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RESEARCH ARTICLE

Estimation of Ground- level Airborne Concentration in an Urban Area

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Abstract

The Gaussian plume model is an atmospheric dispersion model that most widely used for estimating airborne radionuclide exposures within 80 km of the release point. Pollutants are released from various sources near the earth's surface, and the resulting ground-level air concentration patterns have been estimated. The best overall uncertainty determination is a comparison of modeling predictions with observed measurements for conditions similar to those assumed by the model. Thirteen samples have been taken over flat terrain (Inshas site) to measure observed concentrations. The comparisons of modeling predictions using dispersion parameter in power law and observed concentrations are correlated in time and space have been estimated. We get a good agreement between the observed and predicted radionuclide concentrations. Statistical evaluation of predicted and observed concentrations of some isotopes was presented.

Introduction

Emission from industrial stacks should be regulated to protect human health and pure environmental. Study of the airborne concentration spot the light on the degree of dangerous of air pollutants (Mehdizadeh and Rifia 2003). As occur in Fukushima nuclear accident on March 11, 2011, a cloud containing radioactivity formed in air and moved over the Pacific Ocean until diffused over the European continent (Jakobs, 2011). So, the prediction of dispersion of radionuclides to the atmosphere is an important element of the emergency response procedures. Numerical models were used to estimate or to predict the downwind concentration of air pollutants emitted from sources such as industrial plants (Alharbi, 2011). This air concentration depends on atmospheric diffusion process that controls the atmospheric turbulence (Gifford 1977). When the wind speed is greater than 2m/s, the concentrations with dispersion functions in terms of power law will perform the best results in comparison with split sigma, split sigma theta and standard methods (Essa et al. 2005). Power law functions are the most commonly used methods in which plume dispersion coefficients are expressed in terms of downwind distance and atmospheric stability (Maithili Sharan et al. 1995).

The Gaussian plume model is commonly used because it produces results similar to experimental results (Miller and Hively 1987).

Hanna et al. (1977) recommended the use of turbulence measurements to estimate dispersion. Despite these recommendations, most people still use the traditional stability classes (Hanna et al. 1982).

Building wake dispersion modeling is very important for evaluating doses due to both routine and accidental releases since such releases commonly occur in the vicinity of buildings. While the evaluation of doses rather away from buildings, the building wake effects are not important. Meroney 1982 and Hosker 1984 discuss a substantial body of literature exists on building influence from dispersion under neutral atmospheric stability conditions.

Smith, 1962; Ermak 1977; Rao, 1981 introduced early analytical solutions of the Gaussian plume approach with constant wind speed and eddy diffusivities. While Horst and Slinn, 1984; Koch, 1989; Chrysikopoulos et al., 1992 solved the diffusion equation with both wind speed and eddy diffusivities depending on the vertical height.

In this paper we compared modeling predictions with observed concentrations of some isotopes using dispersion parameter in power law putting into consideration the working hours of the emission

sources and the effective height of the plume through thirteen samples. Statistical evaluation of predicted and observed concentrations of some isotopes were presented.

Gaussian plume model

The Gaussian plume model is used in more regulatory application than any other model. It has been used by most of the countries participating in the NATO plume modeling in Federal Republic of Germany (Jost and Gustsche 1976). It is widely used and has been evaluated with many data sets. For a continuous point source, the basis of the model is a single simple formula which assumes constant wind speed "u" and complete reflection from the ground surface:

$$C = \frac{Q}{2\pi u\, \sigma_y \sigma_z}\left[\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left[\exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right)+\exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right)\right]\right] \quad (1)$$

Where the parameters are defined by the following descriptions

C (Bq m^{-3}) = Concentration of air pollutant;

Q (Bq s^{-1}) = Continuous point source strength;

u (m s^{-1}) = Wind speed at height H;

σ_y (m) = Lateral dispersion parameter;

σ_z (m) = Vertical dispersion parameter;

x (m) = Horizontal distance in the direction of downwind.

y (m) = Lateral distance from plume centerline,

z (m) = Height above ground;

H (m) = effective height of plume above ground; H=h=Δh; where his the stack height and Δh is the plume rise equals 3(wD/u); D is the internal stack diameter and w is the exit velocity of the pollutants (Essa et al. 2005).

The ground level air concentration can be obtained if we take z =0 in equation (1) and taking into consideration the dilution factors, one can get:

$$C(x,y) = \frac{2Q}{(2\pi\sigma_y\sigma_z + C_w A)u}\exp\left(\frac{-\lambda x}{u}\right)$$

$$*\left(\exp\int_0^x \frac{dx}{\sigma_z \exp\left(H^2/2\sigma_z^2\right)}\right)^{-(\frac{2}{\pi})^{1/2}(Vd/u)} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z^2}\right)^2 - \frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \quad (2)$$

where

$\exp(-\lambda x/u)$ is the radioactive decay for the specified nuclide;

A is the cross – section area of the building normal to the wind;

C_w is the shape factor that represents the fraction of "A" over which the plume is dispersed; C_w =0.5 is commonly used;

V_d is the deposition velocity, (m/s).

Power law dispersion parameter:

Because of the value of the wind speed is greater than 2m/s, the dispersion parameters σ_y and σ_z can be estimated from the following formula (Essa et al 2005):

$$\sigma y = a\, x^{b} \quad (3)$$

$$\sigma z = c\, x^{d} \quad (4)$$

where a, b, c and d are given in Table 1 (Panofsky 1984).

Table 1. parameters value in the formulas (3) and (4).

Stability	a	b	c	d
A-B	1.46	0.71	0.01	1.54
C	1.52	0.69	0.04	1.17
D	1.36	0.67	0.09	0.95
E-G	0.75	0.70	0.40	0.67

Experimental data

Air samples were collected from 92m to 184m around the first and second research reactor in AEA. Egypt. The study area is flat, dominated by few small building with poor vegetation cover. The study area was divided into 16 sectors (with 22.5 ^{0} width for each sector), beginning from the north direction. Aerosols were collected at a height of 0.7m above the ground on 10.3 cm diameter filter paper with a desired collection efficiency (3.4%) using a high volume air sampler with 220V /50Hz bias. The air sampler had an air flow rate of approximately 0.7m^3/min (25 ft^3/min). Sample collection time was 30min with an air volume of 21.2 m^3 (750 ft^3). This air volume was corrected to standard conditions (25^{o}C and 1013 mb) (Raymond et al. 2000).

The filter paper was directly measured by energy and efficiency calibrated HPGe detectors relative to 3″ x 3″ NaI (T I) detector were 15.6 and 30% measured at 1.332 MeV with source to detector distance of 25cm.

Meteorological data was provided by Inshas metrological tower for four months at a smooth flat site (Inshas area, Egypt) for the year (2006). Vertical temperature gradient ($\Delta T/\Delta z$) was determined by measuring temperature at 10-60m levels from the multilevel meteorological tower of Inshas sitting and Environment Department, National Centre for Nuclear Safety and Radiation control, AEA, Egypt. This tower is located near to the area under study. Fig.1 represents the samples locations around the source. This diagram contains number of samples, directions and distances from the source.

Statistics of model performance evaluation

Statistical analysis of the predictions and observations is worked to the model performance evaluation. The methods discussed by "Fox (1981), Irwin J. S. (1983), Roa et al. (1985a), Johnson (1986) Hanna (1989), and Essa et. al. (2006)" are used for the model evaluation and comparison with the observed data.

In the discussion that fellows, O_i refers to observed concentration and P_i refers to the corresponding predicted concentration at the same location during the same time; N is the total number of observations. The mean values are:

$$\bar{O} = (1/N)\sum_{i=1}^{N} O_i \quad (5)$$

$$\bar{P} = (1/N)\sum_{i=1}^{N} P_i \quad (6)$$

Residuals are defined as the difference between observed and predicted concentrations such that,

$$D_i = O_i - P_i \quad (7)$$

The predicted and the corresponding observed concentrations are treated as pairs in this analysis. The analysis procedure employed are given below

1- Mean difference between predicted and observed values is given by:

$$\bar{D} = \bar{O} - \bar{P} = (1/N)\sum_{i=1}^{N} D_i \quad (8)$$

2- Variance of the difference is calculated by

$$S_d^2 = [1/(N-1)]\sum_{i=1}^{N}(D_i - \bar{D})^2 \quad (9)$$

3- The root mean square error (RMSE) of the difference is given by

$$RMSE = \left[((N-1)/N)S_d^2 + \bar{D}^2\right]^{1/2} \quad (10)$$

4- Average absolute gross error of the concentration difference is given by

$$\left|\bar{D}\right| = (1/N)\sum_{i=1}^{N}\left|D_i\right| \quad (11)$$

Unsystematic and systematic mean square errors (MSE) are computed as

$$MSE_u = (1/N)\sum_{i=1}^{N}(P_i - \hat{P}_i)^2 \quad (12)$$

$$MSE_s = (1/N)\sum_{i=1}^{N}(\hat{P}_i - O_i)^2 \quad (13)$$

where $\hat{P}_i$ is derived from the relation $\hat{P}_i = a + bO_i$; a is the intercept and b is the slope of the linear region line.

Roa et al. (1985a) found that MSE measures can illuminate the sources or types of error, which may be of considerable help in refining a model. If MSE is entirely, or largely, composed of MSE_u, perhaps the model is as good as possible and may not require major modification.

5- Fractional mean bias FB is

$$FB = (\bar{O} - \bar{P})/0.5(\bar{O} + \bar{P}) \quad (14)$$

6- Correlation coefficient (R):

It describes the degree of association or agreement between the variables and is defined as:

$$R = \frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sigma_o \sigma_p} \quad (15)$$

where σ_o and σ_p are the standard deviation of the observed and predicted concentrations. The correlation value lies between 0 and 1 inclusive, and R may assume any value between -1 and +1, if R=1 there is a perfect direct linear correlation between the observed and calculated concentrations, While R= -1 indicates perfect inverse linear correlation. If R=0 the two variables are not correlated.

7. Fraction within a factor of two (FAC2):

It is defined as **FAC2** = fraction of data for which $0.5 \leq P/O \leq 2$ *(Wayne-1987).*

Result and Discussion

Table 2 shows the source strength and the decay constant (AEA, 2006) for I-131, I-133, I-135 and Cs-137. Through 13 samples during the reactors working hours, table 3 contains the working date, thirteen samples, wind speed, stability and the effective height for the two sources (since the height of the first stack reactor 43m and the second stack reactor 27m), and the reactor working hours. Because the wind speed is greater than or equal 2m/s, one can find that the dispersion parameters (σ_y and σ_z) in the power law give results near from observation concentration with respect to other formula (Essa et al. 2005). Also from Table 3 we perform nine experimental on the first reactor and the rest on the second one.

It is to be noted that the abbreviation "obs" refers to observed concentrations (Bq/m^3) and "Pred." refers to predicted concentration (Bq/m^3). Fig.2 shows the comparison of the predicted and observed radionuclide of I-131, I-133, I-135 and Cs-137 with the downwind distances "x". From this figure, one can get the same several peaks between predicted and observed concentrations for I-131, I-133 and I-135 at 92, 97 and 134m from the source due to thermal effect during sunshine time. There are best fitting between predicted and observed concentrations in the case of I-135 and I-131, but in the case I-133 and Cs-137 the predicted concentrations are over predicted the observations concentrations due to increase of the mixing height during the day hours.

From Fig.2 one can notice a good agreement between predicted and observed concentrations with downwind distance for I-135, and I-131, in the case of I-133, the predicted concentrations lie inside a factor of two with the observed concentrations data, while in case of Cs-137, we find that the predicted concentrations are inside a factor of four with the observed and observed concentrations. Table 5 shows the statistical parameters between the observed and predicted concentrations, since the correlation factor R=0.93 and 0.99 for I-131 and I-135 respectively are the best with respect to the other correlations. Fraction bias "FB"=-0.55 and -0.13 for I-131 and I-135 are good because they approach to zero. The values of NMSE=0.51, 0.03 for I-131, and I-135 respectively are the best in comparison others. we get linear fitting relation between predicted concentration of I-135 "P_{I-135}" and observed concentration of "O_{I-135} as follow: $P_{I-135}= 0.01+1.04\ O_{I-135}$. It is the linear fitting between the predicted and observed concentration of I-135 and so on with respect to the other elements. Also $MSE_{u(I-135)}/MSE=40\%$ and $MSE_{s(I-135)}/MSE=60\%$ which are the rate unsystematic and systematic to the mean square errors (MSE) respectively for the concentrations data.

Fig.3 shows the variation of the predicted and observed concentrations in the time of working hours of the reactor since the working hours of the reactor is 48 hours. The working hours from 1.5 to 4.5 hours represent the measuring hours during the first day; from 22to 48 represent the measuring hours during the second day and from 48 to 49 hours after stop working.

Fig.4 shows the variation of modeling estimated and observed concentrations with the effective height "H". The height of the first source is 27m with effective height lies between 30 and 30.8m, we find that maximum ground level concentration at H=30.6m then the concentrations decrease. The height of the second source is 43m, one can get two

peaks for I-131, I-133 and I-135 at H equals 45 and 47m respectively. We get better results between predicted and observed concentrations with respect to I-135 and I-131, but the predicted concentrations are inside factor of two with observed concentrations with respect to I-133 and Cs-137. Also from Fig.4 we can get for Cs-137 two peaks at H equals 45.2 and 46.1m respectively. Fig.5 shows the most predicted concentrations are inside factor of two with the observed concentrations and there are some results lie inside factor of four.

Table 2: Source strength (Bq) and decay distance for the studied fission radionuclide.

Experiment	I-131	I-133	I-135	Cs-137
1	28114286	2811429	1028571	0.555429
2	28700000	2870000	1050000	0.567
3	1171429	117142.9	42857.14	0.023143
4	12885714	1288571	471428.6	0.254571
5	13471429	1347143	492857.1	0.266143
6	140557143	1405714	514285.7	0.277714
7	27528571	2752857	1007143	0.543857
8	28524286	2852429	1043571	0.563529
9	28260714	2826071	1033929	0.558321
10	2928571.4	292857.1	107142.9	0.057857
11	4100000	410000	150000	0.081
12	1171428.6	117142.9	42857.14	0.023143
13	2342857.1	234285.7	85714.29	0.046286
λ	$9.95x10^{-7}$	$9.25x10^{-5}$	$7.3x10^{-10}$	$3.8x10^{-4}$

Table 3: Meteorological data for observed and estimated concentration.

Date(2006)	Experiment	u(m/s)	stability	H(effect height) (m)	Working hours
14-March	1	4	A	49	48
14-March	2	4	A	48	49
02-May	3	6	B	45	1.5
03- May	4	4	C	46	22
03- May	5	4	A	45	23
03- May	6	4	D	45	24
04- May	7	4	E	47	48
04- May	8	4	C	46	48.7
14-March	9	4	A	47	48.25
01-Jan	10	3	D	28	5
22-Jan	11	2	B	28.3	7
15-March	12	3	A	30.8	2
15-March	13	3	A	30.6	4

Table 4: Observed and estimated concentration (Bq/m^3) of I-131, I-133, I-135 and Cs-137 respectively with the working hours.

Experiment I-131	Working hours	Obs. (Bq/m^3)	Est. (Bq/m^3)
1	48	0.025	0.114
2	49	0.037	0.129
3	1.5	0.091	0.122
4	22	0.197	0.219
5	23	0.272	0.307
6	24	0.188	0.473
7	48.5	0.447	0.484
8	48.7	0.123	0.456
9	48.25	0.032	0.109
10	2	0.42	0.833
11	2.5	0.42	0.756
12	4	0.67	1.144
13	4.5	0.67	1.056

Experiment I-133	Working hours	Obs. (Bq/m^3)	Est. (Bq/m^3)
1	48	0.02	0.13
2	49	0.032	0.116
3	1.5	0.055	0.11
4	22	0.063	0.15
5	23	0.15	0.18
6	24	0.15	0.43
7	48.5	0.275	0.44
8	48.7	0.393	0.41
9	48.25	0.028	0.098
10	2	0.2	0.75
11	2.5	0.2	0.68
12	4	0.36	1.03
13	4.5	0.36	0.95

Experiment I-135	Working hours	Obs. (Bq/m^3)	Est. (Bq/m^3)
1	48	0.03	0.048
2	49	0.041	0.043
3	1.5	0.037	0.04
4	22	0.05	0.056
5	23	0.04	0.067
6	24	0.145	0.156
7	48.5	0.14	0.16
8	48.7	0.092	0.15
9	48.25	0.032	0.035
10	2	0.24	0.275
11	2.5	0.24	0.25
12	4	0.34	0.38
13	4.5	0.34	0.35

Experiment Cs-137	Working hours	Obs. (Bq/m^3)	Est. (Bq/m^3)
1	48	0.002	0.028
2	49	0.004	0.025
3	1.5	0.005	0.022
4	22	0.007	0.016
5	23	0.009	0.038
6	24	0.007	0.014
7	48.5	0.007	0.026
8	48.7	0.019	0.052
9	48.25	0.006	0.02
10	5	0.002	0.003
11	7	0.008	0.009

Table 5: The statistical parameters for the predicted and observed concentrations of elementsI-131, I-133, I-135 and Cs-137 respectively.

Factor	I-131	I-133	I-135	Cs-137
R	0.93	0.80	0.99	0.70
Slop	1.48	1.96	1.04	2.06
Intercept	0.07	0.08	0.01	0.01
FB	-0.53	-0.82	-0.13	-1.08
Mean	2.25	2.87	1.22	4.14
NMSE	0.51	1.53	0.03	2.30
M SE_u/MSE	23.4	33.0	40	23.3
MSE_s/MSE	76.6	67.0	60	76.7

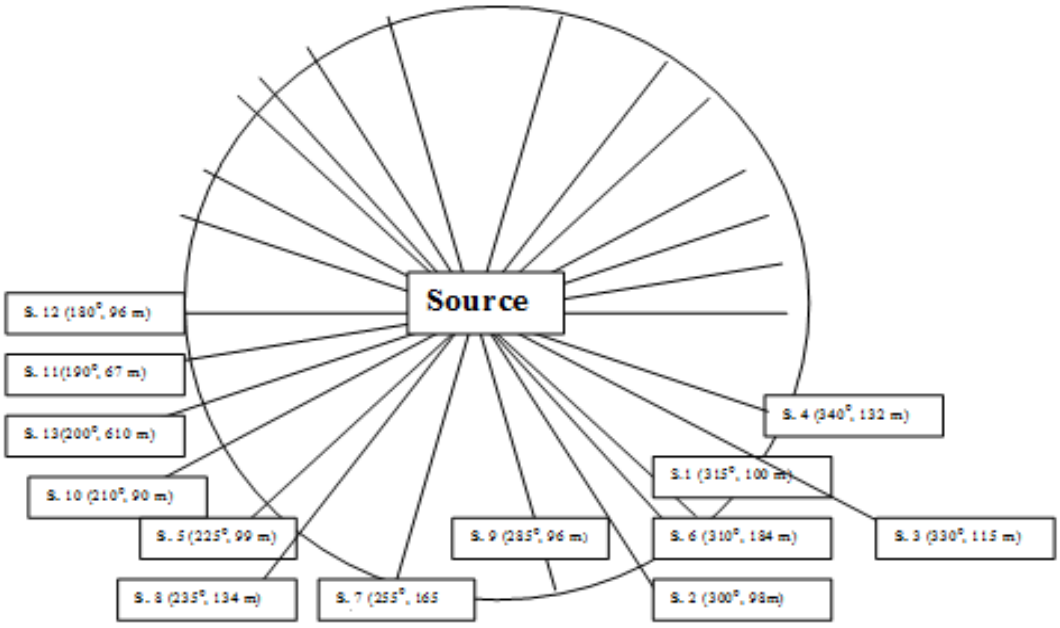

Fig.1: Diagram of Samples locations around the sources, samples from (1-10) for the first source and samples from (11-13) for the second source.

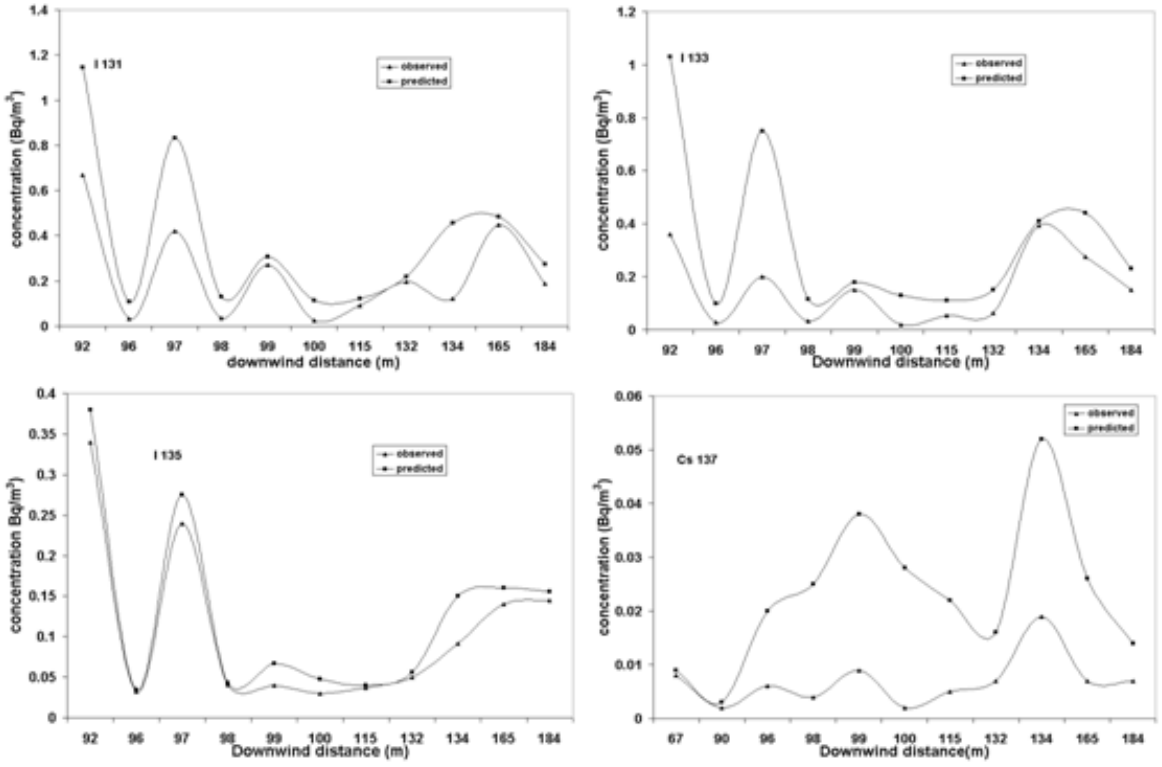

Fig.2: Observed and predicted concentration of I-131, I-133, I-135 and Cs-137 (Bq/m^3) withdownwind distance (m).

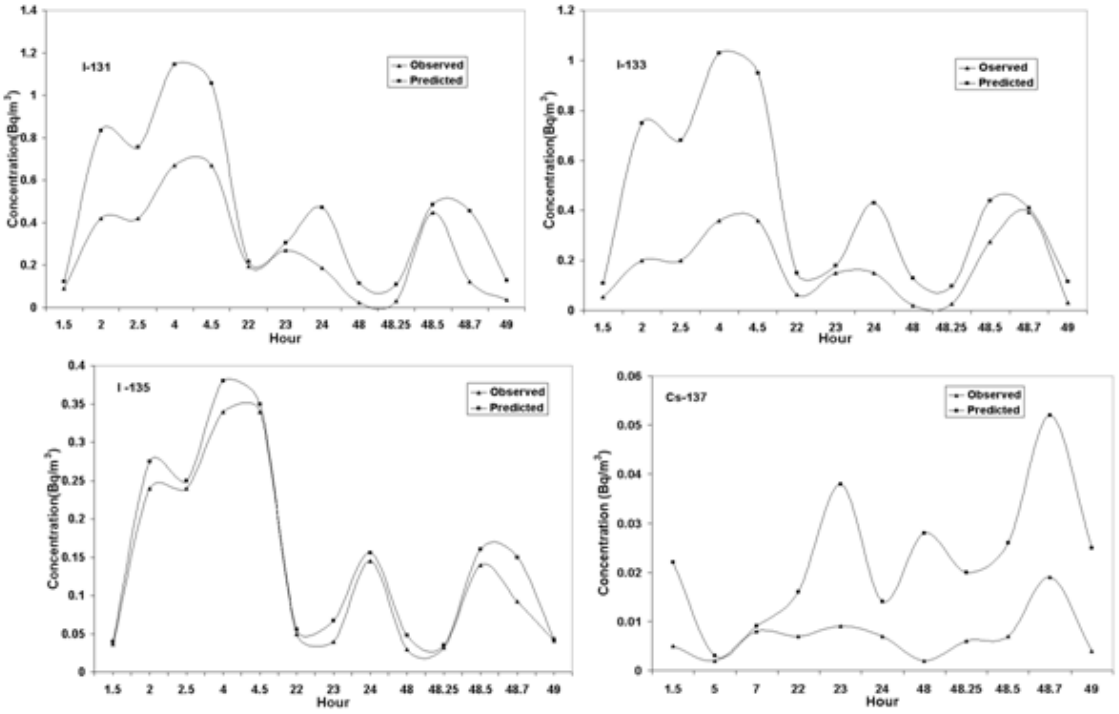

Fig.3: Observed and predicted concentration of I-131, I-133, I-135 and Cs-137 (Bq/m^3) with hours.

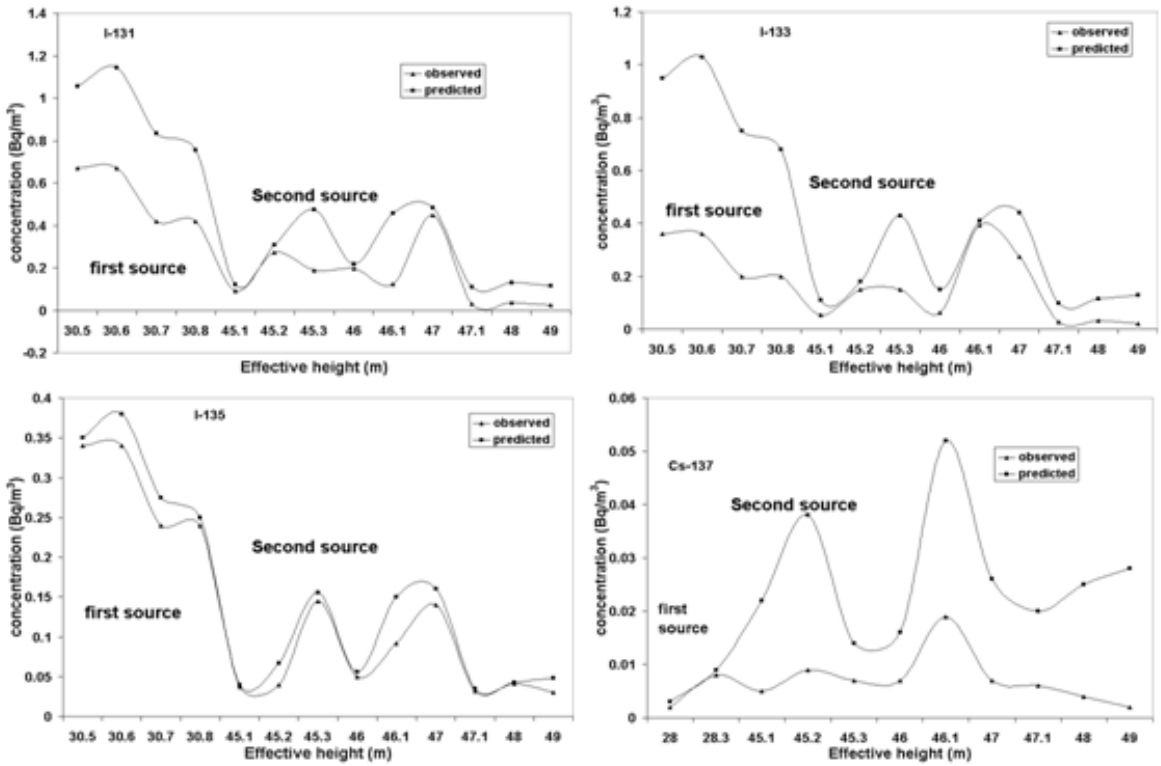

Fig.4: Observed and predicted concentration of I-131, I-133, I-135 and Cs-137 (Bq/m^3) with the effective height (m).

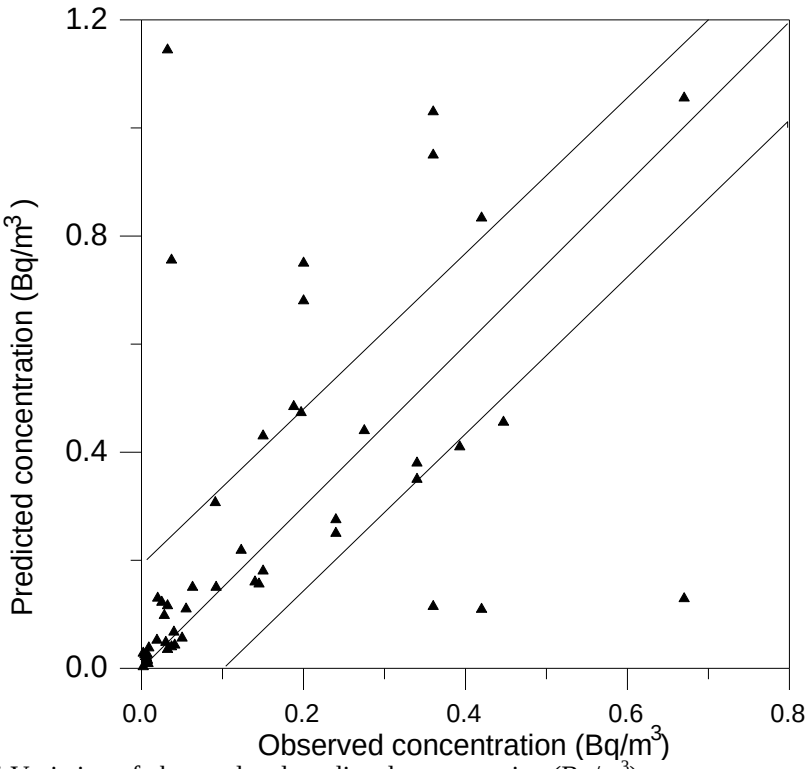

Fig. 5:Variation of observed and predicted concentration (Bq/m^3).

Conclusion

We performed a mathematical modeling for estimating concentrations of I-131, I-133, I-135 and Cs-137. After comparing the results of the modeling and observed concentrations, we get the best results for I-131 and I-135. As for I-133 we have the modeling predicted concentrations are inside a factor of two with the observed concentrations via downwind distance, hours and the effective height. Also with respect to Cs-137 one gets the predicted concentrations data are inside a factor of four with the observed concentrations via downwind and hours while they were inside factor of two via effective height. Statistical study on the concentrations of different isotopes shows best results for I-135 and I-131 than the concentration of I-133 and Cs-137.

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