PARTICULATE MATTER EMISSIONS
FROM COMMERCIAL BEEF CATTLE FEEDLOTS IN KANSAS

by

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Abstract

Large cattle feedlots in Kansas are often considered to be large sources of particulate matter (PM), including PM with equivalent aerodynamic diameter of 10 μm or less (PM_{10}). To control PM emissions from cattle feedlots, water sprinkler systems can be implemented; however, limited data are available on their PM control efficiency. This research was conducted to determine the control efficiency of a water sprinkler system in reducing PM_{10} emission from a cattle feedlot. This was accomplished by monitoring the PM_{10} concentrations, with tapered element oscillating microbalance (TEOM™) PM_{10} monitors, at the upwind and downwind boundaries of a cattle feedlot (KS1) from January 2006 to July 2009. The feedlot was equipped with a sprinkler system that can apply up to 5 mm of water per day. It had approximately 30,000 head of beef cattle and total pen area of approximately 50 ha. The control efficiency of the sprinkler system was determined by considering the PM_{10} data during sprinkler on/off events, i.e., the sprinkler system was operated (on) for at least one day and either followed or preceded by at least one day of no water sprinkling (off). For each of the selected sprinkler on/off events, the percentage reduction in net PM_{10} concentration was calculated and considered to be a measure of the control efficiency. Net PM_{10} concentration was defined as the difference between downwind and upwind PM_{10} concentrations. The control efficiency for PM_{10} ranged from 32% to 80%, with an overall mean of 53% based on 24-h PM_{10} values for 10 sprinkler on/off events. In general, the effect of the water sprinkler system in reducing net PM_{10} concentration lasted for one day or less. The percentage reduction in net PM_{10} concentration at KS1 due to rainfall events was also determined using a similar approach. In addition, a second cattle feedlot (KS2) that was not equipped with a sprinkler system and with approximately 25,000 head of beef cattle and 68 ha pen area was considered. Percentage reductions in net PM_{10} concentrations due to rainfall events were mostly in the range of 60% to almost 100% for both feedlots, with overall means of 75% for KS1 and 74% for KS2. The effects of rainfall events (with rainfall amounts $\geq$ 10 mm/day) lasted for three to seven days, depending on rainfall amount and intensity.

Limited data are also available on PM_{10} emission rates from cattle feedlots in Kansas. This research quantified PM_{10} emission rates from the two feedlots (KS1 and KS2) and a third cattle feedlot (KS3) in Kansas by using inverse dispersion modeling with the AMS/EPA

Regulatory Model (AERMOD), which is the US EPA preferred regulatory atmospheric dispersion model. PM_{10} emission rates were back-calculated using the resulting PM_{10} concentrations modeled by AERMOD, together with measured PM_{10} concentrations (24 months of data for KS1 and KS2, 6 months of data for KS3). Overall mean PM_{10} emission fluxes for the 2-year period were 1.29 g/m^2-day (range: 0.04 – 4.98 g/m^2-day) for KS1, 1.03 g/m^2-day (range: 0.07 – 4.52 g/m^2-day) for KS2, and 2.48 g/m^2-day (6-months; range: 0.05 – 5.00 g/m^2-day) for KS3. The corresponding mean PM_{10} emission factors were 21, 29, and 48 kg/1,000 hd-day for KS1, KS2, and KS3, respectively. The emission factors for KS1 and KS2 were considerably smaller than the published US EPA emission factor for cattle feedlots (i.e., 42 kg/1000 hd-day). The emission factor for KS3 was slightly greater than the US EPA emission factor; however, it was a biased estimate because it was based only on a six-month period.

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List of Acronyms

AERMET	AERMOD meteorological preprocessor
AERMOD	American Meteorological Society/Environmental Protection Agency Regulatory Model
AFO	Animal feeding operation
CAA	Clean Air Act
CAFO	Concentrated animal feeding operation
CBL	Convective boundary layer
CFR	Code of Federal Regulations
EDP	Evening dust peak
EPCRA	Emergency Planning and Community Right-to-Know Act
ISCST3	Industrial Source Complex – Short Term Regulatory Model
NAAQS	National Ambient Air Quality Standards
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NSPS	New Source Performance Standards
NWS	National Weather Service
SAPRA	State Air Pollution Regulatory Agency
TEOM^{TM}	Tapered Element Oscillating Microbalance
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency

List of Symbols

A	Area of feedlot (m^2)
C_A	AERMOD-derived downwind PM_{10} concentration ($\mu g/m^3$) for an emission flux of 100 $\mu g/m^2$-s
$C_{c,s}$	Concentration contribution for both convective and stable conditions
C_o	Measured net PM_{10} concentration ($\mu g/m^3$)
C_T	Total concentration at a specified location from the source ($\mu g/m^3$)
EF	Emission factor (kg/1000 hd-day)
f	Plume state weighting function
$FSRM$	Functional system roadway mileage (mile)
h	Hour (military time/astronomical time)
$L1$	Dimension of parking lot perpendicular to aisles (mile)
$L2$	Dimension of parking lot parallel to aisles (mile)
M	Surface material moisture content under dry, uncontrolled conditions (%)
N	Total number of cattle
p	Number of days with rainfall of at least 0.25 mm/day or 0.01 in./day
P_y	Probability density function for lateral concentration distribution
P_z	Probability density function for vertical concentration distribution
PM	Particulate matter
$PM_{2.5}$	Particulate matter with equivalent aerodynamic diameter of 2.5µm or less
PM_{10}	Particulate matter with equivalent aerodynamic diameter of 10µm or less
Q	Pollutant emission rate (i.e., g/m^2-s for area sources)
Q_a	Assumed emission flux in AERMOD (i.e., 100 $\mu g/m^2$-s)
Q_o	Actual emission flux ($\mu g/m^2$-s)
s	Surface silt content (%)
S	Average vehicle speed (mi/h)
TSP	Total suspended particulates, particulate matter with equivalent aerodynamic diameter of 30µm or less
U	Effective wind speed
VMT	Vehicle mile traveled (miles/year)
w	Average number of vehicle wheels
W	Mean vehicle weight (tons)
x_r	Receptor distance from the source (m)
y_r	Receptor distance from plume centerline (m)
z_p	Receptor height relative to ground (m)
z_r	Receptor height relative to stack base elevation (m)

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CHAPTER 1 - Introduction

Background

The cattle feeding industry in the U.S. is projected to grow in the coming years. USDA (2009) reported an increase in the number of large beef cattle feedlots (1,000-head capacity) from 1,327 in 2002 to 1,554 in 2007. With the projected growth of the cattle feeding industry and corresponding increase in number of large cattle feedlots and/or increase in capacity of existing large feedlots, it is expected that air-quality issues associated with cattle feedlots are expected to become more important. Particulate matter (PM) and gaseous emissions will become more important because of potential health risks to people living in areas near the feedlots and employees working at the feedlots.

Previous research (Razote et al., 2007; Sweeten et al., 1988) reported that the mean daily PM_{10} concentrations measured in the vicinity of cattle feedlots can exceed the U.S. Environmental Protection Agency or US EPA (2008b) 24-h National Ambient Air Quality Standards (NAAQS) for PM_{10} (150 $\mu g/m^3$). In addition, Razote et al. (2007) observed that PM_{10} concentrations in the vicinity of cattle feedlots in Kansas in the late afternoon to early evening period can exceed 1,000 $\mu g/m^3$, possibly due to increased cattle activity and relatively stable atmospheric conditions.

The US EPA has established the New Source Performance Standards (NSPS) to control emissions for specific pollutants from major pollutant sources. Owners and the management of these sources have to comply with the NSPS standards to be able to continue their operations and avoid being penalized (CAA, 2004). While CAFOs are not currently included in the NSPS (CFR, 2008a), air quality regulations are becoming more and more stringent. For example, the US EPA has recently implemented the Emergency Planning and Community Right-to-Know Act or EPCRA on animal feeding operations (CFR, 2008b). Under this new rule, cattle feedlots are required to monitor and report events when ammonia and hydrogen sulfide emissions exceed the limits. Particulate matter may eventually be regulated because of the growth of the cattle industry.

Implementation of PM control methods may also be required in the future and the availability of cost-effective abatement measures will be important for feedlot operators. At present, feedlot operators already implement abatement measures, including pen cleaning and water application on the pen surfaces and unpaved roads. Limited data, however, are available on the effectiveness of these abatement measures.

More research on the measurement and control of PM emissions is needed to establish science-based PM emission standards for cattle feedlots. Emission standards set in NSPS for other pollutant sources were derived from actual measurements of emissions for several years. However, direct measurement of PM emission from cattle feedlots will prove a great challenge given the large area of the feedlot and uncontrolled conditions of the surroundings. Emission rates from cattle feedlots can be estimated through inverse dispersion modeling. If the US EPA is planning to establish PM emission standards for cattle feedlots, best management practices on how to control PM emissions, with scientifically proven control efficiencies, and with effects on other gaseous emissions should be available to feedlot managers. Reducing PM emission rate with the risk of increasing the emission rate of another harmful pollutant is not recommended. With adequate scientific information to develop best management practices, feedlot management can choose control methods that are appropriate to their operations.

Research Objectives

This research was conducted to (1) evaluate the PM control efficiency of water sprinkler system in beef cattle feedlots in Kansas and (2) estimate PM_{10} emission rates at beef cattle feedlots in Kansas through inverse dispersion modeling.

For the first objective, reductions in PM_{10} concentrations associated with sprinkler on/off events were determined from measured PM_{10} concentrations. Estimates of the control efficiency for water sprinkler system will be useful for feedlot operators and policy makers. Knowing the effectiveness of a PM control method, including water sprinkler systems, will assist feedlot operators to decide which PM control method is most appropriate for their operations. The data may also prove helpful to feedlot operators in maximizing efficiency of water application. Understanding when to apply water, with the knowledge when the highest PM concentrations occur and the need to maximize control efficiency, will help the feedlot operators in their design and operation of sprinkler systems.

For the second objective, AERMOD along with the measured PM_{10} concentrations were used to determine PM_{10} emission rates. The emission rates may serve as a basis in revising the published PM_{10} emission factor (i.e., 42 kg/1000 hd-day).

References

Clean Air Act (CAA). 2004. Clean Air Act. 42 U.S. C. 7401 et Seq. Washington, DC.

CFR. 2008a. Code of Federal Regulations, 40CFR, Part 60: Standards for performance for new stationary sources. Available at www.gpoaccess.gov/CFR. Accessed 21 September 2009.

CFR. 2008b. Code of Federal Regulations, 40CFR, Parts 302 and 355: CERCLA/EPCRA Administrative reporting exemption for air releases of hazardous substances from animal waste at farms. Available at www.epa.gov/fedrgstr/EPA-AIR/ 2008/ December/ Day-18/a30003.pdf. Accessed 19 November 2009.

Razote, E. B., R. G. Maghirang, J. P. Murphy, B. W. Auvermann, J. P. Harner, III, D. L. Oard, W. L. Hargrove, and J. M. Sweeten. 2007. Ambient PM_{10} concentrations at a beef cattle feedlot in Kansas. ASABE Publication Number 701P0907cd. St. Joseph, Mich.: ASABE

Sweeten, J. M., C. B. Parnell, R. S. Etheredge, and D. Osborne. 1988. Dust emissions in cattle feedlots. In *Stress and Disease in Cattle, Veterinary Clinics of North America, Food Anim. Prac.* 4(3): 557-578.

U.S. Department of Agriculture (USDA). 2009. 2007 Census of Agriculture. United States Summary and State Data, Vol. 1, Geographic Area Series, Part 51. Washington, D.C.: U.S. Department of Agriculture, National Agricultural Statistics Service.

U.S. Environmental Protection Agency (US EPA). 2008b. Integrated review plan for the National Ambient Air Quality Standards for particulate matter. EPA-452/R-08-004. Research Triangle Park, NC: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards.

CHAPTER 2 - Literature Review

Cattle Feedlot and Particulate Matter Emissions

Concentrated Animal Feeding Operations (CAFOs) are operations in which animals are grown during confinement in a given area and at the same time, CAFOs may be significant contributors of pollutant/s (US EPA, 2008a). The size thresholds for the cattle feeding sector are as follows: less than 300 head for small CAFOs; 300 – 999 head for medium CAFOs; and 1000 or more head for large CAFOs (US EPA, 2008a). From 2002 to 2007, while the total number of feedlots decreased from 80,743 to 50,009 (USDA, 2009a), the number of large cattle feedlots increased from 1,327 to 1,554 and the total number of cattle increased by more than 1 million, from 14.9 million to 16.1 million head. Based on the 2008 statistics (USDA, 2009b), counting only the cattle feedlots with more than 1,000 head capacity, the three states with highest number of cattle were Texas (3 million head), Nebraska (2.7 million), and Kansas (2.6 million). Both Kansas and Nebraska are part of US EPA Region 7 (with Iowa and Missouri). This region has 985 cattle feedlots (56% of the country's total) where 44% of the country's cattle are being fed (US EPA, 2008b).

With the growth of the cattle feeding industry, air quality complaints related to cattle feeding operations are expected to rise (Hargrove, 2004; MWPS, 2002a). Cattle feedlots are sources of gaseous pollutants that are believed to be harmful to the environment and humans; some gaseous emissions, including methane and carbon dioxide, are thought to be contributors to global climate change (MWPS, 2002a). Gaseous and particulate emissions from cattle feedlots are generated by different processes (US EPA, 2001a): (1) microbial decomposition of manure's nitrogen content can produce ammonia and nitrous oxide; (2) degradation of manure's organic matter (carbon content) causes the formation of methane, carbon dioxide, and volatile organic compounds (VOCs); (3) manure decomposition under anaerobic conditions leads to hydrogen sulfide formation; and (4) drying of manure layer can generate particulate matter (PM) once the manure layer gets pulverized by cattle hooves. To date, the cattle feedlot emissions that are being regulated include ammonia and hydrogen sulfide (MWPS, 2002a; CFR, 2008b).

Particulate matter can carry gases and odors (MWPS, 2002a) and are capable of traveling long distances away from cattle feedlots. Several complaints have been filed by the public against feedlots operators due to excessive dust emissions. A publication released by Consumers Union (2000) stated that, after expanding the operation to more than 30,000 head, a feedlot in Texas received complaints related to respiratory concerns due to dust reaching residential homes. The same publication noted a situation in Texas wherein the citizens and companies in the area opposed the proposed expansion of a feedlot. Taylor (2004) reported a case in which a county attempted to pass a resolution that would also affect beef cattle feedlot operations due to public health and safety concerns. It is apparent from these examples that a part of the public sector perceives the cattle feeding industry as a major concern to public health and welfare.

Particulate Matter Sources in Cattle Feedlots

Beef cattle feedlots are large open lots that are exposed to the outside environment, making the lot conditions harder to control especially under harsh weather conditions. Unlike CAFOs with confined buildings, ventilation as a major method of controlling and confining particulate emissions within the feedlot vicinity may not be practical. Due to the open lot confinement for cattle feedlots, high PM concentrations have been monitored in the vicinity of feedlots. Sweeten et al. (1988) measured PM concentrations for 24-h sampling periods at three feedlots in Texas. They reported a mean total suspended particulate (TSP) concentration of 412 $\mu g/m^3$. They also reported that the mean downwind concentrations of PM_{10} (particulate matter with equivalent aerodynamic diameter of 10μm or less) were 40% of the mean TSP concentrations. Razote et al. (2007) reported a mean net PM_{10} concentration at a cattle feedlot in Kansas of 115 $\mu g/m^3$ (range from 35 to 195 $\mu g/m^3$).

Major sources of PM emissions from feedlots are the pen surfaces and unpaved roads; other sources include wind erosion and feed mills. The primary source of PM emission in open cattle feedlots is the pen surface, composed mainly of manure and soil. The amount of manure on the pen surface depends on the number of cattle confined and frequency of pen cleaning/manure harvesting (higher frequency, thinner manure layer). Particulate emission from pen surfaces is often triggered by cattle activity; PM is emitted when cattle walk on the dry, loose layer of soil and manure. As such, the more active the cattle are, the higher the PM emission will be. PM emissions and downwind concentrations tend to vary during the day with concentrations peaking during the early evening periods; one of the factors contributing to this increase in concentrations is the increase in cattle activity/movement during this period (Auvermann et al., 2006). Limiting cattle activity during the early evening periods could be a way of reducing PM generation. Controlling and limiting movement of cattle in the pen (i.e., stocking density), however, may have some negative impact on overall cattle performance (Rahman et al., 2008; MWPS, 2002a).

Another important factor that influences PM emission from the pen surface is the moisture content of the loose manure/soil layer in the pen surface. Miller and Woodbury (2003) reported that the PM emission potential of feedlot soils was lower at certain moisture content levels. Since moisture content is one of the variables affecting PM emission potential, high variability in moisture content of the pen surface can also lead to unpredictability in PM emission. Factors affecting moisture content in the pen surface can be categorized into two: sources contributing to increased moisture content and factors leading to loss of moisture. Sources of moisture for the manure layer are rainfall, cattle urine, and water applied from any water-application system, such as water sprinkler system. Factors that can lead to loss of moisture are wind speed and temperature. High wind speed increases the rate of moisture evaporation from the pen surface; high wind speed and wind shifts may also lead to erosion of the pen surface. High temperature of the surroundings increases evaporation rate of moisture from the pen surface, resulting in a dry, loose pen surface that is prone to dust emission. With the unpredictable trends of weather conditions, the moisture content of the pen surface can be highly variable that also leads to high variability in emission (US EPA, 2001a).

The US EPA has released a set of PM emission factors for the purpose of estimating annual emissions of PM from cattle feedlots (US EPA, 2001b). Annual emission factors are available for Total Suspended Particulates or TSP (US EPA, 1988), PM_{10} (US EPA, 1988, 2001b), and PM with equivalent aerodynamic diameter of 2.5µm or less or $PM_{2.5}$ (US EPA, 2001b):

$$EF_{\mathrm{TSP}} = (27\ tons/1{,}000hd) \tag{2.1}$$

$$EF_{\mathrm{PM}_{10}} = (17\ tons/1{,}000hd) \tag{2.2}$$

$$EF_{\mathrm{PM}_{2.5}} = 0.15 \times EF_{\mathrm{PM}_{10}} \tag{2.3}$$

where EF_{TSP}, EF_{PM10}, and $EF_{\mathrm{PM2.5}}$ are the emission factors for TSP, PM_{10}, and PM2.5, respectively.

Unpaved feed alleys can also contribute to PM emissions from cattle feedlots. PM emissions from unpaved roads are usually important during daytime (Hamm, 2005; Wanjura et al., 2004) when trucks are going around the pens for feeding and manure harvesting operations. The weight of moving vehicles can pulverize the loose, large particles on unpaved road surfaces into finer particulates. When these particles come in contact with the wheels, the rotating wheels can force the particulates into the air (Watson et al., 1996). A study by Hayden and Richards (2004) on PM emissions from unpaved roads in two industrial plants resulted in PM_{10} emission factors ranging from 0.08 to 0.18 lb/vehicle mile traveled or VMT. VMT is defined by US EPA (2001b) by equation 2.4 assuming there are 365 days in one year:

$$VMT = 5 \times FSRM \times 365 \tag{2.4}$$

where *FSRM* is the functional system roadway mileage (mile).

The US EPA has published several equations that can be used to estimate PM emissions while vehicles are traveling on unpaved roads (US EPA, 1988, 2001b). Equations are also provided for PM emissions from unpaved parking lots (US EPA, 1988). The equations include the effect of weight of vehicles, miles travelled, volume traffic, and properties of unpaved road materials. Emission factors for PM emissions from unpaved roads are given by equations 2.5 and 2.6 (US EPA, 1988, 2001b). These emission factors are in pounds per mile and must be multiplied by VMT to estimate the yearly PM emission rates.

$$EF_{\mathrm{PM}_{10}} = 2.1(s/12)\ (S/30)(W/3)^{0.7}(w/4)^{0.5}((365-p)/365\ ) \tag{2.5}$$

$$EF_{\mathrm{PM}_{2.5}} = 0.15 \times E_{\mathrm{PM}_{10}} \tag{2.6}$$

where *s* is the surface material silt content (%), *S* is the average vehicle speed (mph, miles per hour), *W* is the mean vehicle weight (tons), *w* is the average number of vehicle wheels, and *p* is the number of days in a year with at least 0.01 in. of rain per day.

The US EPA (2001b) has released another equation (eqn. 2.7) to estimate unpaved road emissions that represents the average emission factor. Rather than being based on vehicle speed, the equation considers moisture content of the unpaved road material. In this case, the PM_{10} emission factor is in tons per mile and must be multiplied by VMT in monthly basis.

$$EF_{\mathrm{PM}_{10}} = \frac{(2.6/2000)\,(s/12)^{0.8}(W/3)^{0.4}}{(M/0.2)^{0.3}} \times ((365-p*12)/365) \tag{2.7}$$

where *M* is the surface material moisture content under dry, uncontrolled conditions (%).

The PM_{10} emission factor in equation 2.5 is also applicable for determining the PM_{10} emission factor for unpaved parking lots. The US EPA has another PM_{10} emission factor equation for unpaved parking lots. In this equation, the following assumptions were made: average speed of 10 mph, silt content of 12%, average number of wheels of 4, and average weight of 3 tons. This emission factor equation (in grams per vehicle parked) is recommended by US EPA (1988) for estimating PM_{10} emission and is given by equation 2.8.

$$EF_{\mathrm{PM}_{10}} = 0.20((365-p)/365)(L1 + L2) \tag{2.8}$$

where *L1* is the dimension of parking lot (mile) perpendicular to aisles and *L2* is the dimension of parking lot (mile) parallel to aisles.

Air Quality Regulations on Particulate Matter

The US EPA began to set air quality criteria for PM with the creation of the National Ambient Air Quality Standards (NAAQS) starting 1971 (US EPA, 2008c). The NAAQS are established by the US EPA under the Clean Air Act (CAA, 2004) to protect human health and public welfare from air pollutants. These are based on two standard criteria: (1) primary standards defined as standards established for the protection of human health from effects of pollutants; and (2) secondary standards established for the protection of public welfare (Cooper and Alley, 2002). The standards for PM are apparently becoming more stringent. In 1987, the PM indicator was changed from TSP to PM_{10} (Mitloehner and Calvo, 2008) and in 1997, $PM_{2.5}$ was added as an indicator. The addition of $PM_{2.5}$ in NAAQS is important since it represents PM that can go in the airways and alveoli of the lungs (Mitloehner and Calvo, 2008). While $PM_{2.5}$ might have the most damaging effect on human health, PM_{10} is still an important indicator. Not only does it include $PM_{2.5}$, it also includes all PM that can enter the respiratory system. Penetration of PM through the respiratory system can cause adverse health effects in the following ways (CARB, 2009): (1) PM_{10} may cause some reactions inside the human body leading to health problems; (2) may worsen existing respiratory problems; (3) may lessen the body's capability to fight infection; and (4) may cause very serious health problems to children, elderly and high-risk population.

Particulate Matter Standards: NAAQS and NSPS

As summarized by McCarthy (2005), NAAQS requires US EPA to establish minimum national air quality standards for six criteria air pollutants, including $PM_{2.5}$ and PM_{10}. Table 2.1 summarizes the history of the changes on the PM NAAQS. Note that because agricultural operations, including CAFOs, are exempted to some emission and discharge regulations under both federal and state laws (NRC, 2003), NAAQS have not been implemented within the feedlot vicinity.

Another important air quality regulation is the NSPS. The NSPS are emission standards, which were derived from extensive research and actual measurements, for specific sources to control emission rates for specific pollutants (Cooper and Alley, 2002). Cattle feedlots are classified as minor pollutant sources only (NRC, 2003) and are therefore not part of NSPS (CFR, 2008a). Before cattle feedlots are going to be part of NSPS, emission standards for any criteria pollutant, such as $PM_{2.5}$ and PM_{10}, must be established first based on extensive research and scientific principles (NRC, 2003). The US EPA PM_{10} and $PM_{2.5}$ national emission factors are not considered standards and just set for the sole purpose of estimating yearly emissions based on the cattle inventory (US EPA, 2001b).

Table 2.1 History of the National Ambient Air Quality Standards for particulate matter (US EPA, 2008c).

Year	Indicator	Averaging Time	Level[a]	Form
1971	TSP	24-h	260 µg/m^3 (primary) 150 µg/m^3 (secondary)	Not to be exceeded more than once per year
		Annual	75 µg/m^3	Annual average
1987	PM_{10}	24-h	150 µg/m^3	Not to be exceeded more than once per year over a 3-year period
		Annual	50 µg/m^3	Annual arithmetic mean, averaged over 3 years
1997	$PM_{2.5}$	24-h	65 µg/m^3	98th percentile, averaged over 3 years
		Annual	15 µg/m^3	Annual arithmetic mean, averaged over 3 years
	PM_{10}	24-h	150 µg/m^3	Not to be exceeded more than once per year over a 3-year period
		Annual	50 µg/m^3	Annual arithmetic mean, averaged over 3 years
2006	$PM_{2.5}$	24-h	35 µg/m^3	98th percentile, averaged over 3 years
		Annual	15 µg/m^3	Annual arithmetic mean, averaged over 3 years
	PM_{10}	24-h	150 µg/m^3	Not to be exceeded more than once per year over a 3-year period

[a] When not specified, primary and secondary standards are identical.

Federal and State Regulations on Emissions

As stated in the CAA (2004), it is the responsibility of US EPA to regulate emissions from any pollutant source that may impair air quality. Under the CAA, the US EPA requires all State Air Pollution Regulatory Agencies (SAPRAs) to perform the following responsibilities: (1) implement federal air quality standards, (2) monitor actual air conditions to ensure air quality standards are achieved, (3) handle state permitting programs for construction, modification and operation of all pollutant sources, (4) create emissions and discharge regulation laws to address issues not yet included, and (5) modify existing regulation laws as needed (CAA, 2004; NRC, 2003; MWPS, 2002b). Although the CAA requires that all pollutant sources that emit large amounts of pollutants must be regulated (CAA, 2004; NRC, 2003), agricultural operations, such as beef cattle feedlots, are not fully controlled by numerous emissions/discharge regulation laws (NRC, 2003). There are several reasons for making CAFOs exempt from laws regulating gaseous and particulate emissions; the main reason appears to be the lack of scientific data based on extensive research that can indicate emission levels from these sources and feasibility to control these emissions (NRC, 2003).

Part 51 of the CFR (CFR, 1986), which deals primarily with requirements in controlling pollutant emissions, may be used as reference in regulating emissions from CAFOs. However, implementation of regulations under CFR Part 51 (CFR, 1986) for agricultural facilities is too stringent for CAFOs, especially for cattle feedlots. For PM_{10}, the maximum emission is set at 70 tons per year (CFR, 1986). If the US EPA (2001b) emission factor of 17 tons/1000 head - year will be used to estimate PM_{10} emissions, the total number of head may be limited to 4,000 for feedlots without major PM control methods. This number is very low compared with the capacities of existing commercial cattle feedlots that may reach a number of 30,000 head. Also, exceeding the allowable emission will require operators to pay annual emission fees. The State of Kansas has its own air quality regulations as a result of the CAA (KDHE, 2009a). If an industry that had a potential pollutant is planning to build and start an operation in Kansas, it is required to give the state of Kansas an estimate of emissions as part of application process (KDHE, 2009a). Emission estimates can be based on existing monitoring systems, approved emission factors (i.e., US EPA, state) or actual emissions data. Similar to the list of stationary sources included in the CFR (1986), CAFOs are not specified as major pollutant sources in air quality regulations designed by the State of Kansas. If CAFOs were to be included and with Kansas setting its maximum emission at 100 tons per year for all emissions (KDHE, 2009a), the total number of head will be restricted to 5,800 per feedlot. Right now, there are several feedlots in Kansas operating at 30,000 head capacity. Based on the US EPA PM_{10} emission factor, this head capacity is equivalent to a yearly PM_{10} emission of 510 tons, which is five times the limit set applied in Kansas.

Cattle Feedlot Regulations

Lack of emission standards applicable for cattle feedlots does not imply that cattle feedlots are free to operate without regards to their potential pollutant emissions. Although not required to get federal operating permits, cattle feedlots may be required to get authorization in some states before starting with any construction/modification or continuing operations (MWPS, 2002b). In cases involving construction of new feedlots or modifying/expanding existing feedlots, some states/SAPRAs may require operators to approximate emissions/concentrations, especially during worst-case scenarios (MWPS, 2002b). Approximation can be based on actual measurements (i.e., use of flux chambers) or dispersion modeling (NRC, 2003).

For the state of Kansas, the permit application to operate or modify/construct and the filing of annual operation reports require CAFO operators to give details only on their waste (wastewater) discharges and none on emissions (KDHE, 2009b). But even if this is the current practice, air quality concerns due to CAFOs have increased as reflected by the latest US EPA emissions regulations. Starting January 20, 2009, the US EPA requires CAFOs to report hazardous emissions (i.e., ammonia and hydrogen sulfide) coming from animal wastes as stated under the Emergency Planning and Community Right-to-Know Act or EPCRA (CFR, 2008b). Cattle feedlots with more than 1,000 head are required to report to emergency offices (state and local) when one of either emission exceeds 100 lb (45.36 kg) in a 24-h period under EPCRA (CFR, 2008b). Although times when emissions from CAFOs exceed their corresponding specified limits are not classified as emergency situations, notifying concerned groups is suggested by the US EPA (CFR, 2008b). In addition, included in the document released by the US EPA on EPCRA is a commentary about PM from CAFOs: in order to protect the health and welfare of children, emission monitoring of PM and ammonia, which could have formed from these particulates, is highly recommended as it enables operators to take corrective actions and to have sufficient time to give warnings to concerned groups (CFR, 2008b).

With air quality issues from beef cattle feedlots becoming more important, science-based emission standards (emission rate and concentration levels) for cattle feedlots will likely be established in the near future. Beef cattle feedlot operators will eventually need to finds ways to minimize and control emissions for the benefit of the community living near the feedlots.

Particulate Control Methods for Cattle Feedlots

Controlling PM emissions from cattle feedlots is going to be an important part of both particulate emission regulations and feedlot operations. The following general approaches have been used or recommended to reduce PM emissions from feedlot pens: (1) manure layer removal; (2) moisture content manipulation; and (3) control of animal activity during the early evening period (Auvermann et al., 2006; MWPS, 2002a; MWPS, 2002b). Specific abatement measures for controlling PM emissions from cattle feedlots include the following (Table 2.2): (1) surface water application, (2) pen cleaning and manure harvesting, (3) stocking density manipulation, (4) windbreak or shelterbelts, (5) feeding schedule, and (6) surface amendments. These abatement measures are discussed briefly below.

Surface Water Application

Surface water application is aimed at increasing the moisture content of the pen surface to reduce PM emission from cattle feedlots. Water can be applied by means of sprinkler systems or by water trucks equipped with spray nozzles. Water sprinkling is typically done in the afternoon, which is the hottest period in the day, and in the evening when cattle activity is the highest (MWPS, 2002a). In some cases, water sprinkling is done over 24 h because of pump/tank limitations. While it is generally accepted that application of water to the feedlots is effective in reducing PM emission, limited data are available on its control efficiency.

The Natural Resources Conservation Service (NRCS) has released practice standards that can be applied in conservation of air quality from CAFOs, including cattle feedlots. These practice standards can serve as guidelines and as minimum acceptable levels for various states. The practice standard on irrigation and sprinkler systems (NRCS, 2003) established several criteria on sprinkler system design and operations. Design parameters affecting water distribution on pen surfaces are nozzle types, nozzle height, spacing between nozzles, nozzle operating pressure, and pump operating capacity

(NRCS, 2003). Some parameters must be factored in during the design stage. First, the over-lapping of sprinklers (spacing between sprinklers) must be optimized; less overlapping may lead to more dry areas between two sprinklers while excessive overlapping may cause accumulation of water on some areas leading to runoff and odor emissions (NRCS, 2003). Second, the choice of pump must be based on water application rate required to minimize PM emissions. As stated by NRCS (2003), the basis of water application rate must meet the maximum daily evaporation rate. For sprinkler operations, the frequency of sprinkler operation must be scheduled such that daily water application requirement is met without producing runoffs. One recommendation by NRCS (2003) is to study application of water at low rates but high frequency. The sprinkler system must be operated during dry conditions; and if possible, it should automatically shut off in the presence of rainfall. The sprinkler system must also be designed such that in can be operated manually during cases of very dry and dusty conditions.

Based on a comparison made by Carroll et al. (1974) between sprinkled and non-sprinkled feedlots, percentage reductions for TSP were 38% and 49% for two events considered. In a report prepared for the US EPA, Pechan (2006) indicated that watering of beef cattle feedlots, either by sprinkler system or water trucks, had control efficiencies of 50% for PM_{10} and 25% for $PM_{2.5}$. Research done in a California feedlot showed that after stopping the sprinkler system (one data point), the dust concentration increased by 850% (ACFA, 2002; MWPS, 2002a); this was equivalent to 88% reduction in concentration upon operation of the sprinkler system.

One of the major drawbacks of sprinkler systems is the cost of installation and operation. The sprinkler system can be either installed as solid-set sprinkler system or as traveling gun sprinkler system (Amosson et al., 2007). As mentioned by Amosson et al. (2007), each type of sprinkler system has its own advantages and disadvantages: the solid-set sprinkler system has less labor cost but requires higher capital investment; the traveling gun sprinkler system, on the other hand, has lower capital investment but requires some considerations in feedlot designs, particularly the alleys and roads for transport. Harner et al. (2008) summarized the studies made by Amosson et al. (2006, 2007) and from the comparison between the two types of sprinkler system, total (fixed and operational) annual cost per head of solid-set sprinkler system was more than twice the annual cost for the traveling gun. Water can also be applied by using water trucks. Less capital is needed for using water trucks but the costs necessary for its operation, including labor and fuel, are higher (Auvermann et al., 2006).

The recommended amount of water to be applied on the feedlot surface in order to reduce PM emissions is at least 5 mm/day (ACFA, 2002). Harner et al. (2008) indicated that stocking density must be accounted for in computing the recommended amount of water. Harner et al. (2008) showed that decreasing the stocking density (increasing cattle spacing) would increase the amount of water needed to meet the desired moisture content of the pen surface.

Pen Cleaning / Manure Harvesting

Another control method is controlling the manure layer on the pen surface. Particulate emission from a feedlot is triggered by cattle walking on dry, loose layer of soil and manure, therefore removal of this loose layer would greatly reduce the PM emission rate. The loose manure layer can be controlled by manure harvesting in which the manure is removed from the pen using machineries/tractors; and by pen scraping in which loose manure layer is scraped to a certain area of the pen and then compacted (Auvermann et al., 2006). The recommended pen scraping frequency to effectively minimize manure accumulation and loose manure layer is every three or four months (Rahman et al., 2008). The typical frequency of pen cleaning, however, is after each confinement cycle (i.e., 120 – 180 days) and manure harvesting is usually done once a year (MWSP, 2002a).

NRCS (2008) provided the following general guidelines on pen cleaning/manure harvesting: (1) activities involving manure must be done on conditions that would result in lowest formation and less transport of emissions; and (2) consider covering manure to reduce emissions. It may be impractical to consider these suggestions for beef cattle feedlots. For example, delaying pen cleaning to wait for best possible conditions to scrape can result in thicker manure layer. Also, it is not possible to cover the manure mounds in the pens.

Limited data are available on how effective manure harvesting/pen cleaning is in reducing PM emission. Similar to the other control methods, manure harvesting/pen cleaning has its own disadvantages, including the following: (1) high labor requirement,

(2) possible increase in cattle stress (Romanillos and Auvermann, 1999), and (3) high dependence on operators' skills (MWPS, 2002b).

Stocking Density Manipulation

Stocking density refers to the number of cattle confined per area. Another way of reporting this is animal spacing (Auvermann et al., 2006), which is the inverse of stocking density (area allotted per head). Increasing the stocking density can decrease PM emissions from feedlots because increasing the number of cattle per area increases the amount of moisture per area excreted by cattle, thus making the manure layer more compact (Romanillos and Auvermann, 1999); this increase in moisture content of the pen surface might be sufficient to produce significant reduction in PM emission. In addition, reducing cattle space can reduce unnecessary cattle activities that can lead to PM emission (Rahman et al., 2008).

Previous studies have reported relatively modest reduction in PM emission through stocking density manipulation. Romanillos and Auvermann (1999) reported that doubling the stocking density by decreasing cattle spacing from 13.9 m^2/hd to 7.0 m^2/hd led to 5-12% PM_{10} reduction; however, there was not sufficient data to show consistency of these values. MWPS (2002a) cited a 29% reduction in emission by doubling the stocking density.

Increased stocking density can lead to cattle stress and may affect overall cattle performance (Rahman et al., 2008; MWPS, 2002a). Increasing the number of cattle per area would also increase the amount of manure being excreted per area even for just a short period of time and consequently, frequent manure harvesting must be implemented (high labor cost). Another drawback is that the corral must be constructed such that cross fencing is easily done for stocking density manipulation (Auvermann et al., 2006). Extra investments might be needed in redesigning corrals for this to be possible; additional labor costs might also be required.

Shelterbelts / Windbreaks

Unlike other PM control methods, shelterbelts/windbreaks are used to reduce PM concentration downwind of the source and not to reduce PM emission rates from pen surfaces (MWPS, 2002a). Shelterbelts have long been part of emission controls for several dust sources. Shelterbelts, which can be vegetative barriers, reduce downwind concentrations by reducing wind speed, controlling heat and moisture transfer, and limiting pollutant diffusion (Wang et al., 2001). In addition, airborne PM and gaseous emissions are intercepted and trapped by shelterbelts within the pollutant vicinity (NRCS, 2006).

NRCS (2006) has published practice standards for vegetative barriers. Design of vegetative barriers is done using approved wind erosion models. Design parameters included in the models are the following (NRCS, 2006): (1) height of the barrier, which is height of the tallest trees/shrubs; (2) length of the vegetative barrier, which must be long enough to handle high wind direction variability; (3) windbreak density, which depends on effective area of the trees, must range from 50% to 65% to reduce air flow downwind; and (4) distance of the barrier from pollutant source, which also depends on the height of the vegetation. Windbreaks must also be set up such that in case of rains or snow melting, water will flow away from the livestock area. NRCS (2006) also recommended, as part of maintaining good conditions of the vegetative barriers, watering of trees during long, dry periods and replacement of trees as needed.

Shelterbelts/windbreaks are one of the current strategies applied in managing dust emission from poultry houses. According to Patterson and Adrizal (2005), a 3-row vegetative barrier reduced the total dust coming from poultry housing by 50%. Another study done in the U.K. (Tiwary et al., 2008) showed that vegetative barriers can have a collection efficiency of 34% for PM_{10} from ambient air. The effects of shelterbelts have also been evaluated using mathematical models, including computational fluid dynamics (Wang et al., 2001). Using vegetative barriers, Torita and Satou (2007) determined that reduction in wind speed depended on several characteristics of the vegetation used: width, total vegetation area (area of leaf, branch and stem), and tree's crown length just like what was mentioned in the NRCS Conservation Practice Standard (NRCS, 2006). Further studies must be done on the applicability and effectiveness of shelterbelts for feedlots. Their effects on cattle performance must also be considered. For example, Mader et al. (1997) showed that although windbreaks were helpful in minimizing cold stress on cattle during winter, the presence of windbreaks during summer led to lower cattle gains.

Feeding Practice / Feeding Schedule

Feeding practices can be controlled to reduce dust emission during the late afternoon-early evening period when dust emissions are high due to excessive cattle activity. Scheduling the last feeding for the day in this period can reduce PM emissions since cattle will likely spend most of their time feeding rather than engaging on PM-generating activities. Mitloehner (2000) showed that scheduling the last feeding just before sunset decreased $PM_{2.5}$ emission by 37%. In the same study, Mitloehner (2000) did not observe any negative effect of feeding schedule change on cattle performance. He did recommend verifying effects on cattle performance with considerations to type and feed ratio, age and weight of cattle, and other feedlot management practices (e.g., stocking density). Also, this method will require additional cost on labor either for longer shift or additional manpower in order to feed the cattle in the evening (Mitloehner, 2000). More feeding trucks are also needed if it is desired to feed the cattle almost at the same time. If the number of feeding trucks is limited, the effect of changing the feeding time may no longer be significant especially for large cattle feedlots. Further studies must also be done on overall feedlot PM emissions during feeding time; while PM emissions from pen surface may be reduced, PM emissions from unpaved roads may significantly increase.

Surface Amendments

Surface amendments that are applied on pen surfaces may enhance the moisture-holding capacity of the soil-manure layer and reduce evaporative loss (Auvermann et al., 2006). Soil-manure layer with amendments is less exposed to solar radiation and wind, has lower heat and moisture transfer and thus, has reduced evaporation loss. The presence of amendments may also lower the effect of hoof's shearing action by serving as cushion. Evaluations have been made on several materials but testing was under laboratory settings (Rahman et al., 2008). Razote et al. (2005) reported that application of 726 g/m^2 wheat straw and sawdust led to PM_{10} emission reductions of 76% and 69%, respectively. Further, they noted that these values were comparable to reductions that were achieved through water application.

The feasibility of applying surface amendments requires further study. For this method to be consistently effective in reducing PM emission, the materials must be applied frequently on pen surfaces because manure is continually excreted by cattle (Auvermann et. al, 2006). Although the primary materials for surface amendments are cheaper than water, additional labor costs might be necessary if amendments were to be applied manually.

Table 2.2 Summary of PM control methods for beef cattle feedlots.[a]

Control Methods	Control Efficiency for Cattle Feedlots	Drawbacks /Cost			Impact on Cattle Performance
		Capital (System Installation)	Capital (Materials)	Labor	
Water Application: Solid-set Sprinkler System	TSP: 38% - 49% (Carroll et al., 1974) PM_{10}: 50% (Pechan, 2006) $PM_{2.5}$: 25% (Pechan, 2006)	X (Amosson et al., 2006)			O reduce cattle heat stress (Garner et al., 1989)
Water Application: Water Trucks	TSP: 38% - 49% (Carroll et al., 1974) PM_{10}: 50% (Pechan, 2006) $PM_{2.5}$: 25% (Pechan, 2006)		X Water trucks and Fuel (Amosson et al., 2007)	X (Amosson et al., 2007)	O reduce cattle heat stress (Garner et al., 1989)
Manure Harvesting / Pen Cleaning	TSP: - (no data available) PM_{10}: - (no data) $PM_{2.5}$: - (no data)		X Tractors and Fuel	X (Romanillos and Auvermann, 1999)	X may cause cattle stress (Romanillos and Auvermann, 1999)
Stocking Density Manipulation	TSP: - (no data) PM_{10}: 5% - 12% (Romanillos and Auvermann, 1999) $PM_{2.5}$: - (no data)	X Cross-fencing Set-up		X (Amosson et al., 2007)	X may affect cattle performance (Rahman et al., 2008)
Vegetative Barriers	TSP: - (no data) PM_{10}: - (no data) $PM_{2.5}$: - (no data)	X Trees			X may lower cattle gains depending on distance during summer (Mader et al., 1997)
Feeding Practice (Last feeding in the evening)	TSP: - (no data) PM_{10}: - (no data) $PM_{2.5}$: 37% (Mitloehner, 2000)		X Trucks and Fuel	X (Mitloehner, 2000)	? Mitloehner (2000) reported no negative impact /broader evaluation recommended
Surface Amendment Application	TSP: - (no data) PM_{10}: 76% and 69% for wheat straw and saw dust, laboratory testing only (Razote et al., 2005) $PM_{2.5}$: - (no data)		X Materials and Equipment (Auvermann et al., 2006)	X (Auvermann et al., 2006)	? evaluation needed

[a] The symbol 'O' means advantage, 'X' means disadvantage, and '?' indicates that the effect is largely unknown.

Dispersion Modeling

There are three possible approaches to develop PM emission factors (US EPA, 1988): (1) dividing the source of interest into components (e.g., pen surfaces, unpaved roads, and feedmills for a cattle feedlot) that have available PM emission factors; (2) formulation of a new factor from existing factors and size-specific multipliers; and (3) derivation of factors from field measurements. Currently, the US EPA (2001b) has emission factors for TSP, PM_{10}, and $PM_{2.5}$ for both beef cattle feedlots and unpaved roads. The emission factor for TSP was derived based on the assumption that pen surface properties (i.e., particle size distribution) were similar to those of agricultural soils (US EPA, 1988). Then, the PM_{10} and $PM_{2.5}$ emission factors were computed by using the TSP emission factor and particle size multipliers (US EPA, 1988, 2001b). However, one of the most important features of the cattle feedlot pen surface, the presence of loose, dry manure layer, was not accounted for by these emission factors. Hence, these emission factors may not be good approximations of PM emissions from cattle feedlots.

Science-based PM emission factors should be provided for cattle feedlots for emission inventory and regulatory purposes. PM emission factors must be derived from field measurements on cattle feedlots. Small-scale emission flux measurements are not applicable due to the large areas of cattle feedlots (NRC, 2003). Techniques suggested by NRC (2003) for estimating emission factors for area sources like cattle feedlots are (1) micrometeorological techniques, (2) mass balance technique, (3) atmospheric tracers, and (4) dispersion modeling. This research is focused on estimating PM_{10} emission factors from cattle feedlots using dispersion modeling technique.

US EPA (2009a) described dispersion modeling as mathematical simulation of transport of emissions in the atmosphere relative to a pollutant source. Major variables that are accounted for in dispersion modeling are the following: (1) mathematical equations and algorithms, (2) meteorological conditions, (3) emission data for specific pollutants for the source, and (4) source dimensions/description. Most of the available dispersion models are based on the Gaussian formulation (i.e., normal distribution) since this distribution is considered a good mathematical approximation of the true behavior of pollutant dispersion in the atmosphere (Turner and Schulze, 2007). Turner and Schulze

(2007) listed the following assumptions for the Gaussian-based dispersion modeling: (1) the distribution concentration of pollutants follows the Gaussian distribution horizontally and vertically through the pollutant plume; (2) conservation of the mass of the pollutant; (3) steady-state emissions described by constant and continuous pollutant emission; and (4) steady-state meteorological conditions (i.e., weather conditions are the same along the path of the pollutant). The concentrations resulting from modeling are affected by several factors, including pollutant emission rate (mass per time), pollutant source dimensions, wind speed and direction, and dispersion parameters. These dispersion parameters, which are dependent on atmospheric stability and surface characteristics, describe how the pollutant spreads horizontally and vertically in the atmosphere.

Uses of Dispersion Modeling

Atmospheric dispersion models are often used to predict concentrations of air pollutants emitted either by a new or existing source. It can also be used to determine whether specific emission controls are necessary to control specific pollutants. Various models have been developed for simulating pollutant transport in the atmosphere and concentrations at varying locations from the source (Holmes and Morawska, 2006). US EPA (2009b) has recommended various models (Table 2.3), of which AERMOD (AMS/EPA Regulatory Model) is currently the preferred model (CFR, 2005).

Atmospheric dispersion models, combined with upwind-downwind measurement scheme, have also been used to determine emission rates from area sources. Currently, US EPA has emission factors for PM_{10} and $PM_{2.5}$ for cattle feedlots. These factors are used to estimate annual emissions as part of the US EPA inventory and documentation of emissions (US EPA, 2001b). The emission factor for PM_{10} is 17 tons/1000hd-year; this emission factor is multiplied by a factor of 0.15 to get the emission factor for $PM_{2.5}$ (2.55 tons/1000hd-year) (US EPA, 2001b). Note that the US EPA emission factors for cattle feedlots depend only on the number of head in feedlots; the effects of feedlot characteristics (e.g., stocking density), weather conditions, and PM control methods have not been considered. Using dispersion models, feedlot-specific emission rates can be estimated with the effects of the above variables included. Estimation can be done by means of inverse dispersion modeling technique, i.e., emission rates are back-calculated from measured PM concentrations and modeled PM concentrations.

AERMOD – US EPA Preferred Regulatory Model

Starting December 2005, AERMOD has been the preferred regulatory model for dispersion modeling in the U.S. (CFR, 2005). There were several considerations included in designing AERMOD that makes it as the superior model for simulating dispersion. Planetary boundary layer turbulence structure is fully characterized in AERMOD. Another feature of AERMOD is the non-Gaussian dispersion parameter it applies for the vertical concentration distribution because of the non-Gaussian nature of vertical velocity distributions for Convective Boundary Layer (CBL) conditions (US EPA, 2004a).

Several studies have compared the performance of AERMOD with that of ISCST3. Perry et al. (2005) evaluated the two models and concluded that AERMOD performed better than ISCST3 in modeling the concentration distribution for tall, buoyant stacks in both flat and complex terrains. The same study also noted that AERMOD performed close enough to other dispersion models specifically designed for special conditions. However, there are still some uncertainties about its performance and applicability. Similar to other models, AERMOD may not be able to accurately model the dispersion under calm or low wind conditions; and the interactions between plumes are also neglected (Holmes and Morawska, 2006).

AERMET Formulation

US EPA (2004a, b) summarizes the formulations in AERMOD and AERMET, which is the meteorological preprocessor for AERMOD. Meteorological conditions that are specified when running AERMOD makes it possible to approximate dispersion behavior taking into account the effects of surface boundary layer conditions, which can be unstable (convective) or stable (Turner and Schulze, 2007), and weather vertical profiles (US EPA, 2004a). The structure of the meteorological inputs for AERMOD is controlled by AERMET from processing several meteorological data, including upper air soundings data, surface hourly observation data, and on-site data (US EPA, 2004b). Upper air soundings data are meteorological parameters (i.e., pressure, temperature, humidity, wind speed and direction) measured at specific altitudes or pressure levels;

surface hourly data are the weather parameters observed from the earth's surface and parameters measured are similar to upper air soundings data with the addition of precipitation and sky cover (US EPA, 2004a). These two data sets are normally prepared by the National Weather Service (NWS) of National Oceanic and Atmospheric Administration (NOAA). The third data set, if available, is measured from any weather instrumentation at the site being modeled. This data set, referred to in this study as on-site data, can be set up such that parameters monitored are similar to the surface hourly observations.

The atmospheric/planetary boundary layer can either be unstable and stable. It is important to consider the boundary layer condition since it defines the mixing height in which vertical mixing or dispersion of any pollutant can take place; no mixing can occur beyond this height (Turner and Schulze, 2007). For unstable conditions, there is a temperature gradient between the surface (with the higher temperature) and atmosphere as described by Turner and Schulze (2007). This initiates the vertical movements of air parcels only up to a certain height that is also dependent on the temperature gradient (Turner and Schulze, 2007; US EPA, 2004a). Unstable/convective conditions occur when there is temperature difference caused by solar radiation and AERMET computes for convective mixing height values for the 1000 to 1600 h period. During times when there is not much temperature gradient between the surface and atmosphere, the surface boundary layer is stable and has significantly less vertical mixing, typically from 1700 to 0900 h. Mixing heights considered during these times are referred to as mechanical mixing heights. AERMET computes for mechanical mixing height of the boundary layer hourly. For unstable conditions when both convective and mechanical mixing heights have values, AERMET uses the maximum value for characterization of the boundary; for stable conditions, the boundary layer mixing height is equal to the mechanical mixing height.

In computing variables to characterize the boundary layer, properties of the surface are involved in several formulations used in establishing AERMET (US EPA, 2004a, b). Normally called site characteristics, these properties are used to calculate heat fluxes that affect how dispersion takes place in both stable and unstable boundary layer conditions: heat flux is positive (heat being transferred from surface to atmosphere) during unstable conditions and negative (heat transfer from atmosphere to surface) for stable conditions (Turner and Schulze, 2007). These properties are albedo, measure for surface reflectivity (US EPA, 2004a); bowen ratio, ratio of sensible heat to latent heat (Turner and Schulze, 2007) and measure of moisture availability on the surface (US EPA, 2004a); and surface roughness, measure of irregularities on the source landscape (Turner and Schulze, 2007). These three characteristics are all used for the characterization of the structure of the boundary layer during unstable conditions; however, it is only the surface roughness (among the site characteristics) that is involved in the formulation applicable for stable conditions, because both albedo and bowen ratio are properties describing how the surface reacts in presence of solar radiation.

The variables calculated by AERMET are sensible heat flux, surface friction velocity, convective scale, vertical potential temperature gradient, convective and mechanical mixing heights, and Monin-Obukhov length (US EPA, 2004b). These surface layer variables are then used for the vertical profiling of the following variables: wind direction and wind speed; temperature and vertical potential temperature gradient; and vertical and lateral turbulence profiles (US EPA, 2004a). This vertical profiling of several weather parameters is a feature of AERMOD that makes it more effective than ISCST3 (Turner and Schulze, 2007). Also, the parameters given as measures for the turbulence profiles are important in approximating the vertical and lateral dispersions of an air pollutant in the atmosphere.

AERMOD Formulation

Like most atmospheric dispersion models, AERMOD is based on the Gaussian distribution (Holmes and Morawska, 2006). With AERMET, AERMOD is capable of simulating dispersion based on the planetary boundary layer structure. This feature of AERMOD is made possible by having the weather parameters profiled vertically and by approximating vertical and lateral turbulences (US EPA, 2004a, b). For stable conditions, the Gaussian distribution applies to both vertical and lateral distribution of concentration after dispersion just like other dispersion models (US EPA, 2004a). During unstable conditions, the Gaussian distribution still applies for lateral/horizontal distribution of concentration; however, a bi-Gaussian distribution is now used to approximate the vertical concentration distribution after dispersion (US EPA, 2004a). This bi-Gaussian concept, which is a more accurate approximation of actual vertical dispersion, is another feature of AERMOD that makes it different from other models (Turner and Schulze, 2007).

The general equation for the dispersion of an air pollutant for both convective and stable conditions is generalized by US EPA (2004a) as follows:

$$C_T\{x_r, y_r, z_r\} = fC_{c,s}\{x_r, y_r, z_r\} + (1 - f)C_{c.s}\{x_r, y_r, z_p\} \qquad (2.9)$$

where $C_T\{x_r,y_r,z_r\}$ is the total concentration at a specified location from the source, $C_{c,s}\{x_r,y_r,z_r\}$ is the contribution from the horizontal plume state applicable for both convective (unstable) and stable conditions, $C_{c,s}\{x_r,y_r,z_p\}$ is the contribution from terrain-following plume state for both convective and stable conditions, and f is the plume state weighting function.

As explained by US EPA (2004a), a plume, with its flow stable, can have two layers with respect to a critical height. This critical height, termed as dividing streamline height, is the lowest height in the atmosphere in which the plume can maintain a kinetic energy that will enable it to rise whenever it encounters an obstruction such as elevated terrain (US EPA, 2004a). This critical height also depends on the relative height of the plume centerline to the obstruction. The lower layer of the plume tends to flow and stay in horizontal direction even if there is an obstruction (i.e., elevated terrain, buildings) on its path; this is referred to as the horizontal state (US EPA, 2004a). In this state, the plume can either hit the obstruction or just flow around it. For the case of the terrain-following plume state, the upper layer of the plume tends to rise over the obstruction thus avoiding hitting it. The terrain-following plume state has the greatest effect on total concentrations during convective (unstable) conditions (US EPA, 2004b) since there is significant vertical movements during these times due to convective and mechanical mixing. For stable conditions, the resulting total concentration greatly depends on the horizontal plume state because there is less vertical movement (mechanical mixing only). The f function in equation 2.9 depends on wind speed, atmospheric stability, and plume height relative to the obstruction (US EPA, 2004a).

The equation for concentration distributions was further simplified by US EPA (2004a):

$$C\{x,y,z\} = (Q/U)P_y\{y;x\}\,P_z\{z;x\} \tag{2.10}$$

where Q is the pollutant emission rate, U is the effective wind speed, and $P_y\{y;x\}$ and $P_z\{z;x\}$ are the probability density functions (pdfs).

The pdfs are used to simplify the concentration distribution equations. They describe and approximate how an emission will be distributed in the atmosphere, vertically and laterally, based on the condition of the boundary layer (convective or stable). During unstable conditions, they are a function of the convective velocity scale, and vertical and lateral turbulence coefficients; during stable conditions, on the other hand, they are a function of the mechanical mixing height, vertical dispersion coefficient, and plume height (US EPA, 2004a). From equation 2.10, besides the pdfs, the concentration distribution is a function of emission rate and effective wind speed. The resulting concentration at any given location depends on the emission rate: the higher the emission rate, the higher is the concentration. The concentration is inversely related to the effective wind speed; higher wind speeds would mean faster dispersion rates and consequently, the pollutant concentration will be less.

Other features of AERMOD not discussed here that make it much more effective in dispersion modeling include plume buoyancy, plume penetration into elevated inversions, building downwash, deposition and depletion, and modeling of receptors located from the surface up to above plume height (Turner and Schulze, 2007). Overall, comparing the two latest dispersion regulatory models, Turner and Schulze (2007) noted that AERMOD is more powerful and advanced than ISCST3 because of the following features in AERMOD: (1) boundary layer characterization, (2) improved weather vertical profiling, (3) inclusion of the effects of site characteristics on dispersion, (4) application of the bi-Gaussian concept on vertical dispersion during unstable conditions, and (5) application of the two-layer flow (dividing streamline principle) for plumes.

Table 2.3 EPA Recommended dispersion models (CFR 2005; US EPA 2009b).

Dispersion Model	Description	Sources	Transport Distance	Terrain
AERMOD	- AMS/EPA Regulatory Model - designed for short range pollutant dispersion - near field steady state Gaussian plume with dispersion based on boundary layer structure fully characterized using meteorological data (Holmes and Morawska, 2006) - model designed for dispersion of particles (Holmes and Morawska, 2006)	- Surface sources - Elevated sources - Point, line and area sources	< 50km	Flat terrain Complex terrain
ISC3/ISCST3	- Industrial Source Complex – Short Term Regulatory Model - utilizes meteorological data - single source steady state Gaussian plume model (Holmes and Morawska, 2006)	- Industrial source complexes - Point, line and area sources	< 50 km	Flat terrain Rolling terrain
CALPUFF	- California Puff Model - preferred model in simulating long range pollutant transport - non-steady Gaussian state puff dispersion model - uses space and time varying meteorology (Holmes, 2006)	- Point , line and area sources	> 50 km	Flat terrain Complex terrain
BLP	- Buoyant Line and Point Source Model - Gaussian plume dispersion model	- Aluminum reduction plants	< 30 km	Simple Terrain
CALINE3	- California Line Source Model - steady-state Gaussian dispersion model to assess impact of pollutants from transportation facilities - pollutant dispersion characterization based on mixing zone concept (CDT, 1989)	- Line sources (e.g., highways)	< 50 km	Simple Terrain
CTDMPLUS	- Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations - Gaussian model for point source	- Elevated point sources	< 50 km	Complex Terrain
OCD	- Offshore and Coastal Dispersion Model - straight line Gaussian model	- Over water sources / coastal regions		

Summary

The cattle feeding industry is projected to grow based on the trend of cattle beef supply and demand. With this projected growth, air quality issues, including particulate emissions, are expected to become more important because of public health and welfare concerns. Although emission factors for PM_{10} and $PM_{2.5}$ are available for cattle feedlots, these values are for modeling purposes and do not serve as standards for PM emission. More research data are needed to establish PM emission rates for cattle feedlots. In addition, abatement measures for controlling PM emissions need to be developed and evaluated.

References

ACFA. 2002. Other technologies and landscaping options. In *Beneficial Management Practices – Environmental Manual for Feedlot Producers in Alberta*. Alberta, CA: Alberta Cattle Feeders’ Association. Available at: www.agriculture.alberta.ca. Accessed 03 September 2009.

Amosson, S. H., B. Guerrero, and L. K. Almas. 2006. Economic analysis of solid-set sprinklers to control dust in feedlots. Presentation at Southern Agricultural Economics Association Annual Meetings, Orlando, Florida. February 5 – 8, 2006.

Amosson, S. H., F. Bretz, L. New, and L. K. Almas. 2007. Economic analysis of a traveling gun for feedyard dust suppression. Presentation at Southern Economics Association Meeting, Mobile, Alabama. February 3 – 6, 2007.

Auvermann, B., R. Bottcher, A. Heber, D. Meyer, C. B. Parnell, Jr., B. Shaw, and J. Worley. 2006. Particulate matter emissions from animal feeding operations. In *Animal Agriculture and the Environment: National Center for Manure and Animal Waste Management White Papers*, 435-468. J. M. Rice, D. F. Caldwell, F. J. Humenik, eds. St. Joseph, Mich.: ASABE.

California Air Resources Board (CARB). 2009. Air pollution – particulate matter brochure: What is particulate matter (PM_{10})? Sacramento, CA: California Air Resources Board. Available at www.arb.ca.gov. Accessed 21 September 2009.

California Department of Transportation (CDT). 1989. CALINE4 – A dispersion model for predicting air pollution concentrations near roadways. Sacramento, CA: State of California Department of Transportation. Available at: www.ess.co.at. Accessed 01 October 2009.

Carroll, J. J., J. R. Dunbar, R. L. Givens, and W. B. Goddard. 1974. Sprinkling for dust suppression in a cattle feedlot. *California Agriculture* 28(3): 12 -14.

Clean Air Act (CAA). 2004. Clean Air Act. 42 U.S. C. 7401 et Seq. Washington, D.C.

CFR. 1986. Code of Federal Regulations, 40CFR, Part 51: Requirements for preparation, adoption and submittal of implementation plans. Available at www.gpoaccess.gov. Accessed 18 November 2009.

CFR. 2005. Code of Federal Regulations, 40CFR, Part 51: Revision to the guideline of air quality models: Adoption of a preferred general purpose (flat and complex terrain) dispersion model and other revisions.

CFR. 2008a. Code of Federal Regulations, 40CFR, Part 60: Standards for performance for new stationary sources. Available at www.gpoaccess.gov. Accessed 21 September 2009.

CFR. 2008b. Code of Federal Regulations, 40CFR, Parts 302 and 355: CERCLA/EPCRA Administrative reporting exemption for air releases of hazardous substances from animal waste at farms. Available at www.epa.gov. Accessed 19 November 2009.

Consumers Union. 2000. Animal factories: Pollution and health threats to rural Texas. Austin, TX: Consumers Union Southwest Regional Office. Available at www.consumersunion.org. Accessed 29 September 2009.

Cooper, C. D., and F. C. Alley. 2002. *Air Pollution Control – A Design Approach*. 3rd ed. Long Grove, IL: Waveland Press, Inc.

Garner, J. C., R. A. Bucklin, W. E. Kunkle, and R. A. Nordstedt. 1989. Sprinkled water and fans to reduce heat stress of beef cattle. *Applied Engineering in Agriculture* 5(1): 99 – 101.

Hamm, L. B. 2005. Engineering analysis of fugitive particulate matter emissions from cattle feedyards. MS thesis. College Station, TX: Texas A&M University, Department of Biological and Agricultural Engineering.

Hargrove, W. L. 2004. Improved quality of land, air, and water. Long term intended outcome. Manhattan, KS: K-State Research and Extension, Kansas State University. Available at www.ksre.ksu.edu. Accessed 22 September 2009.

Harner, J., R. G. Maghirang, and E. Razote. Water requirements for controlling dust from open feedlots. In: Mitigating Air Emissions from Animal Feeding Operations Conference. Presentation at National Conference on Mitigating Air Emissions from Animal Feeding Operations. Ames, IA: Iowa State University.

Hayden, J., and J. Richards. 2004. TEOM-based measurement of industrial unpaved roads PM_{10}, $PM_{2.5}$ and $PM_{10-2.5}$ emission factors. Alexandria, VA: National Stone, Sand & Gravel Association.

Holmes, N.S., and L. Morawska. 2006. A review of dispersion modeling and its application to the dispersion of particles: An overview of different dispersion models available. *Atmospheric Environment* 40: 5902-5928.

Kansas Department of Health and Environment (KDHE). 2009a. Kansas air quality regulations. Topeka, KS: Kansas Department of Health and Environment.

Kansas Department of Health and Environment (KDHE). 2009b. Permit application form – Livestock waste management program. Topeka, KS: Kansas Department of Health and Environment.

Mader, T. L., J. M. Dahlquist, and J. B. Gaughan. 1997. Wind protection effects and airflow patterns in outside feedlots. *Journal of Animal Science* 75: 26 – 36.

McCarthy, J. E. 2005. Clean Air Act: A summary of the act and its major requirements. CRS Report for Congress. Order Code RL30853. Washington, D.C.: Congressional Research Service, The Library of Congress. Available at http://fpc.state.gov. Accessed 21 September 2009.

Midwest Plan Service (MWPS). 2002a. Outdoor air quality – MWPS-18 Manure Management System Series 18. Section 18. Ames, IA: Midwest Plan Service.

Midwest Plan Service (MWPS). 2002b. Livestock and poultry environmental stewardship (LPES) curriculum: A national education progam. Module E Outdoor Air Quality. Lesson 42 Controlling dust and odor from open lot livestock facilities. Ames, IA: Midwest Plan Service.

Miller, D. N., and B. L. Woodbury. 2003. Simple protocols to determine dust potentials from cattle feedlot soil and surface samples. *Journal of Environmental Quality* 32: 1634-1640.

Mitloehner, F. M. 2000. Behavioral and environmental management of feedlot cattle. PhD dissertation. Lubbock, TX: Texas Tech Universit.

Mitloehner, F. M., and M. S. Calvo. 2008. Worker health and safety in concentrated animal feeding operations. *Journal of Agricultural Safety and Health* 14(2): 163-187.

National Research Council (NRC). 2003. Air emissions from animal feeding operations: Current knowledge, future needs. Washington, D.C.: National Academy of Sciences.

Natural Resources Conservation Service (NRCS). 2003. Conservation practice standard Code 442 – Irrigation system, sprinkler. Available at http://www.nrcs.usda.gov. Accessed 26 November 2009.

Natural Resources Conservation Service (NRCS). 2006. Conservation practice standard Code 380 – Windbreak/shelterbelt establishment. Available at http://www.nrcs.usda.gov. Accessed 26 November 2009.

Natural Resources Conservation Service (NRCS). 2008. Conservation practice standard Code 634 – Waste transfer. Available at http://www.nrcs.usda.gov. Accessed 26 November 2009.

Patterson, P. H., and Adrizal. 2005. Management strategies to reduce air emissions: Emphasis – dust and ammonia. *Journal of Applied Poultry Research* 14: 638-650.

Pechan, 2006. AirControlNET Version 4.1: Documentation report prepared for U.S Environmental Protection Agency. Pechan Report No. 06.05.003/9011.002. Springfield, VA: E. H. Pechan & Associates, Inc.

Perry, S.G., A. J. Cimorelli, A. J., R. J. Paine, R. W. Brode, J.C Weil, A. Venkatram, R. B. Wilson, R.F. Lee, and W.D. Peters. 2005. AERMOD: A dispersion model for industrial source applications. Part II: Model performance against 17 field study databases. *Journal of Applied Meteorology* 44: 694-708.

Rahman, S., S. Mukhtar, and R. Wiederholt. 2008. Managing Odor Nuisance and Dust from Cattle Feedlots. NM-1391. Fargo, ND: North Dakota State University Extension Service.

Razote, E. B., R. G. Maghirang, J. P. Murphy, B. W. Auvermann, J. P. Harner III, T. V. Pesky, and W. L. Hargrove. 2005. Laboratory evaluation of abatement measures for mitigating dust emission from cattle feedlots. ASABE Paper No. 054008. St. Joseph, Mich.: ASABE

Razote, E. B., R. G. Maghirang, J. P. Murphy, B. W. Auvermann, J. P. Harner, III, D. L. Oard, D. B. Parker, W. L. Hargrove, and J. M. Sweeten. 2007. Air quality measurements from a water-sprinkled beef cattle feedlot in Kansas. ASABE Paper No. 074108. St. Joseph, Mich.: ASABE

Romanillos, A., and B.W. Auvermann. 1999. Effect of stocking density on fugitive PM_{10} emissions from a cattle feedyard. ASABE Section Meeting Paper No. 99-4192. St. Joseph, Mich.: ASABE

Sweeten, J. M., C. B. Parnell, R. S. Etheredge, and D. Osborne. 1988. Dust emissions in cattle feedlots. *Stress and Disease in Cattle, Veterinary Clinics of North America, Food Anim. Prac.* 4(3): 557-578.

Taylor, J. M. 2004. Kansas Supreme Court rejects county farm pollution laws. Chicago, IL: The Heartland Institute. Available at www.heartland.org. Accessed 29 September 2009.

Tiwary, A., A. Reff, and J. J. Colls. 2008. Collection of ambient particulate matter by porous vegetation barriers: Sampling and characterization methods. *Journal of Aerosol Science* 39: 40 – 47.

Torita, H., and H. Satou. 2007. Relationship between shelterbelt structure and mean wind reduction. *Agricultural and Forest Meteorology* 145: 186 – 194.

Turner, D. B., and R. H. Schulze. 2007. *Practical Guide to Atmospheric Dispersion Model*. Dallas, TX: Trinity Consultants, Inc. and Air & Waste Management Association.

U.S. Department of Agriculture (USDA). 2009a. 2007 Census of Agriculture. United States Summary and State Data, Vol. 1, Geographic Area Series, Part 51.

Washington, D.C.: U.S. Department of Agriculture, National Agricultural Statistics Service.

U.S. Department of Agriculture (USDA). 2009b. Agricultural Statistics 2008. Washington, D.C.: U.S. Department of Agriculture, National Agricultural Statistics Service.

U.S. Environmental Protection Agency (US EPA). 1988. *Gap filling* PM_{10} *emission factors for selected open area dust sources*. EPA-450/4-88-003. Research Triangle Park, NC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (US EPA). 2001a. *Emissions from Animal Feeding Operations: Draft*. EPA Contract No. 68-D6-0011. Research Triangle Park, NC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (US EPA). 2001b. *Procedures Document for National Emission Inventory, Criteria Air Pollutants 1985 - 1999*. EPA-454/R-01-006. Research Triangle Park, NC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (US EPA). 2004a. *AERMOD: Description of Model Formulation*. EPA-454/R-03-004. Research Triangle Park, NC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (US EPA). 2004b. *User's Guide for the AERMOD Meteorological Preprocessor (AERMET)*. EPA-454/B-03-002. Research Triangle Park, NC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (US EPA). 2008a. Regulatory definitions of large CAFOs, medium CAFOs, and small CAFOs. Research Triangle Park, NC: U.S. Environmental Protection Agency. Available at www.epa.gov. Accessed 11 September 2009.

U.S. Environmental Protection Agency (US EPA). 2008b. Large CAFO estimates for EPA Region 7. Research Triangle Park, NC: U.S. Environmental Protection Agency. Available at www.epa.gov. Accessed 11 September 2009.

U.S. Environmental Protection Agency (US EPA). 2008c. *Integrated Review Plan for the National Ambient Air Quality Standards for Particulate Matter*. EPA-452/R-08-004. Research Triangle Park, NC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (US EPA). 2009a. *Dispersion modeling*. Research Triangle Park, NC: U.S. Environmental Protection Agency. Available at www.epa.gov. Accessed 29 September 2009.

U.S. Environmental Protection Agency (US EPA). 2009b. *Preferred / recommended models*. Research Triangle Park, NC: U.S. Environmental Protection Agency. Available at www.epa.gov. Accessed 29 September 2009

Wang, H., E. S. Takle. and J. Shen. 2001. Shelterbelts and windbreaks: Mathematical modeling and computer simulations of turbulent flows. *Annual Review of Fluid Mechanics* 33: 549 – 586.

Wanjura, J. D., C. B. Parnell, B. W. Shaw. and R. E. Lacey. 2004. A protocol for determining a fugitive dust emission factor from a ground level area source. ASAE/CSAE Paper No. 044018. St. Joseph, Mich.: ASAE.

Watson, J. G., J. C. Chow, J. A. Gillies, H. Moosmuller, C. F. Rogers, D. DuBois. and J. Derby. 1996. Effectiveness demonstration of fugitive dust control methods for public unpaved roads and unpaved shoulders on paved roads. Sacramento, CA: California Air Resources Board.

CHAPTER 3 - Effectiveness of Sprinkler System and Rainfall Events in Reducing PM_{10} Concentrations at Beef Cattle Feedlots in Kansas

Introduction

Open beef cattle feedlots emit various air pollutants, including PM_{10} (i.e., particulate matter or PM with equivalent aerodynamic diameter of 10 µm or less) and $PM_{2.5}$ (i.e., PM with equivalent aerodynamic diameter of 2.5 µm or less). Mitloehner and Calvo (2008) noted that PM_{10} can have adverse health effects because PM of this size can enter the respiratory system.

The primary source of PM in open cattle feedlots is the pen surface, which is composed mainly of manure and soil. Other sources include unpaved roads and feed mills. Several factors can influence the emission of PM from pen surfaces. Cattle activity often triggers PM emission from pen surfaces; cattle hoof action on the dry, loose layer of soil and manure on pen surfaces can generate considerable amounts of PM. The more active the cattle are, the higher the PM emission will be. The emission rate and downwind concentration of PM_{10} vary during the day with concentrations typically higher during the evening, possibly because of increased cattle activity and relatively stable atmospheric conditions during this period. The moisture content of pen surfaces also influences PM emission. If the moisture content of the pen surface is high, the PM emission potential is small. The moisture content of the pen surface depends on the rate of evaporation of moisture from the pen surface and amount of water applied to the surface. Evaporation extracts the moisture, resulting in a dry, loose pen surface that is prone to PM emission. The rate of evaporation greatly depends on weather conditions, such as the temperature and humidity of the surroundings. Water addition from cattle urine, rain, or any water-application system increases the moisture content of the pen surface.

Several studies have measured PM concentrations in the vicinity of cattle feedlots. Sweeten et al. (1988) measured PM concentrations for 24-h sampling periods at three feedlots in Texas. They reported that the mean total suspended particulate or TSP concentration was 412 $\mu g/m^3$ and mean PM_{10} downwind concentrations were 40% of the mean TSP concentrations. Razote et al. (2007) reported a mean net PM_{10} concentration at a cattle feedlot in Kansas of 115 $\mu g/m^3$ (range from 35 to 195 $\mu g/m^3$).

Several methods can be used to control PM_{10} emissions from cattle feedlots: (1) watering pen surfaces to increase moisture content, (2) increasing stocking density, and (3) frequent manure harvesting to remove the dry, loose manure from the pen surface. Watering pen surfaces (i.e., sprinkler system) is an effective way to control PM emission from cattle feedlots (Auvermann et al., 2006); however, limited research has quantified the effectiveness of sprinkler system in controlling PM emission. In a report prepared for the US EPA, Pechan (2006) reported that watering of beef cattle feedlots, either by sprinkler systems or water trucks, had a PM_{10} control efficiency of 50%; however, the original source of the information was not presented. A study by Carroll et al. (1974) comparing a sprinkled feedlot and a non-sprinkled feedlot reported control efficiencies of 38% and 49% for TSP. The said study, however, was able to obtain only two data points. In addition, as mentioned by Carroll et al. (1974), even if the two feedlots were similar in area/size and practices, they differed in many other parameters, including feedlot activities, pen surface conditions, and cattle size/behavior, making comparison between the two feedlots difficult. Research done on a California feedlot reported that after turning off the water sprinkler system for two days, dust concentrations downwind of the pens increased by 850% (ACFA, 2002; MWPS, 2002). This was equivalent to approximately 88% reduction in concentration upon application of sprinkler. Note, however, that only one data point was reported and no others details (e.g., month and year, number of head, sprinkler setting) were reported. Using a laboratory-scale chamber, Razote et al. (2006) observed that addition of at least 3.2 mm of water on a simulated pen surface reduced PM_{10} emission potential by more than 80%.

This study was conducted to evaluate the control efficiency of a water sprinkler system for PM_{10} in a large feedlot. In addition, the control efficiency of the sprinkler system was compared with that of rainfall events.

Materials and Methods

Site Description

Two commercial cattle feedlots in Kansas were considered (Table 3.1). Prevailing wind directions at the feedlots are south-southeast during summer and north-northwest during winter. The first feedlot, KS1, had approximately 30,000 head of cattle with a total pen area (i.e., excluding unpaved roads, alleys, feed mill) of about 50 ha. The feedlot had a water sprinkler system that was normally operated from April through October and during prolonged dry periods. The sprinkler system had an operating capacity of 5.0 mm/day. The feedlot also practiced pen cleaning two to three times a year for each pen, and manure harvesting at least once a year. The second feedlot, KS2, had approximately 25,000 head of cattle and a total pen area of approximately 68 ha. In this feedlot, the main dust control method was pen cleaning at a frequency of five to six times a year for each pen; manure harvesting was done two to three times a year.

This research focused on measurement and analysis of the dataset from the April-to-October period when the sprinkler system at KS1 was typically used. Table 3.1 shows that KS2 (the non-sprinkled feedlot with more frequent pen cleaning) received about 15% more precipitation than KS1. For KS1, the total amount of water applied through the sprinkler system and the number of days the sprinkler system was operated varied from year to year depending on weather conditions. The total amount of water used by the sprinkler system in 2006, 2007, and 2008 were 450 mm, 319 mm, and 200 mm, respectively. The total number of days the sprinkler system was operated was 135 days in 2006, 102 days in 2007, and 60 days in 2008.

Table 3.1 Descriptions of the two feedlots.

	KS1	KS2
Capacity, head	30,000	25,000
Area, ha	50	68
Dust control methods	Water sprinkler system and pen cleaning (2-3 times/year)	Pen cleaning (5-6 times/year)
Weather conditions (April – October, 2006 - 2008)		
Prevailing wind direction	South-southeast	South-southeast
Total precipitation, mm	573	671

Water Sprinkler System Operation

The water sprinkler system at KS1 was operated from April to October and during prolonged dry periods. The sprinkler system had a total of 179 sprinkler heads; a group of three sprinkler heads were operated simultaneously every six minutes at a total water application rate of 1,890 L/min. If the sprinkler system were operated for 24 h, each pen would have been sprinkled four times a day, once every six hours; and the maximum amount of water would be 5mm/day. According to the feedlot manager, the water sprinkler was operated based on a number of factors, including air temperature and dusty conditions at the feedlot. Figure 3.1 shows that the monthly amount of water used for the sprinkler system followed the same trend as the mean air temperature; the higher the mean monthly air temperature, the higher was the amount of water used for the sprinkler system. Using the monthly values, regression analysis indicated that the amount of water used for the sprinkler system was linearly related ($P<0.05$) to the air temperature.

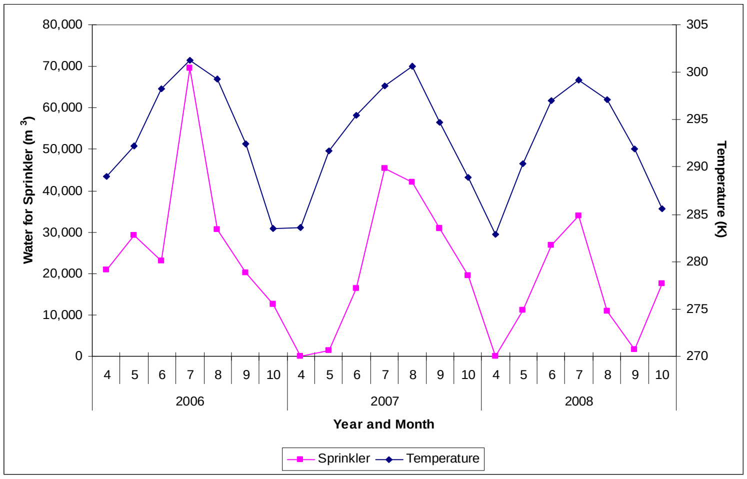
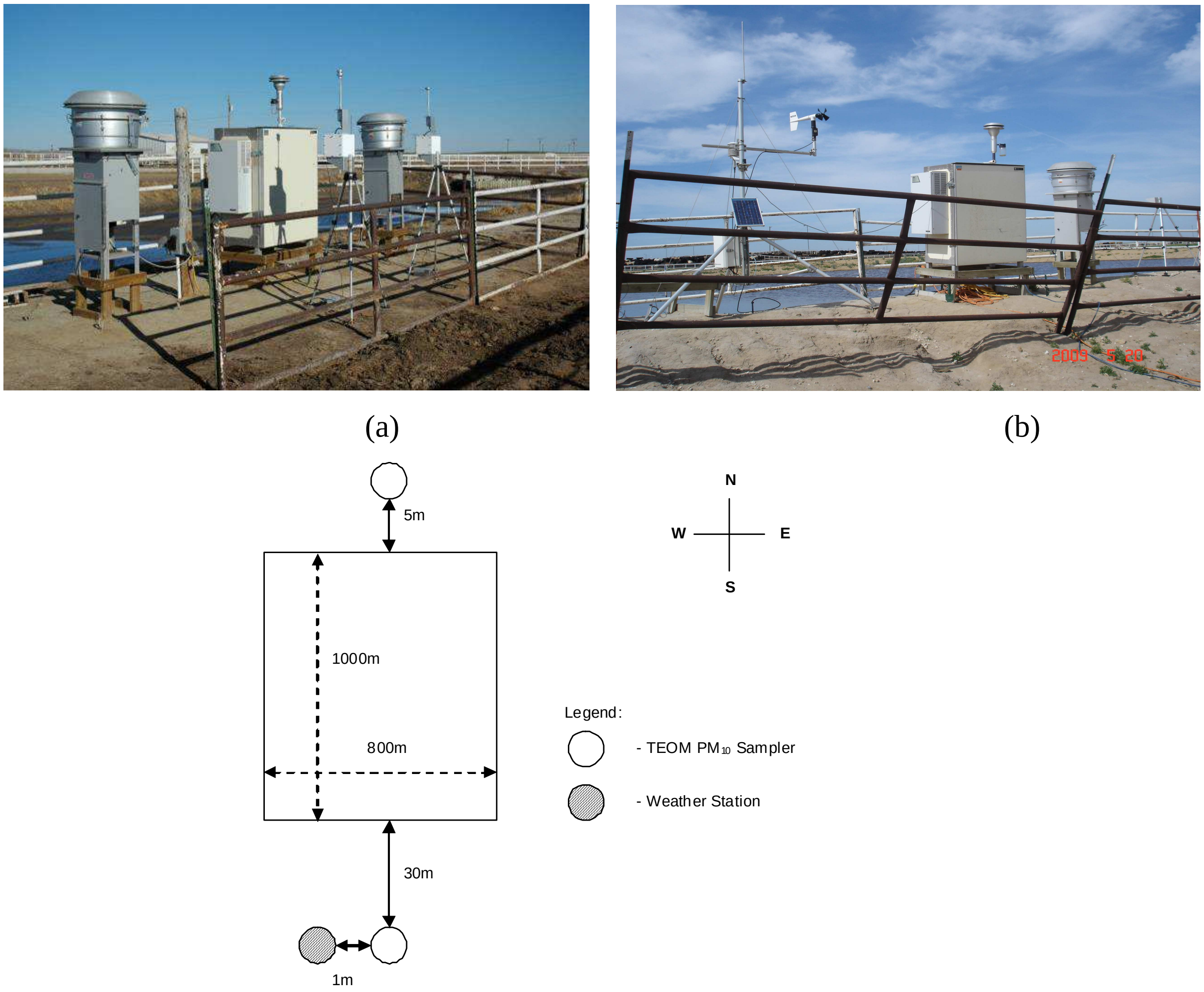


Figure 3.1 Sprinkler system water use and mean air temperature for the April-October period in 2006 to 2008 at KS1.

Measurement of PM_{10} Concentration and Weather Conditions

Mass concentrations of PM_{10} were measured at the north and south perimeters of the feedlots. For KS1, the north sampling site was approximately 5 m away from the closest pen, and the south site was approximately 30 m from the closest pen (fig. 3.2). For KS2, the north and south sampling locations were 40 m and 60 m away from the closest pens, respectively. These differences in the distances from the pens along with differences in amount of precipitation and management practices (e.g., pen cleaning frequency) between the two feedlots prevented meaningful comparison of PM_{10} mass concentration between the sprinkled feedlot (KS1) and non-sprinkled feedlot (KS2).

The PM_{10} concentration was measured with tapered element oscillating microbalance (TEOM) PM_{10} monitors (Series 1400a, Thermo Fisher Scientific, East Greenbush, NY; federal equivalent method designation No. EQPM-1090-079). PM_{10} concentrations were recorded continuously at 20-min intervals and then integrated to hourly averages. During sampling and measurement, the sampled air and TEOM filter were heated at 50°C. Maintenance of the TEOM equipment, which included leak checks and flow audit, was done monthly. For cases of low flow audit results, either the TEOM pump was replaced or software calibration was done to correct the sampling flow rate. The TEOM collection filters were replaced if the filter loading indicated by the TEOM reached the 90% value; TEOM in-line filters were replaced when the amount of dust collected was already significant.



(a) (b)

(c)

Figure 3.2 Measurement of PM_{10} and weather conditions at KS1: photographs of TEOM PM_{10} samplers at the (a) north sampling site and (b) south sampling site and (c) schematic diagram showing the locations of the samplers and the weather station.

Each feedlot was equipped with a weather station (Campbell Scientific, Inc., Logan, UT) to measure and record wind speed and direction (Model 05103-5), atmospheric pressure (Model CS100), precipitation (Model TE525), and air temperature and relative humidity (Model HMP45C). Similar to the PM_{10} concentrations, these parameters were also recorded continuously at 20-min intervals.

Data Analysis

The measurement periods considered were April 2006 to July 2009 for KS1 and January 2007 to December 2008 for KS2. For both feedlots, there were several months that either the TEOM data or the on-site weather station data were incomplete because of equipment-related problems. For KS1, TEOM data were missing in three months in 2006 (i.e., June, July, September) and for KS2, TEOM data were missing in two months in 2007 (i.e., August, October) because of equipment-related problems. For missing on-site weather data (i.e., rainfall amounts from January 2006 to July 2007 for KS1), data from a nearby regional airport were used.

The PM_{10} dataset from the TEOM were first pre-screened based on wind direction. Those that corresponded to wind direction of 120° to 240° (i.e., the north sampling site was downwind of the feedlot and the south sampling site was upwind) were considered. Data outside this range were excluded in the analysis for the following reasons: (1) if the wind direction was from either the east (i.e., 60° to 120°) or west (i.e., 240° to 300°), the PM measured by the TEOMs would not represent the PM emitted from pen surfaces; and (2) if the wind direction was from the north (i.e., 0° to 60° or 300° to 360°), the south sampling site would be downwind of the feedlot and with differences in distance from the closest pens between the north and south sampling sites, it would be difficult to compare the downwind concentrations.

The PM_{10} concentrations were analyzed as net concentrations (i.e., downwind concentration – upwind concentration). Net PM_{10} concentrations were calculated at 20-min intervals, which was the interval of data collection in the TEOMs. In approximately 11% of the 20-min TEOM readings for KS1 and 7% for KS2, upwind concentrations were missing either because of instrument malfunction or negative PM_{10} readings. In these cases, the upwind concentrations were considered zero and the net PM_{10} concentrations were equivalent to the downwind PM_{10} concentrations to maximize use of available downwind data.

From the pre-screened dataset, data values were selected for evaluation of the control efficiency of the water sprinkler system at KS1 and rainfall events at KS1 and KS2. Carroll et al. (1974) compared two different feedlots, sprinkled and non-sprinkled, to estimate the control efficiency of the water sprinkler system in reducing dust concentration. Because of differences between the two feedlots (e.g., KS1 had smaller area and higher stocking density, less pen cleaning, less rain events compared with KS2), this study followed a different approach. The control efficiency of the water sprinkler system at KS1 was determined by selecting sprinkler on/off events, i.e., when the water sprinkler system was operated for at least one day (on) and either followed or preceded by at least one day of no water sprinkling (off). The PM_{10} control efficiency was determined by comparing the period when the sprinkler system was operated with the period when the sprinkler was not operated. The number of days for each period varied from one day to four days, depending on the availability of TEOM concentration and weather data. In addition, sprinkler events should not have any rainfall event five (5) days before or after the day selected because the effect of a rainfall event may last for several days (fig. 3.3).

To illustrate, consider the period September 26, 2008 to October 4, 2008. During this period, the sprinkler system was operated starting September 30, 2008. The average net PM_{10} concentration for time periods when the sprinkler was off, calculated using concentrations measured on September 26 and 28, 2008 (no data for September 27, 29 and 30), was 517 $\mu g/m^3$. The average net PM_{10} concentration for the period when the sprinkler was on (October 2 to 4, 2008) was 316 $\mu g/m^3$. The control efficiency for this example was 45% (i.e., (517 – 316)/517*100). The decrease in concentration was the difference between the two concentrations or 255 $\mu g/m^3$.

The approach for rainfall events was similar except that the event with rainfall for at least one day must be preceded by at least one day of no rainfall. The day after the rainfall event was not used in estimating the percentage reduction in PM_{10} concentration because the effect of rainfall may last for several days. To illustrate, consider the case shown in figure 3.3. The control efficiency for the rainfall event may be calculated in two ways. The first is based on the reduction in net PM_{10} concentration from May 15 to May 16, with May 15 representing the period without rainfall and May 16 the period with rainfall. The resulting control efficiency is 83% (i.e., (380-64)/(380)*100). The second is based on the increase in net PM_{10} concentration after the rainfall event (May 16 to May 17), that is, a lower control efficiency=(177-64)/177*100=64%. Because the effect of a rainfall event can last for several days, the first approach was used in this study.

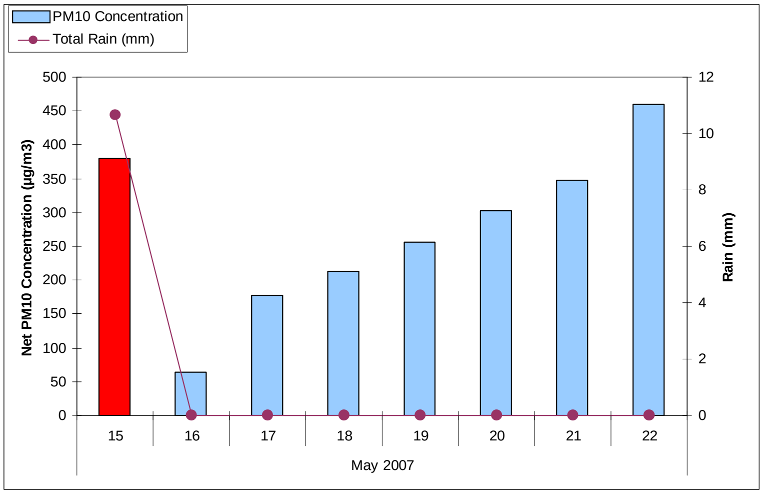


Figure 3.3 Effect of a rainfall event on net PM_{10} concentration.

For 2006 to 2008 (April to October), KS1 had a total of 133 days with rainfall events out of 572 days included in the measurement period. For KS2, out of 367 days in 2007 to 2008 included in the measurement period, 95 days had rainfall events. The sprinkler system at KS1 was operated for 297 out of 642 days in the measurement period. Table 3.2 summarizes the number of data points for each event. The measurement period for evaluating the sprinkler system at KS1 was extended to July 2009 to increase the number of data values. For the water sprinkler system at KS1, there were 42 sprinkler on/off events from April 2006 to July 2009. Of these events, only 14 were used in the analysis. Of the events that were not used, almost half had no TEOM concentration data and the other half were affected by rainfall events. For rainfall events at KS1, 90% (30 out of 33) of the data values were considered acceptable for the study. For KS2, 89% (16 out of 18) of the available data values were acceptable. Note that the number of rainfall events was greater at KS1 than at KS2 because of the longer data period.

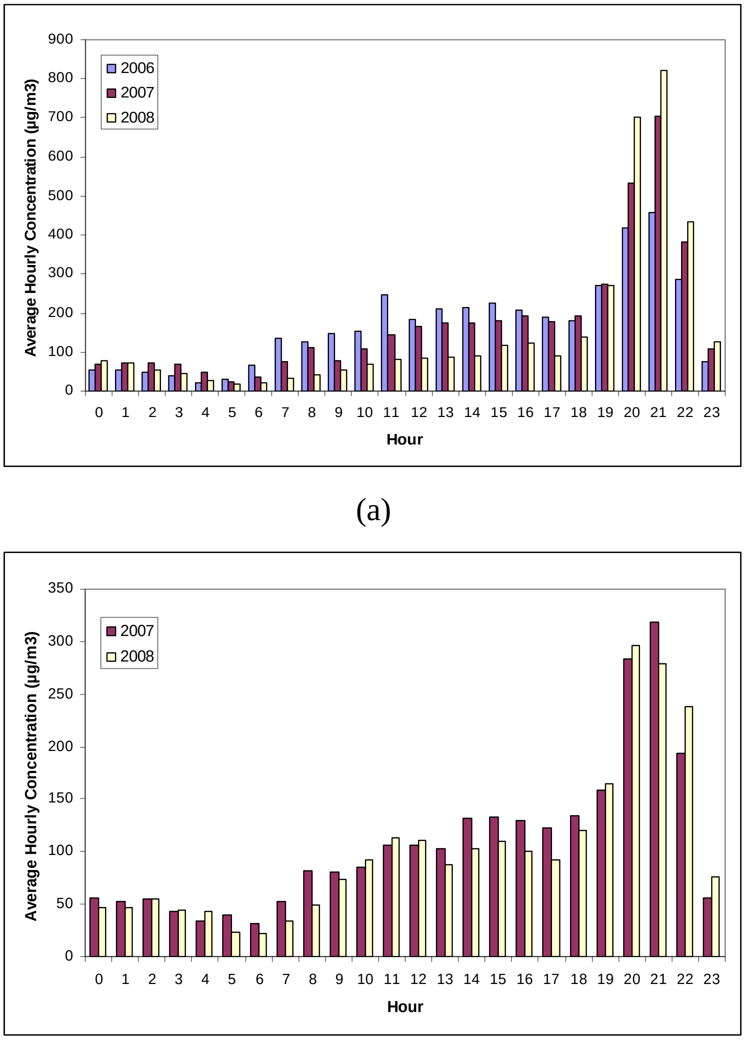
Table 3.2 Measurement period and number of data values for each event.

	Measurement period	Number of days	Number of events	
			Total	Acceptable for the study
Sprinkler system – KS1	April 2006 – July 2009	243	42	14
Rain – KS1	April 2006 – August 2008	160	33	30
Rain – KS2	January 2007 – August 2008	61	18	16

The PM_{10} values were expressed as net concentration, which is the difference between downwind and upwind concentrations. The control efficiency of the sprinkler system in reducing net PM_{10} concentration was estimated in two ways: (1) by computing the decrease in net PM_{10} concentration after the water sprinkler system was turned on, and (2) by computing the increase in net PM_{10} concentration after the sprinkler system was turned off. The control efficiency of a rainfall event was estimated by computing the decrease in net PM_{10} concentration after the rainfall event. Control efficiencies were computed based on 24-hr periods and evening dust peak (EDP) periods (1700 h - 2300 h). In this study, the EDP period of 1700 h to 2300 h was established based on the measured net PM_{10} concentrations as described below.

Figure 3.4 shows the mean net PM_{10} concentrations for KS1 (2006 to 2008) and KS2 (y2007 to 2008). For KS1, the top two highest net PM_{10} concentrations in the day were observed at 2000 h and 2100 h, with the peak occurring at 2100 h. The net PM_{10} concentration started to increase at time 1800 h to 1900 h in 2006 and 2007, and 1700 h and 1800 h in 2008. After the peak, the net PM_{10} concentration started to decline at 2200 h. For KS2, the concentration started to increase at 1800 h, peaking at 2100 h in 2007 and at 2000 h in 2008. As in KS1, concentration started to decrease at 2200 h and ending at 2300 h. Based on these observations, the EDP period in this study was defined as the period from 1700 h to 2300 h to include the start of increase in concentration, the peak in concentration, and the end of decrease in concentration.

Data were analyzed with SAS for Windows version 9.1.3 (SAS, 2002) using the following methods: (1) backward selection to determine factors that influence control efficiency; (2) paired t-test to compare net PM_{10} concentrations between two periods, (e.g., 24-hour and EDP periods, and with sprinkler/rain and without sprinkler/rain periods); and (3) analysis of variance to compare the two feedlots in terms of control efficiency. In all cases, a 5% level of significance was used.



(a)

(b)

Figure 3.4 Hourly concentration trends (April to October): (a) KS1 and (b) KS2 feedlots.

Results and Discussion

Weather conditions and sprinkler system operation

For the measurement periods specified, wind direction was from the south (the north sampling site was downwind of the feedlot) most of the time for both feedlots. For

KS1, which had a 3-year measurement period, wind directions were south 52% of the time, north 30% of the time, east 9% of the time, and west 9% of the time. For KS2, which had a two-year measurement period, wind directions were south 49% of the time, north 28% of the time, east 12% of the time, and west 11% of the time.

The means and ranges of hourly values of temperature, relative humidity, and wind speed are summarized in Table 3.3. Feedlots KS1 and KS2 were similar in terms of temperature and relative humidity. KS1 had higher (26%) mean wind speed than KS2. For precipitation, KS1 had a yearly average of 546 mm for the months of April to October over the 3-year period, with mean monthly precipitation ranging from 2 to 35 mm. KS2 had an average precipitation of 671 mm for 2007 to 2008 (range of 10 mm to 35 mm mean monthly precipitation).

Table 3.3 Weather conditions for the April to October periods (KS1 – 2006 to 2008, KS2 – 2007 to 2008).[a]

	KS1	KS2
Temperature (°C)	20 (-7 – 41)	20 (-7 – 40)
Relative Humidity (%)	64 (10 – 100)	67 (10 – 100)
Wind Speed (mps)	4.71 (0.00 – 18.33)	3.74 (0.00 – 15.87)

[a] Values in parenthesis represent the range.

Measured PM_{10} concentrations and net PM_{10} concentrations are summarized in Table 3.4. Values of concentrations (downwind, upwind, and net) varied widely. The downwind hourly concentrations at KS1 ranged from negligible to 15,983 $\mu g/m^3$, with an overall mean hourly value of 266 $\mu g/m^3$. The upwind hourly concentration ranged from 0 to 2,144 $\mu g/m^3$, with a mean of 61 $\mu g/m^3$. The net hourly PM_{10} concentration ranged from negligible to 15,771 $\mu g/m^3$, with an overall mean of 206 $\mu g/m^3$. For KS2, the downwind hourly concentrations ranged from 3 to 2,949 $\mu g/m^3$, with an overall mean of 154 $\mu g/m^3$; the upwind hourly concentrations had a mean of 27 $\mu g/m^3$, with concentrations ranging from 0 to 468 $\mu g/m^3$; and the net hourly concentrations ranged from 0 to 2,887 $\mu g/m^3$ with a mean of 126 $\mu g/m^3$.

As mentioned in the earlier section, the operation of the water sprinkler system at KS1 was affected by air temperature and rainfall events. Figure 3.1 shows that the trend of the amount of water used for the sprinkler system followed closely the trend of the air temperature. Figure 3.5a shows the trends for sprinkler water use and total amount of rainfall. As expected, the amount of water used for the sprinkler system was high during periods with low rainfall amounts (e.g., July 2006, August and September 2007) and low during periods with high rainfall amount (e.g., May 2007). Figure 3.5b compares the amount of water used for the sprinkler system and number of days with rainfall. In general, the amount of water used for the sprinkler system increased with decreasing number of days with rainfall events. Yearly values of rainfall variables and sprinkler water use are summarized in Table 3.5.

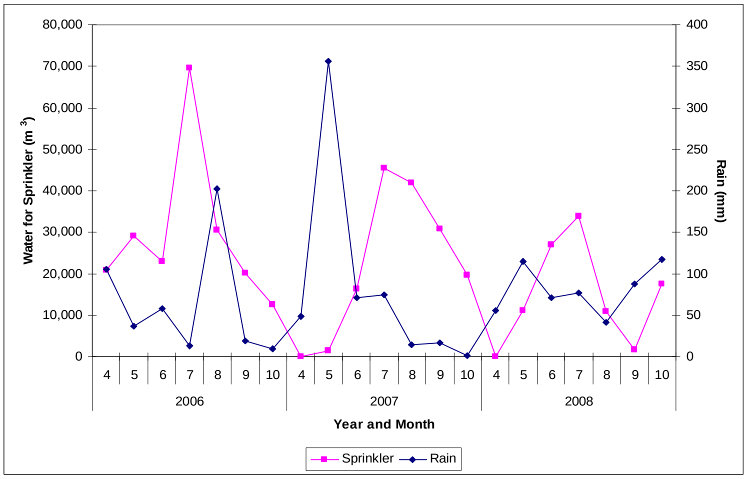
Table 3.4 Measured hourly PM_{10} concentrations for 2006 to 2008.[a]

Year	Concentration (µg/m^3)	KS1	KS2
2006	Downwind	265(3 – 2,656)	-
	Upwind	59 (0 – 720)	-
	Net	225 (0 – 2,638	-
2007	Downwind	265 (0 – 8,078)	148 (3 – 2,060)
	Upwind	62 (0 – 1,653)	26 (0 – 468)
	Net	203 (0 – 8,038)	122 (0 – 1,928)
2008	Downwind	250 (1 – 15,983)	160 (3 – 2,949)
	Upwind	61 (0 – 2,144)	29 (0 – 325)
	Net	189 (0 -15,771)	130 (0 – 2,887)
Overall	Downwind	260 (0 – 15, 983)	154 (3 – 2,949)
	Upwind	61 (0 – 2,144)	28 (0 – 468)
	Net	206 (0 – 15,771)	126 (0 – 2,887)

[a] Values in parenthesis represent the range.

Table 3.5 Sprinkler water consumption and rainfall at KS1 - 2006 to 2008.

Year	Rainfall		Sprinkler Water Use (m^3)
	Amount (mm)	Number of days	
2006	443	48	205,751
2007	583	38	155,417
2008	563	52	102,190
Average	530	46	154,453



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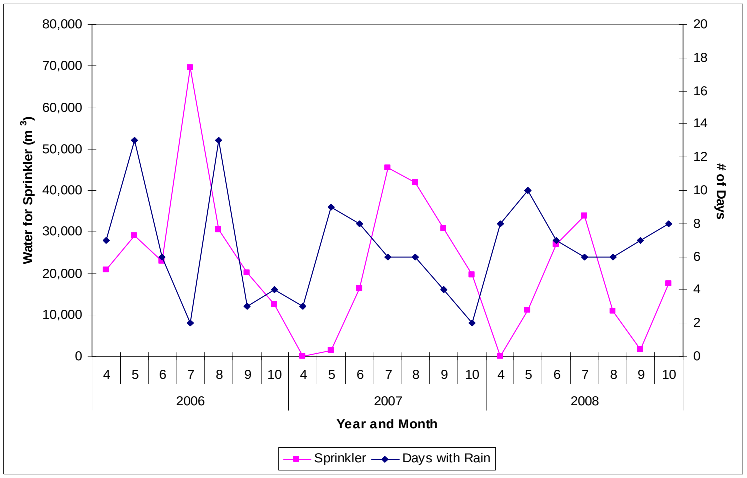
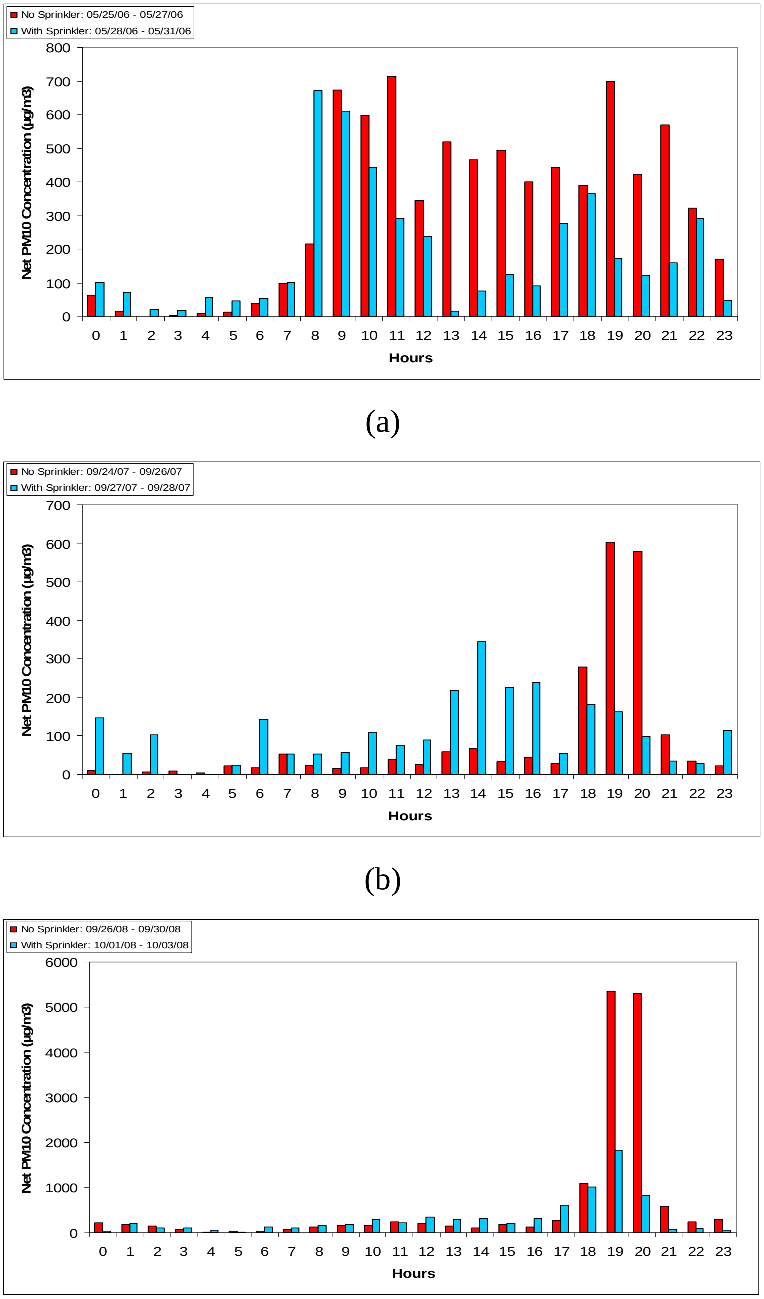


(b)

Figure 3.5 KS1 sprinkler system water use for 2006 to 2008: a) sprinkler water and amount of rain; b) sprinkler water and number of days with rain.

PM_{10} Control Efficiency of Water Application

The hourly trends for net PM_{10} concentration for selected sprinkler on/off events are shown in figures 3.6. In some cases, the effect of the sprinkler system was observed as early as 11:00 a.m. (fig. 3.6a). In other cases, the effect of the sprinkler system was observed only during the evening (fig. 3.6b); the net PM_{10} concentrations were higher during sprinkler operation during the day. In other cases, operation of the sprinkler system greatly reduced the concentration during the EDP period only, with limited influence during the day (fig. 3.6c).



(a)

(b)

(c)

Figure 3.6 Examples of plots of net hourly PM_{10} concentration during "sprinkler off" and "sprinkler on" episodes for a given event: (a) May 25 to May 31, 2006; (b) September 24 to September 28, 2007; and (c) September 26 to October 03, 2008.

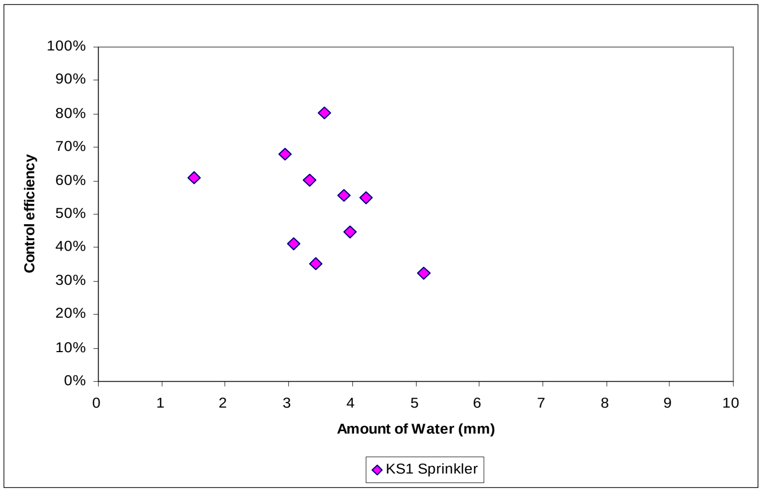
Control Efficiency

Figures 3.7a and 3.7b are plots of the control efficiencies (sprinkler and rainfall events) versus the amount of water applied. For the sprinkler system at KS1, the control efficiencies ranged from 32% to 80%; the amounts of water used ranged from 1.5 mm to 5.1 mm/day. In general, the amount of water applied did not significantly influence the control efficiency of the water sprinkler system, possibly because of the relatively small amount of water applied ($\leq$ 5 mm/day).

For rainfall events, if the rainfall amount was more than 25 mm/day, the control efficiency exceeded 80%. Note that in figure 3.7b, however, there was a case with a control efficiency of 28% with almost 120 mm of rain. Closer examination of that specific event showed that the initial concentration was only 25 $\mu g/m^3$, which was even less than typical ambient PM_{10} concentration. Some rainfall events that had only 5 mm/day of rainfall (equivalent to the capacity of the KS1 water sprinkler system) resulted in more than 80% control efficiency (fig. 3.7b). High reductions achieved by these rainfalls ($\leq$ 5 mm/day) might be due to the high intensity of rainfall in a short period of time. Surprisingly, statistical analysis did not show any significant effect of rainfall amount on control efficiency ($P>0.05$).

Figure 3.8 shows the control efficiencies plotted against initial net PM_{10} concentrations. Statistical analysis did not show any significant ($P>0.05$) correlation between control efficiency and initial PM_{10} concentration for both sprinkler and rainfall events. Table 3.6 lists the statistics for rainfall events and water sprinkler use. The control efficiencies for rainfall events at both KS1 and KS2 were generally significantly higher ($P<0.05$) for the EDP period than for the 24-h period using paired t-tests. Also, KS1 and KS2 did not differ significantly ($P>0.05$) in mean control efficiency associated with rainfall events. For the sprinkler system at KS1, the control efficiencies for the EDP periods were lower but not significantly different ($P>0.05$) from that of the 24-h periods (52% vs. 53%). It should be noted that of the 340 days (Feb 28, 2006 – July 15, 2009) that the sprinkler system was operated, it was activated for at least 20 h/day on 29% of the days and at least 12 h/day on 69% of the days.

The mean control efficiency of the water sprinkler system at KS1 (53%) was close to the values presented in other studies: 43% for in TSP as reported by Carroll et al. (1974) and 50% for PM_{10} as reported by Pechan (2006).



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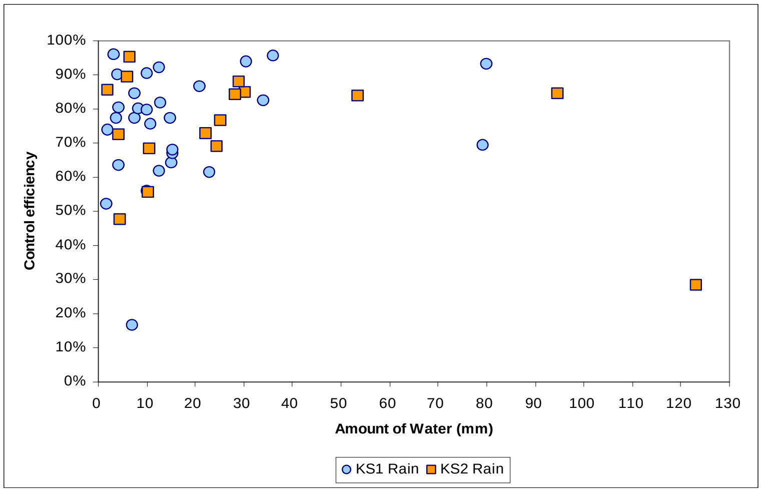
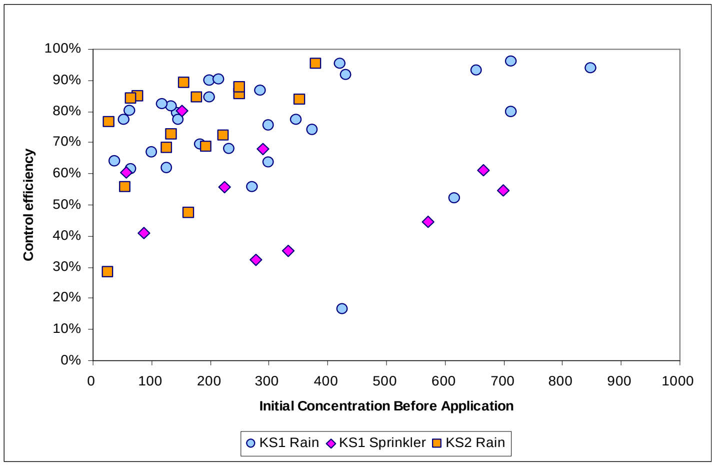


(b)

Figure 3.7 Plots of control efficiency against the amount of water applied for (a) KS1 sprinkler events and (b) KS1 and KS2 rain events.



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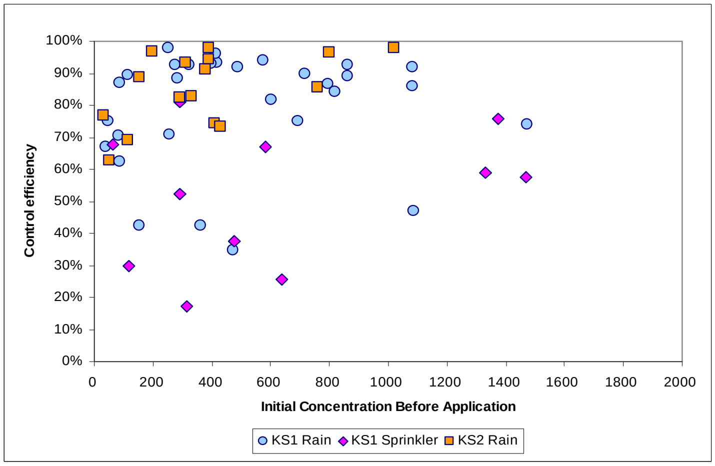


(b)

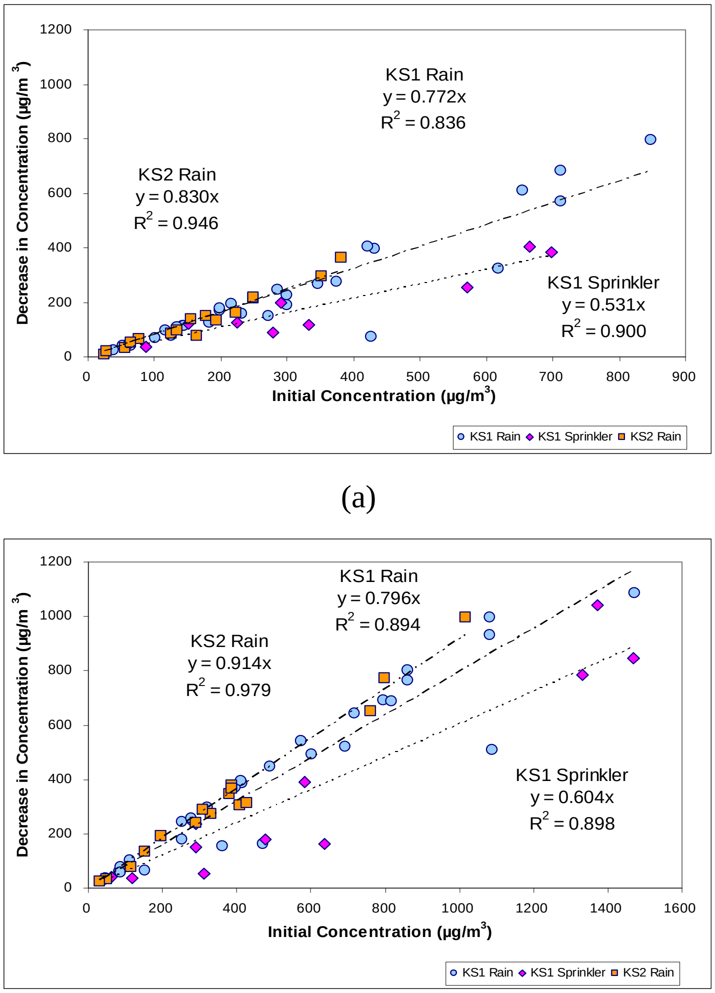
Figure 3.8 Plots of control efficiency and initial PM_{10} concentration based on (a) daily average and (b) evening dust peak average.

Table 3.6 PM$_{10}$ control efficiency for sprinkler events at KS1 and for rainfall events at KS1 and KS2.

Events		Daily (24-h period)	Evening dust peak period (1700h-2300h)
Sprinkler – KS1	No. of events	10	11
	PM$_{10}$ control efficiency Average	53%	52%
	Minimum	32%	17%
	Maximum	80%	81%
	Std. Deviation	15%	21%
Rainfall – KS1	No. of events	29	30
	PM$_{10}$ control efficiency Average	75%	79%
	Minimum	17%	35%
	Maximum	96%	98%
	Std. Deviation	17%	18%
Rainfall – KS2	No. of events	16	16
	PM$_{10}$ control efficiency Average	74%	85%
	Minimum	28%	63%
	Maximum	95%	98%
	Std. Deviation	18%	11%

Decrease in PM_{10} Concentration

Figures 3.9a and 3.9b show the effect of initial net PM_{10} concentration on the decrease in net PM_{10} concentration based on the 24-h values and EDP values, respectively. Unlike control efficiency, the decrease in net PM_{10} concentration was linearly ($P<0.05$) related to the initial net PM_{10} concentration. For the 24-h periods, R^2 values were 0.90 for the sprinkler system at KS1, 0.84 for rainfall events at KS1, and 0.95 for the rainfall events at KS2. The R^2 values were also high for data from the EDP periods.



(a)

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Figure 3.9 Effects of initial net PM_{10} concentration on the decrease in net PM_{10} concentration: (a) daily average and (b) evening dust peak period average.

Duration of the Effects of Sprinkler System and Rainfall

The duration of the effects of water application (from water sprinkler system or rainfall event) depends on the weather conditions (i.e., temperature, solar radiation, wind speed) and amount of water applied. From the net PM_{10} concentration data, the duration of the effects of the sprinkler system and rainfall events were determined. For the sprinkler system, an event that occurred from October 31, 2007 to November 4, 2007 is shown in figure 3.10. From October 31 to November 2, the sprinkler system was "on" with an average water application rate of 3 mm/day. The mean net PM_{10} concentration during this period was 178 $\mu g/m^3$. The day after the sprinkler was turned off, the net PM_{10} concentration increased to 224 $\mu g/m^3$, which was equivalent to a 165% increase in concentration. Another example was an event that occurred on July 4 – 6, 2007. For this event, turning off the sprinkler system resulted in a 60% increase in net PM_{10} concentration (from 41 $\mu g/m^3$ to 66 $\mu g/m^3$). These events show that the effect of the sprinkler system ended almost immediately after it was turned off. Possible reasons for the relatively short duration include the relatively small amount of water being applied, short duration of the application, non-uniform distribution of application, among others.

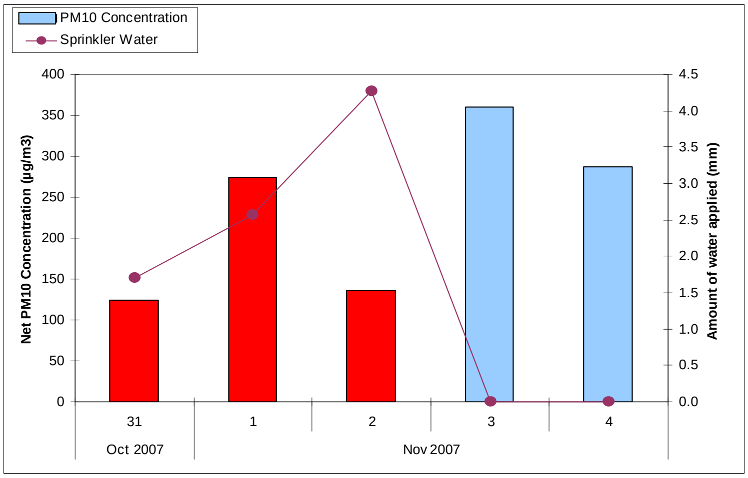
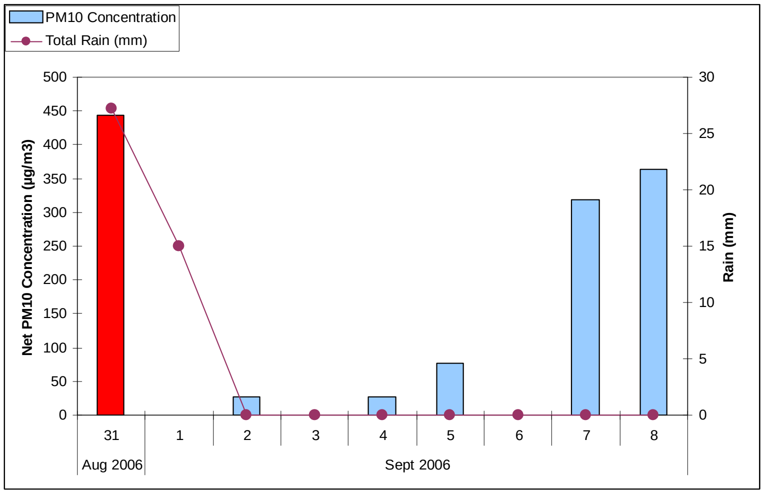


Figure 3.10 Concentration trend after sprinkler operation: October 31 to November 4, 2007.

For the case of rainfall events, the duration of the effect generally lasted from three to seven days, depending on rainfall amount and intensity. To illustrate, two cases are shown in figure 3.11. Figure 3.11a was a rainfall event at KS1 with total rainfall amount of 42 mm. The initial net PM_{10} concentration before the rainfall event was 443 $\mu g/m^3$; the net PM_{10} concentration decreased to 27 $\mu g/m^3$ immediately after the rainfall event and then increased to close to the initial value after six to seven days. Figure 3.11b illustrates a rainfall event for KS2. The trend was similar to that in figure 3.12a: the net PM_{10} concentration decreased from 380 $\mu g/m^3$ to 64 $\mu g/m^3$ immediately after the rainfall event and then increased to about 350 $\mu g/m^3$ five to six days after the rainfall event. Table 3.7 summarizes the 10 cases that show the duration of the effects of rainfall events. For these 10 cases, the average amount of rainfall was 53 mm, ranging from 11 mm to 137 mm. Rainfall intensity varied from 2.54 mm/h to 10.5 mm/h, with an average of 5.13 mm/h. The number of hours with rainfall ranged from 3 h to 19 h, with an average of 9 h. For comparison purposes, the sprinkler system at KS1 had the following operating values if operated for 24 h: total amount of 5.4mm (per day); intensity of 1.35 mm for 6 min per cycle; and application was 4 cycles a day.

Regression analysis indicated that, after a rainfall event, the net PM_{10} concentration increased by 43 $\mu g/m^3$ per day, ranging from 12 $\mu g/m^3$ to 72 $\mu g/m^3$. Statistical analysis also showed that the increase in net PM_{10} concentration per day had a linear relationship ($P<0.05$) with initial net PM_{10} concentration. Neither rainfall intensity, rainfall duration nor its total amount had any significant effect on the increase in net PM_{10} concentration per day ($P>0.05$).

The increasing trend in concentration after rainfall events was further analyzed by grouping the data points according to amounts of rainfall: points 6, 7 and 8 (rainfall amount of 12 mm or less); points 2, 4 and 5 (rainfall amount of 40 to 50 mm); and points 3, 9 and 10 (rainfall amount exceeding 90 mm). One point (point #1) was not used because it could not be classified into any of the groupings made. Computed values for increase in net PM_{10} concentration per day were plotted against their corresponding initial net PM_{10} concentrations. The resulting plots (fig. 3.12) suggest that the increase in net PM_{10} concentration per day (after a rainfall event) depended on the initial net PM_{10} concentration (before the rainfall event). This could mean that if the potential of the pen surface to generate PM_{10} would be higher, then the increase in net PM_{10} concentration (as the effect of rainfall lessens) could be faster and fewer days would be needed to reach the potential concentration.



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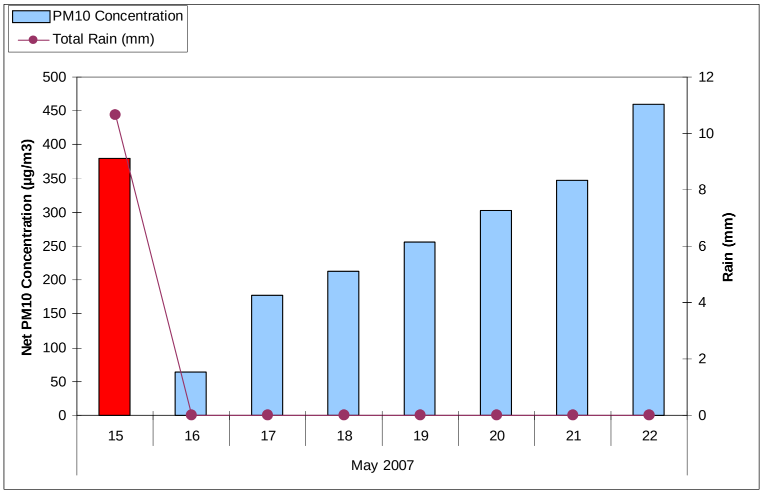
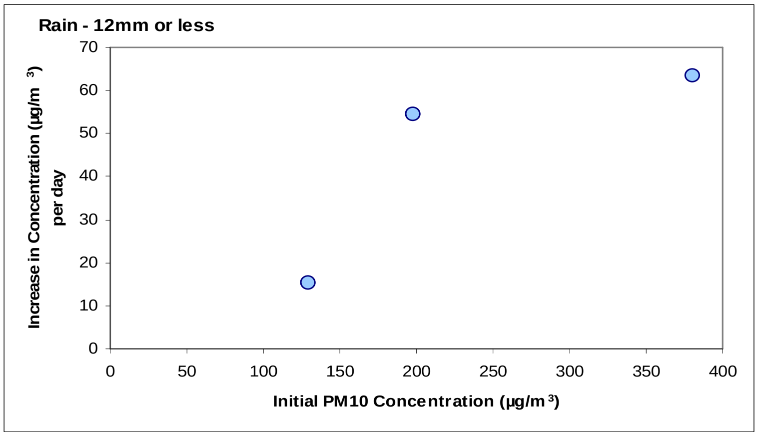


(b)

Figure 3.11 Concentration trend after rainfall events: a) August 31 to September 8, 2006; b) May 15 to 22, 2007.

Table 3.7 Rainfall event descriptions and resulting linear regression variables.

Points	Feedlot	Rainfall Event	Rainfall			Net PM_{10} Concentration ($\mu g/m^3$)		Linear Regression	
			Intensity (mm/h)	Duration (h)	Total Amount (mm)	Before Rain	After Rain	Increase in Concentration / day	R^2
1	KS1	June 16, 2006	4.58	5	22.9	848	16	63	0.64
2	KS1	Aug. 31 – Sept. 01 2006	5.27	8	42.2	443	27	55	0.79
3	KS1	May 06, 2007	7.11	19	136.9	119	14	12	0.70
4	KS1	May 05 - 08, 2008	3.68	13	47.8	373	25	44	0.58
5	KS1	June 15 – 18, 2008	5.33	8	42.7	158	13	25	0.90
6	KS1	July 07, 2008	3.56	3	10.9	130	18	15	0.70
7	KS1	July 18, 2008	2.54	5	13.0	198	74	54	0.72
8	KS2	May 15, 2007	2.67	4	10.7	380	64	64	0.95
9	KS2	May 23, 2007	10.53	9	94.7	459	49	21	0.70
10	KS2	May 08, 2008	6.1	19	115.8	895	26	72	0.67
Mean			5.14	9	53.8	400	33	43	0.74



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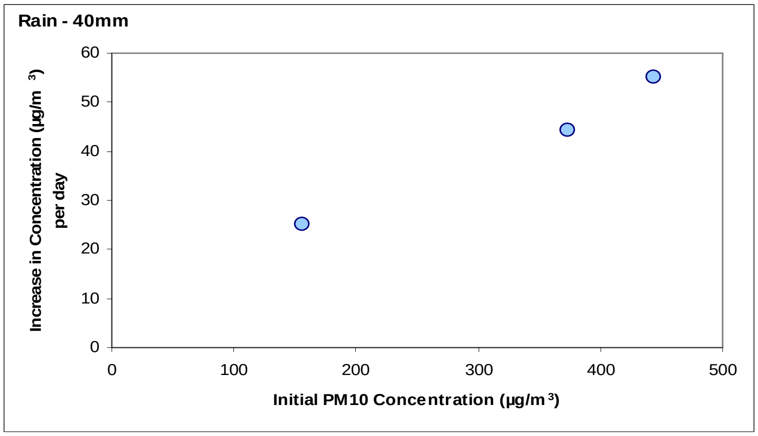

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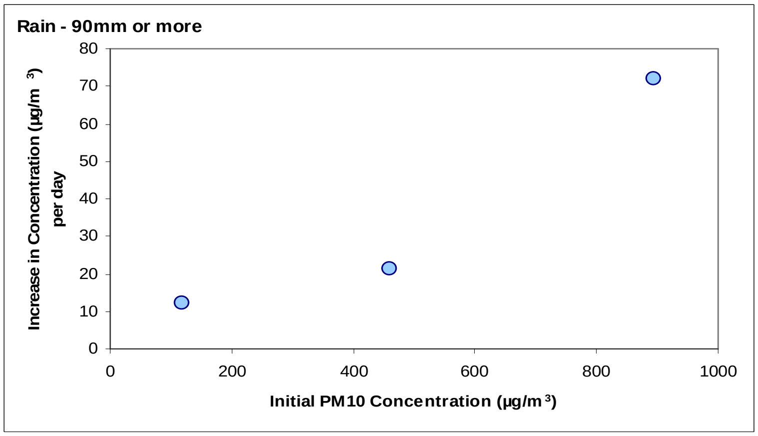


(c)

Figure 3.12 Plots of increase in concentration (µg/m^3) per day against initial PM$_{10}$ concentration: (a) rainfall events with $\leq$ 12 mm precipitation; (b) rainfall events with $\leq$ 40 mm precipitation; and (c) rainfall events with $\geq$ 90 mm precipitation.

Another factor that could affect the degree of increase in net PM_{10} concentration per day after a rainfall event is the amount of rainfall. In order to do the analysis on the amount of rainfall, points 2, 4, 8 and 9 were used because their initial PM_{10} concentrations were close to each other (i.e., 443, 373, 380 and 459 µg/m^3, respectively). Figure 3.13 shows that, as expected, the increase in net PM_{10} concentration per day after a rainfall event was inversely proportional to the total amount of rainfall.

The above analyses could prove useful in improving the effectiveness of the sprinkler system in controlling PM emissions. The duration of the effects of rainfall, expressed as the increase in PM_{10} concentration per day after rainfall events, depended on the initial PM_{10} concentration and rainfall amount. Knowing these two parameters, initial concentration and amount of water applied, the daily increase in concentration could be estimated and appropriate actions could be applied to minimize PM emission once the effect of water application recedes.

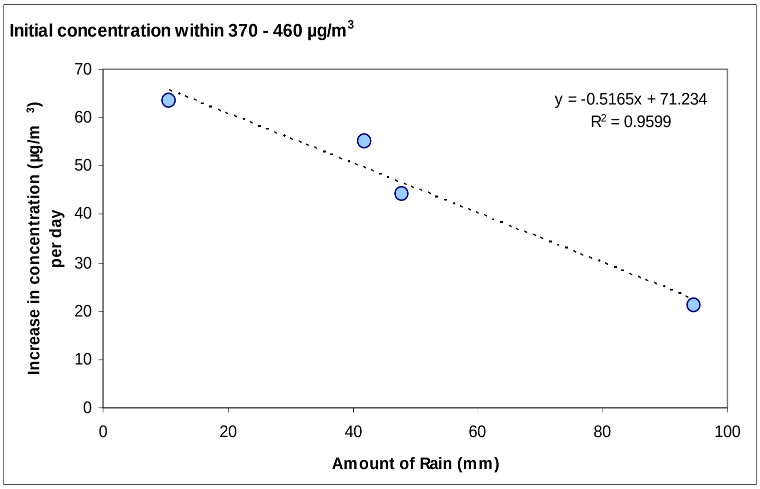


Figure 3.13 Plot of increase in net PM_{10} concentration per day against total rainfall amount.

Summary and Conclusions

The control efficiency for PM_{10} of water application, including rainfall and water sprinkler system, was evaluated at two feedlots in Kansas by comparing PM_{10} concentrations during water application on/off events. The following conclusions were drawn:

- For the water sprinkler system at KS1, the control efficiency for PM_{10}, based on the 24-h mean concentrations, ranged from 32% to 80% with an overall mean of 53%. The control efficiency, based on concentrations during the evening dust peak periods (1700 h - 2300 h), ranged from 17% to 81% with an overall mean of 52%.
- For rainfall events at KS1 and KS2, the control efficiencies for PM_{10} ranged from 17% to 96% for the 24-h mean values and from 35% to 98% for the evening dust peak values.
- The effect of water application through the sprinkler system ($\leq$ 5 mm of water/day) lasted for one day or less. The effect of a rainfall event, on the other hand, generally lasted for three to seven days, depending on the rainfall amount. After a rainfall event, the net PM_{10} concentration increased approximately 43 $\mu g/m^3$ per day.

References

ACFA. 2002. Other technologies and landscaping options. In *Beneficial Management Practices – Environmental Manual for Feedlot Producers in Alberta*. Alberta, CA: Alberta Cattle Feeders' Association. Available at: www.agriculture.alberta.ca. Accessed 03 September 2009.

Auvermann, B., R. Bottcher, A. Heber, D. Meyer, C. B. Parnell, Jr., B. Shaw, and J. Worley. 2006. Particulate matter emissions from animal feeding operations. In *Animal Agriculture and the Environment: National Center for Manure and Animal Waste Management White Papers*, 435-468. J. M. Rice, D. F. Caldwell, F. J. Humenik, eds. St. Joseph, Mich.: ASABE.

Carroll, J. J., J. R. Dunbar, R. L. Givens, and W. B. Goddard. 1974. Sprinkling for dust suppression in a cattle feedlot. *California Agriculture* 28(3): 12-14.

Midwest Plan Service (MWPS). 2002a. Outdoor air quality – MWPS-18 Manure Management System Series 18. Section 18. Ames, IA: Midwest Plan Service.

Mitloehner, F. M., and M. S. Calvo. 2008. Worker health and safety in concentrated animal feeding operations. *Journal of Agricultural Safety and Health* 14(2): 163-187.

Pechan, 2006. AirControlNET Version 4.1: Documentation report prepared for U.S Environmental Protection Agency. Pechan Report No. 06.05.003/9011.002. Springfield, VA: E. H. Pechan & Associates, Inc.

Razote, E. B., R. G. Maghirang, B. Z. Predicala, J. P. Murphy, B. W. Auvermann, J. P. Harner, III, and W. L. Hargrove. 2006. Laboratory evaluation of the dust-emission potential of cattle feedlot surfaces. *Transaction ASABE* 49(4): 1117-1124.

Razote, E. B., R. G. Maghirang, J. P. Murphy, B. W. Auvermann, J. P. Harner, III, D. L. Oard, D. B. Parker, W. L. Hargrove, and J. M. Sweeten. 2007. Air quality measurements from a water-sprinkled beef cattle feedlot in Kansas. ASABE Paper No. 074108. St. Joseph, Mich.: ASABE

SAS. 2002. *SAS for Windows*. Ver. 9.1.3 Service Pack 4. Cary, NC: SAS Institute, Inc.

Sweeten, J. M., C. B. Parnell, R. S. Etheredge, and D. Osborne. 1988. Dust emissions in cattle feedlots. In *Stress and Disease in Cattle, Veterinary Clinics of North America, Food Anim. Prac.* 4(3): 557-578.

CHAPTER 4 - Estimating PM_{10} Emission Rates from Beef Cattle Feedlots in Kansas Using Inverse Dispersion Modeling

Introduction

The open-lot animal feeding industry faces significant air quality challenges, including emissions of particulate matter (i.e., PM_{10} and $PM_{2.5}$), odorous volatile organic compounds, ammonia, and greenhouse gases (i.e., CH_4, N_2O). The long-term sustainability of open-lot animal feeding operations (AFOs) and neighboring rural communities that are economically dependent on these operations will depend upon overcoming these air quality challenges. In addition, AFOs are becoming subject to new regulations on air emissions. Unfortunately, limited data on gaseous and PM emissions exist for large cattle feedlots in the Great Plains, a region that comprises over 70% of the nation's beef cattle production. Gaseous and PM emission rates need to be determined from commercial feedlots to provide a realistic assessment of their impact on the environment. As stated in the report on air emissions from AFOs by the National Research Council (NRC, 2003): "While concern has mounted, research to provide the basic information needed for effective regulation and management of these emissions has languished… Accurate estimation of air emissions from AFOs is needed to gauge their possible adverse impacts and the subsequent implementation of control measures."

In response to the NRC (2003) report, the National Air Emissions Monitoring Study (NAEMS) is being conducted on several swine, dairy, egg layer, and broiler facilities. There is an urgent and critical need to also measure and monitor air emissions from open AFOs. Quantifying air emissions from open AFOs is challenging, largely because of their unique characteristics, including surface heterogeneity and temporal and spatial variability of emission fluxes. An approach that can be used involves measuring upwind and downwind concentrations and back-calculating emission rates with atmospheric dispersion modeling (NRC, 2003).

Atmospheric dispersion models are models that mathematically simulate pollutant dispersion from a pollutant source (US EPA, 2009). Standardization of these atmospheric dispersion models was first mandated under the 1977 Clean Air Act as part of regulating criteria pollutants from existing and new sources (CFR, 2003). Application of dispersion models in estimating pollutant concentrations (CFR, 2003) is considered useful for assessing control strategies and developing emission limits. Existing air quality models are continuously improved to meet regulatory requirements and changes in the industry; also, since no one model is capable of successfully simulating dispersion for all types of sources, new air quality models are also being developed for the purpose of modeling complex sources and conditions (CFR, 2003). Currently, several atmospheric dispersion models are available; the latest model recommended by US EPA for regulatory purposes is the AMS/EPA Regulatory model (AERMOD) (CFR, 2005). Major improvements included in developing AERMOD are the following: (1) meteorological modeling (US EPA, 2004b, c) that fully characterizes the planetary boundary layer, (2) inclusion of effects of surface characteristics on dispersion, and (3) more accurate approximation of vertical dispersion during unstable conditions (Turner and Schulze, 2007).

Several studies have investigated the performance of AERMOD. Cimorelli et al. (2005) examined the formulations behind AERMOD and noted that AERMOD incorporates effective boundary layer characterization and consideration of previous dispersion models that had good performance. Perry et al. (2005) compared AERMOD with the Industrial Source Complex Short-Term model (ISCST3), which was the dispersion model previously preferred by US EPA. Perry et al. (2005) concluded that AERMOD performed better than ISCST3 in modeling the concentration distribution for tall, buoyant stacks in both flat and complex terrains. They also noted that AERMOD performed close enough to other dispersion models (i.e., CTDMPLUS for elevated point sources, Perry et al., 2005) that were designed for special conditions. Faulkner et al. (2009) reported that the emission factors for an almond farm derived from AERMOD and ISCST3 were not significantly different. Note, however, that AERMOD is based on Gaussian plume equations (Holmes and Morawska, 2006); as such, it may not be able to model the dispersion efficiently under calm or low wind conditions (Holmes and Morawska, 2006).

This research was conducted to estimate PM_{10} emission rates from three cattle feedlots in Kansas by using the inverse dispersion modeling technique with AERMOD. Trends of the emission rates were examined on a yearly, seasonal and hourly basis. In addition, possible reasons for occurrence of high PM_{10} concentrations in early evening were explored using the emission fluxes modeled and concentration trends observed at the three feedlots.

Materials and Methods

The emission rates from the feedlots can be expressed on a per unit area basis (i.e., emission fluxes) or per 1000 head basis (i.e., emission factors). Emission fluxes of PM_{10} were determined using the following general procedure: (1) monitoring of PM_{10} concentrations downwind and upwind of cattle feedlots; (2) atmospheric dispersion modeling with AERMOD using an assumed value of emission flux to determine the net PM_{10} concentrations (i.e., downwind-upwind) in the feedlots; and (3) calculation of the emission fluxes by relating the measured concentrations to the AERMOD-derived concentrations. From the emission fluxes and cattle population in the feedlots, emission factors (i.e., kg/1000hd per unit time) were determined.

Field Measurement of PM_{10} Concentration

Feedlot Description

Three commercial cattle feedlots in Kansas (i.e., KS1, KS2, and KS3) were considered. Prevailing wind directions at the feedlots were south-southeast during summer and north-northwest during winter. The first feedlot, KS1, had approximately 30,000 head of cattle with a total pen area of about 50 ha. The feedlot had a water sprinkler system (capacity of 5.0 mm/day) that was normally operated from April through October, and during prolonged dry periods. The feedlot also practiced pen cleaning, which was done year round and two to three times a year for each pen, and manure harvesting, which was done at least once a year. The second feedlot, KS2, had approximately 25,000 head of cattle and a total pen area of approximately 68 ha. The main dust control method at KS2 was pen cleaning at a frequency of five to six times a year for each pen, and manure harvesting two to three times a year. The third feedlot, KS3, had approximately 30,000 head in a total pen area of 59 ha. Pen cleaning and manure harvesting frequencies were similar to that at KS1. Also, during dry periods, water trucks were used to water some of the pens and the unpaved feed alleys.

For all feedlots, feeding was typically done three times a day. The first feeding would usually start at 0600 h and last up to 0830 h; the third feeding would start at 1500 h and could end up to at 1730 h.

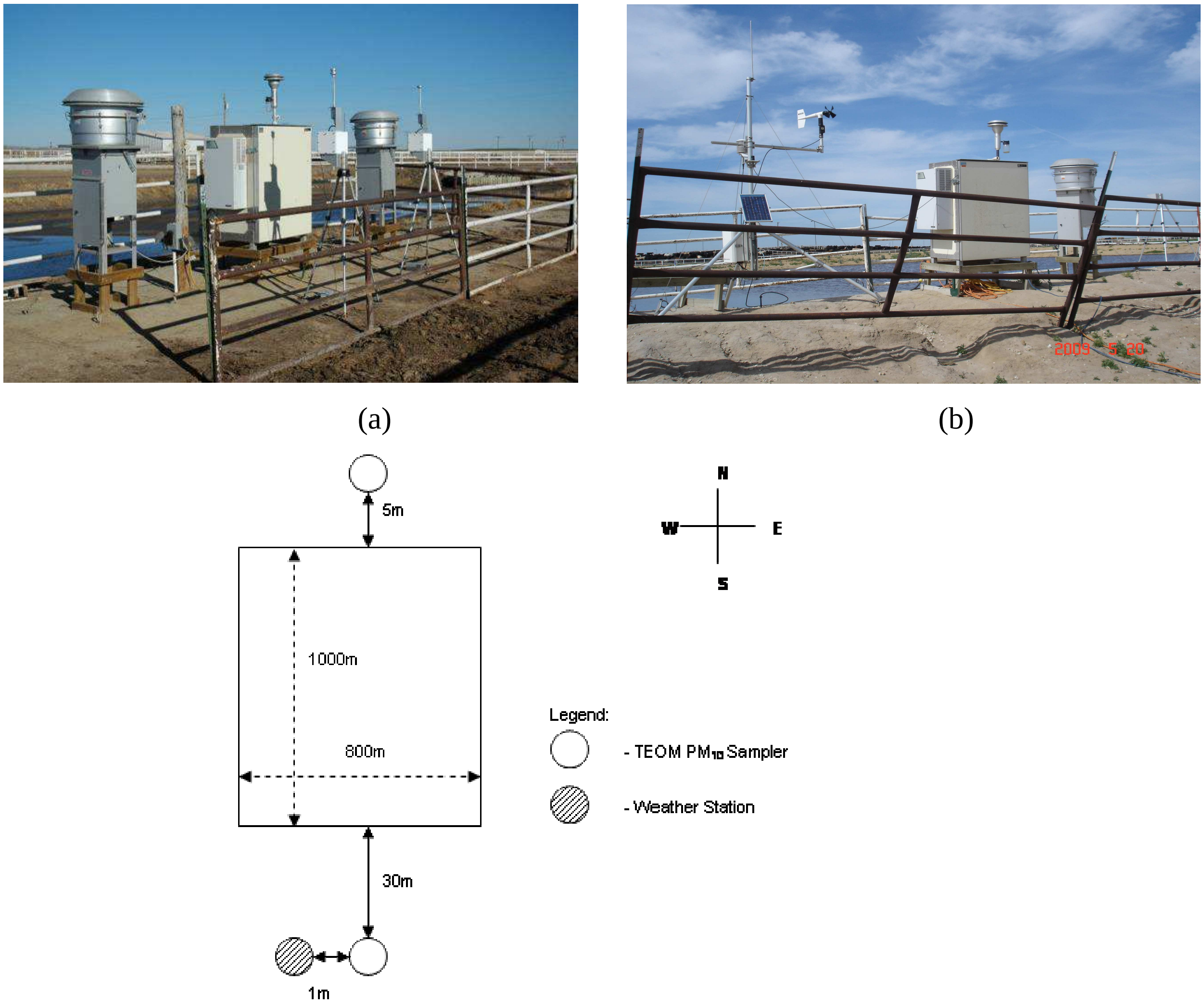
Sampling Locations

Mass concentrations of PM_{10} were measured at the north and south perimeters of each feedlot. Because of differences in feedlot lay-out, power supply availability, and site access, the locations of the samplers varied among the three feedlots. For KS1, the north sampling site was approximately 5 m away from the closest pen and the south sampling site was around 30 m from the closest pen (fig. 4.1). For KS2, the north and south sampling locations were 40 m and 60 m away from the closest pens, respectively. For KS3, the north site was approximately 5 m from the closest pen and the south site was 880 m away from the closest pen (i.e. feedlot lay-out and power supply issue).

Measurement of PM_{10} Concentration and Weather Conditions

The PM_{10} concentrations were monitored with tapered element oscillating microbalance (TEOM) PM_{10} monitors (Series 1400a, Thermo Fisher Scientific, East Greenbush, NY; federal equivalent method designation No. EQPM-1090-079). Measurement periods were as follows: (1) KS1 – January 2007 to December 2008, (2) KS2 – January 2007 to December 2008, and (3) KS3 – June 2008 to December 2008. During the measurement, sampled air and the TEOM filter were heated at 50°C. The TEOM collection filters were replaced if filter loadings indicated by the TEOM reached the 90% value; the TEOM in-line filters were replaced when the amount of dust collected was already significant. Leak checks and flow audits were done monthly; for cases of low flow audit results, either the TEOM pump was replaced or software calibration was done to correct the sampling flow rate.

PM_{10} concentrations were recorded continuously at 20-minute intervals and then integrated to hourly averages for data reduction and analyses. From the hourly values, net PM_{10} concentrations (i.e., downwind – upwind concentrations) were determined. From this dataset, negative PM_{10} concentrations (i.e., downwind, upwind, and net) were excluded. In addition, only cases in which the north sampling site was downwind (i.e. wind direction within the 120° to 240° range) were considered to minimize the effects of unpaved feed alleys (Faulkner et al., 2007). The resulting dataset, together with their corresponding AERMOD-derived concentrations, were used to determine the hourly emission rates.



(a) (b)

(c)

Figure 4.1 Measurement of PM_{10} concentrations and weather conditions at KS1; photographs of TEOM PM_{10} samplers at the (a) north sampling site and (b) south sampling site and (c) schematic diagram showing the locations of the samplers and the weather station.

Feedlots KS1 and KS2 were both equipped with weather stations (Campbell Scientific, Inc., Logan, UT) to measure and record the following: wind speed and direction (Model 05103-5), atmospheric pressure (Model CS100), precipitation (Model TE525), and air temperature and relative humidity (Model HMP45C). Weather conditions were measured in 20-min intervals at a height of 2.5 m. For KS3, which was located within 5 km of KS1, the weather data collected at the weather station at KS1 were used. There was a period for KS1 (January 2006 to July 2007) when there was a problem with the weather station. During this period, wind direction and wind speed from the weather station at KS2 and available rain data from another monitoring site close to KS1 were used.

Evaluation was conducted for the three feedlots using TEOM PM_{10} concentration data measured from 2007 and 2008. However, for KS3, only six months of data were available since PM_{10} measurement started in June 2008. The numbers of days with at least one hourly concentration (out of 24) were 452, 381, and 61 days for KS1, KS2, and KS3, respectively.

The downwind and net concentrations at the feedlots tend to peak during the late afternoon to early-late evening, a period herein referred to as the Evening Dust Peak (EDP) period. Increased cattle activity and/or stable atmospheric conditions during this period could be the major reasons for this trend (Auvermann et al., 2006). In this research, the EDP period was defined as the period from 1700 h to 2300 h. Based on the dataset used for dispersion modeling, 68% of the days had at least one hourly value during the EDP period (Table 4.1). Majority of the days with measured EDP PM_{10} concentrations exhibited peaking of net PM_{10} concentrations during the EDP period (Table 4.1). The EDP trend was observed for both hot (April to October) and cold (January to March, November to December) months.

Table 4.1 Days with Evening Dust Peak (EDP) trend.

Feedlot	Total number of days with at least one hourly value	Number of days with at least one hourly value during EDP	Number of days with peak during EDP
KS1	452	307	230
KS2	381	248	185
KS3	61	43	33

Atmospheric Dispersion Modeling

As mentioned earlier, AERMOD, which is the preferred regulatory model by US EPA, was used. Modeling involved running the AERMET (US EPA, 2004b) preprocessor to prepare the meteorological inputs and then running AERMOD (US EPA, 2004a) to predict concentrations downwind of each feedlot. The AERMAP preprocessor was not implemented because the feedlots had relatively flat terrain.

AERMET Meteorological Data

The three meteorological data types (i.e., upper air data, surface hourly data, and on-site data) were inputted in AERMET. The first two were downloaded from the National Oceanic and Atmospheric Administration (NOAA) website. The on-site data were obtained from the weather stations at the feedlots. Other parameters that must be specified in the preprocessing of meteorological data include albedo (i.e., ratio of the radiation reflected to the radiation that reaches the ground surface), bowen ratio (i.e., ratio of sensible heat to latent heat), and surface roughness (i.e., measure of irregularities on the source landscape) (Turner and Schulze, 2007). Based on the land classification tables provided by US EPA (2008), the following values were used: 0.2 for albedo, 2.0 for bowen ratio; and 0.05 m for surface roughness. To deal with air movement that could not be detected by the weather station, the threshold for calm conditions must be specified (US EPA, 2004b). In this study, calm conditions were defined as having wind speed less than 0.5 m/s. After processing the meteorological data with AERMET, the resulting hourly outputs (i.e., surface and profile data) were then used as meteorological inputs for AERMOD.

AERMOD Dispersion Modeling

The following options and assumptions were specified in the input runstream file: (1) the feedlots were area sources with flat terrain; (2) the regulatory dispersion options of AERMOD were applied to deal with missing meteorological data; and (3) concentration was the variable modeled with a 1-h averaging time. Other parameters indicated in the runstream file were the start and end dates, names of AERMET meteorological files, receptor height (i.e., 2.3 m for KS1 and KS2, 2.0 m for KS3) and locations, and an assumed value of emission rate (i.e., 100 $\mu g/m^2$-s).

One important aspect of modeling area sources is specifying the locations of the area source and locations of the receptors in the feedlot. This was done by encoding the vertices of the area and receptors from a specific point in the feedlot in the AERMOD runstream file. Vertices were determined using the DesignCAD 3M Max18 (DesignCAD, 2007) software using the following steps: (a) feedlot images were uploaded in the software; (b) the feedlot size was corrected with an actual length measurement for any specific location/side of the feedlot; and (c) the vertices of the area sources and receptors were recorded.

Calculation of Emission Rates

The model was executed using an emission flux of 100 µg/m^2-s to predict the hourly concentrations at the downwind sampling location. From the AERMOD-derived and measured concentrations, the actual emission fluxes, Q_O, were calculated:

$$Q_O = \frac{Q_A}{C_A} \times C_O \qquad (4.1)$$

where Q_o is the actual emission flux (µg/m^2-s), C_o is the measured net PM$_{10}$ concentration (µg/m^3), Q_A is the assumed emission flux in AERMOD (i.e., 100 µg/m^2-s), and C_A is the AERMOD-derived downwind PM$_{10}$ concentration (µg/m^3) for an emission flux of 100 µg/m^2-s.

The emission fluxes were converted to hourly emission factors using the following relationship:

$$EF = \frac{Q_O \times A \times 3{,}600}{10^6 \times N} \qquad (4.2)$$

where EF is the emission factor (kg/1000 hd-h), A is the area of feedlot (m^2), and N is the total number of cattle (i.e., 30,000 for KS1, 25,000 for KS2, 30,000 for KS3). Daily emission rates (both emission fluxes and emission factors) were the sum of the hourly emission rates for a given day.

The PM$_{10}$ emission factor used by US EPA for calculating the emissions from cattle feedlot was 17 tons/1000 hd-year (US EPA, 1988, 2001). Apparently, this emission factor was derived from the AP-42 TSP emission factor of 27 tons/1000 hd-yr for cattle feedlots and adjusted based on the aerodynamic particle size ratio of PM_{10} to TSP (US EPA, 1988). There were two assumptions made (US EPA, 1988): (1) particle size distribution of PM emitted from cattle feedlots was comparable to emission from agricultural soil; and (2) TSP was defined as PM_{30} or PM having aerodynamic diameter of 30µm or less. This emission factor was used by US EPA in estimating emissions from cattle feedlots starting 1990 (US EPA, 2001). The equivalent value of this emission factor per day (42 kg/1000hd-day) was used as reference in this research.

In calculating the emission factors from the emission fluxes, the pen area was used on the assumption that the US EPA PM_{10} emission factor for cattle feedlots was based on cattle activity-caused PM emission. Note that the calculated emission factor depends greatly on what area to use. For example, if pen area were used, emission factors from morning until afternoon could be underestimated because unpaved feed alleys would likely contribute to overall emissions during this period. If the overall feedlot area were used, on the other hand, the calculated emission factors particularly during the evening when emission from the unpaved feed alleys is likely very small could be overestimated. From the reference PM_{10} emission factor of 42 kg/1000 hd-day, the equivalent PM_{10} emission fluxes were 2.51 g/m^2-day for KS1, 1.54 g/m^2-day for KS2, and 2.15 g/m^2-day for KS3. KS1 had the highest US EPA equivalent emission flux because of the high number of head (30,000 hd) in a smaller area (50 ha) compared with the other two feedlots.

Calculated emission fluxes and factors were analyzed with SAS for Windows version 9.1.3 (SAS, 2002) using paired t-test for comparison among the three feedlots. A 5% level of significance was used.

Results and Discussion

Weather conditions and PM_{10} concentrations

During the study period (January 2007 to December 2008), the wind direction was from the south approximately 50% of the time for all feedlots (51% for KS1, 49% for KS2, 50% for KS3). Table 4.2 summarizes the weather conditions (temperature, relative humidity, wind speed) for the 24-month period. No considerable difference in temperature or relative humidity was observed among the three feedlots. The average wind speed at KS1 was 20% higher than that at KS2. Weather parameters computed for KS3 were for six months (June to November of 2008) only.

Table 4.3 summarizes the measured hourly PM_{10} concentrations at the feedlots. As expected, for each feedlot, the concentrations varied widely with the downwind concentrations ranging from negligible to over 15,000 $\mu g/m^3$ and the upwind concentrations ranging from negligible to over 2,000 $\mu g/m^3$. Overall mean net concentrations were 161 $\mu g/m^3$, 126 $\mu g/m^3$, and 274 $\mu g/m^3$, for KS1, KS2, and KS3, respectively.

Table 4.2 Weather conditions for 2007 and 2008 (January to December).[a]

	KS1	KS2	KS3 (year 2008)
Temperature (°C)	12 (-20 – 41)	13 (-20 – 40)	13 (-17 – 41)
Relative Humidity (%)	68 (9 – 100)	68 (10 – 100)	66 (9 – 99)
Wind Speed (m/s)	4.29 (0.00 – 15.87)	3.56 (0.00 – 15.87)	4.69 (0.00 – 15.41)

[a] Values in parenthesis represent the range.

Table 4.3 Measured hourly PM_{10} concentrations for 2007 and 2008.[a]

Period		KS1	KS2	KS3
January to December 2007	Number of Hourly Values	2,528	2,123	-
	Downwind concentration ($\mu g/m^3$)	232 (0 – 8,078)	116 (0 – 2,060)	-
	Upwind concentration ($\mu g/m^3$)	56 (0 – 1,653)	21 (0 – 468)	-
	Net concentration ($\mu g/m^3$)	176 (0 – 8,038)	94 (0 – 1,928)	-
January to December 2008 (June to November 2008 for KS3)	Number of Hourly Values	2,607	1,776	784
	Downwind concentration ($\mu g/m^3$)	193 (0 – 15,983)	130 (2 – 2,949)	302 (6 – 9,198)
	Upwind concentration ($\mu g/m^3$)	48 (0 – 2,144)	25 (0 – 325)	28 (0 – 290)
	Net concentration ($\mu g/m^3$)	146 (0 -15,771)	105 (0 – 2,887)	274 (0 – 9,157)
Overall	Downwind concentration ($\mu g/m^3$)	213 (0 – 15,983)	123 (0 – 2,949)	302 (6 – 9,198)
	Upwind concentration ($\mu g/m^3$)	52 (0 – 2,144)	28 (0 – 468)	28 (0 – 290)
	Net concentration ($\mu g/m^3$)	161 (0 – 15,771)	126 (0 – 2,887)	274 (0 – 9,157)

[a] Values in parenthesis represent the range.

Emission Rates

Yearly Emission Rates

The calculated annual emission fluxes for the three feedlots are summarized in Table 4.4a. Total number of days used in the modeling and number of days affected by rainfall events are also shown in Table 4.4a. In 2007, AERMOD-derived PM_{10} emission fluxes were 1.57 g/m^2-day and 1.19 g/m^2-day for KS1 and KS2, respectively. Both fluxes were less than their corresponding US EPA equivalent fluxes (by 38% for KS1 and 23% for KS2). Statistical analysis also showed that the mean emission fluxes in 2007 for KS1 and KS2 were not significantly different ($P>0.05$). In 2008, KS3 had very high PM_{10} emission flux at 2.48 g/m^2-day, which was higher than its US EPA equivalent flux (2.15 g/m^2-day) by 15%. PM_{10} emission fluxes in 2008 for both KS1 (1.01 g/m^2-day) and KS2 (0.87 g/m^2-day) were less than their US EPA equivalent fluxes by 60% and 43%, respectively. Both values were also less than the 2007 values (by 36% for KS1 and 27% for KS2). In 2007, KS2 had more rainfall events than KS1; KS2 had 25% of the days affected by rain while KS1 had 16%. Similar trend was observed for 2008 when the percentages of days with rain were 22% for KS2 and 16% for KS1. Since KS2 had more days affected by rainfall events, lower emission fluxes were expected from KS2 than from KS1. However, paired t-test showed that KS1 and KS2 yearly emission fluxes were not significantly different. Also, the KS2 emission fluxes were less than the US EPA equivalent flux by just 33%; KS1 emission fluxes were lower by 49%. This might be an indicator of effectiveness of sprinkler system at KS1 in reducing PM emissions.

For KS3, there were 12 days out of the 61 days used in the modeling that were affected by rainfall events. Even if the percentage of days with rainfall events was high at 20%, the AERMOD-derived emission flux at KS3 was still high at 2.48 g/m^2-day.

Table 4.4b summarizes the AERMOD-derived emission fluxes based on the same days for the feedlots. Periods were classified into two: January to May (KS1, KS2 for 2007 and 2008) and June to December (KS1, KS2 for 2007 and 2008; KS3 for 2008). In 2007 (151 days), KS1 and KS2 both had emission fluxes that were less than their respective US EPA emission fluxes. The high value of PM_{10} emission flux for KS2 was due to an increase in emission flux from 0.58 g/m^2-day for the January-May period to

1.90 g/m^2-day for the June-December period. During the same period, the emission flux at KS1 only increased by 150% (from 0.62 g/m^2-day to 1.55 g/m^2-day).

Table 4.4 Yearly emission fluxes (weighted-average).[a]

a. For all days (emission flux in g/m^2-day).

Year	KS1			KS2			KS3		
	Days		Mean Flux	Days		Mean Flux	Days		Mean Flux
	Total	With Rainfall		Total	With Rainfall		Total	With Rainfall	
2007	215	34	1.57	188	47	1.19	-	-	-
2008	237	39	1.01	193	42	0.87	61	12	2.48
Overall	452	73	1.29	381	89	1.03	61	12	2.48

b. For selected days (emission flux in g/m^2-day).

Year	Months	Days	KS1		KS2		KS3	
			Mean	Std. Dev	Mean	Std.Dev	Mean	Std.Dev
2007	Jan - Dec	151	1.16	1.42	1.34	1.16	-	-
	Jan - May	64	0.62	0.63	0.58	0.48	-	-
	June - Dec	87	1.55	1.51	1.90	2.13	-	-
2008	Jan - Dec	126	1.40	1.53	0.76	1.19	-	-
	Jan - May	75	1.40	2.15	0.51	0.30	-	-
	June - Dec	49	1.40	0.99	1.12	1.57	2.95	3.28
Overall	Jan - Dec	277	1.29	1.45	1.03	1.60	-	-
	Jan - May	139	1.01	1.63	0.55	0.38	-	-
	Jun - Dec	-	1.48	1.27	1.51	1.91	2.95	3.28

[a] Standard deviations are based on average monthly values.

In 2008, 75 days were used in modeling for the months of January to May. For this period, the mean emission flux for KS1 was 1.40 g/m^2-day and that for KS2 was 0.51 g/m^2-day. Comparing KS1 January to May emission fluxes, KS1 emission flux increased by 0.78 g/m^2-day (percentage increase of more than 120%) from 2007 to 2008. The main reason for this was the drastic increase of emission flux for the month of April for year 2008 compared to 2007. In 2007, the emission flux for April was just 0.10 g/m^2-day (based on 11 days of data); in 2008, on the other hand, the emission flux in April was 5.34 g/m^2-day (based on 10 days of data). The cause of this increase was not known: precipitation was relatively the same at 4.88 mm for April of 2007 and 5.51 mm for year 2008; the sprinkler system was not operated for both periods. Forty-nine days were used for the second part of 2008 modeling. With the number of days decreased from 61 to 49 days for KS3, the resulting emission flux was even higher at 2.95 g/m^2-day. KS1 and KS2 emission fluxes were 1.40 g/m^2-day and 1.12 g/m^2-day respectively. Comparison of emission fluxes between KS1 and KS2 showed that the two did not differ significantly ($P>0.05$) in terms of emissions for both the January to May and June to December periods.

AERMOD-derived PM_{10} emission factors are summarized in Tables 4.5a and 4.5b. Results showed that KS1 generally had the smallest PM_{10} emission factors (overall mean of 21 kg/1000hd-day). Statistical analysis showed that, unlike the emission fluxes, the annual emission factors of KS1 and KS2 were significantly different ($P<0.05$). Similar to the trend on emission fluxes, the KS3 emission factor (for the June to November 2008) was the highest (48 kg/1000hd-day) and even higher than the US EPA emission factor (42 kg/1000hd-day). Again, note that the data for KS3 is for the June to November period only; it is expected that, based on the data from KS1 and KS2, the average emission rate for the January to December period would be considerably less than that for the June to November. As such, the annual emission factor for KS3 would still be considerably less than the US EPA emission factor.

Seasonal (Hot and Cold Months) Emission Rates

KS1 had overall mean emission fluxes of 1.64 and 0.51 g/m^2-day for the hot months (April to October) and cold months (November to March), respectively (Table 4.6a), equivalent to 69% difference. For KS2, overall mean emission fluxes for the hot and cold months were 1.45 and 0.23 g/m^2-day, respectively, which was equivalent to an 84% difference. KS3, which only had six months of data, had emission fluxes of 2.87 and 1.02 g/m^2-day for hot months (June to October) and cold month (November), respectively (difference of 64%). Comparison between KS1 and KS2 showed that emission fluxes from the two feedlots did not differ significantly ($P>0.05$) for both hot and cold months.

Table 4.5 Yearly emission factors (weighted-average).

a. For all days (emission factor in kg/1000 hd-day).

Year	KS1			KS2			KS3		
	Days		EF	Days		EF	Days		EF
	Total	With Rain		Total	With Rain		Total	With Rain	
2007	215	34	26	188	47	33	-	-	-
2008	237	39	16	190	42	24	61	12	48
Overall	452	73	21	381	89	29	61	12	48

b. For selected days (emission factor in kg/1000 hd-day) .

Year	Period	Number of Days	EF		
			KS1	KS2	KS3
2007	Jan – Dec	151	19	37	-
	Jan – May	64	10	16	-
	June – Dec	87	26	52	-
2008	Jan – Dec	126	23	13	-
	Jan – May	75	23	14	-
	June – Dec	49	23	31	58
Overall	Jan – Dec	277	21	25	-
	Jan – May	139	17	15	-
	June – Dec	-	25	42	58

Table 4.6 Comparison of emission fluxes between hot and cold months (weighted-average).

a. For all days (emission flux in g/m^2-day).

Year	Hot Months (April to October)			Cold Months (November to March)		
	KS1	KS2	KS3	KS1	KS2	KS3
2007	2.03	1.80	-	0.45	0.21	-
2008	1.24	1.10	2.87	0.56	0.24	1.02
Overall	1.64	1.45	2.87	0.51	0.23	1.02

b. For selected days (emission flux in g/m^2-day).

Year	Hot Months (April to October)				Cold Months (November to March)			
	Number of Days	KS1	KS2	KS3	Number of Days	KS1	KS2	KS3
2007	105	1.59	1.82	-	46	0.17	0.25	-
2008	39	1.59	1.37	3.38	9	0.62	0.11	1.21
Overall	144	1.59	1.60	3.38	55	0.40	0.18	1.21

Table 4.6b summarizes the PM_{10} emission fluxes for those days in which all the feedlots had emission data. In 2007, the KS1 emission flux for the hot months was lower at 1.59 g/m^2-day (from 2.03 g/m^2-day); for cold months, KS1 had lower emission, which decreased from 0.45 g/m^2-day (for all days) down to 0.17 g/m^2-day (selected days). However, a different trend was observed for KS2 in 2007; differences in PM_{10} emission fluxes for hot and cold months were small at 0.02 g/m^2-day and 0.04 g/m^2-day respectively. KS1 and KS2 emission fluxes during the hot months in 2008 were 1.59 and 1.37 g/m^2-day respectively; both had low emission fluxes during the cold months (0.62 g/m^2-day for KS1 and 0.11 g/m^2-day for KS2). The KS3 emission flux was high for the hot months with an average of 3.38 g/m^2-day; the flux for the cold month was 1.21 g/m^2-day and was considerably higher than those for KS1 and KS2.

Summarized in Tables 4.7a and b are the equivalent emission factors for the hot and cold months. The trends of the emission factors were similar to those for the emission fluxes. Paired t-test showed that KS1 and KS2 did not significantly differ ($P>0.05$) in the emission factor during the hot months; however, their emission factors for the cold months were significantly different ($P<0.05$).

Table 4.7 Comparison of emission factors between hot and cold months (weighted-average).

a. For all days (emission factor in kg/1000 hd-day).

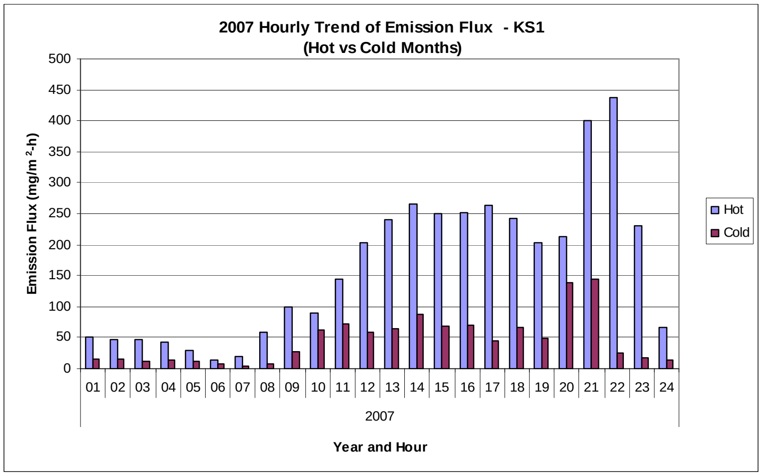
Year	Hot Months			Cold Months		
	KS1	KS2	KS3	KS1	KS2	KS3
2007	34	49	-	8	6	-
2008	21	30	56	9	7	20
Overall	28	40	56	9	7	20

b. For selected days (emission factor in kg/1000 hd-day).

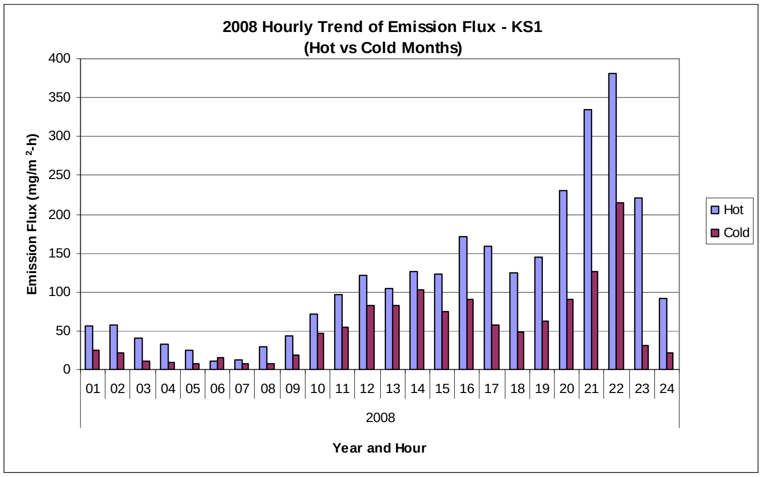
Year	Hot Months				Cold Months			
	Days	KS1	KS2	KS3	Days	KS1	KS2	KS3
2007	105	27	50	-	46	3	7	-
2008	39	27	37	66	9	10	3	24
Overall	144	27	44	66	55	7	5	24

Figures 4.2 and 4.3 summarize the mean hourly emission fluxes for the hot and cold months for each year and for the three feedlots. The mean hourly values for the hot months (April to October) were considerably higher than those for the cold months (November to March). For KS1, a large decrease in emission flux was observed almost the whole day in 2007 (percentage difference of 69%) and from 1600 h until 0500 h in 2008 (average percentage difference of 65%). For KS2, hourly emission fluxes decreased significantly (percentage decrease of 79%) when weather conditions shifted from hot to cold conditions. A large decrease (percentage decrease of 80%, maximum of 96% at 2200 h) due to cold conditions was observed within the EDP period for KS3, specifically from 1700 h until 1100 h. From 1200 h to 1600 h, the decrease in KS3 emission flux was low with an average decrease of 32% (lowest at 1400 h at 13% only).

The hourly emission fluxes during the hot months were generally highest during the EDP periods for KS1 and KS3. For KS1, the overall mean hourly emission flux was highest at 2200h in 2007 and 2008 (figs. 4.2a and b). For KS3, the hourly emission flux during the hot months was highest at 2100 h (fig. 4.3c). For KS2 (figs. 4.3a and b), on the other hand, the hourly trend of emission fluxes differed from those for KS1 and KS3. Although emission fluxes during the EDP periods were generally higher than those during the early morning period (2400 h to 0800 h), emission fluxes were highest in the mid-afternoon (1300 h to1700 h for year 2007, 1100 h to 1700 h for year 2008). Based on the 2-year period at KS1, hourly emission fluxes during the EDP period ranged from 124 to 437 mg/m^2-h for KS1 during the hot months and from 17 to 215 mg/m^2-h during the cold months. For KS2, hourly emission fluxes during the EDP periods ranged from 110 to 263 mg/m^2-h for the hot months and from 4 to 63 mg/m^2-h for the cold months. For KS3, hourly emission fluxes during the EDP periods ranged from 250 to 939 mg/m^2-h for the hot months and from 22 to 142 mg/m^2-h for the cold months. For the rest of the day, highest emission fluxes for the hot and cold months were as follows: for KS1, 267 mg/m^2-h and 102 mg/m^2-h; for KS2, 322 mg/m^2-h and 75 mg/m^2-h; and for KS3, 289 mg/m^2-h and 210 mg/m^2-h.



(a)



(b)

Figure 4.2 Mean hourly emission fluxes: a) KS1 in 2007; b) KS1 in 2008.

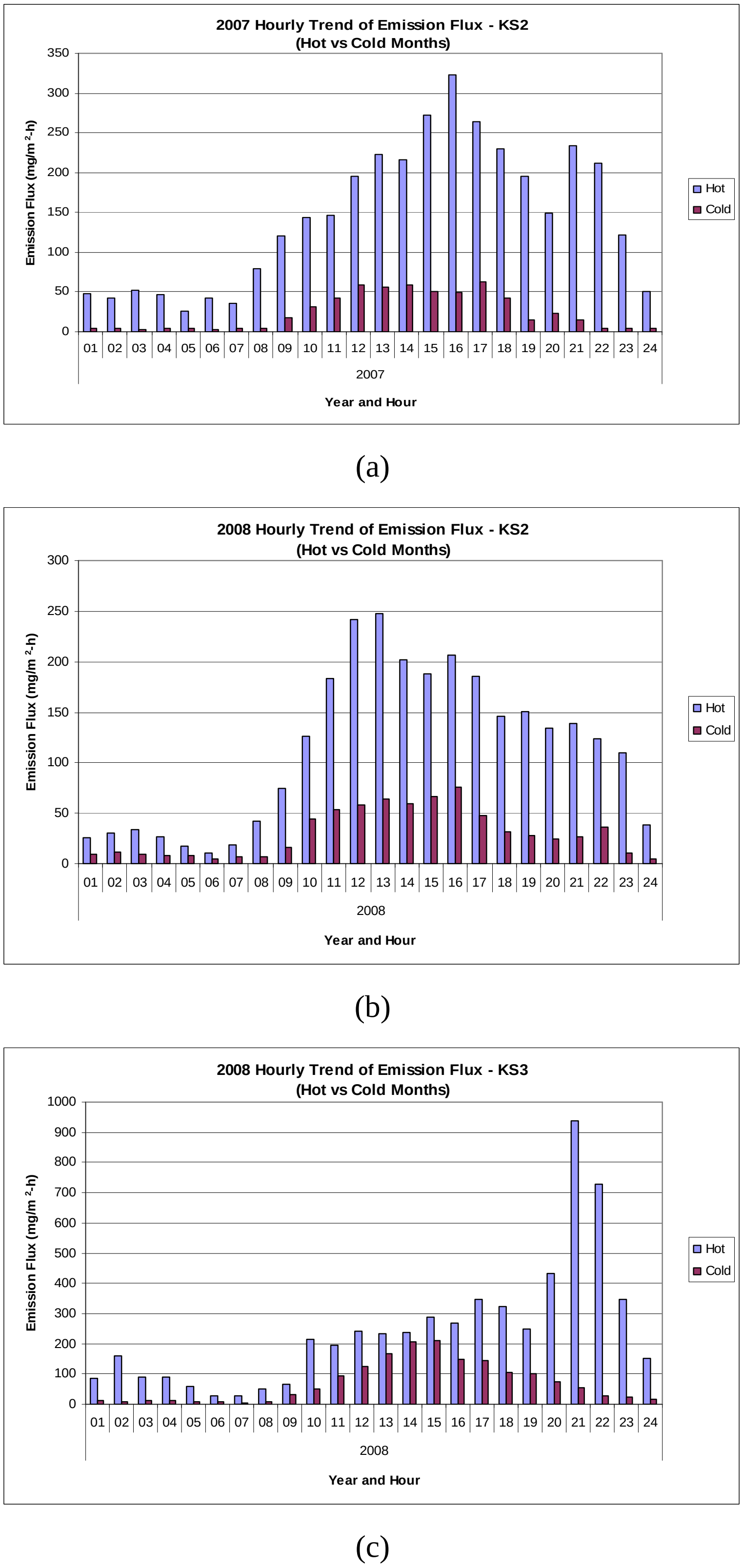


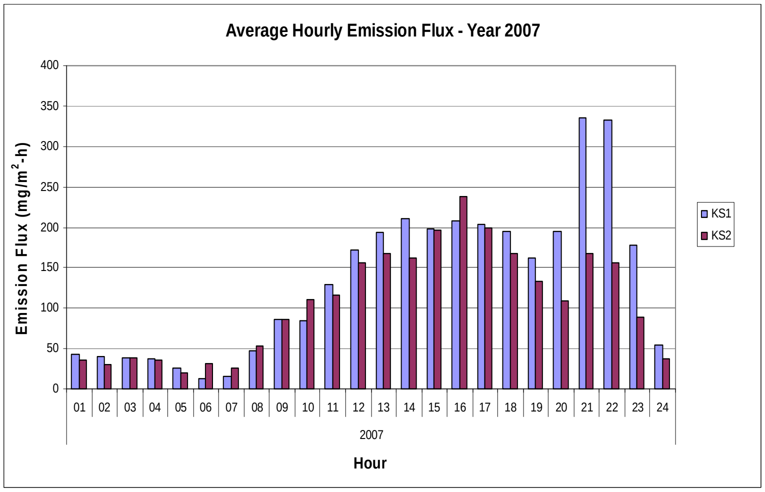
Figure 4.3 Mean hourly emission fluxes: a) KS2 in 2007; b) KS2 in 2008; c) KS3 in 2008.

Hourly Trends of Emission Fluxes and Measured PM_{10} Concentrations

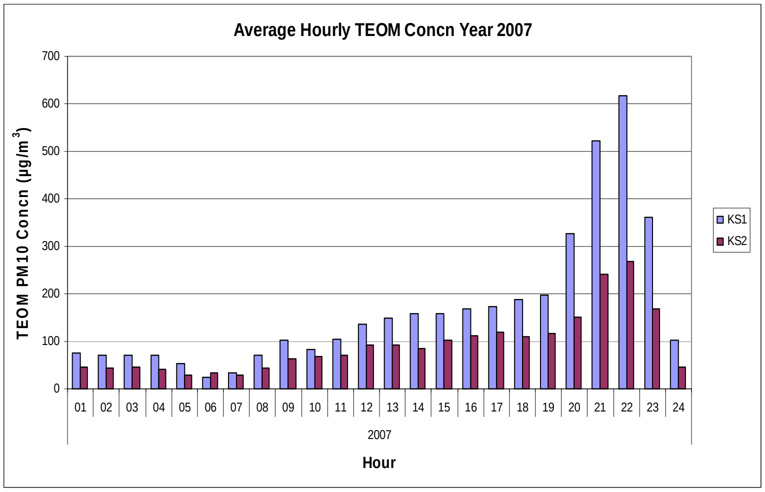
The yearly mean hourly AERMOD-derived emission fluxes and yearly average measured PM_{10} concentrations were also analyzed to verify if the observed increase in PM_{10} concentrations during the EDP periods could be attributed to the increase in emission fluxes. Based on the AERMOD formulation (US EPA, 2004d), there are three variables that affect concentration: emission rate, wind speed, and stability conditions. For KS1, the hourly emission fluxes were generally higher during the EDP period (figs. 4.4a and 4.5a) and this corresponded to the time when high concentrations were measured. The period before the EDP (1200 h to 1600 h) also had relatively high PM_{10} emission fluxes although measured PM_{10} concentrations were generally low (figs. 4.4b and 4.5b). Note that emissions during this period were likely a combination of emissions from pens and unpaved feed alleys. The difference in trends of measured concentrations and emission fluxes could reflect the effects of meteorological conditions (e.g., boundary layer, mixing height) for both periods. Based on the modeling results, atmospheric conditions were unstable during the 1200 h to 1600 h period and stable during the EDP period. As such, the high PM_{10} concentrations measured at KS1 during the EDP period were likely caused by the increase in emission (due to cattle activity) and stable conditions.

For KS2, there was a difference in the PM_{10} emission flux during the EDP periods between 2007 (fig. 4.4a) and 2008 (fig. 4.5a). An increase in PM_{10} emission flux at KS2 during the EDP period (starting 2100 h) was observed in 2007, although the highest emission fluxes were still observed during the mid-afternoon to late afternoon period (1200 h to 1800 h). The corresponding measured concentrations (fig. 4.4b), however, were low similar to what were observed at KS1. Measured concentrations during the EDP period were still higher (by more than 200% compared with the afternoon values) even if the maximum EDP emission flux was not as high (lower by approximately 30%) as the maximum emission flux for the afternoon period. In 2008, however, the trend at KS2 was different. There was no increase in PM_{10} emission flux in the evening; the highest emission fluxes occurred from 1100 h to 1700 h. After 1700 h, emission fluxes almost had no change and were maintained above 100 mg/m^2-h until after 2300 h. Looking at the hourly trends in a monthly basis, the highest emission fluxes at KS2 were still observed in the afternoon; however, KS2 emission fluxes also increased during the EDP periods for several months (i.e., March to June, August to October). Therefore, similar to KS1, increase in emission (i.e., by cattle activity) in stable meteorological conditions contributed to the increase in PM_{10} concentrations during the EDP period for KS2. Comparing the two feedlots, statistical analysis also showed that KS1 and KS2 did not significantly differ ($P>0.05$) in hourly emission fluxes.

KS3 was somewhat a different case. Not only the occurrence of stable atmospheric conditions could have caused the increase in PM_{10} concentrations during the EDP period, KS3 also had high emission fluxes that were almost twice those at KS1. Specifically, at 2100 h to 2200 h (fig. 4.5a), average emission fluxes were 712 and 558 mg/m^2-h, respectively. Comparing KS1 and KS3, which almost had the same stocking densities and pen cleaning frequency, an average of 50% reduction (maximum of 62%) in emission flux was estimated due to sprinkler system operation. This was confirmed by paired t-test; KS1 and KS3 differed significantly ($P<0.05$) in mean hourly emission fluxes.

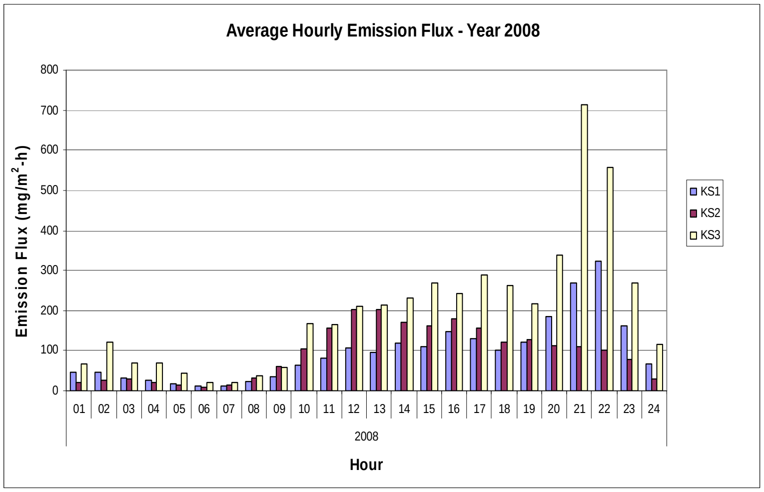


(a)

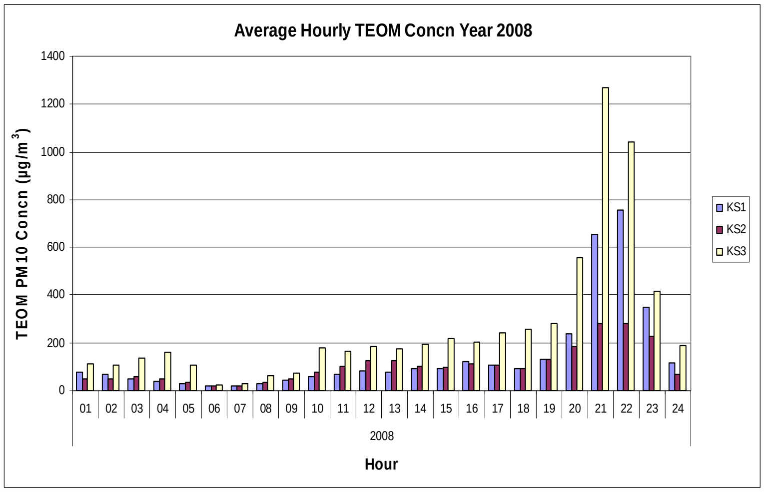


(b)

Figure 4.4 Hourly emission fluxes (a) and measured concentrations (b) in 2007.



(a)



(b)

Figure 4.5 Hourly emission fluxes (a) and measured (TEOM) concentrations (b) in 2008.

These differences in the emission flux trends could have been caused by the effects of several factors: PM control methods (i.e., sprinkler system operation, pen cleaning); pen conditions (i.e., manure layer depth, stocking density); PM emission from road traffic (i.e., unpaved road conditions, feeding schedule, average truck speed, number of trucks); and other activities (i.e., loading/transferring of cattle, feedmill).

For the next analysis, periods in the day were classified into three classes: (1) I - midnight to early morning (2400 h to 0900 h), (2) II - mid-afternoon (1000 h to 1600 h), and (3) III - EDP period (1700 h to 2300 h). Classification was based on the PM_{10} concentration trend; for period I, the concentration would be low mainly due to low emission flux; an increase in concentration would be expected in period II due to higher emissions from the pens plus additional PM emissions from unpaved roads; and for period III (the EDP period), the concentration would be high due to cattle activity and/or stable atmospheric conditions. Using this classification as basis, percent contributions of each period on the cumulative PM_{10} emission fluxes and average measured PM_{10} concentration in the day were determined (Table 4.8).

Table 4.8 Percentage contributions of each period on the overall mean daily concentration and emission flux values.

Feedlot	TEOM PM_{10} Concentration			PM_{10} Emission Fluxes		
	I 2400 to 0900 h	II 1000 to 1600 h	III – EDP 1700 to 2300 h	I 2400 to 0900 h	II 1000 to 1600 h	III - EDP 1700 to 2300 h
KS1	15%	21%	64%	13%	34%	53%
KS2	18%	29%	53%	13%	49%	38%
KS3	15%	21%	64%	13%	32%	55%

KS1 and KS3 showed similar results. The EDP period contributed from 53% to 55% on the cumulative daily emission flux and approximately 64% on the average daily concentration. For KS2, the EDP period also had the highest contribution on the average concentration (53%) but only 38% on the overall emission flux. As such, for KS2, the emission flux and concentration did not follow the same trend. The EDP period can have relatively lower emission rate but still can have high concentration trend possibly due to meteorological conditions for this period.

Effects of Weather Conditions

As shown in Table 4.4a, emission fluxes for KS1 and KS2 were higher by 31% in 2007 than in 2008. Comparison of the weather conditions in 2007 and 2008 (Table 4.9) did not reveal any major factors that could explain the higher emission flux in 2007 than in 2008. For example, the mean air temperatures were generally the same in 2007 and 2008. Total amounts of precipitation were generally higher for both feedlots in 2007 than in 2008, suggesting that the emission flux in 2007 should even be smaller than in 2008.

Table 4.9 Yearly weather values.

Year	Weather Parameter	KS1	KS2
2007	Temp (Avg., °C)	13	13
	Wind Speed (Avg., mps)	3.85	3.74
	Precipitation (mm)	667	782
2008	Temp (Avg., °C)	12	13
	Wind Speed (Avg., mps)	4.77	3.38
	Precipitation (mm)	584	732

The weather conditions during the hot months (April to October) in 2007 and 2008 were also analyzed (Table 4.10). The hot months were considered because, as shown previously, PM_{10} emission fluxes were considerably higher during the hot months than during the cold months. From Table 4.10, there could be two major reasons why the emission flux was higher in 2007 than in 2008: temperature and number of days with rainfall events. The average temperatures for the hot months for KS1 and KS2 were higher in 2007 than in 2008 by 2^{o}C. The relatively higher temperature could have resulted in higher PM emission potential from the feedlot surfaces. Regarding the rainfall events, for KS1, even if the precipitation in 2008 was lower by 20 mm, the number of days when there was rainfall was higher by 14 days in 2008 than in 2007. Similarly for KS2, there were more days with rainfall events in 2008 (65 days) than in 2007 (51 days). Depending on rainfall amount and intensity, based on the measured downwind concentrations, the effect of rain may last for several days (3 - 8 days).

Table 4.10 Weather conditions during the April to October periods.[a]

Year	Parameter	Unit	KS1	KS2
2007	Number of Days (April to October: 214 days)	days	152	116
	Emission Flux	g/m^2-day	2.03 (0.34 – 5.00)	1.80 (0.30 – 4.52)
	Temperature	°C	21 (11 – 82)	21 (11 – 82)
	Wind Speed	m/s	4.11 (3.00 – 5.31)	4.23 (3.00 – 5.86)
	Precipitation	mm	583	640
	Number of Days with Rainfall	days	38	51
2008	Number of Days (April to October: 214 days)	days	158	141
	Emission Flux	g/m^2-day	1.24 (0.77 – 3.82)	1.10 (0.51 – 1.96)
	Temperature	°C	19 (10 – 26)	19 (10 – 26)
	Wind Speed	m/s	4.82 (3.76 – 5.60)	3.40 (2.63 – 4.24)
	Precipitation	mm	563	702
	Number of Days with Rainfall	days	52	65

[a] Values in parenthesis represent the range.

Limitations

There are several weaknesses in this research that relate to PM_{10} monitoring with TEOMs and inherent weaknesses of atmospheric dispersion modeling. The performance bias in inertial pre-separators for particulate samplers (e.g., Buser et al., 2007), which was the TEOM (e.g., Guo et al., 2009) for this study, was ignored largely because of the lack of scientifically validated means of correcting for that bias (Upadhyay et al., 2008). As such, the emission fluxes and factors that were generated from this study were contingent on the use of TEOMs; these fluxes and factors may have to be adjusted when scientifically valid correction factors have been developed for TEOMs. A related limitation was the assumption that the emission flux was uniform and that the mass concentration on the downwind side of the feedlot was also uniform so that a single point measurement of the concentration would be adequate.

The fluxes and factors were also based on AERMOD, which has inherent limitations as presented earlier. Using another dispersion model would likely result in different values of emission rates. The effect of feedlot area (pen area vs. total feedlot area, including pen area and unpaved feed alleys) on the calculated emission factor has been mentioned. A related factor is the number of cattle. This study used average headcount and assumed that the headcount was constant for each feedlot. The actual headcount varied daily and could be up to ±10% of the average value.

Summary and Conclusion

PM_{10} emission rates at three cattle feedlots in Kansas were determined using inverse dispersion modeling technique with AERMOD and measured PM_{10} concentrations. The following conclusions were drawn from this research:

- Based on the 2-year period, KS1, which was equipped with a sprinkler system, had a mean PM_{10} emission flux of 1.29 g/m^2-day, ranging from 0.04 – 4.98 g/m^2-day. KS2, a non-sprinkled feedlot but with more frequent pen cleaning, had a slightly less mean PM_{10} emission flux (1.03 g/m^2-day) than KS1. Based on six months of data, KS3 had the highest mean PM_{10} emission flux of 2.48 g/m^2-day (range of 0.05 – 5.00 g/m^2-day). The corresponding mean PM_{10} emission factors were 21 kg/1000hd-day, 29 kg/1000hd-day, and

48 kg/1000hd-day for KS1, KS2, and KS3, respectively. The emission factors for KS1 and KS2 were considerably smaller than the published US EPA emission factor for cattle feedlots (i.e., 42 kg/1000 hd-day). The emission factor for KS3 was slightly greater than the US EPA emission factor; however, it was a biased estimate because it was based only on the June to December 2008 period.

- For all feedlots, mean PM_{10} emission fluxes during the April to October period were two to nine times higher than those during the November to March period.
- The hourly PM_{10} emission fluxes followed closely the hourly trends of the PM_{10} concentrations for KS1 and KS3 but not for KS2. Both the concentrations and emission fluxes at KS1 and KS3 were highest during the evening period. For KS2, however, the concentration was highest during the evening but emission flux was highest in the afternoon. Still, results suggest that increase in cattle activity and stable conditions both influenced the observed peaks in PM_{10} concentration during the evening for all feedlots.

Despite the acknowledged limitations of the study related to the point measurements with TEOMs and the inherent limitations of AERMOD, the PM_{10} emission rates presented here could serve as basis for estimating actual emission rates from cattle feedlots in Kansas.

References

Auvermann, B., R. Bottcher, A. Heber, D. Meyer, C. B. Parnell, Jr., B. Shaw, and J. Worley. 2006. Particulate matter emissions from animal feeding operations. In *Animal Agriculture and the Environment: National Center for Manure and Animal Waste Management White Papers*, 435-468. J. M. Rice, D. F. Caldwell, F. J. Humenik, eds. St. Joseph, Mich.: ASABE.

Buser, S. D., C. B. Parnell, Jr., B. W. Shaw, and R. E. Lacey. 2007. Particulate matter sampler errors due to the interaction of particle size and sampler performance characteristics: Ambient PM_{10} samplers. Transactions of the ASABE 50(1): 229-240.

Cimorelli, A. J., S. G. Perry, A. Venkatram, J. C. Weil, R. J. Paine, R. B. Wilson, R. F. Lee, W. D. Peters, and R. W. Brode. 2005. AERMOD: A dispersion model for industrial source applications. Part I: General model formulation and boundary layer characterization. *Journal of Applied Meteorology* 44: 682-693.

CFR. 2003. Code of Federal Regulations, 40 CFR, Part 51: Guideline on air quality models.

CFR. 2005. Code of Federal Regulations, 40 CFR, Part 51: Revision to the guideline of air quality models: Adoption of a preferred general purpose (flat and complex terrain) dispersion model and other revisions.

DesignCAD 3M Max18. 2007. Novato, CA: IMSIDesign.

Faulkner, W. B., J. M. Lange, J. J. Powell, B. W. Shaw, and C. B. Parnell. 2007. Sampler placement to determine emission factors from ground level area sources. ASABE Paper No. 074103. St. Joseph, Mich.: ASABE

Faulkner, W. B., L. B. Goodrich, V. S. V. Botlaguduru, S. C. Capareda, and C. B. Parnell. 2009. Particulate matter emission factors for almond harvest as a function of harvester speed. *Journal of the Air & Waste Management Association* 59: 943 – 949.

Guo, L., R. G. Maghirang, E. B. Razote, J. Tallada, J. P. Harner, and W. Hargrove. 2009. Field comparison of PM_{10} samplers. *Applied Engineering in Agriculture* 25(5): 737-744.

Holmes, N.S., and L. Morawska. 2006. A review of dispersion modeling and its application to the dispersion of particles: An overview of different dispersion models available. *Atmospheric Environment* 40: 5902-5928.

National Research Council (NRC). 2003. Air emissions from animal feeding operations: Current knowledge, future needs. Washington, D.C.: National Academy of Sciences.

Perry, S.G., A. J. Cimorelli, A. J., R. J. Paine, R. W. Brode, J.C Weil, A. Venkatram, R. B. Wilson, R.F. Lee, and W.D. Peters. 2005. AERMOD: A dispersion model for industrial source applications. Part II: Model performance against 17 field study databases. *Journal of Applied Meteorology* 44: 694-708.

SAS. 2002. *SAS for Windows*. Ver. 9.1.3 Service Pack 4. Cary, NC: SAS Institute, Inc.

Turner, D. B., and R. H. Schulze. 2007. *Practical Guide to Atmospheric Dispersion Model*. Dallas, TX: Trinity Consultants, Inc. and Air & Waste Management Association.

Upadhyay, J. K., B. W. Auvermann, A. N. Paila, and N. Hiranuma. 2008. Open-path transmissometry to determine atmospheric extinction efficiency associated with feedyard dust. Transactions of the ASABE 51(4): 1433-1441,

U.S. Environmental Protection Agency (US EPA). 1988. *Gap filling* PM_{10} *emission factors for selected open area dust sources*. EPA-450/4-88-003. Research Triangle Park, NC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (US EPA). 2001. *Procedures Document for National Emission Inventory, Criteria Air Pollutants 1985 - 1999*. EPA-454/R-01-006. Research Triangle Park, NC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (US EPA). 2004a. *User's Guide for the AMS/EPA Regulatory Model – AERMOD*. EPA-454/B-03-001. Research Triangle Park, NC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (US EPA). 2004b. *User's Guide for the AERMOD Meteorological Preprocessor (AERMET)*. EPA-454/B-03-002. Research Triangle Park, NC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (US EPA). 2004c. *AERMOD: Description of Model Formulation*. EPA-454/R-03-004. Research Triangle Park, NC: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (US EPA). 2009. *Dispersion modeling*. Research Triangle Park, NC: U.S. Environmental Protection Agency. Available at www.epa.gov. Accessed 29 September 2009.

CHAPTER 5 - Conclusions and Recommendations

Summary and Conclusions

This research was conducted to evaluate the effectiveness of water sprinkler system in reducing downwind PM_{10} concentrations in a cattle feedlot and estimate the PM_{10} emission fluxes in cattle feedlots in Kansas.

The effectiveness of the water sprinkler system was determined from PM_{10} concentration measurements at a sprinkler-equipped cattle feedlot in Kansas (KS1). The sprinkler system at KS1 had control efficiency for PM_{10} ranging from 32% to 80%, with an overall mean of 53%. With a maximum water application rate of 5 mm/day and application setting of 1.25 mm (in 6 min) every 4 h, the effect of water application with the sprinkler system lasted for one day or less. Rainfall events had control efficiencies ranging from 17% to 96%; depending on the rainfall amount and intensity, the effect lasted for three to seven days.

Emission fluxes were estimated by applying inverse dispersion modeling technique with AERMOD on measured concentrations from three feedlots in Kansas: KS1 (sprinkled), KS2 (non-sprinkled feedlot with more frequent pen cleaning), and KS3 (feedlot with water application on both pen surface and unpaved roads). The overall annual PM_{10} emission fluxes were 1.29 g/m^2-day (for January 2007 to December 2008) for KS1, 1.03 g/m^2-day (for January 2007 to December 2008) for KS2, and 2.48 g/m^2-day (for June to November 2008) for KS3. The corresponding annual emission factors were 21 kg/1000hd-day (7.7 tons/1000hd-yr) for KS1, 29 kg/1000hd-day (10.6 tons/1000hd-yr) for KS2, and 48 kg/1000hd-day for KS3. These emission factors (except for KS3 that had only six months of data) were smaller than the published US EPA PM_{10} emission factor (17 tons/1000hd-yr). Analysis of the results from atmospheric dispersion modeling suggests that the peak PM_{10} concentrations that were observed during the late afternoon to early evening period could be due to the combined effects of relatively stable weather conditions (i.e., less mixing) and increased cattle activity during this period (i.e., increased PM_{10} emission fluxes).

Recommendations for Further Study

The following are recommended for future research: (1) development and evaluation of PM control methods; and (2) quantification of PM emission rates at cattle feedlots. Specific topics are the following:

- Determine the contributions of various sources (e.g., pen surface, unpaved feed alleys) on the overall cattle feedlot emissions of PM_{10} and $PM_{2.5}$.
- Determine effects of water sprinkler system parameters (i.e., sprinkler timing, sprinkler uniformity, and water application rate) on pen surface moisture content and emission rates of various constituents (i.e., PM_{10}, $PM_{2.5}$, gaseous components).
- Quantify the effectiveness of pen cleaning/manure harvesting in reducing particulate and gaseous emissions from cattle feedlots.
- Identify variables (e.g., pen surface moisture content, temperature-humidity index, etc.) that can be used in estimating potential particulate emissions and/or concentrations.
- Determine the effect of feeding practices (i.e., feed rations) on particulate and gaseous emissions.
- Quantify emission rates of PM_{10} and $PM_{2.5}$ from cattle feedlots using various methods, including micrometeorological techniques.
- For atmospheric dispersion models, including AERMOD, determine the effect of particle settling in calculated emission rates.

Appendix A - Supporting Data for Chapters 1 and 2

Table A.1 Cattle on Feed - Inventory: 2007 and 2002 (USDA, 2009a).

Number of Head	2007		2002	
	Farms	Number	Farms	Number
1 – 9	15,818	65,809	30,409	129,481
10 – 19	7072	93,242	13,778	179,989
20 – 49	9136	280,083	14,552	432,316
50 – 99	6313	426,159	9,207	615,629
100 – 199	4375	586,624	5,889	780,033
200 – 499	3744	1,118,788	4,139	1,212,797
500 – 999	1997	1,429,215	1,442	966,408
1,000 – 2,499	780	1,152,679	620	942,904
2,500 or more	774	10,946,311	707	9,645,988

Table A.2 Cattle on Feed, 1000+ capacity feedlots, by States (USDA, 2009b).

State	Year 2007 x 1,000 head	Year 2008 x 1,000 head
AZ	334	368
AR	3	3
CA	550	560
CO	1,130	1,140
ID	265	245
IL	215	170
IN	110	110
IA	872	860
KS	2,620	2,630
KY	20	15
MD	10	9
MI	175	170
MN	285	306
MO	75	65
MT	55	40
NE	2,700	2,700
NV	8	7
NM	136	160
NY	20	30
NC	4	3
ND	60	65
OH	185	190
OK	355	355
OR	90	80
PA	75	75
SD	420	400
TN	7	4
TX	2,880	2,980
UT	30	35
VA	30	30
WA	187	170
WV	10	5
WI	240	250
WY	90	70
Other States[a]	22.7	17.7
US	14,268.7	14,316.7

[a] Other States: AL, AK, CT, DE, FL, GA, HI, LA, ME, MA, MS, NH, NJ, RI, SC and VT

Appendix B - Supporting Data for Chapter 3

Table B.1 PM_{10} concentration data for KS1 sprinkler on/off events – 24 hour period.

	Temp (°C)	Water (mm)	Average concentration for the period (µg/m^3)				Maximum concentration for the period (µg/m^3)			
			Before	After	Decrease	% Reduction	Before	After	Decrease	% Reduction
1	25.9	3.08	86	51	35	41%	218	199	19	9%
2	25.1	2.61								
3	28.8	2.18					1354	1156	198	15%
4	9.0	3.42	332	215	117	35%	2344	1679	665	28%
5	20.0	2.94	290	93	197	68%	850	573	276	33%
6	30.1	5.13	278	188	90	32%	1217	875	341	28%
7	17.6	4.22	698	316	383	55%	4985	2051	2935	59%
8	21.8	4.69					399	343	56	14%
9	18.7	3.96	571	316	255	45%	7954	1893	6060	76%
10	10.2	3.32	58	23	35	60%	211	122	89	42%
11	11.4	1.50	665	259	406	61%	5958	927	5032	84%
12	8.9	3.56	152	30	122	80%	480	105	376	78%
13	24.1	3.87					2874	1471	1403	49%
14	24.5	3.87	224	100	125	56%	2874	568	2307	80%

Table B.2 PM$_{10}$ concentration data for KS1 sprinkler on/off events – Evening Dust Peak (EDP) period.

	Temp (°C)	Water (mm)	Average concentration for the period (μg/m^3)				Maximum concentration for the period (μg/m^3)			
			Before	After	Decrease	% Reduction	Before	After	Decrease	% Reduction
1	25.9	3.08	119	84	36	30%	218	199	19	9%
2	25.1	2.61					516	450	66	13%
3	28.8	2.18	313	259	54	17%	1340	1156	184	14%
4	9.0	3.42	637	473	164	26%	2573	1679	894	35%
5	20.0	2.94	290	138	152	52%	850	533	317	37%
6	30.1	5.13	476	298	178	37%	1165	875	290	25%
7	17.6	4.22	1469	624	845	58%	4985	2051	2935	59%
8	21.8	4.69					399	287	112	28%
9	18.7	3.96	1331	547	784	60%	7954	1893	6060	76%
10	10.2	3.32	61	20	42	68%	153	65	89	58%
11	11.4	1.50	1373	331	1042	76%	4474	927	3547	79%
12	8.9	3.56	290	55	235	81%	480	105	376	78%
13	24.1	3.87					2874	1471	1403	49%
14	24.5	3.87	583	193	391	67%	2874	568	2307	80%

Table B.3 PM$_{10}$ concentration data for KS1 rainfall events – 24 hour period.

	Temp (°C)	Rainfall (mm)	Average concentration for the period (µg/m^3)				Maximum concentration for the period (µg/m^3)			
			Before	After	Decrease	% Reduction	Before	After	Decrease	% Reduction
1	22.0	1.78	617	295	322	52%	10458	1567	8891	85%
2	16.6	12.7	432	35	397	92%	1567	35	1532	98%
3	16.5	12.7	125	48	77	62%	693	227	466	67%
4	25.1	36.07	421	19	402	95%	1091	46	1045	96%
5	26.3	30.48	848	53	795	94%	1460	110	1350	92%
6	28.7	7.62	198	30	168	85%	956	90	866	91%
7	23.3	7.62								
8	32.5	80.01	347	79	268	77%	3006	241	2765	92%
9	23.6	3.81	654	45	609	93%	1842	210	1632	89%
10	11.4	15.24	53	12	41	77%	272	31	242	89%
11	10.9	4.06	38	14	24	64%	306	103	203	66%
12	19.6	20.83	199	20	179	90%	2280	64	2216	97%
13	20.8	79.25	285	38	247	87%	1295	189	1106	85%
14	22.1	22.86	182	56	126	69%	437	161	276	63%
15	23.4	4.32	64	25	40	61%	222	79	142	64%
16	19.9	7.11	63	12	50	80%	129	22	108	83%
17	29.5	2.03	426	355	71	17%	7079	1995	5084	72%
18	24.2	4.32	374	97	276	74%	2725	349	2376	87%
19	26.8	8.38	299	109	190	64%	2565	272	2292	89%
20	15.4	3.3	712	143	568	80%	4212	838	3375	80%
21	17.6	10.16	712	29	683	96%	4212	147	4065	97%
22	17.6	10.16	143	29	114	80%	838	147	690	82%
23	25.7	10.16	271	120	151	56%	1304	721	583	45%
24	22.9	14.98	215	21	194	90%	1500	70	1431	95%
25	21.9	15.49	145	33	112	77%	1279	45	1233	96%
26	21.9									
27		15.49	100	33	67	67%	246	45	201	82%
28	27.5	10.92	232	74	158	68%	4052	326	3726	92%
29	23.2	12.95	300	74	226	75%	2600	383	2217	85%
30	24.8	34.04	134	25	110	82%	1528	171	1357	89%

Table B.4 PM$_{10}$ concentration data for KS1 rainfall events – EDP period.

	Temp (°C)	Rainfall (mm)	Average concentration for the period ($\mu g/m^3$)				Maximum concentration for the period ($\mu g/m^3$)			
			Before	After	Decrease	% Reduction	Before	After	Decrease	% Reduction
1	22.0	1.78	1471	383	1088	74%	10458	754	9704	93%
2	16.6	12.7	575	35	540	94%	754	35	719	95%
3	16.5	12.7	114	12	102	89%	577	19	558	97%
4	25.1	36.07	416	28	388	93%	1045	46	1000	96%
5	26.3	30.48	862	62	800	93%	973	110	863	89%
6	28.7	7.62	251	5	246	98%	417	5	412	99%
7	24.2	7.62	472	308	164	35%	1467	510	957	65%
8	32.5	80.01	717	74	644	90%	3006	241	2765	92%
9	23.6	3.81	861	95	767	89%	1842	210	1632	89%
10	11.4	15.24	47	12	35	75%	69	16	53	77%
11	10.9	4.06	41	14	27	67%	115	54	61	53%
12	19.6	20.83	398	27	370	93%	2280	64	2216	97%
13	20.8	79.25	489	40	449	92%	1295	189	1106	85%
14	22.1	22.86	254	74	180	71%	437	161	276	63%
15	23.4	4.32	84	25	59	70%	222	57	165	74%
16	19.9	7.11	87	11	76	87%	129	13	117	90%
17	29.5	2.03	1088	578	510	47%	7079	1924	5156	73%
18	24.2	4.32	796	105	691	87%	2725	315	2410	88%
19	26.8	8.38	693	172	520	75%	2565	272	2292	89%
20	15.4	3.3	1083	153	930	86%	4212	408	3805	90%
21	17.6	10.16	1083	88	995	92%	4212	147	4065	97%
22	17.6	10.16	153	88	65	42%	408	147	260	64%
23	25.7	10.16	360	207	153	43%	1304	541	764	59%
24	22.9	14.98	412	16	396	96%	1500	44	1457	97%
25	21.9	15.49	282	33	249	88%	1279	45	1233	96%
26	21.9	15.49	88	33	55	63%	189	45	144	76%
27	27.5	10.92	601	109	492	82%	4052	326	3726	92%
28	23.2	12.95	818	130	688	84%	2600	383	2217	85%
29	24.8	34.04	321	23	298	93%	1528	100	1427	93%
30	20.5	6.6	277	21	256	93%	728	141	587	81%

Table B.5 PM_{10} concentration data for KS2 rainfall events – 24 hour period.

	Temp (°C)	Rainfall (mm)	Average concentration for the period (µg/m^3)				Maximum concentration for the period (µg/m^3)			
			Before	After	Decrease	% Reduction	Before	After	Decrease	% Reduction
1	20.3	123.18	25	18	7	28%	162	42	120	74%
2	14.2	10.67	125	40	86	68%	1214	99	1116	92%
3	17.7	94.74	177	28	150	84%	1000	121	880	88%
4	18.4	30.35	77	12	65	85%	302	38	264	87%
5	21.2	53.60	352	57	295	84%	1287	251	1036	80%
6	22.9	24.38	193	60	133	69%	935	139	796	85%
7	26.7	10.42	56	25	31	56%	212	87	124	59%
8	14.1	4.57	163	85	78	48%	4125	448	3677	89%
9	23.5	2.03	250	36	214	85%	1113	168	945	85%
10	14.7	4.32	222	61	161	72%	1313	448	865	66%
11	15.9	28.96	249	30	219	88%	3900	265	3635	93%
12	21.7	22.10	134	37	98	73%	618	106	511	83%
13	24.9	6.10	155	17	139	89%	939	61	877	93%
14	25.8	6.60	380	18	362	95%	1943	130	1813	93%
15	22.0	25.15	29	7	22	77%	108	21	87	81%
16	21.2	28.19	65	10	54	84%	239	56	183	77%

Table B.6 PM$_{10}$ concentration data for KS2 rainfall events – EDP period.

	Temp (°C)	Rainfall (mm)	Average concentration for the period ($\mu g/m^3$)				Maximum concentration for the period ($\mu g/m^3$)			
			Before	After	Decrease	% Reduction	Before	After	Decrease	% Reduction
1	20.3	123.18	50	18	31	63%	162	42	121	74%
2	14.2	10.67	290	51	238	82%	1214	97	1117	92%
3	17.7	94.74	379	33	346	91%	1000	121	880	88%
4	18.4	30.35	153	17	136	89%	302	38	264	87%
5	21.2	53.60	760	110	650	86%	1287	251	1036	80%
6	22.9	24.38	388	8	380	98%	935	10	925	99%
7	26.7	10.42	114	35	79	69%	212	79	133	63%
8	14.1	4.57	410	105	305	74%	4125	448	3677	89%
9	23.5	2.03	388	21	366	94%	1092	95	998	91%
10	14.7	4.32	427	114	313	73%	1313	448	865	66%
11	15.9	28.96	800	28	772	97%	3900	99	3801	97%
12	21.7	22.10	331	57	274	83%	618	106	511	83%
13	24.9	6.10	309	21	288	93%	939	34	904	96%
14	25.8	6.60	1018	21	997	98%	1943	66	1878	97%
15	22.0	25.15	31	7	24	77%	62	12	50	81%
16	21.2	28.19	197	6	191	97%	239	56	183	77%

Appendix C - Supporting Data and Modeling Input Files for Chapter 4

Table C.1 Average monthly PM_{10} emission fluxes for KS1, KS2 and KS3 – All available data 2007 and 2008.

Year	Month	KS1		KS2		KS3[a]	
		Number of days	Average E.Flux[b] (g/m^2-day)	Number of days	Average E.Flux[b] (g/m^2-day)	Number of days	Average E.Flux[b] (g/m^2-day)
2007	1	11	0.04	21	0.07		
	2	13	0.18	16	0.25		
	3	9	0.05	11	0.16		
	4	21	0.34	11	0.30		
	5	24	1.49	25	1.17		
	6	22	1.06	22	1.91		
	7	24	0.60	23	1.03		
	8	25	4.98	1	0.39		
	9	18	3.30	23	2.61		
	10	18	2.45	11	4.52		
	11	13	1.81	7	1.00		
	12	17	0.09	17	0.07		
2008	1	25	0.26	9	0.20		
	2	21	0.20	16	0.17		
	3	17	1.56	16	0.41		
	4	14	3.82	11	0.70		
	5	27	0.77	25	0.79		
	6	22	1.10	24	1.10	3	0.05
	7	28	1.12	24	1.72	5	1.22
	8	26	0.95	24	0.51	13	2.03
	9	16	1.07	14	0.82	14	2.87
	10	25	0.93	17	1.96	13	5.00
	11	16	0.44	10	0.10	13	1.02
	12						

[a] KS3 - no data from January 2007 to May 2008

[b] Average emission flux for the month

Table C.2 Average monthly PM_{10} emission fluxes for KS1, KS2 and KS3 – Selected dates for 2007 and 2008.

Year	Month	Number of days	Average monthly emission flux (g/m^2-day)		
			KS1	KS2	KS3[a]
2007	1	11	0.04	0.05	
	2	12	0.19	0.30	
	3	6	0.05	0.10	
	4	11	0.10	0.30	
	5	24	1.49	1.22	
	6	21	1.11	2.00	
	7	22	0.58	1.07	
	8	1	1.34	0.39	
	9	15	3.96	2.86	
	10	11	3.04	4.52	
	11	1	3.38	5.72	
	12	16	0.09	0.07	
2008	1	9	0.21	0.20	
	2	15	0.22	0.19	
	3	16	1.64	0.41	
	4	10	5.34	0.77	
	5	25	0.80	0.79	
	6	3	0.07	0.03	0.05
	7	4	2.21	1.67	1.52
	8	12	1.57	0.64	2.04
	9	15	1.21	0.82	2.87
	10	7	2.74	4.21	9.23
	11	10	0.62	0.11	1.21
	12				

[a] KS3: no data from January 2007 to May 2008

Table C.3 Hourly averages of PM$_{10}$ emission fluxes and net PM$_{10}$ concentration – 2007 and 2008.

Year	Hour	Average Emission Flux (mg/m^2-h)			Average TEOM PM$_{10}$ Concentration (µg/m^3)		
		KS1	KS2	KS3	KS1	KS2	KS3
2007	01	43	36		75	45	
	02	41	31		72	43	
	03	39	39		72	46	
	04	37	35		70	42	
	05	25	20		53	30	
	06	13	31		24	34	
	07	15	26		33	28	
	08	47	53		72	44	
	09	85	86		102	65	
	10	85	111		83	67	
	11	129	116		106	72	
	12	173	156		137	92	
	13	194	168		150	93	
	14	211	162		158	85	
	15	198	197		158	102	
	16	208	238		168	113	
	17	204	199		172	120	
	18	195	168		187	110	
	19	161	134		197	117	
	20	195	109		328	150	
	21	335	168		521	243	
	22	333	156		617	268	
	23	178	88		360	168	
	24	55	37		103	46	
2008	01	45	21	68	78	48	113
	02	45	25	121	65	48	106
	03	31	28	69	48	56	138
	04	25	22	69	41	49	160
	05	19	15	42	29	36	105
	06	13	9	21	21	21	25
	07	11	15	20	19	20	31
	08	22	32	38	30	34	61
	09	35	61	57	42	48	74
	10	63	105	168	57	78	178
	11	81	157	165	70	103	163
	12	107	201	211	84	125	186
	13	96	203	215	79	125	175
	14	118	170	231	93	101	192
	15	108	161	268	90	99	218
	16	147	179	243	121	112	204
	17	130	157	288	106	106	244
	18	101	122	262	91	92	254
	19	121	127	217	132	130	281
	20	186	113	337	239	183	558
	21	268	109	712	656	280	1268
	22	324	101	558	753	280	1041
	23	162	79	269	351	226	417
	24	67	28	116	115	70	187

Table C.4 Average monthly PM_{10} emission factors for KS1, KS2, and KS3 – All available data for 2007 and 2008.

Year	Month	KS1		KS2		KS3[a]	
		Number of days	Average EF[b] (kg/1000hd-day)	Number of days	Average EF[b] (kg/1000hd-day)	Number of days	Average EF[b] (kg/1000hd-day)
2007	1	11	1	21	2		
	2	13	3	16	7		
	3	9	1	11	4		
	4	21	6	11	8		
	5	24	25	25	32		
	6	22	18	22	52		
	7	24	10	23	28		
	8	25	83	1	11		
	9	18	55	23	71		
	10	18	41	11	124		
	11	13	30	7	27		
	12	17	2	17	2		
2008	1	25	4	9	5		
	2	21	3	16	5		
	3	17	26	16	11		
	4	14	64	11	19		
	5	27	13	25	22		
	6	22	18	24	30	3	1
	7	28	19	24	47	5	24
	8	26	16	24	14	13	40
	9	16	18	14	22	14	56
	10	25	16	17	54	13	98
	11	16	7	10	3	13	20
	12						

[a] KS3: no data from January 2007 to May 2008

[b] Average EF: Average emission factor for the month

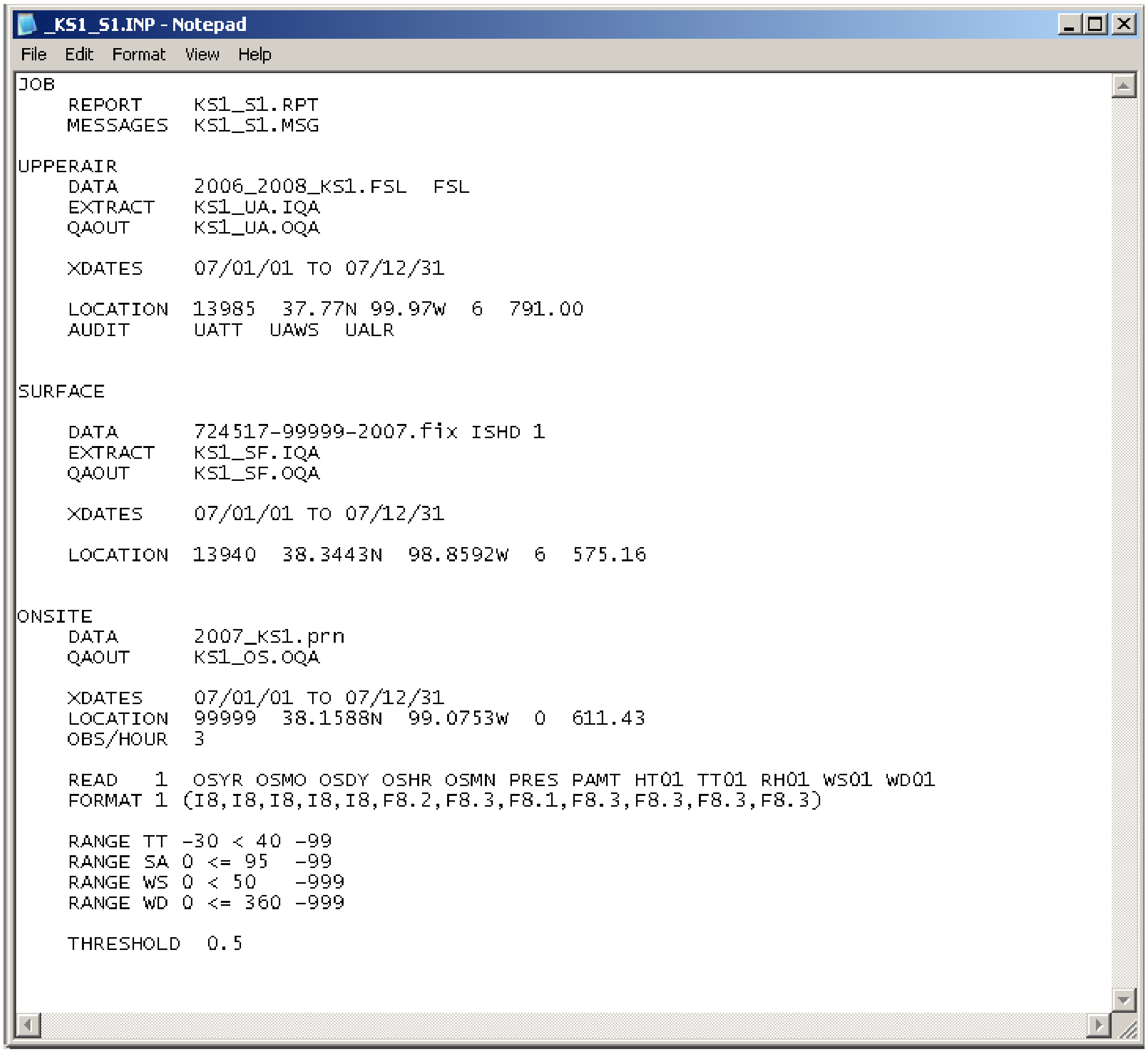
Table C.5 Average monthly PM_{10} emission factors for KS1, KS2, and KS3 – Selected dates from 2007 and 2008.

Year	Month	Number of days	Average monthly emission factor (kg/1000hd-day)		
			KS1	KS2	KS3[a]
2007	1	11	1	1	
	2	12	3	8	
	3	6	1	3	
	4	11	2	8	
	5	24	25	33	
	6	21	19	55	
	7	22	10	29	
	8	1	22	11	
	9	15	66	78	
	10	11	51	124	
	11	1	56	156	
	12	16	2	2	
2008	1	9	4	5	
	2	15	4	5	
	3	16	27	11	
	4	10	89	21	
	5	25	13	22	
	6	3	1	1	1
	7	4	37	46	30
	8	12	26	17	40
	9	15	20	22	56
	10	7	46	115	180
	11	10	10	3	24
	12				

[a] KS3: no data from January 2007 to May 2008

Table C.6 Hourly averages of PM_{10} emission factors and net PM_{10} concentrations – 2007 and 2008.

Year	Hour	Average Emission Factor (kg/1000hd-h)			Average TEOM PM_{10} Concentration ($\mu g/m^3$)		
		KS1	KS2	KS3	KS1	KS2	KS3
2007	01	0.72	0.99		75	45	
	02	0.68	0.83		72	43	
	03	0.65	1.08		72	46	
	04	0.62	0.96		70	42	
	05	0.42	0.55		53	30	
	06	0.21	0.86		24	34	
	07	0.25	0.71		33	28	
	08	0.79	1.45		72	44	
	09	1.43	2.35		102	65	
	10	1.42	3.03		83	67	
	11	2.16	3.18		106	72	
	12	2.88	4.26		137	92	
	13	3.24	4.59		150	93	
	14	3.52	4.42		158	85	
	15	3.31	5.39		158	102	
	16	3.48	6.50		168	113	
	17	3.41	5.44		172	120	
	18	3.26	4.59		187	110	
	19	2.70	3.66		197	117	
	20	3.26	2.99		328	150	
	21	5.60	4.60		521	243	
	22	5.55	4.28		617	268	
	23	2.97	2.42		360	168	
	24	0.92	1.01		103	46	
2008	01	0.75	0.57	1.32	78	48	113
	02	0.75	0.68	2.36	65	48	106
	03	0.52	0.76	1.34	48	56	138
	04	0.42	0.59	1.34	41	49	160
	05	0.31	0.40	0.82	29	36	105
	06	0.21	0.25	0.41	21	21	25
	07	0.18	0.41	0.38	19	20	31
	08	0.36	0.86	0.75	30	34	61
	09	0.59	1.67	1.12	42	48	74
	10	1.05	2.86	3.27	57	78	178
	11	1.35	4.28	3.23	70	103	163
	12	1.79	5.49	4.12	84	125	186
	13	1.61	5.56	4.19	79	125	175
	14	1.97	4.64	4.52	93	101	192
	15	1.81	4.40	5.23	90	99	218
	16	2.46	4.90	4.74	121	112	204
	17	2.18	4.30	5.63	106	106	244
	18	1.69	3.34	5.12	91	92	254
	19	2.01	3.47	4.23	132	130	281
	20	3.11	3.10	6.58	239	183	558
	21	4.47	2.97	13.90	656	280	1268
	22	5.41	2.77	10.89	753	280	1041
	23	2.71	2.16	5.25	351	226	417
	24	1.12	0.77	2.27	115	70	187



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    MESSAGES   KS1_S1.MSG

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    QAOUT      KS1_UA.OQA

    XDATES     07/01/01 TO 07/12/31

    LOCATION   13985  37.77N 99.97W  6  791.00
    AUDIT      UATT  UAWS  UALR


SURFACE

    DATA       724517-99999-2007.fix ISHD 1
    EXTRACT    KS1_SF.IQA
    QAOUT      KS1_SF.OQA

    XDATES     07/01/01 TO 07/12/31

    LOCATION   13940  38.3443N  98.8592W  6  575.16


ONSITE
    DATA       2007_KS1.prn
    QAOUT      KS1_OS.OQA

    XDATES     07/01/01 TO 07/12/31
    LOCATION   99999  38.1588N  99.0753W  0  611.43
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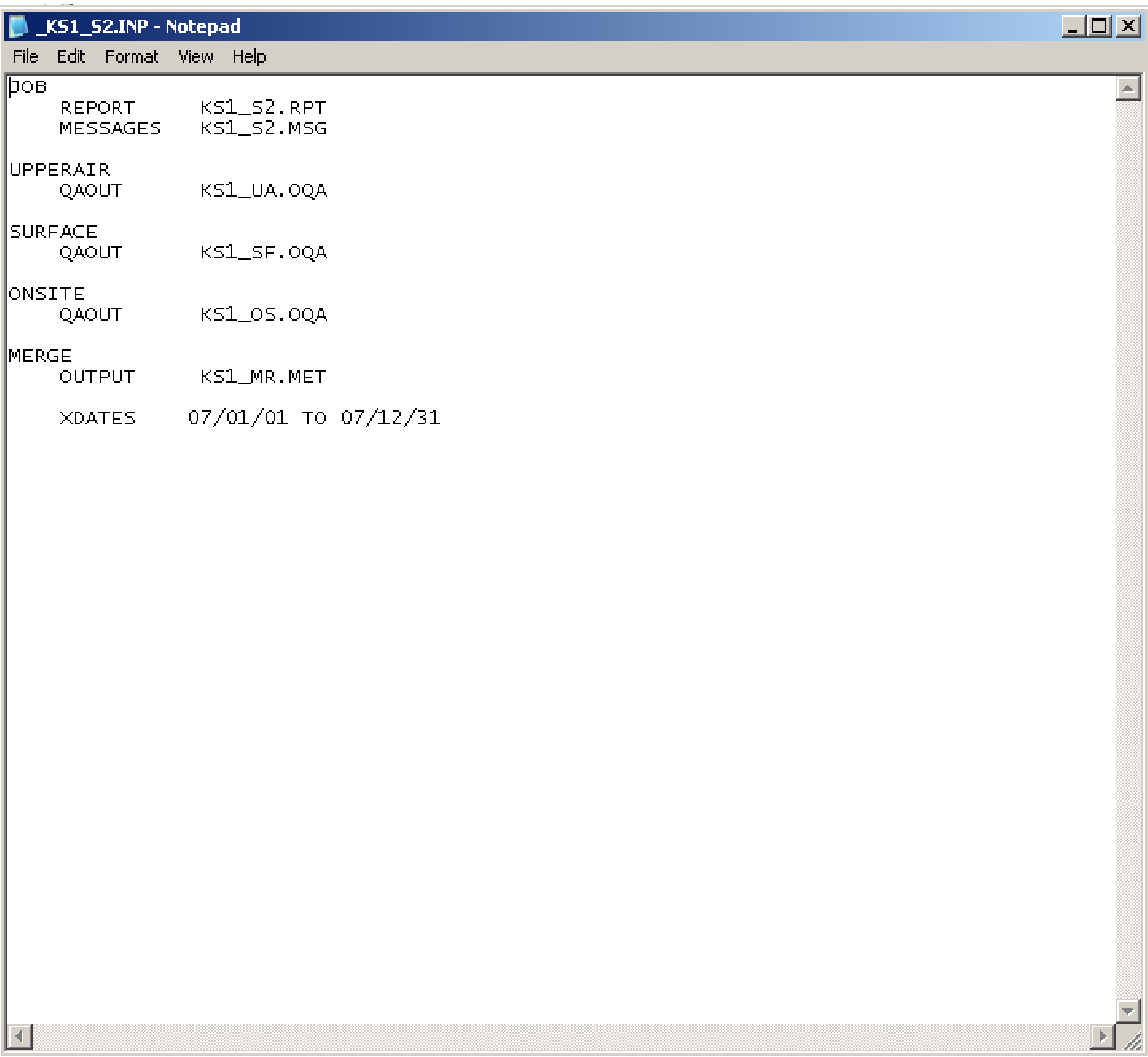
    READ   1  OSYR OSMO OSDY OSHR OSMN PRES PAMT HT01 TT01 RH01 WS01 WD01
    FORMAT 1 (I8,I8,I8,I8,I8,F8.2,F8.3,F8.1,F8.3,F8.3,F8.3,F8.3)

    RANGE TT -30 < 40 -99
    RANGE SA 0 <= 95  -99
    RANGE WS 0 < 50   -999
    RANGE WD 0 <= 360 -999

    THRESHOLD  0.5
```

Figure C.1 Runstream file for AERMET Stage 1.



```
JOB
     REPORT        KS1_S2.RPT
     MESSAGES      KS1_S2.MSG

UPPERAIR
     QAOUT         KS1_UA.OQA

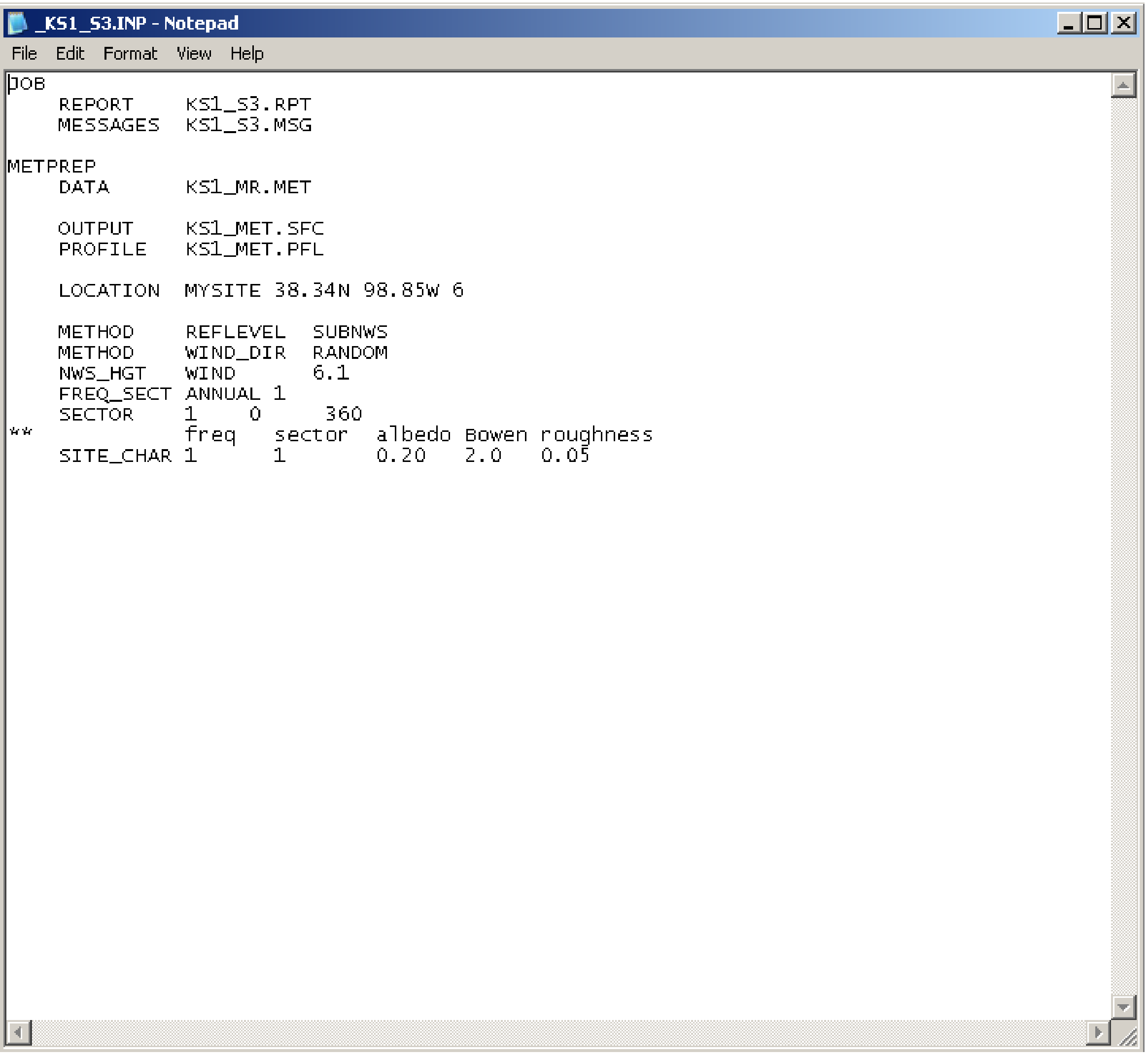
SURFACE
     QAOUT         KS1_SF.OQA

ONSITE
     QAOUT         KS1_OS.OQA

MERGE
     OUTPUT        KS1_MR.MET

     XDATES       07/01/01 TO 07/12/31
```

Figure C.2 Runstream file for AERMET Stage 2.



```
JOB
    REPORT    KS1_S3.RPT
    MESSAGES  KS1_S3.MSG

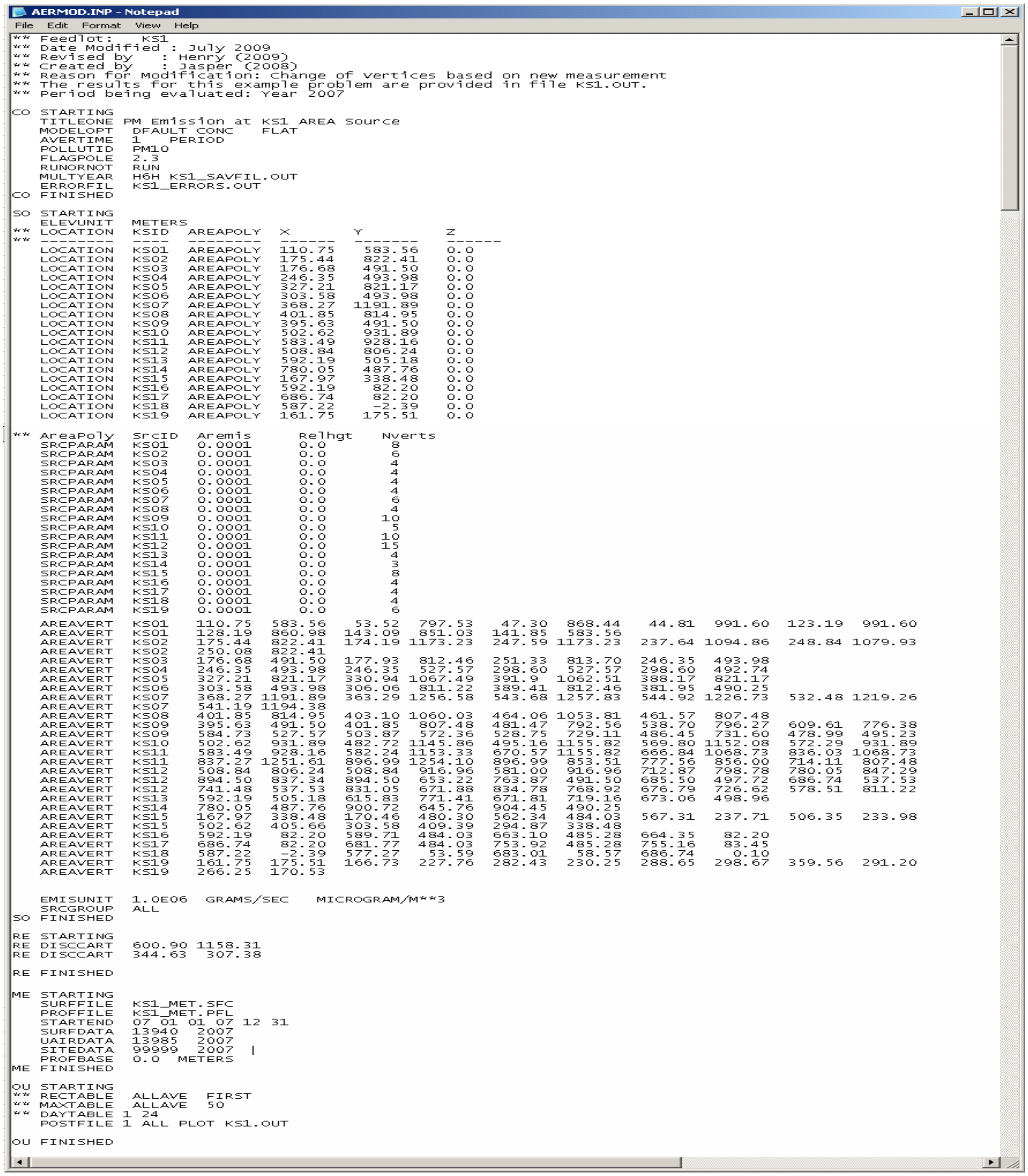
METPREP
    DATA      KS1_MR.MET

    OUTPUT    KS1_MET.SFC
    PROFILE   KS1_MET.PFL

    LOCATION  MYSITE 38.34N 98.85W 6

    METHOD    REFLEVEL  SUBNWS
    METHOD    WIND_DIR  RANDOM
    NWS_HGT   WIND      6.1
    FREQ_SECT ANNUAL 1
    SECTOR    1    0     360
**            freq   sector  albedo Bowen roughness
    SITE_CHAR 1      1       0.20   2.0   0.05
```

Figure C.3 Runstream file for AERMET Stage 3.



```
** Feedlot:     KS1
** Date Modified : July 2009
** Revised by    : Henry (2009)
** Created by    : Jasper (2008)
** Reason for Modification: Change of Vertices based on new measurement
** The results for this example problem are provided in file KS1.OUT.
** Period being evaluated: Year 2007

CO STARTING
   TITLEONE PM Emission at KS1 AREA Source
   MODELOPT  DFAULT CONC    FLAT
   AVERTIME  1    PERIOD
   POLLUTID  PM10
   FLAGPOLE  2.3
   RUNORNOT  RUN
   MULTYEAR  H6H KS1_SAVFIL.OUT
   ERRORFIL  KS1_ERRORS.OUT
CO FINISHED

SO STARTING
   ELEVUNIT  METERS
** LOCATION  KSID  AREAPOLY  X        Y         Z
** --------  ----  --------  ------   -------   ------
   LOCATION  KS01  AREAPOLY  110.75    583.56   0.0
   LOCATION  KS02  AREAPOLY  175.44    822.41   0.0
   LOCATION  KS03  AREAPOLY  176.68    491.50   0.0
   LOCATION  KS04  AREAPOLY  246.35    493.98   0.0
   LOCATION  KS05  AREAPOLY  327.21    821.17   0.0
   LOCATION  KS06  AREAPOLY  303.58    493.98   0.0
   LOCATION  KS07  AREAPOLY  368.27   1191.89   0.0
   LOCATION  KS08  AREAPOLY  401.85    814.95   0.0
   LOCATION  KS09  AREAPOLY  395.63    491.50   0.0
   LOCATION  KS10  AREAPOLY  502.62    931.89   0.0
   LOCATION  KS11  AREAPOLY  583.49    928.16   0.0
   LOCATION  KS12  AREAPOLY  508.84    806.24   0.0
   LOCATION  KS13  AREAPOLY  592.19    505.18   0.0
   LOCATION  KS14  AREAPOLY  780.05    487.76   0.0
   LOCATION  KS15  AREAPOLY  167.97    338.48   0.0
   LOCATION  KS16  AREAPOLY  592.19     82.20   0.0
   LOCATION  KS17  AREAPOLY  686.74     82.20   0.0
   LOCATION  KS18  AREAPOLY  587.22     -2.39   0.0
   LOCATION  KS19  AREAPOLY  161.75    175.51   0.0

** AreaPoly  SrcID  Aremis     Relhgt   Nverts
   SRCPARAM  KS01   0.0001     0.0       8
   SRCPARAM  KS02   0.0001     0.0       6
   SRCPARAM  KS03   0.0001     0.0       4
   SRCPARAM  KS04   0.0001     0.0       4
   SRCPARAM  KS05   0.0001     0.0       4
   SRCPARAM  KS06   0.0001     0.0       4
   SRCPARAM  KS07   0.0001     0.0       6
   SRCPARAM  KS08   0.0001     0.0       4
   SRCPARAM  KS09   0.0001     0.0      10
   SRCPARAM  KS10   0.0001     0.0       5
   SRCPARAM  KS11   0.0001     0.0      10
   SRCPARAM  KS12   0.0001     0.0      15
   SRCPARAM  KS13   0.0001     0.0       4
   SRCPARAM  KS14   0.0001     0.0       3
   SRCPARAM  KS15   0.0001     0.0       8
   SRCPARAM  KS16   0.0001     0.0       4
   SRCPARAM  KS17   0.0001     0.0       4
   SRCPARAM  KS18   0.0001     0.0       4
   SRCPARAM  KS19   0.0001     0.0       6

   AREAVERT  KS01   110.75  583.56   53.52  797.53   47.30  868.44   44.81  991.60  123.19  991.60
   AREAVERT  KS01   128.19  860.98  143.09  851.03  141.85  583.56
   AREAVERT  KS02   175.44  822.41  174.19 1173.23  247.59 1173.23  237.64 1094.86  248.84 1079.93
   AREAVERT  KS02   250.08  822.41
   AREAVERT  KS03   176.68  491.50  177.93  812.46  251.33  813.70  246.35  493.98
   AREAVERT  KS04   246.35  493.98  246.35  527.57  298.60  527.57  298.60  492.74
   AREAVERT  KS05   327.21  821.17  330.94 1067.49  391.9  1062.51  388.17  821.17
   AREAVERT  KS06   303.58  493.98  306.06  811.22  389.41  812.46  381.95  490.25
   AREAVERT  KS07   368.27 1191.89  363.29 1256.58  543.68 1257.83  544.92 1226.73  532.48 1219.26
   AREAVERT  KS07   541.19 1194.38
   AREAVERT  KS08   401.85  814.95  403.10 1060.03  464.06 1053.81  461.57  807.48
   AREAVERT  KS09   395.63  491.50  401.85  807.48  481.47  792.56  538.70  796.27  609.61  776.38
   AREAVERT  KS09   584.73  527.57  503.87  572.36  528.75  729.11  486.45  731.60  478.99  495.23
   AREAVERT  KS10   502.62  931.89  482.72 1145.86  495.16 1155.82  569.80 1152.08  572.29  931.89
   AREAVERT  KS11   583.49  928.16  582.24 1153.33  670.57 1155.82  666.84 1068.73  836.03 1068.73
   AREAVERT  KS11   837.27 1251.61  896.99 1254.10  896.99  853.51  777.56  856.00  714.11  807.48
   AREAVERT  KS12   508.84  806.24  508.84  916.96  581.00  916.96  712.87  798.78  780.05  847.29
   AREAVERT  KS12   894.50  837.34  894.50  653.22  763.87  491.50  685.50  497.72  686.74  537.53
   AREAVERT  KS12   741.48  537.53  831.05  671.88  834.78  768.92  676.79  726.62  578.51  811.22
   AREAVERT  KS13   592.19  505.18  615.83  771.41  671.81  719.16  673.06  498.96
   AREAVERT  KS14   780.05  487.76  900.72  645.76  904.45  490.25
   AREAVERT  KS15   167.97  338.48  170.46  480.30  562.34  484.03  567.31  237.71  506.35  233.98
   AREAVERT  KS15   502.62  405.66  303.58  409.39  294.87  338.48
   AREAVERT  KS16   592.19   82.20  589.71  484.03  663.10  485.28  664.35   82.20
   AREAVERT  KS17   686.74   82.20  681.77  484.03  753.92  485.28  755.16   83.45
   AREAVERT  KS18   587.22   -2.39  577.27   53.59  683.01   58.57  686.74    0.10
   AREAVERT  KS19   161.75  175.51  166.73  227.76  282.43  230.25  288.65  298.67  359.56  291.20
   AREAVERT  KS19   266.25  170.53


   EMISUNIT  1.0E06  GRAMS/SEC   MICROGRAM/M**3
   SRCGROUP  ALL
SO FINISHED

RE STARTING
RE DISCCART  600.90 1158.31
RE DISCCART  344.63  307.38

RE FINISHED

ME STARTING
   SURFFILE  KS1_MET.SFC
   PROFFILE  KS1_MET.PFL
   STARTEND  07 01 01 07 12 31
   SURFDATA  13940  2007
   UAIRDATA  13985  2007
   SITEDATA  99999  2007
   PROFBASE  0.0  METERS
ME FINISHED

OU STARTING
** RECTABLE  ALLAVE  FIRST
** MAXTABLE  ALLAVE  50
** DAYTABLE 1 24
   POSTFILE 1 ALL PLOT KS1.OUT

OU FINISHED
```

Figure C.4 Runstream file for AERMOD - KS1.

```
** Filename : KS2.INP
** Feedlot:   KS2
** Date Modified : July 2009
** Revised by    : Henry (2009)
** Created by    : Jasper (2008)
** Reason for Modification: Change of vertices based on new measurement
** The results for this example problem are provided in file KS2.OUT.
** Period being evaluated: Year 2007

CO STARTING
   TITLEONE PM Emission at KS2                              AREA Source
   MODELOPT  DFAULT CONC    FLAT
   AVERTIME  1    PERIOD
   POLLUTID  PM10
   FLAGPOLE  2.3
   RUNORNOT  RUN
   MULTYEAR  H6H KS2_SAVFIL.OUT
   ERRORFIL  KS2_ERRORS.OUT
CO FINISHED

SO STARTING
   ELEVUNIT  METERS
** LOCATION  KSID  AREAPOLY  X        Y          Z
** --------  ----  --------  ------   -------    ------
   LOCATION  KS01  AREAPOLY  286.93  1004.25    0.0
   LOCATION  KS02  AREAPOLY  248.50   571.94    0.0
   LOCATION  KS03  AREAPOLY  325.36   569.80    0.0
   LOCATION  KS04  AREAPOLY  419.29   567.67    0.0
   LOCATION  KS05  AREAPOLY  484.41   564.46    0.0
   LOCATION  KS06  AREAPOLY  542.05   570.87    0.0
   LOCATION  KS07  AREAPOLY  250.64   220.75    0.0
   LOCATION  KS08  AREAPOLY  332.83   120.41    0.0
   LOCATION  KS09  AREAPOLY  408.62   119.34    0.0
   LOCATION  KS10  AREAPOLY  487.61   138.55    0.0
   LOCATION  KS11  AREAPOLY  573.00   155.63    0.0
   LOCATION  KS12  AREAPOLY  728.85   134.28    0.0
   LOCATION  KS13  AREAPOLY  815.31   121.48    0.0
   LOCATION  KS14  AREAPOLY  899.64   107.60    0.0
   LOCATION  KS15  AREAPOLY  981.83    93.72    0.0
   LOCATION  KS16  AREAPOLY 1065.09    97.99    0.0
   LOCATION  KS17  AREAPOLY 1147.29   160.97    0.0
   LOCATION  KS18  AREAPOLY 1211.33   211.14    0.0
   LOCATION  KS19  AREAPOLY 1356.51   308.28    0.0
   LOCATION  KS20  AREAPOLY 1609.49   517.50    0.0
   LOCATION  KS21  AREAPOLY 1105.66   551.65    0.0
   LOCATION  KS22  AREAPOLY 1110.99   764.08    0.0
   LOCATION  KS23  AREAPOLY  963.69   554.86    0.0
   LOCATION  KS24  AREAPOLY  824.92   586.88    0.0
   LOCATION  KS25  AREAPOLY  676.55   595.42    0.0
   LOCATION  KS26  AREAPOLY  617.84   711.77    0.0

** AreaPoly  SrcID  Aremis      Relhgt    Nverts
   SRCPARAM  KS01   0.0001      0.0        5
   SRCPARAM  KS02   0.0001      0.0        5
   SRCPARAM  KS03   0.0001      0.0        6
   SRCPARAM  KS04   0.0001      0.0        4
   SRCPARAM  KS05   0.0001      0.0        4
   SRCPARAM  KS06   0.0001      0.0        4
   SRCPARAM  KS07   0.0001      0.0        5
   SRCPARAM  KS08   0.0001      0.0        5
   SRCPARAM  KS09   0.0001      0.0        5
   SRCPARAM  KS10   0.0001      0.0        5
   SRCPARAM  KS11   0.0001      0.0        8
   SRCPARAM  KS12   0.0001      0.0        4
   SRCPARAM  KS13   0.0001      0.0        4
   SRCPARAM  KS14   0.0001      0.0        4
   SRCPARAM  KS15   0.0001      0.0        4
   SRCPARAM  KS16   0.0001      0.0        4
   SRCPARAM  KS17   0.0001      0.0        4
   SRCPARAM  KS18   0.0001      0.0        4
   SRCPARAM  KS19   0.0001      0.0        4
   SRCPARAM  KS20   0.0001      0.0        4
   SRCPARAM  KS21   0.0001      0.0        8
   SRCPARAM  KS22   0.0001      0.0        4
   SRCPARAM  KS23   0.0001      0.0        5
   SRCPARAM  KS24   0.0001      0.0        8
   SRCPARAM  KS25   0.0001      0.0        4
   SRCPARAM  KS26   0.0001      0.0        4

   AREAVERT  KS01    286.93 1004.25   285.86 1194.26   316.82 1240.16   341.37 1239.09   342.44 1005.32
   AREAVERT  KS02    248.50  571.94   235.69  622.11   232.49  998.91   317.88 1001.05   311.48  568.73
   AREAVERT  KS03    325.36  569.80   326.42  713.91   348.84  718.18   350.98 1243.36   407.55 1239.09
   AREAVERT  KS03    405.41  565.53
   AREAVERT  KS04    419.29  567.67   413.95 1235.89   471.60 1186.78   474.80  561.26
   AREAVERT  KS05    484.41  564.46   484.41 1172.91   532.44 1169.70   533.51  567.67
   AREAVERT  KS06    542.05  570.87   542.05  663.74   614.63  660.53   616.77  579.41
   AREAVERT  KS07    250.64  220.75   245.30  565.53   314.68  563.40   317.88  192.99   282.66  195.13
   AREAVERT  KS08    332.83  120.41   326.42  561.26   402.21  556.99   389.40  478.00   394.74  119.34
   AREAVERT  KS09    408.62  119.34   405.41  486.54   421.43  555.92   471.60  552.72   475.87  132.15
   AREAVERT  KS10    487.61  138.55   482.27  553.79   532.44  559.13   555.92  500.42   560.19  156.70
   AREAVERT  KS11    573.00  155.63   569.80  485.47   562.33  542.05   619.97  565.53   745.93  505.75
   AREAVERT  KS11    749.13  442.78   712.84  441.71   717.11  133.22
   AREAVERT  KS12    728.85  134.28   724.58  435.30   797.17  434.24   802.50  121.48
   AREAVERT  KS13    815.31  121.48   809.98  432.10   880.43  426.76   885.76  108.67
   AREAVERT  KS14    899.64  107.60   894.30  427.83   967.96  436.37   970.09   96.92
   AREAVERT  KS15    981.83   93.72   976.50  436.37  1052.29  443.84  1052.29   94.79
   AREAVERT  KS16   1065.09   97.99  1062.96  441.71  1135.55  449.18  1135.55  144.96
   AREAVERT  KS17   1147.29  160.97  1147.29  451.31  1201.73  456.65  1200.66  195.13
   AREAVERT  KS18   1211.33  211.14  1215.60  535.64  1329.82  546.32  1342.63  302.94
   AREAVERT  KS19   1356.51  308.28  1340.49  547.38  1498.48  567.67  1503.81  408.62
   AREAVERT  KS20   1609.49  517.50  1608.42  605.03  1699.16  640.25  1701.29  526.04
   AREAVERT  KS21   1105.66  551.65  1112.06  716.04  1162.23  709.64  1176.11  629.58  1261.50  622.11
   AREAVERT  KS21   1335.16  597.55  1334.09  561.26  1207.06  548.45
   AREAVERT  KS22   1110.99  764.08  1140.88  806.77  1218.81  735.25  1166.50  705.37
   AREAVERT  KS23    963.69  554.86   974.36  824.92  1087.51  814.25  1108.86  771.55  1093.92  550.59
   AREAVERT  KS24    824.92  586.88   834.53  877.22   895.37  880.43   900.71  834.53   960.49  829.19
   AREAVERT  KS24    951.95  553.79   884.70  573.00   878.29  580.48
   AREAVERT  KS25    676.55  595.42   686.15  881.49   818.52  884.70   809.98  583.68
   AREAVERT  KS26    617.84  711.77   618.90  885.76   674.41  885.76   668.01  708.57


   EMISUNIT  1.0E06  GRAMS/SEC    MICROGRAM/M**3
   SRCGROUP  ALL
SO FINISHED

RE STARTING
RE DISCCART  729.47  940.47
RE DISCCART  612.48   92.49

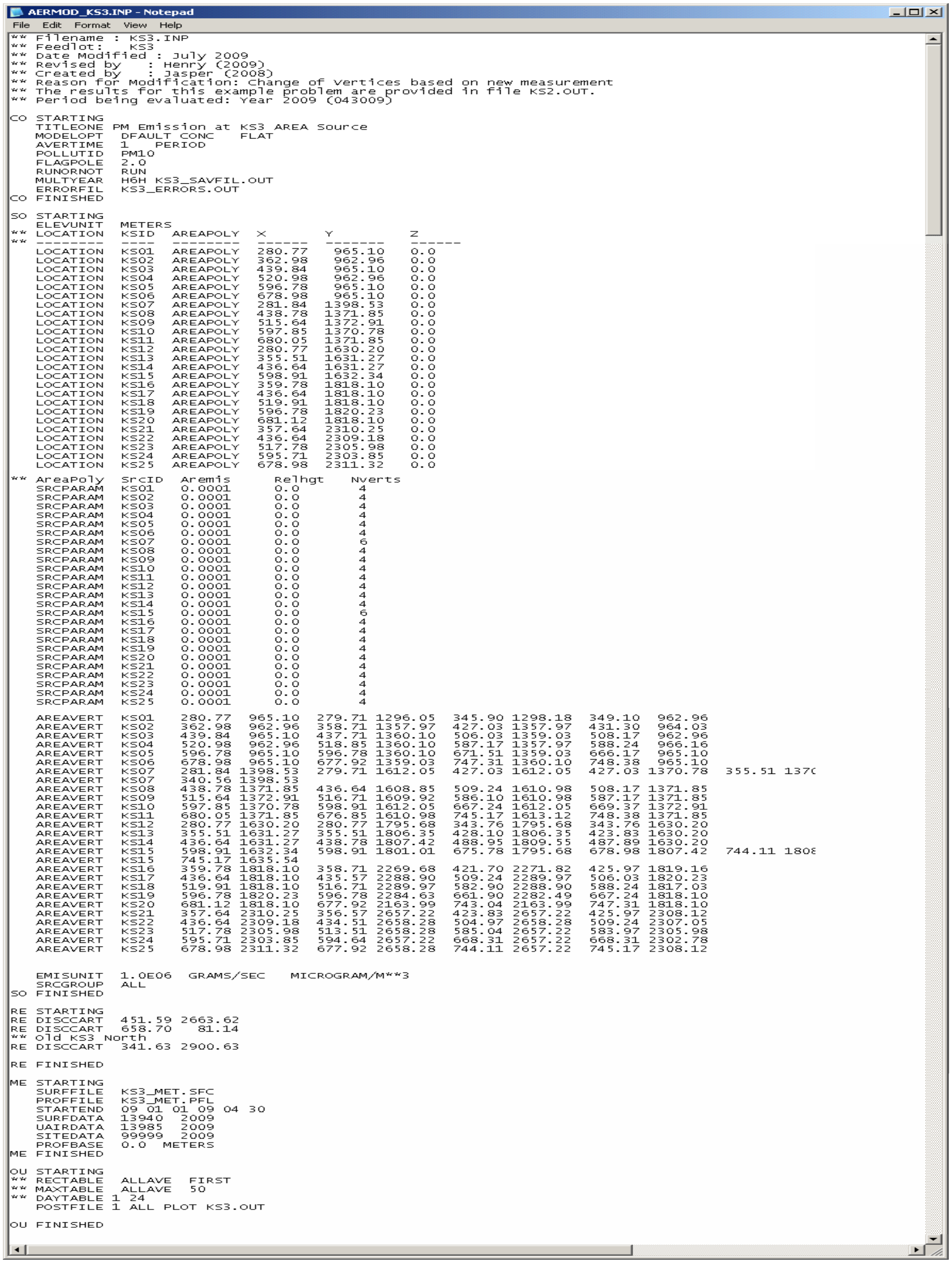
RE FINISHED

ME STARTING
   SURFFILE  KS2_MET.SFC
   PROFFILE  KS2_MET.PFL
   STARTEND  07 01 01 07 12 31
   SURFDATA  13940  2007
   UAIRDATA  13985  2007
   SITEDATA  99999  2007
   PROFBASE  0.0  METERS
ME FINISHED

OU STARTING
** RECTABLE  ALLAVE  FIRST
** MAXTABLE  ALLAVE  50
** DAYTABLE 1 24
   POSTFILE 1 ALL PLOT KS2.OUT

OU FINISHED
```

Figure C.5 Runstream file for AERMOD - KS2.



```
** Filename : KS3.INP
** Feedlot:   KS3
** Date Modified : July 2009
** Revised by    : Henry (2009)
** Created by    : Jasper (2008)
** Reason for Modification: Change of vertices based on new measurement
** The results for this example problem are provided in file KS2.OUT.
** Period being evaluated: Year 2009 (043009)

CO STARTING
   TITLEONE PM Emission at KS3 AREA Source
   MODELOPT  DFAULT CONC    FLAT
   AVERTIME  1    PERIOD
   POLLUTID  PM10
   FLAGPOLE  2.0
   RUNORNOT  RUN
   MULTYEAR  H6H KS3_SAVFIL.OUT
   ERRORFIL  KS3_ERRORS.OUT
CO FINISHED

SO STARTING
   ELEVUNIT  METERS
** LOCATION  KSID  AREAPOLY  X        Y          Z
** --------  ----  --------  ------   -------    ------
   LOCATION  KS01  AREAPOLY  280.77    965.10    0.0
   LOCATION  KS02  AREAPOLY  362.98    962.96    0.0
   LOCATION  KS03  AREAPOLY  439.84    965.10    0.0
   LOCATION  KS04  AREAPOLY  520.98    962.96    0.0
   LOCATION  KS05  AREAPOLY  596.78    965.10    0.0
   LOCATION  KS06  AREAPOLY  678.98    965.10    0.0
   LOCATION  KS07  AREAPOLY  281.84   1398.53    0.0
   LOCATION  KS08  AREAPOLY  438.78   1371.85    0.0
   LOCATION  KS09  AREAPOLY  515.64   1372.91    0.0
   LOCATION  KS10  AREAPOLY  597.85   1370.78    0.0
   LOCATION  KS11  AREAPOLY  680.05   1371.85    0.0
   LOCATION  KS12  AREAPOLY  280.77   1630.20    0.0
   LOCATION  KS13  AREAPOLY  355.51   1631.27    0.0
   LOCATION  KS14  AREAPOLY  436.64   1631.27    0.0
   LOCATION  KS15  AREAPOLY  598.91   1632.34    0.0
   LOCATION  KS16  AREAPOLY  359.78   1818.10    0.0
   LOCATION  KS17  AREAPOLY  436.64   1818.10    0.0
   LOCATION  KS18  AREAPOLY  519.91   1818.10    0.0
   LOCATION  KS19  AREAPOLY  596.78   1820.23    0.0
   LOCATION  KS20  AREAPOLY  681.12   1818.10    0.0
   LOCATION  KS21  AREAPOLY  357.64   2310.25    0.0
   LOCATION  KS22  AREAPOLY  436.64   2309.18    0.0
   LOCATION  KS23  AREAPOLY  517.78   2305.98    0.0
   LOCATION  KS24  AREAPOLY  595.71   2303.85    0.0
   LOCATION  KS25  AREAPOLY  678.98   2311.32    0.0

** AreaPoly  SrcID  Aremis      Relhgt    Nverts
   SRCPARAM  KS01   0.0001      0.0        4
   SRCPARAM  KS02   0.0001      0.0        4
   SRCPARAM  KS03   0.0001      0.0        4
   SRCPARAM  KS04   0.0001      0.0        4
   SRCPARAM  KS05   0.0001      0.0        4
   SRCPARAM  KS06   0.0001      0.0        4
   SRCPARAM  KS07   0.0001      0.0        6
   SRCPARAM  KS08   0.0001      0.0        4
   SRCPARAM  KS09   0.0001      0.0        4
   SRCPARAM  KS10   0.0001      0.0        4
   SRCPARAM  KS11   0.0001      0.0        4
   SRCPARAM  KS12   0.0001      0.0        4
   SRCPARAM  KS13   0.0001      0.0        4
   SRCPARAM  KS14   0.0001      0.0        4
   SRCPARAM  KS15   0.0001      0.0        6
   SRCPARAM  KS16   0.0001      0.0        4
   SRCPARAM  KS17   0.0001      0.0        4
   SRCPARAM  KS18   0.0001      0.0        4
   SRCPARAM  KS19   0.0001      0.0        4
   SRCPARAM  KS20   0.0001      0.0        4
   SRCPARAM  KS21   0.0001      0.0        4
   SRCPARAM  KS22   0.0001      0.0        4
   SRCPARAM  KS23   0.0001      0.0        4
   SRCPARAM  KS24   0.0001      0.0        4
   SRCPARAM  KS25   0.0001      0.0        4

   AREAVERT  KS01   280.77  965.10  279.71 1296.05  345.90 1298.18  349.10  962.96
   AREAVERT  KS02   362.98  962.96  358.71 1357.97  427.03 1357.97  431.30  964.03
   AREAVERT  KS03   439.84  965.10  437.71 1360.10  506.03 1359.03  508.17  962.96
   AREAVERT  KS04   520.98  962.96  518.85 1360.10  587.17 1357.97  588.24  966.16
   AREAVERT  KS05   596.78  965.10  596.78 1360.10  671.51 1359.03  666.17  965.10
   AREAVERT  KS06   678.98  965.10  677.92 1359.03  747.31 1360.10  748.38  965.10
   AREAVERT  KS07   281.84 1398.53  279.71 1612.05  427.03 1612.05  427.03 1370.78   355.51 1370
   AREAVERT  KS07   340.56 1398.53
   AREAVERT  KS08   438.78 1371.85  436.64 1608.85  509.24 1610.98  508.17 1371.85
   AREAVERT  KS09   515.64 1372.91  516.71 1609.92  586.10 1610.98  587.17 1371.85
   AREAVERT  KS10   597.85 1370.78  598.91 1612.05  667.24 1612.05  669.37 1372.91
   AREAVERT  KS11   680.05 1371.85  676.85 1610.98  745.17 1613.12  748.38 1371.85
   AREAVERT  KS12   280.77 1630.20  280.77 1795.68  343.76 1795.68  343.76 1630.20
   AREAVERT  KS13   355.51 1631.27  355.51 1806.35  428.10 1806.35  423.83 1630.20
   AREAVERT  KS14   436.64 1631.27  438.78 1807.42  488.95 1809.55  487.89 1630.20
   AREAVERT  KS15   598.91 1632.34  598.91 1801.01  675.78 1795.68  678.98 1807.42   744.11 1808
   AREAVERT  KS15   745.17 1635.54
   AREAVERT  KS16   359.78 1818.10  358.71 2269.68  421.70 2271.82  425.97 1819.16
   AREAVERT  KS17   436.64 1818.10  435.57 2288.90  509.24 2289.97  506.03 1820.23
   AREAVERT  KS18   519.91 1818.10  516.71 2289.97  582.90 2288.90  588.24 1817.03
   AREAVERT  KS19   596.78 1820.23  596.78 2284.63  661.90 2282.49  667.24 1818.10
   AREAVERT  KS20   681.12 1818.10  677.92 2163.99  743.04 2163.99  747.31 1818.10
   AREAVERT  KS21   357.64 2310.25  356.57 2657.22  423.83 2657.22  425.97 2308.12
   AREAVERT  KS22   436.64 2309.18  434.51 2658.28  504.97 2658.28  509.24 2307.05
   AREAVERT  KS23   517.78 2305.98  513.51 2658.28  585.04 2657.22  583.97 2305.98
   AREAVERT  KS24   595.71 2303.85  594.64 2657.22  668.31 2657.22  668.31 2302.78
   AREAVERT  KS25   678.98 2311.32  677.92 2658.28  744.11 2657.22  745.17 2308.12


   EMISUNIT  1.0E06  GRAMS/SEC    MICROGRAM/M**3
   SRCGROUP  ALL
SO FINISHED

RE STARTING
RE DISCCART  451.59 2663.62
RE DISCCART  658.70   81.14
** old KS3 North
RE DISCCART  341.63 2900.63

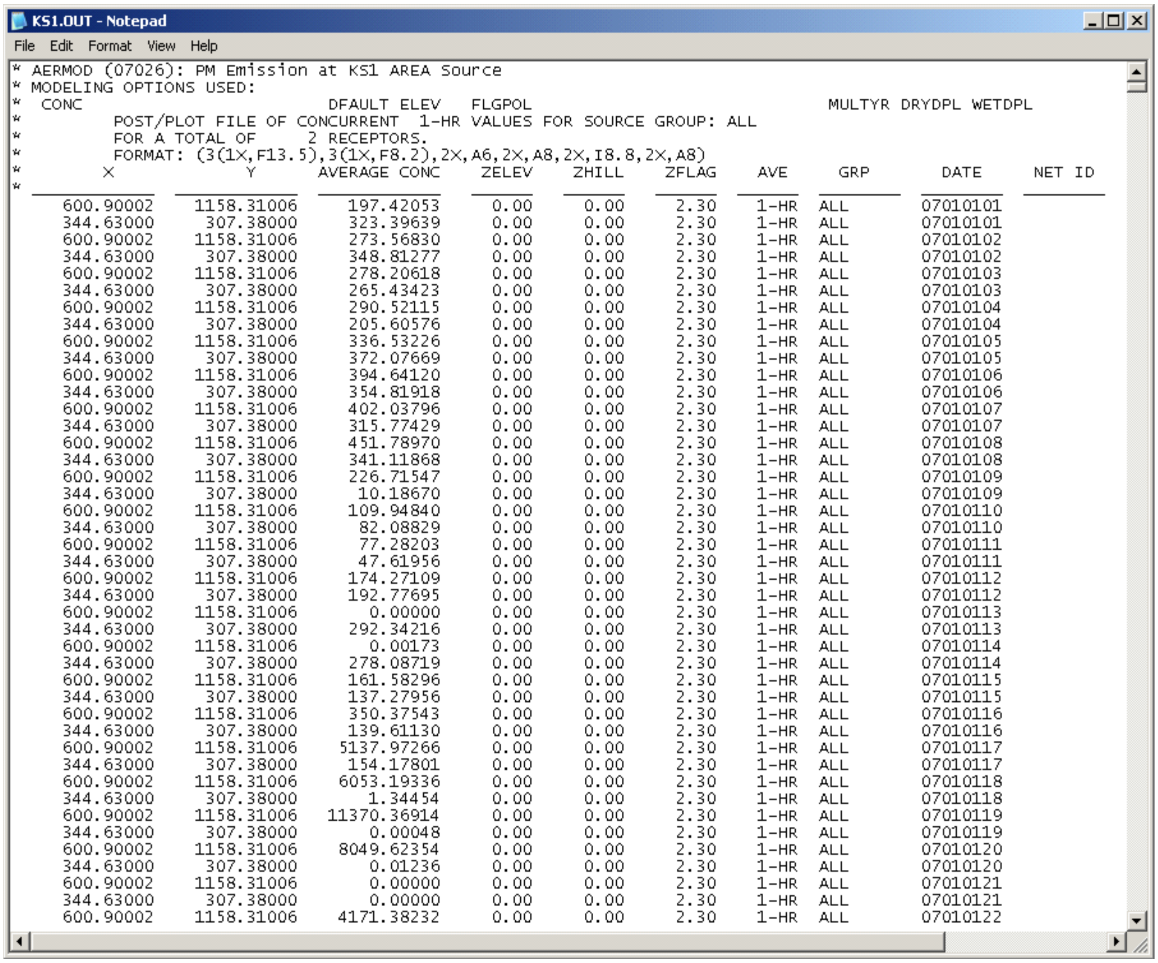
RE FINISHED

ME STARTING
   SURFFILE  KS3_MET.SFC
   PROFFILE  KS3_MET.PFL
   STARTEND  09 01 01 09 04 30
   SURFDATA  13940  2009
   UAIRDATA  13985  2009
   SITEDATA  99999  2009
   PROFBASE  0.0  METERS
ME FINISHED

OU STARTING
** RECTABLE  ALLAVE  FIRST
** MAXTABLE  ALLAVE  50
** DAYTABLE 1 24
   POSTFILE 1 ALL PLOT KS3.OUT

OU FINISHED
```

Figure C.6 Runstream file for AERMOD - KS3.



```
* AERMOD (07026): PM Emission at KS1 AREA Source
* MODELING OPTIONS USED:
*  CONC                       DFAULT ELEV   FLGPOL                                  MULTYR DRYDPL WETDPL
*         POST/PLOT FILE OF CONCURRENT  1-HR VALUES FOR SOURCE GROUP: ALL
*         FOR A TOTAL OF      2 RECEPTORS.
*         FORMAT: (3(1X,F13.5),3(1X,F8.2),2X,A6,2X,A8,2X,I8.8,2X,A8)
*        X             Y      AVERAGE CONC  ZELEV    ZHILL    ZFLAG    AVE     GRP       DATE      NET ID
* ____________  ____________  ____________  ______  ______  ______  ______  ________  ________  ________
     600.90002    1158.31006     197.42053     0.00     0.00     2.30  1-HR    ALL       07010101
     344.63000     307.38000     323.39639     0.00     0.00     2.30  1-HR    ALL       07010101
     600.90002    1158.31006     273.56830     0.00     0.00     2.30  1-HR    ALL       07010102
     344.63000     307.38000     348.81277     0.00     0.00     2.30  1-HR    ALL       07010102
     600.90002    1158.31006     278.20618     0.00     0.00     2.30  1-HR    ALL       07010103
     344.63000     307.38000     265.43423     0.00     0.00     2.30  1-HR    ALL       07010103
     600.90002    1158.31006     290.52115     0.00     0.00     2.30  1-HR    ALL       07010104
     344.63000     307.38000     205.60576     0.00     0.00     2.30  1-HR    ALL       07010104
     600.90002    1158.31006     336.53226     0.00     0.00     2.30  1-HR    ALL       07010105
     344.63000     307.38000     372.07669     0.00     0.00     2.30  1-HR    ALL       07010105
     600.90002    1158.31006     394.64120     0.00     0.00     2.30  1-HR    ALL       07010106
     344.63000     307.38000     354.81918     0.00     0.00     2.30  1-HR    ALL       07010106
     600.90002    1158.31006     402.03796     0.00     0.00     2.30  1-HR    ALL       07010107
     344.63000     307.38000     315.77429     0.00     0.00     2.30  1-HR    ALL       07010107
     600.90002    1158.31006     451.78970     0.00     0.00     2.30  1-HR    ALL       07010108
     344.63000     307.38000     341.11868     0.00     0.00     2.30  1-HR    ALL       07010108
     600.90002    1158.31006     226.71547     0.00     0.00     2.30  1-HR    ALL       07010109
     344.63000     307.38000      10.18670     0.00     0.00     2.30  1-HR    ALL       07010109
     600.90002    1158.31006     109.94840     0.00     0.00     2.30  1-HR    ALL       07010110
     344.63000     307.38000      82.08829     0.00     0.00     2.30  1-HR    ALL       07010110
     600.90002    1158.31006      77.28203     0.00     0.00     2.30  1-HR    ALL       07010111
     344.63000     307.38000      47.61956     0.00     0.00     2.30  1-HR    ALL       07010111
     600.90002    1158.31006     174.27109     0.00     0.00     2.30  1-HR    ALL       07010112
     344.63000     307.38000     192.77695     0.00     0.00     2.30  1-HR    ALL       07010112
     600.90002    1158.31006       0.00000     0.00     0.00     2.30  1-HR    ALL       07010113
     344.63000     307.38000     292.34216     0.00     0.00     2.30  1-HR    ALL       07010113
     600.90002    1158.31006       0.00173     0.00     0.00     2.30  1-HR    ALL       07010114
     344.63000     307.38000     278.08719     0.00     0.00     2.30  1-HR    ALL       07010114
     600.90002    1158.31006     161.58296     0.00     0.00     2.30  1-HR    ALL       07010115
     344.63000     307.38000     137.27956     0.00     0.00     2.30  1-HR    ALL       07010115
     600.90002    1158.31006     350.37543     0.00     0.00     2.30  1-HR    ALL       07010116
     344.63000     307.38000     139.61130     0.00     0.00     2.30  1-HR    ALL       07010116
     600.90002    1158.31006    5137.97266     0.00     0.00     2.30  1-HR    ALL       07010117
     344.63000     307.38000     154.17801     0.00     0.00     2.30  1-HR    ALL       07010117
     600.90002    1158.31006    6053.19336     0.00     0.00     2.30  1-HR    ALL       07010118
     344.63000     307.38000       1.34454     0.00     0.00     2.30  1-HR    ALL       07010118
     600.90002    1158.31006   11370.36914     0.00     0.00     2.30  1-HR    ALL       07010119
     344.63000     307.38000       0.00048     0.00     0.00     2.30  1-HR    ALL       07010119
     600.90002    1158.31006    8049.62354     0.00     0.00     2.30  1-HR    ALL       07010120
     344.63000     307.38000       0.01236     0.00     0.00     2.30  1-HR    ALL       07010120
     600.90002    1158.31006       0.00000     0.00     0.00     2.30  1-HR    ALL       07010121
     344.63000     307.38000       0.00000     0.00     0.00     2.30  1-HR    ALL       07010121
     600.90002    1158.31006    4171.38232     0.00     0.00     2.30  1-HR    ALL       07010122
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Figure C.7 AERMOD Output Sample.