Chapter 8. Open Area Wind Erosion

8.1 Characterization of Source Emissions 8-1
8.2 Emission Estimation: Primary Methodology 8-2
8.3 Emission Estimation: Alternate Methodology 8-5
8.4 Emission Estimation: Other Methodologies 8-6
8.5 Demonstrated Control Techniques 8-18
8.6 Regulatory Formats 8-19
8.7 Compliance Tools 8-19
8.8 Sample Cost-Effectiveness Calculation 8-21
8.9 References 8-23

8.1 Characterization of Source Emissions

Dust emissions may be generated by wind erosion of open areas of exposed soils or other aggregate materials within an industrial facility. These sources typically are characterized by nonhomogeneous surfaces impregnated with nonerodible elements (particles larger than approximately 1 centimeter [cm] in diameter). Field testing of coal piles and other exposed materials using a portable wind tunnel has shown that: (a) threshold wind speeds exceed 5 meters per second (m/s) (11 miles per hour [mph]) at 15 cm above the surface or 10 m/s (22 mph) at 7 m above the surface, and (b) particulate emission rates tend to decay rapidly (half-life of a few minutes) during an erosion event. In other words, these aggregate material surfaces are characterized by finite availability of erodible material (mass/area) referred to as the erosion potential. Any natural crusting of the surface binds the erodible material, thereby reducing the erosion potential. Loose soils or other aggregate materials consisting of sand-sized materials act as an unlimited reservoir of erodible material and can sustain emissions for periods of hours without substantial decreases in emission rates.

If typical values for threshold wind speed at 15 cm are corrected to typical wind sensor height (7 to 10 m), the resulting values exceed the upper extremes of hourly mean wind speeds observed in most areas of the country. In other words, mean atmospheric wind speeds are not sufficient to sustain wind erosion from flat surfaces of the type tested. However, wind gusts may quickly deplete a substantial portion of the erosion potential. Because erosion potential has been found to increase rapidly with increasing wind speed, estimated emissions should be related to the gusts of highest magnitude. The routinely measured meteorological variable that best reflects the magnitude of wind gusts is the fastest mile. This quantity represents the wind speed corresponding to the whole mile of wind movement that has passed by the 1-mile contact anemometer in the least amount of time. Daily measurements of the fastest mile are presented in the monthly Local Climatological Data (LCD) summaries. The duration of the fastest mile, typically about 2 minutes (for a fastest mile of 30 mph), matches well with the half-life of the erosion process, which ranges between 1 and 4 minutes. It should be noted, however, that peak winds can significantly exceed the daily fastest mile.

The wind speed profile in the surface boundary layer is found to follow a logarithmic distribution as follows:

$$u(z) = \frac{u*}{0.4} \ln \frac{z}{z_0} \quad (z > z_0) \tag{1}$$

where,

u = wind speed (cm/s)
u^* = friction velocity (cm/s)
z = height above test surface (cm)
z_o = roughness height (cm)
0.4 = von Karman’s constant (dimensionless)

The friction velocity (u^*) is a measure of wind shear stress on the erodible surface, as determined from the slope of the logarithmic velocity profile. The roughness height (z_o) is a measure of the roughness of the exposed surface as determined from the y-intercept of the velocity profile, i.e., the height at which the wind speed is zero. These parameters are illustrated in Figure 8-1 for a roughness height of 0.1 cm.

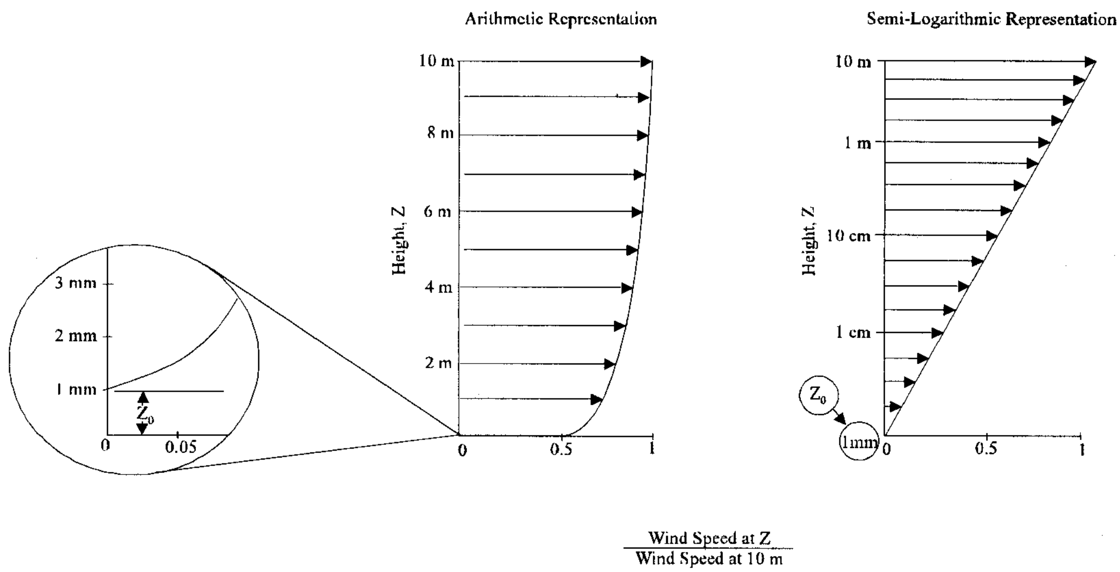

Figure 8-1. Illustration of Logarithmic Wind Velocity Profile

Emissions generated by wind erosion are also dependent on the frequency of disturbance of the erodible surface because each time that a surface is disturbed, its erosion potential is restored. A disturbance is defined as an action that results in the exposure of fresh surface material. On a storage pile, this would occur whenever aggregate material is either added to or removed from the old surface. A disturbance of an exposed area may also result from the turning of surface material to a depth exceeding the size of the largest pieces of material present.

8.2 Emission Estimation: Primary Methodology[1-11]

This section was adapted from Section 13.2.5 of EPA's *Compilation of Air Pollutant Emission Factors (AP-42)*. Section 13.2.5 was last updated in January 1995.

The PM10 emission factor for wind-generated particulate emissions from mixtures of erodible and nonerodible surface material subject to disturbance may be expressed in units of grams per square meter (g/m^2) per year as follows:

$$\text{PM10 Emission Factor} = 0.5 \sum_{i=1}^{N} P_i \qquad (2)$$

where,

N = number of disturbances per year
Pi = erosion potential corresponding to the observed (or probable) fastest mile of wind for the ith period between disturbances (g/m^2)

In calculating emission factors, each area of an erodible surface that is subject to a different frequency of disturbance should be treated separately. For a surface disturbed daily, N = 365 per year, and for a surface disturbance once every 6 months, N = 2 per year. The erosion potential function for a dry, exposed surface is given as:

$$P = 58\,(u^* - u_t^*)^2 + 25\,(u^* - u_t^*) \qquad (3)$$

$$P = 0 \quad \text{for } u^* \leq u_t^*$$

where,

u^* = friction velocity (m/s)
u_t = threshold friction velocity (m/s)

Because of the nonlinear form of the erosion potential function, each erosion event must be treated separately. The PM2.5/PM10 ratio for windblown fugitive dust posted on EPA's CHIEF website is 0.15. This ratio is based on the analysis conducted by MRI on behalf of WRAP.[11]

Equations 2 and 3 apply only to dry, exposed materials with limited erosion potential. The resulting calculation is valid only for a time period as long or longer than the period between disturbances. Calculated emissions represent intermittent events and should not be input directly into dispersion models that assume steady-state emission rates. For uncrusted surfaces, the threshold friction velocity is best estimated from the dry aggregate structure of the soil. A simple hand sieving test of surface soil can be used to determine the mode of the surface aggregate size distribution by inspection of relative sieve catch amounts, following the procedure described below.

FIELD PROCEDURE FOR DETERMINING THRESHOLD FRICTION VELOCITY
(from a 1952 laboratory procedure published by W. S. Chepil[5])

<u>Step 1.</u> Prepare a nest of sieves with the following openings: 4 mm, 2 mm, 1 mm, 0.5 mm, and 0.25 mm. Place a collector pan below the bottom (0.25 mm) sieve.

<u>Step 2.</u> Collect a sample representing the surface layer of loose particles (approximately 1 cm in depth, for an encrusted surface), removing any rocks larger than about 1 cm in average physical diameter. The area to be sampled should be not less than 30 cm by 30 cm.

<u>Step 3.</u> Pour the sample into the top sieve (4-mm opening), and place a lid on the top.

<u>Step 4.</u> Move the covered sieve/pan unit by hand, using a broad circular arm motion in the horizontal plane. Complete 20 circular movements at a speed just necessary to achieve some relative horizontal motion between the sieve and the particles.

<u>Step 5.</u> Inspect the relative quantities of catch within each sieve, and determine where the mode in the aggregate size distribution lies, i.e., between the opening size of the sieve with the largest catch and the opening size of the next largest sieve.

<u>Step 6.</u> Determine the threshold friction velocity from Table 8-1.

The results of the sieving can be interpreted using Table 8-1. Alternatively, the threshold friction velocity for erosion can be determined from the mode of the aggregate size distribution using the graphical relationship described by Gillette.[5, 6] If the surface material contains nonerodible elements that are too large to include in the sieving (i.e., greater than about 1 cm in diameter), the effect of the elements must be taken into account by increasing the threshold friction velocity.[10]

Table 8-1 Field Procedure for Determination of Threshold Friction Velocity (Metric Units)

Tyler Sieve No.	Opening (mm)	Midpoint (mm)	u_t* (cm/s)
5	4		
9	2	3	100
16	1	1.5	76
32	0.5	0.75	58
60	0.25	0.375	43

Threshold friction velocities for several surface types have been determined by field measurements with a portable wind tunnel. These values are presented in Table 8-2.

Table 8-2. Threshold Friction Velocities (Metric Units)

Material	Threshold friction velocity (m/s)	Roughness height (cm)	Threshold wind velocity at 10 m (m/s)	
			z_o = Actual	z_o = 0.5 cm
Overburden[a]	1.02	0.3	21	19
Scoria (roadbed material)[a]	1.33	0.3	27	25
Ground coal (surrounding coal pile)[a]	0.55	0.01	16	10
Uncrusted coal pile[a]	1.12	0.3	23	21
Scraper tracks on coal pile[a,b]	0.62	0.06	15	12
Fine coal dust on concrete pad[c]	0.54	0.2	11	10

[a] Western surface coal mine; reference 2.
[b] Lightly crusted.
[c] Eastern power plant; reference 3.

The fastest mile of wind for the periods between disturbances may be obtained from the monthly local climatological data (LCD) summaries for the nearest reporting weather station that is representative of the site in question.[7] These summaries report actual fastest mile values for each day of a given month. Because the erosion potential is a highly nonlinear function of the fastest mile, mean values of the fastest mile are inappropriate. The anemometer heights of reporting weather stations are found in Reference 8, and should be corrected to a 10-m reference height using Equation 1. To convert the fastest mile of wind (u^+) from a reference anemometer height of 10 m to the equivalent friction velocity (u^*), the logarithmic wind speed profile may be used to yield the following equation:

$$u^* = 0.053\ u_{10}^+ \qquad (4)$$

where,

u^* = friction velocity (m/s)
u_{10}^+ = fastest mile of reference anemometer for period between disturbances (m/s)

This assumes a typical roughness height of 0.5 cm for open terrain. Equation 4 is restricted to large relatively flat exposed areas with little penetration into the surface wind layer.

8.3 Emission Estimation: Alternate Methodology

Duane Ono with the Great Basin Unified APCD and Dale Gillette developed a method called the Dust ID method to measure fugitive PM10 dust emissions due to wind erosion that has been approved for use in PM10 SIPs.[12, 13] This method has been applied to the dry lake bed at Owens Lake, CA using an extensive sand flux monitoring network. Owens Lake is the largest single source of fugitive dust in the United States (estimated to be ~80,000 tons PM10/year). The network consisted of co-located electronic Sensits and passive Cox Sand Catchers (CSCs) deployed on a 1 km x 1 km grid covering 135 square kilometers of the lake bed with their sensor or inlet positioned 15 cm above the surface. Sensits measure the kinetic energy or the particle counts of sand-sized particles as they saltate across the surface. Due to differences in the electronic response of individual Sensits, these units had to be co-located with passive sand flux measurement devices to calibrate their electronic output and to determine the hourly sand flux. The battery powered Sensits were augmented with a solar charging system. A data logger recorded hourly Sensit data during inactive periods and switched to 5-minute data during active erosion periods. CSC's are passive instruments that are used to collect sand-sized particles that are blown across the surface during a dust event. These instruments were designed and built by the Great Basin Unified Air Pollution Control District as a reliable, low-cost instrument that could withstand the harsh conditions at Owens Lake. CSC's have no moving parts and can collect sand for a month at Owens Lake without overloading the collector. As an alternative to hourly sand (saltation) flux measurements relying on Sensits, Ono[14] found that monthly sand flux measurements obtained with CSCs could be applied to a model developed by Gillette et al.[15] to provide a good estimate of hourly sand flux rates.

Hourly PM10 emissions from each square kilometer of the lake bed were estimated from the following equation:

$$F_a = K_f \times q$$

where, F_a = PM10 emissions flux ($g/cm^2/hr$)
q = hourly sand flux ($g/cm^2/hr$) measured at 15 cm above the surface
K_f , called the K-factor, = proportionality factor relating the PM10 emissions flux to the sand flux measured at 15 cm above the surface.

K_f values were determined by comparing CALPUFF model predictions, based on meteorological data from thirteen 10-meter towers and an Upper Air Wind Profiler to generate wind fields using the CALMET model, to observed hourly PM10 concentrations measured at six PM10 monitoring sites utilizing TEOM PM10 monitors. A K-factor of 5×10^{-5} was used to initially run the model and to generate PM10 concentration values that were close to the monitored concentrations. Hourly K-factor values were later adjusted in a post-processing step to determine the K-factor value that would have made the modeled concentration match the monitored concentration at each of the six PM10 monitor sites using the following equation:

$$K_f = K_i\ [(C_{obs} - C_{bac})/C_{mod}]$$

where, K_i = initial K-factor (5 x 10^{-5})
$C_{obs.}$ = observed hourly PM10 concentration (μg/m^3)
$C_{bac.}$ = background PM10 concentration (assumed to be 20 μg/m^3)
$C_{mod.}$ = model-predicted hourly PM10 concentration (μg/m^3)

The results showed that K_f changed spatially and temporally at Owens Lake and that the changes corresponded to different soil textures on the lake bed and to seasonal surface changes that affected erodibility. The results also showed that some source areas were active all year, while others were seasonal and sometimes sporadic. Wind tunnel tests at Owens Lake independently confirmed these seasonal and spatial changes in K_f. Ono et al.[12] concluded that the emission estimates using their Dust ID method were more accurate than the AP-42 method for estimating daily emissions, since the emissions estimates correspond to measured hourly wind erosion on the lake bed. For daily emissions, Ono and co-workers believe that AP-42 drastically overestimates the emissions at low wind speed conditions, and underestimates emissions at high wind speeds. This large discrepancy in the emission estimates is due to the use of a single threshold friction velocity for the entire erosion area in the AP-42 method. The AP-42 method and the Dust ID method of estimating emissions resulted in very close agreement for the annual emissions.

8.4 Emission Estimation: Other Methodologies

Several alternative emission estimation methods for open area wind erosion have been developed that are still in the developmental stage and have not yet been approved by federal or state agencies. Thus, the reader is cautioned in the use of these methods.

8.4.1 MacDougall Method

MacDougall developed a method for estimating fugitive dust emissions from wind erosion of vacant land.[16] This method, which relies heavily on emission factors developed for different vacant land parcels using wind tunnels. The availability of wind tunnel results for the types of vacant land being assessed must be considered when deciding to use this method for other applications. It should be pointed out that in 2003 Environ (under contract to the Western Governors' Association) abandoned this approach due to the paucity of sufficient wind tunnel data for many different vacant land parcels in the western U.S.[17] Also, the WRAP's fugitive dust expert panel had major reservations regarding the MacDougall method.[18] Panel members were skeptical about using the proposed methodology since wind tunnels have shortcomings and do not represent actual conditions in nature. The panel concluded that determining emission factors in the manner proposed will result in significant underestimation of windblown dust for those cases where saltation plays a role. The six steps described in the MacDougall method are summarized below.

<u>Step 1: Categorizing Vacant Land.</u> Vacant land within the study area must be categorized based upon the potential of the parcels to emit fugitive dust during wind

events. Many wind tunnel studies have been conducted in the western United States, and the vacant land descriptions of the wind tunnel test areas should be used to categorize the vacant land within the study area. When categorizing vacant land, it is especially important whether the land has vegetation, rocks or other sheltering elements, whether the soil crust is intact or disturbed, and whether there are periodic activities on the vacant land such as vehicles or plowing that will change the land from fairly stable to unstable. Not every parcel of vacant land will necessarily fit into a category that has been wind tunnel tested. For parcels without a specific vacant land type wind tunnel test, assumptions will need to be made of the best representative land type and uncertainties noted.

Step 2: Identify Wind Tunnel Emission Factors. Based upon the vacant land categorization, wind tunnel results should be reviewed and applied appropriately to each category of vacant land. Wind tunnel results should be reviewed to determine if "spikes" from the initial portion of the test are presented separately or averaged into an hourly factor. Whenever possible, spikes should not be included in an hourly factor. The spike values should be included only at the beginning of each wind event.

Step 3: Develop Meteorological Data Set. For the area to be studied, hourly average wind speeds, rainfall, and if available peak wind gust data should be gathered. If a study area is particularly large, several different meteorological data sets may need to be gathered, and each land parcel matched with the meteorological data that impacts that parcel.

Step 4: Determine Land Type Reservoirs, Threshold Wind Velocities, Wind Events, and Rainfall Events. Based upon the wind tunnel results for each vacant land type, the wind speed when emissions were first measured for the vacant land type, should be set as the threshold wind speed. Most vacant land does not have an endless reservoir of fugitive dust; however, land that has a high degree of disturbance will continue to emit throughout a wind event. Therefore, for each vacant land type, the wind tunnel results should be reviewed and a determination made on the length of time the parcel will emit for a give wind event. It is recommended that an assumption be made that parcels with sheltering elements, vegetated parcels, or parcels with a soil crust will only emit during the first hour of a wind event. Parcels with a relatively high silt component or with frequent disturbance will probably continue to emit throughout a wind event. Because most threshold wind speeds are relatively high (i.e., sustained hourly winds of 25 to 30 mph), a wind event may be defined as any time period when winds reach the threshold wind velocities separated by at least 24 hours before a new wind event is defined. Depending on the soils in an area, rain may have a large impact on wind erosion. Days with rain should not be included in the inventory.

Step 5: Develop Emission Inventory Specific Emission Factors. Using the reservoir determination, threshold wind speeds, wind event determination and rainfall factors, determine hours when wind conditions produced emissions from each vacant land parcel for the time period of the emission inventory. The number of hours with wind speeds in each wind speed category should be totaled. The number of hours can then be multiplied by the wind tunnel emission factor and a total emission factor for the time period of the inventory can be calculated. The emission factor equations for vacant land with and without sustained emissions are given as follows:

(a) With sustained emissions: $EF_1 = (\sum (H\ P))$

where, EF_1 = PM10 emission factor (lb/acre)
H = number of hours when wind conditions result in emissions
P = emission factor for a given vacant land category (lb/hour-acre)

(b) Without sustained emissions: $EF_1 = (\sum (W\ P))$

where, EF_1 = PM10 emission factor (lb/acre)
W = number of wind events when wind conditions result in emissions
P = emission factor for a given vacant land category (lb/acre)

The emission factor equation for spike emissions is given as:

$$EF_2 = (\sum (E\ S))$$

where, EF_2 = spike PM10 emission factor (lb/acre)
E = number of events producing spike emissions
S = spike mass for a given vacant land category (lb/acre)

Emission factors will vary from time period to time period and from vacant land type to vacant land type. Generally speaking, disturbed lands will have unlimited reservoirs and lower threshold wind velocities leading to much higher emissions than stable or sheltered parcels with one hour reservoirs. An emission factor should be developed for each vacant land category in the inventory.

Step 6: Apply Emission Inventory Specific Emission Factors to Vacant Land Categories. Once emission inventory emission factors have been developed, the number of acres in each category should be multiplied by the factor and the emissions totaled. It may be useful to develop certain factors over shorter time periods and then total the emissions over a longer time period. For example, one may want to develop winter factors and summer factors and then total them together for the annual inventory. For large areas, where vacant land categories will change over the duration of an inventory or different meteorological data sets will apply, it is advisable to subdivide the inventory by time period or area, and then total the inventory at the end. Annual emissions for each vacant land category are calculated as follows:

$$E = A\ (EF_1 + EF_2)$$

where, E = annual emissions for a given vacant land category
A = vacant land category acreage
EF_1 = annual emission factor for a given vacant land category
EF_2 = spike emission factor for a given vacant land category

8.4.2 Draxler Method

Based on an evaluation of available algorithms for calculating wind blown fugitive dust emissions, the WRAP expert fugitive dust panel[18] recommended the use of the algorithm developed by Draxler et al.[19] that was based on the earlier work of Marticorena et al.[20] This algorithm received the highest score on the basis of extensive field verification test results and having undergone peer review. Draxler and coworkers developed their algorithm for estimating fugitive dust emissions during desert dust storms in Iraq, Kuwait, and Saudi Arabia using a Lagrangian transport and dispersion model where the vertical dust flux was proportional to the difference in the squares of the friction velocity and threshold friction velocity. A proportionality constant was used to relate the surface soil texture to the PM10 dust emissions, and is defined as the ratio of vertical flux of PM10 to total aeolian horizontal mass flux. PM10 emissions caused by wind erosion were estimated in a stepwise process as follows:

Step I. Obtain large scale and small scale wind fields
Step II. Estimate sand movement (horizontal flux of saltation particles ≥50 μm)
Step III. Calculate vertical resuspended dust emissions

The horizontal flux of sand, Q (μg/meter-second), was modeled as follows:

$$Q = A\ (\rho/g)\ u^{*}\ (u^{*2} - u^{*2}_{t})$$

where, A = a dimensionless constant
ρ = the density of air
g = the acceleration due to gravity
u^{*} = the friction velocity (m/s)
u^{*}_{t} = the threshold friction velocity (m/s) required for initiation of sand movement by the wind.

The value of A is not constant if there is wetting followed by crusting of the surface sediments, or if there is a depletion of loose particles on the surface for a "supply-limited" surface. The value of A ranges from a maximum of ~3.5 when the surface is covered with loose sand to ~0 when the surface has a smooth crust with few loose particles larger than 1 mm. Suspended dust is proportional to saltation or sandblasting as follows:

$$F = K\ Q$$

where, F = the vertical flux of dust (μg/m^2-second)
K = proportionality factor (m^{-1}) that relates the surface soil texture to PM10 dust emissions
Q = the horizontal flux of saltating particles (μg/m-second)

The value of K is not precisely known, but data sets of F versus Q are available so that estimates of K can be made for certain soils. For sand textured soils, K is estimated to be ~5.6 x 10^{-4} m^{-1} and A is ~2.8.

8.4.3 UNLV Method

James and co-workers with the University of Nevada Las Vegas (UNLV) developed a wind blown dust inventory for Clark County, NV based on wind tunnel measurements.[21] The method involved deriving estimates of wind blown fugitive dust emission factors for three categories of vacant land: disturbed vacant land, stabilized vacant land, and undisturbed native desert soils. The emission factors included geometric mean hourly "spike" corrected emission rates (tons/acre-hour) for disturbed vacant land, stabilized vacant land and undisturbed native desert soils as well as geometric mean spike emissions (ton/acre) for disturbed vacant land and undisturbed native desert soils as a function of wind speed and soil type. The emission inventory assumed that the particulate reservoir for disturbed vacant land had no limit. For every hour the sustained wind speeds were within a given wind speed category above the "spike" wind speed, the emissions were calculated. A single "spike" mass was added for each acre of vacant land for those days that the wind speed exceeded a threshold wind speed, assuming each day represented a single wind event and reservoir recharging would not have occurred during a 24-hour period. Wind speeds less than the "spike" speed were not included in the emission calculations. Because the native desert parcels have a limited PM10 reservoir, it was assumed that the reservoir would be depleted within one hour of sustained winds above the "spike" wind speed. Therefore, only one hour of emissions were calculated during each day that winds exceeded the threshold friction velocity ("spike" wind speed) for native desert parcels.

The wind speed threshold for generating fugitive dust emissions was estimated by James et al.[21] to be 20 mph for disturbed vacant land and 25 mph for native desert parcels. Because the parcels stabilized with dust suppressants had been subjected to some disturbance by vehicle traffic that may have caused some dust palliatives to break down, the initial wind threshold for this category was lower than the other categories, namely 15 mph. However, the use of dust palliatives greatly reduced the overall emission factors. Spikes were generally not observed from the stabilized parcels, and emission factors without spike corrections were used for stabilized parcels. As with native desert, it was assumed that the stabilized parcels have a limited PM10 reservoir that would be depleted within one hour of sustained winds above the threshold wind velocity. Therefore, only one hour of emissions was calculated during each day for stabilized parcels.

For a sustained wind speed of 25 mph, the geometric mean hourly spike corrected emission factors across all soil types for Clark County were estimated to be ~5 x 10^{-3} ton/acre-hour for disturbed vacant land, ~2 x 10^{-3} ton/acre-hour for native desert, and ~2 x 10^{-4} ton/acre-hour for stabilized land. The geometric mean spike emissions for a sustained wind speed of 25 mph were estimated to be ~2 x 10^{-3} ton/acre for disturbed vacant land and ~5 x 10^{-4} ton/acre for undisturbed native desert parcels. It should be pointed out that there was significant scatter in the observed data, with within category variability ranging over 1 to 2 orders of magnitude.

8.4.4 WRAP RMC Method

The Dust Emissions Joint Forum (DEJF) of the Western Regional Air Partnership contracted with ENVIRON to develop a particulate emission calculation method for open area wind erosion in 2003. The DEJF extended ENVIRON's original contract (Phase 2) to provide windblown dust emissions inventories, and perform modeling simulations of the effects of those emissions on regional haze for calendar year 2002 and future year projections. The purpose of this additional effort was to improve the windblown dust emissions model developed as part of Phase 1. The results of the initial model runs and subsequent sensitivity simulations had demonstrated a need to revise and/or update various assumptions associated with the development of the emission inventory. To this end, revised estimation methodologies and algorithms were evaluated in Phase 2 in order to address various shortcomings and limitations of the Phase 1 version of the model. Many of the assumptions employed in the Phase 1 methodology were necessitated by a lack of specificity in the underlying data used to characterize vacant land types and soil conditions in relation to the potential for wind erosion. Even in Phase 2, it was necessary to rely on some assumptions where data were lacking.

Summary of the WRAP RMC Method

The WRAP RMC windblown dust method utilizes wind tunnel-based emission algorithms for different soils and accounts for land use and local meteorology. The complete set of documents that describe the method in full detail may be found at www.wrapair.org. The summary of the method presented below is based on ENVIRON's final report submitted to the DEJF on May 5, 2006.[22]

There are two important factors for characterizing the dust emission process from an erodible surface. They are (a) the threshold friction velocity that defines the inception of the emission process as a function of the wind speed as influenced by the surface characteristics, and (b) the strength of the emissions that follow the commencement of particle movement. The two critical factors affecting emission strength are the wind speed (wind friction velocity) that drives the saltation system, and the soil characteristics.

<u>Friction Velocities</u> Surface friction velocities are determined from the aerodynamic surface roughness lengths and the 10-meter wind speeds based on MM5 model simulations. Friction velocity, u_*, is related to the slope of the velocity versus the natural logarithm of height through the relationship:

$$\frac{u_z}{u_*} = \frac{1}{\kappa} \ln \frac{z}{z_o}$$

where u_z = wind velocity at height z (m/s)
u_* = friction velocity (m/s)
κ = von Karman's constant (0.4)
z_0 = aerodynamic roughness height (m)

The threshold friction velocities, u_{*t}, are determined from the relationships developed by Marticorena et al.[20] as a function of the aerodynamic surface roughness length, z_0. Figure 8-2 shows the comparison between Marticorena's modeled relationship of threshold friction velocity and aerodynamic surface roughness length and wind tunnel data obtained by different investigators.[23 – 26]

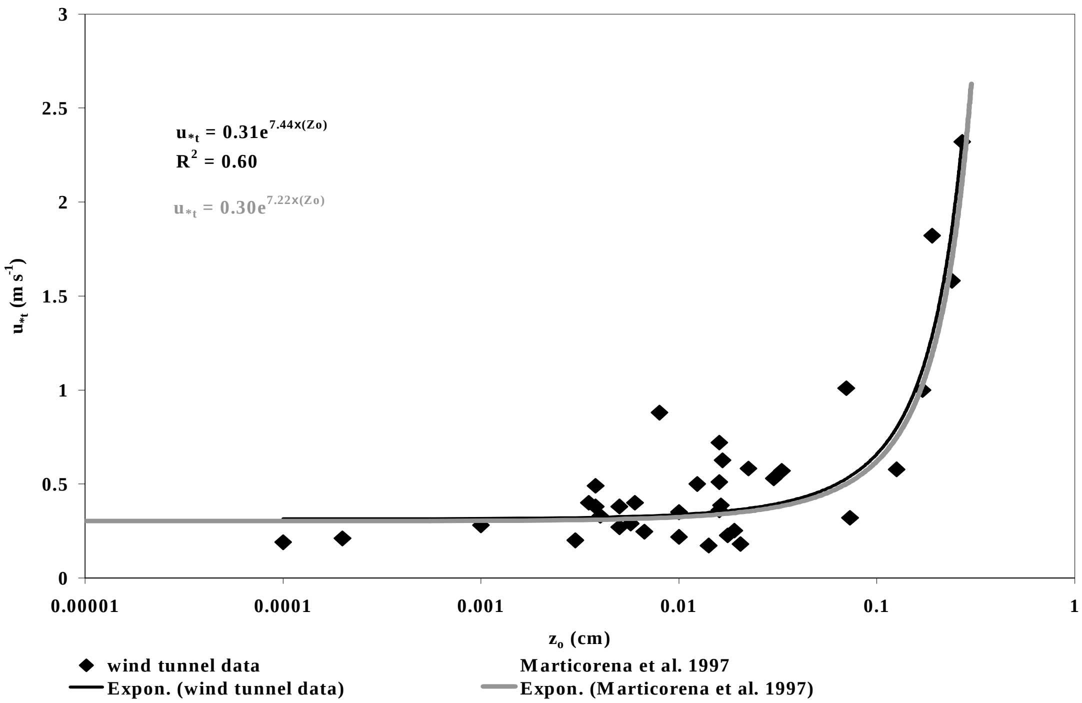

Figure 8-2. Threshold Friction Velocity vs. Aerodynamic Roughness Length

Surface friction velocities, including the threshold friction velocity, are a function of the aerodynamic surface roughness lengths. The surface friction velocities are in turn dependent on surface characteristics, particularly land use/land cover. While these values can vary considerable for a given land type, published data are available which provide a range of surface friction velocities for various land use types and vegetation cover. These data are presented in Table 8-3.

Table 8-3. Threshold Friction Velocities for Typical Surface Types [23-26]

Site Type	Undisturbed u_{*t} (m/s)	Disturbed u_{*t} (m/s)	% change [1-(dist./undist.)]
agricultural fields	1.29	0.55	0.57
alluvial fan	0.72	0.60	0.17
desert flat	0.75	0.51	0.32
desert pavement	2.17	0.59	0.73
fan surface	1.43	0.47	0.67
playa, crusted	2.13	0.63	0.70
playa	1.46	0.58	0.60
prairie	2.90	0.24	0.92
sand dune	0.44	0.32	0.27

Emission Fluxes Emission fluxes, or emission rates, are determined as a function of surface friction velocity and soil texture. The relationships that Chatenet et al.[27] established between the 12 soil types in the classical soil texture triangle and their four dry soil types (silt [FSS], sandy silt [FS], silty sand [MS], and sand [CS]) are of key importance. The relationships developed by Alfaro and others[28, 29] for each of the soil texture groups are used to estimate dust emission fluxes. These relationships are presented in Figure 8-3.

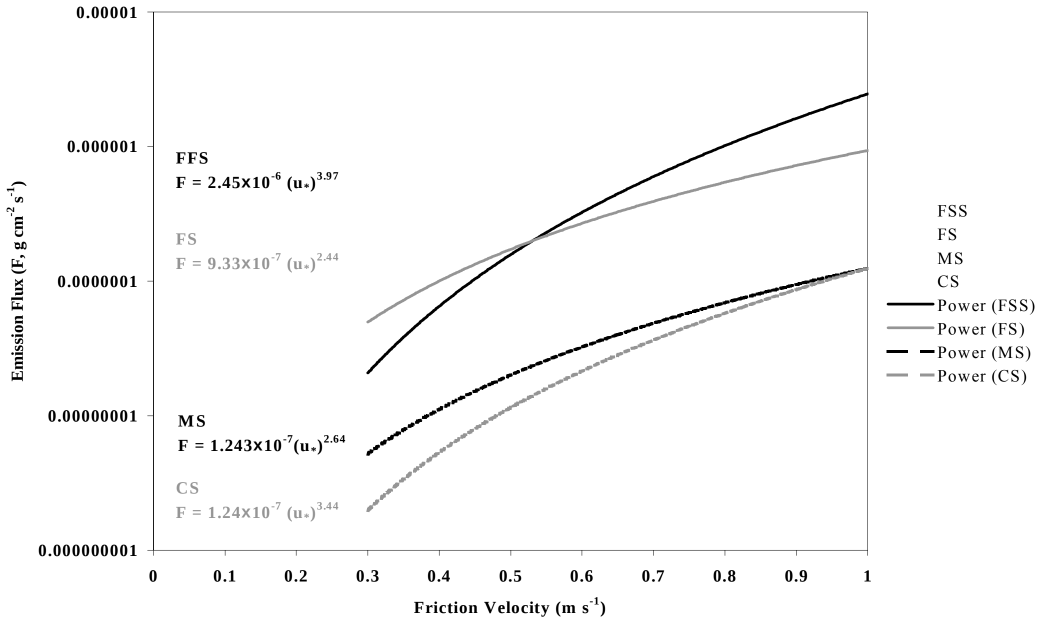

Figure 8-3. Emission Flux vs. Friction Velocity Predicted by the Alfaro and Gomes Model[28] Constrained by the Four Soil Classes of Alfaro et al.[29]

Reservoir Characteristics Reservoirs are classified as limited for stable land parcels and unlimited for unstable land parcels. Classification of reservoirs as limited or unlimited has implications with respect to the duration of time over which the dust emissions are generated. In general, the reservoirs should be classified in terms of the type of soils, the depth of the soil layer, soil moisture content and meteorological parameters. Finally, the time required for a reservoir to recharge following a wind event is influenced by a number of factors including precipitation and snow events and freezing conditions of the soils. A recharge time of 24 hours is assigned to all surfaces. In addition, it is assumed that no surface will generate emissions for more than 10 hours in any 24-hour period.

The duration and amount of precipitation and snow and freeze events will also affect the dust emissions from wind erosion. Barnard[30] has compiled a set of conditions for treating these events based on seasons, soil characteristics and the amounts of rainfall and snow cover. The time necessary to re-initiate wind erosion after a precipitation event ranges from 1 to 10 days, depending on the soil type, season of the year and whether the rainfall amount exceeds 2 inches.

Soil Disturbance The disturbance level of a surface more appropriately has the effect of lowering the threshold surface friction velocity. Except for agricultural lands, which are treated separately in the model as described below, vacant land parcels are typically undisturbed unless some activity is present such as to cause a disturbance (e.g., off-road vehicle activity in desert lands, or animal grazing on rangelands). It is recommended that all non-agricultural land types be considered undisturbed, since there is no *a priori* information to indicate otherwise for the regional scale modeling domain to be considered. Therefore, for the purpose of evaluating the sensitivity of the model to disturbance levels, all grassland, shrubland and barren land areas are assumed to have 10 % of their land area disturbed. Threshold surface friction velocities for these disturbed lands are assigned as follows: 3.1 m/s for grasslands and shrublands, and 0.82 m/s for barren land.

Soil Characteristics Application of the emission factor relations described above requires the characterization of soil texture in terms of the four soil groups considered by the model. The characteristics or type of soil is one of the parameters of primary importance for the application of the emission estimation relations derived from wind tunnel study results. The State Soil Geographic Database (STATSGO) available from the USDA[31] is used to determine the type of soils present in the modeling domain for which the emission inventory is developed. The classification of soil textures and soil group codes is based on the standard soil triangle that classifies soil texture in terms of percent sand, silt and clay. Combining the soil groups defined by the work of Alfaro et al.[29] and Chatenet et al.[27] and the standard soil triangle provides the mapping of the 12 soil textures to the four soil groups considered in their study. The soil texture mappings are summarized in Table 8-4.

Table 8-4. STATSGO Soil Texture and Soil Group Codes

STATSGO Soil Texture	Soil Texture Code	Soil Group	Soil Group Code
No Data	0	N/A	0
Sand	1	CS	4
Loamy Sand	2	CS	4
Sandy Loam	3	MS	3
Silt Loam	4	FS	1
Silt	5	FSS	2
Loam	6	MS	3
Sandy Clay Loam	7	MS	3
Silty Clay Loam	8	FSS	1
Clay Loam	9	MS	3
Sandy Clay	10	MS	3
Silty Clay	11	FSS	1
Clay	12	FS	2

Surface Roughness Lengths Surface roughness lengths can vary considerably for a given land type, as evidenced by examination of the data in Table 8-5. Surface roughness lengths are assigned as a function of land use type based on a review of the information in Table 8-5. The disturbance level of various surfaces has the effect of altering the surface roughness lengths, which in turn impact the potential for vacant lands to emit dust from wind erosion

Table 8-5. Aerodynamic Surface Aerodynamic Roughness Lengths, Z_0

Site Type	Average z_o (cm)	Reference(s)
agricultural fields (bare)	0.031	23 - 26
desert flat/pavement	0.133	23 - 26
fan surface	0.088	23 - 26
playa, crusted	0.059	23 - 26
playa	0.057	23 - 26
prairie	0.049	23 - 26
sand dune	0.007	23 - 26
scrub desert	0.045	26
sparse veg. (0.04% cover)	0.37	33
sparse veg. (8% cover)	5.4	33
sparse veg. (10.3% cover)	6.8	33
sparse veg. (13.5% cover)	7.2	33
sparse veg. (26% cover)	8.3	33
thick grass	2.3	34
thin grass	5	34
sparse grass	0.12	35
agricultural crops	2-4	35
orchards	50-100	35
decid. forests	100-600	35
conf. forests	100-600	35
agricultural crops	15	36
urban	100	36
decid. forests (closed canopy)	121	36
conif. forests (closed canopy)	134	36

An examination of Figure 8-2, which relates the threshold surface friction velocity to the aerodynamic surface roughness length, reveals that for surface roughness lengths larger than approximately 0.1 cm, the threshold friction velocities increase rapidly above values that can be realistically expected to occur in the meteorological data used in the model implementation. Therefore to simplify the model implementation, only those land types with roughness length less than or equal to 0.1 cm are considered as potentially erodible surfaces.

For a given surface roughness, as determined by the land use type[32], the threshold friction velocity has a constant value. Thus, the land use data is mapped to an internal dust code used within the model to minimize computer resource requirements and coding efforts. The mapping of land use types to dust codes 3 and above (except for code 5 that applies to orchards and vineyards) is presented in Table 8-6, which summarizes the surface characteristics by dust code. [Note: Dust codes 1 and 2 refer to water/wetlands and forest/urban, respectively.]

Table 8-6. Surface Characteristics by Dust Code and Land Use Category

Dust Code	3	4	6	7
Land use category	Agricultural	Grassland	Shrubland	Barren
Surface roughness length, $Z_{0\ (cm)}$	0.031	0.1	0.05	0.002
Threshold friction velocity (m/s)	3.72	6.17	4.30	3.04
Threshold wind velocity at 10 meter height (m/s [mph])	13.2 [29.5]	19.8 [44.3]	14.6 [32.8]	12.7 [28.5]

Meteorology Gridded hourly meteorological data, which is required for the dust estimation methodology is based on MM5 model simulation results. Data fields required include wind speeds, precipitation rates, soil temperatures and ice/snow cover.

Agricultural Land Adjustments Unlike other types of vacant land, windblown dust emissions from agricultural land are subject to a number of non-climatic influences, including irrigation and seasonal crop growth. As a result, several non-climatic correction or adjustment factors were developed for applicability to the agricultural wind erosion emissions. These factors included:

- Long-term effects of irrigation (i.e., soil "clodiness")
- Crop canopy cover
- Post-harvest vegetative cover (i.e., residue)
- Bare soil (i.e., barren areas within an agriculture field that do not develop crop canopy for various reasons, etc.)
- Field borders (i.e., bare areas surrounding and adjacent to agricultural fields)

The methodology used to develop individual non-climatic correction factors was based upon previous work performed by the California Air Resources Board in their development of California-specific adjustment factors for the USDA's Wind Erosion Equation.[37]

Other Adjustments Two other adjustments to modeled air quality impacts relate to fugitive dust transportability and partitioning between fine and coarse fractions of PM10. Transportability fractions as a function of land use are assigned on the basis of the methodology described by Pace.[38] New fine fraction values developed by Cowherd[39] from controlled wind tunnel studies of western soils are applied to determine the fine and coarse fractions of wind-generated fugitive dust emissions.

Concerns Regarding the Method

ENVIRON's methodology for calculating wind-generated fugitive dust emissions relies on several assumptions that may not be valid. As was mentioned above, many of the assumptions employed in Phase 1 were necessitated by a lack of specificity in the underlying data used to characterize vacant land types and soil conditions in relation to the potential for wind erosion. Even in Phase 2, it was necessary to rely on some assumptions where data were lacking.

The pertinent vacant land characteristics that are most difficult to characterize are the dust reservoir capacities and resuspension characteristics in relation to the levels of surface disturbance and the presence of protective surface elements (vegetation, rocks). Another complex feature is the recharge time needed to re-establish all or part of the reservoir after depletion by a wind erosion event.

Surface disturbance tends to have a much stronger impact than soil type in providing a high dust reservoir capacity. If the surface is disturbed in such a way that non-erodible elements are minimized, it can be considered as having an "unlimited" erosion potential. This means that the reservoir is large enough to support hours of fine particle emissions during a high-wind event. Therefore, it is important any PM10 emission models or empirical relationships account for not only the soil type but also the state of aggregation of the exposed surface material.

After a surface disturbance that creates an unlimited reservoir of available particles, precipitation events can have a major effect in restoring a surface crust and place the surface in a stable condition for an indefinite period. When this occurs, typically a "limited" reservoir will be present on the surface. This reservoir contains only minor amounts of accumulated deposition from previous area-wide wind erosion events or from other more localized fugitive dust sources such as unpaved roads.

Because of the complexity of determining dust reservoir characteristics and their dynamic features, the Phase 2 methodology also tends to rely on assigned characteristics that do not appear to be well founded for most areas subject to wind erosion. For example, the assumed recharge period of only 24 hours is usually unrealistic. For example in the case of agricultural land, this would require a major disturbance to the soil such as a tilling operation that brings fresh, loose and dry soil to the surface. In the absence of a major surface disturbance, actual recharge times may extend to weeks and even months.[40] In some cases, however, a stable surface can transition to a highly erodible state in the absence of mechanical disturbance. The highly alkaline soils at Owens Lake, California for instance are fairly stable during summer months, but can change to a very unstable surface in the winter and spring following periods with precipitation and cold temperatures.[12]

Another example of concern is the value assumed in the Phase 2 model for the estimated time after a precipitation event that it takes to re-initiate wind erosion. The times given for full restoration of the dust reservoir are in the range of 1 to 4 days, depending on the soil type and whether the precipitation exceeded 2 inches. These values are at variance with the results of a multiyear field study conducted by Cowherd et al. in the western Mojave Desert.[41] That study showed that precipitation events of that order could re-stabilize soil surfaces for indefinite periods pending the next major surface disturbance. In the study area, scattered reservoirs of loose sand were stabilized by the presence of desert vegetation.

Stable soils in windy areas tend to have limited reservoirs of erodible particles consisting of a thin surface layer of deposition from previous high wind events. These layers have been homogenized by successive resusupension and atmospheric mixing during wind erosion over many years. This is illustrated by a recently completed inventory of vacant lands in the Las Vegas Valley.[42] This study showed that the vast majority of the land consisted of "native desert" as characterized by a single reflectance signature from satellite imagery with visible and infrared wavelength components. Landsat TM 5 with a 30-meter pixel size was found to provide a useful reflectance averaging that eliminated the effects of micro-features associated with uneven patterns of vegetation. The thin layers of erodible particles appear to exhibit a relatively uniform chemistry. Therefore, the known soil chemistry differences below the surface layer were not a confounding factor in establishing a single spectral signature for this vacant land category. On the other hand, areas where the soil had been turned as part of land preparation processes for construction projects could not be fitted to a single spectral signature because of surface soil chemistry differences.

Due to the paucity of wind tunnel data, Mansell et al.[17] developed fugitive dust emission factors for wind erosion of vacant land, based on soil texture rather than using area-specific wind tunnel data as recommended by MacDougall.[16] The emission fluxes for four soil aggregate populations were expressed in terms of friction velocity, based on test data from a relatively large portable wind tunnel. It was assumed that the flux would remain constant at any friction velocity for a period of 1 hour or 10 hours depending on whether the surface was classified as having a limited or unlimited reservoir respectively. Mansell and coworkers did not rely on the wind tunnel emission factors derived for Clark County by James et al.[21] because they appeared to be much greater than emission factors measured by other researchers using wind tunnels with a larger cross-section than the UNLV designed wind tunnel (6" wide by 6" high by 60" long).

It should be noted that because ENVIRON's methodology assigns a very short recovery time on (a) replenishing soil losses from high wind events, and on (b) losing the mitigating effects of precipitation, the estimated emissions are driven mostly by wind speed. There is little accounting for the natural tendency of most unlimited reservoir surfaces to re-stabilize for long periods of time in the absence of major surface disturbances or large supplies of available loose sand that can abrade stable crusts. As noted in the land inventory of the Las Vegas Valley cited above, a frequent land disturbance pattern is found only on regularly traveled surfaces, with few exceptions.

Recommendations

In order to use ENVIRON's methodology/model for calculating wind-generated fugitive dust emissions, it is strongly recommended that the user review the necessary inputs for the model, and refine the inputs if better information is available. If a wind blown dust inventory is needed for a planning area, local wind tunnel data, or erosion monitoring using CSC sand flux samplers based on the methodology described by Ono et al.[12] (see Section 8.3) is a very practical approach.

8.5 Demonstrated Control Techniques

Control measures for open area wind erosion are designed to stabilize the exposed surface (e.g., by armoring it with a less erodible cover material) or to shield it from the ambient wind. Table 8-7 presents a summary of control measures and reported control efficiencies for open area wind erosion.

Table 8-7. Control Efficiencies for Control Measures for Open Area Wind Erosion

Control measure	Source Component	PM10 Control Efficiency	References/comments
Apply dust suppressants to stabilize disturbed area after cessation of disturbance	Disturbed areas	84%	CARB, April 2002.[43]
Apply gravel to stabilize disturbed open areas	Disturbed areas	84%	CARB, April 2002.[43] Estimated to be as effective as chemical dust suppressants.

8.6 Regulatory Formats

Fugitive dust control options have been embedded in many regulations for state and local agencies in the WRAP region. Regulatory formats specify the threshold source size that triggers the need for control application. Example regulatory formats for several local air quality agencies in the WRAP region are presented in Table 8-8. The website addresses for obtaining information on fugitive dust regulations for local air quality districts within California, for Clark County, NV, and for Maricopa County, AZ, are as follows:

- Districts within California: www.arb.ca.gov/drdb/drdb.htm
- Clark County, NV: www.co.clark.nv.us/air_quality/regs.htm
- Maricopa County, AZ: www.maricopa.gov/envsvc/air/ruledesc.asp

8.7 Compliance Tools

Compliance tools assure that the regulatory requirements, including application of dust controls, are being followed. Three major categories of compliance tools are discussed below.

Record keeping: A compliance plan is typically specified in local air quality rules and mandates record keeping of source operation and compliance activities by the source owner/operator. The plan includes a description of how a source proposes to comply with all applicable requirements, log sheets for daily dust control, and schedules for compliance activities and submittal of progress reports to the air quality agency. The purpose of a compliance plan is to provide a consistent reasonable process for documenting air quality violations, notifying alleged violators, and initiating enforcement action to ensure that violations are addressed in a timely and appropriate manner.

Table 8-8. Example Regulatory Formats for Open Area Wind Erosion

Control measure	Goal	Threshold	Agency
Watering, fencing, paving, graveling, dust suppressant, vegetative cover, restrict vehicular access	Maintain soil moisture content min 12%; or 70% min of optimum soil moisture content; reduce windblown emissions	Construction sites; fences 3ft-5ft, adjacent to roadways/urban areas;	Maricopa County Rule 310 04/07/2004
Cease ops (wind speed >25mph); applying dust suppressant 2x hr; watering and fencing (as above); for after work hours: gravel, water 3x/day (possibly 4)	Reduce amt of windblown dust leaving site; maintain soil moisture content 12%	Wind speed must be >25mph for 60 min average; fencing must be 3ft-5ft with <50% porosity; watering for after work, holidays, weekends increase to 4x/day during wind event	Maricopa County Rule 310 04/07/2004
Use of one of following for dust control on all disturbed soil to maintain in damp condition: soil crusted over by watering or other, or graveling or treated with dust suppressant	Prevent visible fugitive dust from exceeding 20% opacity, and prevent dust plume from extending more than 100 yd		Clark County Sect. 94 Air Quality Reg. 06/22/2000
Requires application of water or chemical stabilizers prior to wind event 3 times a day (possible increase to 4 times a day if evidence of wind driven dust), or establish a vegetative cover within 21 days after active operations have ceased to maintain a stabilized surface for 6 months		For operations that remain inactive for not more than 4 consecutive days	SCAQMD Rule 403 12/11/1998

Site inspection: This activity includes (1) review of compliance records, (2) proximate inspections (sampling and analysis of source material), and (3) general observations. An inspector can use photography to document compliance with an air quality regulation.

On-site monitoring: EPA has stated that "An enforceable regulation must also contain test procedures in order to determine whether sources are in compliance." Monitoring can include observation of visible plume opacity, surface testing for crust strength and moisture content, and other means for assuring that specified controls are in place.

Table 8-9 summarizes the compliance tools that are applicable to open area wind erosion.

Table 8-9. Compliance Tools for Open Area Wind Erosion

Record keeping	Site inspection/monitoring
Soil stabilization methods; application frequencies, rates, and times for dust suppressants; establishment/ maintenance of wind breaks.	Crust strength determination (e.g., drop ball test); observation of operation of dust suppression systems; inspection of heights and porosities of windbreaks.

8.8 Sample Cost-Effectiveness Calculation

This section is intended to demonstrate how to select a cost-effective control measure for fugitive dust originating from open area wind erosion. A sample cost-effectiveness calculation is presented below for a specific control measure (apply gravel) to illustrate the procedure. The sample calculation includes the entire series of steps for estimating uncontrolled emissions (with correction parameters and source extent), controlled emissions, emission reductions, control costs, and control cost-effectiveness values for PM10 and PM2.5. In selecting the most advantageous control measure for open area wind erosion, the same procedure is used to evaluate each candidate control measure (utilizing the control measure specific control efficiency and cost data), and the control measure with the most favorable cost-effectiveness and feasibility characteristics is identified.

Sample Calculation For Open Area Wind Erosion (Dirt Parking Lot)

Step 1. Determine source activity and control application parameters.

Area of dirt parking lot	10,000 m^2
Disturbance frequency per day	1
Duration of exposure (months)	12
Roughness height (cm)	0.5
Threshold peak wind speed at height of 10 m (m/s)	10

Control Measure	Apply gravel
Control application/frequency	Once every years
Economic Life of Control System (yr)	5
Threshold friction velocity for gravel (m/s)	1.9
Control Efficiency (%)	84
Reference for Control Efficiency	Sierra Research (2003) [44]

The field size, source activity parameters, and control measure parameters are assumed values for illustrative purposes. Applying a 3” deep gravel bed over the dirt has been chosen as the applied control measure.

Step 2. Obtain PM10 Emission Factor.

The PM10 emission factor is obtained from AP-42: PM10 EF = $0.5 \sum_{i=1}^{N} P_i$

P—erosion potential (g/m^2)	$P = 58 (u^*-u^*_t)^2 + 25 (u^*-u^*_t)$ $P = 0$ for $u^* \leq u_t^*$
Threshold friction velocity u^*_t (m/s) = $0.053\ u^+_{10}$	0.53

Step 3. Calculate Uncontrolled PM Emissions. The PM10 emission factor (obtained in Step 2) is applied to each day for which the peak wind exceeds the threshold velocity for wind erosion. The following monthly climatic data are used for illustrative purposes and are assumed to apply to each month of the year.

Monthly erosion potential (P) [a]				
Day of Month	Peak Wind (u^+_{10}) mph	Peak Wind (u^+_{10}) m/s	u* m/s	P g/m^2
6	29	13.0	0.69	5.36
7	30	13.4	0.71	6.41
11	38	17.0	0.90	17.21
22	25	11.2	0.59	1.78
			Sum of P	30.77

[a] Assumed to apply to 12 months of the year.

The annual PM10 emissions are equal to the PM10 emission factor (i.e., 0.5 times the monthly erosion potential) multiplied by 12 and then by the field size (under activity data) and then divided by 454 g/lb and 2,000 lb/ton to compute the annual PM10 emissions in tons per year, as follows:

Annual PM10 emissions = (Emission Factor x Field Size) / (454 x 2,000)
Annual PM10 emissions = (0.5 x 0.77 x 12 x 10,000) / (454 x 2,000)
Annual PM10 emissions = 2.03 tons

Annual PM2.5 emissions = 0.15 x PM10 emissions[12] = 0.15 x 2.03 = 0.30 tons

Step 4. Calculate Controlled PM Emissions. The controlled PM emissions (i.e., the PM emissions remaining after control) are equal to the uncontrolled emissions (calculated above in Step 3) multiplied by the percentage that uncontrolled emissions are reduced, as follows:

Controlled emissions = Uncontrolled emissions x (1 – Control Efficiency).

For this example, we have selected applying gravel over the dirt parking lot as our control measure. Based on a control efficiency estimate of 84% for this control measure, the annual controlled emissions estimate are calculated to be:

Annual Controlled PM10 emissions = 0.33 tons
Annual Controlled PM2.5 emissions = 0.049 tons

Step 5. Determine Annual Cost to Control PM Emissions.

Capital costs ($)	50,000
Annual Operating/Maintenance costs ($)	4,000
Annual Interest Rate	3%
Capital Recovery Factor	0.2184
Annualized Cost ($/yr)	13,173

The capital costs, annual operating and maintenance costs, and annual interest rate (AIR) are assumed values for illustrative purposes. The Capital Recovery Factor (CRF) is calculated from the Annual Interest Rate (AIR) and the Economic Life of the control system, as follows:

Capital Recovery Factor = AIR x $(1+AIR)^{\text{Economic life}}$ / $(1+AIR)^{\text{Economic life}}$ – 1

Capital Recovery Factor = 3% x $(1+ 3\%)^5$ / $(1+ 3\%)^5$ – 1 = 0.2184

The Annualized Cost is calculated by adding the product of the Capital Recovery Factor and the Capital costs to the Annual Operating/Maintenance:

Annualized Cost = (CRF x Capital costs) + Annual Operating/Maintenance costs
Annualized Cost = (0.2084 x 50,000) + 4,000 = 14,918

Step 6. Calculate Cost-effectiveness. Cost-effectiveness is calculated by dividing the annualized cost by the emissions reduction. The emissions reduction is determined by subtracting the controlled emissions from the uncontrolled emissions:

Cost-effectiveness = Annualized Cost/ (Uncontrolled emissions – Controlled emissions)

Cost-effectiveness for PM10 emissions = $14,918 / (2.03 - 0.33) = $8,735/ton
Cost-effectiveness for PM2.5 emissions = $14,918 / (0.30 - 0.049) = $58,234/ton

8.9 References

1. Cowherd, C. Jr., 1983. *A New Approach to Estimating Wind Generated Emissions from Coal Storage Piles,* Presented at the APCA Specialty Conference on Fugitive Dust Issues in the Coal Use Cycle, Pittsburgh, PA, April.

2. Axtell, K., Cowherd, C. Jr., 1984. *Improved Emission Factors for Fugitive Dust from Surface Coal Mining Sources*, EPA-600/7-84-048, U.S. EPA, Cincinnati, OH, March.

3. Muleski, G.E., 1985. *Coal Yard Wind Erosion Measurement*, Midwest Research Institute, Kansas City, MO, March 1985.

4. MRI, 1988. *Update of Fugitive Dust Emissions Factors in AP-42 Section 11.2-Wind Erosion*, MRI No. 8985-K, Midwest Research Institute, Kansas City, MO.

5. Chepil, W.S., 1952. *Improved Rotary Sieve for Measuring State and Stability of Dry Soil Structure,* Soil Science Society of America Proceedings, *16*:113-117.

6. Gillette, D.A., *et al.*, 1980. *Threshold Velocities for Input of Soil Particles into the Air by Desert Soils*, Journal of Geophysical Research, *85*(C10):5621-5630.

7. Local Climatological Data, National Climatic Center, Asheville, NC.

8. Changery, M.J., 1978. *National Wind Data Index Final Report*, HCO/T1041-01 UC-60, National Climatic Center, Asheville, NC, December.

9. Billings-Stunder, J.B., Arya, S.P.S., 1988. *Windbreak Effectiveness for Storage Pile Fugitive Dust Control: A Wind Tunnel Study*, J. APCA, *38*:135-143.

10. Cowherd, C. Jr., *et al*., 1988. *Control of Open Fugitive Dust Sources*, EPA 450/3-88-008, U.S. EPA, Research Triangle Park, NC, September.

11. MRI, 2006. Background Document for Revisions to Fine Fraction Ratios Used for AP-42 Fugitive Emission Factors, prepared for the WRAP by Midwest Research Institute, Project No. 110397, February 1.

12. Ono, D., Weaver, S., Richmond, K. April 2003. *Quantifying Particulate Matter Emissions from Wind Blown Dust Using Real-time Sand Flux Measurements*, paper presented at the 12th Annual EPA Emission Inventory Conference in San Diego, CA.

13. Gillette, D., Ono, D., and Richmond, K., 2004. *A Combined Modeling and Measurement Technique for Estimating Windblown dust Emissions at Owens (dry) Lake, California,* Journal of Geophysical Research 109, F01103.

14. Ono., D., 2006. *Application of the Gillette Model for Windblown Dust at Owens Lake, CA,* Atmos. Environ., 40: 3011-3021.

15. Gillette, D. A., Niemeyer, T. C., Helm, P. J, 2001. *Supply-limited Horizontal Sand Drift at an Ephemerally Crusted, Unvegetated Saline Playa*, Journal of Geophysical Research, 106, 18085-18,098.

16. MacDougall, C., 2002. *Empirical Method for Determining Fugitive Dust Emissions from Wind Erosion of Vacant Land*, memorandum prepared for Clark County Department of Air Quality Management, June.

17. Mansell, G. E., Wolf, M., Gillies, J., Barnard, W., Omary, M, 2004. *Determining Fugitive Dust Emissions from Wind Erosion,* ENVIRON final report prepared for Western Governors' Association, March.

18. Countess Environmental, 2002. *A Review and Update of Fugitive Dust Emissions Estimation Methods*, final report prepared for the Western Governors' Association, November.

19. Draxler, R.R., Gillette, D.A., Kirkpatrick, J.S., Heller, J., 2001. E*stimating PM10 Air Concentrations from Dust Storms in Iraq, Kuwait and Saudi Arabia*, Atmospheric Environment 35:4315.

20. Marticorena, B., Bergametti, G., Gillette, D., Belnap, J., 1997. *Factors Controlling Threshold Friction Velocity in Semiarid and Arid Areas of the United States*, J. Geophys. Res., 102:23277.

21. James, D., Haun, J.A., Gingras, T., Fulton, A., Pulgarin, J., Venglas, G., Becker, J., Edwards, S., January 2001. *Estimation of PM10 Vacant Land Emission Factors for Unstable, Stable and Stabilized Lands Using Data from 1995 and 1998-1999 UNLV Wind Tunnel Studies of Vacant and Dust-Suppressant Treated Lands,* final report prepared for the Clark County Department of Comprehensive Planning.

22. Mansell, G.E., Lau, S., Russel, J and Omary, M., 2006. *Fugitive Wind Blown Dust Emissions and Model Performance Evaluation Phase II,* final report prepared by ENVIRON for Western Governors' Association, May 5.

23. Gillette, D.A., Adams, J., Endo, E. and Smith, D., 1980. *Threshold Velocities for Input of Soil Particles into the Air by Desert Soils*, Journal of Geophysical Research, 85(C10): 5621-5630.

24. Gillette, D.A., Adams, J., Muhs, D. and Kihl, R., 1982. *Threshold Friction Velocities and Rupture Moduli for Crusted Desert Soils for the Input of Soil Particles into the Air,* Journal of Geophysical Research, 87(C10): 9003-9015

25. Gillette, D.A., 1988. *Threshold Friction Velocities for Dust Production for Agricultural Soils*, Journal of Geophysical Research: 93(D10), 12645-12662.

26. Nickling, W.G. and Gillies, J.A., 1989. *Emission of Fine Grained Particulate from Desert Soils*, in: Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport, M. Leinen and M. Sarnthein (Editors), Kluwer Academic Publishers, pp. 133-165.

27. Chatenet, B., Marticorena, B., Gomes, L., and Bergametti, G, 1996. *Assessing the Microped Size Distributions of Desert soils Erodible by Wind*, Sedimentolog*.* 43: 901-911.

28. Alfaro, S. C. and Gomes, L., 2001. *Modeling Mineral Aerosol Production by Wind erosion: Emission Intensities and Aerosol Size Distributions in Source Areas,* J. Geophys. Res.: 106 (16), 18075-18084.

29. Alfaro, S. C., Rajot, J. I., and Nickling W. G., 2003. *Estimation of PM20 Emissions by Wind Erosion: Main Sources of Uncertainties*, Geomophology*.*

30. Barnard, W. 2003. Personal communication between Gerry Mansell of Environ and Bill Barnard of MACTEC Engineering & Consulting, Gainesville, FL, April.

31. USDA, 1994. *State Soil Geographic (STATSGO) Data Base, Data Use Information*. U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Service Center, Miscellaneous Publication Number 1492, December.

32. Latifovic, R., Zhu, Z-L., Cihlar, J. and Giri, C., 2002. *Land Cover of North America 2000*, Natural Resources Canada, Centre for Remote Sensing US Geological Services, EROS Data Center.

33. Wolfe, S. A., 1993. *Sparse Vegetation as a Control on Wind Erosion,* Ph.D. thesis, University of Guelph, Guelph, Ontario.

34. Sutton, O. G., 1953. Micrometeorology, McGraw-Hill, New York.

35. Oke, T. R., 1978. Boundary Layer Climates, Methuen Company, London.

36. Deursen, W. van, Heil, G. W., and Boxtel, A., van, 1993. *Using Remote Sensing Data to Compile Roughness Length Maps for Atmospheric Deposition Models*, International Symposium "Operationalisation of Remote Sensing," ITC Enschede, Netherlands.

37. CARB, 1997. *Section 7.11 - Supplemental Documentation for Windblown Dust - Agricultural Lands,* California Air Resources Board, Emission Inventory Analysis Section, Sacramento, California, April.

38. Pace, T.G., 2005. *Methodology to Estimate the Transportable Fraction of Fugitive Dust Emissions for Regional & Urban Scale Air Quality Analyses*, U.S. EPA, June 2.

39. Cowherd, C., 2005. *Analysis of the Fine Fraction of Particulate Matter in Fugitive Dust*, Draft report prepared by Midwest Research Institute for the Western Governors Association, August 17.

40. Cowherd, C., Jr., Grelinger, M.A. and Kies, C., 2001. *Effect of Wildfires and Controlled Burning on Soil Erodibility by Wind,* final report prepared by Midwest Research Institute for Radian Rocky Flats Environmental Technology Site, May.

41. Cowherd, C., Jr., and M.A. Grelinger, 2005. *Wind Erodibility Assessment of Stabilized Soils in the Antelope Valley,* draft final report prepared by Midwest Research Institute for Southern California Edison.

42. Kemner, W., Hall, F., Cowherd, C. and Borengasser, M., 2005. *Remote Sensing Imagery for an Inventory of Vacant Land Soil Stability and Unpaved Private Roads,* draft final report prepared by Environmental Quality Management and Midwest Research Institute for Clark County NV, December.

43. CARB, April 2002. *Evaluation of Air Quality Performance Claims for Soil-Sement Dust Suppressant.*

44. Sierra Research, 2003. *Final BACM Technological and Economic Feasibility Analysis,* prepared for the San Joaquin Valley Unified APCD, March.