CHARACTERIZING DUST EMISSION POTENTIAL IN THE IVANPAH VALLEY, NEVADA

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LEE WEISS

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ABSTRACT

CHARACTERIZING DUST EMISSION POTENTIAL IN THE IVANPAH VALLEY, NEVADA

Lee Weiss  
University of Guelph, 2009

Advisor:  
Professor W.G. Nickling

Aeolian dust emissions, while vital to various ecosystems worldwide, are in part responsible for declining ambient air quality and pose significant problems in arid and semi-arid regions in the southwest United States. As part of several ongoing dust emission studies in the Mojave Desert, a series of Portable In-situ Wind Erosion Laboratory (PI-SWERL) tests as well as other soil parameter tests (salt and organic content, soil strength and grain size) were performed to gather an abundance of data related to the emission of PM$_{10}$ (particulate matter < 10 μm). The PI-SWERL is a small and lightweight device used to measure dust emissions in the field and has been calibrated with wind tunnels. The tests performed in this study were located on two transects in the Ivanpah Valley, providing a cross-section of a variety of natural and undisturbed soil surfaces.

The results indicate that the PI-SWERL tests, coupled with supplemental soil parameterization data, agreed with established and commonly used dust emission models. In addition, the results agreed with modeled data far more when more data was available, but varied between similar soil types between the two transects.
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1 SIGNIFICANCE OF THE STUDY

1.1 WIND EROSION OVERVIEW

Wind erosion, transport and deposition occur in more than one third of the Earth's land surface (Chen and Fryrear, 1996). The erosion of sediments and soils from the Earth's surface is the main source of atmospheric dust particles larger than 2μm (Pye, 1987). Dust is generally defined as particles with a diameter of less than 100 μm. It is estimated that the annual dust produced from erosion is approximately 3 billion tons, although a sizeable proportion of this dust is deposited in the ocean (Duce et al., 1991). If high enough, these atmospheric dust loadings can also act to absorb heat from the Earth's surface, making it a contributing factor to climate change (IPCC, 2007).

Additionally, dust emission and transport by wind in arid environments have significant impacts on natural habitats through a decline in soil-nutrients (Fryrear, 1981). Soil losses from drylands are associated with the removal of organic matter and the nutrient-rich smaller particles. This reduces vegetative capacity and agricultural productivity (Fryrear, 1981). Increases in atmospheric dust loadings also decrease visibility, which can affect air and road transportation (Houseman, 1961) and adversely impact human health through an increase in respiratory afflictions (Pye, 1987) and transmission of disease (Hyers & Marcus, 1981), primarily in populated areas close to major dust sources.

Conversely, many types of flora and fauna in both arid and tropical environments rely on airborne nutrients for survival. A recent study by Koren et al. (2006) concluded that approximately 40 million tons of dust from the Saharan Bodélé depression is transferred to the Amazonian Rainforest Basin annually and is the principle source of nutrients for this large and vibrant ecosystem. On smaller scales, Reynolds et al. (1999) observed that shrubs in desert grasslands form clusters that act to trap nutrients in the soil.

In response to the Great Smog of 1952 in London, England, several countries worldwide began developing and passing federal legislation to monitor and reduce air pollution, with the overall goal of improving air quality. This legislation, which takes the form of the Clean Air Act (CAA) in both Canada and the United States (U.S.), has led to a widespread demand and use of
atmospheric dispersion models, which is a major driving force behind understanding and quantifying dust emission potential. Results from these models are used to develop effective land-use management guidelines as well as to understand the impacts of dust emissions on local populations and natural environment.

1.2 WIND EROSION AND DUST EMISSION RESEARCH

The complex physics of wind erosion involves atmospheric, soil and land surface processes, making the study of wind erosion multi-faceted and multi-disciplinary. Wind erosion researchers must be well versed in fields such as meteorology, fluid dynamics, soil physics, colloidal science, surface soil hydrology and ecology, among others (Shao, 2000). These highly dynamic networks of interactions are governed by a variety of factors, some of which include atmospheric conditions, soil characteristics, land-surface properties and land-use practices.

Atmospheric systems at various spatial and temporal scales, such as large-scale global circulation and small-scale boundary-layer turbulence, determine precipitation distribution, soil moisture, vegetation cover and therefore, the large-scale features of wind erosion globally. Two integral areas of study in both regional and local system research are direct field measurement and numerical modelling. These research areas are presently growing and drawing upon a vast range of expertise to combine the laboratory and field research in a highly technical and cohesive manner.

Despite the complexity of the dust emission process, various models have emerged providing various insights into this phenomenon. Early research by Bagnold (1941) and Chepil (1956) laid the groundwork for the fundamental concepts of wind erosion used today. The first generation of emission and transport models identified the vertical dust flux (F) as a function of soil transport (Evans and Cooper, 1980) related to the impact of saltating grains, which is ultimately linked to the shear stress created between the air and the surface (Gillette, 1977). These principles were further developed by Gillette and Passi (1988) who suggested that the ratio of vertical dust flux to horizontal sediment flux (q) was a linear function of shear velocity. Shao et al. (1993) extended this work in their evaluation of saltation impacts on a loose dust bed, suggesting that the vertical dust flux (F) is proportional to the cube of shear velocity, u*. A similar model was later proposed by Marticorena and Bergametti (1995), which expressed the vertical dust flux as a linear function of saltation transport rate (q). From this, Alfaro and Gomes
were able to develop a model that integrates both the occurrence of saltation and the sandblasting effect it can have on the surface in the production of dust emission.

1.3 Problem Statement

Currently, much of the focus of aeolian research, as with many other branches of science, is the prediction of atmospheric dust concentrations on larger, regional scales (Alfaro et al., 2004). In order to accurately predict or model dust emission and transport on a global scale, local dust potential must be properly characterized. While several semi-empirical models for dust emission exist, field studies are critical, both as a basis for further refining or representing a given study area, as well as verifying the accuracy of current models and data gathering techniques in field conditions on natural surfaces (Houser and Nickling, 2001).

Much of the understanding surrounding wind erosion phenomena, such as saltation or threshold wind velocity, has come from data collected from wind tunnel operation under controlled laboratory conditions. Portable wind tunnels, set up under field conditions, are particularly useful in observing these phenomena under natural conditions. Both types of data and study have been used to develop, calibrate and further refine current dust emission models. These studies are often complimented with data collected from meteorological stations and instruments, which can provide ongoing background and baseline data. Although these studies have provided substantial insights into wind erosion phenomena, there still exists a serious lack of high-quality and coherent observational data sets to sufficiently provide validation to dust emission schemes (Shao, 2008). A field-based evaluation of dust emissions, combined with the in-situ testing and sampling of a relevant suite of other parameters, could lead to the development of one such needed dataset, for the purpose of providing validation to current dust emission models.

1.4 Study Aim and Objectives

The aim of this study is to develop a coherent dust emission and corresponding soil property data set and to use these data to evaluate current dust emission models. More specifically, the research will use particulate matter less than 10 μm in diameter (PM$_{10}$) dust emission data as well as range of soil properties (i.e. % silt, % clay, crust strength and salt content), from sample sites along two discrete transects to provide validation to various dust emission models, which
will also provide a detailed site characterization of the transect locations. This aim will be achieved through the following research objectives:

i) To develop a standardized field sampling plan of the study area along two transects using the Portable In-Situ Wind Erosion Laboratory (PI-SWERL) as well as other instruments and techniques to measure relevant soil properties.

ii) To undertake an intensive quality assurance and quality control process of the collected PI-SWERL and soil property data.

iii) To evaluate the validity of current dust emission models using the analyzed field data.

The ultimate goal of this study is to practically contribute to the field of wind erosion research through the achievement of these objectives. Currently, the lack of high-quality field data has been identified as an essential research gap and satisfying this study aim will facilitate the further collection of high-quality, in-situ wind erosion data.

To achieve the above objectives, PI-SWERL tests were carried out in the Mojave Desert, near Las Vegas, Nevada. Sixty-five discrete sites were tested and sampled during the period study, between July 5th and 29th, 2008, as well as an additional sixteen adjacent replicate sites. At each site, three PI-SWERL tests were performed; measuring dust emission and saltation, and soil properties were tested and sampled at all sixty-five sites. This allows the PI-SWERL data to be compared to soil properties at the same location. The comparative study that will follow will also provide insights into the accuracy and usefulness of the PI-SWERL and the PI-SWERL technique for future research.

This thesis follows a traditional approach to presenting the findings of this study. The following chapter will provide a literature review of wind dynamics, sediment transport and dust emission. The experimental approach, study location, data collection and analysis will be discussed in the methodology section (Chapter 3). Following the presentation of results (Chapter 4), a detailed discussion (Chapter 5) and a conclusive summary (Chapter 6) describe the findings and their significance to current and future research.
2 RESEARCH CONTEXT

2.1 THE SURFACE WIND

The science of aeolian sediment transport is commonly associated with arid environments. The relatively low annual precipitation these areas receive affects the sparse and limited vegetative cover observed in these areas, which then relates to the abundance of non-cohesive sediment. These factors, working in concert together, make wind erosion an especially dominant phenomenon in these ecosystems. Increased human interaction within these environments has fuelled the pursuit to understand the dynamic processes occurring in these regions.

The process of wind forced movement of soil particles occurs in 3 basic stages: entrainment, transport and deposition. Entrainment is primarily dominated by wind shear at the surface coupled with saltation bombardment, whereas transport is the atmospheric stage dealing with advection and turbulent diffusion. Deposition then occurs and can be both dry and wet removal of particles from the air stream. These stages will be defined and examined more closely in the following sections.

2.2 THE PLANETARY BOUNDARY LAYER (PBL)

Boundary-layer theory was first developed by Ludwig Prandtl in 1904 and it is the thin layer, next to solid boundaries, where fluid viscosity is concentrated (Prandtl, 1905). Climatic mechanisms, such as global precipitation, soil moisture and vegetation are largely influenced by atmospheric circulation patterns in the upper troposphere at a height of approximately 11 km from the Earth's surface. Smaller localized wind erosion events are dominated by turbulent wind shear close to the surface in a thin 1 – 2 km sub-layer of the troposphere called the boundary layer (Figure 2.1). Wind speed in this layer experiences great changes due to the effects of surface friction. The free atmosphere exists above the boundary layer, where the effects of surface friction are no longer observed. Traditionally, the boundary layer is defined as the area where the mean horizontal wind speed (u) is less than 99% of the free stream velocity (Crow et al., 2001). It has also been regarded as the region of flow affected by the frictional influence (Wiggs, 1997).
The boundary layer is characterized by the logarithmic wind velocity profile created by surface roughness, topography, solar radiation and many other factors. Over the course of one day, the exchange of heat, mass and energy within the boundary layer create dynamic changes in air flow regime. Although dominated primarily by turbulence, the boundary layer can be divided in two distinct convective and stable layers, as shown in Figure 2.2: Daily variation in air flow regime during a single day (Shao, 2008).
The convective layer is evident during the morning and afternoon hours. It is during this time when surface heating creates convection through plumes and thermals, or when clouds absorb solar radiation and emit it towards the surface, instead of reflecting it back in the same direction, to initiate radiative cooling. This instigates top-down convection from the cloud-level to the surface. As a result, temperature decreases rapidly with increasing height from the surface and increases with increasing height at the cloud level while the pressure remains constant. This phenomenon creates a “capping” mechanism, which acts to keep pollutants and specifically dust, inside the PBL by creating a sinking motion. The turbulent flow generated mixes heat, momentum, moisture and dust vertically ultimately allowing dust particles to settle from the force of gravity.

The stable layer generally increases in potential temperature with increasing height from the surface. This phenomenon usually occurs at night, as the surface cools by emitting long-wave radiation, which facilitates the development of an inversion layer close to the surface. Although turbulence is substantially less than in the convective layer, this stable stratification of the atmosphere can generate sporadic increases in turbulence called jets, which ultimately get absorbed by the surface (Mahrt, 1999).

Although both layer types display distinct characteristics, their structures are heavily defined by the level of turbulent flow observed. Turbulent flow is dynamic in nature, where wind flow layers are constantly mixing; facilitating the transfer of momentum thereby producing flow patterns of different speeds and directions. In contrast, flow layers that do not mix and intertwine are considered laminar. These types of flows do not readily exist in nature (Lancaster and Nickling, 1994) and as a result, have little relevance in the field of wind erosion.

2.3 DRIVING FORCES

The following section highlights four aspects of wind erosion that are major contributors to dust entrainment and transport in the PBL. They include turbulence and momentum, which encompass concepts such as drag exerted by wind and aerodynamic lift, saltation, which discusses the impacts of rolling or bouncing particles on surface erosion and grain-size effects, which can act as both a driving and resisting feature of wind erosion. Additionally, the effects of anthropogenic disturbance are an important contributor to dust emissions worldwide.
2.3.1 Turbulence and Momentum

The turbulent nature and dynamic transference of momentum in the PBL has been regarded as the dominant process that controls wind erosion and dust emissions (Gillette, 1999). It is known that the speed of fluids, and in this case wind, varies with height, as shown in the wind profiles (Figure 2.3). The basis of boundary-layer theory is Prandtl’s Mixing-Length theory, which defines the turbulent wind profile in the PBL; where the presence of surface roughness facilitates increased mixing, increasing the slope of the wind profile at the surface, increasing shear stress in contrast to the slope produced under the influence of the viscous sub-layer alone (Wiggs, 1997). The characteristic impedance of wind speed by friction at the base of the profile, followed by eddies in all directions is often described as fluid drag.

![Figure 2.3: Boundary Layer](image)

*(over smooth & rough surfaces where \( \delta \) represents the PBL thickness, \( y \) is the height above the surface and \( U \) is the wind speed - Nickling, Sedimentary Processes course manual)*

This mixing action or fluid drag can be best demonstrated by considering a mass of fluid with a relatively higher momentum having a tendency to accelerate the lower-velocity fluid in the region into which it moves. The result is an exchange of momentum, commonly regarded as an apparent shear stress (\( \tau_{\text{app}} \)) to the fluid and referred to as Reynold’s stress. This property, in addition to wind speed within the PBL, are regarded as scalars, travelling in the same uniform direction as the shear stress with increasing height (Lumley et al., 1964). On smooth surfaces,
momentum-exchange does not occur to the same extent, so the turbulent flow is not generally studied in these situations. As a result of the turbulent flow over rough surfaces, the wind profile is not fragmented and the logarithmic portion represents a layer with uniform shear stresses, which is most useful when studying the phenomenon. This drag force or shear stress, \( \tau \), which is exerted on the surface, is expressed as a force per unit and is related to the shear velocity \( (u^*) \) and air density \( (\rho) \) by:

\[
\tau = \rho u^* \cdot ^2
\]

Momentum sinks are created on the surface by the active transferring of momentum from the atmosphere to the surface by the force of friction. This phenomenon is further discussed in Section 3.2.1. Quantitatively, these momentum exchanges are occurring on a constant basis causing the shear velocity value to fluctuate. As a result, the shear velocity represents a time-averaged flow over the surface, or wall. With these tools, the vertical wind speed profile, or logarithmic boundary layer wind speed profile over a rough surface, also known as the "law of the wall" or the Prandtl-von Kármán equation can be described as:

\[
u(z) = \frac{u^*}{\kappa} \ln \left( \frac{z - d}{z_0} \right)
\]

where, \( u \) is the wind speed (m/s) at height \( z \) (m), \( u^* \) is the shear, drag or friction velocity (m/s), \( d \) is the zero plane displacement height (m), \( z_0 \) is the height of the surface roughness (m) and \( \kappa \) is the universal turbulence constant, or von Kármán's constant, which changes with temperature gradient. The value of the universal turbulence constant relates the depth required for an eddy to become completely integrated into the surrounding flow pattern and has been the subject of considerable debate although the general consensus is that it is approximately 0.4 for most conditions (Hogstrom, 1988). The height of the surface roughness, \( z_0 \), was typically considered 1/30 of the diameter of the particles on the bed surface (Prandtl, 1935; Bagnold, 1941); although Greeley and Iversen (1985) later validated this constant for grain configurations that are closely packed or spaced far apart (Figure 2.4).
As illustrated in Figure 2.4, both closely packed particles and those spaced far apart, create a uniform surface, where the $z_0$ is approximately $1/30$ of the mean grain diameter. For grain sizes with medium separation, $z_0$ is closer to $1/8$ of the mean grain diameter. The effects of grain size on the various modes of sediment transport will be further discussed in Chapter 3. The displacement height, $d$, is used when the plane of zero velocity (i.e. the surface of the ground) must be shifted upwards vertically, in order to capture roughness elements, such as dense vegetation (Pye, 1987).

Shear stress at the surface or wall is among the primary driving mechanisms for the initiation of sediment transport. Although it is often difficult to directly measure this parameter, wind profiles are easily measured and the Prandtl-von Kármán equation is then used to calculate the surface shear stress. A different approach to calculating the surface shear stress that is often used by researchers and practitioners is the Reynold's Stress approach, which uses measured data from transfers in momentum on a time averaged basis, using the following relation:

\[
\tau_{app} = -\rho u'v'
\]

where, $\tau_{app}$ is the apparent shear stress or Reynold's stress, $\rho$ is the air density and $u'$ and $v'$ are the horizontal and vertical components of the velocity fluctuations respectively.
Current research is focused on understanding the dynamics of turbulence and momentum exchange, specifically improving the characterization of the critical threshold shear velocity ($u_{cr}$), which relates the minimum force required for the driving forces to overcome the resting forces on a particle. This research will enable scientists to improve the use of erosion barriers more accurately.

2.3.2 Saltation

The entrainment of dust particles can occur through aerodynamic forces, as discussed above, or through the impact of saltating grains, termed dynamic entrainment (Houzer and Nickling, 2001). Dust particles are associated with strong cohesive forces, introducing resistance to aerodynamic entrainment (Greeley and Iversen, 1985). The impact of saltating grains has been identified and proven to be more disruptive on inter-particle forces than aerodynamic mechanisms (Bagnold, 1941; Shao et al., 1993) and has been shown to increase the rate of re-suspension of particles into the wind stream by a factor of six and seven (Fairchild and Tillery, 1982).

Surface creep is the combination mechanism of sliding and rolling together as a result of drag effects by the wind and impacts of saltating sediment. Anderson and Heff (1988) describe a transitional process between saltation and creep called reptation, which involves the low-level skipping of grains prior to the high velocity impact of a single saltating grain. Figure 2.5 illustrates the processes outlined above.
Saltation and suspension are controlled by different mechanisms; saltation occurs when the vertical component of the turbulent air flow is not affecting the particle’s path whereas suspension occurs when the shear velocity is very large compared to the particle’s settling velocity. The trajectory of some particles may be affected by both the energy in the turbulent air flow, or inertial forces, and its own settling velocity. This transport mode, termed modified saltation, appears as a random trajectory through the air stream (Figure 2.5) (Nalpanis, 1985; Nalpanis and Hunt, 1986).

Once entrained, a particle’s motion can include sliding, rolling, saltation or it may remain in suspension (Pye, 1987). A particle in suspension remains in transported above the surface when the settling velocity of the particle is less than the vertical component of the wind (Kalinske, 1943). Saltating sediment transport is characterized by the ejection, transportation and subsequent deposition of particles at a downwind location. The ejection of particles is dominated by lift forces, which are the sum of all the forces acting in the perpendicular direction to wind flow (Figure 2.5).
The average vertical extent that particles will reach is (Tsoar and Pye, 1987):

**Equation 2-4**

\[ h = \sqrt{2 \varepsilon t} \]

where \( \varepsilon \) is the coefficient of turbulent exchange, indicating the degree of vertical air mixing:

**Equation 2-5**

\[ \varepsilon = \sqrt{\left(w'^2\right)l} \]

This equation relates the coefficient of turbulent change to the vertical component of the fluctuating velocity, denoted as \( w' \) (or \( v' \) as earlier denoted) and the mixing length, \( l \). To assess the mixing length, Prandtl (1935) developed the following relation:

**Equation 2-6**

\[ l = \alpha K z \]

Where \( \alpha \) is the measure of atmospheric stability (>> 1 for unstable, convective conditions, =1 for neutral conditions and << 1 for stable conditions), \( K \) denotes von Kármán constant and \( z_0 \) is the surface roughness, as discussed in the previous section. This process initiates a type of momentum transfer where, upon impact between the saltating particle and the surface, more grains are entrained through the fallout effects of the force of impact with the surface. Visually, this can be depicted as an abrasive process imposed on the surface by the bombardment of saltating particles. With naturally crusted soils, this abrasive process is the dominant process in breaking up soil crust and aggregates and releasing dust into the air (Chepil, 1945; Gillette et al., 1974; Hagen, 1984). In soils with high levels of salt concentration, Nickling (1984) described an effect where the displaced soil particles exposed to the air stream effectively increase the effects of fluid drag on the surface particles, entraining particles or aggregates at lower shear.
velocities, compared to soils with lower salt concentration. Once the protruding sediments have been removed, shear velocity must then increase to entrain the newly exposed surface particles. At the initial stage of this process, however, the particle movement begins by impacting and scouring the pristine surface crust, exposing weakly bonded soils below, which will entrain sediment at lower shear velocities (Nickling, 1984).

The connection between saltation transport rate and shear velocity, as described by Bagnold (1941) and later by Owen (1964), laid the framework for Shao et al., (1993) to quantify the vertical dust flux \( F \), as proportional to shear velocity, \( u_- \):

\[
F = \alpha u_-^3 \left( 1 - \left( \frac{u_{cr}}{u_-} \right)^2 \right)
\]

where \( \alpha \) is a dimensionless parameter describing the efficiency of the bombardment process:

\[
\alpha \approx \frac{c_N m_d \rho}{\psi}
\]

where \( c_n \) is the proportion of the incoming saltation energy available to disrupt inter-particle bonds, \( \psi \), \( m_d \) is the mass of the dust material and \( \rho \) is air density. The inclusion of inter-particle bonds is essential, since the emission of dust from the surface is based on the surface controls for particle release, rather than the transport capacity of the wind (Houser and Nickling, 2001).

2.4 GRAIN SIZE EFFECT

Grain-size effect is inherently related to various Aeolian transport modes and has been extensively studied as a parameter of wind erosion. This section will relate both sediment transport modes with the analysis of grain-size effect. Figure 2.5 illustrates various modes of sediment transport, as well as the characteristic range of grain sizes associated with each type of movement.

The critical threshold shear velocity, \( u_{cr} \), is the wind velocity required to initiate sediment movement off a surface. Bagnold (1941) characterized this parameter as a force balance on the aerodynamic drag and the force of gravity on a single particle:
Equation 2-9

\[ u_{*r} = A \sqrt{\frac{\rho_p - \rho_a \cdot gD}{\rho_a}} \]

where \( \rho_p \) and \( \rho_a \) are the relative densities of grains and air (g/cm\(^3\)) respectively, \( g \) is acceleration due to gravity (cm/s\(^2\)), \( D \) is the mean grain diameter (cm) and \( A \) is an empirical coefficient in the 0.1-0.2 range for particle-friction Reynolds numbers (Re\(_p\)) greater than 3.5. The particle friction Reynolds’ number is a measure of the level of turbulence around a single particle:

Equation 2-10

\[ \text{Re}_p = \frac{u_*D}{v} \]

where \( v \) is the kinematic viscosity of air. For smaller particles, it was found that \( u_{*r} \) increases rapidly with decreasing grain diameter, which is counter-intuitive. Initially, this behaviour was interpreted as particles being particularly less susceptible to aerodynamic drag in the viscous sub-layer immediately above the ground surface. This was later proven to be a result of inter-particle cohesion (Sagan and Bagnold, 1975; Iversen et al., 1976; Iversen and White, 1982; Greeley and Iversen, 1985). Figure 2.7 demonstrates this disparity, comparing the “Bagnold Scheme” with the updated principles of particle cohesion commonly regarded as the “Greeley and Iversen Scheme”.

Inter-particle cohesion can increase the fluid threshold curve, as shown in Figure 2.7 above, for particles finer than 75-80\( \mu \)m (Pye, 1987). To account for the effects of cohesion, Greeley and
Iversen (1985) suggested a modification to the empirical coefficient for particle friction Reynold’s numbers:

Equation 2-11

\[ A = A_1 F(Re_{p,cr}) G(d) \]

The \( F(Re_{p,cr}) \) function accounts for the aerodynamic drag force on the particle, which is dependent on the particle-friction-velocity Reynold’s number at the critical threshold shear velocity. The constant \( A_1 \) and the two functions, \( F \) and \( G \) were determined by fitting observed wind tunnel data to particle force-balance equations:

Equation 2-12

\[ G(d) = \sqrt{1 + \frac{0.006}{\rho_p g D^{2.5}}} \]

The values for \( A_1 \) and \( F(Re_{p,cr}) \) are listed in Table 2-1 for different flow regimes.

<table>
<thead>
<tr>
<th>( Re_{p,cr} ) Values and F Function Formulae (source: Shao, 2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Re_{p,cr} )</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>( 0.03 &lt; Re_{p,cr} &lt; 0.3 )</td>
</tr>
<tr>
<td>( 0.3 &lt; Re_{p,cr} &lt; 10 )</td>
</tr>
<tr>
<td>( Re_{p,cr} \geq 10 )</td>
</tr>
</tbody>
</table>

Further modifications to this scheme have been developed by explicitly defining the cohesive force component and its contribution to the magnitude of the critical threshold shear velocity (Phillips, 1980, 1984 and Shao and Lu, 2000). Inter-particle cohesion takes the form of moisture films or capillary forces, van der Waals forces, electrostatic forces and chemical binding (Mahanty and Ninham, 1976). These forces are closely related to soil properties, such as particle shape, surface texture, soil mineralogy, packing arrangement and the presence of soil moisture and soluble salts (Shao, 2000). Van der Waals forces are the primary cohesive force acting on spherical particles, in the absence of moisture and chemical binding (Shao, 2000). Using this modified approach, it was found that the critical threshold shear velocity for larger particles, between 50 to 1800 \( \mu m \), is dominated by the balance between the aerodynamic and
gravity forces whereas for particles less than 50 μm, the balance between the aerodynamic and cohesive forces determines the magnitude of the $u_{cr}$ (Shao and Lu, 2000).

Upon the initiation of sediment movement along the surface, grain-size effects can have a tremendous influence on saltation and abrasive movement. As discussed earlier, particles can undergo a bombardment process where moving sediments impact the surface, ejecting new grains, lowering the critical threshold velocity. Bagnold (1941) referred to this as “impact threshold”, $u_{cr}$, and related this phenomenon to grain size, $D$:

$$u_{cr} = 680\sqrt{D \log\left(\frac{30}{D}\right)}$$

As previously discussed, smaller grains require a higher fluid shear velocity to initiate movement, although Bagnold (1960) noted that smaller particles and fine sediments can be easily ejected from the surface by the ballistic impact of a particle larger than 100μm. The speed and trajectory of the impacting particle determines the number and size of particles which are ejected from the surface (Pye, 1987). Nickling (1983) identified a creep movement in finer particle soils immediately before the onset of saltation, whereas creep movements are initiated by saltating grains for larger particles (Pye, 1987). In the case of natural crusted soils, the release of fine particles into the airstream is primarily caused by the abrasive impact of particles breaking up the soil aggregates (Chepil, 1945; Gillette et al., 1974; Hagen, 1984).

2.5 NATURAL AND ANTHROPOGENIC DISTURBANCE

Anthropogenic and natural disturbances can have detrimental effects on the environment. Wilshire (1980) describes large amounts of dust raised into the atmosphere during ploughing and harrowing or dry soils, construction activities, military manoeuvres in desert areas and by vehicles on dirt roads. It is estimated that a four-wheel drive vehicle travelling at 60 km/h along a dirt road containing 12% silt will raise 3.7 kg/km of dust (Hall, 1981). Bagnold (1960) and later Nickling and Gillies (1989) observed that areas with crusted soils, disturbed by the passage of animals or vehicles, caused sharp edges to protrude into the windstream, making the surface more susceptible to erosion; however, once the irregularities were ‘smoothed’, no further sediment movement occurs.
In addition to creating small, localized turbulence patterns, disturbance can also disrupt soil crusts. A conservation program lead by the Desert Foothills Land Trust called “Don’t Bust the Crust” was specifically geared to drivers and recreational visitors in desert areas in an attempt to conserve desert crusts. The objective of this campaign was to inform the public about the importance of soil crusts in arid environments and encourage the public to stay on established roads and trails. This campaign included recreational users, such as hikers, who are encouraged to use trails to hike the washes and rocks. Campers are requested to stay in designated campgrounds or in areas where crusts would not normally grow, like slickrock, beaches or groves of trees. Natural processes, such as volcanic eruptions, also expel large amounts of dust into the atmosphere, although generally to much greater heights, due to the explosive nature of the eruption.

2.6 RESISTING FORCES

While the previous section described the four major ways that dust and sediment are ejected into the atmosphere, the following section discusses resisting forces that keep soil particles on the surface and combat the forces of erosion. This section will expand three main categories of resisting forces: surface roughness and texture, which includes vegetation, rocks and other features, crusts and soil moisture.

2.6.1 Surface Roughness and Texture

Surface roughness, in the form of vegetation and other non-erodible elements on a surface, reduce the amount of soil transport by wind. As surface roughness increases, a greater proportion of the energy of the wind shear stress is absorbed by the elements, leaving less shear stress to entrain finer, more erodible particles (Lyles et al., 1974; Lyles, 1977). Put another way, the wind speed reduction proportionally decreases the available shear force to the surface, thereby reducing wind erosion potential (Grant and Nickling, 1998). More specifically, the configuration of the surface roughness is an important feature; Logie (1982) experimentally verified that the spacing of the elements along the surface directly influenced the critical threshold shear velocity, \( u_{cr} \), as well as the manner of the particle entrainment.

In addition to reducing the amount of soil loss, vegetation is among the most ideal choices to decrease wind erosion due to its porous and flexible properties, which extracts momentum more efficiently than bluff barriers (Gillies et al., 2002); however, Logie (1982) also observed
turbulent eddies developed around arrays of uniform roughness elements in low-density configurations, resulting in increased erosion in the lanes or streets between the islands of roughness elements. Higher density configurations reduced the erosion. Through these wind tunnel experiments, Logie (1982) coined the term *inversion point*, which states the point at which critical cover density for roughness elements changes from protection to activation of erosion for various sizes of roughness elements. In addition to height, irregular-shaped gravel produced more turbulence than glass spheres (Logie, 1982).

Okin and Gillette (2001) have continued this research and have shown that the lanes that do appear, as identified by Logie (1982), expand in both length and width over time as the continual movement of sediments from these areas produce environments lacking in soil profile and nutrients. This positive feedback mechanism stems from the strong seasonal winds, which have limited directional variety and moisture availability, resulting in unprotected soil patches being eroded (King et al., 2006). The critical threshold wind velocity for a vegetated surface is dependent on wind speed, height, width and spacing of vegetation, soil particle size, moisture content and crust development (Wolfe and Nickling, 1996), in addition to the roughness density ($\lambda$), which is a value representing the size and number of roughness elements per unit area (Gillies et al., 2006). This roughness density ($\lambda$) affects the effective shear stress ($\tau$) at the surface and Marshall (1971) was the first to suggest a shear stress partitioning arrangement between the erodible surface and the vegetation. This arrangement incorporates the sheltering capacity of vegetated surface in the roughness density. This work was further developed by Raupach (1992) who developed a shear stress partitioning model using the geometry and aerodynamic properties of roughness to predict the effective stress imposed by wind on the surface and estimate the level of soil loss and dust emissions (King et al., 2005).

Olson (1958), Chepil and Woodruff (1963) and Bressolier and Thomas (1977) all studied the effects of vegetation in changing the wind velocity profile and reducing the shear velocity. In general, however, a surface requires approximately 30% vegetative cover to ensure that no sediment movement occurs (Ash and Wasson, 1983). Current advances in this area of aeolian research are focussed on testing existing shear stress and drag partitioning models on different types of surfaces and making improvements or modifications where required.

2.6.2 Crusts
Anthropogenic disturbance is one of the driving forces behind sediment entrainment and transport. From a regional perspective, both recreational and grazing land uses in arid environments are causing significant disturbance and accelerating desertification processes at an unprecedented rate (Belnap et al., 2001). Surface crusts are crucial in controlling wind erosion in arid environments worldwide. Research in soil crusts began in the 1950s and was descriptive and qualitative in nature. In the 1960s, the abilities of crusts to fix nitrogen and influence hydrologic processes such as runoff and infiltration rates, started raising interest and awareness (Belnap et al., 2001).

With naturally crusted soils, the abrasive or saltating process is the dominant process in breaking up soil aggregates and releasing dust into the air (Chepil, 1945; Gillette et al., 1974; Hagen, 1984). In soils with high levels of salt concentration, Nickling (1984) described an effect where the displaced soil particles exposed to the air stream effectively increased the effects of fluid drag on the surface particles, entraining particles or aggregates at lower shear velocities. Once the protruding sediments have been removed, shear velocity must then increase to entrain the remaining surface particles. Particle movement begins by impacting and scouring the pristine surface crust, exposing weakly bonded soils below, which can be entrained at lower shear velocities (Nickling, 1984).

The three main types of crust: sedimentary (clays), precipitate/chemical (salts) and microphytic (biological/bacterial), each formed by a variety of distinct biophysical processes. McKenna Neuman & Maxwell (1999) examined the strengthening role that various types of fungi have on soils and found that crusts were resistant to free stream velocities of approximately 10 m/s, depending on the species of fungus. In a previous study, McKenna Neuman et al. (1996) found that photoautotrophic organisms are stable to free stream velocities of approximately 19 m/s.

The effectiveness of sedimentary crusts, such as silt and clays, depends on their relative proportion in the sand-sized material and a mixture of 20-30% clay, 40-50% silt and 20-40% sand produces the greatest number of non-erodible clods and displays the highest level of mechanical stability and resistance to abrasion (Chepil and Woodruff, 1963). Salts, in low concentrations, act as a cementing agent at points of contact between the grains, which in turn, also increases the critical threshold velocity (Pye, 1980; Nickling and Ecclestone, 1981; Nickling, 1984).
relationship between the NaCl and KCl content in a given soil sample and \( u_{cr} \) is given by the following relation, developed by Nickling and Ecclestone (1981):

\[
\text{Equation 2-14} \quad u_{cr} = A(0.97e^{0.1031S}) \left( \frac{P}{\rho} gd \right)
\]

where \( S \) is the salt content in mg/g of soil and \( A \) is a function of the dimensionless coefficient expressing the ratio of the applied tangential force to the force resisting grain movement.

Due to the variation of crust types, and the varying strength of inter-particle bonds and structural and textural characteristics, there is a considerable variation in the vertical dust flux for a given shear velocity. Although there have been over 3,000 scientific studies on surface crusts alone (Belnap et al., 2001), there still exists a great degree of uncertainty on the role that saltation abrasion has on surface crusts and dust emissions.

2.6.3 Surface and Soil Moisture

Surface and soil moisture content is also an important variable that effectively limits and controls the entrainment and transport of sediment by wind. When sand is wetted, moisture is retained on the surface in the form of a film at the areas of contact between the grains (Pye and Tsoar, 1990). The tensile force between the water molecules and the grains is the observed surface cohesion (Chepil, 1956; Bisal and Hsieh, 1966).

Early studies, by Belly (1964) and Johnson (1965) observed that gravimetric moisture contents of approximately 0.6% can more than double the critical threshold velocity of medium-sized sands and within the range of 0.05%-4%, as expressed in:

\[
\text{Equation 2-15} \quad u_{cr,w} = u_{cr}(1.8 + 0.6\log W)
\]

where \( W \) is the moisture content (%) and \( u_{cr,w} \) is the critical fluid threshold velocity for wet sand. Moisture contents greater than 5% make sand-sized materials inherently resistant to entrainment by most natural winds (Belly, 1964; Azizov, 1977; Logie, 1982). Horikawa et al. (1982) and Hotta et al. (1985) later suggested a linear relationship as the following:
Equation 2-16

\[ u_{cr,w} = u_{cr} + 7.5W \]

This was further expanded by Hotta et al. (1985) to include the drying effects of evaporation, using the following modification:

Equation 2-17

\[ u_{cr,w} = u_{cr} + 7.5W_l \]

where \( l_w \) is the evaporation rate, ranging from 0 to 1. These relationships implicitly account for the influence of the cohesive force, \( F_c \), which consists of van der Walls forces, capillary forces, chemical binding and electrostatic forces (Mahanty and Ninham, 1976). To account for the effect of soil moisture on \( u_{cr} \), McKenna-Neuman (2003) developed the following relation:

Equation 2-18

\[ F_i = \beta_c d + | \Delta P | A_c \]

where \( \beta_c \) is a dimensional parameter, \( d \) is particle diameter, \( P \) is the capillary-suction pressure deficit and \( A_c \) is the contact area between adjacent grains. With this scheme, a coefficient must be used to account for the effects of temperature on the critical shear velocity. More recently, field studies revealed similar results, where soil moisture of 2% had minimal impact on the particle movement, but movement was greatly reduced at soil moisture rates between 4% and 6% (Wiggs et al., 2003).

At present, much of the focus regarding surface and soil moisture modeling is occurring on regional and continental scales. The challenge today involves integrating wind erosion models and aeolian research with recent progresses in soil moisture modeling (Shao, 2000).

2.7 Field Measurement of Dust Emission

Much of the current understanding of aeolian wind erosion occurred as a result of controlled experiments in wind tunnels to investigate saltation, the determination of critical threshold shear velocity, the process of drag partitioning, the equilibration of saltation, the process of dust emission and the formation and evolution of sand dunes (Shao, 2000). Portable wind tunnels, used in the field, have also been developed to study wind erosion on natural soil surfaces.

Samplers are primarily used to measure the streamwise saltation flux (\( q \)) and the vertical dust flux (\( F \)) parameters. The sand or saltation flux, \( q \), is generally measured using sand traps,
whereas F is derived by measuring the profile of dust concentration. Samplers are either active or passive; the former involves maintaining airflow through their intakes using pumping devices as opposed to passive samplers, which rely on wind to maintain flow. Generally, active samplers are more accurate in measuring fine particles, though inaccurate in sampling a larger variety of particle sizes or dust particles (Shao, 2000). They tend to disrupt the flow of air, causing streamlines to diverge at the opening of the sampler. Passive samplers do not have this issue and are cheaper and easier to operate, making them far more utilized in field experiments.

Field measurements are carried out at various scales and provide valuable verification for wind erosion models (Shao, 2000). The atmospheric and land-surface parameters generally involved in field measurements include sand flux densities at different levels, profile of dust concentration, profile of wind speed, wind direction, air temperature, humidity and pressure, solar radiation, soil moisture, frontal area index and soil particle-size distribution. These devices are usually mounted on a tower and are spaced according to the characteristic logarithmic distribution.

2.8 DUST EMISSION MODELS

While dust emission over discrete areas can be estimated using field measurement techniques, it can often be logistically difficult and costly to obtain consistent, multi-dimensional dust emission and flow field data. As an alternative, many environmental managers and research professionals have numerically estimated dust emission based on various dust emission models. While several models have been developed to model dust emission in the absence of saltation, based on the concepts identified by Bagnold (1941), which rely solely on wind velocity, it has generally accepted that saltation plays a significant role in the overall emission of dust and should be represented in any widely accepted dust emission model (Shao, 2008). Although aerodynamic entrainment contributes a great deal to dust emission, the models developed to date represent either field data, through the development of empirical models, or the interaction between dust emission and saltation through both energy-based or volume-removal based models.

One of the earliest empirical models developed, integrating the effect of saltation on dust emission, is that of Gillette (1977). This model was developed by determining the ratio of dust emission to total soil movement and verified using data related to wind and soil parameters.
gathered by the Agricultural Research Service. The model was developed by defining the ratio between vertical dust flux, \( F \) (kg m\(^{-2}\) s\(^{-1}\)) and horizontal or streamwise sediment flux, \( q \) (kg m\(^{-2}\) s\(^{-1}\)) and relating it to parameters such as soil texture, wind speed, mineralogy and physical weathering. Owen (1980) added to this approach by suggesting that dust emission was also as a result of the turbulent air regime created by the wakes of saltating grains after impaction. This laid the framework for Gillette and Passi (1988) to conclude that \( F/q \) is linearly related to shear velocity, \( u_* \).

An energy-based model, such as the model developed by Shao et al. (1993) (Equation 2-7), creates a system energy balance and argues that the aerodynamic lift component, as described by Owen (1980), is far less significant to dust emission than inter-particle cohesion. Instead, energy-based models view the emission of dust primarily as a result of the forces of wind velocity and saltation bombardment overpowering the binding strength of dust particles. Based on this theory, an updated model was developed by Gillette and Passi (1988), which described vertical dust flux, \( F \), as a function of soil moisture and surface roughness through the critical shear velocity, \( u_{cr} \):

\[
F = c_0 u_*^4 \left( 1 - \frac{u_{cr}}{u_*} \right)
\]

where \( c_0 \) is a dimensional constant. This model, however, does not discretely account for the energy required to overcome the strength of interparticle bonding, as discussed previously by Shao et al. (1993). To account for this, as well as the variability of erosion conditions, Marticorena and Bergametti (1995) developed an entirely empirical dust production model by fitting the average ratio of \( F/q \) to the fraction of clay content using the dataset of Gillette (1977):

\[
F = 0.01 q \exp(0.308\eta_c - 13.82)
\]

where \( \eta_c \) represents the clay fraction and \( F/q \) is in m\(^{-1}\). This model is limited, in that it does not account for other factors that affect the erosion threshold, such as soil moisture, salt content and organic matter. The model also assumes that all surfaces continually emit dust, neglecting the supply limited condition, and can only be applied to loose soil surfaces, since crusted soils are not taken into account.
Distinct from both empirical and energy-based models, Lu and Shao (1999) proposed a volume-removal-based dust emission model, which estimates dust emission on the basis of the volume removed by the sand grains as they plough into the surface soil:

\[
F = c_b g \eta \frac{\rho_b}{P} \left(1 + 10u \sqrt{\frac{\rho_b}{P}}\right) q
\]

where \(c_b\) is a constant of proportionality less than 1 and \(\rho_b\) is the bulk density of the soil. In this model, saltation bombardment is considered to be the primary means for dust emission and is supported by data from wind tunnel experiments performed by Rice et al. (1996) and Alfaro et al. (1997). Using high-speed photography, Rice et al. (1996) showed sand grains saltating on a loosely-packed crusted surface of fine particles of diameter less than 53 \(\mu\)m and Alfaro et al. (1997) observed that a proportion of saltating sand grains in a similar environment do not rebound. This model suggests that the volume of the crater that develops as a result of the bombardment, \(V\), is proportional to its impact velocity \(u_i^n\), and that vertical dust flux, \(F\), is proportional to shear velocity, \(u^{n+1}\), where \(n\) is between 3 and 4. Lu and Shao (1999) also indicate that \(F/q\) is linearly proportional to the mass fraction of dust in the surface soil, \(\eta\), and inversely proportional to soil hardness, denoted \(\rho^{k1}\), where \(k1\) is between 1 and 1.5. One of the major limitations of this model is the omission of the effect of elastic forces and as a result, is not useful for highly crusted soils where elastic strains are comparable to plastic strains. This limitation was identified by Raupach and Lu (2004), who noticed that the model compared well with field data from Gillette (1977), but did not perform as well for soils with surface structure such as clay soils.
3 CHAPTER THREE: METHODOLOGY

To meet the objectives outlined in Chapter 1, a field-based study was conducted in the Mojave Desert, Nevada between June 3rd and June 26th, 2008. The particular valley selected, just south of Las Vegas, has gained considerable attention in the past few years, as it is the proposed site for the new Las Vegas international airport. The controversy for this site is based on the feasibility of this location, due to the dust emission potential of the site, as well as the destruction of habitat of the endangered Desert Tortoise. The purpose of this study is to gather dust emission data and use the data to validate various models, as well as the sampling methodology using the PI-SWERL. The following section will discuss the field data acquisition methodology, as well as the subsequent steps that occurred during quality assurance and control and analysis of the data.

3.1 STUDY AREA

The study site is located in the Ivanpah Valley located in the Mojave Desert, along Interstate 15 south of Las Vegas, immediately north east of the Mojave National Preserve and west of the Lake Mead National Preserve (Figure 3.1, 3.2).

Figure 3.1: Map of National Preserves in the Mojave Desert (DesertUSA website)
This area is characterized by basin and range topography with sparse vegetation and central salt flats, or playas, which fill with storm water runoff during large-scale precipitation events. As a result, borax, potash and salt are commonly extracted from these salt-rich areas. In addition to typical high salt concentrations in the soil, this site is also characterized by a high variability of both sensitive crusted soil surfaces and loosely packed surfaces (Figure 3.3).
As this is the proposed site for the construction of the Ivanpah Valley Airport, an extensive data gathering effort is currently underway, as part of the Environmental Impact Assessment. For the purpose of flood hazard analysis, Park et al. (2003) conducted an in-depth mapping study of the valley and determined that the western mountain ranges are composed of Paleozoic limestone with scattered Mesozoic igneous intrusions and the eastern ranges are composed of Tertiary volcanic and Precambrian igneous intrusions. The resulting soil types are predominantly carbonate rich and clay rich soils, although variations in soil types can occur in the vicinity of playas, due to hydrologic and aeolian transport. This mapping study also observed that the surface is largely dominated by a creosote/bursage plant community and that the infiltration and runoff rates vary within the valley with surface and soil characteristics, as expected. In a similar mapping study of the Ivanpah Valley by Miller et al. (2003), it was concluded that these valley-axis floodplains and playas are sources for aeolian sand and dust, as shown by extensive Aeolian deposits downwind of the valley.

Although the study area is slated for land development, the Bureau of Land Management (BLM) imposes extremely strict restrictions on vehicular use in certain portions of the valley. Despite this, ecosystem disturbance is quite common through wind surfing and off-road
recreational driving. Although grasses are short lived and scarce, many parts of the valley are actively used for cattle grazing. For research purposes, soil and topographical maps have been well established for this site and permits have been granted for the installation of three (3) meteorological towers. Each tower contains a pyranometer to measure solar radiation, five anemometers placed logarithmically to gather wind profile data, a wind vane, for wind direction and tipping bucket rain gauges to record precipitation events. In addition, each site is equipped with soil moisture probes.

The area was selected, in part, due to the high-profile nature of the area, as well as its proximity to major urban areas and the relative ease of access to the valley. Given the highly variable nature of the soils and conditions, it is an excellent site for collecting dust emission data, to verify existing dust emission models, as well as to verify the sampling methodology using the PI-SWERL.

3.2 EXPERIMENTAL APPROACH

Table 3-1 documents the tests performed, the samples taken and the corresponding frequency.

Table 3-1: Summary of Parameters Measured, Methods and Frequency

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>Method</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical dust flux, $F$</td>
<td>PI-SWERL</td>
<td>Jean Lake – 30 sites, 4 reps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roach Lake – 35 sites, 17 reps</td>
</tr>
<tr>
<td>Salt content</td>
<td>Conductivity meter</td>
<td>Jean Lake – 28 sites</td>
</tr>
<tr>
<td>Organic matter</td>
<td>Loss of ignition test</td>
<td>Roach Lake – 33 sites</td>
</tr>
<tr>
<td>Particle size distribution</td>
<td>LISST – Portable</td>
<td></td>
</tr>
<tr>
<td>Crust strength</td>
<td>Pen penetrometers</td>
<td></td>
</tr>
<tr>
<td>Vegetation survey</td>
<td>Visual observations</td>
<td>Jean Lake – 23 surveys</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roach Lake – 21 surveys</td>
</tr>
</tbody>
</table>

According to topographic and soil maps, much of the valley drains to the dry lakebeds, which fill with water during rainfall events. As a result, the soils have become stratified almost in
a perpendicular fashion to the dry lakebeds, running almost parallel to the adjacent mountain ranges (Figure 3.4).

Figure 3.4: Surficial geology of Jean Lake

The drainage area immediately to the east of Jean Lake, adjacent to the mountain range is made up of young, undivided alluvium, made up of course grained alluvial fan and wash deposits from principal drainages and mixed Aeolian sand and alluvium. The Jean Lake playa, similar to Roach Lake, is made of up of lighter silt, clay and minor sand. In addition to the soil types listed above, the Roach Lake vicinity contains slightly more variation than at Jean Lake (Figure 3.5), including young active, alluvium, which is active wash and alluvial fan deposits of poorly to moderately sorted gravel, sand and minor silt, interlaced with young, active alluvium and recently abandoned active alluvial surfaces.
Transects at each dry lake bed were selected as the best sampling method to capture the variation in soil types, starting from the meteorological towers, as a point of reference, and extending to the each of the dry lakebeds (Figure 3.6 and Figure 3.7).
Figure 3.6: Aerial view of Jean Lake transect
(Selected sampling locations from meteorological tower in the east to dry lakebed in the west)

Figure 3.7: Aerial view of Roach Lake transect
(Selected sampling locations from meteorological tower in north east to dry lakebed to the south west)
In addition to capturing a broad range of soil types by using a transect-based sampling approach, changes in vegetation and surface topography was also captured, as sampling progressed away from the meteorological tower towards the dry lakebeds.

The fundamental criterion for test site selection was that the site was undisturbed. Sampling sites included both crusted, uncrusted, close proximity to vegetation as well as in open spaces. Ideally, the test site was representative of the micro-area, for example, a test in the sand bar would be in the sand, and an area in a gully would have a test in a wash or gully. To ensure consistency, repetition tests were performed within 5 meters of the original test sites.

3.3 TECHNIQUES AND INSTRUMENTATION

Various techniques are commonly used to measure and characterize in-situ dust emission, including portable wind tunnels and sediment traps. For this study, dust emission, in the form of vertical dust flux, was measured, recorded and calculated using the PI-SWERL. The PI-SWERL is a portable device that can be operated by a single individual. For the purpose of this study, a typical test was completed in less than ten (10) minutes. Using this device for this study facilitates the economical and speedy collection of a large number of measurements in a relatively short period of time. Direct comparison of PI-SWERL measurements with the University of Guelph, straight-line field wind tunnel at 17 sites in the Mojave Desert (Etyemezian et al., 2006; Sweeney et al., 2008) showed an acceptable correlation between the two measurement methods.

The PI-SWERL consists of a cylindrical chamber with an open end placed over the soil surface to be tested (Figure 3.8).
Figure 3.8: Schematic of the PI-SWERL (Source: Etyemezian et al., 2007)

Foam placed along the rim of the open chamber creates a seal with the test surface. The PI-SWERL measurement cycle consists of a maximum of 16 steps or levels that make up a time-series of measurements. For each step, the user can specify the duration of the step in seconds, the rate of ventilation of the cylinder with filtered air, and the rate of rotation of the PI-SWERL annular blade, which corresponds to changing the shear stress applied to the surface.

Ventilation of the PI-SWERL chamber is accomplished by a blower and monitored by a mass flow meter. Filtered air introduced by the blower mixes with the air in the chamber and exhaust flow is released through a port at the top of the chamber. A clean air flow rate of 200 lpm corresponding to 14 air changes per minute has been found to provide a satisfactory degree of ventilation while avoiding the undesirable suspension of dust by inlet blower air (Etyemezian et al., 2007).
Once the user has specified a sampling program and the measurement cycle begins, a nephelometer-style dust monitor, or DustTrak, measures the concentration of PM2.5 or PM10 emitted from the surface at a variety of applied shear stresses, manifested as revolutions per minute (RPM) of the annular blade within the chamber. The shear stress is then measured with Irwin sensors, which have shown that shear stress is concentrated in an area beneath the annular blade. The target RPM is maintained for some prescribed time interval before the second step begins and is repeated through all steps. Ideally, the duration of each time step should be sufficient to allow a peak emission of PM10 from the surface, followed by an asymptotic decline (Etyemezian et al., 2007). For the purpose of this study, the step test used for all sites was kept consistent (Table 3-2).

<table>
<thead>
<tr>
<th>Revolutions Per Minute (RPM)</th>
<th>Duration (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flush cycle (0 RPM)</td>
<td>60</td>
</tr>
<tr>
<td>1000</td>
<td>60</td>
</tr>
<tr>
<td>2000</td>
<td>90</td>
</tr>
<tr>
<td>3000</td>
<td>120</td>
</tr>
<tr>
<td>4000</td>
<td>150</td>
</tr>
<tr>
<td>Flush cycle (0 RPM)</td>
<td>60</td>
</tr>
</tbody>
</table>

Flush cycles are important to include to ensure proper cleaning of the system, and that each test remains a discrete test, avoiding contaminating each other with residual dust in the system. As stated earlier, the duration of each step should ensure that the peak dust emission is expelled from the surface, with sufficient time to show a stable decline or trend. For this reason, the step durations were lengthened at higher RPMs, as the expectation is that it would require more time to observe a stable trend immediately following the peak dust flux.
Crust strength was measured using a modified pen penetrometer (Gillette et al., 1982; Houser and Nickling, 2001), which measures the modulus of rupture, an important component in sediment entrainment and dust flux calculations. The device is approximately 25 cm long and is used by applying an increasing pressure on the surface until the probe penetrates the surface and induces brittle failure (Figure 3.9).

One of the major limitations of the “off the shelf” pen penetrometer device is the narrow range of strengths that can be measured as a result of the combination of tip diameter and spring strength, upon which the scale on the device is calibrated. In anticipation of a highly variable sampling transect, three additional pen penetrometers were purchased and their springs were changed to 10%, 30% and 50% fractions of the commercially available spring’s strength. These modified devices were then calibrated using an automated press (Figure 3.10). For each penetrometer, the press would apply a known weight onto the device, and the displacement along the penetrometer’s scale was recorded. This effectively calibrated the modified penetrometers with their existing linear scales. Representative calibration curves are shown in Figure 3.11 to Figure 3.14. The penetrometers were calibrated prior to the field season, on May 13th, 2008 and used the following month for data collection.
Upon returning from the field season, the penetrometers were re-calibrated once again on November 6\textsuperscript{th}, 2008 to ensure consistency.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{penetrometer_calibration.png}
\caption{Default penetrometer calibration}
\end{figure}
Figure 3.12: 10% spring strength penetrometer calibration

Figure 3.13: 30% spring strength penetrometer calibration
The benefit of using a suite of modified penetrometers, in addition to the standard device, is that the scale at which soil crust can be measured is effectively widened, enabling far more soil crusts to be measured. This is particularly useful in areas, such as the Ivanpah Valley, which have a high variability of soil types. As part of the field sampling program, 20 penetrometer tests were performed at each site, to ensure that the data is statistically relevant and consistent. Each test consisted of 5-10 test runs, to determine which penetrometer strength would be most appropriate to allow for a majority of the penetrometer results to fall mid-range on the linear scale of the device.

3.5 PARTICLE SIZE ANALYSIS

In addition to the PI-SWERL data, grab samples of surface soil to a depth of 1 cm were collected and analyzed for particle size, conductivity and organic matter at each site. The particle size analysis was conducted using the LISST-Portable particle size analyzer for the silt and clay fractions (fines) (Figure 3.15).
To prepare the sample, the gravel component of each sample was dry sieved using a 4mm sieve. To eliminate the sand content, between 4mm and 63 μm, the sample was wet sieved using a 63 μm sieve. After drying, approximately one (1) gram of fines from the sample was assumed to be representative and mixed with 10 mL of calgon, to disperse the sample. The sample was then mixed with 90 mL of distilled water for three (3) minutes, at which time the sample was sufficiently well mixed. From this suspension, 10 mL was taken and placed in the LISST and topped to the overfill hole with distilled water, to ensure that the device would not be overloaded with sediment, and that the result would be accurate. After five (5) minutes of testing, the LISST outputs a spreadsheet of the particle size analysis to an Excel spreadsheet complete with histograms. This process was repeated for every site sampled along both transects.

3.6 Salt Content Analysis

Salt content for each sample was estimated using electrical conductivity. To prepare the sample, the large gravel, sticks and other debris were removed using a 250 mm sieve. In accordance with the study performed by Karakouzian et al. (1996), the sample was then diluted at a 5:1 ratio or 10 grams of sample with 50 mL of distilled water, and left mixing for 24 hours, to ensure a uniform solution of soluble salts. Once mixing was completed, the solution was left for
8 hours and the supernatant of each sample was tested using a YSO electrical conductivity meter, which reads conductivity as an inverse of resistance, or mhos (1/Ω).

Percent organic matter was assessed using a standard loss on ignition (LOI) test (ASTM F1647-02a), where a random sample of 11 grams is taken from the total grab sample and ignited for 24 hours at 550 degrees Celsius.

### 3.7 Vegetation Surveys

Apart from the analyses performed on the grab sample, detailed vegetation surveys were completed at approximately 20 locations along each transect. This was done at approximately every 100 meters along the transect in discrete and representative areas, which displayed similar vegetation properties, for a total of 23 surveys at Jean Lake and 20 at Roach Lake. In a box 10 meters by 10 meters, the number of plants, according to species, was recorded, as well as the average height and width. Using this data, the total vegetation cover was calculated. These data were also used to calculate the shear stress partitioning ratio.

To provide context to the data collected, detailed photographs were taken at each site, as well as GPS coordinates and elevation. A Garmin eTrex® H handheld GPS unit was used for this purpose. The topographic cross-sectional profile along the transect was also recorded using an inclinometer and confirmed using elevations provided by GPS.

### 3.8 Data Collection and Analysis

For each test site, the PI-SWERL was used to quantify the rate of dust emission at varying applied shear stresses. As a system, the PI-SWERL records the date, time and location (GPS coordinates) of each test, in addition to the instantaneous concentrations of dust being emitted from the surface. Internal programming converts this raw, one-second concentration reading to average emissions of PM10 using the following relation:

\[
    F_i = \frac{\sum_{t_i} C \times Q \times t_s}{t_{i_n} - t_i \times A_{eff}}
\]

where \( C \) is the recorded dust concentration (mg m\(^{-3}\)), \( Q \) is the blower flow rate (4.1 L/s), \( A_{eff} \) is the effective test area underneath the PI-SWERL annular ring (0.07 m\(^2\)) and \( t \) represents time in...
seconds. To compare PI-SWERL data to conventional wind tunnel data, the instantaneous dust flux calculated in Equation 3-1 must be summed according to each RPM target level.

Due to malfunctions with the equipment, the Dustrak readings were not consistently recorded every second. Upon review of the data, it was determined that all tests with fewer than 30% missing data could be kept, but those exceeding 30% missing data were excluded from the study. The tests with data missing up to 30% were corrected by using a moving average approach, where data before and after the hole were averaged and the result placed in the missing portion.

The vegetation surveys were translated to lateral cover, $L_c$, and aerodynamic roughness, $z_0$, using the following relations:

**Equation 3-2**

$$L_c = DA_S$$

where $D$ is canopy population density (number of individuals per unit area) and $AS$ is the mean frontal-silhouette area (height x width) per canopy, and:

**Equation 3-3**

$$z_0 = L_c H$$

where $H$ is the mean height of the individual canopy. There were four discrete types of vegetation generally found in each of the 10 m x 10 m surveys. Each of the four types was counted and the base and the height were measured.

### 3.9 Model Comparison

The data collected for this study was used to verify existing dust emission models, as well as to determine the consistency of the resulting using the PI-SWERL for model validation studies. Data collected using the PI-SWERL will be compared to current established models to confirm the accuracy of the PI-SWERL. Typically, wind tunnels have been used to develop and calibrate existing models. Table 3-3 outlines the models used for comparison purposes, as well as the parameters required and how these parameters will be determined, given the nature of the data collected. Additionally detail on the models was provided in Chapter 2.
### Table 3-3: Dust Emission Models to be compared using collected Field Data

<table>
<thead>
<tr>
<th>Model Expression</th>
<th>Reference</th>
<th>Parameters required</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F = c_0 u_\star^4 \left(1 - \frac{u_{\text{cr}}}{u_\star}\right)$</td>
<td>Gillette and Passi (1988)</td>
<td>$u_\star, u_{\text{cr}}$, $f(D)$, various constants, $c_0$ (constant)</td>
</tr>
<tr>
<td>$F = 0.01 q \exp(0.308 \eta_c - 13.82)$</td>
<td>Marticorena and Bergametti (1995)</td>
<td>$q$, $f$ (constant of 1.5, $u_\star$), percent clay, $\eta_c$</td>
</tr>
<tr>
<td>$F = c_b \eta \frac{\rho_b}{P} \left(1 + 10 u_\star \frac{\rho_b}{P}\right) q$</td>
<td>Lu and Shao (1999)</td>
<td>$c_b$ constant of 0.5, $u_\star$, $q$, horizontal component, $P$, percent dust, $\eta$</td>
</tr>
<tr>
<td>$F = \alpha u_\star^3 \left(1 - \frac{u_{\text{cr}}^2}{u_\star^2}\right)$</td>
<td>Shao et al. (1993)</td>
<td>$\alpha$, $f(c_4$ constant of 0.8, $m_o$, $\Psi$, $u_\star$, $u_{\text{cr}}$)</td>
</tr>
</tbody>
</table>

This comparison exercise will shed light on which model best describes the sample sites, which will then provide insights into how best to describe the behaviour of the site. Using the data collected to verify established models will also provide a basis for using the PI-SWERL and other instrumentation and techniques to quickly and accurately assess a given site with confidence, or if various correction factors are required to account for practical gaps in data collection.
Two discrete series of PI-SWERL tests were conducted on a variety of undisturbed surfaces in the Mojave Desert, NV, to ultimately validate the use of PI-SWERL tests as a surrogate for wind tunnel tests, as well as to characterize the area by applying the field data collected to various types of established dust emission models. The PI-SWERL test involves sampling dust concentrations at four (4) increasing RPM or shear stresses. In addition to these tests, soil grab samples were taken for grain size, salt content and organic matter analyses and crust strength was measurements were made to evaluate the contribution of soil strength to overall dust emission.

The aim of this chapter is to use observed dust emission data and surface characteristics to validate field equipment and methodology, as well as to test established dust emission models (Table 4 above). The following section presents soil texture data, organic matter, salt content and crust strength associated with each site. Later sections contain a presentation of the dust emission data gathered using the PI-SWERL as well as the data presented in the previous two sections to verify the four established dust emission models outlined in Table 3-3.

4.1 SURFACE PROPERTIES

4.1.1 Surface topography

Profiles of the ground elevation were completed for both transects to facilitate an understanding of the surface drainage pattern of the valley. The sampling site numbers start from the meteorological towers, located within 2-3 km of each dry lakebed, and progress incrementally towards the playa. The distance between each station at Jean and Roach Lakes was approximately 100 meters and 40 meters respectively. Samples from the dry lakebed, or playa, where there is no longer any vegetation, started at J25 and R32 onwards for the Jean Lake and Roach Lake transects respectively (Figures 3.6 and 3.7).
Figure 4.1: Jean Lake Transect Topographical Profile

Figure 4.2: Roach Lake Transect Topographical Profile
Figure 4.1 and Figure 4.2 both show a gentle decline in elevation. An important characteristic of both profiles is that the lowest point in the curve is not the playa itself, but the onset or beginning of the playa. This feature could be the result of a variety of disturbances, including the effects that recreational driving may have on the area.

4.2 Soil Texture Analysis

Based on the representative soil samples obtained at each site (Tables 4-1 and 4-2), ternary diagrams depicting the percentage of sand and clay were plotted for all samples by transect (Figure 3.6 and Figure 3.7). These samples demonstrate not only the uniformity of certain portions of the transect, but also the gradual variability in soil texture that exists with closer proximity to the playa.

Table 4-1: Soil texture analysis for Jean Lake transect sites

<table>
<thead>
<tr>
<th>Jean Lake Transect</th>
<th>%Gravel</th>
<th>%Sand</th>
<th>%Silt</th>
<th>%Clay</th>
<th>Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>J01</td>
<td>14.9</td>
<td>77.9</td>
<td>7.1</td>
<td>0.1</td>
<td>sand</td>
</tr>
<tr>
<td>J02</td>
<td>12.6</td>
<td>76.6</td>
<td>10.7</td>
<td>0.2</td>
<td>sand</td>
</tr>
<tr>
<td>J03</td>
<td>15.8</td>
<td>64.6</td>
<td>18.4</td>
<td>1.2</td>
<td>loamy sand</td>
</tr>
<tr>
<td>J04</td>
<td>19.3</td>
<td>74.1</td>
<td>6.6</td>
<td>0.1</td>
<td>sand</td>
</tr>
<tr>
<td>J05</td>
<td>12.8</td>
<td>78.9</td>
<td>8.0</td>
<td>0.3</td>
<td>sand</td>
</tr>
<tr>
<td>J06</td>
<td>15.6</td>
<td>68.7</td>
<td>12.2</td>
<td>3.5</td>
<td>loamy sand</td>
</tr>
<tr>
<td>J07</td>
<td>18.9</td>
<td>74.5</td>
<td>6.4</td>
<td>0.1</td>
<td>sand</td>
</tr>
<tr>
<td>J08</td>
<td>7.7</td>
<td>83.4</td>
<td>8.7</td>
<td>0.2</td>
<td>sand</td>
</tr>
<tr>
<td>J09</td>
<td>11.4</td>
<td>76.6</td>
<td>9.3</td>
<td>2.7</td>
<td>sand</td>
</tr>
<tr>
<td>J10</td>
<td>5.7</td>
<td>81.8</td>
<td>11.3</td>
<td>1.3</td>
<td>sand</td>
</tr>
<tr>
<td>J11</td>
<td>6.2</td>
<td>83.1</td>
<td>10.5</td>
<td>0.2</td>
<td>sand</td>
</tr>
<tr>
<td>J12</td>
<td>11.3</td>
<td>76.5</td>
<td>11.9</td>
<td>0.3</td>
<td>sand</td>
</tr>
<tr>
<td>J13</td>
<td>31.9</td>
<td>61.2</td>
<td>7.0</td>
<td>0.0</td>
<td>sand</td>
</tr>
<tr>
<td>J14</td>
<td>9.4</td>
<td>82.1</td>
<td>8.2</td>
<td>0.3</td>
<td>sand</td>
</tr>
<tr>
<td>J15</td>
<td>13.0</td>
<td>76.7</td>
<td>9.9</td>
<td>0.3</td>
<td>sand</td>
</tr>
<tr>
<td>J16</td>
<td>14.6</td>
<td>75.9</td>
<td>7.7</td>
<td>1.7</td>
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</tr>
<tr>
<td>J17</td>
<td>6.4</td>
<td>84.4</td>
<td>8.4</td>
<td>0.8</td>
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</tr>
<tr>
<td>J18</td>
<td>2.7</td>
<td>89.1</td>
<td>8.0</td>
<td>0.3</td>
<td>sand</td>
</tr>
</tbody>
</table>
### Jean Lake Transect

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>%Gravel</th>
<th>%Sand</th>
<th>%Silt</th>
<th>%Clay</th>
<th>Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>4.2</td>
<td>84.6</td>
<td>10.0</td>
<td>1.2</td>
<td>sand</td>
</tr>
<tr>
<td>sand</td>
<td>10.8</td>
<td>80.7</td>
<td>7.3</td>
<td>1.1</td>
<td>sand</td>
</tr>
<tr>
<td>loamy sand</td>
<td>10.9</td>
<td>72.3</td>
<td>13.9</td>
<td>2.8</td>
<td>loamy sand</td>
</tr>
<tr>
<td>sandy loam</td>
<td>3.1</td>
<td>55.1</td>
<td>31.0</td>
<td>10.8</td>
<td>sandy loam</td>
</tr>
<tr>
<td>silt loam</td>
<td>2.8</td>
<td>48.2</td>
<td>49.0</td>
<td>0.0</td>
<td>silt loam</td>
</tr>
<tr>
<td>silt loam</td>
<td>0.0</td>
<td>40.1</td>
<td>52.1</td>
<td>7.8</td>
<td>silt loam</td>
</tr>
<tr>
<td>loam</td>
<td>0.0</td>
<td>28.7</td>
<td>49.3</td>
<td>21.9</td>
<td>loam</td>
</tr>
<tr>
<td>silty clay loam</td>
<td>0.0</td>
<td>17.7</td>
<td>45.8</td>
<td>36.5</td>
<td>silty clay loam</td>
</tr>
<tr>
<td>silty clay loam</td>
<td>0.0</td>
<td>14.7</td>
<td>54.7</td>
<td>30.6</td>
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</tr>
<tr>
<td>silty clay loam</td>
<td>0.0</td>
<td>9.8</td>
<td>51.0</td>
<td>39.2</td>
<td>silty clay loam</td>
</tr>
</tbody>
</table>

**Figure 4.3:** Plot results of textural analysis on textural plot for Jean Lake transect.
Table 4-2: Soil texture analysis for Roach Lake transect sites

<table>
<thead>
<tr>
<th>Roach Lake Transect</th>
<th>%Gravel</th>
<th>%Sand</th>
<th>%Silt</th>
<th>%Clay</th>
<th>Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>R01</td>
<td>13.7</td>
<td>72.9</td>
<td>12.7</td>
<td>0.7</td>
<td>sand</td>
</tr>
<tr>
<td>R02</td>
<td>9.2</td>
<td>80.0</td>
<td>10.9</td>
<td>0.0</td>
<td>sand</td>
</tr>
<tr>
<td>R03</td>
<td>28.0</td>
<td>63.0</td>
<td>8.8</td>
<td>0.2</td>
<td>sand</td>
</tr>
<tr>
<td>R04</td>
<td>19.7</td>
<td>73.7</td>
<td>6.4</td>
<td>0.2</td>
<td>sand</td>
</tr>
<tr>
<td>R05</td>
<td>0.0</td>
<td>91.2</td>
<td>8.3</td>
<td>0.6</td>
<td>sand</td>
</tr>
<tr>
<td>R06</td>
<td>16.2</td>
<td>74.6</td>
<td>9.1</td>
<td>0.1</td>
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</tr>
<tr>
<td>R07</td>
<td>28.5</td>
<td>61.8</td>
<td>9.5</td>
<td>0.2</td>
<td>sand</td>
</tr>
<tr>
<td>R08</td>
<td>15.9</td>
<td>74.5</td>
<td>9.5</td>
<td>0.1</td>
<td>sand</td>
</tr>
<tr>
<td>R09</td>
<td>16.7</td>
<td>75.7</td>
<td>7.5</td>
<td>0.1</td>
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</tr>
<tr>
<td>R10</td>
<td>8.1</td>
<td>79.6</td>
<td>12.1</td>
<td>0.2</td>
<td>sand</td>
</tr>
<tr>
<td>R11</td>
<td>18.3</td>
<td>71.0</td>
<td>9.5</td>
<td>1.2</td>
<td>sand</td>
</tr>
<tr>
<td>R12</td>
<td>31.1</td>
<td>60.3</td>
<td>8.3</td>
<td>0.4</td>
<td>sand</td>
</tr>
<tr>
<td>R13</td>
<td>27.1</td>
<td>66.0</td>
<td>6.7</td>
<td>0.2</td>
<td>sand</td>
</tr>
<tr>
<td>R14</td>
<td>25.6</td>
<td>60.7</td>
<td>12.7</td>
<td>1.1</td>
<td>loamy sand</td>
</tr>
<tr>
<td>R15</td>
<td>19.5</td>
<td>70.1</td>
<td>10.1</td>
<td>0.4</td>
<td>sand</td>
</tr>
<tr>
<td>R16</td>
<td>20.6</td>
<td>68.8</td>
<td>10.3</td>
<td>0.3</td>
<td>sand</td>
</tr>
<tr>
<td>R17</td>
<td>16.9</td>
<td>71.9</td>
<td>10.1</td>
<td>1.1</td>
<td>sand</td>
</tr>
<tr>
<td>R18</td>
<td>13.3</td>
<td>76.0</td>
<td>10.5</td>
<td>0.3</td>
<td>sand</td>
</tr>
<tr>
<td>R19</td>
<td>7.3</td>
<td>82.6</td>
<td>10.0</td>
<td>0.2</td>
<td>sand</td>
</tr>
<tr>
<td>R20</td>
<td>27.6</td>
<td>62.1</td>
<td>10.2</td>
<td>0.1</td>
<td>sand</td>
</tr>
<tr>
<td>R21</td>
<td>26.4</td>
<td>65.3</td>
<td>8.0</td>
<td>0.4</td>
<td>sand</td>
</tr>
<tr>
<td>R22</td>
<td>22.2</td>
<td>65.9</td>
<td>11.3</td>
<td>0.6</td>
<td>loamy sand</td>
</tr>
<tr>
<td>R23</td>
<td>5.3</td>
<td>73.9</td>
<td>17.1</td>
<td>3.7</td>
<td>loamy sand</td>
</tr>
<tr>
<td>R24</td>
<td>13.1</td>
<td>49.3</td>
<td>37.6</td>
<td>0.0</td>
<td>sandy loam</td>
</tr>
<tr>
<td>R25</td>
<td>12.0</td>
<td>66.3</td>
<td>20.8</td>
<td>0.9</td>
<td>loamy sand</td>
</tr>
<tr>
<td>R26</td>
<td>9.5</td>
<td>61.1</td>
<td>21.9</td>
<td>7.5</td>
<td>sandy loam</td>
</tr>
<tr>
<td>R27</td>
<td>10.4</td>
<td>66.8</td>
<td>19.5</td>
<td>3.3</td>
<td>loamy sand</td>
</tr>
<tr>
<td>R28</td>
<td>9.4</td>
<td>62.5</td>
<td>27.5</td>
<td>0.6</td>
<td>sandy loam</td>
</tr>
</tbody>
</table>

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Figure 4.3 and Figure 4.4 both show that a majority of the sites are predominantly sandy soils with scattered sandy loam, loam, silt loam and silty clay loam samples that are closer or on the playa. Although this distinct trend is apparent through the soil analysis, it is evident, based on Figures 4.3 and 4.4 that the Ivanpah Valley is dominated by sand, loamy sand and sandy loam soils types, where only 6 out of the 12 textural classes specified by the U.S. classification scheme are represented. Despite this, the data represented on the triangle plots reveal distinct soil texture trends, where, as expected, the soil becomes more dominated by fines (i.e. silty clay loam) with closer proximity to the playa, as further shown in Table 4-1 and Table 4-2, where
sites J01 and R01 are on undisturbed areas close to the meteorological towers on each transect and J28 and R35 correspond with sites on the dry lakebeds. The test sites at the Jean Lake transect were taken approximately 100 m apart and the Roach Lake transect were taken approximately 50 meters apart. Every attempt was made to ensure that the test sites taken between the meteorological tower and the dry lakebed were taken at evenly spaced increments.

The trends are due to the natural topographic and hydrologic drainage pattern of the valley, where surface runoff from rain events transport particles of larger sizes at higher elevations and smaller particles travel further downslope, depending on transport competency. Over the course of this transport mechanism, larger particles will settle first, allowing smaller particles, such as silt and clay, to settle closer to and on the playas. In addition to this, the coarse sites, or those with a higher sand content, were often also associated with pebble and gravel lags (Figure 4.5 and Figure 4.6).

![Figure 4.5: Pebble and gravel lags along Roach Lake transect](image)

![Figure 4.6: Close-up of pebble and gravel lags along Roach Lake transect](image)

The patches of gravel and pebbles gradually diminished with closer proximity to the playas, which were predominantly silt loam and silty clay loam in texture. The results of this textural regime are ideal for aeolian sand transport and bombardment, given the high sand content associated with the coarse sites. Although, it was consistently noted in the field that the vegetation present on the sandy areas (Figure 4.15) will inhibit sediment transport ability. As a result, most of aeolian transport observed occurred on or near the dry lakebeds, in proximity to the fine textured sites (Figure 4.7 and Figure 4.8).
Figure 4.7: Jean Lake dust event (A)
restricted to the playa whereas disturbed soils among higher elevation vegetated areas experience relatively no Aeolian movement

Figure 4.8: Jean Lake dust event (B)
(restricted to the playa and relatively no Aeolian movement at higher elevation vegetated areas)

While the fine textured sites were observed to experience more frequent transport events, these same sites were also associated with significant crust formations (Figure 4.9 and Figure 4.10).
Figure 4.9 and Figure 4.10 are consistent with the analyses completed, namely that the smallest particles, such as silt and clay, accumulate at the playa, resulting in a sedimentary crust. Based on the topography of both subwatersheds (Jean and Roach Lakes), it is expected that parameters, such as organic matter and salt content, would accumulate at the lowest points of both areas, in a flat, trough-like region. As a result of the natural topography, as well as the analysis above, the percentage of fines increases on the playas as well. The impact of these natural drainage and wind blown processes on dust emission is discussed in later sections.

4.3 Organic Matter and Salt Content Analyses

Grab samples were taken at each test site and in addition to soil texture analysis, organic matter and salt content analyses were conducted. Organic matter samples were taken at each site along the transect and the results of the tests for both Jean and Roach Lake transects are shown in Figure 4.11 and Figure 4.12 respectively.
Figure 4.11: Jean Lake Transect Loss on Ignition Organic Content
Both figures show a clear trend of increasing organic matter content with closer proximity to the playa. An initial analysis of the graphs would suggest that more vegetation exists on the playa, as a result of more available moisture and increasing plant productivity; however, an analysis of the salt content at the playa (below), as well as visual field observations show the playa free of plant life. This can be attributed to the surface runoff drainage pattern within the valleys, transporting the lighter, organic particles farther along to the lowest point of the valley, the dry lakebed.

A similar trend is also apparent in the salt content analysis performed at each site along both transects (Figures 4.13 and 4.14). Nickling (1984) describes total surface soluble salt content as a bonding agent that effectively increases threshold shear velocity, thereby stabilizing the soil making it more resistant to erosion. The following graphs present the results from the salt content analysis for each transect, according to site number, which also
corresponds to proximity to the dry lakebed. The scale on the graphs for both transects was kept consistent to allow for an easier comparison of the results, which showed both transect's salt content around the $1.00 \times 10^{-4}$ Mho with a distinct upward trend at Roach Lake on the playa. Both transects show that surface soluble salt content on the playa is relatively uniform throughout, with a spike in salt content at the Roach Lake playa.

Figure 4.13: Jean Lake Transect Surface Soluble Salt Content
The Jean Lake transect had increasing levels just before reaching the playa in its long transition zone, where sparse vegetation exists (Figure 4.15).
In general, the Roach Lake transect exhibits more uniformity in surface topography, soil texture, organic matter and soluble surface salt content than the Jean Lake transect. One possible explanation for the more uniform vegetation and soil chemistry may be related to the land uses for each lake. Jean Lake has historically been more heavily visited by both cattle and people, which may account for the diversity in micro-landscape. The average salt content results, organized by soil type, are presented in Table 4-3 for each transect.

Table 4-3: Average salt content results for each transect (10^4 mho)

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Jean</th>
<th></th>
<th>Roach</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Std Deviation</td>
<td>Average</td>
<td>Std Deviation</td>
</tr>
<tr>
<td>Sand</td>
<td>1.9</td>
<td>0.45</td>
<td>0.96</td>
<td>0.29</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>1.9</td>
<td>0.69</td>
<td>1.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>2.9</td>
<td>n/a</td>
<td>1.2</td>
<td>0.17</td>
</tr>
<tr>
<td>Silt loam</td>
<td>3.8</td>
<td>0.59</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>Loam</td>
<td>2.1</td>
<td></td>
<td>32</td>
<td>27</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>2</td>
<td>0.07</td>
<td>0.96</td>
<td>0.29</td>
</tr>
</tbody>
</table>
Based on these results, the standard deviations show consistency for some soil types, such as sand, sandy loam, silty clay loam, and inconsistency for others, specifically the loam soil type. In addition, there were not sufficient samples of loam and silt loam to determine if the data gathered is statistically consistent. In addition, the mean values were consistent for the sand soil type, but inconsistent for loam and silt loam between the two transects.

4.4 CRUST STRENGTH ANALYSIS

The penetrometer field results were converted into discrete forces for each site and for this analysis, error bars were calculated using the standard deviation. It should also be noted that the pen penetrometer was not able to penetrate the playa sites for the Jean Lake transect (site numbers J28, J29 and J30) and the Roach Lake transect (site numbers R32, R33, R34 and R35), as well as a sub-site in a wash along the Roach Lake transect (R14-b). For this reason, these sites were excluded from the analysis below.

Figure 4.16: Crust Strength Results from Jean Lake transect
Figure 4.17: Crust strength results from Roach Lake transect

Based on the graphs above, it is apparent that the soil strength increases with closer proximity to the playa, as do the variability of measurements taken. The range shown in both graphs indicates the minimum and maximum measurements observed at each location, as well as the average value for each site. This variability can be attributed to variations in soil type, which can weaken the crust on smaller scales, as well as the higher level of disturbance experienced, in contrast to other sites along the transect. The majority of both transects consist of soil strength in the 5 N range. Houser (1999) and Brown (1989) both used a similar hand penetrometer device for their field studies. Houser (1999) observed a minimum of 18 N and Brown (1989) observed a minimum crust strength of 8 N on crusted soils. The maximum crust strength observed was approximately 30 N for both Jean and Roach transects, and also lower than the maximum crust strength observed by both Houser (1999) and Brown (1989) of 86 N. This could be attributed to the soil composition, where lower salt content in the soil could result
in weaker bonds and weaker crust strength. Additionally, the penetrometers used by Houser (1999) and Brown (1989) could have been calibrated in a different way, therefore slightly skewing results.

Although crust strength varies at the study sites and likely has an impact on dust emission potential, it is not incorporated into the dust emission models quantitatively.

4.5 Vegetation Surveys

Vegetation surveys were completed on both transects in representative areas. From these surveys, the lateral cover, $L_c$, and aerodynamic roughness, $z_0$, were calculated. The following table outlines these parameters for each survey site at both Jean and Roach Lake transects. The lateral cover and mean roughness decrease with increasing proximity to the playa at the Jean Lake transect, but remains consistent at the Roach Lake sites.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Mean $z_0$ (m)</th>
<th>Lateral Cover ($L_c$)</th>
<th>Survey</th>
<th>Mean $z_0$ (m)</th>
<th>Lateral Cover ($L_c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JV01</td>
<td>1.25</td>
<td>0.11</td>
<td>RV01</td>
<td>2.28</td>
<td>0.17</td>
</tr>
<tr>
<td>JV02</td>
<td>1.01</td>
<td>0.07</td>
<td>RV02</td>
<td>0.59</td>
<td>0.06</td>
</tr>
<tr>
<td>JV03</td>
<td>2.09</td>
<td>0.11</td>
<td>RV03</td>
<td>1.35</td>
<td>0.14</td>
</tr>
<tr>
<td>JV04</td>
<td>2.94</td>
<td>0.13</td>
<td>RV04</td>
<td>1.34</td>
<td>0.11</td>
</tr>
<tr>
<td>JV05</td>
<td>2.82</td>
<td>0.12</td>
<td>RV05</td>
<td>1.20</td>
<td>0.11</td>
</tr>
<tr>
<td>JV06</td>
<td>3.37</td>
<td>0.15</td>
<td>RV06</td>
<td>1.17</td>
<td>0.09</td>
</tr>
<tr>
<td>JV07</td>
<td>3.04</td>
<td>0.12</td>
<td>RV07</td>
<td>1.33</td>
<td>0.08</td>
</tr>
<tr>
<td>JV08</td>
<td>1.98</td>
<td>0.09</td>
<td>RV08</td>
<td>0.67</td>
<td>0.06</td>
</tr>
<tr>
<td>JV09</td>
<td>2.37</td>
<td>0.12</td>
<td>RV09</td>
<td>1.23</td>
<td>0.10</td>
</tr>
<tr>
<td>JV10</td>
<td>3.45</td>
<td>0.14</td>
<td>RV10</td>
<td>1.11</td>
<td>0.08</td>
</tr>
<tr>
<td>JV11</td>
<td>0.95</td>
<td>0.08</td>
<td>RV11</td>
<td>1.04</td>
<td>0.09</td>
</tr>
</tbody>
</table>
### Table

<table>
<thead>
<tr>
<th>Survey</th>
<th>Mean $z_0$ (m)</th>
<th>Lateral Cover ($L_c$)</th>
<th>Survey</th>
<th>Mean $z_0$ (m)</th>
<th>Lateral Cover ($L_c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JV12</td>
<td>0.79</td>
<td>0.04</td>
<td>RV12</td>
<td>1.16</td>
<td>0.09</td>
</tr>
<tr>
<td>JV13</td>
<td>0.24</td>
<td>0.03</td>
<td>RV13</td>
<td>0.97</td>
<td>0.10</td>
</tr>
<tr>
<td>JV14</td>
<td>0.22</td>
<td>0.02</td>
<td>RV14</td>
<td>2.79</td>
<td>0.20</td>
</tr>
<tr>
<td>JV15</td>
<td>0.08</td>
<td>0.01</td>
<td>RV15</td>
<td>0.97</td>
<td>0.09</td>
</tr>
<tr>
<td>JV16</td>
<td>0.10</td>
<td>0.01</td>
<td>RV16</td>
<td>2.50</td>
<td>0.12</td>
</tr>
<tr>
<td>JV17</td>
<td>0.02</td>
<td>0.00</td>
<td>RV17</td>
<td>0.98</td>
<td>0.10</td>
</tr>
<tr>
<td>JV18</td>
<td>0.05</td>
<td>0.01</td>
<td>RV18</td>
<td>0.39</td>
<td>0.06</td>
</tr>
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<td>JV19</td>
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<td>0.07</td>
<td>RV19</td>
<td>0.40</td>
<td>0.05</td>
</tr>
<tr>
<td>JV20</td>
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<td>0.01</td>
<td>RV20</td>
<td>0.23</td>
<td>0.03</td>
</tr>
<tr>
<td>JV21</td>
<td>0.04</td>
<td>0.00</td>
<td>RV21</td>
<td>1.22</td>
<td>0.16</td>
</tr>
<tr>
<td>JV22</td>
<td>0.61</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JV23</td>
<td>1.94</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The surveys were performed in increasing order towards the playa. For example, JV01 would be at the meteorological tower, and JV23 is in proximity to the playa. The vegetation surveys were conducted in areas where vegetation was present. Areas on or around the playas did not have enough measurable vegetation to perform a sufficient survey.

### 4.6 DUST EMISSION DATA ANALYSIS

Dust emission step tests were conducted at each site, in addition to the data above. Thirty (30) dust emission step tests were performed at Jean Lake and thirty-five (35) at the Roach Lake transect, each 540 seconds in duration. In addition to these tests, 4 replicate tests were performed at Jean Lake and 17 replicate tests at Roach Lake to ensure the data collected was consistent. Each test was carried out in the same manner: the PI-SWERL's annular ring begins rotating at 1000 RPM at a constant rate, incrementally increasing in revolutions to a sustained maximum of 4000 revolutions per minute. Several trends were apparent among groups of tests.
The first was the expected ‘supply-limited’ trend, where the initial increase in RPM of the annular ring generates enough shear stress to eject the lightest dust particles off the surface but then emission decreases for the duration of the step (Figure 4.18).

![Figure 4.18: Step test dust emission time series data for site J10](image)

Based on Fig. 4.18, a consistent response to periods of increased Aeolian activity result in a rapid increase of dust emissions followed by a decline in dust emission, making sites such as these limited in their supply of dust as once it has been expelled, the site no longer has dust to emit. This remains the case until another increase or step in surface shear occurs, and the same pattern follows.

In contrast, many sites exhibited a consistent ‘supply unlimited’ response to the step test (Figure 4.19).
Dust emissions increase with each increase in RPM step and is maintained relatively consistently for the duration of the step. This is in contrast to the ‘supply limited’ graph (Figure 4.18), which shows emission rates decreasing rapidly once the supply of dust is been exhausted.

At some sites, dust emission showed a ‘supply-limited’ response until a threshold was reached, usually around 4000 RPM, which then instigated a supply-unlimited response to the surface shear (Figure 4.20).
The time series graphs for each site on both Jean and Roach Lake transects are available in Appendix 1. Despite taking various samples on similar soil types, there was a large degree of variance between sites, which is indicative of the natural variability of dust emissions from these soils, as well as others presented in literature (Houser, 1999; Marticorena and Bergametti, 1995). For example, sites J01 and J07 were both taken on sandy soils, as identified in the previous section, yet show varying levels of dust concentration off the surface, as well as different characteristic responses to step-wise increases in surface shear, as illustrated on their respective time series graphs. The table below summarizes three characteristic shapes for the time series dust emission data and which sites fall under which shape.
Table 4-5: Site Characterization based on Dust Emission Data

<table>
<thead>
<tr>
<th>Shape</th>
<th>Roach Lake</th>
<th>Jean Lake</th>
</tr>
</thead>
</table>

Upon initial observation, the shape of the dust emission data, as a time series, can indicate whether a given site is supply limited, unlimited or a combination of both. It should be noted, however, that due to high degree of variance with the results, several replicates should be performed on a site to ensure consistency. As shown in Table 4-5 above, using the site characterization tool based on dust emission data, can be informative, but it must be coupled with several replicates at the same site. For example, both site J22 and its replicate J22-R, both
were combination sites, but R01 and R01-R were characterized differently, despite being sampled in the same relative location. In addition, most of the sites were either supply limited or combination sites. Despite these considerations, dust emissions for all sites were in agreement with other studies, such as Houser (1999), who observed vertical dust flux values ranging from 0.702 to 45.472 mg/m$^2$·s. This was also on the same order of magnitude as other studies, such as Gillette (1977) and Nickling and Gillies (1989).

Although it is useful in characterizing a site, the dust emission data was primarily used to calculate the vertical dust flux for each RPM level, which was then compared to four established dust emission models. Tables 4-6 and 4-7 summarize the field results, which are compared to model results in following section. The values in the table below were calculated by organizing each site according to soil type. From there, the average dust flux values for each test were used to determine an average dust flux for each soil type. The dust flux values in Table 4-6 and Table 4-7 were calculated by averaging the dust flux calculations for each soil type. The following tables also illustrate how many sites represent each soil type.

Table 4-6: Average dust flux for each soil type & step test interval (Jean Lake Transect)

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Dust flux at each RPM (mg/m$^2$·s)</th>
<th>#sites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>Sand</td>
<td>0.147</td>
<td>0.146</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.039</td>
<td>0.049</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0.022</td>
<td>0.035</td>
</tr>
<tr>
<td>Loam</td>
<td>0.020</td>
<td>0.084</td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.018</td>
<td>0.054</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>0.033</td>
<td>0.090</td>
</tr>
</tbody>
</table>
Table 4-7: Average dust flux for each soil type & step test interval (Roach Lake Transect)

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Dust flux at each RPM (mg/m²·s)</th>
<th>#sites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>Sand</td>
<td>0.037</td>
<td>0.039</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.034</td>
<td>0.061</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0.025</td>
<td>0.135</td>
</tr>
<tr>
<td>Loam</td>
<td>0.049</td>
<td>0.385</td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.046</td>
<td>0.047</td>
</tr>
</tbody>
</table>

Sandy soils dominated both transects, representing 50% and 60% of all sites sampled for Jean and Roach Lakes respectively. Both transects also had comparable average dust emission results for each step test, with the exception of loam soils, which differed between the two transects by an order of magnitude. It should be noted however, that Jean Lake had 2 loam soil sample sites and Roach Lake had 1, which does not provide sufficient data to allow for a reasonable speculation regarding the difference in values. It might also indicate that additional factors, such as the position of vegetation (streets) and soil moisture, influence the dust flux rate at each site, regardless of the commonality of soil type or geospatial location. Although the numbers are scattered, they all fall within the same order of magnitude, as expected.

Separating the transect according to soil type is essential for the application of most dust emission models, as many of them are based on factors such as particle diameter, and clay or dust fractions. While this method of data organization has been used in this study, it can also be helpful to analyze the data based on average vertical dust flux in the geospatial context, along the transect. The following figures illustrate the dust flux values for each site along the transect with samples taken from the playa clearly marked.
Figure 4.21: Vertical dust flux results for each site along Jean Lake Transect

Figure 4.22: Vertical dust flux results for each site along Roach Lake Transect
Figures 4.21 and 4.22 demonstrate that the proximity of the transects and the relative similarities in landscape result in similar dust emission characteristics. Emissions fall between the 0.1 – 5 mg/m$^2$ s with one to two peaks at different distances from the playa. With the exception of a single peak value on the Jean Lake transect, dust flux results from the playa test were among the lowest values, which is in accordance with other field studies (Houser, 1999; Macpherson, 2006; Sweeney et al., 2008).

4.7 MODEL APPLICATION AND RESULTS

Four vertical dust flux models described in Chapters 2 and 3 were compared to dust flux results from the PI-SWERL field data. Some parameters were based on field data while others were based on published values for similar field conditions. The following section elaborates on each model and how they were applied in this study.

4.7.1 GP88 – Gillette and Passi (1988)

Theoretically derived and verified experimentally, this model was developed using data from the U.S. Department of Agriculture’s detailed soil and land use inventory. The model calculates total dust production:

$$\text{Equation 4-1} \quad F = c_0 u_0^4 \left( 1 - \frac{u_{cr}}{u_*} \right)$$

where $c_0$ is a constant, calculated by performing a least squares polynomial fitting, as per Gillette and Passi (1988). An extremely important parameter is the critical shear velocity for dust production, $u_{cr}$, which is dependent on soil texture and atmospheric precipitation, among other factors. The critical shear velocity is:

$$\text{Equation 4-2} \quad u_{cr} = \sqrt{f(Re_\gamma) \left( \sigma_{pg} D + \frac{\gamma}{\rho D} \right)}$$

where $f(Re_\gamma)$ accounts for the impacts of aerodynamic drag on the Reynold’s number, and $\gamma$ have been fitted using values of 1.23x10$^{-2}$ and 1.65x10$^{-4}$ respectively (Shao and Lu, 2000). To account for grain and air densities, $\rho_b$ and $\rho_a$ are estimated at 1200 and 1.184 kg/m$^3$ respectively. For this study, $D$ was calculated for each soil type, based on the United States Department of Agriculture’s (USDA) soil classification, as shown in Table 4-8.
Table 4-8: USDA Mean grain size diameters

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>D (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>1.25</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0.375</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.175</td>
</tr>
<tr>
<td>Loam</td>
<td>0.075</td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.03</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>0.006</td>
</tr>
</tbody>
</table>

For this model, as well as all others, the shear velocity, $u_*$, was calculated based on a relationship derived from several PI-SWERL tests in a wind tunnel and takes the following form:

**Equation 4-3**

$$u_* = 0.00108 \times RPM^{0.77651}$$

The resulting shear velocities used in this study are 0.231 m/s, 0.395 m/s, 0.541 m/s and 0.677 m/s for 1000, 2000, 3000 and 4000 RPM respectively.

4.7.2 MB95 – Marticorena and Bergametti (1995)

This empirical dust emission model was developed to address the desert dust cycle. The two major factors characterized in this model are the grain size analysis, which controls the critical shear velocity, and the surface roughness, which impacts the shear velocity.

**Equation 4-4**

$$F = 0.01qe^{(0.308\eta_v-13.82)}$$

where $\eta_v$ is the clay fraction and $q$ is the streamwise flux expressed using the Owen (1964) equation:

**Equation 4-5**

$$q = \frac{c\rho u_*^3}{g} \left(1 - \frac{u_{cr}^2}{u_*^2}\right)$$

where $c$ is a function of the ratio between the particle terminal velocity, $v_p$, and the shear velocity, $u_*$. 
Equation 4-6
\[ c = 0.25 + \frac{v_t}{3u}. \]

The terminal velocity, \( v_t \), was calculated using the following formula:

Equation 4-7
\[ v_t = \sqrt{\frac{4gD}{3C_d} \left( \frac{\rho_b - \rho}{\rho} \right)} \]

The clay fractions used are shown in Table 4-9 below.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Jean Lake</th>
<th>Roach Lake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.029</td>
<td>0.030</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0.112</td>
<td>0.018</td>
</tr>
<tr>
<td>Loam</td>
<td>0.219</td>
<td>0.113</td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.039</td>
<td>0.103</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>0.297</td>
<td>-</td>
</tr>
</tbody>
</table>

This model was developed by fitting \( F/q \) ratios with the clay fraction using the Gillette (1977) data set.

4.7.3 LS99 – Lu and Shao (1999)

Using a volume removal based approach, Lu and Shao (1999) developed a theoretical dust emission model based on saltation bombardment. The output of this model has been demonstrated using wind tunnel and field observations:

Equation 4-8
\[ F = c_b g \eta \frac{\rho_b}{P} \left( 1 + 10u_e \sqrt{\frac{\rho_b}{P}} \right) q \]

where \( c_b \) is a constant of proportionality, assumed to be less than 1 that reflects a portion of dust particles will remain attached to the aggregates. For the purpose of this study, a value of 0.8 was assigned to this parameter, consistent with the value used by Lu and Shao (1999).
are specified by the dust fraction and soil hardness parameters, \( \eta \) and \( P \) respectively. Table 4-10 below outlines the values used for each of these parameters.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>( \eta )</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.106</td>
<td>1500</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.202</td>
<td>1000</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0.431</td>
<td>1000</td>
</tr>
<tr>
<td>Loam</td>
<td>0.713</td>
<td>10000</td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.552</td>
<td>50000</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>0.859</td>
<td>100000</td>
</tr>
</tbody>
</table>

The common parameters, such as grain density and shear velocity are consistent for all model runs.

4.7.4 SH93 – Shao et al. (1993)

The final model used to verify the PI-SWERL data is one similar to GP88; however, SH93 uses an energy based approach, taking the following form:

\[
F = a u^3 \left( 1 - \frac{u^2}{u^2} \right)
\]

where \( a \) is a dimensional parameter that determines the efficiency of the bombardment process, which is directly related to the function of the mass of a dust particle, density, the proportion of the incoming bombardment energy available for breaking bonds and inversely related to the resistance of the surface to breakdown by this available energy. For the purpose of this study, the efficiency of the bombardment process was valued at approximately 0.7 (Shao, 2008). Table 4-11 provides a summary of all the values used for each model, as outlined in the section above.
### Table 4-11: Model Parameter summary table

<table>
<thead>
<tr>
<th>Model Name and Expression</th>
<th>Parameters</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gillette and Passi (1988)</strong></td>
<td>( u_* )</td>
<td>varies</td>
<td>Calculated based on PI-SWERL RPM (DRI)</td>
</tr>
<tr>
<td>( F = c_0 u_<em>^4 \left( 1 - \frac{u_{cr}}{u_</em>} \right) )</td>
<td>( c_0 )</td>
<td>1.2</td>
<td>Coefficient fitted to incomplete gamma function</td>
</tr>
<tr>
<td></td>
<td>( u_{cr} )</td>
<td>varies</td>
<td>Shao-Lu Scheme for critical shear velocity</td>
</tr>
<tr>
<td></td>
<td>( f(Re_{cr}) )</td>
<td>0.0123</td>
<td>Fitted using wind tunnel observations (Shao and Lu, 2000)</td>
</tr>
<tr>
<td></td>
<td>( \gamma )</td>
<td>( 1.65 \times 10^{-4} )</td>
<td>Fitted using wind tunnel observations (Shao and Lu, 2000)</td>
</tr>
<tr>
<td></td>
<td>( \rho_s )</td>
<td>1.184</td>
<td>Air density at standard temperature and pressure (kg/m³)</td>
</tr>
<tr>
<td></td>
<td>( \rho_b )</td>
<td>1200</td>
<td>Particle density (kg/m³)</td>
</tr>
<tr>
<td></td>
<td>( \sigma_p )</td>
<td>1013.514</td>
<td>Specific gravity (( \rho_b/\rho_a ))</td>
</tr>
<tr>
<td></td>
<td>( g )</td>
<td>9.81</td>
<td>Acceleration due to gravity (m/s²)</td>
</tr>
<tr>
<td></td>
<td>( D )</td>
<td>varies</td>
<td>Grain size diameter (m)</td>
</tr>
<tr>
<td>( u_* = 0.00108 \times RPM^{0.77651} )</td>
<td>( \eta_c )</td>
<td>varies</td>
<td>Shao-Lu Scheme for critical shear velocity (see above)</td>
</tr>
<tr>
<td><strong>Marticorena and Bergametti (1995)</strong></td>
<td>( q )</td>
<td>varies</td>
<td>Bagnold-Owen saltation equation</td>
</tr>
<tr>
<td>( q = c_\rho u_<em>^3 \left( 1 - \frac{u_{cr}^2}{u_</em>^2} \right) )</td>
<td>( \rho_a )</td>
<td>1.184</td>
<td>Air density at standard temperature and pressure (kg/m³)</td>
</tr>
<tr>
<td></td>
<td>( g )</td>
<td>9.81</td>
<td>Acceleration due to gravity (m/s²)</td>
</tr>
<tr>
<td></td>
<td>( u_{cr} )</td>
<td>varies</td>
<td>Shao-Lu Scheme for critical shear velocity (see above)</td>
</tr>
<tr>
<td></td>
<td>( u_* )</td>
<td>varies</td>
<td>Calculated based on PI-SWERL RPM (see above)</td>
</tr>
<tr>
<td></td>
<td>( c )</td>
<td>varies</td>
<td>Ratio between particle terminal velocity and the shear velocity</td>
</tr>
<tr>
<td></td>
<td>( v_t )</td>
<td>varies</td>
<td>Particle terminal velocity (m/s)</td>
</tr>
<tr>
<td></td>
<td>( D )</td>
<td>varies</td>
<td>Grain size diameter (m)</td>
</tr>
<tr>
<td></td>
<td>( C_d )</td>
<td>0.47</td>
<td>Drag coefficient for a spherical particle</td>
</tr>
<tr>
<td><strong>Lu and Shao (1999)</strong></td>
<td>( c_b )</td>
<td>0.8</td>
<td>Constant of proportionality (Lu and Shao, 1999)</td>
</tr>
<tr>
<td>( F = c_b \eta \frac{\rho_b}{\rho} \left( 1 + 10u_* \sqrt{\frac{\rho_b}{\rho}} \right) q )</td>
<td>( u_* )</td>
<td>varies</td>
<td>Calculated based on PI-SWERL RPM (see above)</td>
</tr>
<tr>
<td></td>
<td>( P )</td>
<td>varies</td>
<td>Soil hardness (Table 14) based on simulated and observed vertical dust fluxes</td>
</tr>
<tr>
<td></td>
<td>( \eta )</td>
<td>varies</td>
<td>Dust fraction (Table 14) based on grain size analysis</td>
</tr>
<tr>
<td></td>
<td>( \rho_b )</td>
<td>1200</td>
<td>Particle density (kg/m³)</td>
</tr>
<tr>
<td></td>
<td>( g )</td>
<td>9.81</td>
<td>Acceleration due to gravity (m/s²)</td>
</tr>
<tr>
<td></td>
<td>( q )</td>
<td>varies</td>
<td>Bagnold-Owen saltation equation (see above)</td>
</tr>
<tr>
<td><strong>Shao et al. (1993)</strong></td>
<td>( u_* )</td>
<td>varies</td>
<td>Calculated based on PI-SWERL RPM (see above)</td>
</tr>
<tr>
<td>( F = \alpha u_<em>^3 \left( 1 - \frac{u_{cr}^2}{u_</em>^2} \right) )</td>
<td>( u_{cr} )</td>
<td>varies</td>
<td>Shao-Lu Scheme for critical shear velocity (see above)</td>
</tr>
<tr>
<td></td>
<td>( \alpha )</td>
<td>0.7</td>
<td>Bombardment efficiency dimensionless parameter (Shao et al., 1993)</td>
</tr>
</tbody>
</table>

#### 4.7.5 Variation of Parameters

An analysis involving variance of the key model parameters was performed for each model in order to gain an understanding of the relative importance of the only variable parameters that change in each model. To ensure that all the values fell within reasonable or realistic ranges,
data from the modeling exercise were used. Due to the nature of the models themselves, the key variables were shear velocity and grain size diameter and as a result, only those parameters were varied. Many of the parameters used in these models are largely theoretical and derived using statistical tests or based on data gathered from previous studies.

The effect of grain size was tested using sand, sandy loam and silt loam soil types while keeping the 3000 RPM level consistent for shear velocity. Shear velocity was tested using the sandy loam soil type consistent against the 1000, 3000 and 4000 RPM levels. Tables 4-12 and 4-13 outline the results of the analysis for each model.

**Table 4-12: Variation of parameters for GP88**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>1/7x</th>
<th>1/41x</th>
<th>Control</th>
<th>2x</th>
<th>3x</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u^*$ (m/s)</td>
<td>0.541</td>
<td>0.541</td>
<td>0.541</td>
<td>0.231</td>
<td>0.541</td>
<td>0.677</td>
</tr>
<tr>
<td>D (m)</td>
<td>1.25E-03</td>
<td>1.75E-04</td>
<td>3.00E-05</td>
<td>1.75E-04</td>
<td>1.75E-04</td>
<td>1.75E-04</td>
</tr>
<tr>
<td>F (mg/m$^3$·s)</td>
<td>0.029</td>
<td>0.075</td>
<td>0.091</td>
<td>0.001</td>
<td>0.075</td>
<td>0.197</td>
</tr>
<tr>
<td>Impact on F</td>
<td>2.5x</td>
<td>3x</td>
<td></td>
<td></td>
<td>60x</td>
<td>160x</td>
</tr>
</tbody>
</table>

**Table 4-13: Variation of parameters for M895**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>1/7x</th>
<th>1/41x</th>
<th>Control</th>
<th>2x</th>
<th>3x</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u^*$ (m/s)</td>
<td>0.541</td>
<td>0.541</td>
<td>0.541</td>
<td>0.231</td>
<td>0.541</td>
<td>0.677</td>
</tr>
<tr>
<td>D (m)</td>
<td>1.25E-03</td>
<td>1.75E-04</td>
<td>3.00E-05</td>
<td>1.75E-04</td>
<td>1.75E-04</td>
<td>1.75E-04</td>
</tr>
<tr>
<td>F (mg/m$^3$·s)</td>
<td>1.154E-09</td>
<td>1.847E-09</td>
<td>7.041E-09</td>
<td>1.50E-10</td>
<td>1.85E-09</td>
<td>3.05E-09</td>
</tr>
<tr>
<td>Impact on F</td>
<td>1.5x</td>
<td>6x</td>
<td></td>
<td></td>
<td>12x</td>
<td>20x</td>
</tr>
</tbody>
</table>

**Table 4-14: Variation of parameters for LS99**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>1/7x</th>
<th>1/41x</th>
<th>Control</th>
<th>2x</th>
<th>3x</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u^*$ (m/s)</td>
<td>0.541</td>
<td>0.541</td>
<td>0.541</td>
<td>0.231</td>
<td>0.541</td>
<td>0.677</td>
</tr>
<tr>
<td>D (m)</td>
<td>1.25E-03</td>
<td>1.75E-04</td>
<td>3.00E-05</td>
<td>1.75E-04</td>
<td>1.75E-04</td>
<td>1.75E-04</td>
</tr>
<tr>
<td>F (mg/m$^3$·s)</td>
<td>4.463E-01</td>
<td>1.728E+00</td>
<td>7.624E-03</td>
<td>0.071</td>
<td>1.728</td>
<td>3.471</td>
</tr>
<tr>
<td>Impact on F</td>
<td>4x</td>
<td>1/50x</td>
<td></td>
<td></td>
<td>24x</td>
<td>50x</td>
</tr>
</tbody>
</table>
Table 4-15: Variation of parameters for SH93

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>1/7x</th>
<th>1/41x</th>
<th>Control</th>
<th>2x</th>
<th>3x</th>
</tr>
</thead>
<tbody>
<tr>
<td>u* (m/s)</td>
<td>0.541</td>
<td>0.541</td>
<td>0.541</td>
<td>0.231</td>
<td>0.541</td>
<td>0.677</td>
</tr>
<tr>
<td>D (m)</td>
<td>1.25E-03</td>
<td>1.75E-04</td>
<td>3.00E-05</td>
<td>1.75E-04</td>
<td>1.75E-04</td>
<td>1.75E-04</td>
</tr>
<tr>
<td>F (mg/m²·s)</td>
<td>0.052</td>
<td>0.099</td>
<td>0.088</td>
<td>0.004</td>
<td>0.099</td>
<td>0.201</td>
</tr>
<tr>
<td>Impact on F</td>
<td>1.9x</td>
<td>1.7x</td>
<td>28x</td>
<td>57x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on the tables above, it is clear that the parameter with the most impact on each model result is the shear velocity, $u_*$, as expected, given the exponential relationship established in all models. By doubling and tripling the shear velocity, the models responded by increasing flux values by 12 to 160 times respectively. This result is intuitive, especially in the case of GP88, which has the shear velocity raised to the fourth power. Conversely, decreasing the grain size diameter by various orders of magnitude often resulted in marginal dust flux increases and in a singular case, with the LS99 model, the dust flux declined. In the context of this analysis, this result seems out of place, however in the context of other silt loam results using the LS99 model, the dust emissions do increase with smaller grain size diameters, though not substantially.

4.8 MODEL COMPARISON

PI-SWERL data were used in the models described above to provide an indication as to whether the data collected using this device could be confidently used alongside similar data collected using field wind tunnels. The following graphs were produced; however, the values obtained using MB95 were significantly lower than any other model or within the upper and lower ranges of data observed, illustrated using dashed lines in the figure below, and were therefore omitted from the analysis. The two parameters used in the MB95 model, clay fraction ($\eta_c$) and horizontal flux ($q$), were consistent for all four models used in the analysis. Based on the figure below, it would appear that the Ivanpah Valley, as a regional system, cannot be characterized using this empirical model since this model did not fit with either transect. Since the data used to develop
the MB95 model were from agricultural fields, this model may be only applicable for nutrient-rich soils.

![Graph showing model comparison including MB95 for sandy soils at Jean Lake transect](image)

**Figure 4.23: Model comparison including MB95 for sandy soils at Jean Lake transect**

In addition, several of the results produced negative values for dust flux, since the critical shear velocity calculated was, at times, a smaller value than the shear velocity used. This produces a negative dust flux in several of the models and is therefore, omitted from the graphs, in order to allow a logarithmic analysis of the results.
As discussed above, three of the four models used could not process the lower level of shear velocity and resulted in negative flux values. Despite this, the actual results matched well for the sandy soil at Roach Lake, as shown above in Figure 4.24. All three models analyzed fell within the upper and lower ranges for actual results, indicated by the dashed lines, and LS99 results for 3000 and 4000 RPM levels matched the actual results quite well. The same holds true for many of the following graphs, which indicates that the models perform more accurately at higher shear velocities, possibly due to the fact that many parameters, such as surface cover or roughness elements play less of a role at higher shear velocities.
Figure 4.25: Roach Lake loamy sand soil dust flux model comparison

In the figure above, all three models fall within the range of observed flux results and LS99 performed particularly well once again. The LS99 model additionally performed well in the initial 1000 RPM level, falling between the lower and average range of actual dust flux. The LS99 model was also most accurate for the highest 4000 RPM level as well and GP88 and SH93 values were similar for the 4000 RPM to each other and also fell within the lower and average range of actual field results. The following model result figures, by in large, show that the LS99 model agrees with the actual field results most closely; however, for the most part, all three models used in this analysis fell within the range of values observed in the field.
Figure 4.26: Roach Lake sandy loam soil dust flux comparison

Figure 4.27: Roach Lake loam soil dust flux comparison
Figure 4.28: Roach Lake silt loam soil dust flux comparison

Figure 4.29: Jean Lake sandy soil dust flux comparison
Figure 4.30: Jean Lake loamy sand dust flux comparison

Figure 4.31: Jean Lake sandy loam soil dust flux comparison
Figure 4.32: Jean Lake loam soil dust flux comparison

Figure 4.33: Jean Lake silt loam dust flux comparison
The silty clay loam graph for Jean Lake did not yield modelling results within the range of observed data. The fines modeled on the Roach transect yielded more favourable results, however this same soil class performed well on Jean Lake as well, as shown in Figure 4.33. Another similarity between the two transects lies in the modelling of the loam soil type. Both Jean and Roach lakes exhibit very close results and the shape of the graphs match quite well, though not in the range of observed results.

The LS99 model for Jean Lake silty clay loam did not capture the results as closely as the GP88 and SH93 models and is therefore, not as capable of capturing fines as the other two models. The following section will discuss the results in the context of each of the models, as well as the other parameters measured at the site.

Another method used to test and compare model performance uses a discrepancy ratio, $R_d$, which is the predicted or modeled value divided by the measured result (Chandler and Kostaschuk, 1994). A discrepancy ratio greater or less than 1 is either an over-prediction or under-prediction respectively. Model accuracy can be measured by determining the percentage
of ratios within a factor of 0.5-2 (Yang and Wan, 1991). Since this parameter is a quotient, geometric statistical analysis is required, which is appropriate for this particular study (Mau and Brooks, 1990). Using the discrepancy ratio, the geometric mean, \( \log GM \) is:

\[
\log GM = \frac{\sum \log R_d}{n}
\]

where \( n \) is the number of observations. The geometric standard deviation, \( \log GSD \) is then calculated:

\[
\log GSD = \sqrt{\frac{\sum (\log R_d - \log GM)^2}{(n-1)}}
\]

A model will over-predict and under-predict when the GM is greater or less than 1 respectively and GSD values greater than 1 indicate data scatter. The mean geometric deviation, MGD, uses a single value to evaluate the predictive ability of a model:

\[
MGD = \left( P_{rd} \right)^{\frac{1}{n}}
\]

where \( P_{rd} \) is the product of all \( R_d \) values. Tables 4-16 and 4-17 summarize the statistical analysis of the measured and modeled values by soil type.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>GP88 % of ( R_d )</th>
<th>GM</th>
<th>GSD</th>
<th>MGD</th>
<th>LS99 % of ( R_d )</th>
<th>GM</th>
<th>GSD</th>
<th>MGD</th>
<th>SH93 % of ( R_d )</th>
<th>GM</th>
<th>GSD</th>
<th>MGD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>4</td>
<td>0.30</td>
<td>2.36</td>
<td>16.3</td>
<td>38</td>
<td>0.78</td>
<td>1.68</td>
<td>2.72</td>
<td>13</td>
<td>0.40</td>
<td>2.08</td>
<td>8.62</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0</td>
<td>0.32</td>
<td>2.26</td>
<td>13.4</td>
<td>0</td>
<td>0.43</td>
<td>1.88</td>
<td>7.01</td>
<td>0</td>
<td>0.45</td>
<td>1.83</td>
<td>6.36</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0</td>
<td>0.36</td>
<td>2.30</td>
<td>10.5</td>
<td>100</td>
<td>1.08</td>
<td>1.20</td>
<td>1.33</td>
<td>0</td>
<td>0.48</td>
<td>1.84</td>
<td>5.38</td>
</tr>
<tr>
<td>Silt loam</td>
<td>0</td>
<td>1.60</td>
<td>2.68</td>
<td>2.96</td>
<td>0</td>
<td>0.19</td>
<td>3.81</td>
<td>44.21</td>
<td>50</td>
<td>0.77</td>
<td>1.37</td>
<td>1.82</td>
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<tr>
<td>Loam</td>
<td>0</td>
<td>0.45</td>
<td>1.88</td>
<td>6.18</td>
<td>0</td>
<td>0.51</td>
<td>1.71</td>
<td>4.68</td>
<td>0</td>
<td>0.61</td>
<td>1.49</td>
<td>3.16</td>
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<tr>
<td>Silty clay loam</td>
<td>0</td>
<td>0.31</td>
<td>2.28</td>
<td>14.5</td>
<td>0</td>
<td>0.05</td>
<td>6.57</td>
<td>925.01</td>
<td>0</td>
<td>0.40</td>
<td>2.00</td>
<td>8.02</td>
</tr>
<tr>
<td>Soil Type</td>
<td>% of R</td>
<td>GM</td>
<td>GSD</td>
<td>MGD</td>
<td>% of R</td>
<td>GM</td>
<td>GSD</td>
<td>MGD</td>
<td>% of R</td>
<td>GM</td>
<td>GSD</td>
<td>MGD</td>
</tr>
<tr>
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</tr>
<tr>
<td>Sand</td>
<td>13</td>
<td>0.37</td>
<td>2.17</td>
<td>10.6</td>
<td>50</td>
<td>1.24</td>
<td>1.69</td>
<td>2.57</td>
<td>17</td>
<td>0.49</td>
<td>1.93</td>
<td>6.12</td>
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<tr>
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<td>1.90</td>
<td>2.02</td>
<td>5.65</td>
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<td>0.57</td>
<td>1.96</td>
<td>3.92</td>
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<tr>
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<td>0.37</td>
<td>2.00</td>
<td>9.58</td>
<td>17</td>
<td>1.77</td>
<td>1.62</td>
<td>3.71</td>
<td>17</td>
<td>0.50</td>
<td>1.72</td>
<td>4.92</td>
</tr>
<tr>
<td>Loam</td>
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<td>0.25</td>
<td>2.20</td>
<td>24.85</td>
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<td>0.27</td>
<td>2.12</td>
<td>21.25</td>
</tr>
<tr>
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<td>1.40</td>
<td>1.89</td>
<td>0</td>
<td>0.37</td>
<td>2.02</td>
<td>9.69</td>
<td>40</td>
<td>1.58</td>
<td>1.55</td>
<td>2.88</td>
</tr>
</tbody>
</table>

Tables 4-16 and 4-17 show that the SH93 and LS99 models agreed best with the data, according to MGD values, however this varied greatly between soil types. Overall, LS99 was able to relatively more accurate in the larger to mid-range soil types, such as sand and sandy loam. Based on the GM, all three models greatly under-predict emissions, with the exception of LS99, which agreed relatively well for the larger soil types.
5 CHAPTER 5: DISCUSSION

The results presented in the previous section describe various soil parameters and dust emission potential from a variety of soil types. The following section provides a discussion of the soil parameterization exercise and how these parameters contribute to the characterization of an area, as well as the dust emission potential. Following that is a discussion on the models and the interpretation of the model comparison with respect to the use of the PI-SWERL in conjunction with other soil parameters measured. The chapter will close with a brief discussion of sources of error with this study and how these errors could be avoided in the future.

5.1 SOIL PARAMETERIZATION

An understanding and analysis of the surface or soil properties are required to better understand the impacts and influence they have on wind erosion and dust emission. In this study, the surface parameters analyzed were soil texture, salt content, organic matter and surface strength. In particular, soil strength was measured using a pen penetrometers calibrated in replicate using an automatic press. Although the calibration was consistent, the results from the penetrometers analysis showed considerable scatter, primarily in closer proximity to the playa. Similarly, the standard deviations for the organic content and salt content analyses also showed a wide range of values for each soil type. Despite this, all four analyses show strong trends with increasing proximity to the playa. Soil texture shows an increase in fines for sites closer to the playa, which reflects the topographic reality of the playa being at the lowest point in the valley, similar to the phenomenon observed by Gill et al., (2001) at the Owens Lake playa in California. This was also manifested in the organic content and surface strength parameters. Organic matter showed a clear trend increasing towards the playa, which follows the same logic as the fines, where the lightest particles will flow and settle in the lowest elevation in the area. Salt content also increased, which positively correlated with surface strength and confirms Nickling (1984) result of salt as an effective soil particle bonding agent. Although characterized as a sedimentary crust, the elevated levels of salt and organic matter content at the playa may also be in part attributed to organic secretions, which can bind particles together (McKenna Neuman et al., 1996; McKenna Neuman and Maxwell, 1999). Leys and Eldridge (1998) discussed the effect of undisturbed microbiotic crusts in sandy soils, which can provide insights into the
dust flux results in this study. In that study, fine grains were found to bind to be the binding agent for larger grains. Although much of the aeolian activity is observed on the playas, the PI-SWERL results do not show an elevated dust emission response from the playa. Furthermore, as previously mentioned, although soil strength is higher with closer proximity to the playa, soil strength, as compared to studies conducted by Houser (1999) and Brown (1989) indicate that the crust strengths along the two transects is relatively weak. For this reason, documenting the total area of crusted surface is essential to modelling regional dust emission.

Current dust emission models use soil classes, or more accurately, mean grain size diameter, as a major function in the prediction of dust potential. For this reason, the soil parameters measured were also analyzed among soil properties. Although the overall trend, when organized by site number, showed a coherent trend, there were no obvious inconsistencies of that nature when the data were divided by soil type. The sandy soil type for both Jean and Roach Lakes were very similar to each other in system response. The GP88 model was farthest from the actual results, followed by SH93 and LS99 was the closest to actual in both cases. Additionally, all models fell within the upper and lower ranges of actual field data values. Conversely, while the loamy sand soil results for both transects generally agreed with the actual results, the system response was less alike between the two transects than the previous sandy soil example. In the loamy sand comparison, values at 3000 and 4000 RPM exceed the actual field results at Roach Lake, whereas they fall well below the actual results at Jean Lake. The pattern then returns with the sandy loam comparison, where the system responses for both Jean and Roach Lakes agree quite well with one another and the LS99 model is most similar to the actual field results for both transects. The finer soil types showed considerable variation in results and many of the models used did not agree with the actual field results. One of the major reasons might be the varying geological nature of the soil distribution that exists in this region, as per Figure 3.4 and Figure 3.5. Since the stronger trends appeared when the data was analyzed spatially, as opposed to by soil type, dust emission models should also be able to capture surface properties spatially, in relation to other sites, as opposed to strictly by soil type (Okin and Gillette, 2001).

Although much of the data contained a great deal of variability, care was taken to perform each test, including field tests and laboratory analyses, in replicate. This was done to reduce error and to instill a sense of confidence with the values produced. As shown in Appendix 1,
many of the replicate sites agreed strongly with the initial site. This further verifies the validity of using the PI-SWERL as a reliable and consistent instrument for the measurement of dust emission potential on a varied landscape.

5.2 Model results

Although the four models used were developed using different approaches, they all generally use the same set of parameters, namely percent dust or clay, mean grain size diameter. Parameters, such as soil strength and salt content can be indirectly captured in the model, through saltation energy factors, while parameters such as organic matter and vegetation are not captured quantitatively. Field wind tunnels gathering in-situ data can capture the effects of vegetation by the nature of their methodology; they are large enough to gather erosion data around vegetation. The GP88 model captured the effects of vegetation in the values selected for the threshold velocity and is the only model that did so. Conversely, the PI-SWERL cannot capture the effects of vegetation on dust emissions, which is reflected in the results of the modeling exercise, where the general trend was for the actual results to be somewhat higher than the results of any of the three models analyzed. More specifically, the capture of the effects of vegetation may likely be the reason that the GP88 model is consistently the lowest in estimating dust emission.

Specifically, PI-SWERL results were consistently higher, on both transects, for finer soil types, such as silt loam and silty clay loam. In addition, the loam soil type was also consistently under estimated by all models for every RPM level or shear velocity, implying that the model is optimal at grain diameters greater than 0.075 mm. One of the main reasons for this is possibly due to the complexity of capturing a system’s response to surface crust. Shao (2004) used various estimates of soil hardness, $P$, to account for varying levels of surface crust. The $P$ values were determined using the maximum soil penetration observed by Rice et al. (1997). Although many studies have analyzed the effect of surface crust on shear velocity (Argaman et al., 2006), as well as the effect of saltation on surface crust (Rice and McEwan, 2001), many of the established models were developed theoretically and verified using data that may not have incorporated the dynamic of vegetation, crusted surfaces and other surface cover features in an arid landscape. Further, the model greatly underestimated the dust emission for the lower RPM or shear velocity run. This also implies that the optimal shear velocity for these dust emission models is greater than 0.4 m/s.
The results from the statistical comparison of the models (Tables 4-16 and 4-17) reflect the performance of the models against an entire test and quantitatively show that many of the models are under-predicting emissions. Results from the analysis also show that the models were especially inaccurate for smaller soil types. This indicates that the process of dust emission on exposed, crusted surfaces is a complex one, not yet captured fully by any of the models in this study.

Similar to the previous section, a great deal of care was taken to ensure reliable data was gathered in-situ. Tests were performed in replicate and the repeated tests are in general agreement. An unavoidable error that exists with this study is the inability to measure the shear velocity at each test site, prior to initiating the PI-SWERL test. As a result, an empirical relationship was used to generate the shear velocity values used to correspond to the different RPM steps used for each test. This means that soil properties, such as texture and roughness ordinarily captured through the shear velocity characterization were not captured in this study. Undertaking field-scale dust sampling programs without capturing a wind profile is generally not standard practice and therefore has no supporting literature. Given the positive trends in this study and with further refinement, it is quite probable that the PI-SWERL can be used as an index for understanding a dust emission regime, on any given site. Despite this, the actual results of the field program generally agree with the results generated by three accepted dust flux models, all verified using wind tunnels.
6 CHAPTER SIX: CONCLUSIONS

A field-based methodology for characterizing dust emission potential was carried out at various locations within the Mojave Desert, NV, to develop a coherent dust emission and corresponding soil property data set and to use this data to evaluate current dust emission models. In doing this, the study will also be verifying the validity of using the PI-SWERL among other techniques and equipment used to measure soil properties in situ. The research objectives for this study focused on evaluating a suite of soil properties and qualitatively determining the influence on these parameters on dust emission results. The following section presents the major conclusions associated with each research objective, outlined in Chapter 1:

i) To develop a standardized field sampling plan of the study area along two transects using the Portable In-Situ Wind Erosion Laboratory (PI-SWERL) as well as other instruments and techniques to measure relevant soil properties.

The data collected using the field sampling plan showed a great deal of variability among soil types; however there were clear trends observed when analyzed spatially and in proximity to the playa. Parameters, such as salt and organic matter content increased dramatically with closer proximity to the playa. Although varied, penetrometer results indicated increased soil strength, due to crusting, with closer proximity to the playa as well. Although the soil parameters showed consistency in this regard, the dust emission data did not appear to show any identifiable trend, spatially or by soil type. Although there were no discrete trends, the models generally agreed with the courser soil dust flux results and to a far lesser extent with the finer soil types. Three site characterizations were identified using the dust emission data: supply limited, supply unlimited and combination sites; however, this analysis also showed a great deal of variability, even among common sites. Despite this, the average dust emission data collected, as well as the upper and lower ranges of results observed agree with accepted dust emission models and the soil parameters collected also show clear spatial patterns. For the purpose of this study, the soil parameters measured were used to qualitatively provide insights into the results of the PI-SWERL analysis, however, a model that could possibly incorporate soil and site properties, such as lateral cover, soil strength, salt content, organic matter content and soil
texture would be able to provide far more insights into the accuracy and validity of the PI-SWERL as an index for dust emission potential.

ii) To undergo an intensive quality assurance and quality control process of the collected PI-SWERL and soil property data.

Due to limitations in instrumentation, the PI-SWERL gaps in the data often required filling, by using a rolling or moving average approach to data management. This approach was used when the dust concentration output was either 0 or a negative value, both of which are impossibilities. While many tests did not require any form of data management, others required significant cleaning. Based on the shape of the time series graph, it was decided that tests with more than 30% dropped data values were not to be used, while tests that had fewer than 30% dropped data still sufficiently captured the dust emission character of that site. This approach has proven effectively, as the resulting dust emission data is relatively consistent with model results.

While each of the soil parameters measured showed some level of variability, the spatial analysis showed strong patterns, generally increasing with closer proximity to the playa. This positive correlation agrees with the theoretical understanding of these soil properties and implies that the spatial relationship that exists between the soil samples is far stronger than that of similar soil types.

iii) To evaluate the validity of current dust emission models using the analyzed field data.

Using the data collected, actual dust emission results were compared to four established dust emission models, all developed using different approaches. The empirical model, MB95, based primarily on clay content, predicted dust emission potential several orders of magnitude lower than any other model, as well as the field data. For this reason, it was omitted from the analysis. All other models generally agreed with the field results, but resulted in values consistently lower than the field data. Based on the model comparison, SH93 generally predicted dust emission potential more accurately for finer soil types while LS99 predicted larger soil types with greater consistency. Although there were no discrete trends, the models
generally agreed with the courser soil dust flux results and to a far lesser extent, with the finer soil types.

While the soil parameter data showed a great deal of variability, each parameter showed positive correlations when compared spatially. For this reason, dust emission models that capture spatial relationships, as opposed to models based on soil type classification, would provide far more insights into the characterization of this site. Although the statistical analysis shows considerable scatter, overall, the dust emission data generally agreed with the models, which were separated by soil type.

6.1 POSSIBLE NEXT STEPS

One of the major limitations in this study was the rough estimation of shear velocity used to analyze the dust emission data. If a methodology or model was developed to capture the effects of surface roughness and vegetation in-situ, coupled with the dust emission data from the PI-SWERL, then the results would likely agree far more with the established models. This would involve making a model or factor specific for the PI-SWERL, since the device can not measure the wind profile prior to each test, as is the case with a field wind tunnel. In addition, using a more reliable mechanism for the soil strength parameter would possibly yield more meaningful results, as the results from this study appear to be lower than similar studies conducted with a similar device.

Another limitation encountered was the inability to quantitatively incorporate many of the soil parameters measured into the dust flux models. While capturing these soil parameters made the field program far more onerous, this data has the potential to increase the accuracy of dust potential models dramatically. Specifically, accounting for parameters such as surface cover and crust would provide a great deal of accuracy and depth to dust potential estimates.
REFERENCES CITED


Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R01
GPS Coordinates: 35.6861727716, -115.3830041914
Description: Sandy, some gravel, vegetation; close to meteorological tower

The graph shows time series data for TRPM, RPM, and DT_PM10 (mg/m^3) over time (s).
Appendix 1 - Roach Lake Transect
Time Series Data

Site Number: R01-R
GPS Coordinates: 35.6861727716, -115.3230041914
Description: Sandy, some gravel, vegetation; close to meteorological tower
Site Number: **R02**
GPS Coordinates: 35.6859767654, -115.3232570802
Description: *Some vegetation; rocks and gravel*
Site Number: **R02-R**     *Note – 68% dropped data*

GPS Coordinates: 35.6859767654, -115.3232570802  
Description: **Some vegetation; rocks and gravel**
Site Number: R03
GPS Coordinates: 35.6857689759, -115.3234585341
Description: Gravel and sand
Site Number: R03-R
*Note – 44% dropped data
GPS Coordinates: 35.6857689759, -115.3234585341
Description: Gravel and sand
Site Number: R04
GPS Coordinates: 35.6852868025, -115.3236441975
Description: Gravel, east side of wash; sand
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R04-R  
*Note – 43% dropped data
GPS Coordinates: 35.6852868025, -115.3236441975
Description: Gravel, east side of wash; sand
Site Number: **R05**
GPS Coordinates: 35.6849436408, -115.3239479889
Description: Gravel, east side of wash; some sand and vegetation
Site Number: R05-R  *Note – 40% dropped data
GPS Coordinates: 35.6849436408, -115.3239479889
Description: Gravel, east side of wash; some sand and vegetation
Site Number: **R06**
GPS Coordinates: 35.6845750213, -115.3242471313
Description: **Mixed sand, gravel and rocks**
Appendix 1 - Roach Lake Transect Time Series Data

Site Number: R06-R
GPS Coordinates: 35.6845750213, -115.3242471313
Description: Mined sand, gravel and rocks

![Graph](image-url)

- TRPM
- RPM
- DT_PM10 (mg/m³)

Dust concentration (mg/m³)

- Time (s)
- RPM
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R07
GPS Coordinates: 35.6848991919, -115.3253985051
Description: Small gravel, rocks, mixed vegetation

[Graph showing TRPM, RPM, and DT_PM10 data over time]
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R07-R
GPS Coordinates: 35.6848991919, -115.3253985051
Description: Small gravel, rocks, mixed vegetation
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: **R08**
GPS Coordinates: 35.6847007284, -115.3254838272
Description: **Small gravel, rocks, mixed vegetation**
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R09
GPS Coordinates: 35.684119321, -115.3255535556
Description: Small gravel, rocks, mixed vegetation
Site Number: R10
GPS Coordinates: 35.6830162469, -115.3255465185
Description: North side of road
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: **R11**
GPS Coordinates: 35.682595, -115.325915
Description: **Transition zone; south side of road**
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R11-R
GPS Coordinates: 35.682595, -115.325915
Description: Transition zone; south side of road
Site Number: R12
GPS Coordinates: 35.6822029279, -115.3262102102
Description: Gravel, crust present, transition zone to smallest vegetation zone
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R12-R
GPS Coordinates: 35.6822029279, -115.3262102102
Description: Gravel, crust present, transition zone to smallest vegetation zone
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R13
GPS Coordinates: 35.6817978642, -115.3265035
Description: Small gravel lags, small vegetation
Appendix 1 – Roach Lake Transect

Time Series Data

Site Number: R13-R1  *Note – 66% dropped data
GPS Coordinates: 35.6817978642, -115.3265035
Description: Small gravel lags, large vegetation
Site Number: R13-R2  *Note – 67% dropped data
GPS Coordinates: 35.6817978642, -115.3265035
Description: Small gravel lags, large vegetation
Appendix 1 - Roach Lake Transect
Time Series Data

Site Number: **R14**
GPS Coordinates: 35.6814315354, -115.3268095932
Description: **Small gravel lags, large vegetation**

![Graph showing time series data with TRPM, RPM, and DT_PM10(mg/m3) axes.]

![Images of the transect site and surrounding environment.]
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R14-R
GPS Coordinates: 35.6814315354, -115.3268095932
Description: Small gravel lags, large vegetation
Site Number: R15
GPS Coordinates: 35.6810389951, -115.3271083333
Description: Small gravel lags, sparse and dry vegetation

No photographs available
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R15-R  *Note – 45% dropped data
GPS Coordinates: 35.6810389951, -115.3271083333
Description: Small gravel lags, sparse and dry vegetation

No photographs available
Site Number: **R16**
GPS Coordinates: 35.6805834877, -115.3274872531
Description: **Small gravel lags, sparse and dry vegetation**

No photographs available
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R16-R
GPS Coordinates: 35.6805834877, -115.3274872531
Description: Small gravel lags, sparse and dry vegetation

No photographs available
Appendix 1 - Roach Lake Transect
Time Series Data

Site Number: R17
GPS Coordinates: 35.6802687915, -115.3277400199
Description: Small gravel lags, sparse and dry vegetation

![Graph showing TRPM, RPM, and DT_PM10 over time](image)

No photographs available
Appendix 1 - Roach Lake Transect
Time Series Data

Site Number: **R17-R**
GPS Coordinates: 35.6802687915, -115.3277400199
Description: Small gravel lags, sparse and dry vegetation

No photographs available
Site Number: R18
GPS Coordinates: 35.679868679, -115.3280362469
Description: Small gravel lags, sparse and dry vegetation

No photographs available
Site Number: **R18-R**
GPS Coordinates: 35.679868679, -115.3280362469
Description: Small gravel lags, sparse and dry vegetation

No photographs available
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: **R19**
GPS Coordinates: 35.6794937623, -115.3284278064
Description: **Creosote transition**

No photographs available
Site Number: R19-R
GPS Coordinates: 35.6794937623, -115.3284278064
Description: Creosote transition

No photographs available
Site Number: **R20**
GPS Coordinates: 35.6791518827, -115.3286589383
Description: **Creosote transition**
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: **R20-R**
GPS Coordinates: 35.6791518827, -115.3286589383
Description: **Creosote transition**

![Graph showing RPM, TRPM, and DT_PM10 values over time.](image)

No photographs available.
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: **R21**
GPS Coordinates: 35.6787669074, -115.3289846667
Description: **Creosote transition**

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No photographs available
Site Number: R22
GPS Coordinates: 35.678315, -115.3293116667
Description: End of creosote transition zone; sparse vegetation

No photographs available
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R23
GPS Coordinates: 35.6779285309, -115.3297262716
Description: End of creosote transition zone

No photographs available
Site Number: R23-R
GPS Coordinates: 35.6779285309, -115.3297262716
Description: End of creosote transition zone

No photographs available
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: **R24**
GPS Coordinates: 35.6775672469, -115.3300072469
Description: **End of creosote transition zone**
Site Number: **R24-R**
GPS Coordinates: 35.6775672469, -115.3300072469
Description: **End of creosote transition zone**
Site Number: **R25**
GPS Coordinates: 35.677065, -115.3302966667
Description: Small gravel lags, crusted; transition zone to dry vegetation
Appendix 1 – Roach Lake Transect

Time Series Data

Site Number: R25-R

GPS Coordinates: 35.677065, -115.3302966667

Description: Small gravel lags, crusted; transition zone to dry vegetation
Site Number: **R26**

GPS Coordinates: 35.6766981227, -115.3306759046

Description: Small gravel lags, transition zone to dry vegetation
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: R26-R
GPS Coordinates: 35.6766981227, -115.3306759046
Description: Small gravel lags, transition zone to dry vegetation

[Graph showing time series data for TRPM and RPM with DT_PM10 concentrations in mg/m³]
Site Number: R27
GPS Coordinates: 35.676297358, -115.3310288025
Description: Small gravel lags, transition zone to dry vegetation
Appendix I – Roach Lake Transect
Time Series Data

Site Number: R28
GPS Coordinates: 35.675997202, -115.3313917172
Description: Small gravel lags, transition zone to dry vegetation
Site Number: R28-R
GPS Coordinates: 35.675997202, -115.3313917172
Description: Small gravel lags, transition zone to dry vegetation
Site Number: **R29**  
GPS Coordinates: 35.6755038435, -115.331657415  
Description: Small gravel lags, transition zone to dry vegetation
Site Number: **R30**

GPS Coordinates: 35.6751996173, -115.3319483951

Description: Gravel and sparse vegetation

![Graph showing time series data with TRPM, RPM, and DT_PM10 concentrations over time.](image-url)
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: **R31**
GPS Coordinates: 35.6741465679, -115.3327058148
Description: Gravel bed
Appendix 1 - Roach Lake Transect
Time Series Data

Site Number: R32
*Note - 45% dropped data
GPS Coordinates: 35.636404317, -115.33228213
Description: Playa

[Graph showing dust concentration (mg/m³) vs. RPM and time (s)]
Appendix 1 – Roach Lake Transect
Time Series Data

Site Number: **R33**
GPS Coordinates: 35.6731314259, -115.3338046358
Description: Playa
Appendix 1 - Roach Lake Transect
Time Series Data

Site Number: R34
GPS Coordinates: 35.6723179233, -115.334647209
Description: Sand dunes - small vegetation
Appendix 1 - Roach Lake Transect
Time Series Data

Site Number: **R35**  *Note – 30% dropped data*
GPS Coordinates: 35.6637844646, -115.3402212222
Description: Deep playa (center)
Site Number: J01
GPS Coordinates: 35.77925878, -115.2218425
Description: Sandy, some gravel, no crust, large, sporadic vegetation
Site Number: J01-R
GPS Coordinates: 35.77925878, -115.2218425
Description: Sandy, some gravel, no crust, large, sporadic vegetation
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J02
GPS Coordinates: 35.77950344, -115.223015
Description: More dense grasses, some gravel, sandy, some crust
Site Number: J03
GPS Coordinates: 35.77963831, -115.2241011
Description: Some grasses, gravel, large vegetation
Site Number: \textbf{J04}

GPS Coordinates: 35.78004565, -115.2251233

Description: Sandy, gravel patches, large vegetation and grasses

![Graph showing time series data with TRPM, RPM, and DT_PM10 (mg/m³) axes.](image)
Appendix 2 - Jean Lake Transect

Time Series Data

Site Number: J04-R

GPS Coordinates: 35.78004565, -115.2251233

Description: Sandy, gravel patches, large vegetation and grasses

![Graph showing dust concentration over time with RPM and TRPM scales.]
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J05
GPS Coordinates: 35.78020583, -115.2262309
Description: Sand, some crust, gravel lags, large, sporadic vegetation
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J06
GPS Coordinates: 35.7804628, -115.2272947
Description: Sandy, some crusting, smaller vegetation and grasses present
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J07
GPS Coordinates: 35.78060107, -115.2284395
Description: Gravel, significant crusting, large vegetation
Site Number: J07-R
GPS Coordinates: 35.78060107, -115.2284395
Description: Gravel, large vegetation, few small grasses present
Site Number: J08
GPS Coordinates: 35.78072523, -115.2295649
Description: Gravel, large, sporadic vegetation
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J09
GPS Coordinates: 35.78091091, -115.2306363
Description: Gravel, some crusting, sporadic vegetation of various sizes
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J10
GPS Coordinates: 35.7811095, -115.2316997
Description: Heavy gravels present, mixed vegetation, some crusting
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J10-R
GPS Coordinates: 35.7811095, -115.2316997
Description: Gravel, transition to grasses mixed vegetation
Appendix 2 - Jean Lake Transect

Time Series Data

Site Number: J11
GPS Coordinates: 35.78117903, -115.2325853
Description: Gravel, transition to grasses, few creosote bushes

[Graph showing time series data with a graph of RPM and dust concentration over time]
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J12
GPS Coordinates: 35.78128203, -115.2336853
Description: Gravel, crust present, transition to short grasses
Site Number: J13
GPS Coordinates: 35.78146725, -115.2348357
Description: Gravel, crust present, transition to short grasses, few creosote bushes
Site Number: J13-R
GPS Coordinates: 35.78146725, -115.2348357
Description: Gravel, crust present, short grasses, few creosote bushes, some disturbance from grazing present
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J14
GPS Coordinates: 35.78162427, -115.2359679
Description: Gravel, crust present, short and dead grasses transition zone

![Graph showing dust concentration over time with labels TRPM, RPM, and DT_PM10(mg/m3)]

![Image showing gravel and crust in the field]
Site Number: J15
GPS Coordinates: 35.78180527, -115.2370698
Description: Gravel, crust present, transition zone to smallest vegetation zone
Site Number: J16
GPS Coordinates: 35.78200041, -115.2381648
Description: Gravel, crust present, transition zone to smallest vegetation zone
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J16-R
GPS Coordinates: 35.78200041, -115.2381648
Description: Gravel, crust present, transition zone to smallest vegetation zone

-DTRTRPM
-RPMDTRPM

[Graph showing dust concentration over time with RPM on the x-axis and concentration on the y-axis]
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J17
GPS Coordinates: 35.78226102, -115.2393168
Description: Gravel, crust present, transition zone to sparse grasses
Site Number: J18
GPS Coordinates: 35.78244787, -115.2403891
Description: Gravel, crust present, transition zone to sparse grasses
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J19
GPS Coordinates: 35.78268674, -115.2415451
Description: Gravel, crust and sandy soils present, transition zone to sparse grasses
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J19-R
GPS Coordinates: 35.78268674, -115.2415451
Description: Gravel, crust and sandy soils present, transition zone to sparse grasses
Site Number: J20
GPS Coordinates: 35.78282064, -115.2426646
Description: Gravel, crust and sandy soils present, transition zone to sparse grasses

No photographs available
Site Number: J21  *Note - 45% dropped data
GPS Coordinates: 35.78307437, -115.2437449
Description: Gravel, crust and sandy soils present, transition zone to sparse grasses

No photographs available
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J22
GPS Coordinates: 35.78330001, -115.2449022
Description: Gravel, crust and sandy soils present, transition zone to sparse grasses

No photographs available
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J22-R
GPS Coordinates: 35.78330001, -115.2449022
Description: Gravel, crust and sandy soils present, transition zone to sparse grasses

No photographs available
Appendix 2 - Jean Lake Transect

Time Series Data

Site Number: J23
GPS Coordinates: 35.78346845, -115.2459794
Description: Gravel, crust and sandy soils present, transition zone to sparse grasses

Graph showing dust concentration (mg/m³) over time (s) with RPM as another variable.
Appendix 2 - Jean Lake Transect

Time Series Data

Site Number: J24
GPS Coordinates: 35.78369431, -115.2470357
Description: Small gravel lags, heavily crusted, transition zone to very sparse and dry vegetation
Appendix 2 - Jean Lake Transect

Time Series Data

Site Number: J25
GPS Coordinates: 35.78392388, -115.2481582
Description: Few gravel lags, heavily crusted, transition zone to barren playa
Site Number: J25-R  *Note - 75% dropped data
GPS Coordinates: 35.78392388, -115.2481582
Description: Few gravel lags, heavily crusted, transition zone to barren playa
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J26
GPS Coordinates: 35.78403624, -115.2492091
Description: Few gravel lags, heavily crusted, transition zone to barren playa
Site Number: J27
GPS Coordinates: 35.78418757, -115.2495972
Description: Heavily crusted, playa, no vegetation
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J28
GPS Coordinates: 35.78494856, -115.251843
Description: Heavily crusted, playa, no vegetation
Site Number: J28-R  *Note – 75% dropped data
GPS Coordinates: 35.78494856, -115.251843
Description: Heavily crusted, playa, no vegetation
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J29
GPS Coordinates: 35.78519701, -115.2531318
Description: Heavily crusted, playa, no vegetation
Appendix 2 - Jean Lake Transect
Time Series Data

Site Number: J30
GPS Coordinates: 35.78534559, -115.2541994
Description: Heavily crusted, playa, no vegetation

Dust concentration (mg/m³)

RPM

TRPM

DT_PM10(mg/m³)

4000
3500
3000
2500
2000
1500
1000
500

0

Time (s)

Rpm

4500

0

500

100

200

300

400

500

600