AERMOD AIR DISPERSION MODELING AND HEALTH RISKS OF GAS AND OIL FUELED HEATING PLANT EMISSIONS

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A significant part of the population in Serbia relies on central heating systems during the winter months, with around fifty heating plants in operation across the country. Common fuels used in these plants primarily include fossil fuels such as fuel oil and natural gas. Combustion of some of these fuels leads to significant emissions of air pollutants. This study evaluates the impact on the air quality of the two heating boilers at the Valjevo city (Serbia) heating plant. Air emissions were measured separately for two heating boilers in the facility using standard reference methodology. The AERMOD air dispersion model was used to estimate the dispersion of various pollutants. A combination of topographical and meteorological data was used to set up a receptor grid exposed to air pollution within a 10 km radius around the heating plant. It was found that the resulting distribution and concentration gradient of pollutant gases and particles were less inclined towards the city centre and instead spread eastwards into the surrounding villages. The health risk from the fuel oil boiler was shown to be significantly higher than that caused by the natural gas-fuelled boiler. Nevertheless, the calculated carcinogenic and non-carcinogenic health risks were within acceptable limits. However, further research is required to adequately assess the cumulative health risk generated by other surrounding emitters.

Key words: *AERMOD, hazard index, air emission, carcinogenic, stack, exposure*

1. Introduction

District heating systems are widely used during winter as an efficient means of generating and distributing heating energy. Depending on the number of households served in the corresponding urban area, these systems are usually powered by one or multiple heating plants. One big downside concerning district heating systems is their heavy reliance on fossil fuels at a time where CO_2 emission reduction is encouraged. These include natural gas, heating oil, coal, and more environment-friendly alternatives such as biomass or refuse. Another issue with district heating systems is their proximity to the urban areas they provide heating energy for. Studies have shown that their detrimental contribution to air and land pollution is significant [1]. Despite this, district heating has a net less harmful environmental impact than local heating solutions [2].

District heating plants in Serbia started operating about half a century ago. Currently, around fifty heating plants are operating across the country to accommodate the heating needs of the ever-increasing urban population of the country. Unfortunately, the centrally and often inefficiently planned city layouts and infrastructure during the latter half of the 20th century meant that many cities in the country were left with power and heating plants positioned alarmingly close to the respective city centres and residential areas. The Valjevo heating plant is not an exception to this.

A positive trend that has been present in the past fifty years in Europe and since the 21st century in Serbia is the transition from fuel oil-based heating plants and boilers to natural gas. The environmental footprint of combusted natural gas emissions is considered to be significantly lower than that of fuel oil. However, little research has been done to determine the environmental and health benefits of switching from oil to natural gas fuelling. In that regard, the Valjevo heating plant was an ideal testing ground for this study. Since 2019, the plant has been operating two heating boilers, one fuelled by fuel oil (mazut) and the other by natural gas. Even though coal is still used in some heating plants in Serbia and still remains a primary source of air pollution around the globe, it was omitted from this study as this heating plant does not use coal as a fuel.

The aim of this study is twofold. Firstly, based on the measured emission data, ground-level concentration maps of the various pollutants will be created, and health risk will be evaluated at certain chosen sampling points located in the densely populated city centre. Secondly, and per the previous discussion, the impact on public health and air quality will be compared based on the fuel being used. Several studies were done using various air dispersion models and on-site measurements or estimated emission data [3, 4], though mainly evaluating industrial emitters [4-9] or power plants [3, 10-15], and some of them omitting health risk assessment altogether [16]. A recent work [17] deals with AERMOD modelled dispersion from natural gas and fuel oil emitters but with a smaller set of pollutants. Significant difference between this and similar studies in the same field of research is the combination of on-site measured data, air dispersion modelling, health risk assessment and comparative analysis between two fuel types. In this work, the emission rates of the individual pollutants were acquired with modern measurement devices at the heating plant. The subsequent concentration distribution was obtained with real meteorological and topological data through air dispersion modelling.

2. Materials and methods

This study was executed in several steps, explained in the following subchapters. Firstly, familiarization with the site area, city layout, as well as the location of the power plant and its characteristics. Afterwards, on-site data had to be obtained by measuring the emission from the respective stacks using appropriate methods and equipment. Based on the data collected, emission rates of multiple pollutants were extrapolated based on EPA emission factors for the fuels that are used at the two stacks. By comparing these emission rates with the reference concentration (RfC) and inhalation unit risk (IUR) values obtained from the Agency for Toxic Substances and Disease Registry (ATSDR) and the Integrated Risk Information System (IRIS) on a per-pollutant basis, sulphur dioxide, arsenic, cadmium and formaldehyde concentrations were determined to have the greatest impact on the health and cancer risk caused by emissions from gas and fuel oil emissions. The emission rates of these selected pollutants were used as input for the AERMOD dispersion model and concentration maps were obtained for the impacted region. Lastly, a methodology for obtaining the health and cancer risks based on the acquired ground concentrations was applied.

2.1. **Description of the studied area and heating plant**

Valjevo is the second-largest city in western Serbia, with an urban population of about 60000. It is the administrative centre of the Kolubara district. It is located (Figure 1) on the estuary of the Kolubara River, which is formed by the Jablanica, Obnica, and Gradac rivers. This creates a valley suitable for urban development amidst extensive mountain ranges, which occupy the city's surroundings. The Medvednik, Jablanik, Povlen, Maljen and Suvobor mountains surround the city. This city has a mild Mediterranean climate and average rainfall amounts throughout the year. Owing to the stark contrast between the river valley and the surrounding mountains, the city experiences relatively strong winds coming from the east.

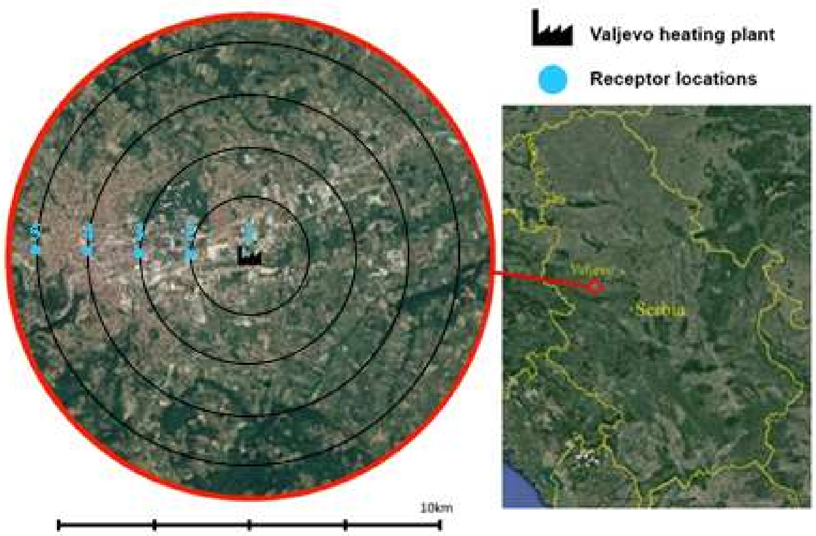

Figure 1. Valjevo heating plant, receptor locations of interest and the surrounding area

The Valjevo heating plant is the largest in western Serbia, with a total capacity of 80 MW of heating energy. It is located in the eastern part of the city. It has two major heating boilers in addition to two 0.29 MW local boilers, which are used for the purposes of the heating plant. The heating gas-fuelled boiler has a heating capacity of 30 MW, a working temperature of 107 ℃ and a working pressure of 9.9 bar. A burner powers it with a variable power that goes from 4 up to 30 MW. The fuel gas-fuelled boiler has a capacity of 50 MW and a working temperature of 130 ℃. Two burners power it with a power of 29 MW. Both boilers operate based on the same principles - fuel is being burned in the boiler stokehole. The generated heat increases the temperature of the water, which is then distributed across the heating system network. Any flue gases are emitted directly into the environment via two 50 m stacks. The surrounding area is sparsely populated to the east, but a dense city centre is just under 3 km away from the heating plant.

2.2. **Flue gas measurement**

On-site flue gas measurements are performed by inserting the sampling probe into the cavity of the emission stack from outside through specially designed sampling ports. In this case, flue gas parameters were thus measured at the height of 20 m from the base of both stacks. The stack diameters of the natural gas and fuel oil boilers at the access points were 1.4 and 1.6 meters. Three measurements of the concentrations and flow rates of the pollutants were taken across five hours simultaneously. During the measurement, the boilers were operating at their default operation modes. Automatic particle and gas analysers were employed for the measurements, and the concentrations were obtained using methods described in Table 1. Similar methods were employed in another paper dealing with the on-site measurement of a heating plant located in Zrenjanin, Serbia [18]. The parameters which were measured include flue gas temperature and flow as well as the concentrations of total particulate matter (TPM), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2).

Table 1. Pollutants, methods, measurement devices and principles

Pollutant/ /Parameter	Methods	Method reference	Devices	Measurement principle
Velocity/flow	ISO 10780	[19]	TCR Tecora Isostack G4	Pitot tubes
O2	EN 14789	[20]	Horiba PG350E	Paramagnetic
CO	EN 15058	[21]	Horiba PG350E	Non-dispersive infrared
NOx	EN 14792	[22]	Horiba PG350E	Chemiluminescence

SO2	ISO 7935	[23]	Horiba PG350E	Non-dispersive infrared
TPM	ISO 9096	[24]	TCR Tecora Isostack G4	Isokinetic sampling

2.3. **Air dispersion modelling**

The EPA recommended AERMOD model was used to model the pollutant dispersion and obtain the ground level concentrations [4-6, 15, 25, 26] of SO_2, arsenic, cadmium and formaldehyde. These specific contaminants were chosen because it was determined that they have the greatest impact on the health risk indices explained later. AERMOD is a steady-state plume model, which simulates air dispersion while considering various factors such as planetary boundary layer turbulence, topography, and surface characteristics of various types of terrain. Figure 2 shows the flow chart for the various input pathways of the AERMOD dispersion model. For the assessment of the ground-level concentrations, five years of meteorological data were obtained from the local weather station. This data includes hourly records of the local temperatures, wind speed and direction, humidity, atmospheric pressure, precipitation, etc. (Table 2). The raw values were pre-processed in the AERMET pre-processor, and usable surface and profile meteorological data were generated.

Table 2. – Valjevo meteorological parameters

	Temperature [°C]	Wind speed [m/s]	Wind direction [degrees]	Humidity [%]	Pressure [kPa]	Precipitation [mm]
Min	-18.8	0	-	13	986	0
Max	39.9	68.1	-	100	1049	278.9
Average	11.5	8.4	207.7	74.8	1021.7	0.14

A total of 40000 ground-level receptors were set up, spanning an area of about 100 square kilometres around the city of Valjevo. These are used for the generation of ground-level concentration maps for all of the pollutants. The area was carefully chosen in order to encompass as much of the inhabited area as possible.
In addition to meteorological data, AERMOD also requires topographical terrain data. For this study, SRTM3 global map data with an average resolution of 90 meters was used. They were pre-processed through the AERMAP pre-processor, and the height data was applied to the whole receptor grid.

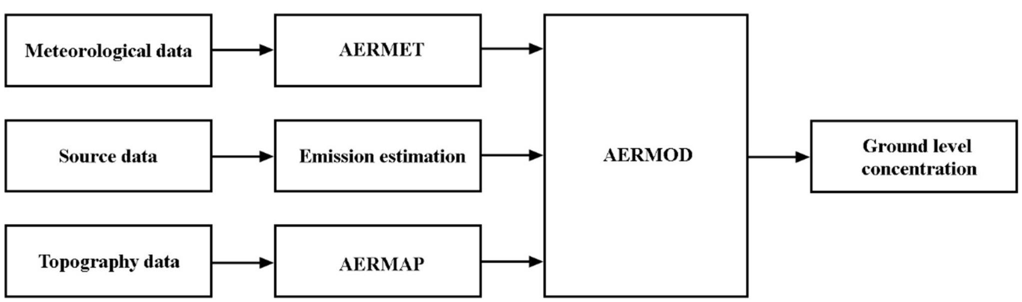

Figure 2. Flow chart showing the AERMOD workflow with the respective input and output pathways

Finally, the measured emission rates were used to estimate the spreading of pollutants. The EPA AP-42 compilation of air emissions factors was used for obtaining the relative emission factors for a number of pollutants [4]. Estimates of the emission factors (Eq. 1). ER_n represents the emission rate of the pollutant, ER_{NOx} is the emission rate of NO_x, EF_n is the emission factor corresponding to the pollutant while EF_{NOx} is the emission factor of NO_x for the given fuel and boiler type. They are based on the on-site acquired NO_x emission rates as these measurements proved to be most consistent across both heating boilers and AP-42 lists NO_x as having a type "A" emission factor rating in our particular case, meaning that it's very reliable for use in calculations. In this way, emission rates of arsenic, cadmium and formaldehyde were obtained, which were essential to assess the health risk.

$$ER_n = (EF_n / EF_{NO_x}) \times ER_{NO_x} \tag{1}$$

The data generated by the various input pathways and pre-processors allows AERMOD to be run. Three distinct emission scenarios were set up: emission by each of the boilers separately, as well as the combined emission of both of the boilers. In each of these scenarios, the emission of TPM, SO_2, arsenic, cadmium and formaldehyde were modelled with both a 1-hour averaging period and an averaging period spanning the whole time period of five years.

2.4. **Health risk assessment (HRA)**

The assessment of the health risk caused by the heating plant is based upon the obtained ground level concentrations of the pollutants, out of which health risk indices are going to be derived – the health index and total cancer risk. In respect to the modelled data, three distinct scenarios were evaluated and the mentioned indices were calculated separately for each of the scenarios. One in which only the fuel oil powered boiler emissions were taken into account, one in which only the gas powered boiler emissions were taken into account and one in which the cumulative emissions were assessed. This would give a good basis for a general health risk assessment and enough data for a comparative analysis between the two fuel sources.

Apart from the measured inorganic gases such as SO_2 and CO, the suspended particulate matter is composed of a wide variety of other elements and compounds. Among these, one can find heavy metals [13, 27], water-soluble substances [28] as well as incompletely combusted hydrocarbons [7, 29]. These are significant contributors to the generated environmental and health risk from heating plants and other combustion-based sources. They can have a noticeable impact on mortality [30] and also increase the carcinogenic risk for the local population.

Five equidistant receptor locations were setup for the purposes of the health risk assessment. The first one is 125 m away from the plant itself, and the remaining 4 points are 1 km away from each other away from the plant. It is to be noted that all of them are located in populated parts of the city but with an increasing distance from the heating plant. The reference concentration (R_fC) values were obtained from a combination of sources, primarily from the Integrated Risk Information System (IRIS) [31]and the Agency for Toxic Substances and Disease Registry (ATSDR)[32].

Individual pollutant Hazard Quotients were calculated through the comparison of the estimated exposure concentrations and the respective reference concentrations (Eq. 2). The hazard index represents the sum of all hazard quotients (Eq. 2) [25].

$$HQ_n = EC_n / R_f C_n \tag{2}$$

$$HI = HQ_1 + HQ_2 + \cdots + HQ_n \tag{3}$$

where EC_n is the exposure concentration of pollutant n, R_fC_n is its reference concentration, HQ_n is its hazard quotient, and HI represents the hazard index. Health index and health quotient values above and around 1 mean that the health of the affected population is significantly impacted by the generated pollution.

Similarly, the cancer risk was evaluated by summing up the individual cancer risk contributions of the individual elements. The individual contributions were obtained as a product of the inhalation unit risk (IUR) and the exposure concentrations of the various pollutants (Eqs. 4-5) [25].

$$CR_n = EC_n \times IUR_n \tag{4}$$

$$CR = CR_1 + CR_2 + \cdots + CR_n \quad (5)$$

Where EC_n is the exposure concentration of pollutant n, IUR_n is the inhalation unit risk, CR_n is the individual cancer risk, and CR is the total cancer risk. Cancer risk values above the 1×10^{-6} threshold mean that the carcinogenic potential of the inhaled pollutants can be considered significant.

It is to be noted that both the hazard index and the cancer risk are cumulative values dependent on the number of pollutants that were considered for the health risk assessment. Thus it is difficult to calculate an all-encompassing value without considering all possible pollutants. In this study, NO_x, arsenic, cadmium, and formaldehyde were found to have the most significant impact and are thus the pollutants modelled and factored into the calculations.

3. Results and discussion

3.1. Emission data of the studied heating plant

Both stacks were monitored during the heating season while at full capacity. Following the specified methods, concentrations of the various pollutants in flue gas were obtained. Together with the measured exhaust gas flow rates and the stack diameter, their emission rates were calculated. It is to be noted that the measured concentrations of TPM and SO_2 emitted by the natural gas-powered boiler were lower than the method detection limit. Thus, it was estimated that their concentrations were approximately equal to half the limit of detection. The emission rates for the natural gas-powered boiler were calculated to be 115 g/h and 2499 g/h for CO and NOx, respectively. For the fuel oil-powered boiler, the emission rates are as follows: 507 g/h for CO, 8449 g/h for NO_x, 23049 g/h for SO_2 and 6253 g/h for TPM.

The obtained emission rates are in line with existing studies that focus on air dispersion modelling from thermal plants in particular [14, 15]. However, the measured values are slightly lower than in the mentioned studies because the Valjevo heating boilers have a significantly lower heating capacity.

Based on the emission data obtained on site, and based on the emission factors mentioned in section 2.3, emission rates were determined for a wide range of pollutants. Out of these, As, Cd, HCHO were found to have the most significant impact on the air quality (Table 3) and, accordingly, on the non-cancer and cancer risks involved.

Table 3. Emission rates of main pollutants (g/h)

Pollutant	Gas boiler	Fuel oil boiler
SO_2	107	23049
As	0.0196	0.0720
Cd	0.00357	0.24
HCHO	1.34	5.97

3.2. Evaluation of the modelling results

The obtained meteorological, topological, and emission rate data were used as input parameters for the air dispersion model. The resulting wind rose generated by AERMET shows that the most severe winds were coming from the western direction (Figure 3).

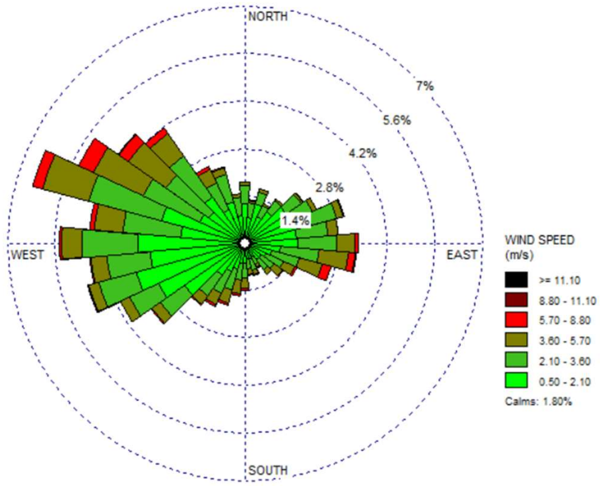

Figure 3. Valjevo wind rose

The obtained ground-level pollutant distributions were in accordance with this. Figure 4 shows the ground level distribution of the emitted particulate matter, and the dispersion maps of the other pollutants have a similar pattern. The relatively tall stack heights of 50 m combined with the strong west winds ensure that the city's urban part is spared from the brunt of the polluting fumes. The area with the highest pollution is next to the power plant itself, which is located in the sparsely populated industrial area in the eastern part of the city. The moderately polluted area reaches the west half of the city centre due to the occasional east winds and also encompasses the more sparsely populated "Novo Naselje" eastern part of the city. About two-thirds of the total particles are carried in the southeastern direction towards the village of Beloševac and the mountainous region on the southern edge of the city.

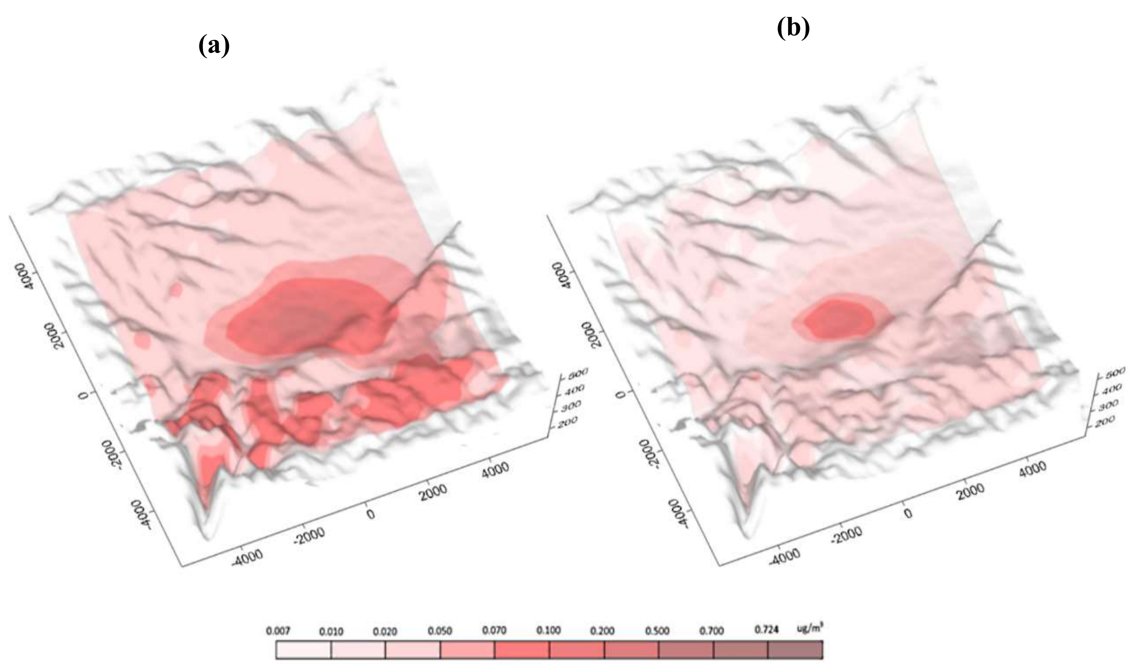

Figure 4. TPM ground level distribution emitted by (a) fuel oil-fuelled boiler and (b) natural gas-fuelled boiler

Due to extremely low emission rates of SO_2, the natural gas boiler emitted ground-level pollution is almost non-existent compared to the fuel oil boiler concentrations. Similar patterns can be observed for the other pollutants, signifying the significantly lower pollution footprint generated by the natural gas-fuelled boiler. The resulting health risks were proportionally more minor, which will be further explained in the following sections of this study. Compared to similar studies featuring thermal plants [14, 15], the observed pollution levels are slightly smaller, again owing to the smaller heating capacity of the Valjevo heating plant. At all receptor locations, estimated sulphur dioxide ground-level concentrations attributed to the emission from this plant never exceeded 0.254 $\mu g/m^3$, which is still below the limit value set by national regulations[33, 34]. The estimated ground-level concentrations of sulphur dioxide emitted by the natural gas boiler were consistently around 200 times lower than that of the fuel oil boiler. Even considering the smaller heating capacity, this shows a remarkable reduction in pollutant emissions and concentrations.
Results obtained for the remaining pollutants (arsenic, cadmium, formaldehyde) showed similar trends. Due to their emitted concentrations being extrapolated via respective emission factors and AERMOD using similar modelling equations for non-standard pollutants, the ground level concentration distributions were similar. Again, most of the pollution was carried eastward onto the suburbs and industrial zone of the city. The ground-level concentrations of these pollutants were far below the values set by regulatory guidelines.

3.3. **Non-carcinogenic health risk**

In accordance with the all-around lower pollutant concentrations emitted by the natural gas-fuelled boiler, the health risk is equally lower (Table 4). The four most significant contributors to the hazard index were determined to be arsenic, cadmium, formaldehyde and SO_2, with SO_2 being the main contributing pollutant for the fuel oil boiler and cadmium being the main contributing pollutant for the natural gas boiler. The resulting calculated HQs show no significant long-term health risk in a diameter of 10 km around the city, as all the hazard indices are considerably smaller than 1. However, contributions from other emitters in the city could cumulatively cause concern. In addition, the transition from fuel oil being the only energy source to natural gas has had a considerable impact on health risk. Hazard indices tend to be 1-2 orders of magnitude lower when natural gas is used as the primary fuel.

Table 4. Hazard index values at the receptor locations

	1	**2**	**3**	**4**	**5**
Fuel oil	9.34×10^{-3}	8.00×10^{-3}	3.57×10^{-3}	2.33×10^{-3}	1.67×10^{-3}
Natural gas	1.04×10^{-4}	8.36×10^{-5}	4.02×10^{-5}	2.66×10^{-5}	1.94×10^{-5}

The individual pollutant contributions to the hazard index on a per-boiler basis are shown in Figure 5.

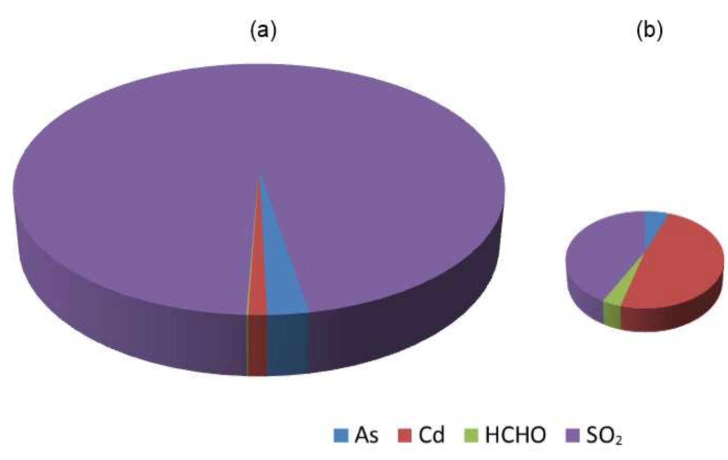

Figure 5. Hazard index contributions of the various pollutants emitted by the (a) fuel oil boiler and (b) natural gas boiler

In comparison to similar studies [12], the observed health risk was comparable but slightly lower because the power plant has a slightly smaller heating capacity. Generally, the health risk estimates surrounding heating plants are significantly smaller than those generated by coal power plants [25] though still not negligible.

3.4. **Carcinogenic health risk**

Arsenic, cadmium, and formaldehyde were found to be the pollutants that have the greatest cancer risk contributions. SO_2 does not have an inhalation unit risk and thus was not evaluated. Arsenic is the pollutant with the largest cancer risk contribution, followed by cadmium and formaldehyde. The total cancer risk for the pollutants considered is significantly smaller than the 1×10^{-6} threshold (Table 5). Similar to the hazard quotient, the risk produced by the natural gas boiler is one order of magnitude lower than that produced by the fuel oil boiler. Therefore, it can be concluded that the area around the heating plant has a low cancer risk when only the contribution from the plant itself is considered. A more comprehensive study is required to assess the cumulative influence of other polluting emitters in the Valjevo industrial zone. In addition, other carcinogens not covered by this study would also have to be taken into account.

Table 5. Cancer risk values at the receptor locations

	1	**2**	**3**	**4**	**5**
Fuel oil	1.69×10^{-8}	1.82×10^{-8}	8.90×10^{-9}	6.04×10^{-9}	4.50×10^{-9}
Natural gas	1.75×10^{-9}	1.34×10^{-9}	6.86×10^{-10}	4.60×10^{-10}	3.39×10^{-10}

Similar to the non-carcinogenic health risk assessment results provided previously and similar to results reported by Shaikh et al. (2018), the carcinogenic health risks obtained were far below any level that would cause concern.

4. Conclusion

Based on the obtained concentration maps, and as a result of the local meteorology and observations of the wind rose, it can be said that due to strong east and northeast winds, the bulk of the pollutants is carried away from the populated city centre. Still, there remains a non-negligible amount of pollution around the thermal plant. However, only 375 meters away (based on the data from receptor point 3), the health risk decay by around 50 percent. Risk assessments reveal with high certainty that natural gas-fuelled boilers present a significantly lower risk to the human health of the population exposed to their emissions than fuel oil boilers. However, it also needs to be pointed out that the obtained hazard risks by no means represent a finite hazard risk that the population in Valjevo is subjected to, neither by the emissions from the heating plant nor in general. Various other pollutants would be necessary to consider getting a more accurate understanding of the actual health risk in the investigated area. In addition, other emitters, which are present in the industrial zone of Valjevo, would also have to be considered. Nevertheless, this study provides valuable insight into the relative health risk generated by the studied heating plant. Furthermore, it points out the significance of switching from heavier fuels such as fuel oil to natural gas in pursuit of a greener and more environment-friendly solution to the heating demands of a mid-sized city. Finally, it is of note that the air pollution and health risk caused by the thermal plant would be cut by almost a factor of ten if the fuel oil boiler was to be replaced with natural gas powered one.

Acknowledgements

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