Mathematical and experimental study of hydrogen sulfide concentrations in the Kahrizak landfill, Tehran, Iran

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ABSTRACT

The emission of hydrogen sulfide (H₂S) from the Kahrizak landfill was studied. Firstly, the field measurements were conducted in the summer and winter seasons; and the samples were analyzed using Jacob method. We predicted the H₂S concentrations in the downwind using AERMOD and ISCST3. According to the AERMOD, the maximum concentration of H₂S in the summer and winter were 117 µg/m³ and 205 µg/m³, respectively. The downwind concentrations reached zero at the distance of 35 km from the leachate treatment plant. The Geometric mean bias, Geometric variance, Fractional bias, Fraction of predictions within a factor of two of the observations and Normalized mean square error for the AERMOD were 0.58, 1.35, -0.12, 1.91 and 0.042, respectively in the summer and 1.39, 1.35, -0.05, 1.46 and 0.027 in the winter; and for the ISCST3, were 0.85, 1.03, 0.02, 1.45 and 0.04 in the summer and 1.18, 1.03, 0.15, 1.16 and 0.04 in the winter. The results of the AERMOD were compared with the ISCST3 and indicated that the AERMOD performance was more suitable than the ISCST3.

Keywords: AERMOD, Hydrogen sulfide emission modeling, ISCST3, Landfill

1. Introduction

Municipal solid waste (MSW) landfills are potential sources of the offensive odor emission and annoyance in neighboring urban areas. The odor pollution has become a growing concern during the last decades for urban communities. The annoying odors released to the atmosphere from landfills may cause decreased quality of life, and possibly more negative consequences for human health and welfare [1].

Many people in the world have complained against emission of odor [2-4]. The odor has a considerable impact on the health of people such as triggering possible harmful reflexes and modifying olfactory function [2].

Hydrogen sulfide (H₂S) is a colorless, flammable, very toxic and dangerous gas with rotten egg smell. The main way of exposure is inhalation and can swiftly be absorbed by the lungs. The Human can smell the odor of H₂S at low concentration in the air. H₂S as an irritant and a chemical asphyxiate influences on the control nervous system and oxygen utilization and at the low concentration and irritates the nose, eyes, throat and respiratory system [5, 6].

Odor (particularly H₂S) control is a major concern in the operation of existing landfills as well as in the design of future landfills for complying with the odor standard [7]. The odor emission rate depends on several factors, such as the thickness of the cover, the age of the waste, type of cover, the landfill moisture. The odor emission is affected by the wind speed, wind direction, atmospheric conditions, temperature and topographic conditions of the region [8].

To assess odor pollution impacts in the downwind, mathematical modeling is a cost effective and less time consuming and can be assumed as a valuable substitute for the field measurements. Pollution plume modeling can give us pollutant concentrations in the air over a period of time in any geographic location. This is a good way to assess the effects of pollution sources on the quality of air in the surrounding area. In most of models that relate to the emission of gases, a Gaussian Plume method is used.

Schauberger et al. [9] predicted the emission rate of H₂S of a wastewater treatment plant based on its environmental concentrations and meteorological parameters. Hanna et al. [10] examined

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Received July 31, 2018 Accepted November 23, 2018

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the predicted air pollutant concentrations by AERMOD and ISC3 models for the 5 field data series, and the results indicated that the AERMOD predictions was closer to experimental data.

Plaza et al. [11] selected five types of cover for landfill, including sandy soil, sandy soil amended with lime, clayey soil, fine concrete to control H_2S . The sandy soil amended with lime and the fine concrete were most effective for control H_2S emission. Xu et al. [12] checked the emission rate of H_2S from a landfill with the different landfill cover material. They indicated that the compost, yard trash and soil amended with quicklime and calcium carbonate covers attenuated H_2S emission rate.

Saral et al. [7] modeled H_2S and 22 VOCs using ISCST3 to forecast, hourly concentration of odor. Their results indicated that the short term average of three of VOCs namely ethyl mercaptan, methyl mercaptan and H_2S did exceed their odor threshold. Latos et al. [13] measured the H_2S concentration at the different locations during the summer by a portable device in a wastewater treatment plant in Greece and used AERMOD Gaussian model to estimate maximum odor concentration.

Jeong [14] used an AERMOD model to predict odor concentration (regardless of the type of odorous gas, measured based on odor unit) around an industrial complex. Samples were collected at the site in 11 stations and during 5 d, and the meteorological data were measured on the site. Bolyard [8] measured the concentrations of H_2S gas at different locations in Florida landfill and estimated the emission rate by using the modeling method and then calculated the H_2S buffering distance by AERMOD model. Rood [15] reviewed the efficiency of the diffusion modeling software such as AERMOD. He measured the ratio of the simulated to the field and calculating the differences in percentages. The ratio varied between 5% to 85% of cases that indicate the suitability of the AERMOD model.

Asadollahfardi et al. [4] evaluated the efficiency of ISC3 model to simulate the ammonia emission from Kahrizak landfill. The predicted concentrations at a distance less than 300 m from the sources had a deep gap in comparison with the field measurement. However, at a distance more than 300 m, ISC had a good performance.

On the one side, to the best knowledge of the authors, the emission of H_2S from landfills has not sufficiently been discussed in terms of experimental and mathematical studies.

The odor pollution has influenced human welfare and gave rise to some concerns among the people who settle in the nearby of the Kahrizak landfill and raising public criticisms against the local jurisdictions. In addition, the odorous pollution is a nauseating issue for the passengers who travel to the international airport via the surrounding highways [4]. The adverse health effects of exposure to H_2S have not been sufficiently addressed and the results of study of different researchers are inconsistent. The vital health effects from a low level and chronic exposure have not still been reported [16]. Nonetheless, the exposure to H_2S in concentrations of 10 ppm to 500 ppm may negatively influence the central nervous system, respiratory and blood issues, especially vulnerable populations such as children with asthma [17, 18].

The first aim of this study was to monitor H_2S concentrations in the downwind of the Kahrizak landfill during the winter and

summer seasons. The measurements were compared with each other to demonstrate the environmental situation in the observed data. Afterwards, we employed the AERMOD and ISCST3 models to estimate the H_2S concentrations at the upwind and downwind. The results were assessed using the observed data to reveal the suitable model for estimating H_2S emission.

2. Materials and Methods

2.1. The Study Area

The study area was Kahrizak complex, which covered a surface area of 14 km² and located in the south of Tehran, Iran [19]. The geographic coordinate of the study area is 35° 27' 52" N and 51° 19' 19" E. The elevation of the complex varies from 1,020 m to 1,060 m [3]. The prevailing wind directions are westerly and northwesterly winds. The average annual temperature varies from -5°C to 40°C. The annual mean precipitation and evaporation are 240 mm and 250 mm, respectively [20].

Averagely, about 7,500 tons per day of municipal solid waste is unloaded at the complex, which 50% transferred to the composting site, 5% managed to reuse, and 45% disposed in the landfill. Totally, a daily average of 3,600 tons of valueless dry waste enters into the complex, due to the high thermal value of these wastes, 200 tons per day is transferred to an incinerator for combustion, which produces 2 MW electricity [19]. The Kahrizak Complex consists of landfills A and B, landfill A was operated in 1973 and closed in 1998, and landfill B started operating in 1998 and will be closed by 2020. One leachate treatment plant with a capacity of 1,400 cubic meters per is active in the complex.

2.2. Field Measurement of Atmospheric H_2S

Due to the prevailing wind direction and accessibility, we selected eleven locations to monitor hydrogen sulfide in the summer and winter, respectively. The access to the eastern region of emission sources was limited, which was assumed as a restriction ahead of the field measurement. Table 1 indicates the position of monitoring station related to the landfills A and B. The measurements were not carried out in the rainy days. Rainfall causes substantial pollutant concentration decline by washing out particles and absorbing pollutants [21, 22]. In addition, site accessing in the rainy weather and experimental expenses were other research limitations.

To measure H_2S concentration, the variation of the methylene blue after exposure to the ambient air was analyzed (Jacobs method) [20]. Using a sampling pump in a flowrate between 1 to 1.5 L/min, the air was bubbled through 45 mL absorption solution in a macro impinger. The sampling time varied between 30 to 45 min. The sampling pump was universal PCXR8, manufactured by SKC United Kingdom.

We added amine test reagent and ferric chloride solution to the collected samples. Afterwards, we agitated the mixture and waited for 30 min to assure the reaction was done. The H_2S concentration was obtained using a spectrophotometer (DR 2800) at 670 nm wavelength [23].

Table 1. Site and Weather Condition in the Autumn Season

Station	Geographical coordination	Time of sampling		Temperature (°C)		Average wind speed (m/s)		Wind direction		DLA (m)	DLB (m)
		summer	winter	summer	winter	summer	winter	summer	winter		
1	35°27'30"N 51°20'29"E	08/24/16	02/22/17	28	9	2.22	5.5	S-SW	W	130	480
2	35°28'0.0"N 51°19'59"E	08/24/16	02/22/17	28	9	2.22	5.5	S-SW	W	360	150
3	35°28'0.0"N 51°19'20"E	08/24/16	02/22/17	28	9	2.22	5.5	S-SW	W	750	862
4	35°27'55"N 51°19'30"E	08/24/16	02/22/17	28	9	2.22	5.5	S-SW	W	185	400
5	35°28'18"N 51°19'47"E	08/24/16	02/22/17	28	9	2.22	5.5	S-SW	W	960	380
6	35°29'27"N 51°15'06"E	-	02/22/17	-	9	-	5.5	-	S-SW	7,530	7,811
7	35°29'11"N 51°14'50"E	-	02/22/17	-	9	-	5.5	-	S-SW	7,782	8,047
8	35°28'52"N 51°14'37"E	-	02/22/17	-	9	-	5.5	-	S-SW	8,137	8,202
9	35°26'31"N 51°12'18"E	-	02/22/17	-	9	-	5.5	-	S-SW	11,566	12,252
10	35°26'19"N 51°12'14"E	-	02/22/17	-	9	-	5.5	-	S-SW	11,608	12,188
11	35°29'48"N 51°20'47"E	08/24/16	-	28	-	2.22	-	S-SW	-	3,981	3,146

DLA = Distance relative to the landfill A

DLB = Distance relative to the landfill B

2.3. Dispersion Models

The basic Gaussian dispersion equation considers a constantly releasing point source emanating via a coordinate system with its origin at the base of the source. Eq. (1) depicts the Gaussian diffusion equation for predicting ground level concentrations directly downwind from a point source [24]

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

Where C is the concentration ($\mu\text{g}/\text{m}^3$) at (x, y, z) and Q is the emission rate ($\mu\text{g}/\text{s}$), σ_z and σ_y are the vertical and horizontal spread parameters, which are functions of the distance (X) from emission, and atmospheric stability class and u is the average wind speed in (m/s), z is the vertical distance above the ground in (m), y is the horizontal distance from the centerline of the plume (m), H is the effective height of the stack (m).

The ISCST-3 model deploys a steady-state Gaussian flow equation for modelling the dispersion of emissions from various sources [25] (Eq. (2) to (4)).

$$C = \frac{Q_p}{\pi\sigma_y\sigma_z u} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \quad (2)$$

$$C = \frac{2Q_L}{\sqrt{2\pi}\sigma_z u} \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \quad (3)$$

$$C = \frac{Q_A}{2\pi u} \int_X \frac{V}{\sigma_y\sigma_z} \left(\int_Y \exp\left[-\frac{y^2}{2\sigma_y^2}\right] dy \right) dx \quad (4)$$

Where C is the downwind pollutant concentration (g/m^3), Q_p is the point source pollutant emission rate (g/s), Q_L is line source pollutant emission rate (g/ms), Q_A is the area source odor emission rate ($\text{g}/\text{m}^2 \text{ s}$), σ_y and σ_z are the Pasquill-Gifford plume spread parameters based on stability class, u is the average wind speed at pollutant release height (m/s). H is the effective height above ground of emission source (m). V is the vertical term used to describe vertical distribution of the plume and x is the upwind direction (m), and y the cross wind direction (m).

AERMOD as a steady-state Gaussian dispersion model that is able to compute contaminants spreading from point, area and volume sources in rural and urban areas. The model assumes that a ratio of the plume (moved from a buoyant source) goes

up and stays near the top of the boundary layer [26]. The model simulates flat and complex terrains in stable and convective boundary layers (SBL and CBL). In the stable condition, a Gaussian probability distribution function is employed to anticipate the concentration of a contaminant in vertical and horizontal directions. In convective situation, the horizontal and vertical dispersions are defined by Gaussian and Bi-Gaussian probability distribution functions, respectively [27, 28]. The model holds two preprocessors, encompassing AERMET and AERMAP. AERMET calculates boundary layer parameters, entailing friction velocity (u_*), Monin-Obukhov length (L), convective velocity scale (w_*), temperature scale (θ_*), mixing height (z_i) and surface heat flux (H). Therefore, the vertical profiles of wind speed (u), lateral and vertical turbulence fluctuations (σ_v , σ_w), potential temperature gradients ($d\theta/dz$) and potential temperatures (θ) can be computed [26, 29]. AERMAP uses gridded terrain data to analyze a representative terrain influence height (h_c) in each receptor location. h_c can specify the dividing streamline height. In addition, AERMAP presents the receptor's location (x_r , y_r), its height above mean sea level (z_r) and h_c . AERMOD applies the processed data from AERMET and AERMAP to obtain concentrations of the pollutant (Eq. (5)).

$$C_T\{x_r, y_r, z_r\} = f \cdot C_{C,S}\{x_r, y_r, z_r\} + (1-f) C_{C,S}\{x_r, y_r, z_p\} \quad (5)$$

Where $C_T\{x_r, y_r, z_r\}$ is the total concentration; $C_{C,S}\{x_r, y_r, z_r\}$ is the contribution from the horizontal plume state in convective (C) and stable (S) condition. $C_{C,S}\{x_r, y_r, z_p\}$ is the contribution from the terrain – following state. f is the plume state weighting function; $\{x_r, y_r, z_r\}$ is the coordinate representation of a receptor, which z_r measured relative to stack base elevation. $z_p = z_r - z_t$ is the height of a receptor above local ground and z_t is the terrain height at a receptor (in flat terrain $z_t = 0$). A complete and comprehensive explanation of the AERMOD can be found in [26].

AERMOD View, which developed by Lakes EnvironmentalTM, includes EPA's AERMOD and ISCST3 models. The meteorological data is the backbone of the meteorological processor, which entails wind speed, wind direction, precipitation, station pressure, dew point, temperature, relative humidity and sky cover. The meteorological data was obtained from Imam Khomeini International Airport, located in the distance of 16.5 km from the complex and the altitude of 990 m from the sea level.

Input data to the models includes meteorological data, albedo coefficient, Bowen coefficient and roughness length, meteorological data was obtained from the nearest meteorological station, Imam Khomeini international airport. The study area was considered as a rural area and the type of terrain was considered flat because there are not significant up and down in the region. The albedo coefficient, Bowen coefficient and roughness length, assuming that the study area is desert terrain, was considered to be 0.3275, 4.75 and 0.2625, using the coefficients determined by the Environmental Protection Agency for the desert terrain [28]. The emission rate, topography of the area, the characteristics

of the existing buildings in the region, and the characteristics of the sources of publication, such as area and geographic location, were also given to the models.

2.4. Model Efficiency

The convergence of AERMOD predictions with the field measurement was evaluated using the the coefficient of determination (R^2), Index of agreement (d) and Nash-Sutcliffe coefficient (E), which are shown in Eq. (6) to (8) [30-32]:

$$R^2 = \frac{(\sum (O_i - \bar{O})(P_i - \bar{P}))^2}{\sum (O_i - \bar{O})^2 \sum (P_i - \bar{P})^2} \quad (6)$$

$$d = 1 - \frac{\sum_{i=1}^N (O_i - P_i)^2}{\sum_{i=1}^N (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (7)$$

$$E = 1 - \frac{\sum_{i=1}^N (P_i - O_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} \quad (8)$$

Where O_i is the observed concentration; P_i is the predicted concentration; N is the number of stations and $\bar{O}$ is the mean field concentrations. While the results of R^2 , d and E approach to one, the model efficiency are very well.

In addition, Geometric mean bias (MG), Geometric variance (VG), Fraction of predictions within a factor of two of the observations (FAC2), Fractional bias (FB) and Normalized mean square error (NMSE) were used to evaluate the model efficiencies, which recommended by EPA [33]. Eq. (9) to (13) describe them:

$$MG = \exp(\overline{\ln C_o} - \overline{\ln C_p}) = \exp\left(\overline{\ln\left(\frac{C_o}{C_p}\right)}\right) \quad (9)$$

$$VG = \exp[(\overline{\ln C_o} - \overline{\ln C_p})^2] \quad (10)$$

$$FAC2 = C_p / C_o \quad (11)$$

$$FB = \frac{\sum (C_o - C_p)}{0.5 \sum (C_o + C_p)} \quad (12)$$

$$NMSE = \overline{(C_o - C_p)^2 / C_o C_p} \quad (13)$$

Where C_o and C_p represent the measured and estimated concentrations, respectively. The value of 1 for MG, VG and FAC2 shows the perfect performance of the model. FB and MG are measures of mean relative bias and indicate only systematic errors, whereas NMSE and VG are measures of mean relative scatter and reflect both systematic and unsystematic (random) errors.

FAC2 quantitatively assesses the model scatter. If the fraction of model prediction within a factor of two observations is 50%, then it is a good performing model. The value of 0 for the FB and NMSE indicates the ideal efficiency of the model. The FB and NMSE are linear indices and sensitive to the high

concentrations. The MG and VG, as logarithmic indices, are more flexible to the variation of data. MG is used for the determination of model overestimation ($MG > 1$) and underestimation ($MG < 1$). Nonetheless, $MG = 1$ does not mean that predictions coincide with measurements.

3. Results and Discussion

3.1. Field Concentrations

As shown in Table 2, the monitoring indicated that the H_2S concentrations in the winter were generally higher than the summer, which demonstrated that the temperature might not be a crucial factor affecting the gas emission. Williams [34] reported that the weather changes might not be effective in the bacteria activities and consequently gas emission rate at the depths of landfill.

Table 2. The Average Concentration of Two Samples Taken Simultaneously at Each Station

Station	Geographical coordination	Concentration (ppb)	
		summer	winter
1	35°27'30"N 51°20'29"E	94.7	145
2	35°28'0.0"N 51°19'59"E	7.948	11
3	35°28'0.0"N 51°19'20"E	10.54	2
4	35°27'55"N 51°19'30"E	3.45	8
5	35°28'18"N 51°19'47"E	6.29	14
6	35°29'27"N 51°15'06"E	-	16
7	35°29'11"N 51°14'50"E	-	4
8	35°28'52"N 51°14'37"E	-	3.5
9	35°26'31"N 51°12'18"E	-	4
10	35°26'19"N 51°12'14"E	-	3
11	35°29'48"N 51°20'47"E	2.66	-

According to the OSHA standard set by the US Labor Organization, the permitted concentration of H_2S is 20 ppm and the maximum concentration for 10 min. exposure is 50 ppm [35]. According to the Massachusetts Environmental Protection

Organization, an hourly and 8 h limits of H_2S concentration are 30 and 15 ppb, respectively [36]. The station 1 was located near to the Landfill and refinery, where the average measured H_2S concentration was 119.58 ppb. This concentration did not meet the Massachusetts standard. While the detected H_2S in the other stations met the Massachusetts standard.

3.2. H_2S Emission Rate

The landfills and leachate treatment plants were assumed as the main sources of gas and H_2S emissions. The inflowrate, influent and effluent chemical oxygen demand (COD) in the leachate treatment were 1,400 m³/d, 55.5 g/L and 0.8 g/L, respectively. Therefore, the removal rate of COD was 98.5%. According to Youssefi [37], the emitted biogas could be 0.52 L per 1 g removed of COD. Therefore, the daily production of biogas from the leachate treatment plant could be 728 m³/d, which H_2S contribution might vary between 0.728 m³/d to 7.28 m³/d. Due to the density of H_2S (which is 1.36 g/L), the H_2S emission rates varied between 0.11 to 0.011 g/s. In 2016, the total gas emission from the landfill could be estimated around 14×10^6 m³ and the contribution of H_2S varied between 0 to 1%. Therefore, H_2S emission rate from the landfill might be assumed between 0 to 6 g/s. The emission rate of H_2S using Lang-gem software was obtained 1.1 g/s [37].

The models were run in four scenarios with different H_2S emission rates, as shown below:

- Scenario 1: Emission from the landfill (g/s) = 1.1; Emission from the leachate treatment plant (g/s) = 0.095
- Scenario 2: Emission from the landfill (g/s) = 1; Emission from the leachate treatment plant (g/s) = 0.09
- Scenario 3: Emission from the landfill (g/s) = 0.7; Emission from the leachate treatment plant (g/s) = 0.07
- Scenario 4: Emission from the landfill (g/s) = 0.65; Emission from the leachate treatment plant (g/s) = 0.07

The AERMOD and ISCST3 estimations at the monitoring stations as well as the observed concentrations are indicated in Table 3.

3.2.1. AERMOD output

The level of H_2S in the sources varied between 100-117 µg/m³ in the summer and between 200-205 µg/m³ in the winter (Fig. 1). R^2 , d and E values between predicted and observed data in the summer were 0.98, 0.98 and 0.94, respectively. While, the

Table 3. The Results of AERMOD and ISCST3 Models under Defined Scenarios

H_2S concentration in the summer (ppb)	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	AERMOD (ppb)	ISCST3 (ppb)	AERMOD (ppb)	ISCST3 (ppb)	AERMOD (ppb)	ISCST3 (ppb)	AERMOD (ppb)	ISCST3 (ppb)
94.7	113.3	155.48	107.4	105.21	83.5	81.83	83.5	81.83
7.94	34	43	30.9	27.96	21.9	19.57	20	18.14
10.54	17.1	7.36	15.6	4.78	10.9	3.34	10	3.7
3.45	14.6	18.6	13.3	12.08	9.3	8.43	8.6	7.79
6.29	20.5	16	18.7	10.42	13.1	7.29	12.1	6.71
2.66	13.1	12.23	11.9	7.97	8.4	5.57	7.1	5.21
Error (%)	59.5	64	56.1	52.3	43.8	44.7	41.6	42.3

Fig. 1. Concentration contours output from the AERMOD model for the Kahrizak complex in the summer and winter. (a) Summer, (b) Winter

mentioned values in the winter were 0.96, 0.99 and 0.96, respectively. Therefore, the predictions of the model were acceptable and robust.

3.2.2. ISC output

The maximum level of H_2S in the summer and winter were $123 \mu g/m^3$ and $171 \mu g/m^3$, respectively (Fig. 2). R^2 , d and E values between predicted and observed data in the summer were 0.96, 0.98 and 0.94, respectively. While, the mentioned values in the winter were 0.98, 0.98 and 0.95, respectively. Therefore, the predictions of the model were acceptable and robust.

The MG values for ISCST3 and AERMOD in the summer were less than 1, which shows the underestimation of model predictions. The values in the winter were larger than 1, which means the overestimation of the predictions. Nonetheless, the ISCST3 predictions had more agreements with observed data. In the other words, the MG values were closer to 1 in comparison with AERMOD predictions. The VG for ISCST3 predictions in the summer and winter were closer to 1 in comparison with AERMOD anticipations, which shows the lesser variance from the mean value. The predictions of ISCST3 had lower FAC2, which indicates

the model scatter was smaller. According to FB values, the AERMOD and ISCST3 predictions were overestimated and underestimated, respectively. In the summer, the prediction of ISCST3 was closer to the observed data. Nevertheless, the winter prediction of AERMOD was more accurate. The values of NMSE demonstrates a relatively well performing of the models in the space and time (Table 4).

The attained R^2 , d and E for AERMOD and ISCST3 models demonstrated the acceptable performance of both model in the prediction of H_2S emissions from the landfill and treatment plant. Nonetheless, the values of MG, VG, FAC2, FB and NMSE represented a relatively better performance of ISCST3.

Hanna et al. [10] examined the MG, VG and FAC2 values of the AERMOD model which were 1.70, 2.9 and 0.46, respectively, and these values in the ISC3 model were 0.70, 7.7 and 0.33, respectively. They concluded that the AERMOD's performance was more accurate.

Jeong [14] used the AERMOD model to predict odor concentration (regardless of the type of odorous gas, measured based on odor unit). The values of FB, MG, NMSE, VG and FAC2 were equal to -0.019, 1.392, 0.499, 2.461, and 1.019, respectively. He

Fig. 2. Concentration contours output from the ISCST3 model for the Kahrizak complex in the summer and winter. (a) Summer, (b) Winter

concluded that the AERMOD has a reasonable match to the measured data. While the values of VG and NMSE in our study were acceptable compared to Jeong [14].

The results depicted that the predicted concentrations of H_2S in the downwind would reach zero at a distance of 35 km from the sources in AERMOD, and at 38 km in ISCST3 (Fig. 3). The AERMOD predicted upwind concentrations of H_2S would reach zero at a distance of 30 km. While the ISCST3 predicted upwind concentrations would reach zero at the distance of 35 km from the sources.

The AERMOD and ISCST3 predictions in the distance of 5 km away from the sources had a good convergence with each other. Behind 5 km from the sources, the difference between AERMOD and ISCST3 predictions became more distinctive. In the winter, more fluctuations in the prediction of the AERMOD were noticed, which might be attributed to the changes in weather conditions (Fig. 3).

The maximum concentrations of the AERMOD were averagely 3% lower than ISCST3. The US Environmental Protection Agency [39] compared the predicted maximum concentrations of the models; and reported that the AERMOD's predictions were about 4% lower than that of ISCST3's estimation.

Table 4. MG, VG, FAC2, FB and NMSE Factors for AERMOD and ISCST3 Models for H_2S Prediction at the Kahrizak Complex

Factor	AERMOD		ISCST3		Limitation*
	summer	winter	summer	winter	
MG	0.58	1.39	0.85	1.18	0.5-2
VG	1.35	1.35	1.03	1.03	< 1.6
FAC2	1.91	1.46	1.45	1.16	0.5-2
FB	-0.12	-0.05	0.02	0.15	-0.67-0.67
NMSE	0.042	0.022	0.04	0.04	< 0.5

*Patryla [38]

The management strategies can be summarized in the following: Imam Khomeini Airport as the most significant international airport of Iran, is located nearby of the Kahrizak complex. Any odor nuisance can adversely affect the airport and bring economic damage; this study helps to assess odor pollution in terms of H_2S around the airport. In addition, using the applied methodologies, the other odor compounds' influence can be evaluated; this study is helpful in future planning for locating other landfill;

Fig. 3. Trend of AERMOD and ISCST3 predictions in the downwind and upwind of the complex at the summer and winter. (a) Summer: Downwind, (b) Summer: Upwind, (c) Winter: Downwind, (d) Winter: Upwind

Fig. 4. The dispersion of H_2S in the wind speed of 2.22 m/s.

the urbanization development brings the population to nearby of landfills. To assess the odor pollution impacts on human health, the study of its emission is inevitable. Consequently, the results are of interest to a great variety of stakeholders such as decision makers, municipal jurisdiction and health bodies.

For the sensitivity analysis, we ran AERMOD for the wind speed of 8 km/h (2.22 m/s). The results demonstrated that the highest concentration of H_2S would reach to $8 \mu\text{g}/\text{m}^3$. While in the normal condition, the maximum concentration was predicted $117 \mu\text{g}/\text{m}^3$.

4. Conclusions

Considering the experimental and mathematical study of Kahrizak complex, we summarized the following conclusions:

- The field measurement during the summer and winter in-

dicated that the temperature changes did not affect the concentration of H_2S in the surrounding area of the complex. H_2S levels around the leachate treatment plant were significantly higher than other areas, which might be attributed to the anaerobic treatment of leachate. The average concentration in the summer and winter were 94.7 ppb and 145 ppb, respectively. The average concentration in the other stations was less than 10 ppb.

- The coefficient of determination (R^2), Index of agreement (d) and Nash-Sutcliffe coefficient (E) between the predictions and field measurements were more than 0.94, which shows a good consensus between models performance and observed data. Nevertheless, the coefficients demonstrated that the AERMOD predictions were more robust in comparison with ISCST3.
- The MG, VG, FAC2, FB and NMSE indicators showed that the ISCST3 predictions were slightly more reliable than in comparison with the AERMOD results. Such that, the AERMOD results were more overestimated.
- According to the AERMOD model, the maximum predicted concentrations of H_2S was observed in the leachate treatment plant and was equal to $117 \mu\text{g}/\text{m}^3$ in the summer and $205 \mu\text{g}/\text{m}^3$ in the winter and in the case of ISCST3 it was equal to $123 \mu\text{g}/\text{m}^3$ in the summer and 171 in the winter.
- The concentration of H_2S in the wind direction reached zero at a distance of 35 km from sources in AERMOD and in the ISCST3 reached zero at a distance of 38 km. In the opposite direction, this distance was 30 km for AERMOD and 35 km for ISCST3.
- According to the standard of 1 h concentrations of H_2S by the Massachusetts Environmental Protection Agency, which is 30 ppb; in an approximate distance of 2 km around the leachate treatment plant, the amount of H_2S was higher than the standard.

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