

**Atmospheric Salt Emissions from the Concentration of Agricultural
Drainage Water by Sprinkler Evaporator**

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Abstract

The Integrated On-Farm Drainage Management system that is being developed for use on the Westside of the San Joaquin uses a solar evaporator as the final disposal mechanism for the salt laden water. The solar evaporator works by circulating the water through a network of horizontal fan sprinklers placed close to the ground. The use of these sprinklers increases evaporation, but salt particulate is entrained in the air and carried away from the perimeter of the solar evaporator. This study developed a method to quantify the deposition flux downwind of the solar evaporator. The deposition downwind of the system was quantified for multiple sprinkler heights, and water sources and regression lines fit to the deposition to have a more complete understanding of the extent of the effects downwind of the system. Although no statistically significant differences were found between the regression lines, it was possible to accurately determine the deposition fluxes out to a distance of approximately 200 meters. At that point there was minimal difference between the measured deposition flux and background levels. While no specific particle size measurements were possible with the time and resources available, it was possible to estimate the proportion of the salt particles that might be subject to regulation as PM₁₀. The predominantly large sprinkler droplets produced by the system in the evaporator result in large salt particles that are significantly larger than the size that would be of air quality concern.

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Introduction

Identification of project and sponsor?

Dates of investigation:

Field sampling for this study began in June of 2004 and continued through July of 2005.

General statement of the nature and purpose of investigation:

Integrated On-Farm Drainage Management (IFDM) systems have been developed in recent years as a solution to the drainage problems that plague the Westside of the San Joaquin Valley. These systems employ managed reuse of irrigation water on sequentially higher salt tolerant crops. The final result of the sequential reuse of the irrigation water is effluent with a high level of dissolved solids that must be disposed of. The disposal of this water is conducted through a solar evaporator. The solar evaporator works by circulating the drainage water through a low level sprinkler system to increase the rate of evaporation. Spraying the water into the air introduces the possibility of atmospheric entrainment of the water droplets. These droplets then may completely vaporize leaving behind the dissolved solids in crystalline form that then may be transported away from the solar evaporator perimeter. Droplets that do not completely vaporize may also be carried outside the perimeter of the system.

The goal of the work is to characterize the extent of these emissions as they are transported outside the extents of the solar evaporator. The primary concern with the emissions from the evaporator is redeposition on productive farm land outside the system. The redeposition of the solids back to the farm land is highly undesirable due to the effects ground quality.

Methods

Multiple methods were considered for the measurement of airborne particulate concentrations. Due to the nature of the emissions, standard EPA PM₁₀ samplers were deemed as ineffective due to the oversampling issues described by Buser et al., (2003). According to Buser et al., (2003) PM₁₀ samplers do not correctly separate the larger particulate from the PM₁₀ in environments with ambient particle size distributions that have a mass median diameter (MMD) greater than 10 μ m. Shaw et al., (2004) demonstrated the potential errors for specific agricultural sources with large MMDs. Following an initial site investigation and preliminary deposition measurements, there was a strong indication that the ambient particle size distribution downwind of the solar evaporator was much greater than 10 μ m. Therefore, specialized total suspended particulate samplers as described by Wanjura et al., (2003) would be the only appropriate method for ambient aerosol measurements. While the full design specification of these samplers is available, the excessive cost of building them ourselves prohibited their use on this project. Estimated cost for construction of samplers is approximately \$12,000 per sampler with a minimum of three samplers needed for appropriate measurement protocols. This was determined as cost prohibitive for this project and an alternate measurement method was investigated.

Due to the excessive cost of construction of our own samplers and the lack of available equipment, it was decided that direct measurement of deposition would be the easiest and most productive method for determining the emissions of the solar evaporator. It is assumed that the deposition pattern will approximate the extent of the plume for design purposes. The basic analytical plan was devised in order to make measurements as easily and accurate as possible. This included both the field sampling and the lab analysis. The field sampling portion of the research consisted of determining the best method for measurement of deposition, the appropriate array in which to measure the deposition, and finally the optimal sampling time for the measurements.

All methods found in the literature review consisted of passively intercepting the aerosol of interest before it reaches the ground. For example, Israel et al., (1976) used a moisture sensitive paper to intercept water droplets to determine diameter and mass of deposition downwind of cooling towers using sea water. William and Moser (1976) used petri dishes to intercept depositing salt aerosols from sea spray along the coast. These papers lead us to use a similar procedure to measure deposition. We decided that using petri dishes to collect the aerosol at ground level would be the most effective method of capturing the deposition.

The next issue was determining the actual mass deposited on the petri dish during the sampling period. Due to the expected small deposition masses that we would observe a highly sensitive method was required. Since the salts are highly soluble in water, the petri dishes could be rinsed with deionized water and the mass of dissolved solids in the water could then be attributed to the petri dish because of the relationship between electrical conductivity and dissolved solids. There is extensive literature available on the subject of determining the mass of dissolved solids in water allowing for established methods to be used. The approach was to rinse the petri dish with 40 ml of deionized water and place the solution in clean containers. Once all petri dishes were rinsed, the conductivity of each solution was determined using a conductivity cell of the appropriate range (Model AB30, Accumet). Calibration was conducted every 10 samples using Traceable one-shot conductivity standards.

To relate the conductivity of a sample to the total dissolved solids, the California Water Institute (CWI) was employed to determine TDS of a subset of samples. Due to the lack of funds from the funding agency at the time of analysis, no fee was charged for the analysis.

The CWI laboratory used the conductivity data to determine the best dilution scheme for analysis of the component ions by ion chromatography. The CWI laboratory is not currently certified by the EPA or the California Department of Health Services. As the analysis of these samples was provided free of charge as a courtesy to Dr. Krauter, no additional QA procedures (duplicates, spikes, performance evaluation samples, etc.) other than calibration of the analyzer was performed. The calibration line for all ions reported showed a linear regression of <0.998 correlation coefficient. Standards were produced by dilution of premixed stock solutions purchased from the Dionex Corporation. In addition, the ion chromatograph was being used on a concurrent basis for other projects in which soil extracts from the National Agricultural Proficiency Testing (NAPT) program were analyzed using the same standards. Results from said samples were within the QA acceptance limits for this type of extract.

The method for anions (fluoride, chloride, nitrate, and sulfate) was similar to the US EPA method 300.0, however the holding times could not be determined as the time between dissolution of the salt residue and the analysis was not recorded. The ions were separated by ion chromatography using a Dionex AS 14 column and 3.5 mM sodium carbonate plus 1.0 mM sodium bicarbonate at 1.2 mL/min. A 100 µL loop was used for samples and standards. Detection was performed using the CD25 conductivity detector and ASRS Ultra 4mm suppressor.

The method for cations, (sodium, potassium, ammonium, magnesium, and calcium) while not an EPA method, follows the manufacturer's protocol. The column used was a Dionex CS12A column with 20 mM methanesulfonic acid at 1.0 mL/min. as eluent. Detection was performed using the CD25 conductivity detector and CSRS Ultra II 4mm suppressor.

Project Description

Task Order Objectives: To develop an air sampling system to monitor salt emissions produced by the pilot solar evaporator at Red Rock Ranch in accordance with EPA guidelines for air quality monitoring. The task order objectives will be accomplished by the following: implement a 5-month sampling program; test various methods to capture the salt particles; and use a dispersion model to calculate salt particle emission factors.

Description of the Planned Work:

Determine an effective method to measure airborne salt particles. Sampling program: perform 2 days of field work and 5-8 days of laboratory work per month for a 5-month period.

Once the optimum method of particle sampling has been determined, continue monthly sampling as described in the sampling plan and begin particle determination for size determination.

Continue monthly sampling for the remainder of the 5-month period. Resume further evaluation of the experimental process. The results of the analysis will be used with a dispersion model to calculate salt particle emission factors. Prepare a written technical report with the results, conclusions, and recommendations of the 5-month monitoring study. Submit the final report to the DWR and Westside Resource Conservation District (WRCD).

Summary of Results of Work Performed

A preliminary sampling excursion was conducted in order to test this method of measurement. This sampling trip was conducted in late June and consisted of placing petri dishes on three radials extending to the south, south-east, and east of the system. The placement of these radials was done according to the prevailing north-westerly wind direction. The extent of the initial sampling pattern was determined by placing the petri dishes within the road that borders the evaporation system at approximately 40-50 meters from the edge of the evaporator. The petri dishes were placed in the sampling locations and uncovered as quickly as possible in order for all petri dishes to represent the same time period. After 4 hours the petri dishes were collected and returned to the California Water Institute for analysis. The analysis method consisted of rinsing the petri dishes with 40 ml of deionized water and placing the rinsate in a container with an additional 40 ml of DI water. The rinsate was then analyzed for electrical conductivity for later correlation to total dissolved solids (TDS). Initial analysis indicated that the EC was below

range of the conductivity probe we were using. We subsequently purchased a new probe within the desired range. Once the new probe was purchased, a second analysis of the results showed more consistent readings at the low end of the measurements. The results of this analysis were deemed acceptable although it was determined that a greater number of sample locations were required to more accurately characterize the plume.

Sampling Scheme

The sampling pattern for the preliminary study is shown in Figure 1. This pattern was selected to determine if the amount of deposition was going to be measurable with our selected procedure. The results of this initial analysis showed that the deposition rates that we were going to measure would be small but within the available analytical range. The rinsate was analyzed for both EC and a subset of the samples were analyzed for TDS.

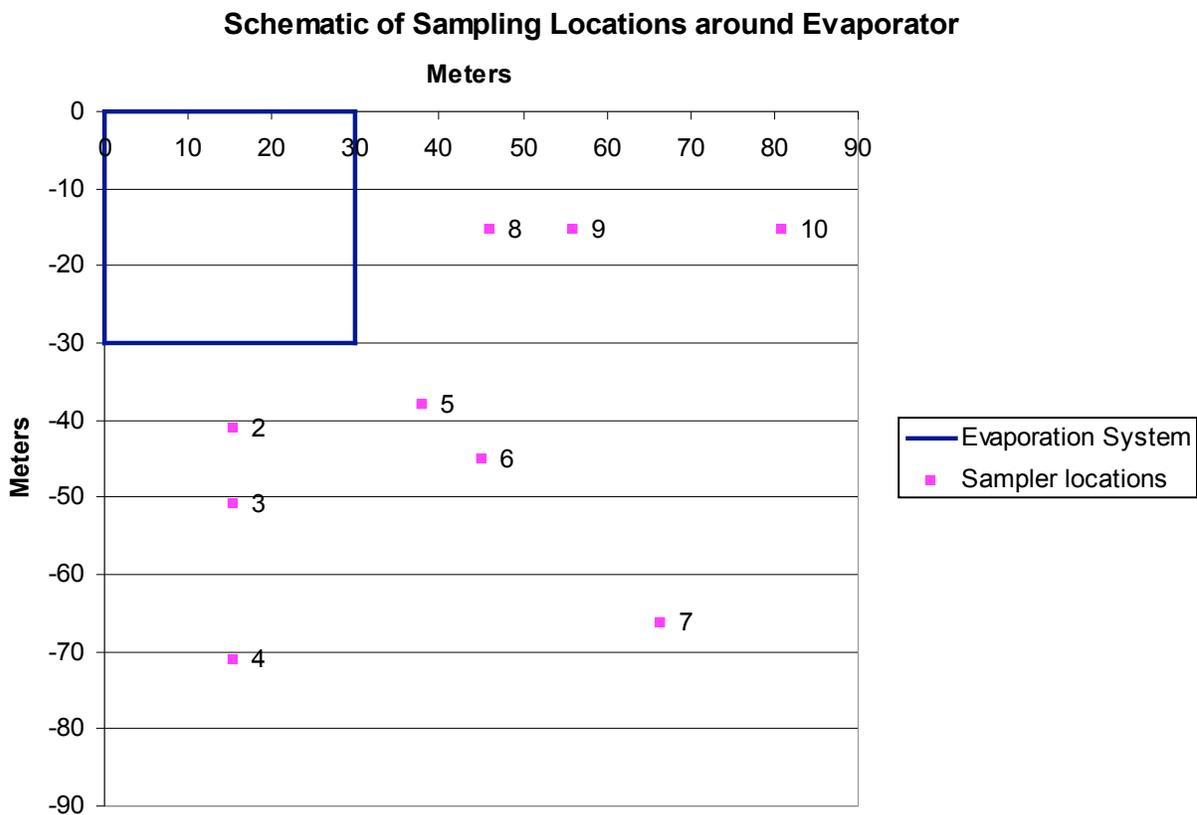


Figure 6. Schematic of preliminary sampling scheme.

The results of this analysis showed that the salt deposition plume extended beyond our initial sampling area. Therefore, we significantly extended our sampling net to include distance up to 180 meters from the north and west edge of the evaporation system. Figure 2 shows the final sampling scheme used along with the radials that were used to characterize the results. For this sampling scheme columns were labeled with letters from the left to right (A-H) and rows were

labeled from top to bottom with numbers (1-8). For example, the first sampling location in the first column is location A3. Row 7 and column G were eliminated for the later tests in the interest of time and due to the difficulty of reaching the sampling locations in the field.

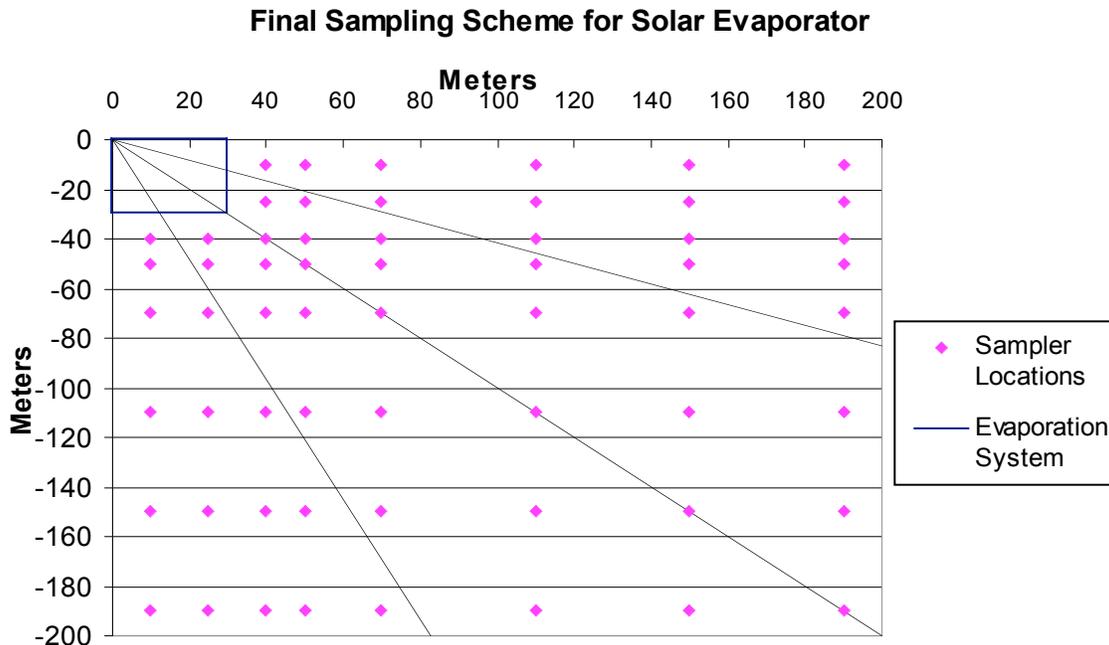


Figure 7. Final sampling scheme used for analysis of deposition from solar evaporator emissions. The solid lines extending from the origin represent the dividing lines between the radials. The points that fall on the 45 degree line were grouped into the second radial.

It was assumed that the deposition would be dependant on the ambient concentration of the salts suspended in the air above the sampling location. This assumption is based on the EPA approved dispersion model Industrial Source Complex-Short Term version 3 (ISC), which contains a deposition algorithm. The algorithm uses ambient particle size distribution data to determine the deposition velocity of the particles. Using the predicted concentration and the deposition velocity, it is then predicts the deposition at a given point. The input for the deposition calculations is the particle size distribution of the emissions which was not attained during this work. The result of the deposition algorithm for any given particle size distribution is that the relative deposition flux decreases faster than the relative concentration values as the distance from the source increases. This is due to the removal of the particles with higher settling velocities will be removed quickly, thus decreasing the average settling velocity for all particles. Therefore, a prediction of concentration using ISC does not accurately reflect the decay of deposition values experienced in the field.

Results

The initial analysis of each sample was completed immediately after returning from the field, while the IC analysis was done after all samples were completed. Due to the large variation in

EC measurements, the IC results were divided into 2 groups that corresponded with the 2 calibration levels of the EC probe. The first group corresponds to all EC's less than 50 $\mu\text{s}/\text{cm}$ and the second group consists of all EC's greater than 50 $\mu\text{s}/\text{cm}$. This creates two different regression equations for the relationship between EC ($\mu\text{s}/\text{cm}$) and TDS (mg/l). The results of each of these regression equations are shown in table 1.

Table 5. Results of regression analysis between measured EC and TDS.

Group	Slope	Intercept	R ²
<50	0.774	-1.495	0.941
>50	0.780	-17.180	0.993

Once the IC analysis was completed the deposition flux ($\text{mg}/\text{m}^2\text{-h}$) could be calculated using the recorded EC's, the known rinsate volume, petri dish area, and sample time. This allowed for the deposition flux to be compared across tests regardless of sample duration. This resulted in the final measurement that can be used to analyze the characteristics of the system.

The deposition ($\text{mg}/\text{m}^2\text{-h}$) at each sampling point within a radial is assumed to be described as strictly a function of the distance r in meters. The deposition within each radial was then plotted versus the distance 'r' and a best fit line was established. To describe the analytical process the sampling period on August 2, 2004 will be used (All other scatter plots are contained in the appendix of this report). The scatter plot of deposition flux versus radial distance for radial 1 is shown in Figure 3. This shows that the decay rate is not linear with distance.

The data was then transformed to find a better fit for the data. The transformation that provided the best fit was a log-log transformation. This was done by fitting a straight line to the plot of the natural log of radial distance versus the natural log of deposition. Figure 4. shows this plot along with the best fit linear trend-line. For this data set the r^2 of this line is 0.89 after outliers were removed. The result is a best fit equation of the form in Equation 1. and Equation 2. which is transformed back to the original units.

$$\ln(\text{deposition}) = m * \ln(\text{radial distance}) + b \quad (1)$$

or

$$\text{deposition} = \exp(b) * (\text{radial distance})^m \quad (2)$$

where:

- m = slope of straight line, and
- b = intercept of straight line.

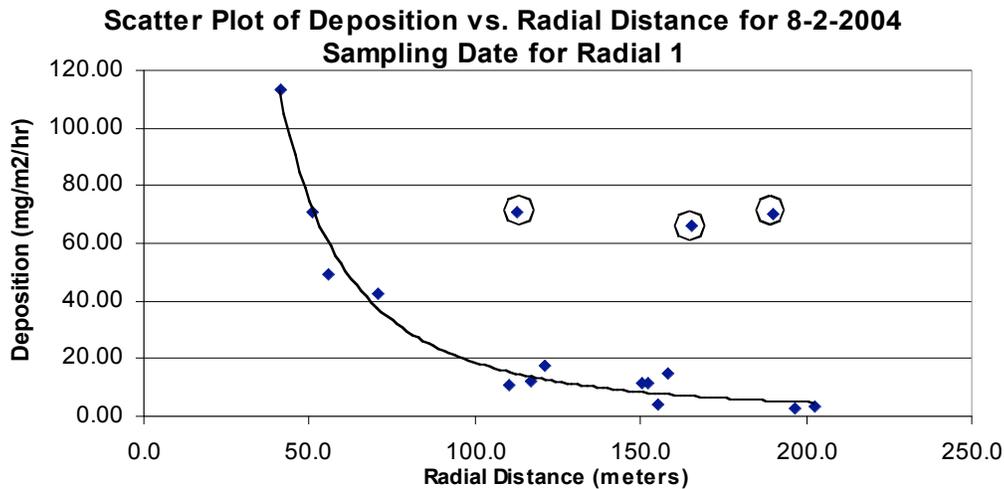


Figure 8. Scatter plot and trend line of the deposition flux vs. the radial distance for the 8-2-2004 sampling date. The circled points indicate outliers that are not included in the trend line.

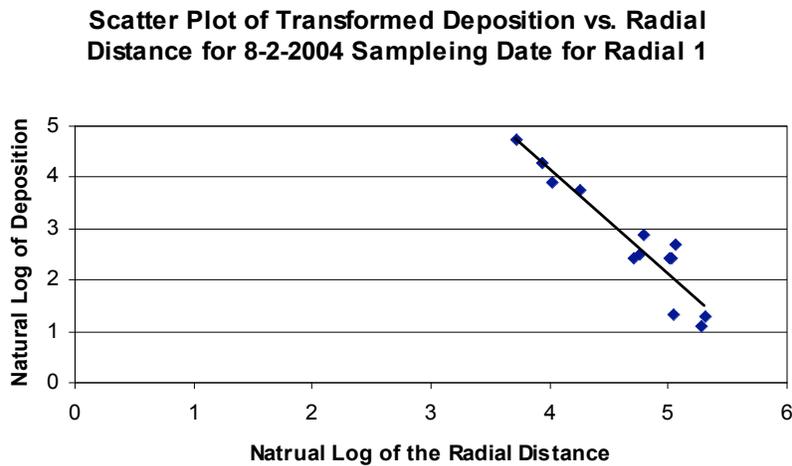


Figure 9. Log-Log scatter plot of the deposition vs. radial distance for radial 1 on the 8-2-2004 sampling date. Outlying data points have been removed.

The results of the statistical analysis show that the deposition for any single radial is clearly dependant on the downwind distance of the sampling location. The results of this analysis for each sampling period are shown below in Table 2., with outliers removed from the data. The coefficients are in the form of equation 2 above. Although the coefficients appear to be drastically different, the end result of a statistical analysis of the data is that there is no statistically significant difference in the regression equations. This is due to the exponential term in Equation 2. A small change in either the slope (m) or the intercept (b) in the transformed data represents a very large change in the final predictive equation. Therefore, a small standard error in the transformed trend line leads to a broad confidence interval for the final regression line. It can be seen that most of the regression lines have r^2 values that are greater than 0.8. While there

are some trend lines, like radial 4 on 8/2/04, that have extremely low r^2 values. The lower values can be attributed to the lack of deposition from the solar evaporator. Therefore, there is no decay in deposition as distance from the solar evaporator increases.

Table 2. also shows the conditions that existed during each testing period. Each sampling period is associated with a duration, average reference evapotranspiration, water source (either tub number or sump location), average wind speed and average wind direction. All values are obtained from the California Irrigation Management Information Systems weather station number 190 that is located on site. This station recorded all the relevant information on an hourly basis. Vector averaging of the wind speed and direction was used to obtain an average for each sampling period. The average wind direction was relatively consistent across all tests, with the exception of the second test 10/1/2004. These variables were recorded in an attempt to statistically differentiate between tests, but the lack of statistical difference between the regression equations made this task impracticable. All sampling periods used water from sump 'D' except for the sampling conducted on 9/7/04. This sampling period used the highest concentrate water available represented as a mix from tub 4 and tub 2.

On 9/24/04 sampling was conducted to measure background levels of deposition, without the system running. The results of this analysis showed a random distribution of deposition rates across the entire sampling grid with no discernable pattern. The mean deposition rate collected from this 2 hour test was $10.1 \text{ mg/m}^2\text{-hr}$ with a standard deviation of 10.3. The sampling on this day was complicated by high wind speeds (4.5 m/s) that probably lead to higher than usual background readings due to blowing particulate matter that landed in our sampling devices. This is confirmed by the comparison of this data to that measured upwind during all the tests. The average deposition upwind during all tests was recorded as, $0.9 \text{ mg/m}^2\text{-h}$. This clearly shows that the sampling date on 9/24/04 was influenced by blowing debris being deposited in the sampling devices due to the high wind speed. Therefore, the background number that will be compared to for analysis is the average of the upwind sampling locations and not that determined from the 9/24/04 sampling date. This level of deposition is also accounts for of the amount of TDS found in the deionized water and is therefore, a valid background number for comparison purposes. The 9/24/04 sampling also measured the possibility of blowing salts when the solar evaporator is not operational. Due to the lack of trends in the resulting deposition analysis it can be assumed that there is minimal entrainment of the solids deposited in the evaporator during non-operational times. This is logical after a close inspection of the solids in the evaporator. The solids tend to form layers on the gravel in the evaporator as opposed to being in a loose granular form.

Due to the lack of statistical differences between the lines, an approach of evaluating the trend lines at specific locations downwind of the source is used to draw conclusions. The downwind locations that the regression equations were evaluated at were the closest sampling location for each radial, 100 meters downwind, and 200 meters downwind. The closest sampling point for each radial is different due to the reference point location used. This is only done for the first evaluation point on each radius because applying the closest points of radials one and four, to radials two and three represent points that are actually inside the solar evaporator system for those radials. The closest sampling point was selected to evaluate the differences of the various configurations and source strengths, while the points at greater distances were selected to see how the changes affected the overall extent of the deposition. Table 3 shows the deposition rates

at these three locations for each sampling period. The column on the left once again shows the deposition rates before the sprinklers were lowered and the left column shows the deposition rates after the sprinklers were lowered. It can be seen that the deposition rates at the closest sampling location are somewhat lower after the change in sprinkler height although the variation in the trend lines do not allow for statistical analysis. It can also be seen that the deposition at 100 and 200 meters appears to lower for the lowered sprinklers. This makes sense in that a lower emission point will lead to less suspension of salt particulate initially and therefore less deposition downwind.

There is a large change (although not statistically significant) in the deposition rates on the 9/7/04 sampling date. On this sampling date, water from the final tub (tub 4) was introduced into the system for operation. There was not enough of water in this tub for complete operation of the system and therefore, water from tub 2 was added for sufficient operating volume. The addition of this water left the final source strength significantly higher than all other sampling dates. This process lead to the highest recorded deposition rates by a large margin at the closest sampling points. It can be seen in Table 3. that the regression equations also predict drastically higher deposition rates at the closest sampling location on this day. This is due to the increase in TDS concentration of the source water that leads to a higher emission rate.

In order to determine the total mass of emissions being deposited by the system, a 3-dimensional surface of the deposition was created using the surface mapping program known as Surfer. Using this program with the measured deposition fluxes allows for an approximation to be made of the mass deposition rate downwind of the solar evaporator for each test. This is done by integrating the area under the 3-dimensional surface that describes the deposition. Total deposition rates were determined using a 100 meter array and a 200 meter array. Table 4 shows the calculated total deposition rates for both array sizes for each of the tests. The final column is the ratio of 100 meter array to the 200 meter array. The average ratio is 0.5 indicating that half of the total deposition within 200 meters occurs on 25% of the total area.

Table 6. Summary of regression equation coefficients for all sampling periods for equation 2. The left column represents samples acquired before the sprinklers were lowered, while the right column represents the data after the sprinklers were lowered.

Date	8/2/2004	ET	0.69 mm		Date	9/10/2004	ET	0.63 mm
Duration	3 hours	Water Source	D		Duration	2 hours	Water Source	D
Average WD	326	Average WS	3 m/s		Average WD	334	Average WS	2.4
Radial	exp(b)	m	R ²		Radial	exp(b)	m	R ²
1	2.239E+05	-2.043	0.889		1	1.089E+04	-1.554	0.752
2	2.625E+06	-2.492	0.848		2	1.027E+07	-3.079	0.9907
3	1.909E+08	-3.710	0.844		3	1.543E+06	-2.803	0.9252
4	6.286E+02	-1.000	0.07		4	8.484E+03	-1.907	0.4719
Date	8/31/2004	ET	0.74 mm		Date	9/10/2004	ET	0.76 mm
Duration	3 hours	Water Source	D		Duration	2 hours	Water Source	D
Average WD	336	Average WS	2.4		Average WD	336	Average WS	2.6
Radial	exp(b)	m	R ²		Radial	exp(b)	m	R ²
1	8.440E+04	-1.816	0.76		1	3.232E+05	-2.325	0.8921
2	4.143E+05	-2.216	0.8727		2	6.382E+06	-2.968	0.9198
3	2.294E+04	-1.742	0.7085		3	6.936E+09	-4.801	0.9648
4	1.857E+04	-1.750	0.731		4	3.963E+02	-0.922	0.5176
Date	9/7/2004	ET	0.73 mm		Date	9/28/2004	ET	0.48 mm
Duration	3 hours	Water Source	#4 and #2		Duration	4 hours	Water Source	D
Average WD	339	Average WS	2.6		Average WD	296	Average WS	0.6
Radial	exp(b)	m	R ²		Radial	exp(b)	m	R ²
1	1.004E+06	-2.028	0.8386		1	8.378E+04	-2.024	0.2825
2	1.228E+07	-2.553	0.7078		2	1.250E+08	-3.630	0.7451
3	7.089E+07	-3.282	0.9784		3	7.481E+08	-4.290	0.8858
4	2.078E+05	-2.328	0.6319		4	1.237E+12	-6.617	0.8586
Date	9/7/2004	ET	0.67 mm		Date	10/1/2004	ET	0.40 mm
Duration	3 hours	Water Source	#4 and #2		Duration	4 hours	Water Source	D
Average WD	336	Average WS	2.8		Average WD	353	Average WS	1.7
Radial	exp(b)	m	R ²		Radial	exp(b)	m	R ²
1	1.494E+07	-2.652	0.8713		1	1.558E+06	-2.687	0.7852
2	1.965E+08	-3.352	0.6832		2	2.431E+10	-4.803	0.7966
3	1.606E+06	-2.583	0.7463		3	1.826E+05	-2.226	0.9587
4	1.211E+08	-3.905	0.988		4	2.356E+00	-0.007	0.0218
Date	9/8/2004	ET	0.74 mm		Date	10/1/2004	ET	0.51 mm
Duration	3 hours	Water Source	B and D		Duration	4 hours	Water Source	D
Average WD	301	Average WS	2.8		Average WD	12	Average WS	1.6
Radial	exp(b)	m	R ²		Radial	exp(b)	m	R ²
1	4.679E+05	-2.096	0.7722		1	4.25E+03	-1.400	0.5598
2	1.239E+08	-3.189	0.9016		2	1.82E+06	-2.738	0.7350
3	1.469E+08	-3.374	0.921		3	1.50E+06	-2.858	0.9147
4	3.908E+07	-3.476	0.7889		4	2.10E+03	-1.374	0.3858

Table 7. Predicted deposition rates at three locations in each radial downwind of the solar evaporator in mg/m²-h. The left column represents the deposition before the sprinklers were lowered while the right column represents the deposition after the sprinklers were lowered.

Date	8/2/2004	ET	0.69 mm		Date	9/10/2004	ET	0.63 mm
Duration	3 hours	Water Source	D		Duration	2 hours	Water Source	D
Average WD	326	Average WS	3 m/s		Average WD	334	Average WS	2.4
Radial	Closest	100 m	200 m		Radial	Closest	100 m	200 m
1	112.6	18.4	4.5		1	33.7	8.5	2.9
2	176.7	27.2	4.8		2	109.4	7.1	0.8
3	117.5	7.3	0.6		3	45.9	3.8	0.5
4	15.3	6.3	3.1		4	7.1	1.3	0.3
Date	8/31/2004	ET	0.74 mm		Date	9/10/2004	ET	0.76 mm
Duration	3 hours	Water Source	D		Duration	2 hours	Water Source	D
Average WD	336	Average WS	2.4		Average WD	336	Average WS	2.6
Radial	Closest	100 m	200 m		Radial	Closest	100 m	200 m
1	98.5	19.7	5.6		1	56.8	7.2	1.4
2	80.8	15.3	3.3		2	102.8	7.4	0.9
3	27.8	7.5	2.3		3	122.6	1.7	0.1
4	27.7	5.9	1.7		4	12.9	5.7	3.0
Date	9/7/2004	ET	0.73 mm		Date	9/28/2004	ET	0.48 mm
Duration	3 hours	Water Source	#4 and #2		Duration	4 hours	Water Source	D
Average WD	339	Average WS	2.6		Average WD	296	Average WS	0.6
Radial	Closest	100 m	200 m		Radial	Closest	100 m	200 m
1	533.0	88.2	21.6		1	45.2	7.5	1.8
2	655.2	96.4	16.4		2	172.0	6.9	0.6
3	227.5	19.4	2.0		3	88.4	2.0	0.1
4	36.1	4.6	0.9		4	25.5	0.1	0.0
Date	9/7/2004	ET	0.67 mm		Date	10/1/2004	ET	0.40 mm
Duration	3 hours	Water Source	#4 and #2		Duration	4 hours	Water Source	D
Average WD	336	Average WS	2.8		Average WD	353	Average WS	1.7
Radial	Closest	100 m	200 m		Radial	Closest	100 m	200 m
1	778.3	74.1	11.8		1	71.3	6.6	1.0
2	482.2	38.9	3.8		2	425.5	6.0	0.2
3	76.2	11.0	1.8		3	46.5	6.5	1.4
4	59.7	1.9	0.1		4	2.3	2.3	2.3
Date	9/8/2004	ET	0.74 mm		Date	10/1/2004	ET	0.51 mm
Duration	3 hours	Water Source	B and D		Duration	4 hours	Water Source	D
Average WD	301	Average WS	2.8		Average WD	12	Average WS	1.6
Radial	Closest	100 m	200 m		Radial	Closest	100 m	200 m
1	192.7	30.0	7.0		1	23.4	6.8	2.6
2	568.0	51.8	5.7		2	69.1	6.1	0.9
3	330.6	26.3	2.5		3	36.3	2.9	0.4
4	95.2	4.4	0.4		4	12.7	3.7	1.4

Table 8. Surfer analysis of deposition (g/hr) downwind from the solar evaporator for two array sizes. The ratio of the arrays indicates that half the deposition occurs within 100 meters of the solar evaporator.

Test	Array Dimension		Ratio
	100mx100m	200m x 200m	
8/2/2004	369	842	0.44
8/31/2004	255	437	0.58
9/7/2004 T1	1615	3507	0.46
9/7/2004 T2	1104	1916	0.58
9/8/2004	919	1759	0.52
9/10/2004 T1	124	243	0.51
9/10/2004 T2	150	403	0.37
9/28/2004	168	301	0.56
10/01/2004 T1	195	371	0.52
10/01/2004 T2	123	285	0.43
		average	0.50

Testing continued in June of 2005 with a single test designed to ascertain the effects of the fence on the emissions of the system. This was done by extending the sprinkler pattern beyond the fence to the east. The resulting sprinkler pattern was half as deep from north to south and twice as wide from east to west. An enhanced sampling array was used in hopes of determining the effects of the sprinklers outside the fence. Figure 5 shows the enhanced sampling scheme used along with the dimensions of the fenced area and the non fenced area.

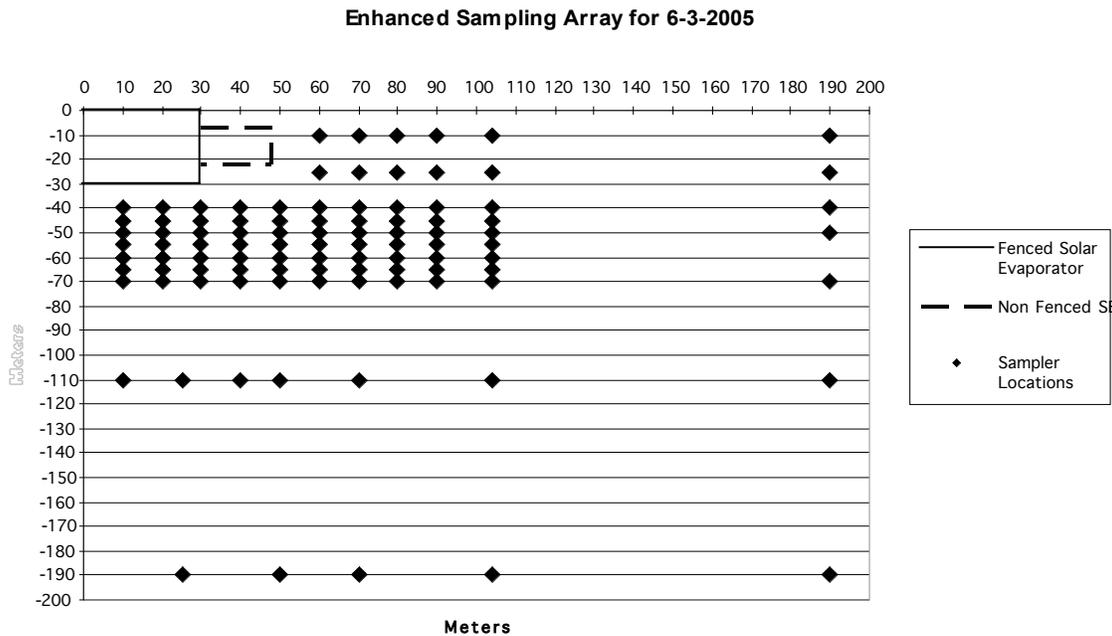


Figure 10. Schematic of enhanced sampling pattern used for measurement of solar evaporator on 6-3-2005.

Estimated PM₁₀ Emissions

While direct measurement of the particle size was not possible with the methods available for this study, an estimate can be made of the potential for emissions of PM₁₀ and smaller particles of salt that could be subject to air quality regulation. It is clear from the rapid decrease in deposition rate with distance downwind from the solar evaporator that almost all of the particles are much larger than 10 μ and would not be subject to regulation. The particles formed from the evaporation of a drop would be a function of the droplet size and its concentration of salt. The size of the droplets from a sprinkler depends upon the design of the nozzle and the operating pressure. The sprinklers in the solar evaporator were low pressure, fan type nozzles and would produce large droplets of about 4mm diameter or larger. The concentration of salt in the droplets would vary with the particular operating conditions of the solar evaporator. For estimation purposes, the EC of the water was assumed to be 20. If 1 unit of EC is approximately equal to 700ppm of the typical salts found in drainage water and if the salt particle that forms when the droplet evaporates is assumed to be spherical, then the theoretical particle size can be calculated from the diameter of the droplet and the concentration of salt. A table of estimated particle sizes from a droplet spectrum is shown in Table 5.

Table 5. Estimated salt particle size as a function of droplet size

Drop size (mm)	0.5	0.65	1	2	3	4	5
EC	20	20	20	20	20	20	20
Salt in drop (mg)	0.00009	0.00020	0.00074	0.00594	0.02005	0.04752	0.09282
Particle size (mm ³)	0.00004	0.00008	0.00028	0.00224	0.00757	0.01793	0.03503
Particle diameter (μ)	7.8	10.2	15.6	31.3	46.9	62.5	78.1
Drop size (mm)	0.5	0.65	1	2	3	4	5
EC	10	10	10	10	10	10	10
Salt in drop (mg)	0.00005	0.00010	0.00037	0.00297	0.01002	0.02376	0.04641
Particle size (mm ³)	0.00002	0.00004	0.00014	0.00112	0.00378	0.00897	0.01751
Particle diameter (μ)	6.2	8.1	12.4	24.8	37.2	49.6	62.0
Drop size (mm)	0.5	0.65	1	2	3	4	5
EC	5	5	5	5	5	5	5
Salt in drop (mg)	0.00002	0.00005	0.00019	0.00149	0.00501	0.01188	0.02320
Particle size (mm ³)	0.00001	0.00002	0.00007	0.00056	0.00189	0.00448	0.00876
Particle diameter (μ)	4.9	6.4	9.8	19.7	29.5	39.4	49.2

The theoretical droplet size that would result in a PM₁₀ salt particle is 0.65 mm in diameter for water of EC = 20. Droplets of that small size are only formed when sprinklers are operated at very high pressure. The low pressure, fan nozzles used in the solar evaporator will produce droplets of at least 4 mm diameter or larger. The size of the salt particle is inversely proportional to the cube of the radius of the droplet so operation of the evaporator to dispose of waters that are less than EC = 20 will not result in salt particles that are significantly smaller as shown in the table for EC = 10 and 5.

The total salt emissions from an average of the summation of the modeled plumes is about 1 kg of salt per hour of operation under the tested conditions. The potential emissions of both total salt and PM₁₀ are shown in Table 6.

Table 6. Estimated emissions of total salt and PM₁₀ from the operation of the solar evaporator

Emission rate of 1kg/hr			
Total Salt Emissions			
Days of Operation	365	180	120
Hours per day	24	12	8
Emissions/day (lb)	52.8	26.4	17.6
Emissions/year (T)	9.6	2.4	1.1
Potential PM-10 Emissions			
Estimated PM-10 %	0.1	0.05	0.02
Estimated PM-10 T/yr	0.96	0.12	0.02

The maximum estimated salt emissions from the solar evaporator, if operated continuously under the tested conditions would be 9.6 tons/year. Since the tested high evaporation conditions exist only during summer days, this total is not relevant. It should be noted that the current trigger value for permitting a source of PM₁₀ is 12.5 tons/year and the point at which mitigation is required is 25 tons/year. If all salt from the evaporator were PM₁₀ and if it operated at summer day conditions continuously, it would still not reach the level requiring a permit. A realistic, intensive schedule would be 12 hours of operation for half the year (180 days). At that rate the salt particles would total 2.4 tons/year. An even more realistic schedule would be periodic operation when the volume of drainage water was sufficient to run the system during peak evaporation hours. This schedule of 8 hours a day for 120 days produces a total of 1.1 tons/year of salt particles. If the PM₁₀ percentage of the particles were as high as 10%, which is very unlikely given the droplet size spectrum estimated in Table 5, the emission rate subject to regulation could be as high as 0.96 tons/year for continuous operation. A more likely percentage (2%) with the most likely schedule of operation would result in a PM₁₀ emission rate of 0.02 tons/year. This emission rate is more than a thousand times less than the level that would require PM₁₀ mitigation practices.

The tested solar evaporator, while of significant size, may be smaller than those to be built in the future. The effects of scaling the unit up to larger sizes can be minimized with respect to the salt plume, the size of a buffer area, and the potential for air quality regulation. Modeling of the

plume indicates the critical factor is the width of the facility perpendicular to the wind direction. In the case of the tested solar evaporator, the wind direction was normally from the NE (about 300 degrees) during the period of operation. If the facility were expanded with the long dimension in a NE/SW direction, the evaporator could be made larger with very little increase in the size or composition of the salt plume. Salt particles produced at the NE end of the facility would be deposited inside the evaporator before they reached the SW (downwind) edge.

Conclusions

The universal constant for all sampling dates is a significant drop in deposition rate as the radius increases close to the system with decreasing change as distance increases. This leads to the law of diminishing returns when deciding what an appropriate buffer zone around the system would be. It is clear that at 200 meters downwind of the source there is insignificant salt deposition during normal operating periods (evaporation of sump water). Although operation during the highest source strength did yield some measurable deposition at that distance, the frequency of operation in these conditions is minimal. Therefore, 200 meters appears to be the maximum amount of buffer needed downwind of the evaporator to prevent significant deposition from occurring on sensitive crops. It may be that some salt deposition is acceptable on the crop in that area and the distance could be reduced to 100 meters or less. This decision will depend on the crop that is planted in this area and its specific tolerance to salt deposition.

This analysis was only conducted on the south and east sides of the evaporator due to the prevailing wind and available sampling locations around the source. There should be some consideration given to a buffer zone on the upwind side of the facility if the system is to be operated during all wind directions. There should also be some concern as to the salt deposition on the western sides of the facility. Although measurements were not made in this area, it can be logically assumed to have some deposition in this area due to the horizontal dispersion that may occur.

The particle emissions from the operation of the solar evaporator are a combination of those that are large enough to be deposited on the soil surface within the downwind plume and those that are small enough to remain entrained in the air. The small particles are those that could subject the solar evaporator facility to air quality regulations related to PM standards.

1. The re-deposition of salt within the downwind plume was considered to be the primary problem, as stated in the title of the project. A methodology from the literature enabled field data to be collected to measure salt deposition so that a dispersion model could be used to predict the quantity and location of the deposition. Several sampling episodes under a variety of operating conditions produced data that could be modeled to characterize the deposition. The average deposition of salts from the solar evaporator was less than 1 kg/hour and occurred within 200m of the source. A single sampling event when the most concentrated drain water was being evaporated produced the maximum of 3.5 kg/hr deposition. The deposition rate beyond the 200m point was not significantly different than the upwind, ambient levels. It should also be pointed out that half of the deposition occurred within the first quarter of the plume area, indicating the particles were predominantly large. A mass balance could be calculated for the

evaporator if the operating times with the usual drainage water as well as the times when the highest concentration water was being used were applied to the 1 kg/hour and 3.5 kg/hour emission rates for the documented days of operation.

2. While it was not possible within the time and budget available to directly measure the small particles that remained in the air, it is possible to determine their significance with regard to the potential for regulation of a solar evaporator as a PM source. The particles produced by the solar evaporator were predominantly larger than the size that would remain entrained in the air, as shown in the deposition patterns discussed above. The total mass of deposited particles would be at least an order of magnitude, and perhaps two or more greater, than any entrained particles. The emissions of these particles which may be small enough to be classified as PM₁₀ or PM_{2.5} are insignificant compared to the levels that would result in regulation or even permitting of a facility. The threshold for permitting a facility is 12.5 tons of emissions/year. The threshold for regulation is 25 tons/year. The total salt emission rate (both deposited and entrained) from the solar evaporator would average about 1 kg/hr. This total, from continuous (24/7/365) operation of the solar evaporator would only be 9.6 tons/year. A more realistic operating schedule would be approximately a third or less of that maximum. The particles small enough to be regulated are a very small fraction of that total so the PM emissions from the solar evaporator can be considered to be insignificant.
3. The solar evaporator could be scaled up from the size of the tested facility without a significant increase in the plume of deposited large particles or entrained small particles. The salt plume is primarily a function of the dimension normal to the wind direction. If the size were increased with the length of the area along the axis of the prevailing wind direction and the cross wind width was kept at a minimum size, the area could be increased without significantly increasing the size of the salt plume. Operation of the sprinklers at the lowest practical pressure would also minimize the plume and especially the proportion of the salt particles that would be small enough to be of concern as PM₁₀. Low pressure operation would also minimize energy requirements for the facility.

Appendix A: Comments related to the preliminary report draft

There were 12 specific comments as a result of the draft report circulated in June, 2005.

Responses to those comments are:

1. *What are the emissions? Are the emissions significant? Will the emissions be subject to air quality regulation?* See conclusion 2 above.
2. *Include scientific terms related to air quality and definitions of terms pertaining to Federal and California codes.* These were not included in the draft but have been addressed in the final version of the report.
3. *The report does not incorporate communication of stakeholders such as government representatives that have a stake or concern about how air quality is managed for operation of SE, air quality data and state and national air quality standards.* The respondents are unclear as to what is in question regarding this comment.
4. *The amount of salt lost as airborne emissions is not quantified. Provide a material balance between mist and dry particles.* The total rate of the deposited particles plus the entrained particles that may be small enough to be regulated averages 1 kg/hr. It was not possible within the budget or time allowed for this project to directly measure the particles that may be subject to regulation but they are a small fraction of the total. Since the total is far below the threshold of regulation, it is of academic interest only to quantify the PM emissions from the operation of the solar evaporator. Mist particles would not be measurable as PM for regulation. The contribution from mist as deposited particles would be included in the total but cannot be separated from the dry deposition.
5. *The results of the analysis were not used with a dispersion model to calculate an emission factor.* A complete discussion of the modeling of the field data with the ISC model is included in the final report.
6. *Include a description of QA/QC procedures regarding the procedures in the laboratory.* The QA/QC procedures from the laboratory and a discussion of their application to this project are included in the final report.
7. *The units, mg/m²/hr, contain hours therefore, represents intensity of depositions instead of deposition.* Emission rates, by definition must contain a time factor. The values in the report are shown in the usual format for emission rates. When combined with the time of operation (information we were not provided) the emission rate can be used to calculate total deposition.
8. *Discuss wet drift emissions in the report to address droplets that do not completely evaporate that will carry salt downwind from the evaporation area.* Deposition of salt from droplets cannot be separated from dry deposition as discussed in item 4. Droplets small enough to be considered PM cannot exist for sufficient time to be carried any significant distance and could not be measured in any case so their contribution to PM emissions is negligible.
9. *Develop scatter plot versus radial distance graphs for each sampling period.* This has been done and is included in the final version of the report.
10. *Discuss particulate emissions that may occur when salts stored in the SE are subjected to wind.* No definable plume of particles could be detected when the solar evaporator was not in operation so the movement of salt particles is not a significant component. The deposition of salt within the evaporator appears to be strongly adsorbed on the gravel and does not exist in a form that could be picked up by wind and redistributed.

11. *How does the fence affect salt drift.* Operation of the solar evaporator with the fence in place decreases the total emissions of particles by interference and reduction of entrainment of salt particles. More of the deposition would occur closer to the solar evaporator with the fence. Operation without the fence increases the emissions somewhat but would spread the deposition over a wider area due to the reduction in turbulence and increasing the wind speed. The result would be a lower deposition rate per unit of area.
12. *Use the technical report format.* The required format has been used for the final version of the report.

The significant issues of salt deposition and emission from the operation of the solar evaporator have been addressed, at least qualitatively and quantitatively where possible. While there are some remaining questions that could be answered by further work, those answers would be of academic rather than substantial value. We thank the Westside Resources Conservation District for supporting us through the past year while we investigated an interesting problem. We are confident that our findings provide sufficient information to allow the district to proceed with the development of the IFDM concept without concern for air quality problems that could have limited it had they been found to be significant. We consider the project complete. We will certainly be available to present these results and discuss their significance at subsequent district meetings where air quality issues may be raised but we will not be able to pursue any further field work or modeling.

Appendix B: Cover letter to Westside Resources Conservation District

July 19, 2005

To: Sarge Green, Manager, Westside Resources Conservation District

From: Charles Krauter, PI, Salt Deposition Downwind of a Soar Evaporator project

Subject: Final report summary and comments

The final report of the project titled Measurement of Salt Deposition Downwind of a Solar Evaporator is attached. A preliminary draft of this report was circulated last month and comments were received. Many of the comments were related to results and conclusions that had not been completed when the preliminary report was written. These have been completed or addressed in the current version. This cover memo will summarize the conclusions from the project and address the 12 specific comments received with regard to the preliminary draft.

Summary of Conclusions

The particle emissions from the operation of the solar evaporator are a combination of those that are large enough to be deposited on the soil surface within the downwind plume and those that are small enough to remain entrained in the air. The small particles are those that could subject the solar evaporator facility to air quality regulations related to PM standards.

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2. While it was not possible within the time and budget available to directly measure the small particles that remained in the air, it is possible to determine their significance with regard to the potential for regulation of a solar evaporator as a PM source. The particles produced by the solar evaporator were predominantly larger than those that would remain entrained as shown in the deposition patterns discussed above. The mass of deposited particles would be at least an order of magnitude and perhaps two greater than the entrained particles. The emissions of these particles which may be small enough to be classified as PM₁₀ or PM_{2.5} are insignificant compared to the levels that would result in regulation or even permitting of a facility. The threshold for permitting a facility is 12.5 tons of emissions/year. The threshold for regulation is 25 tons/year. The total salt emission rate (both deposited and entrained) from the solar evaporator would average about 1 kg/hr. This total, from continuous (24/7/365) operation of the solar evaporator would only be 9.6 tons/year. The particles small enough to be regulated are a very small

fraction of that total so the PM emissions from the solar evaporator can be considered to be insignificant.

3. The solar evaporator could be scaled up from the size of the tested facility without a significant increase in the plume of deposited large particles or entrained small particles. The salt plume is primarily a function of the dimension normal to the wind direction. If the size were increased with the length of the area along the axis of the prevailing wind direction and the cross wind width was kept at a minimum size, the area could be increased without increasing the size of the salt plume. Operation of the sprinklers at the lowest practical pressure would also minimize the plume and especially the proportion of the salt particles that would be small enough to be of concern as PM₁₀. Low pressure operation would also minimize energy requirements for the facility.