within the study area, the relationship obtained by Thornthwaite for computing the variable $\frac{P}{E}$ out of precipitation and temperature was used, as shown in equation 5.

$$\frac{P}{E} = 11.5 \left(\frac{P}{T - 10} \right)^{1.11} \quad \text{Eq. 5}$$

in which P is precipitation (inches) and T is the temperature (degrees Fahrenheit). In this way, monthly precipitation–evaporation ratios were obtained and added up according to equation 3 to yield the PeE index.

If the parameter M is considered, then the wind erosion climatic factor C as computed by equation 2 indicates the relative mean rate of wind erosion that would occur at any geographic location as a percentage of the mean rate that would occur at Garden City, Kansas if conditions other than climate were the same (Chepil et al., 1962). The wind erosion equation was developed at Garden City, Kansas, where the climate factor was designated as 100 percent. Therefore, the climatic factor differs from this base figure for areas other than Garden City. Originally, for Garden City, $V = 13.5$ miles hr^{-1} , $PeE = 29$, and $M = 2.9$, so that $C = 100$ %.

Recurrence of average wind velocities

A more objective way to analyze and to project the impact of any climate event is through the analysis of the probability of occurrence. In this way, the evaluation of the risk of extreme weather events, such as high-speed winds, requires methods to statistically estimate their recurrence or return periods from the measured data (Makkonen, 2006). The return period R (in years) of an event is related to the probability Pb of not exceeding this event in one year, as shown in equation 6.

$$R = \frac{1}{(1 - Pb)} \quad \text{Eq. 6}$$

For computing R , first, the ranking of the data in increasing order of magnitude from the smallest to the largest is required. Then it is necessary to associate each value to a cumulative probability Pb value. Then, an X (return period) – Y (value of the variable) is plotted in any spreadsheet and a line is fitted. Using this graph, one can interpolate, or extrapolate, to estimate the return period of the extreme value of interest.

In this way, one may estimate the average time that will elapse between two events of the same magnitude; or, the probability that a given event will be equalled or exceeded once each “ R ” years. The return period R is the inverse of probability and is tied to the magnitude of the event.

RESULTS

The weather stations with the highest wind velocity were Peñon Blanco and Parras recording up to 75 km h^{-1} , while the lowest of the maximum velocity was for Tanque Nuevo at 18.5 km h^{-1} (Table 3). All the weather stations recorded calm conditions (wind $< 2 \text{ km h}^{-1}$) during the period of the data analyzed. Nevertheless, on average, the most critical stations in this regard are Agua Nueva and Puerta de Cabrera. However, the $\frac{P}{E}$ are high, which contributes to lower C value and, consequently, lower erodability. Regional average annual results for wind velocity and direction are shown in figure 2. The wind rose also shows the percentage of the total wind velocity values that fall within a given category of intensity. As illustrated, the prevailing wind direction within the region of study comes from the southeast reaching a yearly average of up to 12.96 km h^{-1} (3.60 m s^{-1}); however, winds also blow from south of the study region. A less proportion of the wind data (5-10 %) accounts for winds from the southwest and east.

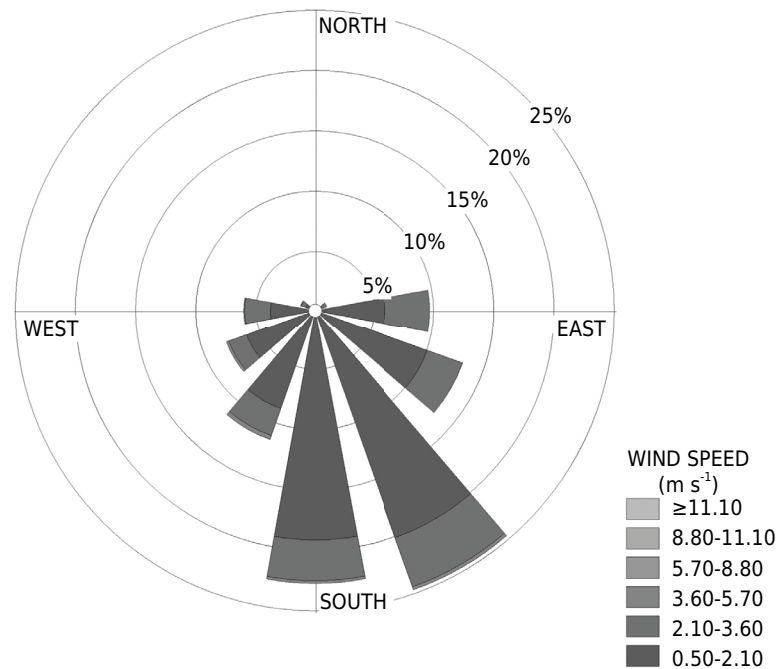


Figure 2. Regional average annual wind velocity and direction for the study area.

It is readily understood that when the $\frac{P}{E}$ ratio approaches a value of 1.0, the system is in equilibrium (precipitation equals to atmospheric demand). Conversely, the lower the $\frac{P}{E}$ value, the greater the water deficit. The C parameter computed by equation 2 reflects the global climatic factor for a specific weather station. Nevertheless, the monthly variation can be analyzed considering the monthly $\frac{P}{E}$ values instead.

The relationship among $\frac{P}{E}$ values and wind velocity is shown in figure 3, which is a graphical representation of equations 2, 3, and 5 and constitutes the core of the findings of the paper. The mathematical structure of equation 2 states that the smaller the value of the soil moisture index (PeE), or its partial monthly value $\frac{P}{E}$, the more the C value increases. On the other hand, if the velocity (V) increases under a decreasing $\frac{P}{E}$ value, then the C value increases as well. The highest C value (68.10) was for the Tanque Nuevo and the lowest for Santa Clara (2.55) weather stations.

The classification of C given by Chepil et al. (1962) is as follows: very low (0-17 %), low (18-35 %), intermediate (36-71 %), high (72-150 %), and very high (>150 %). Accordingly, only three weather stations (Uruza, Tanque Nuevo, and Parras) fall within the “intermediate” category where the ratio $\frac{P}{E}$ is relatively small (0-0.1) with wind velocities from 15 to 30 km h⁻¹. As previously stated, given the relationship between variables depicted in equation 2, C values tend to be higher with low $\frac{P}{E}$ values and high wind velocity.

Usually, higher wind velocities in the study area occur during the first quarter of the year (dry season) when precipitation events are scarce. During that period is when dust storms (“tolvaneras”) occur. After this period, the agriculture irrigation cycle begins (May-June) in the irrigation district (maintaining the soil humid) and early summer rains (monsoon season) begin, which helps to settle down dust particles. Despite rainfall events registered in most of the weather stations, the range of the precipitation-evaporation ratio, as shown in figure 3, is $0 < \frac{P}{E} \leq 6.0$, which characterizes the zone as an arid region. The recurrence of a $\frac{P}{E}$ value of a given magnitude, according to equation 6, is shown in figure 4 where it can be noted that for a given return period (e.g., 5-year as shown in figure 4), the value of this variable is different.

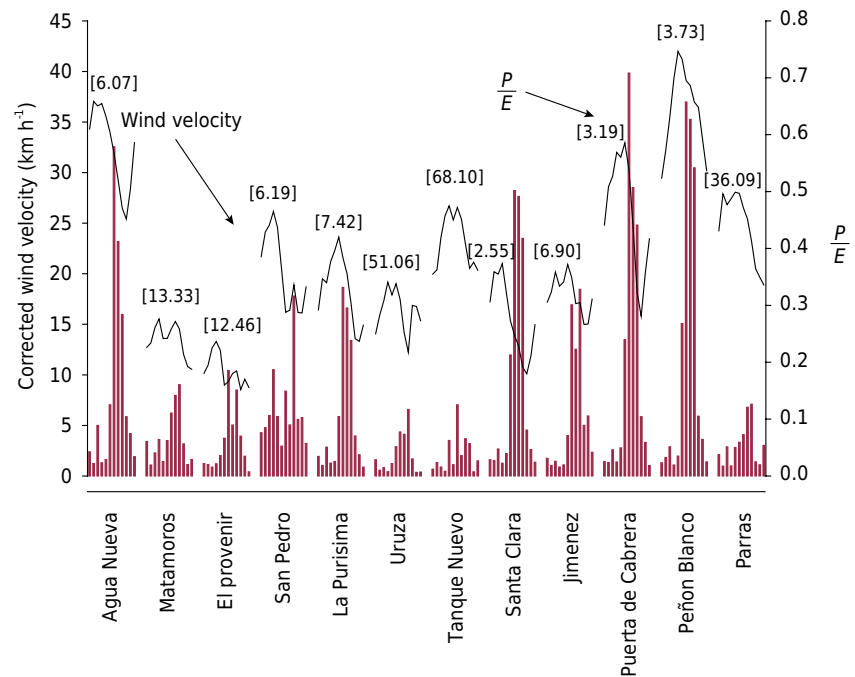


Figure 3. Monthly variation of the precipitation effectiveness ($\frac{P}{E}$) and maximum wind velocity for the weather stations considered within the study area. The number in brackets is the C value for the specific weather station. Each bar represents a month for a given station.

DISCUSSION

Weather characterization is a prerequisite for natural resources conservation and management. We characterized the patterns of wind and the occurrence of precipitation within a study region and the linkage to soil water status through indexes. The region is prone to have dust storms caused by these two factors. Under dry conditions, the soil is more prone to be lifted by wind since the cohesion among soil particles diminishes, and the amount of soil to be removed by wind will depend upon the physical structure of the primary soil particles (clay with negative charges is more cohesive than sand or silt) (Penn, 2004). Results have shown the practicality and applicability of the method since it utilizes readily available information as precipitation, temperature, and wind velocity as a means to reach useful information for evaluating and planning purposes.

A region-specific model was parameterized following the lack of field infrastructure for the assessment of wind erosion. Areas with higher C values (e.g., Tanque Nuevo $C = 68.10$) are potential sources of wind erosion and should be considered in any conservation or management plans. In simpler terms, the dryer the soil, the more prone to be eroded under high wind velocities. Despite the propensity of soil for being eroded by wind in the study area, neither preventive nor corrective actions have been implemented (López-Santos et al., 2017). In addition, a considerable impact on wind and water erosion is expected under conditions of climate change for the region (López-Santos et al., 2012). The results of this research, which showed that C values tend to be higher with low $\frac{P}{E}$ values and high wind velocity, are in agreement with the findings of Klik (2008), in Austria. Moreover, the C value indicates the propensity of soil to be eroded; the greater the value, the worst. However, relatively small values of C do not imply that the area is free of such a risk. It would imply a relatively less wind erosion, but the coupling of this parameter with the other parameters of the wind erosion equation (equation 1) will dictate the final value of soil erosion by wind. As shown in table 1, the type of soil around the Uruza weather station is Calcisol, which are well-drained soils with fine to medium texture prone to be eroded by wind. The Tanque Nuevo weather station has Solonchak type of soils that are defined by high soluble salt accumulation; they are formed by saline

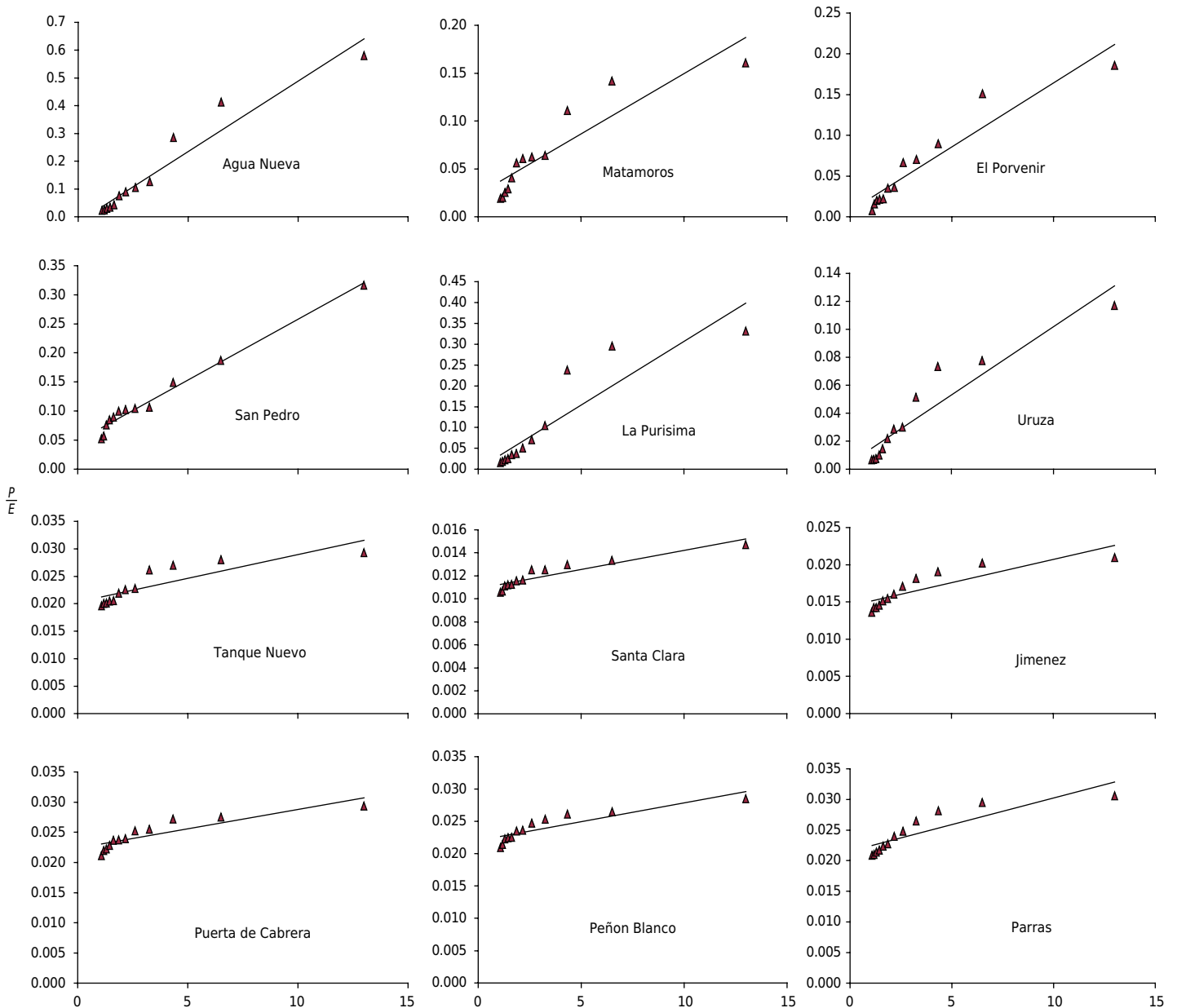


Figure 4. Magnitude-frequency of the $\frac{P}{E}$ parameter for the weather stations considered in the study. Note that the vertical scale (y-axis) is different for each weather station because of the magnitude of the event.

parent material under conditions of high evaporation. Finally, for weather station Parras, the predominant type of soil is Regosol, which is a very weakly developed mineral soil prone to be eroded. Soil moisture content, wind velocity, and soil cover are the main factors that influence soil movement; the situation worsens under aridity conditions when the soil is dry and soil cover diminishes.

Considering that rainfall effectiveness is related to soil erosion (given that the dryer the soil the more prone to be eroded), the return period serves to indirectly foresee what should be expected in terms of dust pollution according to site-specific characteristics. The greater the return period, the more different the $\frac{P}{E}$ values among weather stations (Figure 4). These sites are differentiated by their climatologic conditions (precipitation and wind velocity mainly) and physical location (such as proximity to mountains, slope, and soil cover).

In this study, no statistical correlation between observed and measured data was performed since it was not the objective of the research. Moreover, the models presented

are a means of quantifying the propensity of soils to be eroded given climate and soil characteristics. The practical use of the results of the research is for decision-makers and natural resources conservationists for the process of planning preventive measures of soil erosion by wind.

CONCLUSIONS




The wind rose shows wind direction and intensity and provides useful information for the implementation of local dust control and wind erosion mitigation strategies. In this study, dust pollution prone areas were identified, showing areas where conservation strategies should be directed. Through the analysis of data, a wind rose was obtained highlighting the wind characteristics (intensity and direction) that may induce dust storms. For the region, dust source areas have been identified and the assessment of the climatic factor C of the wind erosion equation as well as the rainfall evaporation ratio (P/E) were computed. For local mitigation strategies, vegetative barriers perpendicular to the predominant wind direction would prevent or minimize dust pollution through the cities. The approach used to deliver a record of the conditions governing wind erosion and dust storm patterns for an arid zone in northern Mexico could be replicated elsewhere. Given that data from weather stations can be easily obtained, the methodology can be followed by other researchers to develop their own regional or local models.




Based on the findings of this work, the aim of future research will include fieldwork to collect air and dust samples during different seasons. The amount and type of pollutants adhered to dust particles are yet to be determined. Combined with the maps that show wind direction and velocity, this data would allow better decision planning regarding the prevention and mitigation of soil erosion by wind.




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