Quantifying Particulate Matter Emissions from Wind Blown Dust Using Real-time Sand Flux Measurements

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ABSTRACT

An extensive sand flux monitoring network was installed on the dry lake bed at Owens Lake, California to determine hourly PM-10 emissions. The network consisted of 135 co-located electronic and passive sand flux samplers covering 135 square kilometers of the lake bed. The network measured the hourly sand flux at each site for 30 months. Previous researchers found that PM-10 emissions due to wind erosion are proportional to the saltation (or sand) flux. Hourly PM-10 emissions from each square kilometer were estimated by the equation, PM-10 = $K_f \times q$, where q is the sand flux measured at 15 cm above the surface, and K_f is the proportional relationship between the sand flux and the PM-10 emissions. K_f values were determined by comparing CALPUFF model predictions to observed concentrations at six PM-10 monitor sites. 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. As part of the Owens Lake Dust Identification (Dust ID) Program, the locations of the active areas identified by the sand flux network were confirmed by observers who visually mapped the dust source areas, by remote time-lapse video cameras, and by surface inspections using a Global Positioning System. This paper also compares the Dust ID method to other methodologies used to estimate particulate matter emissions from wind blown dust, such as those contained in the USEPA's AP-42 guidance document. Using the Dust ID results, hourly PM-10 emission rates for each square kilometer were input to the CALPUFF model to predict air quality impacts around the Owens Lake shoreline and at monitored receptors.

INTRODUCTION

The Great Basin Unified Air Pollution Control District has been studying air pollution caused by wind blown dust from Owens Lake for over 20 years. This paper describes the methodology and results of a project at Owens Lake, California to quantify PM-10 emissions from different areas of the exposed lakebed. The Owens Lake Dust Identification (Dust ID) Program provides real-time data on saltation flux, PM-10 concentrations and meteorological parameters to estimate PM-10 emissions and model ambient impacts of dust events.[1] Emissions estimated using the Dust ID method are also compared to daily and annual emission estimates using the method described in AP-42 for Industrial Wind Erosion.[2]

BACKGROUND

The dried bed of Owens Lake in Inyo County, California is the largest single source of particulate matter pollution in the United States.[3] The lakebed covers an area approximately 110 square miles (285 sq. km) and is a natural saline lake at the terminus of the Owens River. When the Owens River was diverted by the City of Los Angeles into an aqueduct in 1913, it caused the lake to become virtually dry by 1928. A small permanent brine pool is what remains at the lowest part of the basin. It is surrounded by exposed, dry alkali soils. Wind blown dust from the exposed lakebed can cause 24-hour average PM-10 concentrations to exceed 12,000 $\mu g/m^3$ at the historic shoreline – more than 75 times higher than the federal PM-10 standard. The air quality monitor site at the Town of Keeler averaged 19 violations per year of the federal 24-hour PM-10 standard (150 $\mu g/m^3$) from 1987-1995. Dust storms often affect the health and welfare of people living within 50 miles (80 km) of the lake.[4]

In 1993, the US Environmental Protection Agency (US EPA) designated the southern Owens Valley as a 'Serious' PM-10 nonattainment area. As a result, a State Implementation Plan (SIP) was developed with a control strategy that would bring the area into attainment by December 31, 2006. The SIP established interim requirements for implementing dust controls on 16.5 square miles (43 sq. km) of the lakebed by the end of 2003.[4] Large-scale implementation of shallow flooding was started in 2001 and managed vegetation in 2002. The City of Los Angeles is expected to meet the 16.5 square mile target by the end of 2003. Through the Dust ID Program additional areas will be identified for control measure implementation to bring the area into attainment with the PM-10 NAAQS by the statutory deadline of December 31, 2006.

THEORY

Dust ID Method of Estimating PM-10 Emissions

Before the Dust ID Program, PM-10 emissions from wind erosion were estimated using equations for open area wind erosion and agriculture found in US EPA Guidance documents, such as AP-42.[2] At Owens Lake, wind tunnel tests were also used to estimate PM-10 emissions for wind erosion.[4] These emission estimation methods are based on knowing the threshold friction velocity of a surface, which is the wind speed that will initiate wind erosion. Those estimation methods also assume that a fixed portion of the dust is composed of PM-10. Wind tunnel measurements at Owens Lake showed that the threshold friction velocity and the proportion of PM-10 in the eroding soil will change with different surface conditions, such as soil moisture content, soil texture, and soil binding properties.[5,6] Aeolian experts have developed more complex equations to estimate PM-10 emissions. The Shao, et al.[7] expression for the PM-10 vertical flux (F_a) of suspended particles produced by the impact of saltating particles is

Equations:

Equation (1) $$F_a = \gamma \; m_d \left(\frac{g}{Y}\right) \; Q \; f\left(\frac{V_H}{u_*}\right)$$

where

Y = binding energy
γ = a constant
m_d = mass per particle size
g = acceleration of gravity
Q = total horizontal saltation flux
V_H = horizontal velocity of a saltating particle
u_* = friction velocity.

Ono, et al. showed that the ratio of F_a /Q, which represents the ratio of the vertical PM-10 flux to the horizontal sand flux can be considered to be almost constant for areas with similar soil textures and binding energy. The binding energy, which is related to the aggregate strength, appears to change seasonally with precipitation, temperature and surface soil chemistry. For certain areas and periods, the ratio of F_a /Q would be nearly constant if the soil particles were of similar mass and size in that area and the binding strength was similar for that period in the same area. Therefore, the ratio F_a /Q, could be used to characterize the ratio of the vertical PM-10 flux to the horizontal sand flux for a certain area and period. Measurements at Owens Lake found that the total horizontal sand flux was proportional to the sand flux measured at a single height, q, in this case measurements were taken at 15 cm above the surface. The PM-10 emissions could be estimated using the following equation based on q and a dimensionless proportionality factor, K_f that can be determined through monitoring and modeling.[8]

Equation:

Equation (2) $$F_a = K_f \times q$$

where

q = horizontal sand flux rate at 15 cm above the surface [g/cm^2/hr].

K_f, which is called the K-factor can be inferred from the CALPUFF model by using hourly sand flux as a surrogate for PM-10 emissions. Modeled PM-10 predictions can be compared to monitored concentrations at 6 PM-10 monitor sites to determine the K-factor that would correctly predict the monitored concentration for each hour. Since K_f is a dimensionless value the units for F_a are the same as for q. For modeling using CALPUFF, F_a is converted to g/s for each square kilometer. The hourly sand flux rate, q is directly measured during dust storms with instruments centered in each square kilometer of a 135 square kilometer monitoring network.[1, 9, 10]

AP-42 Method of Estimating PM-10 Emissions

The AP-42 method of estimating emissions uses the difference between the friction velocity and the threshold friction velocity to estimate particulate matter emissions, and a constant value to convert emissions to Total Suspended Particulates, PM-10 or PM-2.5. Equations 3 and 4 show the AP-42 method to estimate PM emissions.[2]

Equations:

Equation (3) $$\textit{Emission Factor} = k \sum_{i=1}^{N} P_i \qquad [\mathrm{g/m^2/event}]$$

where

k is a particle size multiplier
- $k = 1.0$ for particles < 30 um
- $k = 0.6$ for particles < 15 um
- $k = 0.5$ for particles < 10 um
- $k = 0.2$ for particles < 2.5 um

N = number of disturbances per year

P_i = erosion potential corresponding to the observed (or probable) fastest mile of wind for the i^{th} period between disturbances

Equation (4) $$P = 58(u^* - u_t^*)^2 + 25(u^* - u_t^*)$$
$$P = 0 \text{ for } u^* \leq u_t^*$$

where

u^* = Friction Velocity for the Fastest Mile (m/s)

u_t^* = Threshold friction velocity (m/s), 0.26 m/s at Owens Lake

The wind speed profile in the surface boundary layer can be estimated using Equation 5 to convert the 10-m wind speed to friction velocity. The fastest mile wind speed approximates the measurement of wind gusts. The daily fastest mile wind speed data were taken from a 10-m tower on the lakebed (B-Tower Site) and was assumed to be the highest 5-minute average wind speed for each day. Fastest mile data does not have a set averaging time, but is around 2 minutes for a fastest mile of 30 mph.[2]

Equations:

Equation (5) $$u(z) = (u^*/0.4) \ln(z/z_o)$$

Where

$u(z)$ = wind speed at a certain height above the surface (cm/s)

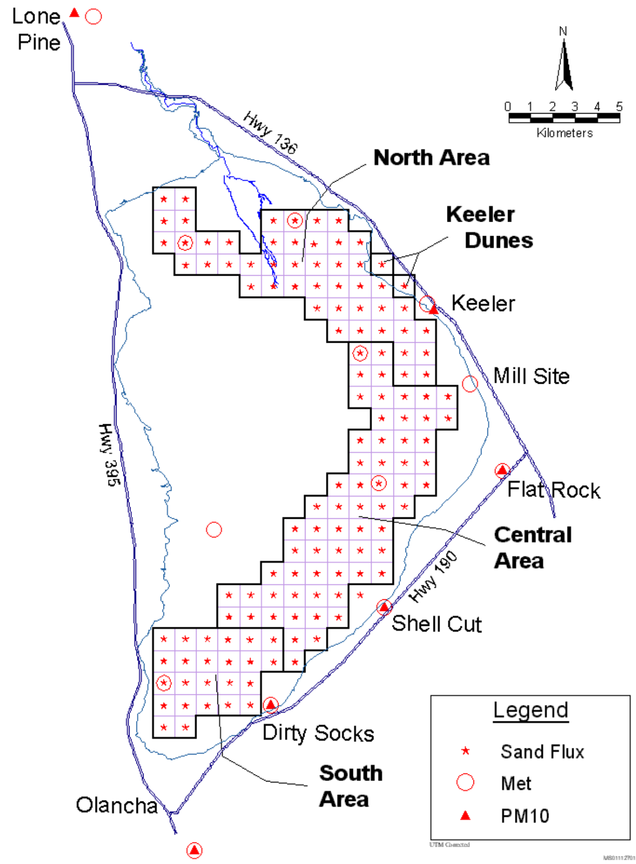
u^* = friction velocity for fastest mile

z = height above the surface (cm), 1000 cm for 10 m anemometer height

z_o = surface roughness height (cm), assume 0.01 cm for Owens Lake

0.4 is von Karman's constant, dimensionless

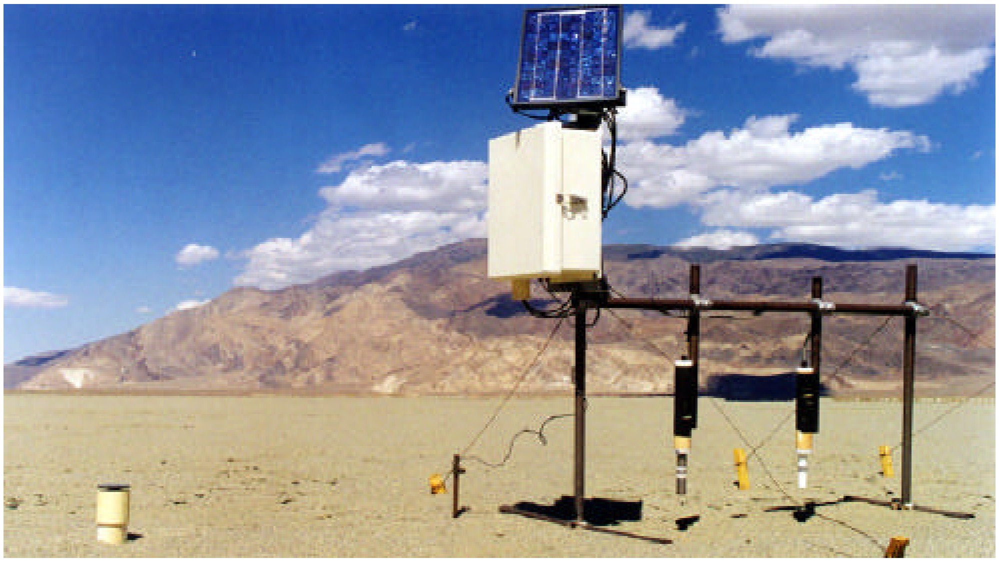
Figure 1. Owens Lake Dust ID monitoring network.



METHODOLOGY

A network of sand flux samplers, met towers and continuous PM-10 monitors were operated at Owens Lake for 30 months to collect data on wind erosion. Figure 1 shows a map of Owens Lake with the location of the Dust ID instrumentation. To help verify the location of dust source areas, time-lapse video cameras were installed at 3 sites to continuously record dust events during daylight hours and three observers mapped dust source areas and plumes during the storms on regular workdays. In addition, the erosion boundaries of some source areas were mapped with the aid of a Global Positioning System (GPS) after a storm. The GPS data and the visual observer's maps were put into a Geographic Information System (GIS) database along with the sand flux data to corroborate the location of dust producing areas.[1]

Figure 2. Two Sensits are seen suspended above the ground and a CSC is located to the left at this Owens Lake test site used to compare the performance of different saltation measurement instruments.

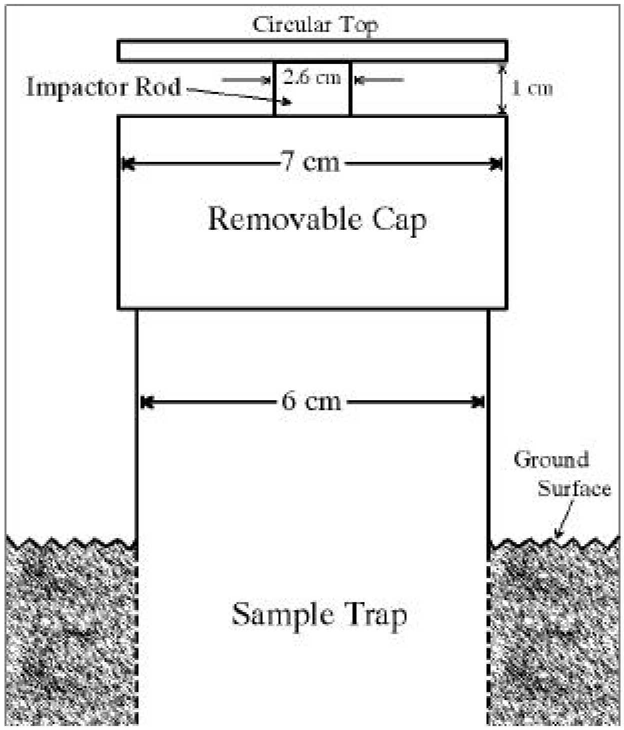


Sensits™ and Cox Sand Catchers

Co-located Sensits™ and Cox Sand Catchers (CSC's) were used to measure hourly sand flux rates at 135 locations as shown in Figure 1. The instruments were placed 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, they must be co-located with passive sand flux measurement devices to calibrate the electronic output and to determine the hourly sand flux.[11, 12] Figure 2 shows two Sensits suspended above the ground and a CSC in the ground to the left. The photo was taken at a site that was used to test the accuracy of Sensits and CSC's before the Dust ID Program began. The battery powered Sensits are augmented with a solar charging system. A data logger records hourly Sensit data during inactive periods and switches 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 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. A diagram of the CSC is shown in Figure 3. Not shown in the diagram are an internal sampling tube and a height adjustment sleeve. The internal sampling tube can be removed from the PVC casing to measure the sand catch sample. The length of the sampling tubes and casings are adjusted to accommodate the amount of erosion in each area and to avoid overloading the CSC's. The CSC length ranges from about 2 to 4 feet. Because the

Figure 3. Diagram of the Cox Sand Catcher (CSC) used to measure sand flux at Owens Lake.



PVC casing is buried in the ground, an adjustment sleeve is used to keep the inlet height at 15 cm to compensate for surface erosion and deposition.

Before the start of the study, the CSC sampler was calibrated against the Big Spring Number Eight (BSNE) sampler used by the US Department of Agriculture and others for wind erosion studies.[13] Figure 4 compares the CSC collected sand mass to the BSNE ($r^2 = 0.97$). This comparison was also used to determine the apparent size of the inlet opening of the CSC to calculate the sand flux. BSNE's have a defined inlet area size that can be used with the collected mass to calculate the sand flux [mass/area]. The CSC's circular design, however, does not have an obvious inlet area size for a flux calculation. By comparing the CSC sand catch to the BSNE flux, the CSC was found to have an apparent inlet size of 1.435 cm^2. During the same tests it was found that the CSC's had better precision than the BSNE's. The precision for 3 co-located CSC's was ± 3%, while the BSNE's had a ± 8% precision.

An example of the linearity between the CSC collected sand mass and the particle count data for a Sensit is shown in Figure 5. The Sensit particle count data was normalized for the three Sensits by dividing the total particle count for each Sensit to the average of 3 CSC's summed for all the runs. This type of comparison is routinely used to check the calibration of individual Sensits every month, however, the calibration curve that is generated is not normally used to determine the hourly sand flux. Because the electronic

Figure 4. Test results for CSC's compared to the average sand catch for 3 BSNE's.

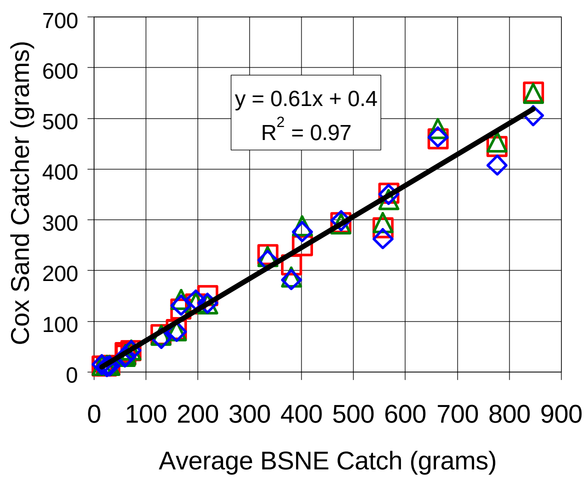
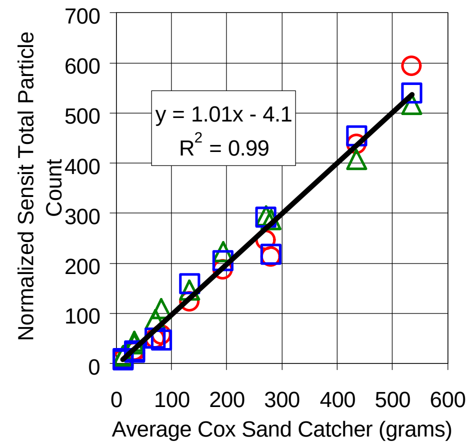


Figure 5. Test results for Sensit readings compared to 3 CSC's.



Sensit response and calibration can drift, the Sensits were used in combination with CSC's to determine the hourly sand flux. This combination takes advantage of the good precision and accuracy of the CSC sand catch data, and the ability of Sensits to time-resolve the sand flux for each hour of the CSC sampling period. In this way, the sum of the hourly sand catches always matches the CSC sand catch for each monthly sampling period, and it minimizes the error in the hourly sand flux. Samples from most of the CSC's were collected once a month, and 10 intensive sites were collected after every dust storm.

PM-10 & Meteorological Data

Hourly PM-10 data were collected at 6 sites around Owens Lake using TEOM PM-10 monitors (Figure 1). These monitors were co-located with filter-based PM-10 monitors including: PM-10 Partisols and Wedding and Andersen Hi-Vol Size-Selective Inlet PM-10 monitors. A previous study by Ono, et al. showed that the TEOM PM-10 monitors were well suited to measure wind blown dust at Owens Lake and to provide hourly PM-10 data.[14] Meteorological parameters were measured at 13 sites on and around Owens Lake. A wind profiler was operated at Dirty Socks and later moved to the Mill Site to collect wind data aloft to supplement the surface wind observations. The wind profiler also included a Radio Acoustic Sounding System (RASS) for the collection of vertical virtual temperature profiles.

K-factors

K-factors were determined through a combination of dispersion modeling, sand flux rates and monitored PM-10 concentrations. Dispersion modeling was performed using the

CALPUFF modeling system, which utilized meteorological data from thirteen 10-meter towers and an Upper Air Wind Profiler to generate wind fields using the CALMET model.[9, 10] CALPUFF was used to model the dust impacts at six PM-10 monitor sites using Equation 6 with the hourly sand flux (*q*) from each square kilometer to generate the hourly PM-10 emission rates. A K-factor of 5 x 10^{-5} was used to initially run the model and to generate 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 6 PM-10 monitor sites. The initial K-factor was adjusted using Equation 7.

Equation:

Equation (7) $$K_f = K_i \left(\frac{C_{obs.} - C_{bac.}}{C_{mod.}} \right)$$

where

K_i = Initial K-factor (5 x 10^{-5})
$C_{obs.}$ = Observed hourly PM-10 concentration. [µg/m^3]
$C_{bac.}$ = Background PM-10 concentration (assumed 20 µg/m^3)
$C_{mod.}$ = Model-predicted hourly PM-10 concentration. [µg/m^3]

K-factors were calculated for every hour that had active sand flux in cells which were upwind of a PM-10 monitor. These hourly K-factors were then screened to remove hours that did not have strong source-receptor relationships between the active source area and the downwind PM-10 monitor. For example, the screening criteria excluded hours when the edge of a dust plume may have impacted a PM-10 monitor site. Because the edge of a dust plume has a very high concentration gradient a few degrees error in the plume direction could greatly affect the calculated K-factor. Ten different screening criteria were used to find the K-factor hours that had the best source-receptor relationships. Examples of the screening criteria included: hourly modeled and monitored PM-10 were both greater than 150 µg/m^3, the sand flux was greater than 2 g/cm^2/hr in at least one cell that was located within 10 km and ±15º upwind from a monitor site, and more than 65% of the PM-10 contribution at a monitor site came from the target source area. The screening criteria deleted a number of outliers and also many points that were in the expected K-factor range, but overall resulted in reducing the K-factor variability.

A constant background concentration of 20 ìg/m^3 was included in the K-factor adjustment instead of hourly background concentrations. It was not practical to collect actual hourly background concentrations upwind from every source area. The adjustment for the background concentration, however, was usually minor since the hourly background concentration was much lower than the downwind monitor concentration. Downwind PM-10 concentrations were always greater than 150 ìg/m^3 and often greater than 1,000 ìg/m^3 when K-factors were calculated.

Figure 6. Dust source areas are scattered around a 35 square mile (90 sq. km) area of the Owens Lake bed in this aerial photo of a dust storm.

RESULTS

Sand Flux and Observation Maps

For the Dust ID Program, observers were stationed at 3 locations around the lake to map the location of dust source areas and record the plume trajectories. These maps were hand drawn every 15 minutes during the storms. The aerial photo in Figure 6 shows an example of an Owens Lake dust storm. The dust source areas in this photo, taken around 1989, are scattered around a 35 square mile (90 sq. km) area of the east side of the lakebed. The Dust ID observations were supplemented with information from time-lapse video cameras. The visual observations were used to help corroborate the source area location information provided by the Sensits and CSC's and to verify plume heights and trajectories for the CALMET and CALPUFF models. Figure 7 shows the dust plume observations and the total sand flux at each site for a large storm that started on February 6, 2001 and continued for 53 hours. Although the dust plume maps were only drawn for 6 hours of the storm, they show good agreement with the sand flux measurements that were taken for the entire storm. The observer maps also provided useful information on the location of small dust source areas that were not caught by the 1 km spaced sand flux

Figure 7. The daytime observed dust plumes correspond very closely to the total sand catch mass for each CSC/Sensit site as demonstrated by this wind blown dust event on February 6-8, 2001.

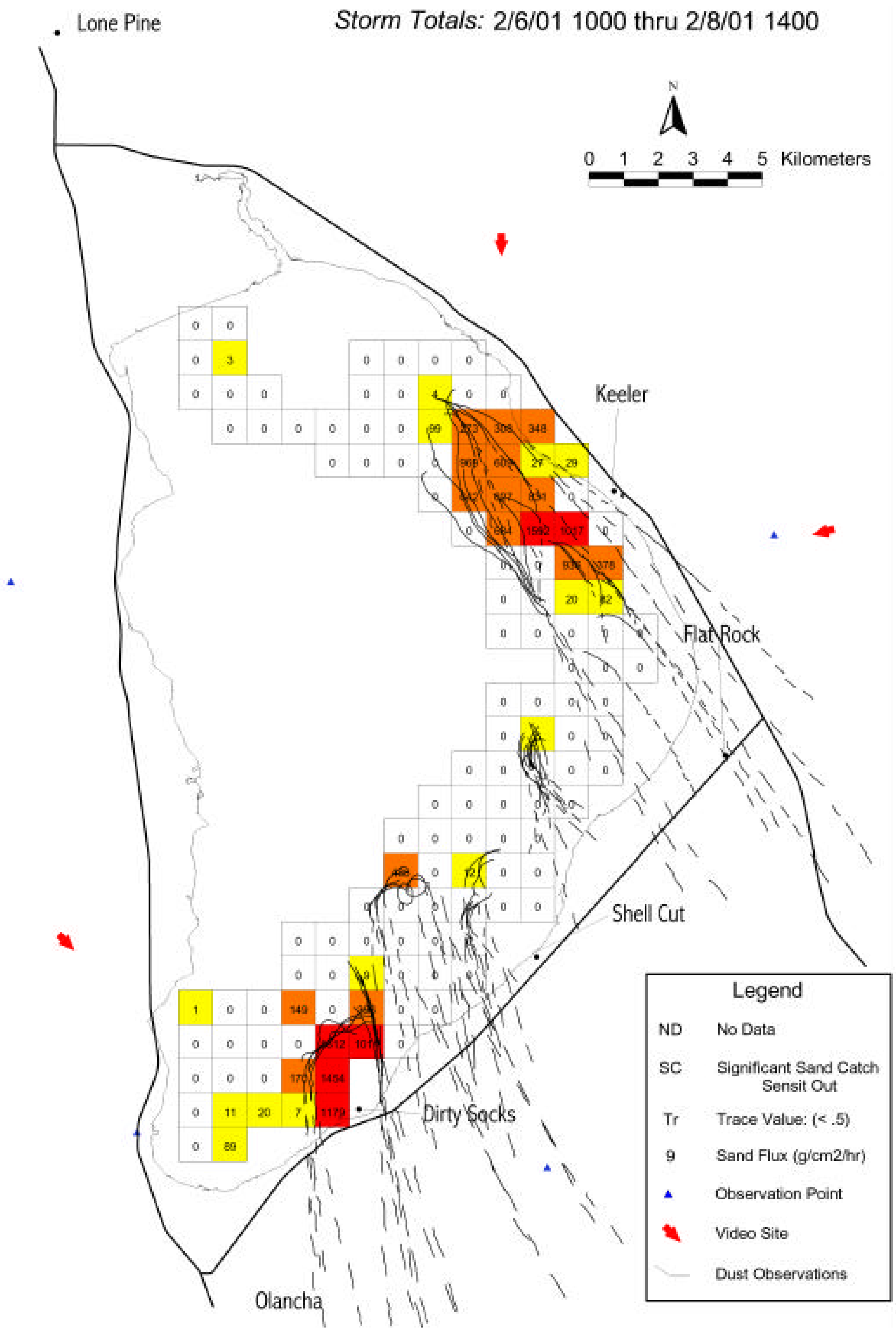
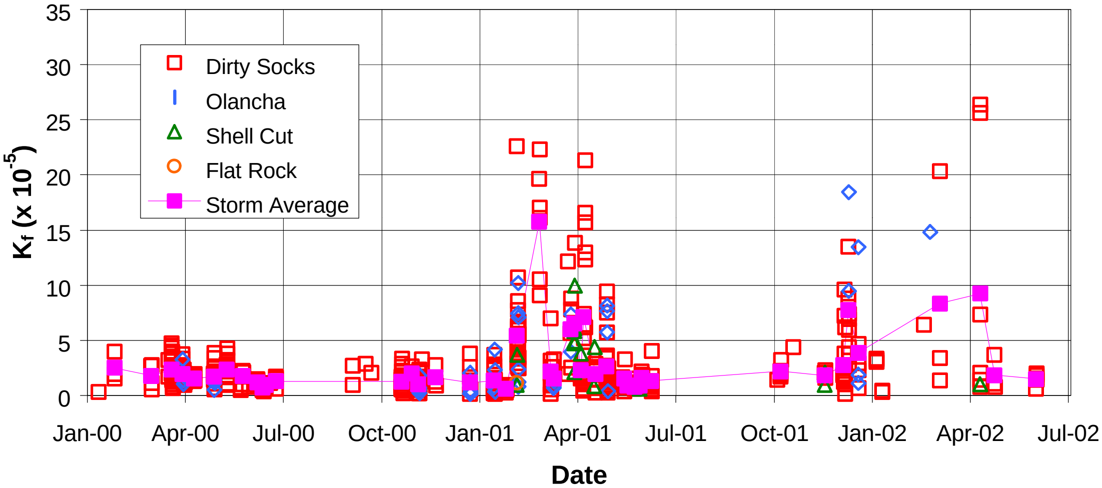


Figure 8. Hourly K-factors were compiled for four different areas of the lakebed and evaluated for temporal variations. K-factors are shown for the South Area.



network. Sensits recorded sand flux every 5 minutes throughout the dust storms and provided erosion data when plumes could not be seen, such as at night, and when the plume itself obscured the observer's view of erosion on the surface.

Temporal and Spatial K-factors

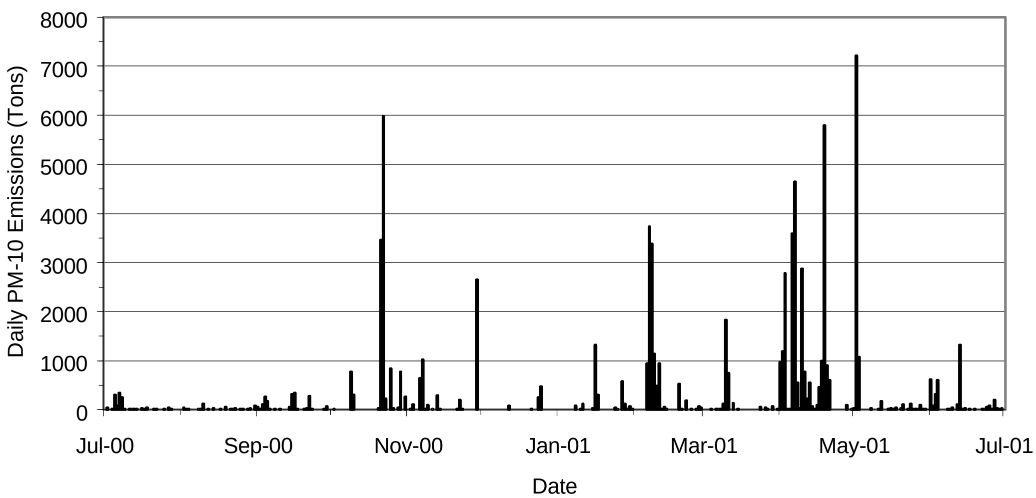
About 1,000 hours of screened data were used to generate temporal and spatial K-factors. Figure 8 shows the hourly K-factors for the South Area of the lakebed. The results show scatter in the hourly values, but a fairly constant average K-factor for each storm during certain periods of the year. The storm average for the South Area, as well as other areas usually increases during the winter and early spring. This period corresponds to the formation of an efflorescent salt on the surface that forms a very powdery and loose surface. Efflorescent salts form annually at Owens Lake with increased precipitation and cold temperatures.

In addition to the South Area, three other areas of the lakebed were identified for the spatial K-factor sets: the Keeler Dunes, the North Area, and the Central Area. The boundaries of the four areas, which are shown on the map in Figure 1, were delineated by a soil survey of the surface soil textures. All four areas showed temporal K-factor trends, as well as some differences that may be attributed to different soil textures. Data plots similar to Figure 8 for the South Area were generated to determine spatial and temporal K-factors for all four areas. Table 1 shows a summary of the temporal and spatial K-factors that were generated from the screened K-factor data. The 75% K-factor set is used because it was found to provide the best model performance for the high PM-10 days.[1]

Table 1. 75-percentile storm-average K-factors were determined to provide spatial and temporal values to estimate hourly emissions and model ambient PM-10 impacts.

Period	K-factors (10^{-5})			
	Keeler Dunes	North Area	Central Area	South Area
1/1/00-2/3/01	5.1	2.1	6.6	1.9
2/4/01-4/18/01	5.1	2.1	26	6.7
4/19/01-11/30/01	5.1	2.1	6.3	1.9
12/1/01-3/8/02	20	7.6	36	5.8
3/9/02-4/18/02	5.5	5.0	6.9	9.0
4/19/02-6/30/02	5.5	5.0	6.6	1.8

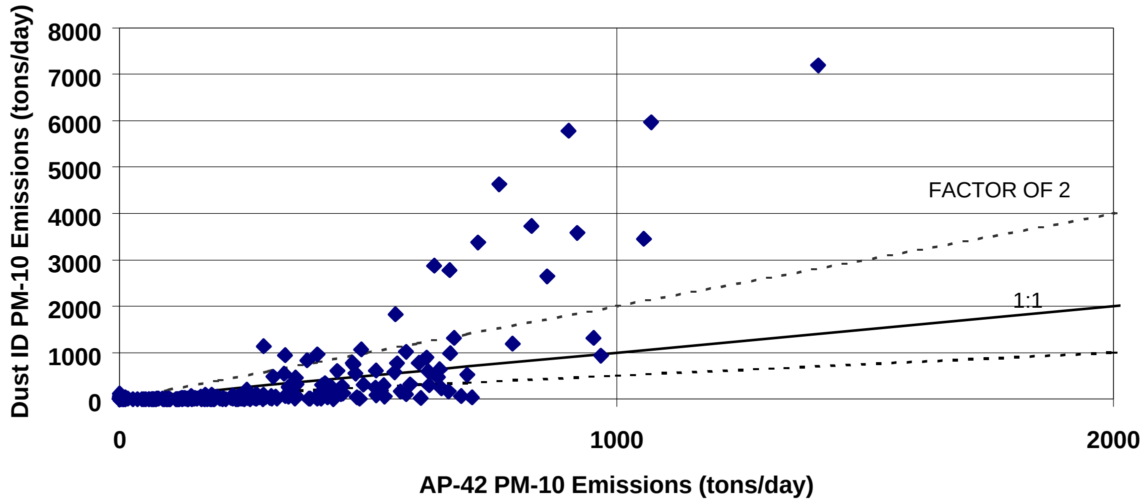
Figure 9. Using the Dust ID method, daily PM-10 emissions were measured as high as 7,200 tons on May 2, 2001 and total emissions for one year totaled 79,200 tons.



PM-10 Emissions

Using the Dust ID method, hourly, daily, and annual PM-10 emissions can be calculated using Equation 2. Figure 9 shows the daily PM-10 emissions based on the hourly sand flux for each cell and the appropriate temporal and spatial K-factor from Table 1. The highest daily emission total during the program was calculated at 7,200 tons of PM-10 (6,540 metric tons) on May 2, 2001. The annual PM-10 emissions for Owens Lake were determined to be 79,200 tons (72,000 metric tons) from July 2000 through June 2001. This 12-month period was used to estimate the annual emissions because the full sand flux network was in place during this period and it was not influenced by the dust controls that were implemented at the end of 2001. Currently, PM-10 emissions are on the decline as the result of dust mitigation efforts that started in 2001. Emissions are expected to continue their decrease as more dust areas are controlled through 2006.

Figure 10. Comparison of daily PM-10 emissions at Owens Lake estimated using the Dust ID Method and the AP-42 method (July 2000 – June 2001).

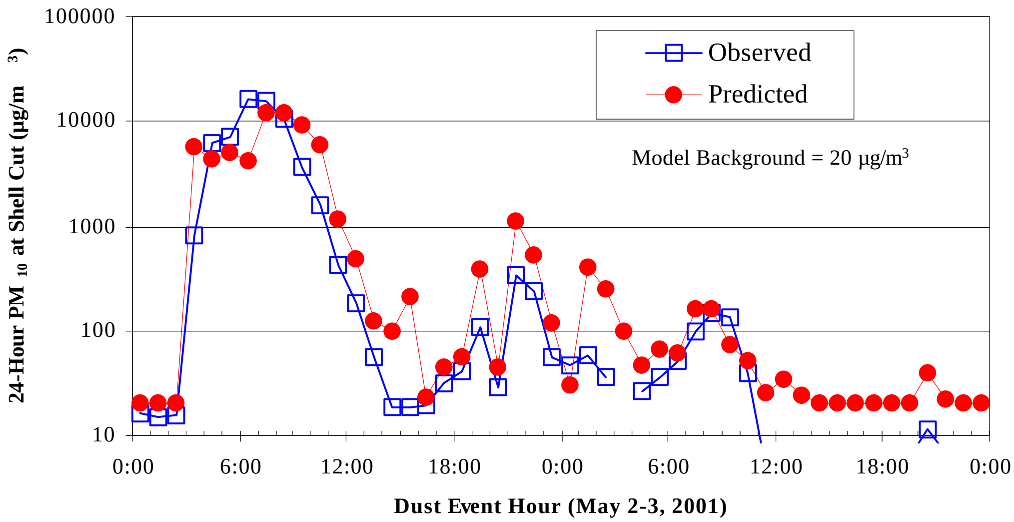


Daily and annual PM-10 emissions were calculated using the AP-42 method from Equation 3. The threshold friction velocity was taken from Sensit data that showed that erosion on the lakebed could start when the friction velocity was around 0.26 m/s. The threshold friction velocity will change temporally and spatially at Owens Lake. However, variable threshold friction velocity information is not typically available to those that use the AP-42 Method. For comparison purposes of the two methods a single threshold friction velocity was used for the emission estimates using the AP-42 method. The highest 5-minute average wind speed for each day was used to approximate the fastest mile wind speed. Wind gust and fastest mile data are not collected at the meteorological sites. The 5-minute average data may be slightly lower than the fastest mile data. Data was taken from a 10-m tower at the B-Tower Site located on the lakebed. The results showed the highest daily PM-10 emissions were 1,400 tons (1,300 metric tons) on May 2, 2001. Using the AP-42 method, the annual emissions were estimated to be 71,600 tons (6,500 metric tons) from July 2000 through June 2001.

DISCUSSION

The AP-42 method and the Dust ID method of estimating emissions resulted in very close agreement for the annual emissions, but very poor agreement for daily PM-10 emissions. Annual emissions were estimated at around 72,000 tons of PM-10 using AP-42 and 79,000 tons of PM-10 using the Dust ID method. Figure 10 shows a comparison of the daily PM-10 emissions estimated using AP-42 as compared to the Dust ID method. For daily emission, the authors 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. As previously, mentioned this was done since this is the normal practice when using AP-42. Daily emission

Figure 11. This plot compares the model-predicted and observed PM-10 concentrations at the Shell Cut site for a large dust event on May 2-3, 2001.



estimates using the two methods would likely have been much closer, if daily threshold friction velocities for each square kilometer of the lakebed could have been determined.

Emission estimates using the Dust ID method are believed to have better accuracy than the AP-42 method, since the emissions correspond to measured hourly erosion on the lakebed. In addition, the Dust ID emissions result in good model performance when compared to monitored PM-10 concentrations. Figure 11 shows the hourly modeled and monitored PM-10 concentrations for an Owens Lake dust event using the Dust ID hourly emission estimates. This example plot shows that the model-predicted concentrations using the hourly Dust ID emissions, closely matches the monitored concentrations and trends at Shell Cut. A detailed model performance evaluation was completed using data for all 6 PM-10 monitor sites shown in Figure 1. The results of the model performance are discussed in more detail in Richmond, et al., 2003.[10]

Sand flux was found to be the most critical factor that affected PM-10 emissions. Hourly sand flux rates were found to vary by more than a factor of 100 in active areas, while the hourly K-factor rarely varied by more than a factor of 2 or 3 from the storm-average value. Although the sand flux rate had the strongest influence on the PM-10 emission estimates, much of the focus of the Dust ID Program was on the variability of the hourly K-factors. Ten screening criteria were used to remove hours that may have had a weak source-receptor relationship. These criteria objectively screened-out many hourly values that appeared to be outliers and significantly reduced the variability of the average temporal and spatial K-factors.

Table 2. Comparison of temporal and spatial K-factors measured with a wind tunnel and the Dust ID method at Owens Lake.

		Average K-factor	
Dust ID Period	**Area**	**Wind Tunnel**	**Dust ID**
1/1/00 - 2/3/01	North Area	2.3×10^{-5}	1.8×10^{-5}
1/1/00 – 2/3/01	Keeler Dunes	1.3×10^{-5}	3.5×10^{-5}
2/4/01 - 4/18/01	Central Area	9.7×10^{-5}	24.1×10^{-5}
2/4/01 - 4/18/01	South Area	6.6×10^{-5}	5.9×10^{-5}
4/19/01 - 11/30/01	Central Area	16.0×10^{-5}	5.7×10^{-5}
4/19/01 - 11/30/01	South Area	3.1×10^{-5}	2.0×10^{-5}

One of the confirming points about the K-factor method was the apparent agreement with K-factors that were calculated from different monitor sites, which were in different directions and distances from the target source area. Figure 8 shows that the hourly K-factors generated for the South Area were very similar when generated from Olancha, Dirty Socks, or Shell Cut.

By inspecting data plots such as the one shown in Figure 8 for each area, it was found that the average K-factors were relatively constant most of the time. However, during the late winter and early spring K-factors increased by about a factor of 5 in some areas. This increase in the K-factor appears to correspond to precipitation events and cold temperatures. The surface change generally appears as a white efflorescent powdery salt on the surface and there is a general breakdown of any surface crusts that may have existed. This change may affect the entire lakebed, or just parts of it. Since these periods have some of the largest dust storms, it is important that these changes in the surface conditions and K-factors are defined to properly model this period.

Wind tunnel tests were performed by Nickling et al., and Nickling and Brown to provide comparative information on the K-factors using a different measurement method than the Dust ID Program.[5,6] Wind tunnel measurements were not taken randomly since the runs were performed on surfaces that had been observed to be active erosion areas. Individual test runs using the wind tunnel showed a large range of K-factor values for the same sites that could be more than 100 times different. However, as shown in Table 2, the averages of the runs showed similar averages to those measured by the Dust ID method for the same areas and during the same period. It is important to note that individual wind tunnel runs measure erosion on a 12 square meter surface, whereas the Dust ID method measures the average K-factor for a minimum of 1 to 3 million square meters at one time. This assumes that the Dust ID K-factor is based on sand flux for a large area and that 1 to 3 square kilometer areas may be the size of the primary dust source areas during any single hour that K-factors are generated. The wind tunnel runs demonstrated the large variability in small-scale wind erosion measurements that is common to all surfaces, even when they may appear to be quite uniform. By averaging the results from many runs, the average wind tunnel generated K-factors became more representative of the value for a large erosion area as measured using the Dust ID method.

Measurements of K-factors and wind erosion are expected to continue at Owens Lake for the purpose of monitoring the implementation of control measures and to identify any new source areas that may cause or contribute to NAAQS violations. The authors believe the Dust ID method can be applied in other wind erosion areas and that additional research should be done to measure K-factors and sand flux for other places. For other areas, the extensive monitoring performed for the Dust ID Project could be substantially reduced in size or concentrated in smaller areas to locate wind blown dust sources and to measure their PM-10 emissions.

CONCLUSION

A monitoring program, known as the Dust Identification (Dust ID) Program, was started in the year 2000 to identify dust source areas that caused or contributed to NAAQS violations. Based on previous research that found that PM-10 emissions were proportional to sand flux, a network of sand flux monitors were installed at Owens Lake. Passive and electronic sand flux monitors were placed on 135 sq. km of the lake bed at a 1 km spacing to measure the hourly sand flux at each site for 30 months. This sand flux information was used with the CALPUFF modeling system to model PM-10 impacts at shoreline receptors, including 6 PM-10 monitor sites. Hourly PM-10 emissions from each square kilometer were estimated by the equation, $PM\text{-}10 = K_f \times q$, where q is the sand flux measured at 15 cm above the surface, and K_f (K-factor) is the non-dimensional ratio of the PM-10 emission flux to the sand flux at 15 cm. Initial model runs used a constant K_f value. After the initial model run, hourly variations of K_f were evaluated by comparing the model predictions to the observed concentrations at the PM-10 monitor sites. Average K_f values were found to change spatially and temporally at Owens Lake. These changes corresponded to different lake bed soil textures and to seasonal changes in the surface erodibility. Wind tunnel tests at Owens Lake independently confirmed these seasonal and spatial changes in K_f.

The results of the Dust ID Program showed that sand flux measurements can be used with K-factors to quantify PM-10 emissions for wind blown dust areas. Data collected from the Dust ID network provided valuable information on the location, frequency and intensity of PM-10 dust source areas at Owens Lake. During the study period, the peak daily PM-10 emissions from Owens Lake were estimated to be 7,200 tons on May 2, 2001, and the annual emissions were estimated to be 79,200 tons from July 2000 through June 2001.

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KEYWORDS

Wind Blown Dust, PM-10 Emissions, Owens Lake, CALPUFF, K-factor