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Research Paper:

Evaluating CO, NO_2, and SO_2 Emissions From Stacks of Turbines and Gas Furnaces of Oil and Gas Processing Complex Using AERMOD

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ABSTRACT

Background & Aims of the Study: Air pollution is currently one of the most important industry challenges for countries. Much progress has been made in modeling air pollution, one of which is the AERMOD model, which is based on the Gaussian model. This study investigates the temporal changes of NO_2, SO_2, and CO pollutants emitted from the stack of turbines and gas furnaces of Maroon oil and gas facilities in Omidieh City, Iran.

Materials and Methods: First, the concentration of pollutants was measured using a Testo x-350 analyzer with an average accuracy of ±3 ppm for all three pollutants in cold and hot seasons from 2018 to 2019. Each pollutant was measured 3 times for 15 minutes at 24-hour intervals. Then, the emission rate of each pollutant from the stack was obtained by calculations. The modeling was performed in 2500 Km^2 by entering the emission rate data, technical specifications of the turbines and furnaces, and topographic and meteorological data into the AERMOD program. For validation, the concentrations of all three pollutants were measured by an aeroqual-200 analyzer with an accuracy of 0-25 ppm for CO, 0-1 ppm for NO_2, and 0-10 ppm for SO_2 in 10 stations. Each pollutant was measured 3 times for 20 minutes at 24-hour intervals. The modeled results were then compared with the Iranian and US-EPA environmental standards and measurements.

Results: The hourly concentrations for CO pollutants in hot and cold seasons were 102 $\mu g/m^3$ and 156 $\mu g/m^3$, respectively, and less than the standard (40000 $\mu g\ m^3$), SO_2 1.18 $\mu g/m^3$ and 1.78 $\mu g/m^3$ and less than the standard (196 $\mu g/m^3$), NO_2 16 $\mu g/m^3$ and 27 $\mu g/m^3$ and less than the standard (200 $\mu g/m^3$). The measured results were higher than the modeled ones.

Conclusion: The results of the concentration of SO_2 and NO_2 pollutant gases showed a close agreement with the modeled results. The concentration of the produced pollutants was higher in the cold season than in the warm season due to reasons such as the increase in the volume of heavier compounds and moisture in the gases, as well as the decrease in the wind. AERMOD model had a good estimate in places where there was no background concentration of pollutant.

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1. Introduction

Air pollutants can penetrate the lungs and cause numerous health problems, such as asthma, chronic obstructive pulmonary disease, cardiovascular disease, respiratory disease, and cancer [1-5]. In recent years, much research has been done on the health impacts of air pollutants because of the importance of global and regional climate cycles [6]. These adverse impacts on humans have persuaded policymakers in urban and industrial areas to consider air pollution control strategies [7]. Combustion of associated petroleum gas in oil and gas processing units wastes energy and economic resources. Also, the emissions of greenhouse gases lead to global warming and have deleterious impacts on human health and other living organisms [8]. NO_2, CO, and SO_2 pollutants are other gas combustion products in the industry. Inhalation is the most important transmission route of these pollutants to the body. CO and SO_2 pollutants have health impacts on body systems, such as the cardiopulmonary system [9]. One of the concerns about the concentration and displacement of a pollutant in the industry is the prediction of pollutant emissions [7].

Industrialization and urbanization are causing climate change in the region [7]. By modeling the air quality, it is possible to provide information about air pollution with a relatively simple approach [7, 10]. Also, local and climatic meteorology are critical parameters for modeling the dispersion of air pollutants [11]. AERMOD model is a Gaussian column model (bell-like) that can evaluate the concentration of pollutants output from different sources and simulate the distribution of pollutants from fixed sources for short distances (up to 50 km). This model includes two preprocessors called AERMAP and AERMET. AERMAP is a meteorological preprocessor for area topographic analysis, and the AERMET program requires three surface features of the area, namely Albedo, Bowen ratio, and surface roughness [12]. Data such as the emission rate of each pollutant, meteorological information (temperature, humidity, wind speed, cloudiness, etc.), technical specifications such as stack height, stack diameter, flow velocity, and exhaust gas temperature, exhaust gas flow rate are entered into the AERMOD program.

Furthermore, the model simulates the concentration of each pollutant in the study area. Due to the establishment of a considerable number of oil and gas industries in the south of Iran, and based on the Kyoto and Montreal protocols and the Global Gas Flaring Reduction Partnership (GGFR), the need for a comprehensive environmental study is increasingly heightened. Therefore, air quality modeling can be a suitable tool for predicting air quality and determining pollutant emission control strategies [13]. Considering the more-than-a-century-old history of the oil and gas industry in the country, and the requirements of sustainable development, in addition to the adverse effects of these industries on public health, the present study aims to model the emission of NO_2, CO, and SO_2 from gas combustion in turbines and furnaces using the AERMOD modeling program.

2. Materials and Methods

In this study, all pollutants emitted from the stacks were modeled. The study area is the Maroon processing complex in the National Iranian South Oilfields, located northwest and 67 km from Omidieh City in Khuzestan Province (Figure 1). Its longitude is 49° 18’ 55”, and its latitude is 31° 7’ 57”, and its altitude is 63 m above sea level. This complex includes gas and liquefied petroleum gas units, exploitation, desalination, and gas pressure boost. The location of each unit is shown in Figure 2. The area affected by the dispersion of pollutants in turbines and gas furnaces with an area of 2500 square kilometers was selected (Figure 3). The study period is from March to August as the hot season and September to February as the cold season from early 2018 to early 2019. Three turbines in the gas and liquefied petroleum gas unit and 2 in the gas pressure booster unit are used to increase the pressure of associated gases, and 6 turbines in the exploitation unit are used to supply energy to rotate the axis of oil transfer pumps. These are Reston-type turbines. Four heating furnaces and one pre-heating furnace are used to heat crude oil in the Maroon desalination unit, and 3 boiling furnaces in gas and liquefied petroleum gas units are used to increase the glycol temperature. Glycol is used in gas and liquefied petroleum gas units to regulate the temperature of the gas received from the exploitation unit.

Emitted pollutant concentrations were measured from the stacks of turbines and gas furnaces using a 350 Testo analyzer with an average accuracy of ±3% ppm for all three pollutants in the cold and hot seasons of 2018 and 2019. Each pollutant was measured 3 times for 15 minutes at 24-hour intervals. Then, the emission rate at the mouth of each stack was calculated for further use in the modeling. Testo analyzer is capable of sampling and direct reading pollutant concentrations. The direct reading method is common for the concentration of gaseous pollutants. A portable gas analyzer system with the quality of continuous measurement performance in long and adjustable periods is designed for applications regarding environmental measurements. This device determines the pollution concentration by directly reading sensors and a program installed on the device. In this measurement, the concentrations of NO_2, CO, and SO_2 were obtained in ppm. Sampling was performed using a probe from a suitable place, i.e., at a distance between 2 stack diameters from the gas inlet and 0.5 stack diameter from the upstream of the stack tip. Before each measurement, the date of the calibration label of the analyzer device and the technical label, battery charge, and sensors were checked for measuring the pollutant of the device, and the accuracy of each was confirmed. With each sampling, the information about the type of inlet fuel gas for each device, temperature, and flow rate of the emitted gas was obtained from the unit officials. It was ensured that the temperature of the emitted gas was appropriate to the temperature tolerance range of the device sensors. Industrial props were used in these samples. Measurements were performed in the first six months as the hot season and the second six months of the year as the cold season. The average duration of sampling in each turn was 15 minutes. To increase the measurement accuracy, the number of samples for each pollutant in each stack was 3 times with a 24-hour interval. The mean numbers are recorded in the results table. After studying the documents of turbine and furnace manufacturers, first, we determined the total mass flow rate of the output from each stack and then multiplied the concentration of each pollutant by the mass flow rate and calculated the emission rate of each pollutant in each device according to Equation 1.

1: *Emission rate(g/s)=pollutant concentration ppm (mass)×stack dry mass flow rate (g/s)*

To validate the results obtained from modeling the pollutants emitted from the stacks, the concentrations of SO_2, CO, and NO_2 pollutants at 10 points around the complex were measured by an aeroqual-200 analyzer with accurate measurement of 0-25 ppm for CO, 0-1 ppm for NO_2, and 0-10 ppm for SO_2 at 10 stations. Each pollutant was measured 3 times for 20 minutes at 24-hour intervals. These points were selected at almost the same distance from each other and on four different sides of the Maroon facility, and the distance from each point of the complex fence was 50 meters. After selecting the appropriate location for the measurement, we set the device in place so that the sensors were located one and a half meters above the ground in the breathing area. Then, we programmed the device and determined the duration of the measurement. The device used its sensors to measure the pollutants in the air in real-time, and the numbers displayed on the monitor were read and recorded. The modeled results were compared with the measured, the US-EPA, and the environmental protection standards. To determine the concentration of pollutants in the selected points around the Maroon complex by the modeling program, points with approximately the same distance from each other on the four sides of the facility were selected. Also, the distance of each point from the fence was the same. In the modeling program, individual acceptors were created, and in this way, the software provided separate data for selected points during modeling, which were compared and analyzed with the measured data. Observational meteorological data of the upper atmosphere and surface hourly meteorological data are two important parameters for the AERMOD model [7]. Concentrations of surface pollutants resulting from the AERMOD modeling program are commonly used to assess compliance with air quality requirements [14]. It uses a station data model, assuming that the weather is horizontally uniform throughout the study area [7]. The AERMOD model has special capabilities to simulate the distribution of air pollutants because of the gas combustion [15, 16], which in this study has used version 8.9.0. The program is a premium regulatory model and the first choice of the US-EPA for industries with a distance of less than 50 km. It is based on the Gaussian model, designed for modeling in urban and rural areas, and it can evaluate the change in the smoke direction because of the attenuating effect of buildings and obstacles [17]. It has also been selected as an alternative to the ISC3 model [18] because this model examines the effects on complex and flat terrains, is more comprehensive than ISC3, and provides a more reliable simulation [19]. In this model, the meteorological preprocessor uses the land surface characteristics around the site and the hourly meteorological data to provide more realistic estimates of the parameters affecting the emission and dispersion of pollutants [20].

Meteorological data were obtained from the synoptic station of Omidieh City in Khuzestan Province for one year, from March 2018 to February 2019. Before modeling, meteorological data were compiled hourly in an Excel file and introduced to AERMET. Then, by entering the coordinates of the meteorological station and other parameters, AERMET began to extract the necessary data, and the processed meteorological file was extracted and loaded into the AERMOD program. The spatial data map of the study area with an area of 2500 km^2 was first converted into a reference land map using global mapper software, and it was loaded with coordinates in the AERMOD program. The AERMOD model has special capabilities for simulating the emission and dispersion of combustion air pollutants [16, 21]. Table 1 shows the

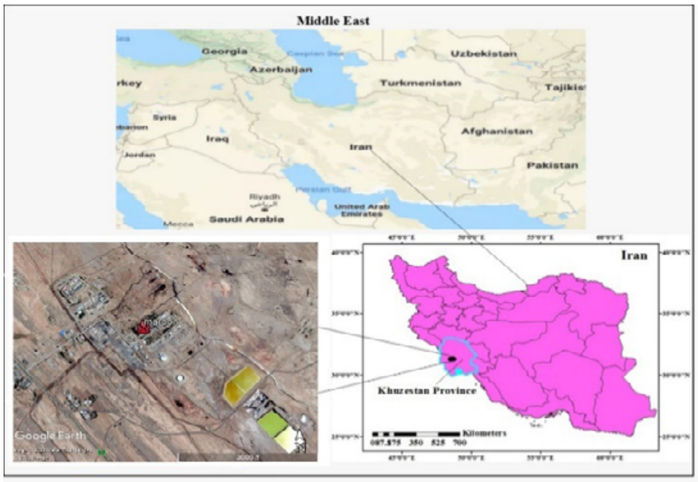

Figure 1. Location of Maroon complex in the country map from 2019 to 2018

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input data and output results of the AERMOD modeling program. Villages, towns, and areas around the complex were determined as receivers after determining the characteristics of turbines and furnaces and the amount of pollutants produced. Then, the modeling was performed by the AERMOD program for turbines and furnaces in which the gas burns and leads to the production of CO, NO_2, and SO_2 pollutants.

3. Results

Figure 4 shows the minimum and maximum concentrations of pollutants obtained from the modeling. The maximum concentration of each pollutant can be seen in red in the upper right corner of each figure. After modeling the emission and dispersion of pollutants from the stack of turbines and furnaces, it was found that the maximum hourly concentration of CO pollutants in the hot season was 102 μg/m³ and 156 μg/m³ in the cold season, which not only did not exceed the standard limit (40000 μg/m³), but also was much lower (Figure 4, parts 1 and 2). The maximum 8-hour concentration of CO pollutants in the hot season was 77 μg/m³ and 118 μg/m³ in the cold season (Figure 4 parts 3 and 4), which, in this case, did not exceed the standard limit (10000 μg/m³). The maximum hourly concentration of SO_2 pollutants was 1.18 μg/m³ in the hot season and 1.78 μg/m³ in the cold season, which is less than the allowable threshold (196 μg/m³) (Figure 4, parts 5 and 6). The maximum 3-h concentration of this pollutant was 0.9 μg/m³ in the hot season and 1.27 μg/m³ in the cold season (Figure 4, parts 7 and 8), which in both cases did not exceed the allowable limit (1300 μg/m³) and has been much lower. The maximum 24-h concentration of this pollutant was 0.37 μg/m³ in the hot season and 0.4 μg/m³ in the cold season (Figure 4, parts 9 and 10), which is lower than the allowable limit (395 μg/m³). The maximum NO_2 pollutants per hour concentration were 16 μg/m³ in the hot season and 27 μg/m³ in the cold season, lower than the allowable limit (200 μg/m³) in both cases (Figure 4, parts 11 and 12). The maximum annual concentration of NO_2 in both hot and cold seasons was 1 μg/m³ (Figure 4, parts 13 and 14), which in both cases was much lower than the allowable limit (100 μg/m³).

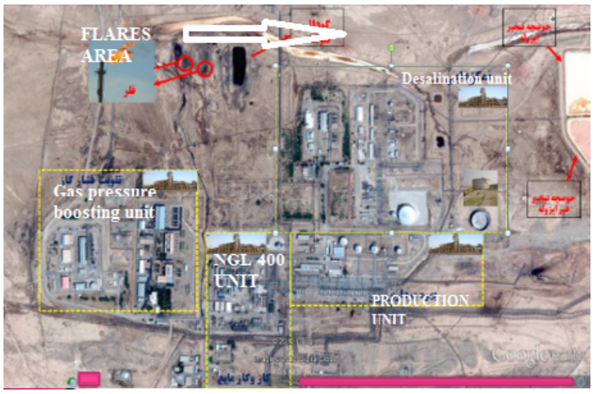

Figure 2. The area affected by pollutants around Maroon complex during 2018-2019

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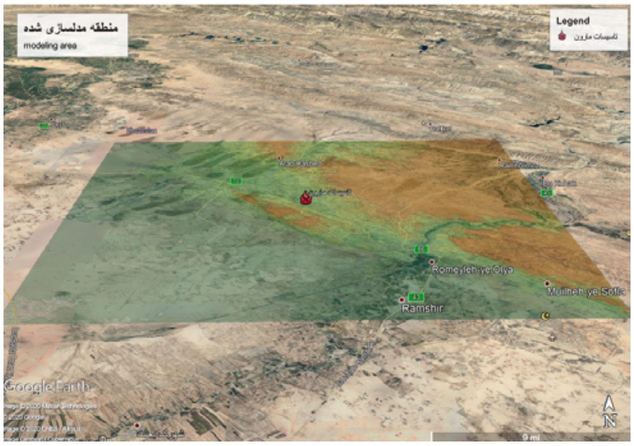


Figure 3. Location of Maroon complex units during 2018-2019

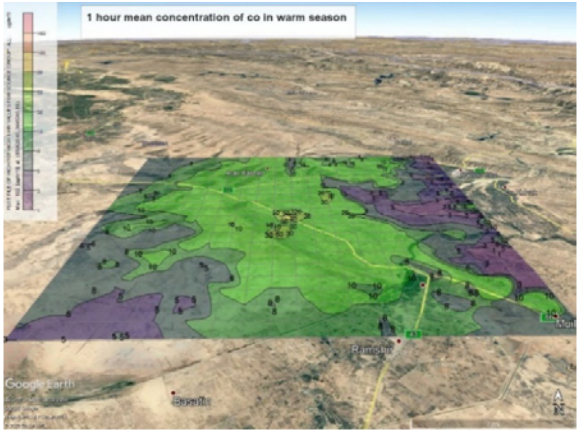
4. Discussion

By modeling the pollutants and comparing them with the standard, it was found that the maximum concentrations in both hot and cold seasons have not exceeded the allowable limits of national and international standards at any point. The concentration of all pollutants in the cold season was higher than in the hot season; according to the wind rose map of the region, the reduction of the wind speed in the cold season can prevent the natural dilution of air by wind, and more accumulation of pollution. The wind rose map from the data recorded at the stations is shown separately for the whole year, including cold and hot seasons. (Figure 5, parts 1, 2, and 3). In this region, 4.42% of the winds are calm, 95.58% are directional and fast, 14% are prevailing, and 8% of the winds blow from the northwest, while 6% blow from the southeast. The wind speed in the northwest direction is higher than in the southeast, and in general, the wind speed is lower during the cold season, where 7.47% of the winds are calm, compared to the hot season, in which 1.48% of the winds are calm, which has been influential in the accumulation of pollutants produced from stacks.

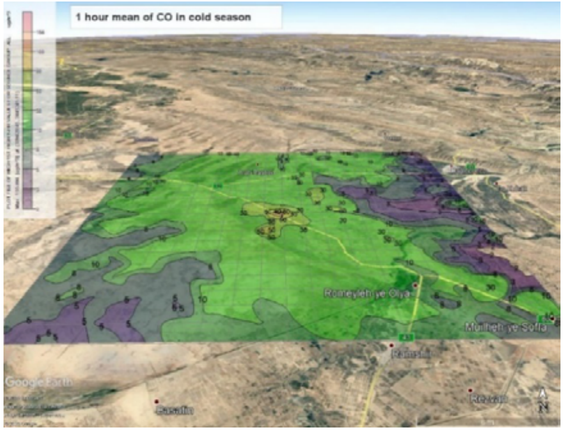
The reason for higher concentrations of SO_2, CO, and NO_2 pollutants in the cold season can be the increase in the humidity in the crude oil sent from wells to the complex and increased furnace flames that raise the temperature of the crude oil in the desalination unit, the glycol in the glycol reduction unit, and the gas and liquefied petroleum gas unit. Other reasons for the higher concentration of SO_2 in the cold season include the entry of H2S into the fuel composition of turbines and furnaces. Meanwhile, the results of SO_2 emissions in the cold season show its importance too. The concentrations measured in both seasons for CO and SO_2 were slightly higher than the modeled concentrations and are related to the underlying concentrations of pollutants from gas flares and wells during exploration and production operations in the study area, which are not included in the modeling. Also, the concentration of these two modeled and measured pollutants did not exceed the standard al-

Table 1. Input data and output results of modeling program (AERMOD) used to model pollutants in the Maroon complex

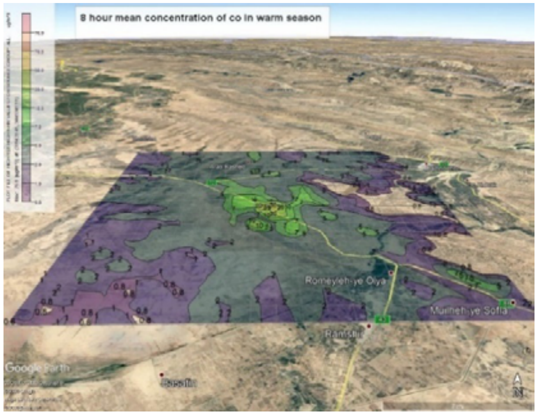
Model Section	Input Data	Output Data	Data Interval
AERMET	Meteorological data (wind speed and direction, cloudiness, humidity, temperature, precipitation with average hourly)in XLS format, land use, coordinates and altitude of the meteorological station above sea level, altitude of meteorological measuring devices	File with extensions of pfl, scf amf, and windrose	2018
AERMOD	Files with the extension of pfl, scf, amf	Pollutants concentration and graphical view of their emission and dispersion on the map, pollutants concentration table by an hour in receiving areas, maximum pollutants concentration table by the hour, date, and coordinates in the whole study area	Average 1, 3, 8 hours, the seasonal and total year 2018
AERMOD	Coordinates of turbines and furnaces and receptors, geographic information, and topography of the modeled area		
AERMOD	Inlet gas flow, stack height, base elevation, calorific value, the volume percentage of inlet gas compounds, type of pollutant, emission rate, stack diameter, velocity, and temperature of emitted gas		



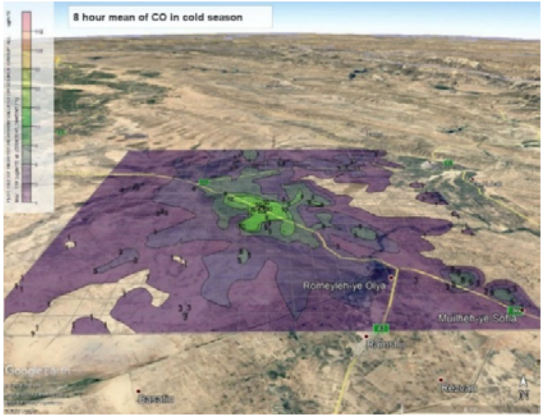
1. One-hour concentration of CO (hot season)



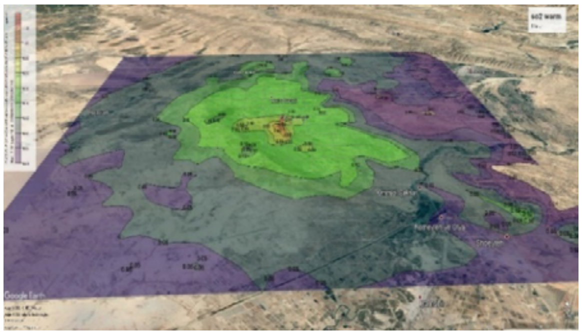
2. One-hour concentration of CO (cold season)



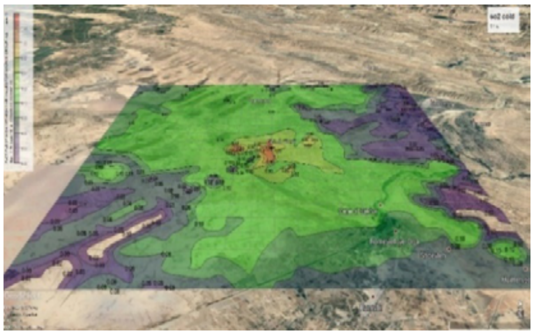
3. Eight-hour concentration of CO (hot season)



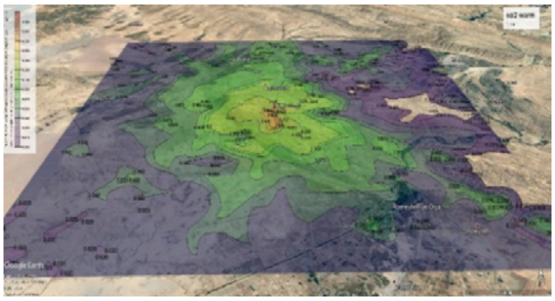
4. Eight-hour concentration of CO (cold season)



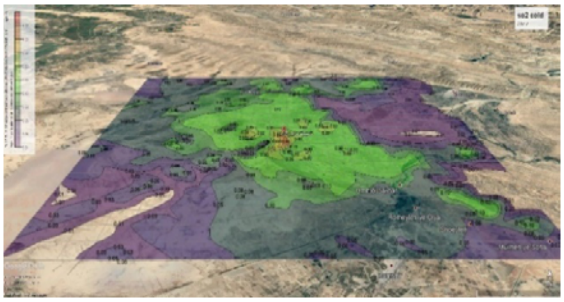
5. One-hour concentration of SO_2 (hot season)



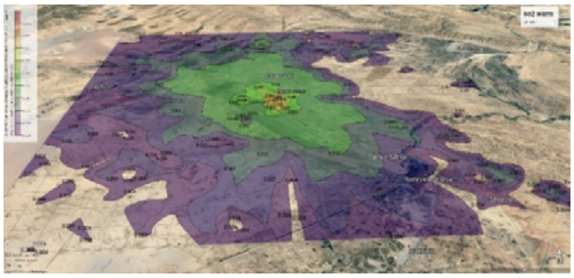
6. One-hour concentration of SO_2 (cold season)



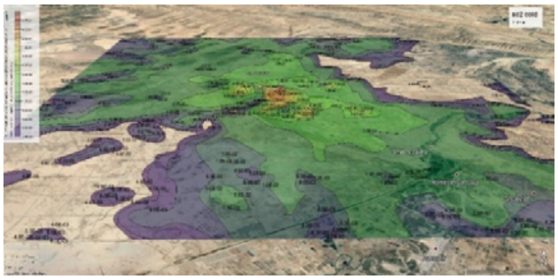
7. Three-hour concentration of SO_2 (hot season)



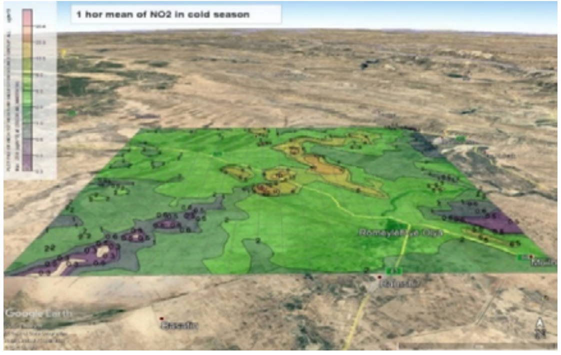
8. Three-hour concentration of SO_2 (cold season)



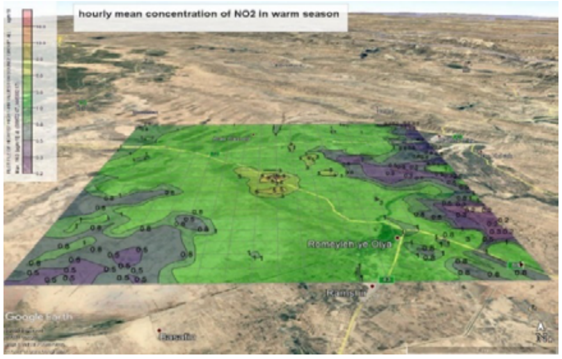
9. Twenty-four-hour concentration of SO_2 (hot season)



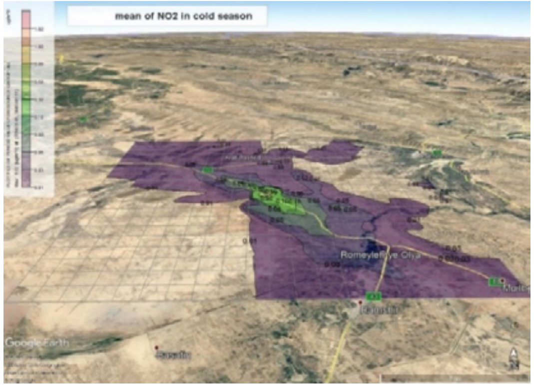
10. Twenty-four-hour concentration of SO_2 (cold season)



11. One-hour concentration of NO_2 (hot season)



12. One-hour NO_2 concentration (cold season)



14. Annual NO_2 concentration (cold season)

13. Annual NO_2 concentration (hot season)

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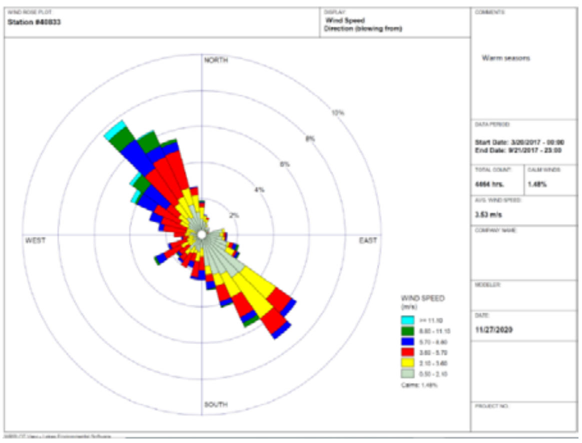
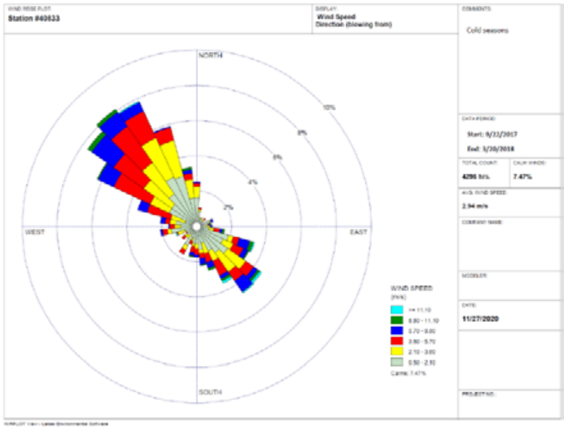
Figure 4. The concentration of pollutants emitted from flues in hot and cold seasons in the Maroon complex from 2017 to 2018

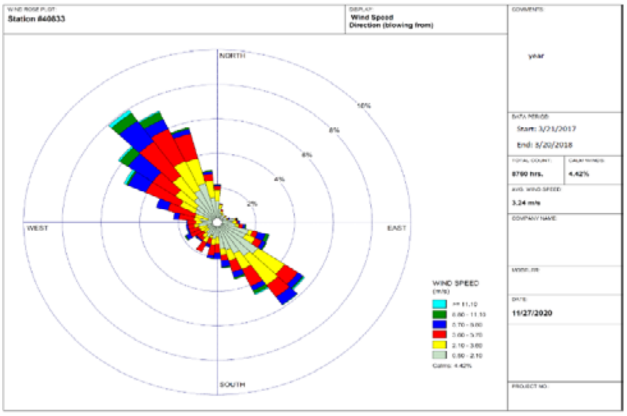
lowable limit. A measured and modeled comparison of NO_2 concentrations shows the values to be consistent or have minimal differences in results because of the lack of underlying concentrations. Therefore, modeling has provided acceptable results in estimating pollutant emissions. Although all concentrations were less than the allowable standard, it is recommended to purchase and install electric compressors instead of gas turbines in exploitation units for boosting gas pressure and gas and liquefied petroleum gas 400 in the Maroon complex. Meanwhile, installing filters to treat impurities of associated petroleum gas sent to the furnaces of the desalination unit and gas and liquefied petroleum gas 400 to help burn gas in combustion chambers will prevent the flaring of this volume of gas and, of course, reduce the exposure to pollutants. These are administrative measures and monitoring programs to formulate a policy to control the industrial air pollutants resulting from the AERMOD modeling program in this research. In diagrams A, B, and C, the measured results of CO, SO_2, and NO_2 pollutants at ten points around the fence of the Maroon complex are compared with the modeling results at the same points. The results show that in both hot (Figure 6, part 1) and cold (Figure 6, part 2) seasons, the measured



1. Hot season



2. Cold season



3. Annual

Figure 5. Windrose of the study area in the Maroon oil and gas facilities from 2018 to 2019

CO concentrations were much higher than the modeled CO concentrations. In Maroon Industrial Complex, gas is burned in 13 flares in routine and emergency or turbulence conditions of units. This condition leads to the production of pollutants such as CO and SO_2. Furthermore, because the AERMOD program does not consider the underlying concentrations of the pollutants, this situation has led to more measurement results than modeling.

Comparing the modeled and measured SO_2 concentrations by the device in the hot season (Figure 7, part 1) shows that the measured SO_2 was slightly higher than the modeling one at 8 points. In two points, No. 4 and 5, the amount of measurement was much higher than modeling, and the reason can be the existence of an underlying concentration of sulfur dioxide emitted from the flare and wells of oil fields being explored and produced at the time of measurement. That can be attributed to an underlying concentration of sulfur dioxide emitted from the burners and wells of oil fields being explored and produced at the time of measurement around the two stations and not related to their modeling program.

Comparing the modeled and measured SO_2 in the cold season (Figure 7, part 2) was also very consistent in stations 1 and 3. In station number 2, the measured value was less than the modeled one. The probable reasons can be the shutdown of several turbines and furnaces because of breakdown or power outages and wind and dilution of SO_2 concentration in the air around Station 2 at the measurement time. In the other 7 points, the measured value was slightly higher than the modeled one because of the presence of SO_2 concentration as the result of gas flaring in the flares and wells around them, which increases the concentration of SO_2 pollutants in the air around Maroon oil and gas processing facilities.

Comparing the modeled and measured NO_2 concentrations in the hot season (Figure 8, part 1) shows that the NO_2 concentrations measured at stations 1, 5, and 10 are very close. At 7 other points, the measured value is higher than the modeled one; therefore, the difference between the measured and modeled results was minimal. In modeling, atmospheric conditions are considered over six months; however, the measurement is in the same

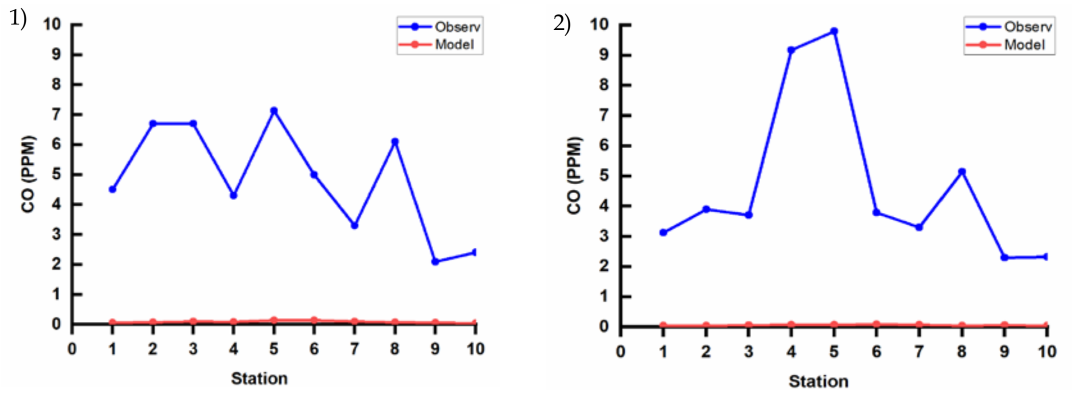


Figure 6. Comparison of The Results of Measured and Modeled CO Pollutants in hot (1) and cold (2) seasons in the Maroon Complex From 2018 to 2019

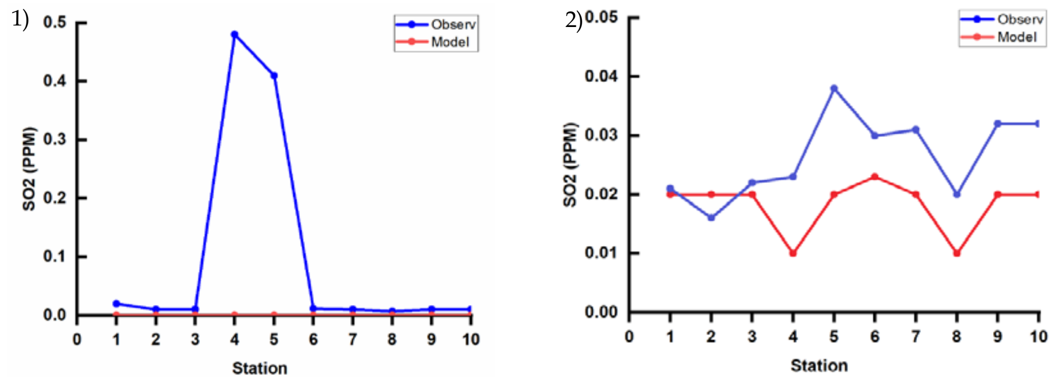


Figure 7. Comparison of the results of measured and modeled SO_2 concentration in hot (1) and cold (2) seasons in the Maroon complex from 2018 to 2019

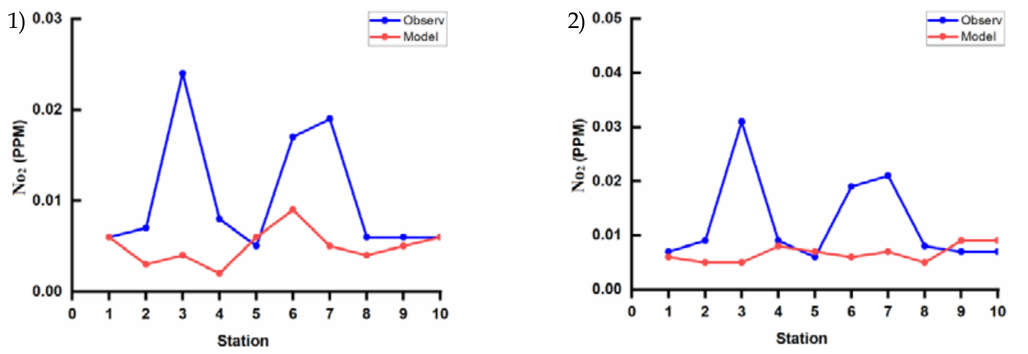


Figure 8. Comparison of measured and modeled NO_2 pollutant concentrations in hot (1) and cold (2) seasons

instantaneous conditions, and the difference in the concentration values is not naturally unexpected. A comparison of the modeled and measured NO_2 concentrations in the cold season (Figure 8, part 2) shows that the NO_2 concentrations measured in the 6 measuring stations are almost identical. In the other 4 stations, the measured concentrations were slightly higher than the modeled results. In a similar study in 2015, Bigharaz et al. modeled the dispersion of benzene, toluene, xylene, SO_2, and NOX pollutants produced in flares located in the South Pars Energy Special Economic Zone of Iran using the AERMOD simulation program. They concluded that under normal (operating conditions) and abnormal conditions, the concentrations of benzene, hydrogen sulfide, and sulfur dioxide pollutants were all above the standard. In normal and abnormal operating conditions, the measured concentrations were higher than the modeled concentrations [8]. In 2016, Shamsipour et al. studied the dispersion of suspended particles in the south of Tehran using the AERMOD model. According to their results, the greatest impact of PM10 pollutant occurred at 1 to 5 km from the source [22]. In 2013, Ma et al. simulated the air quality soon based on China's latest gas emission control policies using the AERMOD modeling program [23]. They stated that using the AERMOD modeling program, the emission and dispersion of SO_2 and NOX pollutants and their impact on air quality can soon be simulated using atmospheric middle layer meteorological data. In a similar study, Seangkiatiyuth et al. used the AERMOD model to assess the environmental impact of NO_2 emissions in Bangkok [6]. Their results showed that the maximum NO_2 concentration occurred 1 to 5 km from the emission sources [6]. In this study, the NO_2 concentration in the dry season was higher than the average compared to the wet season. That can be attributed to the high deposition of wet NO_2 [6].

This result is similar to the present study because of the similarity in climatic conditions in wet and dry seasons. Ding et al. have analyzed the environmental impacts of air above the pollutants released by power plants [24]. Based on the results of their study, the average daily concentrations of SO_2 and NO_2 at ground level were 53.3% -26.7% and 58.3% -16.7%, respectively [24]. They demonstrated that SO_2 and NO_2 in the air above the Beilun area were relatively higher. In 2011, Hagan et al. evaluated the concentration of mercury from silver mining and its residues in the soil of the Potosi region of Bolivia using AERMOD [25]. The mercury concentration predicted by AERMOD was 0.105 to 155 mg/kg [25]. Based on their results, the obtained emission rate can model and estimate the exposure rate for existing mercury pollutants. In another study, Huertas et al. estimated the impact of air quality on various open-pit coal mines in northern Colombia [26]. Using the collected meteorological data, they assessed the total concentration of suspended particles by AERMOD [26]. They have proven that environmental policies should be based on air quality modeling results, similar to our study in Iran. Heidari Chaharlang et al., in a similar study in 2020, investigated the emission and dispersion of CO pollutants emitted from the stacks of gas turbines of the Maroon 5 oil and gas exploitation unit using the AERMOD model [27]. The modeling results showed that the maximum concentration of CO during summer in the average period of 1 hour was 55.97 $\mu g/m^3$, and the maximum concentration in almost all seasons because of the short length of the stacks occurred around the exploitation unit. Furthermore, the concentration of pollutants in the population centers of the study area was very low. Also, the concentrations did not exceed the standard limits in all cases. In a similar study in 2019, Al-Mayahi investigated the emission and dispersion of CO, NOx, and SO_2 gaseous pollutants from the stacks of the Maroon 3 oil and gas exploitation unit in Khuzestan Province using the AERMOD model [28]. According to their results, the maximum concentration of pollutants occurred in spring, at an average time of 1 hour. For CO pollutant gas, its concentration was 0.147 $\mu g/m^3$ or 0.00013 ppm; for Nox pollutant, its concentration was 0.136 $\mu g/m^3$ or 0.04 ppb, and for SO_2 pollutant, its concentration was 0.00778 $\mu g/m^3$ or 2.07 ppb. The dispersion direction of pollutants was mainly to the southeast of the study area, indicating the region's prevailing wind direction. Also, in winter, the maximum concentration occurred farther from the designated origin than in other seasons, which indicates an increase in the wind intensity. In all cases, the concentrations were below the standard range. In a similar study in 2020, Heidari Chaharlang et al. investigated the emission and dispersion of NO_2 emitted from the stacks of gas turbines of the Maroon 5 oil and gas exploitation unit using the AERMOD model [29].

The modeling results showed that the maximum concentration of NO_2 pollutant related to spring with the average period of 1 hour was 52.8 $\mu g/m^3$ or 0.0281 ppm, and the maximum concentration in almost all seasons because of the short length of the stacks occurred around the exploitation unit. Also, the concentration of pollutants in the populated centers of the study area was very low. In addition, the concentrations did not exceed the standard limits in all cases. In a similar study in 2018, Fawole et al. modeled the emission and dispersion of CO, BC, O2, SO_2, and PAH pollutants produced in flares based in the Niger Delta in Nigeria using AERMOD simulation programs and ADMS [15]. They reported that surface concentrations were higher during WAM months and were mainly dispersed to internal population centers. Also, masses with less buoyancy than smaller flares and lower heat-burned gases increase the concentration of the ground's surface in areas close to the flares. Judging the differences between the Niger Delta research and the present study, it is possible to disregard real data related to the characteristics of pollution sources located in the study area (flare height, flare diameter, inlet gas flow, etc.) and use of the characteristics of flares in similar research, i.e., the use of estimated emissions coefficients instead of accurately calculating the pollution produced in the flares orifice, and not measuring the concentration of pollutants in the study area to compare and validate the modeling results with the measured results. In 2018, Omidvar Borna et al. compared the estimated emissions of SO_2 and NO_2 pollutants from a flare and two stacks of the Tema oil refinery in Ghana using two AERMOD and CALPUFF modeling programs in an area of 1024 km^2 [30].

The emission rate in the flare and two stacks was calculated by the computational method (material balance) according to the ideal gas law and only under normal conditions. AERMOD program has modeled the emission and dispersion of pollutants in three seasons of high rainfall, low rainfall, and a dry year better than CALPUFF. Pollutants were measured over 12 days to validate the modeling results. A comparison of modeling and measurement results showed that AERMOD could predict changes in the number of pollutants compared to the measurement results slower than CALPUFF. In fact, the difference between CALPUFF's data is more ambiguous than that of AERMOD in measurement. The measurement results were compared with the modeling, and the results of AERMOD were less and closer than the measurement, but the results of the CALPUFF model were more different and, in some places, lower or higher than the measurement. In 2014, Rahul et al. [31] modeled the emission of NO exit from cars and industrial stacks using the AERMOD program in an industrial area in Ranchi, India. They calculated temperature, wind speed, wind direction, relative humidity, air pressure, light radiation, and cloud cover for only 7 days in April 2010 and then generalized it to a whole year. However, in the present study, meteorological data were related to a period of one year. In addition, the upper atmosphere climate data from the measurement station at the University of Wyoming are used, in addition to the wind flow profile, to calculate the boundary layer properties, such as surface friction, surface wind speed, roughness, and heat flow in stable and unstable conditions. Accordingly, in the present study, the capabilities of the modeling program were used to estimate the characteristics of the upper atmosphere and the boundary layer. The similarities between these two studies can be the comparison of the measured and modeled values, fewer modeling results than measured, and underlying concentrations in the study areas in Iran (2500 km^2) and India (400 km^2). In 2016, Baawain et al. simulated the emission of H2S pollutants from the municipal wastewater treatment plant in the Al-Ansab neighborhood in Muscat, Oman, using AERMOD [32].

This pollutant's emission sources include the connection points of sewage tanker, bio-filter, odor control unit, and raw sewage canals in the study area. The maximum daily concentration of pollutants on the ground around the treatment plant has been 40 $\mu g/m^3$, which is higher than the national standard of Oman. The highest concentration was considered in the worst-case scenario and was 450.9 $\mu g/m^3$ in the adjacent freeway when the tank doors of 8 of the 33 sewage trucks were open while being unloaded. The highest concentrations of H_2S on the ground surface were in March and the lowest in December. Also, the impact of the smell during summer was more than in other seasons because of the higher temperature, which was a source of complaint by the surrounding residents. One of the similarities between the mentioned research and the present study is the calculation of emission rate, unit conversions, and modeling results validation by performing measurements with a gas meter in several surrounding points. Comparison with the standard, considering the worst-case scenario (the openness of the connections of 8 tankers during the discharge of sewage), as well as the combustion of gas in the flares in unusual conditions in the present study, comparing hourly and daily concentrations of pollutants with the standard, using local synoptic meteorological station data and the study of pollution in different seasons. The accuracy of the measurement results is compared with modeling based on different land uses. It was concluded that the measured value is closer to the modeled one in the case of forest or urban land use, and the reason was the urban land use around the wastewater treatment plant. In this study, because the cause of pollutant modeling is the prediction of odor emission and the dispersion is more in the area close to the ground, the modeling was done in an area of 18 km^2, while the distance between the receptors was 100 m. In the present study, the smoke emission from the flare is much higher than the odor; therefore, the study area is 2500 km^2, and the distance between the receivers is 2 km. In 2017, Goodarzi et al. evaluated the CO, CO_2, and SO_2 emissions from Maroon Complex flares using AERMOD [33].

In this study, the emission and dispersion of pollutants from 13 flares of the Maroon complex were simulated using the AERMOD model. First, the gases sent to each flare in cold and hot seasons were sampled, and by injection in a Gas Chromatography (GC) device, the type of compounds and their molar, volumetric, and weight percentages were determined. Then, the emission rate was determined by stoichiometric method and engineering calculations by determining the combustion reactions and products. The modeling was performed in 2500 km^2 by entering data such as emission rate, flare characteristics, and topographic and meteorological data of the study area into the AERMOD program. The results show that the maximum one-hour concentration of SO_2 in the cold season was 215 $\mu g/m^3$ and above the standard. Also, the maximum eight-hour concentration of CO in the cold season was 13441 $\mu g/m^3$, which was higher than the standard. However, in the hot season, it was 9755 $\mu g/m^3$, which was close to the standard. Because of the wind direction from the northwest, pollution can adversely affect the health of the population of 100 employees of the complex, the villages of Morad Beigi, Mashrageh, and Alwan Asherah, and the occupants of passing vehicles. The concentration of pollutants produced was higher in the cold than in the hot season because of the increased volume of heavier compounds in the gases. The comparison of the results of CO and SO_2 concentrations measured in 10 stations was higher than the modeling results.

5. Conclusion

In this study, the emission and dispersion of pollutants from 19 stacks related to turbines and furnaces of the Maroon complex were simulated using the AERMOD model. The modeling results in a region with an area of 2500 km^2 show the maximum concentration of 1 hour, 3 hours, and daily SO_2 pollutant, the maximum concentration of 1 hour and 8 hours of CO, and maximum annual concentration of 1 hour NO_2 pollutant in both cold and hot seasons. They did not exceed the US-EPA and DOE standards in no cases. A comparison of modeling results with field measured results also shows that the concentration of measured CO pollutants was higher than the modeled ones because of the underlying concentration of this pollutant caused by gas combustion in Maroon flares. The measured concentrations of SO_2 and NO_2 pollutants closely correlate with the modeled results. The concentration of pollutants produced for reasons such as increasing the volume of heavier compounds and moisture in the gases and reducing wind in the cold season was higher than in the hot season. The AERMOD model has a good estimate in places that do not have a background concentration of pollutants.

Ethical Considerations

Compliance with ethical guidelines

The authors have observed ethical issues including plagiarism, informed consent, misconduct, data fabrication and or falsification, double publication and or submission, and redundancy.

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Authors' contributions

All authors equally contributed to preparing this article.

Conflict of interest

The authors declared no conflict of interests.

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