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Air pollution levels at an area under energy transition (Western Macedonia, Greece).

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Abstract. In the lignite basin of Western Macedonia, Greece, the lignite long-lasting exploitation and the mining activities have an impact on the environment and air quality. In this study, we focus on the air quality in the cities of Kozani, Kastoria, Grevena and Florina in Western Macedonia, Greece to assess the levels of air pollutants concentrations and investigate their variations at different timescales. The particle pollution in the region exhibits seasonality patterns associated with the weather conditions and the local emissions sources. As for the ozone pollution in the region, there is a minor number of alert days that exceed the European Union (EU) limit value, but ozone concentrations are high based on World Health Organization (WHO) standards. Also, we evaluate the air quality through the Air Quality Health Index (AQHI) which is a health risk-based air pollution index. We concluded that the majority of days found in the category of "moderate" health risk associated with the air quality, while for a small number of days the relevant health risk is "high".

1 Introduction

In Greece, significant lignite reserves are located in the region of Western Macedonia where the country's major coal-fired power plants operate. This region is largely dominated by lignite mining activities and lignite power plants electricity production, that are an important part of the country's economy and have established the region as Greece's energy hub for decades [1-9]. Studies have shown that there are declining trends in rock excavations and lignite production which are mainly consequences of the energy transition towards climate neutrality and decommissioning of lignite power units [3]. However, Western Macedonia is an area burdened by environmental hazards due to lignite long-lasting exploitation [1-7].

The ambient air quality of the region has been studied by the data of a dense network of monitoring stations. Based on these data on air pollutants' concentrations and meteorological variables, many researchers have investigated the relationship between ambient air quality deterioration and surface mining, lignite power plants and related activities [1-7]. The different characteristics of the emission sources, the lignite mining processes, the lignite-fired power plants, the biomass burning and heating systems in correlation the local meteorological conditions affect the air pollution in the region [1-7]. On the other hand, the lignite phase-out plan for power generation, contribute to the decreasing trends of PM levels over the last decade [1,3,9]. An examination of the long-term changes in the background concentrations in an agricultural monitoring station in the region revealed a statistically significant decreasing annual trend of PM_{10} concentrations due to the air quality improvement of the region in the last decade [8].

The air quality in the region has also been assessed through the European Air Quality Index (EAQI) based on measurements on PM_{10} [7]. The analysis showed that the air quality for the majority of the days classified as 'good' or 'fair' and a small number of days at specific locations classified as "extremely poor' [7]. As for the health impact of air pollution on the region, researchers investigated the health conditions of lignite miners and residents concluding that the exposure to particle pollution is a risk factor for respiratory system tract infections [9].

In this study, we investigate the air quality in the cities of Kozani, Kastoria, Grevena and Florina in Western Macedonia based on air pollutants' concentrations and meteorological data from the National Air Pollution Monitoring Network. The research objectives are: (1) to identify the temporal and spatial distribution of $PM_{2.5}$, PM_{10}, CO, NO, NO_2, NO_X, O_3 and SO_2 concentrations; (2) to calculate the Air Quality Health Index (AQHI).

2 Data and Methodology

2.1. Study area

The region of Western Macedonia, located in North-western Greece, is divided into the regional units of

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Florina, Grevena, Kastoria, and Kozani. At the Kozani–Ptolemaida–Amyntaio–Florina axis in this region, it is located one of the major geologic lignite reserves in the country that is exploited for energy purposes (Figure 1).

The operations regarding the extraction and use of lignite in thermal power plants began in September 1956. So, for decades, the majority of the electricity production in Greece and especially in Northern Greece is covered from the exploitation of lignite deposits of Western Macedonia. As an example, in the years 2001–2004, the lignite production in Western Macedonia exceeded 55 million tons per year [5].

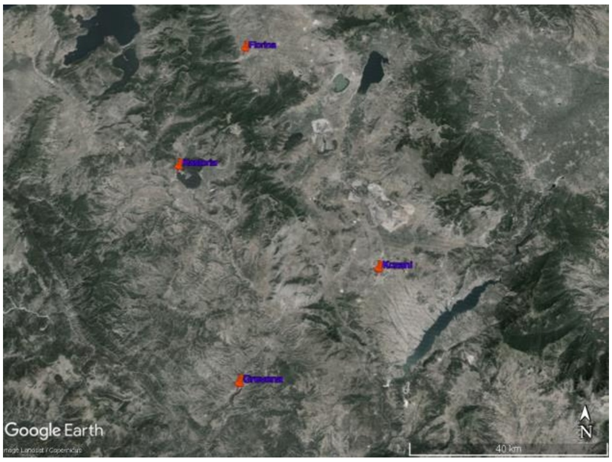


Figure 1. Location of the cities of Kozani, Kastoria and Grevena in Western Macedonia [10]

2.2 Data and statistical analysis

We analyzed the concentrations of $PM_{2.5}$, PM_{10}, CO, NO, NO_2, NO_X, O_3 and SO_2 and meteorological variables (temperature, relative humidity, wind speed and direction) at four cities in Western Macedonia (Figure 1). The data from the cities of Kozani, Kastoria and Grevena covers the period from 1 January 2023 to 31 December 2023, while the data from the city of Florina covers the period from 1 January 2022 to 19 February 2023.

To investigate the impact of air quality (in terms of $PM_{2.5}$, NO_2 and O_3 concentrations) and the related health risk in the population of Kozani, Kastoria and Grevena, the Air Quality Health Index (AQHI) was used. The AQHI is a widely used index in Canada to inform the public about the human health risks posed by air pollution [11]. The AQHI is expressed on a scale from 1 to 10+ and associated with four categories of health risk: low; moderate; high; and very high (Table 1). In each category, there are specific health messages for both vulnerable groups and general population about potential health effects and recommendations to reduce personal exposure and relevant information [11]. The AQHI has also been used for the assessment of air quality in Rhodes Island, Greece [12].

Based on Yao et al., 2020 [11], the AQHI was calculated using the Equation 1, where NO_2, O_3, and $PM_{2.5}$ are the measurements of the NO_2, O_3, and $PM_{2.5}$ concentrations.

$$AQHI = \frac{10}{10.4} * (100 * (e^{0.000871*NO_2} - 1 + e^{0.000537*O_3} - 1 + e^{0.000487*PM_{2.5}} - 1)) \quad (1)$$

To study the temporal variation of air pollutant concentrations and AQHI in the cities of Kozani, Kastoria and Grevena, the hourly mean concentration of $PM_{2.5}$, NO_2 and O_3 are used to calculate the daily AQHI values.

Table 1. Categories of the Air Quality Health Index (AQHI) and their associated health messages.

Health risk	AQHI	Health messages	
		At-risk population	General population
Low	1–3	Enjoy your usual outdoor activities.	Ideal air quality for outdoor activities.
Moderate	4–6	Consider reducing or rescheduling strenuous activities outdoors if you are experiencing symptoms.	No need to modify your usual outdoor activities unless you experience symptoms such as coughing and throat irritation.
High	7–10	Reduce or reschedule strenuous activities outdoors. Children and the elderly should also take it easy.	Consider reducing or rescheduling strenuous activities outdoors if you experience symptoms such as coughing and throat irritation.
Very high	Above 10	Avoid strenuous activities outdoors. Children and the elderly should also avoid outdoor physical exertion.	Reduce or reschedule strenuous activities outdoors, especially if you experience symptoms such as coughing and throat irritation.

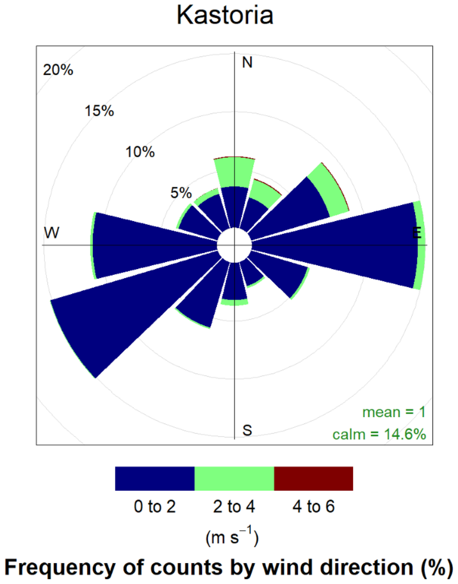
3 Results and Discussion

The air pollutant concentrations and meteorological variables in the four cities of Western Macedonia for the study period are summarized in Table 2. The mean concentrations of PM_{10} and $PM_{2.5}$ ranged from 19.9 μg/m^3 and 11.7 μg/m^3 in Kozani to 24.0 μg/m^3 and 17.8 μg/m^3 in Florina, respectively. Based on the available data the highest mean annual concentrations of gaseous air pollutants (NO, NO_2, NO_X, CO and SO_2) were registered in Kastoria. The highest mean annual O_3 concentrations (66.9 μg/m^3) were registered in Kozani, while the lowest in Grevena (42.3 μg/m^3).

As for the meteorological variables, the mean temperatures ranged between 11.3 °C in Florina and 14.3 °C in Kozani, while Grevena registered the highest relative humidity values (76.2 %). Also, Figures 2 (a) and 2 (b) show the wind roses for the cities of Kastoria and Florina.

Table 2. An overview of mean annual air pollutant concentrations (PM_{10}, $PM_{2.5}$, NO, NO_2, NO_X, CO and SO_2) and meteorological variables (wind speed and direction, Temperature and Relative Humidity) in the cities of Kozani, Kastoria, Grevena and Florina for the study period.

Air pollutant / Meteorological variable	Kozani	Kastoria	Grevena	Florina
PM_{10} (μg/m^3)	19.9	22.4	22.3	24.0
$PM_{2.5}$ (μg/m^3)	11.7	14.6	13.7	17.8
NO (μg/m^3)	1.8	3.2	4.7	0.7
NO_2 (μg/m^3)	7.9	11.0	7.8	7.0
NO_X (μg/m^3)	9.7	14.2	12.5	7.8
SO_2 (μg/m^3)	3.9	2.4	2.1	5.3
CO (mg/m^3)	0.2	0.2	0.2	0.2
O_3 (μg/m^3)	66.9	56.6	42.3	59.4
wind speed (m/s)	0.9	1.0	1.2	1.1
wind direction (degrees)	201	174	158	209
Temperature (°C)	14.3	13.7	12.8	11.3
Relative Humidity (%)	64.8	68.4	76.2	69.7



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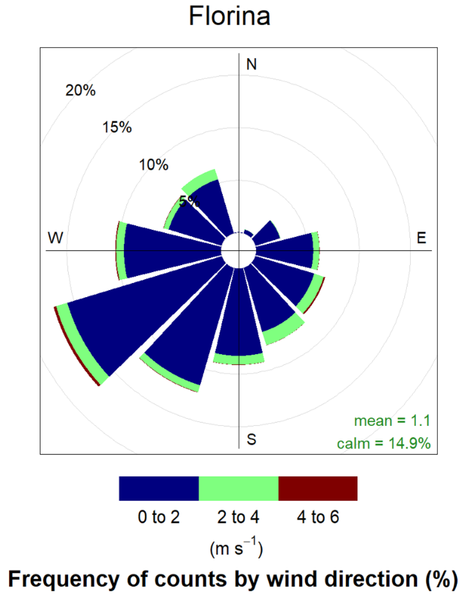


(b)

Figure 2. Average frequency of counts by wind speed and wind direction, in the cities of (a) Kastoria and (b) Florina for the study period.

Table 3 displays the mean monthly PM_{10} and $PM_{2.5}$ concentrations in the cities of Kozani, Kastoria, Grevena and Florina for the study period. The PM_{10} concentrations reached to high values during the winter months. For example, in Kastoria, Grevena and Florina the highest PM_{10} values of 34.9 μg/m^3, 38.3 μg/m^3 and 30.7 μg/m^3 were registered in February and March. In the city of Kozani the highest monthly mean concentrations of PM_{10} were registered in July (30.1 μg/m^3). High concentrations of coarser PM during the summer months are associated with the prevailing strong winds that favor the resuspension of soil and dust from dry surfaces [1]. In contrast, the highest mean monthly $PM_{2.5}$ concentrations, were observed during the cold period, with the highest values in Florina reached up to 26.2 μg/m^3 in December. The high $PM_{2.5}$ levels during wintertime were mostly due to the increased electricity demand from the lignite-fired power plant and the domestic heating emissions [1].

For the study period 2010-2022, Evagelopoulos et al. (2022) found that $PM_{2.5}$ concentrations varied between 13.54 μg/m^3 at the village Koilada in Kozani and 24.51 μg/m^3 in Florina [1]. As for PM_{10}, the concentrations varied from 24 μg/m^3 in Koilada and Amyntaio to 56.79 μg/m^3 in the village Oikismos [1].

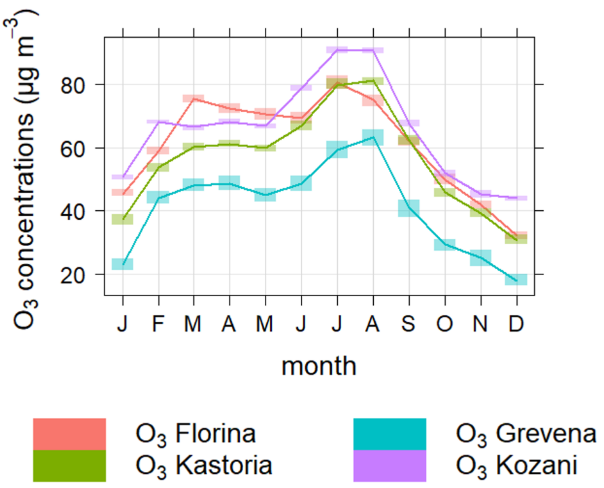
Table 3. An overview of mean monthly PM_{10} and $PM_{2.5}$ concentrations in the cities of Kozani, Kastoria, Grevena and Florina for the study period.

Month	PM_{10} (μg/m³)	$PM_{2.5}$ (μg/m³)	PM_{10} (μg/m³)	$PM_{2.5}$ (μg/m³)
	Kozani		Kastoria	
January	18.5	12.3	26.7	20.7
February	28.2	16.5	34.9	23.3
March	13.2	9.2	18.0	12.1
April	14.6	10.5	14.2	10.3
May	16.6	11.0	16.5	11.1
June	19.4	11.5	17.0	10.6
July	30.1	13.0	26.7	12.5
August	20.8	11.5	18.5	11.5
September	26.1	13.8	23.3	13.0
October	23.8	12.8	23.3	12.9
November	11.5	7.1	17.6	12.5
December	16.8	11.6	32.0	24.8
Month	PM_{10} (μg/m³)	$PM_{2.5}$ (μg/m³)	PM_{10} (μg/m³)	$PM_{2.5}$ (μg/m³)
	Grevena		Florina	
January	24.3	17.5	28.6	25.1
February	38.3	21.9	28.3	24.8
March	19.5	12.4	30.7	23.4
April	14.0	9.7	18.7	11.4
May	17.3	11.3	18.6	10.8
June	18.9	11.2	20.6	11.5
July	26.1	12.8	21.6	11.0
August	19.3	11.9	21.4	11.6
September	22.3	13.1	13.7	7.9
October	23.3	12.9	22.3	15.4
November	19.6	12.0	25.3	20.4
December	25.7	17.9	30.2	26.2

Figures 3 (a), 3 (b) and 3 (c) show the monthly, hourly and weekly variations of O_3 concentrations in the areas under study. The mean monthly concentrations of O_3 exhibit seasonality patterns with the highest levels during the summer months (July and August) and the lowest levels during the cold period (from October to January). The mean monthly O_3 concentrations in Kozani ranged between 44 μg/m³ in December and 91 μg/m³ in July and August. The lowest mean monthly O_3 concentrations were observed in Grevena with the lowest values in December (18 μg/m³) and the highest values in August (63 μg/m³).

As for the hourly O_3 concentrations, at all cities the levels reach their maximum over the fixed period 13.00-16.00 local time with an observed value up to 80 μg/m³. Although the lowest hourly O_3 concentrations observed in the early morning before sunrise at all cities, these values exhibit differences among the cities. In Grevena, the hourly O_3 concentrations reach their lowest levels (almost 10 μg/m³) at 05.00 local time, while in Kozani the lowest levels were almost 55 μg/m³ at 07.00 local time.

As for the weekday variations, O_3 concentrations tend to be higher on the weekends (Saturday and Sunday) compared to the weekdays (from Monday to Friday). This phenomenon is particularly observed in the cities of Kozani and Kastoria compared to the cities of Florina and Grevena, where the O_3 concentrations are approximately equal during the week. This weekly pattern of O_3 concentrations is the "ozone weekend effect". The pattern has been widely observed in various regions, as well as in Ioannina city, a city in north-western Greece with common characteristics with the under study cities in Western Macedonia [13]. According to the ozone photochemical theory, changes in NO_X emissions at weekends is the possible chemical cause of "ozone weekend effect".



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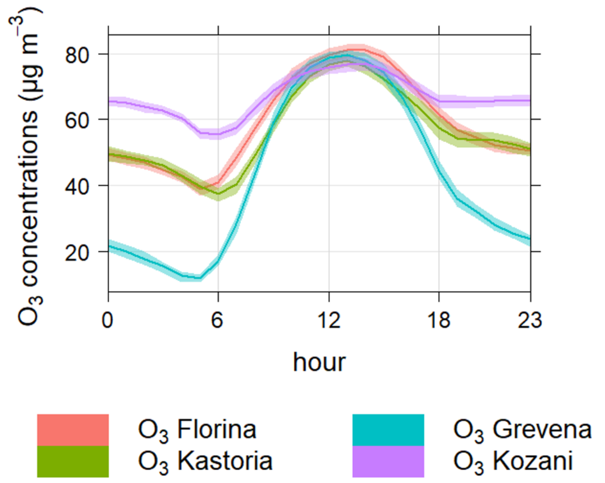

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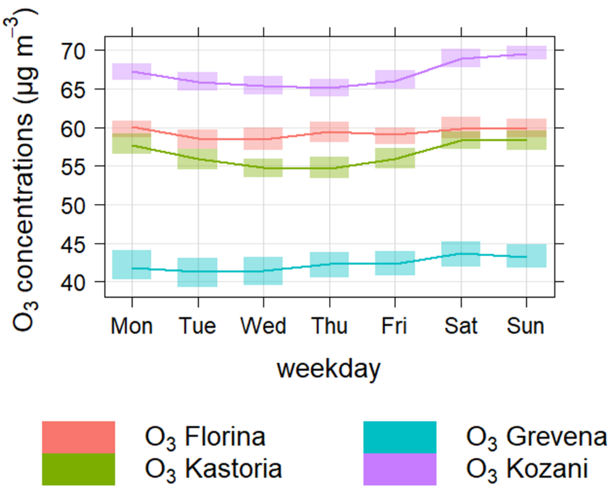

(c)

Figure 3. Temporal variations of O_3 concentrations at (a) monthly level and (b) hourly level and (c) weekly level, in the cities of Kozani, Kastoria, Grevena and Florina for the study period.

Figure 4 shows the time series of the maximum daily 8 h O_3 concentrations. The European Union (EU) air quality standards of 120 μg/m^3 for the maximum daily 8-hour mean O_3 concentrations was exceeded only on the 29th of July 2022 in Florina and on the 29th of July 2023 in Grevena. The World Health Organization (WHO) 8-hour O_3 mean of 100 μg/m^3 was exceeded for the 16 % of the days in Florina, 11 % of the days in Kastoria and 13 % of the days in Grevena and Kozani. As for the WHO peak season limit value of 60 μg/m^3, more than 90 % of the days exceeded this value.

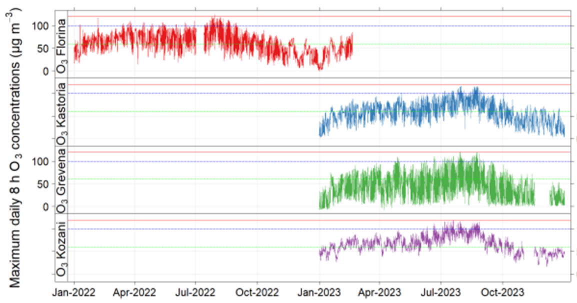

Figure 4. Maximum daily 8 h O_3 concentrations (μg/m^3) in the cities of Kozani, Kastoria, Grevena and Florina for the study period. The red line corresponds to the EU maximum daily 8 h mean limit value of 120 μg/m^3. The dotted blue line corresponds to the WHO maximum daily 8 h mean limit value of 100 μg/m^3, while the dotted green line corresponds to the WHO peak season limit value of 60 μg/m^3.

Table 4 shows the results of correlation analysis between ozone and air pollutants concentrations and meteorological parameters in the under study cities. In general, negative Pearson correlation coefficients between O_3 concentrations and concentrations of PM_{10}, $PM_{2.5}$, NO, NO_2, NO_X, SO_2 and CO were observed. The highest positive correlation coefficients were observed between O_3 concentrations and temperature. The moderate positive correlation coefficient between wind speed and O_3 concentrations is uncommon because high O_3 levels are expected during periods of low wind speed. This can be attributed to dispersion of O_3 inhibitors or lower NO as a result of greater dispersion due to higher wind speed [14]. A study conducted in Kozani found that ozone was positively correlated with wind speed, when background O_3 or its precursors from distant sources (e.g. coal-fired power plants) are transferred or accumulated under sunlight [15]. Also, moderate to high negative correlation have been found between O_3 and relative humidity. Studies have found that relative humidity decrease ozone levels and also alleviate the positive effect of temperature on ozone generation [16].

Table 4. Pearson correlation coefficients (R) between ozone concentrations and air pollutants concentrations and meteorological parameters in the cities of Kozani, Kastoria, Grevena and Florina for the study period.

	Kastoria	**Grevena**	**Kozani**	**Florina**
	O_3	**O_3**	**O_3**	**O_3**
PM_{10}	-0.25	-0.06	0.11	-0.24
$PM_{2.5}$	-0.47	-0.39	-0.06	-0.42
NO	-0.46	-0.30	-0.27	-0.15
NO_2	-0.53	-0.30	-0.32	-0.43
NO_X	-0.55	-0.34	-0.33	-0.38
SO_2	0.09	-0.03	-0.18	0.14
CO	-0.56	-0.36	-0.44	-0.43
O_3	1.00	1.00	1.00	1.00
ws	0.46	0.57	0.20	0.44
wd	-0.31	-0.18	-0.22	-0.05

Temp	0.66	0.68	0.67	0.58
RH	-0.72	-0.86	-0.67	-0.77

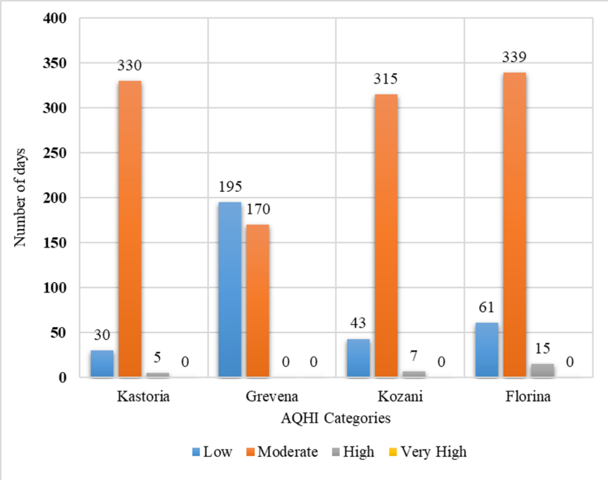

Figure 5. Number of days in each AQHI category in the cities of Kozani, Kastoria, Grevena and Florina for the study period.

Figure 5 shows the number of days in each category of AQHI for all the under study areas. The majority of days found in the category of "moderate" health risk associated with the air quality, while for a small number of days the relevant health risk is "high". The number of days in the category of "high" health risk were 5, 7 and 15 in Kastoria, Kozani and Florina, while in Grevena 0 days categorized as "high" risk.

Evagelopoulos et al. (2022) implemented the EAQI based on PM_{10} concentrations for the period 2010-2020 and found that the air quality for the majority of the days classified as 'good' or 'fair' in the air quality monitoring stations of Western Macedonia but for a few days at specific locations, such as the villages Oikismos and Anargyroi, the air quality classified as "very poor" or "extremely poor' [7].

3 Conclusions

The analysis revealed relatively high concentrations of both particulate and gaseous air pollutants over the study period in the four cities of Western Macedonia. Their spatiotemporal patterns associated with weather conditions and local air emission sources. As for the ozone pollution in the region, there are two alert days that exceed the EU limit value, but ozone concentrations are high based on WHO standards As for the AQHI values, we found that the majority of days were in the category of "moderate" health risk associated with the air quality, while for a small number of days the relevant health risk is "high".

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