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Air Pollution Impact of Medical Waste Incineration in Semi-Arid Areas

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Abstract

Breeze AERMOD software is used to predict the impacts of medical waste incineration on ambient air quality in a semi-arid region of Jordan. The air quality impact is evaluated based on the predicted concentrations of sulfur dioxide, nitrogen dioxide, and carbon monoxide. Procured results reveal that the maximum average predicted concentrations of the three oxides are below their corresponding national and international standards and are expected to occur at a short distance of about 200m downwind from the incinerator main stack. The screening option in the model is used to calculate the hourly concentration at worst conditions for each month. Most of the maximum concentrations occur at nighttime hours (18:00 and 00:00 GMT), where stable conditions dominate the tropospheric boundary layer. The adequacy of AERMOD is also evaluated by comparing the predicted concentrations against measured values of the three criteria oxides. The findings demonstrated great deal of agreement between predicted and measured concentrations of nitrogen dioxide (R^2= 0.94), and carbon monoxide ($R^{2=}$ 0.98). However, predicted sulfur dioxide showed a lower correlation with the measured data ($R^{2=}$ 0.49).

Keywords: Air pollution, Dispersion, Incineration, Medical Waste, AERMOD, Modeling.

1. Introduction

Medical Waste (MW) is one of the most sensitive issues relating to the environment, so the threat extends to be one of the most serious sources of environmental pollution to the citizens surrounding the incinerators (Cole and Mickey, 2011).

Ministry of Health (MoH) is the government agency responsible of MW disposal and has regulations issued in 2011 deals with the management of MW. The regulations define the MW as all the waste, solid, liquid and gaseous wastes resulting from health care establishments, medical laboratories, medical research centers, pharmaceutical factories, human and veterinary medicines, veterinary clinics and institutions home nursing (MoH, 2014).

MW in Jordan has a witnessed rapid development as a result of rapid growth of population and the migration from neighboring countries. Populations were 5.6 million in 2006 and increased to 9.5 million in 2015 with 6.9 % average growth rate (DoS, 2015).

The number of hospitals increased from 101 hospitals with 11,049 total numbers of beds and an average occupancy rate of 60.9 % in 2006 to 104 with total number of beds of 12407 and an average occupancy rate of 50.3 % in 2014. In addition to that, the number of Health Care Centers (HCCs) was 671 in 2006 and has increased to 677 in 2014 (MoH, 2012). In Jordan, hazardous waste divided to industrial hazardous waste with 25,600 tons in 2002, and estimated to increase to 52,780 tons by 2015; and medical hazardous waste with the amount of 3,470 tons in 2002, and estimated in 2015 to 5,100 tons [METAP, 2005].

Incineration has been the most widely used treatment technology for MW disposal. The primary purposes for Medical Waste Incineration (MWI) are to transform the waste into non-hazardous residues and to reduce the volume (about 90 %) and mass (about 70 %) of the waste. These objectives are achieved by burning the waste at high temperatures over a sufficiently long period of time to sanitize infectious and contagious pathogenesis and burn the combustible portion of the waste (El-Hamouz, 2002; USEPA, 1993).

From environmental perspectives, incineration is not considered a clean process because toxic air pollutants emanated from incinerators unless properly operated and managed, because medical waste typically contains a variety of plastic materials, such as Polyvinyl Chloride (PVC) (Jang et al., 2006).

The present paper aims to investigate air emissions from the MW incinerators at the campus of Jordan University of Science and Technology (JUST) and to assess their impact on local air quality by applying BREEZE AERMOD Pro Plus version 7.0 for air dispersion modeling.

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2. Methods and Materials

2.1. Study Area

JUST incinerator is located within JUST campus at Latitude 34.48 N and Longitude of 35.89 E. The incinerator is located on a rural flat land with an elevation of approximately 590 meters above mean sea level. It is located about 20 km to the east of Irbid city. JUST incinerator is surrounded by agricultural areas in east, south and west directions. The west side is near the main road and JUST buildings are located in the north of incinerator.

A Hoval pyrolysis incinerator is used to incinerate MW generated from various Health Care Establishments (HCEs), including King Abdullah University Hospital (KAUH), 13 hospitals of the MoH and 8 private hospitals in northern governorates and other hospitals and centers in Amman and Zarqa. The incinerator was established in 1983 and occupies an area of 900 m^2 with a capacity of 2800 kg/hr. The temperature of combustion is sustained in the range of 800-900 °C with a residence time of the waste at least one hour. The hot gases released from the combustion process are flowing up into the secondary chamber in which further combustion of these gases occur at a temperature in the range of 1100-1200 °C with a minimum residence time of two seconds and 100 % excess air.

2.2. Description of Dispersion Model

The dispersion model used in the present study was BREEZE AERMOD Pro plus Version 7.0, developed by the Trinity Consultants.

AERMOD model is a steady-state plume model, calculates the spread of a plume from planetary boundary layer structure and scaling concepts, including treatment of both surface and elevated sources and both simple and complex terrain (USEPA, 2004). It assumes that the concentrations at all distances during modeled hour are governed by the set of hourly meteorological inputs.

AERMOD is a recommended model by USEPA and it is an updated version of the Industrial Source Complex Short Term (ISCST) model. This model is used to estimate the dispersion from industrial source points, flares, lines, areas, or volumes. AERMOD generates daily, monthly and annually concentrations in the ambient air and unlimited number of point sources, source groups, receptors, and short- and long-term averages can be modeled.

In general, AERMOD modeling system consists of the dispersion model (AERMOD) and two pre-processors (AERMET and AERMAP). AERMET is a meteorological preprocessor which can accept a range of inputs including surface characteristics in the form of Albedo, surface roughness, Bowen Ratio, and standard meteorological data; wind speed and direction, temperature and cloud cover (USEPA, 2004). AERMET then calculates the planetary boundary layer parameters including friction velocity, Monin-Obukhov length, convective velocity scale, temperature scale, mixing height, and surface heat flux. These parameters are used to calculate vertical profiles for wind speed, lateral and vertical turbulent fluctuations, potential temperature gradient and potential temperature.

During the present study, AERMOD was run using hourly surface data from the nearest station; Ar Ramtha station and the upper air data from the only station in the Jordan; Al Mafraq station.

AERMAP is a terrain preprocessor that calculates terrain and critical hill height values for each receptor for input into AERMOD. During the study, AERMAP was not used because the area is flat.

2.3. Meteorological Data

Meteorological data include hourly surface data and upper air data for the year 2010. Hourly surface data were obtained for Ar Ramtha station in the SCRAM format and upper air data for Al Mafraq station were used. Upper air data include pressure; height; temperature; dew point; wind speed; and wind direction in FSL format and can be downloaded from National Oceanic and Atmospheric Administration (NOAA) website http://www.esrl.noaa.gov/raobs/.

Wind rose (Figure 1) showed that the prevailing winds blow from the northwest much of the time and comprise about 38 % of all hourly wind directions. The frequency distribution of wind speeds of 5.7 – 8.8 m/s, 3.6 – 5.7 m/s and calms wind equal to 18.6 %, 20.2 % and 40.6 %, respectively. Wind speeds up to and including 0.514 m/s (1 knot) are considered to be calm (USEPA, 2012).

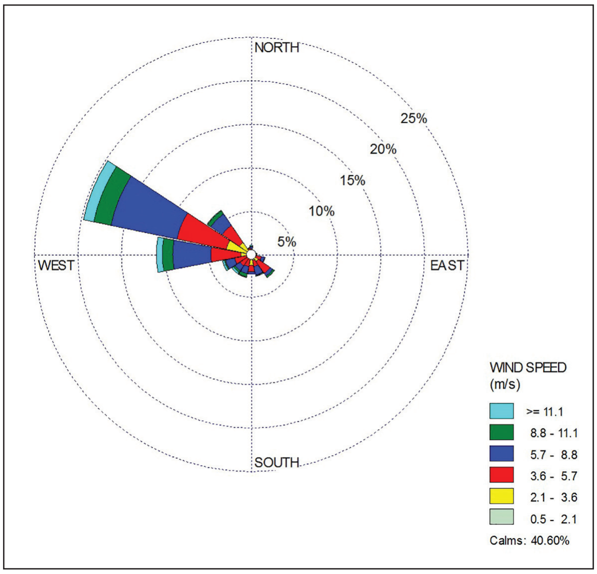

Figure 1. Wind rose for meteorological data of year 2010.

2.4. Emission Data

Real-time stack emissions measurements from the incinerators were conducted for 2-weeks. The capacity, technology and other specifications of the incinerators are shown in Table 1.

Table 1. Description of Medical Waste Incinerators

Capacity (Kg/hr)	Technology	Fuel	No. of Stacks per Incinerator	Stack Height (m)	Stack Diameter (m)
2800	Hoval Pyrolysis	Diesel	1	7	0.54

The stack emissions were measured for the following pollutants; Carbon Monoxide, Nitrogen Oxides, and Sulfur Dioxide. The sampling and analysis of flue gases from the stacks of incinerators were conducted using an electrochemical cells analyzer and this method is approved in the Jordanian Standard JS1189/2006.

The measurement of gaseous pollutants was carried out using a MRU VARIO plus Industrial stack gas analyzer which compiles with US EPA CTM methods 030 and 034. The MRU analyzer is equipped with electrochemical and NDIR sensors. The measurement range of the gas sensors were carbon Monoxide, 0 – 4,000 ppm; Nitrogen Oxide, 0 – 5,000 ppm; Nitrogen Dioxide, 0 – 1,000 ppm; and Sulfur Dioxide, 0 – 5,000 ppm. The pollutants measured in the present study were SO_2, NO_2, and CO and the emissions were compared with the Jordanian standard JS 1189/2006 of air pollutants emitted from the stationary source.

The pollutants concentrations and stacks data obtained from each incinerator over a 2-weeks period were statistically averaged and are presented in Table 2.

Table 2. Stack Emissions Data of MW Incinerators

#	Parameter	Stack 1	Stack 2
1	Average flue gas temperature (°C)	750.95	823.45
2	Flue gas velocity (m/s)	4.6	4.6
3	Volumetric flow rate of flue gas (m^3/s)	1.05	1.05
4	Average concentration of Carbon Monoxide in flue gas (mg/m^3)	19.98	20.88
5	Emission rate of Carbon Monoxide (g/s)	0.021	0.022
6	Average concentration of Nitrogen Dioxide in flue gas (mg/m^3)	116.75	159.47
7	Emission rate of Nitrogen Dioxide (g/s)	0.123	0.168
8	Average concentration of Sulfur Dioxide in flue gas (mg/m^3)	122.45	140.48
9	Emission rate of Sulfur Dioxide (g/s)	0.129	0.148

The MRU analyzer, used for the measurements, was new and the sensors were factory-calibrated; in addition to that, the analyzer was calibrated at the site. The MRU analyzer has a program for auto zero calibration using an integrated solenoid valve. A solenoid valve allowing the analyzer air to be discharged into the in-situ cell, forcing out the flue gas, and enabling the analyzer to check zero. So, zero calibration was done with respect to the Oxygen present in the atmosphere at 20.9%.

All of the experimental work was carried out by implementing the following quality control and quality assurance protocols. The MRU analyzer was zero calibrated before each measurement, calibration was carried out at the stack base, so the possibility of mixing the flue gas with the breathable atmosphere expected to be nil. It can, therefore, be assumed that the calibration of the analyzer with reference to the atmospheric Oxygen was acceptable.

Measurements were also taken by repeatedly using another analyzer; Testo 350 xl Portable Emissions Analyzer. This analyzer is used by the Queen Rania Al-Abdullah Center for Environmental Science & Technology to assure that the incinerators emissions are within JS 1189/2006 limits.

Testo 350 xl analyzer is equipped with electrochemical cells to measure flue gases and it has a program for self-calibration, and once the equipment is switched on, it automatically initiates fresh air and zeroing phase for 1-minute.A real-time EVM-7 ambient gas analyzer was used to measure the hourly concentration of the pollutants at 22 receptors in the study area for model evaluation purposes. EMV-7 analyzer is an electrochemical cell analyzer used to simultaneously measure toxic gases, such as Sulfur Dioxide, Nitrogen Dioxide, and Carbon Monoxide.

The monitoring sites are situated mainly at the north direction where the JUST buildings and other service facilities were located. 1.6 meter receptor height was used based on the height of the average human nose (Al Smadi et al., 2009). The analyzer was factory calibrated and the measured concentrations were compared with the ambient air quality standards 1140/2006 in Jordan, Ministry of Health (MoH) standards and National Ambient Air Quality Standards (NAAQS).

2.5. Model Performance Evaluation

Model performance evaluation was tested by comparing the predicted pollutants concentrations with those measured actual concentrations (hourly concentrations) at 22 discrete receptors.

Several measures used to evaluate model performance. Hanna et al. (1991; 1993) recommend the use of the following statistical performance measures; Fractional Bias (FB), Geometric Mean (MG), Normalized Mean Square Error (NMSE), Geometric Variance (VG), Correlation Coefficient (R), and the Factor of 2 (FAC2).

During the present study, the following statistical measures were used to evaluate the model performance; fractional Bias (FB), Normalized Mean Square Error (NMSE), Factor of 2 (FAC2), and Correlation Coefficient (R).

Fractional Bias (FB) is the mean error that defines the residual of the observed and the predicted concentrations. In this evaluation, it has been selected because it is a dimensionless number which is convenient for comparing the results from studies involving different concentration levels or even different pollutants and because it is symmetrical and bounded from -2 (extreme under-prediction) to 2 (extreme over-prediction).

It has the value of zero for an ideal model and express as (Chang and Hanna, 2004):

$$B = 2 \times \left(\frac{\overline{C}_o - \overline{C}_p}{\overline{C}_o + \overline{C}_p} \right) \quad \text{.. 1}$$

where $\overline{C_o}$: Average observed concentration

$\overline{C_p}$: Average predicted concentration

Values of the FB that are equal to -0.67 are equivalent to over-predictions by a factor of 2; while values that are equal to +0.67 are equivalent to under-predictions by a factor of 2.

Normalized Mean Square Error (NMSE) emphasizes the scatter in the entire set and it is an estimator of the overall deviations between the observed and predicted values. The normalization by the product C_o*C_p assures that the NMSE will not be biased towards models that over predict or under predict. It is expressed as (Chang and Hanna, 2004):

$$NMSE = \frac{\overline{(C_o - C_p)^2}}{\overline{C}_o \times \overline{C}_p} \quad \text{.. 2}$$

where C_o: observed concentration

C_p: Predicted concentration

Normalized mean square error measures the mean relative scatter and reflects both the systematic ($NMSE_{s)}$ and unsystematic ($NMSE_u$) errors. The lower the NMSE; the better the model ability to provide accurate predictions. For an ideal model performance, NMSE value is zero indicating no scatter between observed and predicted concentrations. For NMSE values less than 1.0; the magnitude of the scatter is less than the mean concentration and a value of 1.0 indicates that a typical difference between predictions and observations is approximately equal to the mean.

Factor of Two (FAC2) gives the fraction of the predictions that are within a factor of two of observations that satisfy 0.5 ≤ FAC ≤2.0. The FAC2 is the most robust performance measure because it is not affected by the low and high outliers. It is expressed as (Chang and Hanna, 2004):

$$FAC2 = \frac{C_p}{C_o} \quad \text{...(3)}$$

The ability of the model to predict at least 50% of the concentrations within a FAC2 of the observed concentrations is a fundamental requirement to accept the model (Derwen et al., 2010). In general, for an ideal or perfect model, both FB and NMSE equal zero and FAC2 equals one, and due to the random atmospheric processes, there is no such a thing. Hence, the acceptable limits according to the study of Kumar et al. (1993) are taken into consideration:

-0.5 ≤ FB ≤ +0.5

NMSE ≤ 0.5

FAC2 ≥ 0.8

The correlation coefficient (R) represents the strength of a linear relationship between two variables on a scatter plot; it is expressed as (Chang and Hanna, 2004):

$$R = \frac{\overline{(C_o - \overline{C_o}) \times (C_p - \overline{C_p})}}{\delta_{Cp} \times \delta_{Co}} \quad \text{......................................(4)}$$

where δ_C is the standard deviation over the data set.

A correlation coefficient of 1.0 indicates a perfect linear relationship; whereas a correlation coefficient of 0.0 means that there is no linear relationship between the variables.

3. Results and Discussion

3.1. Emissions from Source

Uniform Cartesian grid receptors network of 10 km x 10 km cover the study area with 2601 receptors was studied. The region within this field is mostly cultivated land, with other facilities scattered intermittently throughout the entire study area.

The stack emissions data were reported on a 3 % O_2 basis; the results were normalized to 8 % oxygen according to the Jordanian standard JS1189/2006 as presented in (Table 3)

Table 3. The sources parameters used as input to AERMOD

Parameter	Stack 1	Stack 2
UTM Coordinates (m)	3597783.595 Northing 779674.604 Easting	3597786.974 Northing 779668.394 Easting
Elevation (m asl)	590	590
Fuel Type	Diesel	Diesel
SO_2 emission rate (g/s)	0.129	0.148
NO_2 emission rate (g/s)	0.123	0.168
CO emission rate (g/s)	0.021	0.022
Velocity (m/s)	4.6	4.6
Temperature (°K)	750.95	823.45
Stack Inside Diameter (m)	0.54	0.54
Stack Height (m)	7	7

Normalization was done using the following equation:

$$C_{8\%} = C_{3\%} \times \left(\frac{20.9\% - 8\%}{20.9\% - 3\%} \right) \text{.................................(5)}$$

where $C_{8\%}$: pollutants concentrations at 8% O_2

$C_{3\%}$: pollutants concentrations at 3% O_2

20.9 %: the percent of O_2 in the air.

The stack exit concentrations were compared with the Jordanian standards (JS 1189/2006) and there are no exceedances occurred (Table 4).

Table 4. Concentrations of gases from the stacks

Stack ID	Concentration measured at 3% (mg/m³)			Concentration normalized to 8 % (mg/m³)		
	SO_2	NO_2	CO	SO_2	NO_2	CO
Stack 1	122.4	116.7	19.9	88.3	84.1	14.3
Stack 2	140.4	159.4	20.9	101.2	114.9	15.1
Jordanian standards				6500	200	---

3.2. Ambient air Quality

AERMOD was run using meteorological data for a whole year (2010) to identify the highest expected ground level concentrations (GLCs) during that year. AERMOD results are summarized in (Table 5).

Table 5. Concentrations of gases from the stacks

Pollutant	Maximum Predicted Concentration (µg/m³)			
	Hourly	8-hours	Daily	Annual
SO_2	28.86	-	4.25	3.63
Jordanian standards	779	--	363.7	104
NO_2	30.29	-	4.46	3.81
Jordanian standards	392	--	149	93
CO	4.48	1.31	-	-
Jordanian standards	29556	10231	-	-

The maximum 1 hr, 24 hr and annual SO_2 levels were 28.86µg/m³, 4.25µg/m³ and 3.63µg/m³ respectively (Figure 2).

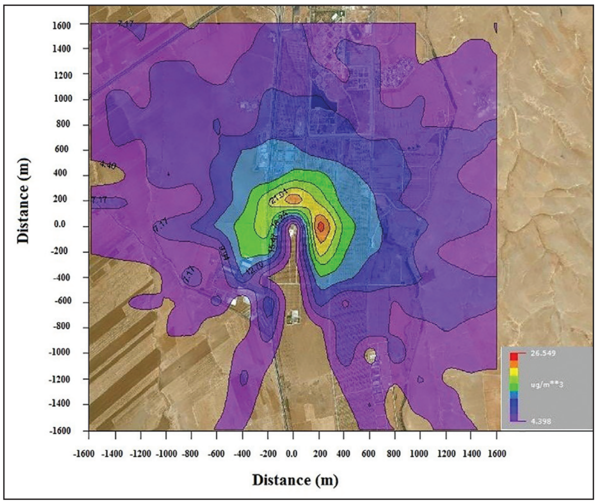

Figure 2a. Hourly concentration

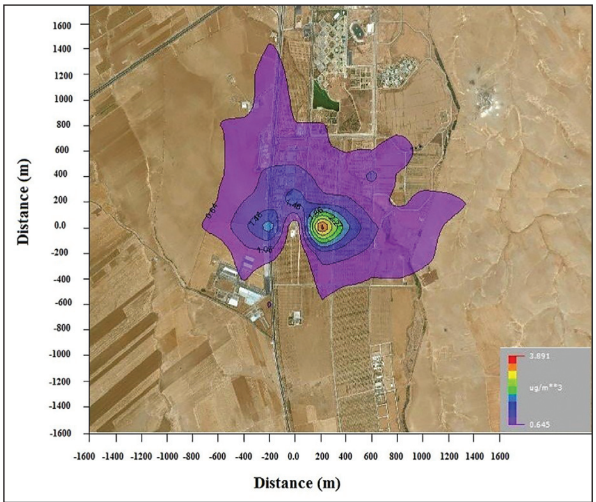

Figure 2b. Daily concentration

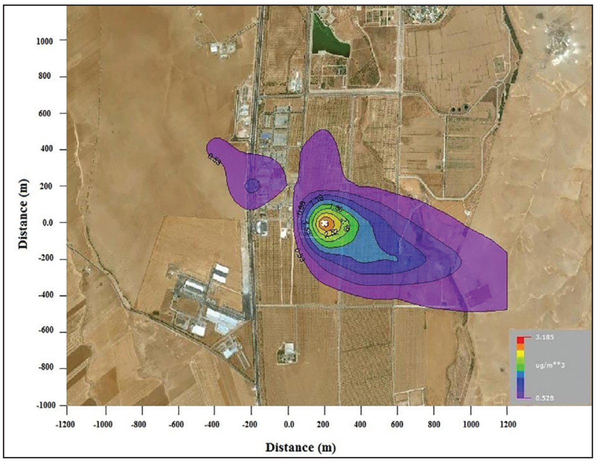

Figure 2c. Annual concentration

Figure 2. The average GLC of SO_2 in µg/m³

The concentrations of pollutant were very high at a downwind distance of about 200 m from the sources in the north direction for 1hr averaging period and in the east direction for daily and yearly. The higher 1 hr concentration is predicted to have occurred on the 15th of January/2010 at 06:00 while it is in October for 24 hr averaging period. The maximum 1hr, 24 hr and annual SO_2 concentrations predicted were comply with Jordan standards for these averaging periods.

The maximum levels of NO_2 predicted were 30.29 µg/m³ for 1 hr, 4.46 µg/m³ for 24 hr and 3.81 µg/m³, for annual averaging period (Figure 3). The max concentration is located at a downwind distance of 200 m in the north direction for 1hr averaging period and in the east direction for daily and yearly periods. The higher 1 hr concentration was found in 15th January at 06:00 (calm wind = 44.35%) while it is in October (calm wind = 51.61%) for 24 hr averaging period.

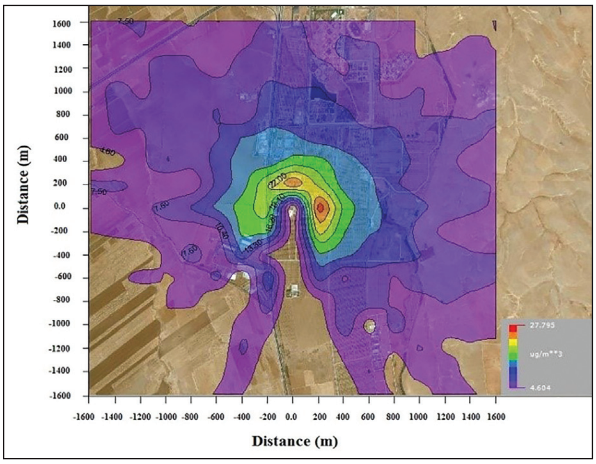

Figure 3a. Hourly concentration

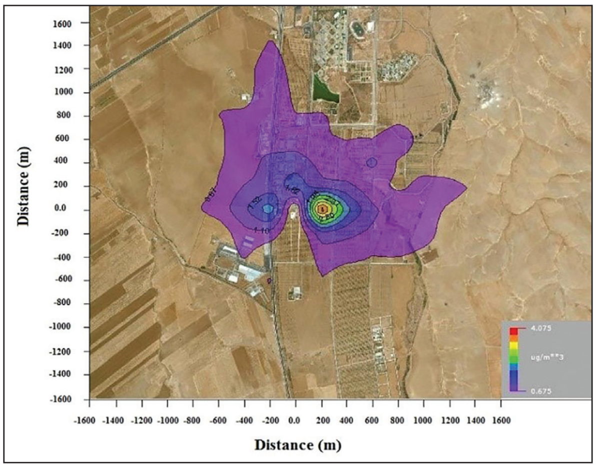

Figure 3b. Daily concentration

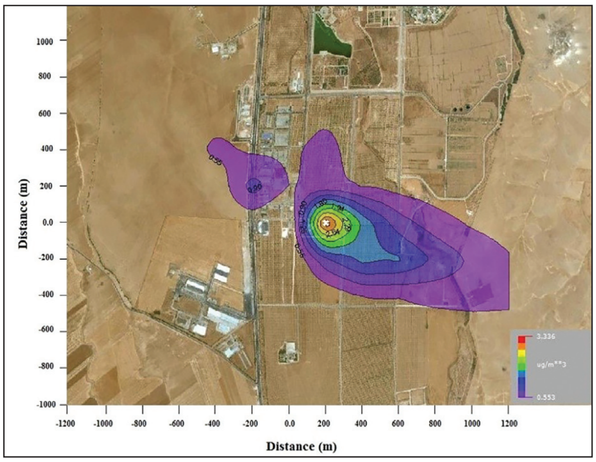

Figure 3c. Annual concentration

Figure 3 The average GLC of NO_2 in μg/m^3

The maximum 1hr, 24 hr and annual NO_2 concentrations predicted comply with Jordan standards for these averaging periods as well as NAAQS.

The maximum 1 hr and 8 hr levels of CO were 4.48μg/m^3 and 1.31μg/m^3, respectively (Figure 4). These concentrations were found at a downwind distance of 200 m in the east direction from the sources. The max concentrations for these averaging periods were founded in October (30th October at 00:00 am) and there is no exceedance of the national and international ambient air quality standard.

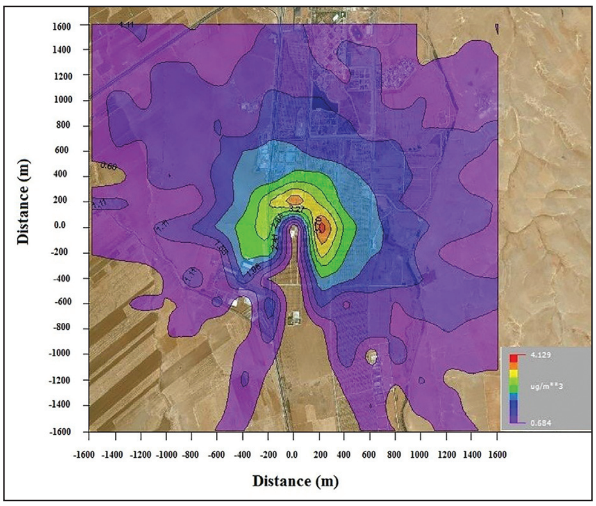

Figure 4a. Hourly concentration

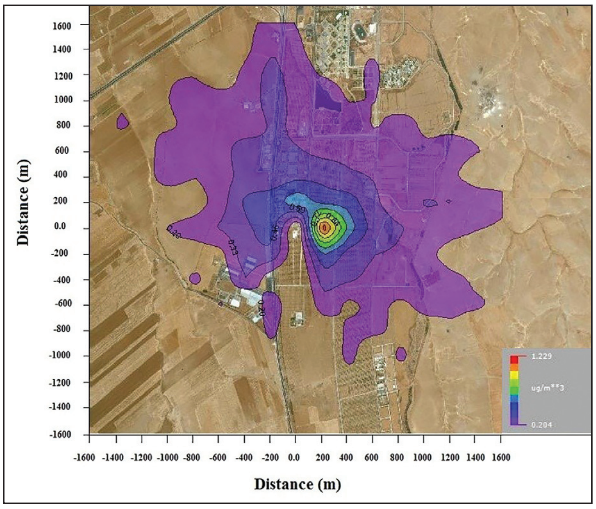

Figure 4b. 8-hours concentration

Figure 4. The average GLC of CO in μg/m^3

The maximum concentrations occur in cold months (January and October) due to emissions from stoves and other heating sources in addition to higher emission rates from motor vehicles during cold start ignition [Al-zboon, 2017]. Another important reason for higher concentrations of air pollutants is the frequent thermal inversion that which becomes more frequent in winter months. Thermal inversion is a natural phenomenon results during the night and early morning hours due to cooling of Earth surface and adjacent air at rates faster than air aloft. It could lead to poor air quality at urban areas because it obstructs the dilution of air pollution.

3.3. Worst Case Results

An initial screening analysis was conducted to identify the worst case for each month. The meteorological condition that yields the highest concentration was considered as the worst case. The screening procedure utilizes the Gaussian dispersion equation to estimate the maximum 1-hour GLC. The impact of other averaging periods is provided using the scaling factors presented in (Table 6).

Table 6. Recommended Factors to Convert Maximum 1-hour Average Concentrations to Other Averaging Periods (California EPA, 2003)

Averaging Time	Range	Recommended Multiplying Factor
3-hours	0.8 – 1.0	0.9
8-hours	0.5 – 0.9	0.7
24-hours	0.2 – 0.6	0.4
30-days	0.2 – 0.3	0.3
Annual	0.06 – 0.10	0.08

Tables 7 and 8 show the worst meteorological conditions and the maximum concentrations for each month, respectively except for November because no data is available for that month.

Table 7. Worst Meteorological Conditions for Each Month

Month	Hour	Ws (m/s)	Wd (degree)	T (°C)	H (w/m²)	L (m)	Mixing Height (m)
Jan	18	7.2	100	20	-22.5	325.3	677
Feb	18	7.2	260	18.4	-22.6	323.4	677
Mar	18	5.14	200	23.2	-18	247	528
Apr	18	5.14	290	26.8	-2.7	1725.6	544
May	18	5.14	300	20	-2.4	1931.2	545
Jun	00	5.14	280	20	-29.8	573.7	1036
Jul	00	3.09	310	18.8	-17.7	199.5	471
Aug	06	3.09	300	24.8	-12	308.1	482
Sep	18	5.14	300	28	-20.5	295.4	616
Oct	18	5.14	160	11	-20.6	294	616
Nov	NA	NA	NA	NA	NA	NA	NA
Dec	18	7.2	260	12.4	-23.1	316.4	677

W_s: Wind Speed, W_d: Wind Direction, NA: Not Available

Most of the worst cases shown in (Table 7) were in the nighttime at 18:00 GMT and 00:00 GMT where the stable boundary layers occur and once a daytime at 06:00 GMT. At night, the air is too stable and does not allow the plume to lift, whereas the measured wind speed may appear sufficient to move it.

Stability conditions can be identified form the values of sensible heat (H) and Monin-Obukhov Length (L) calculated by AERMET. AERMET define stable conditions if $H < 0$ and $L > 0$ and convective conditions if $H > 0$ and $L < 0$. Atmospheric stability is a primary influence on plume dispersion and it is most stable at nighttime hours and the least at daytime hours. In the presence of stable air; convective and turbulence are inhibited, while they are enhanced in unstable conditions.

From mixing height values in Table 7, it can be shown that the highest mixing height was 1036 m in June, that means a larger volume is available to dilute pollutant emissions. The lowest value was 471 m in July month but it can be noticed that the concentration in this month was not the highest and this violates the fact that the lower mixing height lead to higher concentration. In such a case, cold temperature in this month may have an opposite influence on the plume dispersion. Heat is responsible for the upward movement of the air. At high temperatures, pollutants will not hang at the ground level, but will disperse quickly. This would not happen at cold temperatures.

The maximum GLCs occurred at 200 m from source in the north and east directions and this distance is very close to the source. This may due to short stack height (7m). This condition has allowed the building downwash phenomena to occur which drawing the plume to the ground near the source.

Table 8. Maximum Concentrations for each month at the worst meteorological conditions

Month	CO Concentration (μg/m³)		SO_2 Concentration (μg/m³)			NO_2 Concentration (μg/m³)		
	1 hr	8 hr*	1 hr	24 hr**	Annual***	1 hr	24 hr**	Annual***
Jan	4.639	4.175	29.868	17.921	2.987	31.354	18.812	3.135
Feb	4.633	4.170	29.829	17.897	2.983	31.314	18.788	3.131
Mar	4.489	4.040	28.892	17.335	2.889	30.316	18.190	3.032
Apr	4.663	4.197	30.017	18.010	3.002	31.506	18.904	3.151
May	4.641	4.177	29.874	17.924	2.987	31.358	18.815	3.136
Jun	2.867	2.580	18.466	11.080	1.847	19.398	11.639	1.940
Jul	3.933	3.540	25.308	15.185	2.531	26.553	15.932	2.655
Aug	3.983	3.585	25.633	15.380	2.563	26.899	16.139	2.690
Sep	4.508	4.057	29.021	17.413	2.902	30.465	18.279	3.047
Oct	4.506	4.055	29.011	17.407	2.901	30.455	18.273	3.046
Dec	4.611	4.150	29.693	17.816	2.969	31.171	18.703	3.117

* Multiplied by 0.9, ** Multiplied by 0.6, *** Multiplied by 0.01

3.4. Model Performance Evaluation

To evaluate the performance of the model; predicted and observed concentrations at 22 receptors (Figure 5) were compared using statistical measures as presented in (Table 9).

Figure 5. Locations of the receptors

FB values have both positive and negative values, the majority of which (91%) lie between -0.5 and +0.5 for NO_2 and CO, indicating predicted results are close approximations of the observed data but 41% of SO_2 results fall out of the recommended range. The positive values of FB indicate that the model has a tendency towards under-prediction as compared to observed values (Khare et al., 2012).

NMSE is an indicator of variance and its values are > 0.5 for 36% of SO_2 predicted values indicating that the observed and predicted results are not in a good agreement with each other. For NO_2 and CO, NMSE values are within the acceptable range (NMSE ≤ 0.5) except for NO_2 at R1 and R15 and for CO at R1. Most of the predictions (68.2%, 72.7%, 60% for SO2, NO2, CO, respectively), FAC2 values are > 0.8 that means a good model performance.

Table 9. Model performance evaluation results

Receptor ID	SO_2			NO2			CO		
	FB	NMSE	FAC2	FB	NMSE	FAC2	FB	NMSE	FAC2
R1	0.831	0.835	0.413	0.803	0.770	0.427	0.790	0.740	0.434
R2	0.541	0.316	0.574	0.612	0.414	0.531	0.495	0.261	0.603
R3	-0.147	0.022	1.158	-0.180	0.033	1.198	-0.196	0.039	1.217
R4	0.030	0.001	0.971	-0.473	0.237	1.620	-0.024	0.001	1.024
R5	-1.613	7.444	9.337	-0.389	0.158	1.484	0.252	0.065	0.776
R6	-0.474	0.238	1.621	-0.466	0.230	1.608	0.378	0.149	0.682
R7	0.013	0.000	0.987	0.497	0.263	0.602	-0.036	0.001	1.036
R8	0.465	0.229	0.623	0.434	0.197	0.644	0.419	0.184	0.654
R9	0.058	0.003	0.944	0.025	0.001	0.975	0.009	0.000	0.991
R10	-0.077	0.006	1.080	-0.110	0.012	1.116	-0.126	0.016	1.135
R11	-0.088	0.008	1.093	-0.122	0.015	1.130	-0.139	0.019	1.149
R12	-0.484	0.248	1.638	-0.159	0.026	1.173	0.539	0.313	0.576
R13	-1.264	2.663	4.437	0.085	0.007	0.919	0.058	0.003	0.944
R14	-0.780	0.718	2.279	-0.164	0.027	1.179	-0.185	0.035	1.204
R15	1.656	8.710	0.094	1.645	8.367	0.097	0.294	0.088	0.744
R16	0.683	0.528	0.491	-0.015	0.000	1.015	-0.030	0.001	1.030
R17	0.172	0.030	0.842	0.139	0.019	0.870	0.125	0.016	0.882
R18	-0.023	0.001	1.023	-0.056	0.003	1.058	-0.070	0.005	1.073
R19	-0.369	0.141	1.452	-0.001	0.000	1.001	-0.413	0.178	1.521
R20	0.105	0.011	0.901	0.072	0.005	0.931	0.456	0.219	0.629
R21	0.791	0.741	0.433	0.110	0.012	0.896	0.094	0.009	0.910
R22	0.999	1.331	0.334	0.367	0.140	0.690	0.352	0.128	0.701

The correlation coefficient (R^2) reflects the linear relationship between the predicted and observed concentrations. Scatter plots and correlation coefficients indicate that the relation between the observed and predicted data for NO_2 and CO are linear and that the correlation coefficient was high while there is lower correlation in the case of SO_2 (Figure 6). Putter (2000) found poor agreement between the model and the raw measurement of SO2. USEPA, reported that the AERMOD predicted to observed ratio for annual averages SO2 concentration ranges from 0.30 to 1.64, with a geometric mean of 0.73 (USEPA, 1989).

Kho et al. (2007) evaluated the performance of AERMOD for NO_2 and SO_2 and found that the results are within FB acceptable ranges (-0.5- 0.5) except for NO_2 at one location, and 90% of the hourly average values within a factor of two (with ≥0.8).

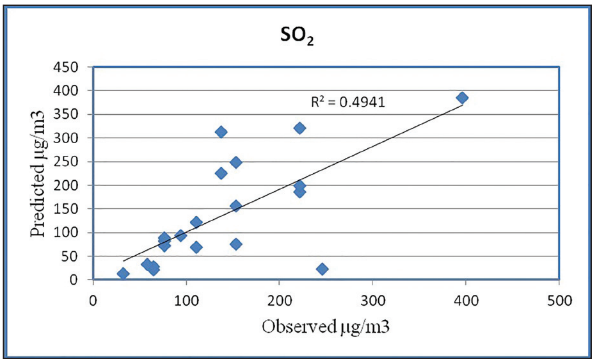

Figure 6a. SO_2 Concentration

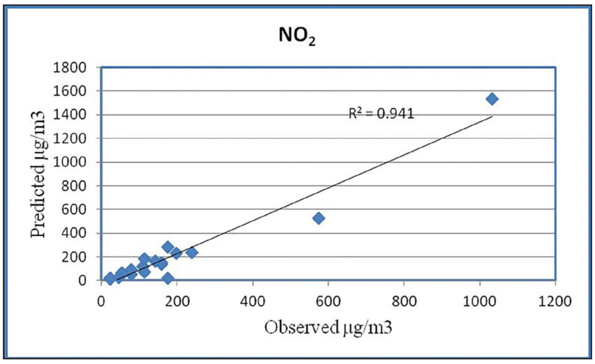

Figure 6b. NO_2 Concentration

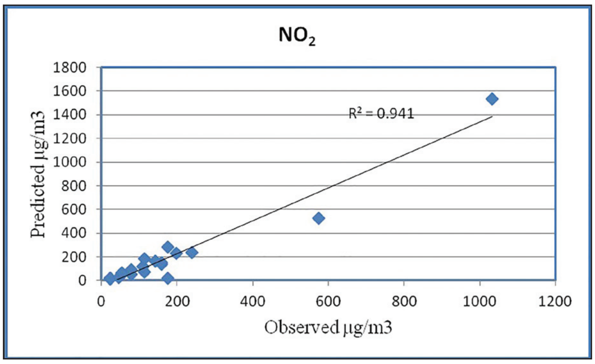

Figure 6c. CO Concentration

Figure 6. Scatter Plots of Observed and Predicted Concentrations

4. Conclusions and Recommendations

Stacks exit concentrations are within the allowable limits set by the Jordanian standards for stationary sources. Most of the time, pollutants are dispersed near the incinerators within 200 m in the downwind distances (north and east directions). The worst-case concentrations were found at nighttime hours where the more stability conditions occurred.

Predicted results from AERMOD show a good agreement with the observed results and better to the NO_2 and CO more than for SO_2. It is recommended that the stacks height be increased to reduce the maximum GLC and increase dispersion of pollutants. The decision makers should consider air modeling in Environment Impact Assessment (EIA) studies in order to asses proposed project›s impact on air quality. Conduct periodic monitoring program of emissions to detect any exceedances and to take the necessary preventive measures.

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