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Dispersion modeling of SO_2, NO_2, and CO emitted from the Sahand thermal power plant using AERMOD software

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ABSTRACT

In this research, the dispersion of gaseous pollutants emitted from the Sahand thermal power plant was simulated using AERMOD software to determine the concentrations of sulfur dioxide, nitrogen dioxide, and carbon monoxide in the surrounding area. AERMOD was used to analyze the concentration patterns of these pollutants within a 35.9 km^2 domain, covering the cities of Bonab, Ajabshir, and Khoshehmehr, along with their nearby villages. For this purpose, two years of meteorological data, along with geographical information and emission source characteristics, were utilized to estimate pollutant concentrations over averaging periods of 1 hour, 3 hours, 24 hours, and annual averages. Comparison of the modeled results with the limits defined in the environmental standards indicates that the maximum concentrations of nitrogen oxide and carbon monoxide in residential areas are within the permissible limits. However, the highest concentration of sulfur dioxide exceeds the limits in some villages, suggesting a potential health risk for residents.

1. Introduction

The modeling of atmospheric pollutant emissions is a fundamental tool for investigating air quality conditions and the dispersion patterns of harmful substances that threaten both human health and the environment. The complete elimination of industrial pollutants remains an unattainable goal given current technological capabilities.

Therefore, it is imperative to identify the specific substances emitted by power plants and assess their environmental impacts, as failure to do so could lead to serious health risks for citizens. Consequently, comprehensive research and analysis are essential to mitigate the dangers posed by these pollutants. Globally, 6% of annual deaths are attributed to premature mortality caused by air pollution. In Iran, this figure is even higher, around 10% [1]. Estimating the dispersion of air pollutants from various sources is the first step towards controlling environmental conditions and improving public health. Experimental measurements of air pollution provide valuable information about pollutants and their concentrations within a given region [2]. However, such measurements are limited to the specific

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locations and times, and cannot be generalized to other areas, particularly in regions with complex terrain. Furthermore, determining the maximum pollutant concentrations in a given area requires repeated measurements at multiple locations and times, which can be time-consuming and costly.

Nevertheless, it is possible to estimate pollutant concentrations at unmeasured locations or future times, even with limited data, by applying data-driven methods such as artificial neural networks [3] and support vector machines. These estimating methods are subject to uncertainties arising from various factors that influence pollutant distribution, making them less suitable for use in environmental monitoring programs. In contrast, model-based techniques can offer a more comprehensive understanding of pollution dispersion by describing the complex interactions between pollutant emissions, meteorological parameters, and regional topography. Mathematical models of pollutant dispersion can therefore provide more detailed guidance for implementing control measures and evaluating the effectiveness of different strategies to reduce pollutant concentrations.

The Gaussian model is one of the oldest methods for modeling the dispersion of atmospheric pollutants and remains the most widely used and accepted method for calculating the pollutant concentrations at specific points, compared to other methods such as the Eulerian and Lagrangian models [4, 5]. Gaussian models are valuable tools for simulating point sources of pollutant emissions, such as those from power plants and refinery chimneys. Also, it is possible to develop relationships that allow the application of Gaussian models to line sources (e.g., roads) and area sources (e.g., fires in pastures and forests). To conduct an air pollution dispersion analysis using a Gaussian model, it is essential to gather information on pollutant sources, including the mass emission rate of the materials, the velocity and temperature of exhaust gases, and the emission height. Additionally, meteorological data, such as wind speed and direction, ambient air temperature, and other parameters used to determine the atmosphere stability class, must also be collected [4].

American Meteorological Society-Environmental Protection Agency Regulatory Model (AERMOD) is a steady-state Gaussian plume-based emission modeling software that performs transport calculations within a wind field [6]. In addition to modeling point sources, it can also be used to model linear pollutant sources generated by vehicular movement on roads and streets [7-14]. AERMOD includes two preprocessors, AERMET for meteorological data processing and AERMAP for terrain and land-use information, to prepare the input data required for pollutant dispersion modeling based on the Gaussian model. AERMOD has been widely used to model the dispersion of conventional pollutants emitted from various industrial activities, including power plants [15-19], refineries [20-27], steel industries [28], and cement factories [29]. AERMOD has also been applied widely in specialized studies, such as modeling of sulfur dioxide emissions from airports near coastlines [30], sulfur compounds emissions from sewage reservoirs [31-33], odor emissions from livestock farms [34] and landfills [35], benzene emissions from gas stations [29], particulate matter emissions from cotton ginning factories [36] and open-cast copper mines [37], gaseous pollutant emissions of from ships [38, 39], dispersion of SARS-CoV-2-laden particulate matters [40], heavy metal emissions from coke plants [41], radon gas emissions from uranium mines [42, 43] and the release of radioactive materials from nuclear power plants [44]. In all these cases, AERMOD has provided reliable results.

Thermal power plants that burn fossil fuels near urban areas are among the primary sources of air pollution emissions, continuously affecting the environment [15]. The combustion of fossil fuels releases air pollutants, such as carbon oxides (COx), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM), into the atmosphere [45-48]. To determine the impact of each power plant on the surrounding region, it is necessary to perform precise modeling of pollutant emissions using the geographical and meteorological data of that area. In this research, a point source was used in AERMOD to model pollutant emissions from the Sahand thermal power plant. The cities of Bonab, Ajabshir, and Khoshehmehr, along with their surrounding villages, are located near the Sahand

thermal power plant. This closeness highlights the importance of accurately modeling the pollutant emissions from this power plant to assess its environmental impacts. In this paper, the concentrations of sulfur dioxide, nitrogen dioxide, and carbon monoxide in the vicinity of the Sahand thermal power plant were determined using AERMOD to model pollutant dispersion. Comparing the concentrations of these pollutants with the permissible limits defined in relevant standards reveals the environmental impact of the power plant on the surrounding area. The novelty of this research lies in conducting a realistic and detailed analysis characterized by the following features:

- Development of a detailed AERMOD model based on the specific geometric data of the Sahand thermal power plant chimney, actual pollutant emission rate measurements, two years of meteorological data from the nearest synoptic weather station, and terrain elevation data that accounts for surrounding mountains and the plant's cooling towers.
- Simultaneous dispersion modeling of the three major pollutants (sulfur dioxide, nitrogen dioxide, and carbon monoxide) over four time scales (1-hour, 3-hour, 24-hour, and the annual average).
- Evaluation of the calculated pollutant concentrations in both cities and villages within a 50 km radius of the plant, and comparison of the results with the corresponding limits specified in Iranian national standards and WHO guidelines.

2. Materials and methods

2.1. Dispersion modeling with AERMOD

In this study, the AERMOD software, which is based on the steady-state Gaussian plume model for short-range dispersion (less than 50 km), was used to investigate the dispersion patterns of pollutants emitted from the chimney of the Sahand thermal power plant. The power plant is located in the southwest of East Azerbaijan province, in northwestern Iran (Figure 1).

The geographical coordinates of the Sahand power plant are 589,609 meters east and 4,142,366 meters north, with an elevation of 1,292 meters above sea level. According to the Mercator global coordinate system, it falls within the S38 zone.

The power plant consists of two units operating on a steam Rankine cycle, each with a nominal production capacity of 325 MW.

Table 1 shows the dimensions of the power plant chimney and the properties of the released gases. The release rate of pollutant gases (in grams per second) was calculated using measured mass concentration (in grams per cubic meter) and the total volumetric flow rate.

The total volumetric flow rate of exhaust gases was obtained by multiplying the measured velocity of exhaust gases by the cross-sectional area of the chimney outlet. The properties of the exhaust gases were measured by the Iranian Department of Environment (DOE) using a Testo combustion gas analyzer under ambient conditions of 10°C and 86.35 kPa. During the measurement period, Unit 1 of the power plant operated on liquid fuel to produce 260 MW of electricity, while Unit 2 was undergoing scheduled maintenance.

In this study, the Sahand thermal power plant was modeled as a point emission source within a square domain with a side length of 35.9 km.

The computational domain includes 129,600 receptors arranged orthogonally in a 360×360 grid, with a spacing of 100 meters between receptors.

Table 1. Characteristics of the power plant chimney and the emission rate of released gases.

Chimney height (m)	Chimney diameter (m)	Exhaust gas temperature (°C)	Exhaust gas velocity (m/s)	Release rate of SO_2 (g/s)	Release rate of NO_2 (g/s)	Release rate of CO (g/s)
200	4.5	151.5	27.84	1460.3	86.33	2.08

Fig. 1. Location of the Sahand thermal power plant.

To model pollutant emissions, it is essential to consider not only the characteristics of the emission source but also the ground effects and meteorological conditions of the study area. The required meteorological parameters include wind speed and direction, dry-bulb temperature, humidity, pressure, cloud cover, and rainfall. As mentioned earlier, meteorological data processing in AERMOD is performed using the AERMET preprocessor. AERMET uses meteorological data and land surface characteristics to calculate intermediate parameters such as Albedo, Bowen ratio, and surface roughness for each receptor. The average values of Albedo, Bowen ratio, and surface roughness calculated for the study area over two years were 0.18, 0.75, and 0.065, respectively. AERMET then computes atmospheric boundary layer parameters, including the friction velocity, Monin-Obukhov length, convective velocity scale, temperature scale, mixing height, and surface heat flux. Boundary layer parameters are subsequently used to generate vertical profiles of wind speed, lateral and vertical turbulence fluctuations (σ_v, σ_w), potential temperature gradient ($d\theta/dz$), and potential temperature (θ) within the AERMOD model [49]. Also, the AERMAP preprocessor uses WGS84 elevation data to evaluate the effects of terrain height and determine the spatial relationship between the pollutant emission source (i.e., power plant chimney location) and each receptor.

The following assumptions were adopted in this modeling process: temporal independence of emissions, absence of interactions among different emission sources, and no reduction in pollution concentration due to chemical interactions, absorption, or sedimentation. Also, the calculated pollutant concentrations for each receptor represent the maximum values over the averaging periods of 1-hour, 3-hour, 24-hour, and annual average.

In this research, meteorological data from the Bonab synoptic meteorological station, provided by the Iranian Meteorological Organization, were used for the period 2020/12/21 to 2022/12/22. These data were collected at 3-hour intervals and include wind speed and direction, temperature, humidity, pressure, cloud cover, and rainfall for all days. The processed results from the AERMET preprocessor indicate that the prevailing wind direction during these two years was predominantly from east to west (Figure 2).

3. Results and discussion

The results of the dispersion modeling for sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO) pollutants are presented in Figures 3 to 5, respectively. These figures illustrate the highest concentrations of pollutants recorded at all receptors located in the vicinity of the Sahand thermal power plant during the two-year simulation period. For each pollutant, the maximum concentration values were calculated

using four averaging periods, i.e., 1-hour, 3-hour, 24-hour, and annual average, which are denoted as (a), (b), (c), and (d) in the figures, respectively.

According to the Iranian ambient air quality standard [50], the permissible limits for the maximum concentrations of sulfur dioxide, carbon monoxide, and nitrogen dioxide gases in various averaging periods are as follows:

- Sulfur dioxide: 196 $\mu g.m^{-3}$ in a 1-hour period and 395 $\mu g.m^{-3}$ in a 24-hour period,
- Nitrogen dioxide: 200 $\mu g.m^{-3}$ in a 1-hour period and 100 $\mu g.m^{-3}$ as an annual average,
- Carbon monoxide: 40 $mg.m^{-3}$ in a 1-hour period and 10 $mg.m^{-3}$ in an 8-hour period.

On the other hand, the World Health Organization recommends the following criteria for these pollutants [51]:

- Sulfur dioxide: 40 $mg.m^{-3}$ in a 24-hour period,
- Nitrogen dioxide: 200 $\mu g.m^{-3}$ in a 1-hour period, 25 $\mu g.m^{-3}$ in a 24-hour period, and 10 $\mu g.m^{-3}$ as an annual average,
- Carbon monoxide: 35$mg.m^{-3}$ in a 1-hour period, 10 $mg.m^{-3}$ in an 8-hour period, and 4 $mg.m^{-3}$ in a 24-hour period.

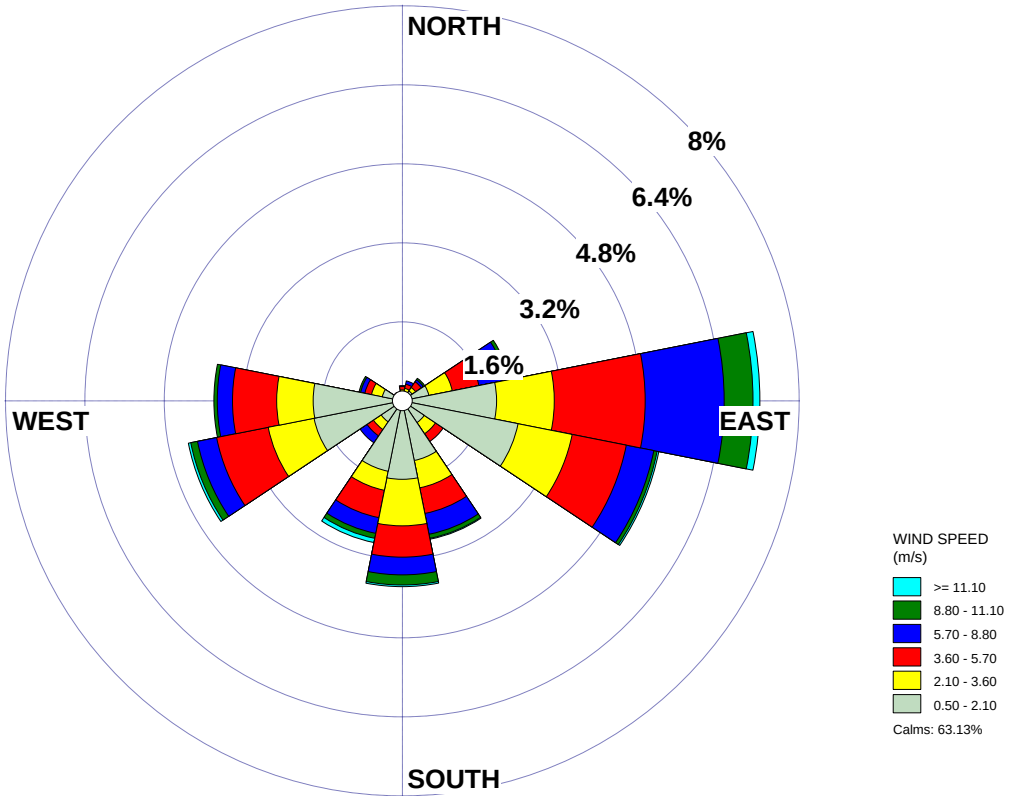

Fig. 2. Wind rose diagram of the study area.

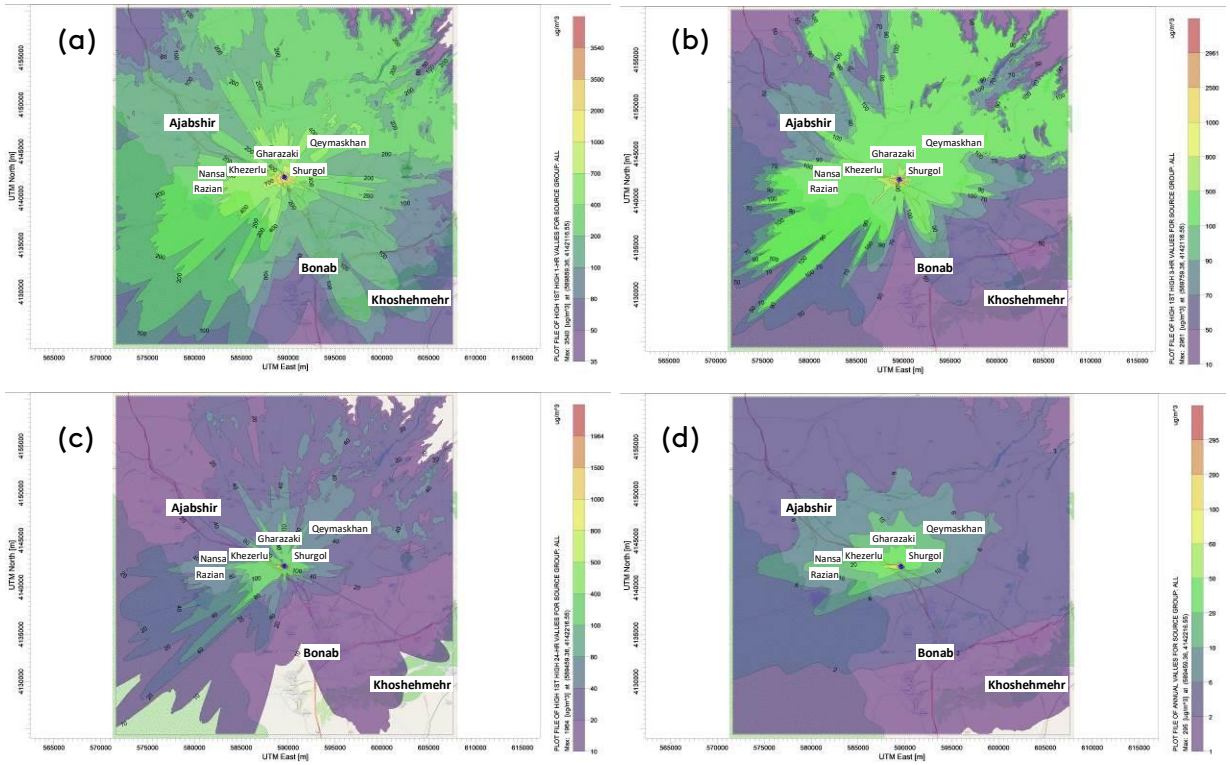

Fig. 3. Highest SO_2 concentration in different periods: (a) 1-hour, (b) 3-hour, (c) 24-hour, and (d) annual average.

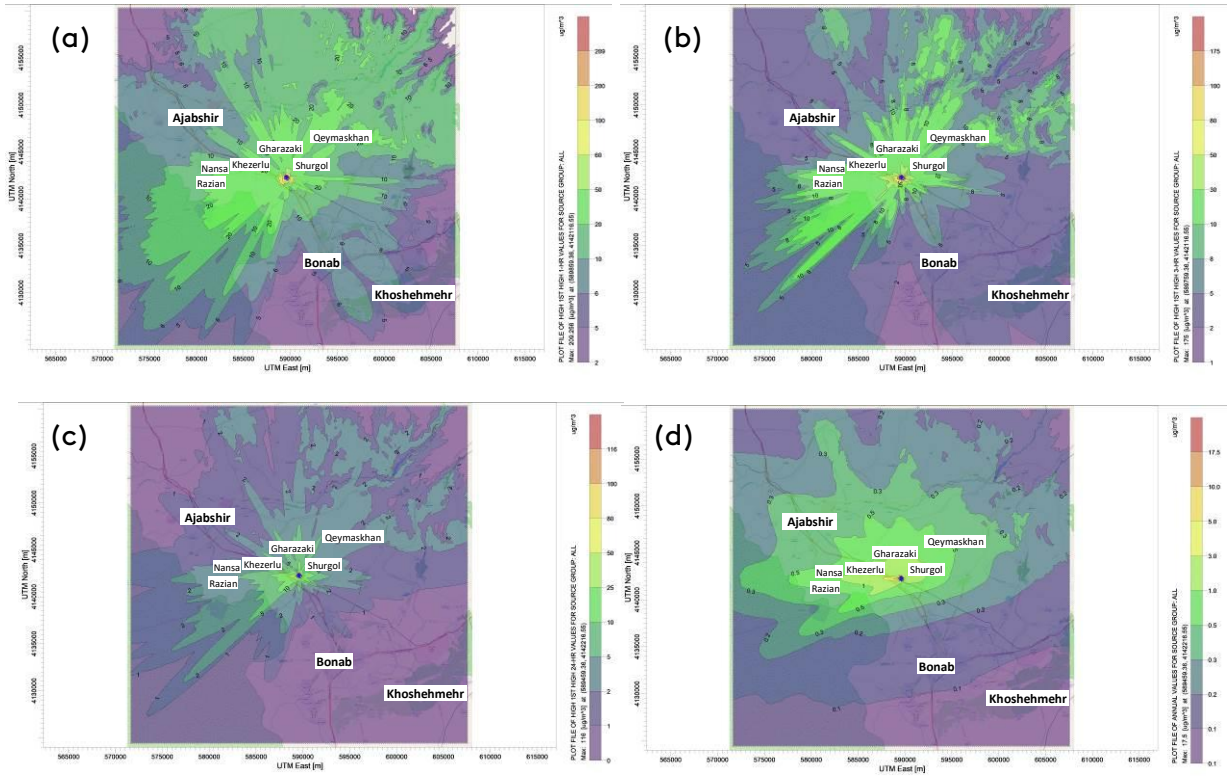

Fig. 4. Highest NO_2 concentration in different periods: (a) 1-hour, (b) 3-hour, (c) 24-hour, and (d) annual average.

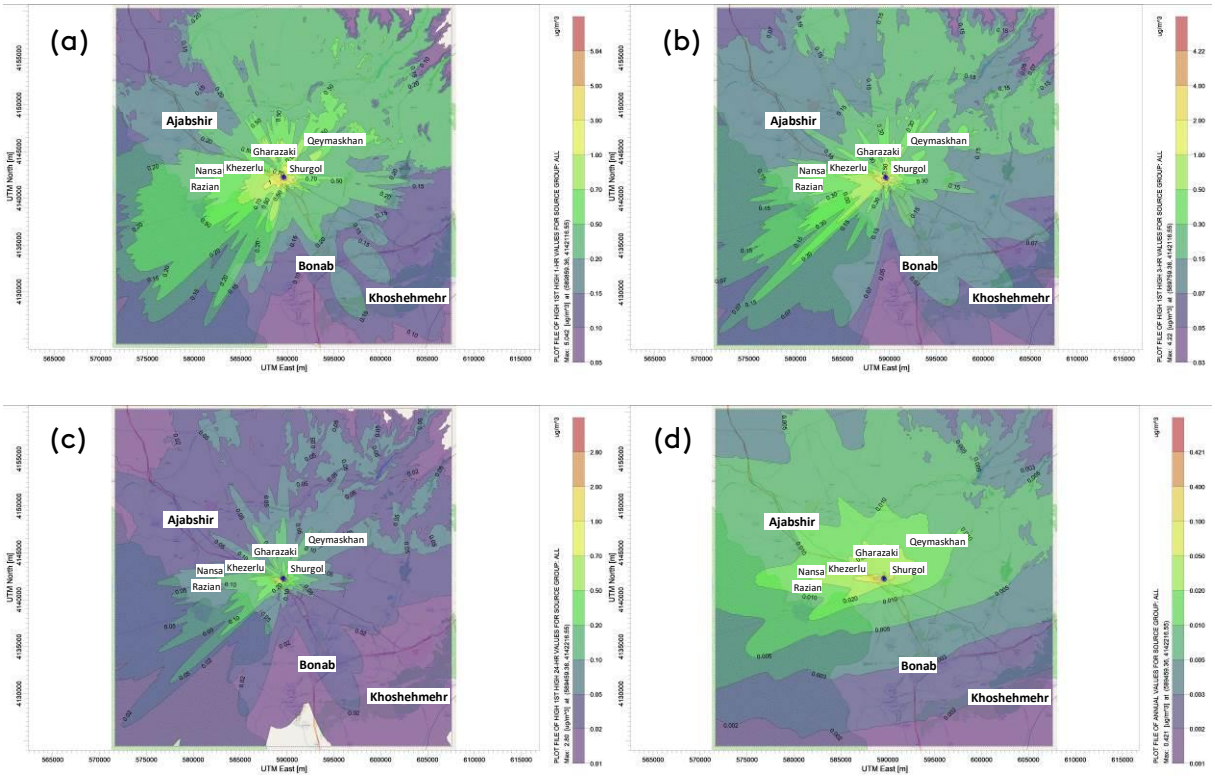

Fig. 5. Highest CO concentration in different periods: (a) 1-hour, (b) 3-hour, (c) 24-hour, and (d) annual average.

According to the modeling results, the highest 1-hour concentration of sulfur dioxide is 3539.63 $\mu g.m^{-3}$ (Figure 6a), the highest 1-hour concentration of nitrogen dioxide is 209.25 $\mu g.m^{-3}$ (Figure 6b), and the highest 1-hour concentration of carbon monoxide is 5.04 $\mu g.m^{-3}$ (Figure 6c). All three maximum concentration points are located within the Sahand power plant site, approximately 100–139 meters from the emission source (chimney). The presence of large structures near the chimney, such as the cooling towers, induces turbulence, leading to downwash effects that increase pollutant concentrations near the ground. According to these results during a 1-hour averaging period, the maximum concentration of sulfur dioxide is approximately 18 times higher than the Iranian standard, the maximum concentration of nitrogen dioxide is about 5% higher than both the Iranian and WHO limits, and the maximum concentration of carbon monoxide is 7000 times lower than the permissible limit of the WHO and 8000 times lower than the limit of Iranian standard.

The following presents and compares the calculated concentrations of pollutants emitted from the Sahand thermal power plant for densely populated residential areas adjacent to the plant with the criteria specified in both the Iranian and the WHO standards.

1-hour averaging period:

The maximum 1-hour concentration of sulfur dioxide (Figure 3a) was below 196 $\mu g.m^{-3}$ (the Iranian 1-hour limit) in all nearby cities of the Sahand power plant (Bonab, Ajabshir, and Khoshehmehr). However, in several nearby villages, the sulfur dioxide concentration exceeded this limit, reaching up to twice the limit in Qeymaskhan, Khezerlu, Nansa, and Nabrin, and up to three times the limit in Shurgol and Gharazaki. According to the 1-hour distributions of nitrogen dioxide and carbon monoxide in Figures 4a and 5a, respectively, the maximum concentrations of both pollutants outside the power plant were below the permissible limits set by both the Iranian and WHO standards.

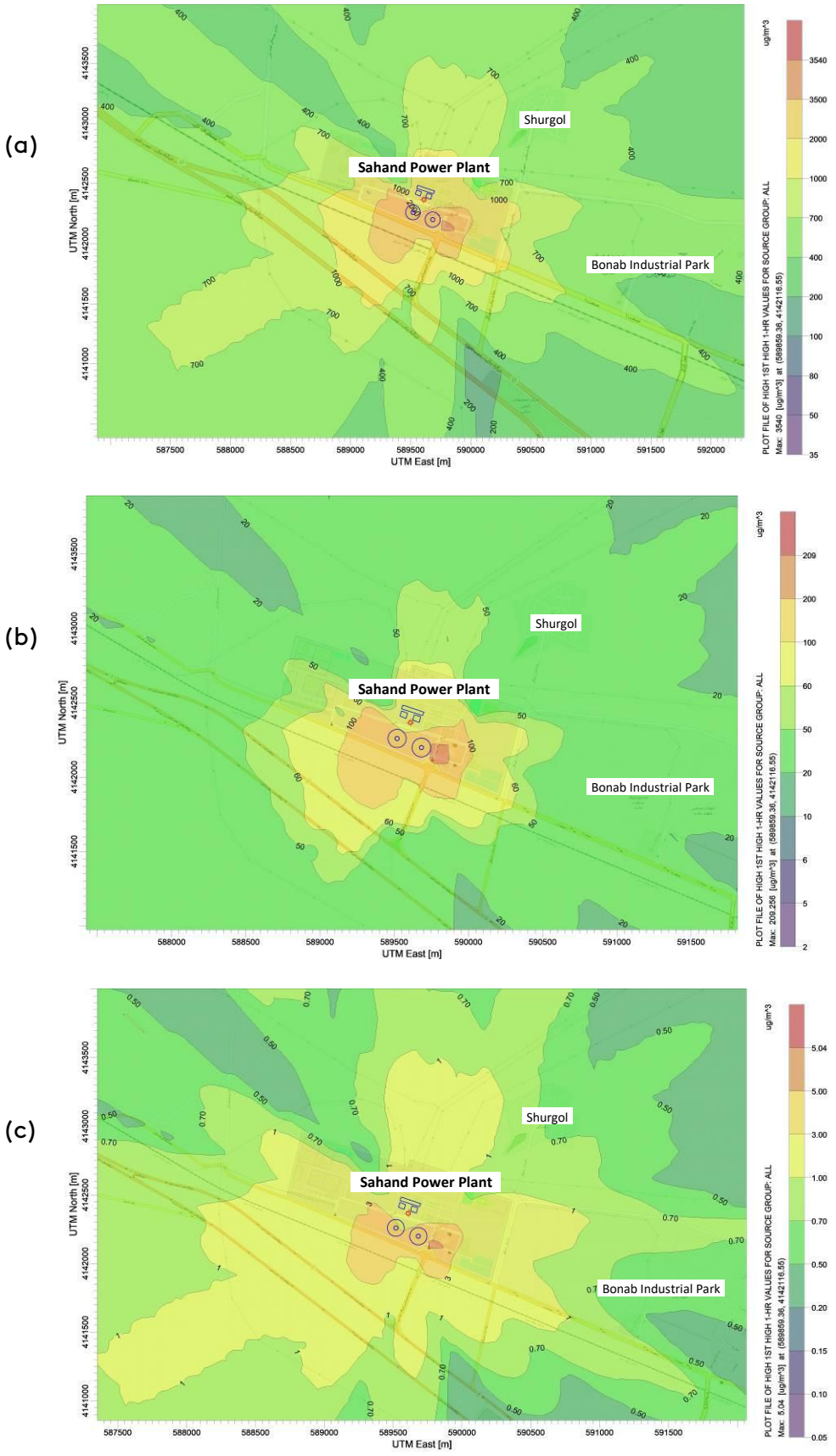

Fig. 6. The location of the highest 1-hour pollutant concentrations: (a) sulfur dioxide, (b) nitrogen dioxide, and (c) carbon monoxide.

In the cities of Bonab, Khoshehmehr, and Ajabshir, the concentrations of nitrogen dioxide ranged from 5 to 10 $\mu g.m^{-3}$, which is approximately 20 times lower than the permissible limit. Additionally, the concentrations of carbon monoxide ranged from 0.3 to 0.5 $\mu g.m^{-3}$ in the above-mentioned cities, significantly below the corresponding thresholds.

3-hour averaging period:

Figures 3b, 4b, and 5b illustrate the maximum concentrations of sulfur dioxide, nitrogen dioxide, and carbon monoxide over a 3-hour averaging period, respectively. The highest concentration of sulfur dioxide was below 100 $\mu g.m^{-3}$ in the cities of Bonab, Khoshehmehr, and Ajabshir, but increased to 500 $\mu g.m^{-3}$ in the Shurgol village. Also, the highest concentration of nitrogen dioxide ranged from 2 to 6 $\mu g.m^{-3}$ in the nearby cities of the Sahand power plant. Finally, the maximum carbon monoxide concentration was 4.22 $\mu g.m^{-3}$ across the entire modeling domain.

24-hour averaging period:

Figure 3c shows that the maximum 24-hour averaging concentration of sulfur dioxide remained below 40 $\mu g.m^{-3}$ (the WHO limit) in all the cities surrounding the power plant. However, in several villages (Shurgol, Gharazaki, Khezerlu, Nansa, Nabrin, and Razian), it rose to about 180$\mu g.m^{-3}$, which was still lower than the Iranian limit of 395 $\mu g.m^{-3}$. The maximum concentration of nitrogen dioxide (Figure 4c) in all cities and villages around the power plant was below 25 $\mu g.m^{-3}$, satisfying the WHO standard. Additionally, the highest 24-hour concentration of carbon monoxide (Figure 5c) was 2.8 $\mu g.m^{-3}$, well below the WHO limit.

Annual average:

The annual average concentration of sulfur dioxide (Figure 3d) in the cities of Bonab and Khoshehmehr was below 3 $\mu g.m^{-3}$, while in Ajabshir, it ranged between 5 and 8 $\mu g.m^{-3}$. In Shurgol village, the sulfur dioxide concentration increased to 35$\mu g.m^{-3}$. The annual average concentration of nitrogen dioxide (Figure 4d) was below 10 $\mu g.m^{-3}$ (the WHO limit) in all nearby cities, though it reached up to 40 $\mu g.m^{-3}$ in some villages, still below the Iranian standard limit. Furthermore, the highest concentration of carbon monoxide in all the areas surrounding the Sahand power plant was 0.4 $\mu g.m^{-3}$, far below the permissible levels in both standards.

4. Conclusion

In this research, the dispersion of pollutant gases emitted from the Sahand power plant chimney was modeled using AERMOD software. The maximum concentrations of the sulfur dioxide, nitrogen dioxide, and carbon monoxide in the different averaging periods (1-hour, 3-hour, 24-hour, and annual average) were calculated for 129600 receptors arranged orthogonally with a spacing of 100 m. The modeling domain covered the cities of Bonab, Ajabshir, and Khoshehmehr, along with their surrounding villages. Comparison of the simulated results with the environmental standards of Iran and the WHO revealed the following findings:

- Sulfur dioxide concentrations in all surrounding cities were below the limits set by both the Iranian and WHO standards for the 1-hour and 24-hour averaging periods. However, in several nearby villages, the highest 1-hour concentration of sulfur dioxide exceeded the Iranian limit, reaching up to three times the standard value. In the 24-hour averaging period, the sulfur dioxide concentrations in all villages were below the Iranian limit, although in some villages close to the power plant, they reached 4.5 times the WHO limit.
- Nitrogen dioxide concentrations were below both the Iranian and WHO standards for the 1-hour averaging period and below the WHO limit for the 24-hour averaging period. The annual average concentration of this pollutant in the cities surrounding the plant remained within the WHO limit. However, it reached up to four times the WHO limit in some villages, remaining below the Iranian limit.
- Carbon monoxide concentrations across the entire modeling domain were well below both Iranian and WHO limits in 1-hour and 24-hour averaging periods.

Overall, the findings indicate that among the pollutants emitted from the chimney of the Sahand thermal power plant, sulfur dioxide poses the greatest potential health risk to nearby residents,

particularly in the surrounding villages. To reduce sulfur dioxide concentration in nearby villages, the emission of this pollutant can be mitigated by switching from liquid fuel to natural gas or by using a mixture of liquid fuel and natural gas. This approach would decrease the amount of sulfur dioxide released and consequently its ambient concentration.

Furthermore, it is possible to optimize fuel type management based on meteorological conditions and prevailing wind directions, thereby minimizing the impact of emissions on nearby residential areas.

For future studies, it is recommended to extend the modeling to include pollutant emissions from other industrial sources located in the Bonab industrial park, which lies adjacent to the Sahand power plant.

This approach would enable a comprehensive assessment of the cumulative air pollution impacts in the region.

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Author's contribution

Mahdi Saghafi: conceptualization, literature research, methodology, visualization, supervision, writing, reviewing, and editing. Ali Hajiabdollahi Mamaghani: conceptualization, data curation, modeling, visualization, writing. All the authors reviewed the manuscript before submission.

Conflict of interest

No potential conflict of interest was reported by the authors.

Data availability

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