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The Effects of Surface Lignite Mines Closure on the Particulates Concentrations in the Vicinity of Large-Scale Extraction Activities †

Francis Pavloudakis [1,*], Chariton Sachanidis [2] and Christos Roumpos [2]

[1] Department of Mineral Resources Engineering, School of Engineering, University of Western Macedonia, Koila, 50100 Kozani, Greece
[2] Mining Engineering Department, Public Power Corporation of Greece, 10432 Athens, Greece; ca.sachanidis@dei.gr (C.S.); c.roumpos@dei.gr (C.R.)
* Correspondence: fpavloudakis@uowm.gr; Tel.: +30-2461068087

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Abstract: The European green deal and energy transition policies and the competition primarily shaped by the high price of carbon dioxide emission allowances and the consistently reduced cost of renewable energy technologies directly affect the coal and lignite extraction industry. Lignite production in Western Macedonia Lignite Centre reduced from 43.2 million tons in 2010 to 10.3 million tons in 2020. This development affects the ambient air quality of the large lignite mine area, as evidenced by the records of 10 monitoring stations incorporating the laser light scattering method. All stations measure reduced particulate matter (PM_{10} and $PM_{2.5}$) concentrations compared to the period before 2010, while the number of annual exceedances of the limit value for the daily average PM_{10} concentrations has been decreased. Moreover, differences in air quality measurements of monitoring stations related to their distance from mining activities now tend to be minimized. Based on these facts, it can be predicted that, after the closure of lignite extraction and the electricity generation activities, the concentration of particulates in the atmosphere will reach the typical levels for rural areas of Southern Europe, no matter what the mines' land reforestation and repurposing program will include.

Keywords: coal; surface mines; ambient air quality; environment

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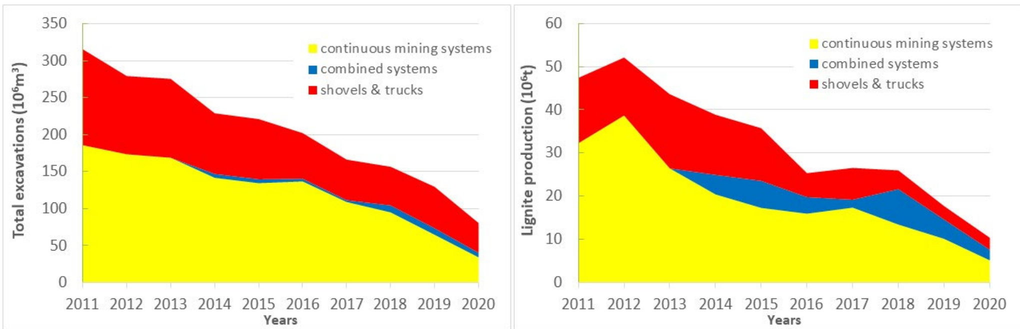
1. Introduction

The elimination of coal and lignite use for power generation is a priority of the European energy strategy. In this context, many power utilities located in EU28 countries are implementing programs to gradually reduce the use of coal and lignite, turning either to natural gas as a transitional fuel or directly to renewable energy sources [1,2].

Regarding the exploitation of the lignite deposits located at Ptolemaida basin (Region of Western Macedonia, Greece), this area has dominated the power sector of the country for more than six decades, boosting economic growth, regional development, and energy security [3–5]. Since 1975, the lignite mines have been the property of the Public Power Corporation (PPC). The mines form the PPC's largest operational unit, called Western Macedonia Lignite Centre (WMLC). After a long period of steady growth, WMLC achieved the record figures of 55.8 million tons of lignite production and 332 million cubic meters of total rock excavations in 2002 and 2005, respectively. Nowadays, the surface mines of WMLC occupy 17,000 ha. They are equipped with 42 bucket wheel excavators, 250 km of belt conveyors, and 17 spreaders, while shovels and trucks are used to excavate and transport the hard rocks present in the overburden strata [1].

The remaining exploitable reserves in the lignite fields under exploitation by PPC are estimated to be 820 million tons, while private mines reserves are 120 million tons. PPC also has the rights to exploit 460 million tons of lignite that have not been developed so far. Taking into consideration these facts, until recently, the plans were provided for the operation of mines and steam power stations until 2042 [3]. However, under the pressure of competition shaped mainly by the high prices of CO_2 emission allowances, domestic lignite has transformed from a blessing to an environmental, social, political, and economic problem [5].

In this frame, lignite production dramatically decreased after 2012 (Figure 1), following the reduced demand for lignite power. Electricity generated from lignite fell from 31 TWh in 2012 to 5.7 TWh in 2020 because of emissions trading, the rapid growth of low-cost renewable energy sources, increased energy imports, and a lower overall electricity demand as a result of the economic crisis [1]. Consequently, the closure of lignite mines has been rescheduled for 2028 [1]. However, there are still doubts about how this evolution will be environmentally friendly [5], socially just, and effective across multiple sustainability criteria [4].



(**a**) (**b**)

Figure 1. Decrease in total rock excavations (**a**) and lignite production (**b**) in the mines of Western Macedonia Lignite Centre during the 10-year period 2011–2020.

Further to the obvious threats for society, this development enhances the ambient air quality of the large lignite mines area, as evidenced by the data of a dense network of monitoring stations, which makes the basin of Ptolemaida the best-monitored area throughout Greece. Based on these records, many researchers have thoroughly investigated the relationship between particulate emissions and ambient air quality with the surface mining and electricity generation activities carried out in the Ptolemaida basin. A spatiotemporal analysis of the particle size distribution of fly ash and fugitive dust in combination with the Total Suspended Particles and PM_{10} concentrations recorded in 13 monitoring stations for a seven-year period indicated that the complex topography, the different characteristics of the emission sources and the variable meteorological conditions affect the pollution considerably due to emissions of particulates [6]. In addition, a fractal analysis [7] of measurements carried out in the commercial center of Kozani, the capital city of Western Macedonia region, showed that the mean PM_{10} and $PM_{2.5}$ concentrations exceeded the specified limits, while the average $PM_{2.5}/PM_{10}$ ratio was 0.42, which was indicative of the large percentage of coarser particles in the total mass of particulates. The study also concluded that the emission sources responsible for measurements carried out in periods of low concentrations are not the same as those responsible for the exceedances. Another study, which examined the contribution of fly ash emissions from lignite-fired power stations to the air pollution of the Western Macedonia region, determined that fly ash particles, such as cenospheres, vesicular spheres, spheroids, dense spheres, and chars in almost every filter collected in the area, compared with those located nearby power plants, have apparently more and coarser fly ash particles [8]. A measurements campaign conducted in three Australian coal mines also concluded that the proportion of fine particulates in each sample increased with the distance from the source of emissions, with the coarse fraction being a more significant proportion of total suspended particulates close to the source.

Dispersion simulation models are usually used to quantify particulate emissions, incorporating emission factors that characterize various pollution sources. However, the literature provides limited information about such factors, which are not representative of all mining operations [9–11]. Therefore, in the case of the lignite surface mines of Western Macedonia Lignite Centre, a three-year campaign of field measurements was carried out to collect the necessary meteorological data and upwind–downwind concentration levels in the proximity of surface mining equipment (e.g., stackers) and operations (e.g., road haulage) that are considered as the main particulates emission sources [10]. Furthermore, by applying inverse dispersion using two different models, emissions factors were calculated, and empirical formulas were determined for the calculation of the total annual fugitive dust emissions, in accordance with the EU Regulation 166/2006, which obligates mining companies to quantify their emissions from fugitive sources [11–13]. Prior to this project, emissions factors had been calculated in the frame of an EU-funded research aimed at developing methods for optimizing pollution prevention plans and for early warning of extreme pollution episodes. Using various data sources and the CORINAIR (COoRdination of Information on AIR emissions) methodology, emissions factors were estimated for the main industrial and non-industrial activities in that region: power plants, lignite mines, road transport, and central heating systems. In addition, biogenic sources, such as animal husbandry and agricultural activities, were also examined. Data gaps were filled using default values from CORINAIR or other sources. An emissions inventory concerning major pollutants (PM, SO_2, NO_x, CO, N_2O, VOC, CH_4, and NH_3) was compiled for the period 2001–2004 [14].

Another PM_{10} measurement campaign was carried out throughout a year at three receptor sites. The highest PM_{10} concentration values were measured in the city of Ptolemaida, where, although the annual average concentration was equal to the limit value of 40 $\mu g/m^3$, 23% of PM_{10} concentrations exceeded the daily EU limit value (see next paragraph). Source apportionment results of a positive matrix factorization (PMF) receptor model identified that in Kozani, the main particulates sources were lignite-fired plants and road-traffic; in Ptolemaida lignite-fired plants, road-traffic, and diffuse sources of surface mines; and in Eratyra (rural area far away from the lignite mines) were the agricultural activities and biomass-wood burning [15].

Furthermore, the contribution of fugitive dust emissions from the lignite mines to the ambient levels of PM_{10} in the surroundings was also estimated by performing chemical mass balance (CMB) receptor modelling. Vehicular traffic, biomass burning, and secondary sulfate and nitrate aerosol were sources of significant contribution. The estimated total contribution of mines ranged between 9% and 22% in the cold period and was increased to 36–42% in the dry, warm period [16], despite the preventive, containment, and suppression measures applied to control all emissions [17]. In order to assess the contribution of the mining activities to the air quality of the surrounding areas, a three-dimensional, nestable, prognostic meteorological, and air pollution model was also used [18]. A study carried out in seven open-pit mines operating in the northern territories of Colombia showed that the traffic of trucks and other vehicles on unpaved roads is the mining activity that contributes more to the total emissions. This contribution may be reduced by up to 72% by spraying water on the road surfaces [19].

Finally, it is worth noticing that, according to a study conducted in Australia, particulates emissions were significantly higher from coal mining than from other types of monitored sites. Furthermore, results of the same study indicated that the increase in coal quantities mined over the study period also corresponded to increased levels of particulate matter, metals, and nitrogen oxides [20]. In this framework, the present paper investigates this direct relation between mine production and ambient air quality in the greater mining area to predict ambient air quality in the basin of Ptolemaida after the closure of the lignite-fired thermal power units.

2. Materials and Methods

The control of particulates emissions in a mining activity of the size of WMLC is a complex issue. Its difficulty is enhanced by the fact that most emissions within surface mines are fugitive and cannot be subjected to objective measurements. Consequently, any conclusions concerning the contribution of various sources in the air pollution problem are based on ambient air quality measurements.

In the frame of the present study, ambient air quality measurements were collected by a network of ten monitoring stations GRIMM 180 that PPC has dispersed in the entire basin of Ptolemaida (Figure 2). The stations record the concentrations of particulate matter (PM_{10} and $PM_{2.5}$) incorporating the laser light scattering principle. According to this, the scattering light of the single particles is measured, where a semiconductor laser serves as the light source. When particles cross the laser beam, they emit a light pulse. The electric signal of the converted light pulse is classified into 31 different size channels after an adequate amplification. This enables a size determination of the particles and also establishes a weighting curve for PM_{10} and $PM_{2.5}$. Finally, the sample air, which is being volume controlled, is sucked through the optical measurement chamber and a fine filter.

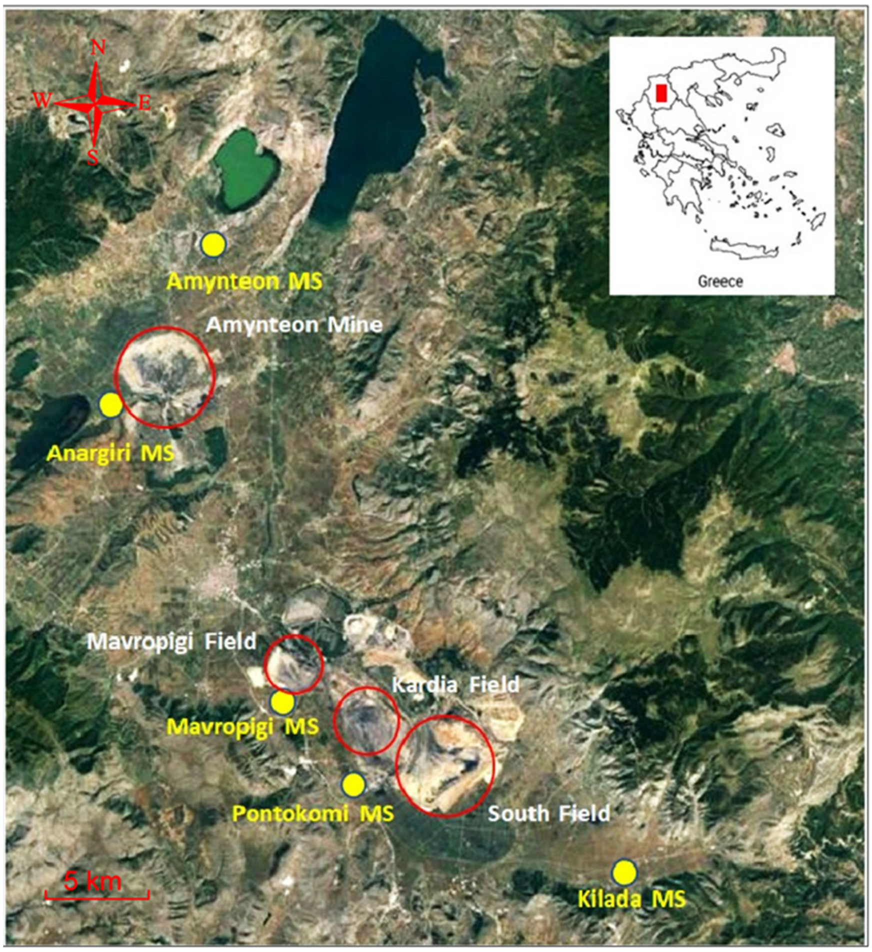


Figure 2. Google map of Florina–Ptolemaida–Kozani lignite bearing basin, where the location of surface mines and ambient air quality monitoring stations (MS) are indicated.

The measurements collected in this way are processed by ENVIDAS (ENVIronmental Data Acquisition System) software provided by ENVITECH ltd (Givataim, Israel). and are stored in a database developed with MS SQL2000 software. These data are accessed on-line by the Environmental Agency of the Region of Western Macedonia, which has the authority to supervise the operation of all lignite extraction and power generation activities.

Decisions concerning the implementation of emissions control measurements in case of pollution episodes are made also based on these series of measurements.

Furthermore, the initial data series was analyzed and reported using ENVIEW2000 software, which has also been developed by ENVITECH ltd. As a result, various reports and graphs were available for evaluating ambient air quality.

Specifically, PM_{10} and $PM_{2.5}$ concentrations were processed and evaluated based on the following criteria:

- the daily average limit value of PM_{10} is 50 μg/m^3 and must not be exceeded more than 35 times per calendar year;
- the annual average limit value of PM_{10} is 40 μg/m^3; and
- the annual average limit value of $PM_{2.5}$ is 25 μg/m^3.

The aforementioned criteria are determined by the EC Directive 2008/50/EC.

Furthermore, ambient air quality measurements were correlated with the total rock excavations and lignite production of the surface mines, which were obtained from the annual and monthly operational reports of the Western Macedonia Lignite Centre of PPC. For correlation purposes, the linear (Equation (1)) and exponential regression (Equation (2)) tools available in MS Excel software were used.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \quad (1)$$

$$y = \beta_0 + \beta_1 \exp(\beta_2 x_1 + \ldots + \beta_{k+1} x_k) + \varepsilon \quad (2)$$

where $x_1, x_2, \ldots, x_k$ the independent variables, y the dependent variable, $\beta_0, \beta_1, \beta_2, \ldots, \beta_{k+1}$ the regression coefficients, and ε the error term.

The R-squared (coefficient of determination) parameter (Equation (3)) was used for comparing the results of different cases that were examined:

$$R^2 = \left(\frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2] \times [n\sum y^2 - (\sum y)^2]}}\right)^2 \quad (3)$$

where x and y the values of the two correlated parameters and n the number of measurements.

Other statistical parameters, which were used in order to confirm the hypothesis of strong dependence between mining operations and particulates concentrations in the vicinity of the lignite mines of Western Macedonia region, include:

1. The p-value (between 0 and 1). It gives the probability of observing a test statistic as extreme as the one observed, assuming that the null hypothesis H_0 (there is not a significant relationship (correlation) between x and y) is true. p-values provide a relative measure of the strength of evidence against H_0. The smaller the p-value, the stronger the evidence for rejecting the H_0. A p-value $p < 0.001$ indicates very strong evidence against H_0, $p < 0.01$ strong evidence, $p < 0.05$ moderate evidence, $p < 0.1$ weak evidence or a trend, and $p \geq 0.1$ indicates insufficient evidence that the observed data are sufficiently inconsistent with the null hypothesis so that the null hypothesis may be rejected.
2. The standard error of the regression (s_r) (Equation (4)),

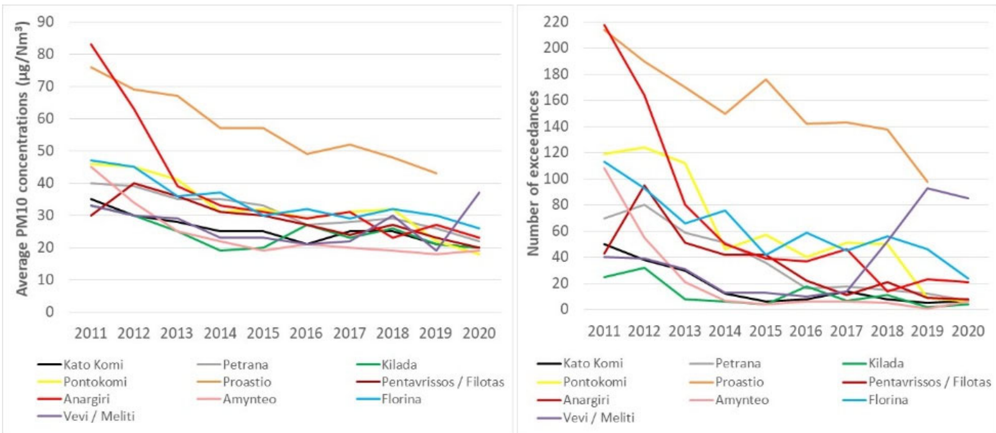
   $$s_r = \frac{SSR}{n-2} \quad (4)$$

   where SSR is the sum of squared residuals, and residual is the difference in the measured y value minus the y value calculated by the regression equation using the x value that corresponds to the measurement.
3. The t statistic (Equation (5))

   $$t = \frac{R\sqrt{n-2}}{\sqrt{1-R^2}} \quad (5)$$

3. Results

In terms of particulates concentration, the ambient air quality in the greater area of lignite mines of Western Macedonia improved significantly during the decade 2011–2020. Ambient air quality is expressed as annual average PM_{10} and $PM_{2.5}$ concentrations and number of exceedances per annum of the daily average PM_{10} concentration limit of 50 μg/m^3. For simplicity, the later parameter will be referred to in the following paragraphs as air pollution episodes. Figure 3 shows the downward trend of the above parameters in 10 Monitoring Stations (MS) dispersed in the greater lignite-bearing basin of Florina–Ptolemaida–Kozani. Some of these stations are located in towns and villages of the area under investigation, not necessarily close to the sources of the particulates so that the ambient air quality measurements to be directly linked to the quality of life of the inhabitants. For this reason, the stations record various sources of particulate release (e.g., traffic, heating systems) not related to the mining and power generation activities.



(**a**) (**b**)

Figure 3. Average PM_{10} concentrations (**a**) and number of exceedances (**b**) per annum of the daily average PM_{10} concentration limit of 50 μg/m^3 in 10 monitoring stations located in the basin of Florina–Ptolemaida–Kozani.

The MS of Florina and Vevi–Meliti are located in the northern part of the basin, where small private mines are active, and the 330 MW Meliti power plant is in operation. In addition, these stations measure imported pollution from the Republic of North Macedonia due to mining and power generation activities operating close to the borders [21].

The MS of Amynteon, Anargiri, and Pentavrisos–Filotas have been installed around the mine and power plant of Amynteon. Their ambient air quality measurements seem to be inversely proportional to their distance from the mining operations. However, previous studies [14] have shown that particulates collected in Pentavrisos MS originated from the mining complex of Ptolemais rather than this of Amynteon; although, Ptolemais mines are located further from this station and to the south, a direction that does not favor the transfer of particulates when blowing the prevailing winds of the basin. This is a proof of the existence of local wind currents that complicate further the air pollution pattern in the area under investigation.

The MS of Proastio (Ikismos) and Pontokomi are located in the core of the lignite exploitation activities. The settlement of Ikismos, which was constructed to accommodate the mines and power plants personnel, was abandoned for many years and officially at the end of the period 2011–2020 that is examined in this study. For the village of Pontokomi, there is a decision for relocation. Although the properties have already been expropriated, the village is still habited. Therefore, it is crucial to understand the mechanism of ambient air quality fluctuations in the area surrounding the village.

The MS of Kilada, Kato Komi, and Petrana are in the south edge of the lignite-bearing basin. The two latter are not affected by lignite exploitation activities and can be considered a reference to background pollution. The MS of Kilada is located relatively close to the power plant of Agios Dimitrios. With an installed capacity of 1595 MW, this power plant is one of the largest in Europe. However, this monitoring station always recorded low concentrations of particulates, even in the periods of intensive mining and power generation operations, when the annual lignite demand of the plant exceeded 20 million tons (early years of decade 2000).

In Figure 3, it is evident that all stations have recorded a decrease in particulates concentrations and number of episodes of increased pollution, except for the Vevi–Meliti MS, where an increasing trend coincides with the relocation of the station to the village of Meliti (June 2018). The observed decrease in particulates concentrations is more significant at monitoring stations located closer to sources of particulates release: the station of Proastio (Ikismos) is next to Ptolemais TPP and the station of Anargiri next to the Amynteon mine. It must be noticed that the sharp drop in particulates concentrations recorded by the station of Anargiri in 2013 is partly due to the relocation of the monitoring station from the crest of the Amynteon mine pit to the square of the village, at a distance of 500 m away from the initial installation point.

Furthermore, four rosette diagrams are presented in Figure 4 that correlate the wind directions recorded in two monitoring stations with the daily average PM_{10} concentrations of an entire calendar year. The diagrams concern the MS of Anargiri and Pontokomi. These MS were selected due to their proximity to particulates emissions sources related to lignite extraction and combustion activities in Amynteon and Ptolemais area, respectively. For each MS, two years were selected to be compared, one at the beginning and one at the end of the examined decade 2011–2020, to show the different characteristics of ambient air quality before and after reducing the lignite mines exploitation activities. Moreover, the years that were finally selected were chosen to have a similar distribution of wind directions so that the probability of contribution of various particulates emissions sources that are dispersed around each MS be equal (i.e., to eliminate wind direction from the variables of this investigation).

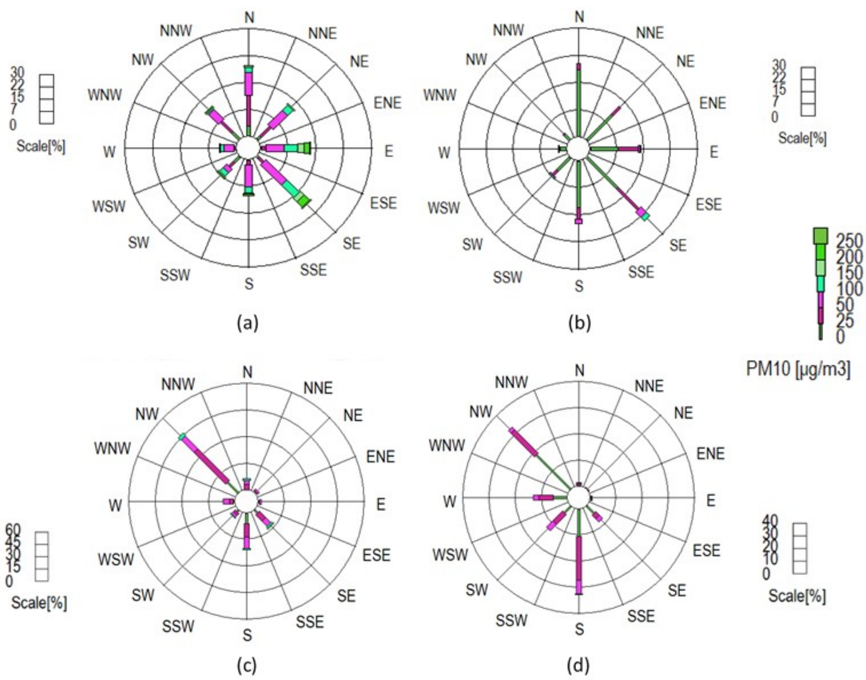


Figure 4. Correlation of wind direction with the daily average PM_{10} concentrations: (**a**) Anargiri MS—year 2010, (**b**) Anargiri MS—year 2020, (**c**) Pontokomi MS—year 2011, and (**d**) Pontokomi MS—year 2020.

Anargiri MS is mainly affected by emissions of particulates coming from the Amynteon mine, which is located west of this station, and the external dumping area of the Amynteon mine, which is located south, southwest. There are agricultural activities to the north of this monitoring station, while to the east, there is Lake Chimaditis and agricultural activities. Pontokomi MS is affected by the operation of both Mavropigi and Kardia mines, located to the north and east, respectively, and by the thermal power plant of Kardia, located to the east. South Field mine, which is the largest in the area in terms of total excavations, is also located east of Pontokomi MS but at a further distance than the Kardia mine and power plant. It is obvious in Figure 4 that the reduction in particulates concentrations is more significant at the station of Anargiri. This result is partly because, in this area, the initial concentrations were considerably higher than in the area of Pontokomi. In addition, while, in 2010, increased concentrations of particles were associated with all wind directions, in 2020, increased concentrations occur when blowing winds come from the side of the external dumping area. In Pontokomi MS, although particulate concentrations were reduced from the beginning of the examined 10 years period, there is also a clear tendency to decrease the number of severe air pollution episodes (i.e., PM_{10} concentration above 100 $\mu g/m^3$) related to northwest, north, and southeast winds.

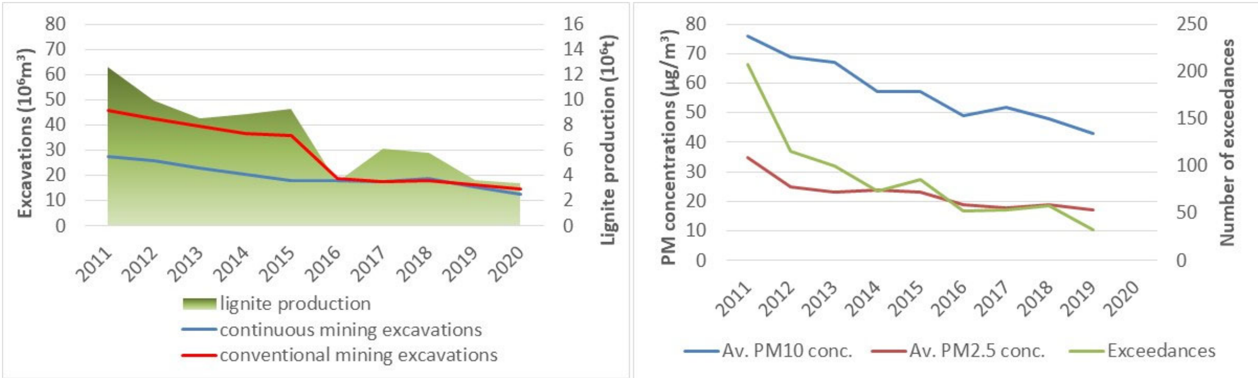
The above-presented data are indicative of the correlation between the reduced excavated rock volumes, the lignite quantities burnt in the mine-mouth located thermal power plants, the considerable improvement of ambient air quality and the minimization of air pollution episodes. In order to investigate further the characteristics of this correlation, in Figure 5, a series of diagrams is presented that juxtapose the reduced activities of the four largest lignite mines of the area under investigation for the decade 2011–2020 with the fluctuations of particulates concentrations and the number of pollution episodes that were recorded by the monitoring station that is located in close proximity to each of the four mines.

As far as the mines' operation figures are concerned, although the general trend is negative everywhere, there are great differences from mine to mine in relation to the rate of this reduction. The average rate of total rock excavations reduction ranged from 1.5 to 5.2 million cubic meters per year for the continuous excavation, transportation, and dumping systems and from 0.2 to 3.6 million cubic meters per year for the operations of sub-contractors working with conventional diesel-engine equipment. In three out of the four mines, the reduction in total rock excavations was more remarkable for the continuous mining systems.

The decrease in annual lignite production in the four examined mines ranged between 500 and 1300 thousand tons per year and, in some cases, did not follow the corresponding decrease in total rock excavations.

Concerning the improvement of monitored ambient air quality parameters, the decrease in the PM_{10} concentrations in the examined ten years period was higher than that of $PM_{2.5}$. Nevertheless, it is clear that the most remarkable improvement of ambient air quality, in all four cases of mines vs. monitoring stations shown in Figure 4, regard the number of pollution episodes.

In Figure 6, the correlation of mines operation with ambient air quality is investigated based on a regression analysis. Air quality parameters are correlated both with total rock excavations and lignite production. Total rock excavations are representative of the entire mine operations no matter the variations in the stripping ratio. Lignite production reflects, apart from the mining activities, the operation of the mine-mouth located thermal power plants, which also contribute to the air pollution problem by burning almost the whole quantity of the produced lignite.



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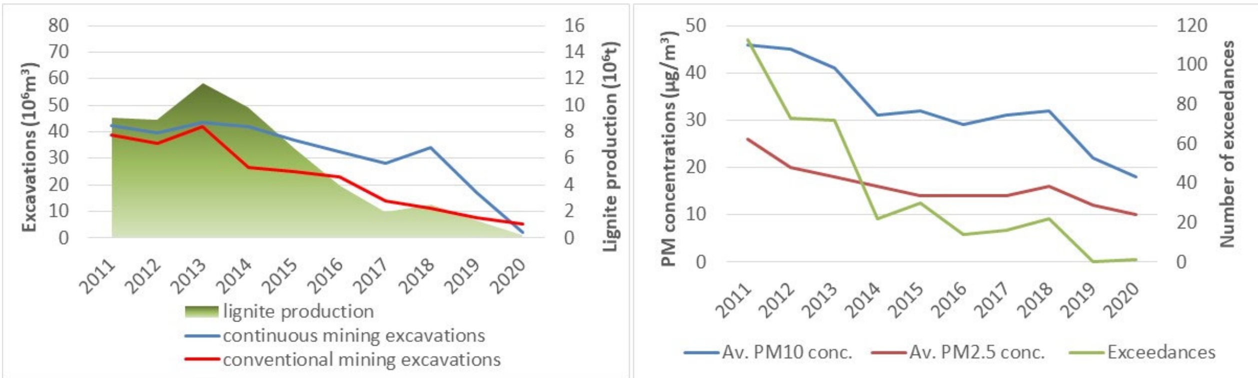

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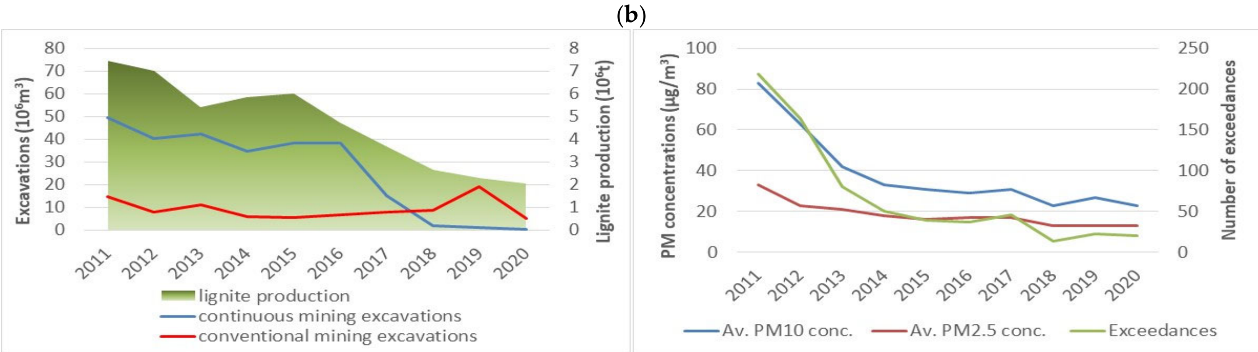

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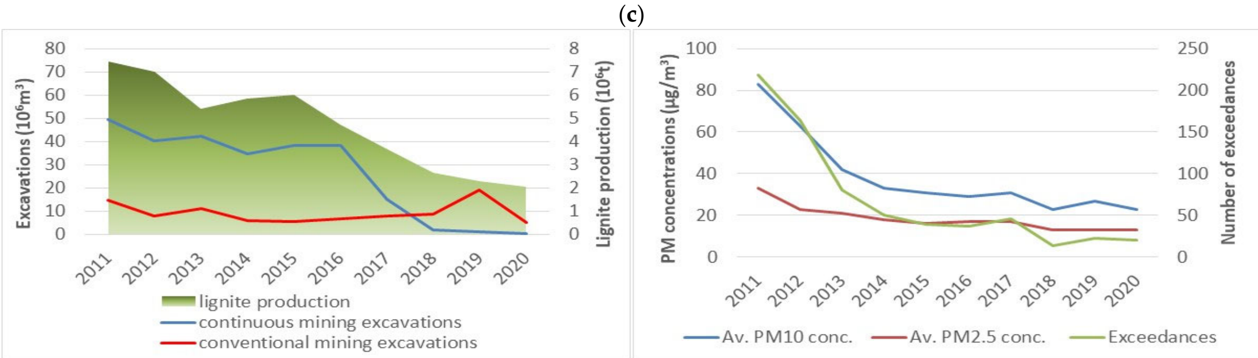
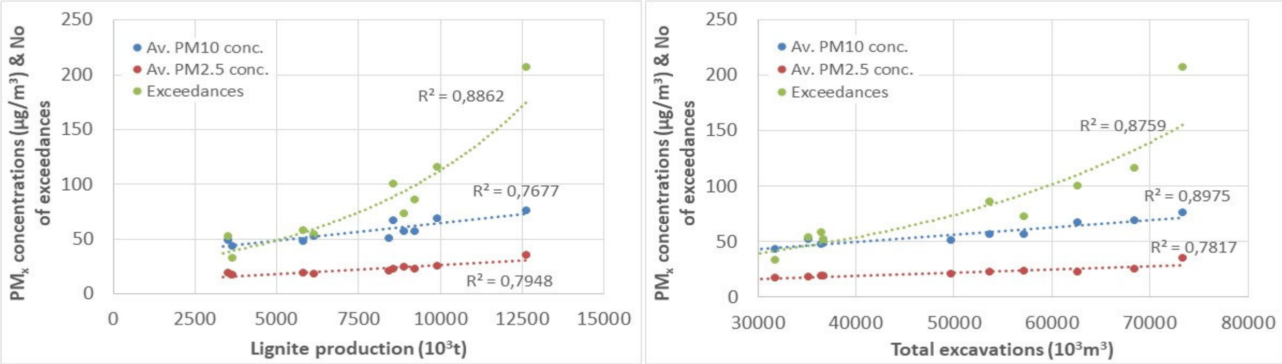


(**d**)

Figure 5. Annual variations in lignite production and rock excavations in four different lignite mining fields of Ptolemaida basin vs. Average PM_{10} and $PM_{2.5}$ concentrations and number of exceedances of the daily average PM_{10} concentrations from the limit value of 50 μg/m^3 as recorded in monitoring stations (MS) located in the vicinity of the mines; (**a**) Main Field vs. Proastio MS; (**b**) Kardia Field vs. Pontokomi MS; (**c**) South Field vs. Kilada MS; (**d**) Amynteon mine vs. Anargiri MS.



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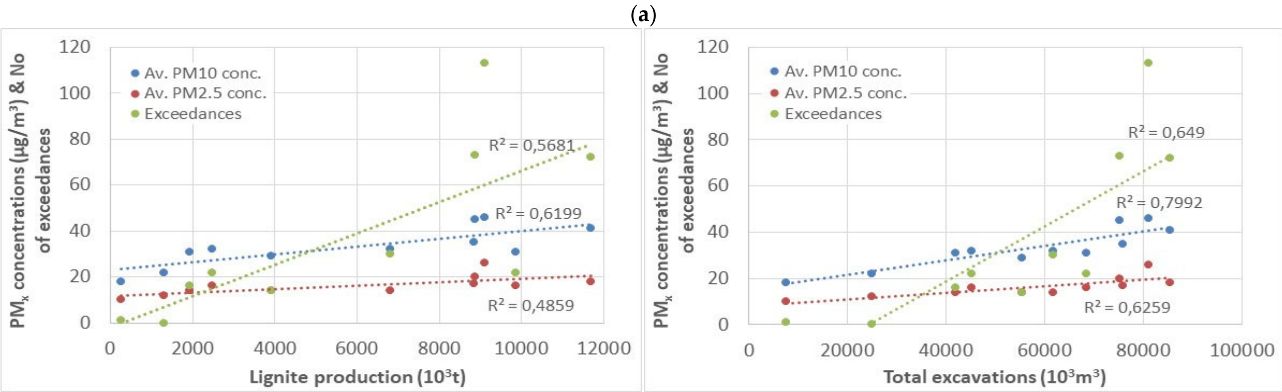

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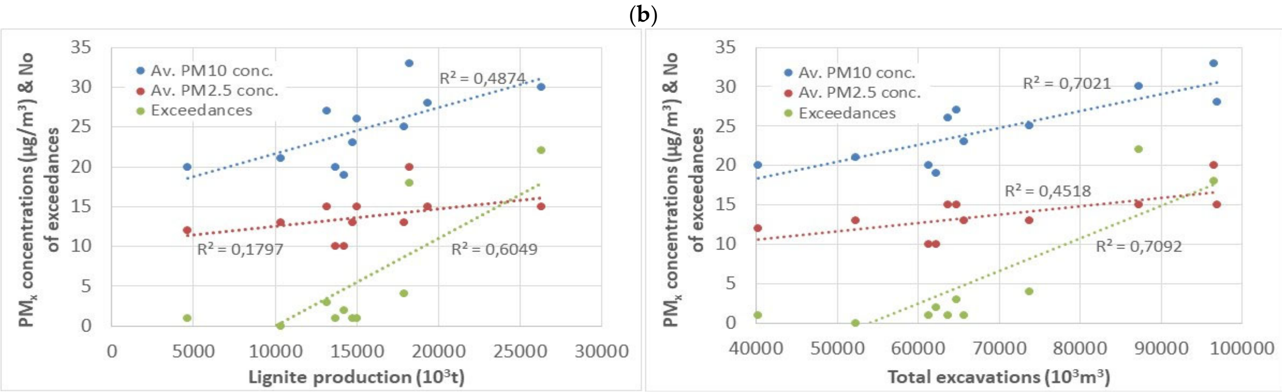

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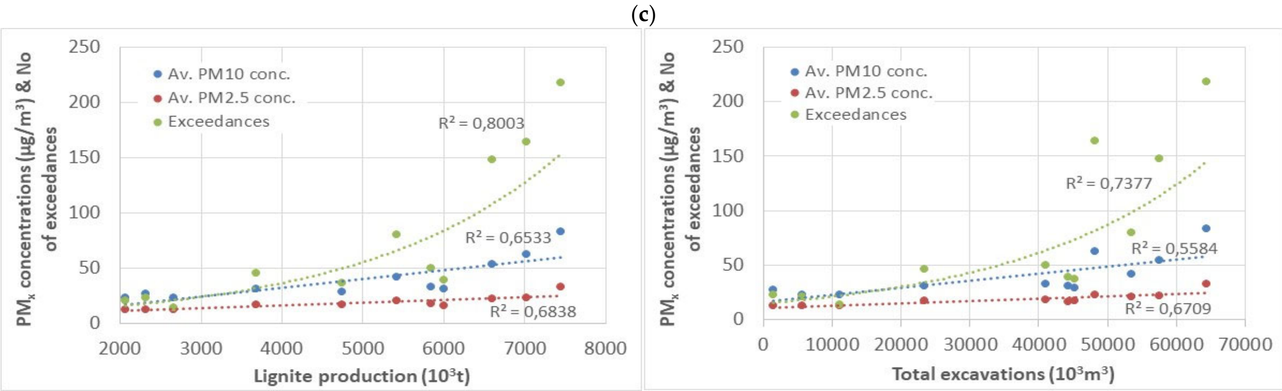

(**d**)

Figure 6. Correlation of the average PM_{10} and $PM_{2.5}$ concentrations and number of exceedances of the daily average PM_{10} concentrations from the limit value of 50 μg/m^3, as recorded in monitoring stations (MS) located in the vicinity of the mines, with the total annual rock excavations in four different lignite mining fields of Ptolemaida basin: (**a**) Main Field vs. Proastio MS; (**b**) Kardia Field vs. Pontokomi MS; (**c**) South Field vs. Kilada MS; (**d**) Amynteon mine vs. Anargiri MS (with dashed lines the linear and exponential regression lines).

The correlation coefficients shown in the diagrams of Figure 6 correspond to linear regression equations. Exponential regression was used only in cases where they had a significantly higher correlation coefficient than linear equations (these cases are illustrated in Figure 6).

According to the illustrated results, the correlation is considered strong for all four mines. Mavropigi mine (Figure 6a) exhibits the highest *R*-squared value for linear regression for all the three examined ambient air quality parameters: PM_{10} and $PM_{2.5}$ concentrations and the number of exceedances of daily average PM_{10} limit (i.e., pollution episodes). As it is observed, the correlation of both lignite production and total rock excavations with all ambient air quality parameters exhibits high *R*-squared values, ranging between 0.77 and 0.90. Kardia Field, South Field, and Amynteon mines (Figure 6b–d) also demonstrate high *R*-squared values.

In general, lignite production exhibit greater *R*-squared values when correlated with the number of pollution episodes, while, when correlated with PM_{10} and $PM_{2.5}$ concentrations, the *R*-squared values are similar. In addition, total rock excavations exhibit similarly high *R*-squared values for PM_{10} concentrations and the number of pollution episodes. However, in three out of the four examined cases, *R*-squared values for $PM_{2.5}$ were significantly lower than those of the other air quality parameters.

The results of the regression analysis are summarized in Table 1. The relatively wide range of fluctuations of R^2 values in most of the examined cases can be explained by uncertainties introduced by various site- and time-specific conditions. Especially in cases that exhibit low R^2 values, these uncertainties probably occurred due to changes in: (i) the areas within a mine, where excavations and dumping works are active; (ii) the route and distance of waste rocks haulage; (iii) the stripping ratio; (iv) the water quantities used for dust depression; and (v) the relevant position of sources and monitoring stations of particulates. These changes were occurred in the same time with the decrease in lignite mining activities and it is impossible to be distinguished.

Table 1. Range of fluctuation of *R*-squared value resulted from the linear or exponential regression (which was the maximum) of the correlated mines operation, and ambient air quality parameters of the four examined cases of mine–monitoring station.

		Ambient Air Quality Parameter		
		PM_{10}	**$PM_{2.5}$**	**No of Pollution Episodes**
Mine operation parameter	Lignite production	0.49–0.77	0.18–0.79	0.56–0.89
	Total rock excavations	0.56–0.90	0.45–0.78	0.65–0.88

In order to validate further the hypothesis of strong correlation between lignite extraction activities and ambient air quality in the vicinity of the mines of Ptolemaida basin, in Table 2 is presented a series of statistical parameters calculated for 16 simple regression tests carried out using lignite production and excavation volumes as independent variables and PM_{10} concentrations and number of exceedances as dependent variables. All the determined parameters confirm the correlation of all pairs of compared variables for all the four cases of mines vs. monitoring stations. However, this correlation is not equally strong in all cases. The PM_{10} concentrations recorded from Proastio MS, when related with total excavations of Main Field, exhibit t- and *p*-values of 9.42 and 0.00003, respectively. On the contrary, the PM_{10} concentrations recorded from Kilada MS, when related with lignite production of the South Field mine, exhibit t- and *p*-values of 2.62 and 0.03078, respectively. For the 12 out of the 16 cases that were examined *p*-values were <0.01, a value that is considered as evidence of strong correlation, while for the other four cases, the *p*-values were <0.05, a value that is indicative of moderate correlation.

Table 2. Main statistical parameters calculated from the regression tests using mines production figures as independent values and ambient air quality measurements as dependent values.

	Statistical Parameter	Lignite		Total Excavations	
		PM_{10}	Exceedances	PM_{10}	Exceedances
Main Field vs. Proastio MS	Coef. of correlation, R	0.9158	0.8867	0.9627	0.8663
	Coef. of determination, R^2	0.8386	0.7862	0.9268	0.7505
	Standard error of regression, s_r	4.72	25.72	3.18	27.79
	No of observations, n	9	9	9	9
	t-test	6.03	5.07	9.42	4.59
	p-value	0.00053	0.00144	0.00003	0.00252
Kardia Field vs. Pontokomi MS	Coef. of correlation, R	0.7940	0.7537	0.9072	0.8056
	Coef. of determination, R^2	0.6304	0.5681	0.8229	0.6490
	Standard error of regression, s_r	5.88	25.9	4.07	23.34
	No of observations, n	10	10	10	10
	t-test	3.69	3.24	6.10	3.84
	p-value	0.00610	0.01181	0.00029	0.00490
South Field vs. P Kilada MS	Coef. of correlation, R	0.6792	0.7778	0.8578	0.8422
	Coef. of determination, R^2	0.4613	0.6049	0.7359	0.7092
	Standard error of regression, s_r	3.64	5.26	2.55	4.51
	No of observations, n	10	10	10	10
	t-test	2.62	3.50	4.72	4.41
	p-value	0.03078	0.00808	0.00150	0.00223
Amynteon Mine vs. Anargiri MS	Coef. of correlation, R	0.7946	0.7936	0.7282	0.7232
	Coef. of determination, R^2	0.6314	0.6297	0.5304	0.5230
	Standard error of regression, s_r	12.59	43.88	14.21	49.81
	No of observations, n	10	10	10	10
	t-test	3.70	3.69	3.00	2.96
	p-value	0.00603	0.00614	0.01693	0.01810

Furthermore, in order to achieve better correlation of ambient air quality measurements of the Kilada monitoring station with independent variables, the rock excavations of the South Field mine were combined with meteorological data from the National Observatory of Athens monitoring station, which was installed on the roof of the central building of South Field mine. Table 3 presents the annual average values of the main meteorological parameters for the period 2011–2020.

Table 3. Annual average values of main weather parameters recorded in the South Field mine meteorological station in the period 2011–2020.

Year	Mean Temperature (°C)	Mean Outside Humidity (%)	Rain (mm)	Mean Wind Speed (km/h)
2011	12.1	65.0	440	5.1
2012	12.9	62.6	440	3.7
2013	13.1	63.8	464	4.5
2014	13.0	69.5	643	4.0
2015	12.7	65.8	616	3.9
2016	13.0	65.0	569	3.4
2017	12.9	62.6	408	3.2
2018	13.0	67.2	491	3.2
2019	12.8	64.2	596	4.4
2020	12.7	63.2	491	6.6

By applying multiple regression analysis and considering the annual precipitation values and the annual average wind speeds, the R-squared values for the correlation of the South Field mine operation parameters and ambient air quality parameters were determined (Table 4). According to this analysis, annual precipitation seems to have some correlation with air pollution. On the contrary, this is not the case for annual average wind speed. Although annual average wind speed exhibits also significant fluctuations, these do not coincide with the fluctuation of ambient air quality recorded in the closest located monitoring station. Obviously, the average wind speed is not representative of the number and the severity of extreme weather conditions (in terms of wind speed) that are implicated in air pollution episodes. Nevertheless, the present study tries to correlate the annual variations in mining activity with the records of particulate concentrations in order to predict the ambient air quality after the mine's closure. The whole range of operational, meteorological, etc., parameters that affect ambient air quality in the vicinity of the lignite mines have been described in detail in several studies [6–8,11,12,14–18,22].

Table 4. Comparison of *R*-squared values resulted by simple regression and multiple regression analysis for the correlation of operational parameters of the South Field mine and ambient air quality parameters recorded by Kilada MS.

		Ambient Air Quality Parameter		
		PM_{10}	**$PM_{2.5}$**	**No of Pollution Episodes**
Mine operation parameter	Lignite production	0.60 *0.49*	0.38 *0.18*	0.63 *0.60*
	Total rock excavations	0.79 *0.70*	0.57 *0.41*	0.71 *0.71*

In italics: the *R*-squared values of simple regression, for reasons of comparison.

It is emphasized that the number of pollution episodes used for the production of the relevant diagrams in Figure 6 does not include the exceedances that are certified to be associated with causes not related to the operation of mines and steam power stations.

Finally, in the case of the Amynteon mine, the records of two monitoring stations are compared in Figure 7. Anargiri MS is located in a village close to the mining activities, while Amynteon MS is located in a small town 5 km north of the mine. The reduction in rock excavations of Amynteon mine tends to minimize the differences between ambient air quality parameters measured in the two stations.

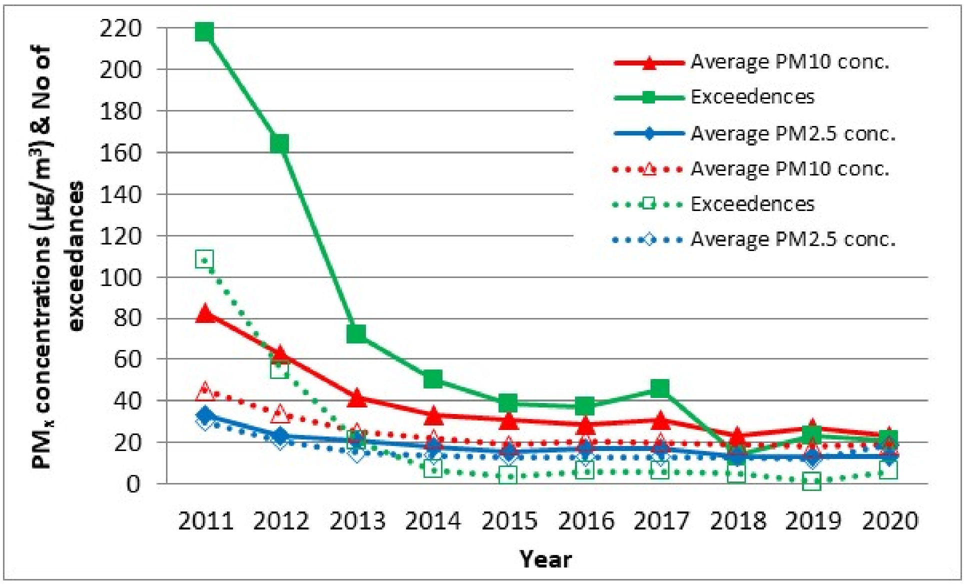

Figure 7. Comparison of ambient air quality parameters recorded in Anargiri and Amynteon MS, both located in the vicinity of Amynteon mine.

4. Discussion

Based on the above presented information regarding lignite mining activities in the basin of Ptolemaida, it is clear that in the 10-year period 2011–2020, both lignite production and total excavations volumes have been significantly reduced. This development can be justified in many ways: reduction in electricity demand due to the economic crisis that started in 2009; rapid development of renewable energy; and strong competition from natural gas-fired power stations and imported power due to the implementation of the European emissions trading scheme. The average reduction in total rock excavations with continuous mining equipment in the four mines under investigation was 78% and ranged from 55% to 99%, while for conventional mining systems (shovels and trucks), this reduction was 69% and ranged from 50% to 86%. As far as lignite production is concerned, the average reduction was 78%, and its range was from 72% to 97%. The fluctuations of lignite production follow those of total excavations volumes with two exceptions: (i) the South Field mine, where sub-contractors move large volumes of overburden in a new mining area, and (ii) in Amynteon mine, where extensive earth moving works were necessary after a landslide occurred in the upper benches of the mine.

Moreover, all mine production figures exhibited large year-to-year fluctuations in all mines. This fact indicates the significant variation in the stripping ratio from year to year, a development common in large lignite mines that supply almost exclusively a single thermal power plant. Consequently, the mines can operate in conditions that prioritize increased lignite production for short periods of high fuel demand, while in periods of low demand, they intensify operations relevant to the removal of overburden strata.

Notwithstanding the annual fluctuations, the 10-year period 2011–2020 was characterized by a significant reduction in lignite mining activities in Ptolemaida basin. This reduction resulted in considerable improvement of all monitored ambient air quality parameters. The decrease in the PM_{10} concentrations was higher than that of $PM_{2.5}$. Nevertheless, the most remarkable improvement of ambient air quality in all four cases of mines vs. monitoring stations shown regards the number of pollution episodes. Specifically, the reduction in the annual number of exceedances of the daily average PM_{10} concentration limit of 50 μg/m^3, which was recorded at five monitoring stations (Anargiri, Amynteo, Proastio, Pontokomi, and Kilada), varied between 78% and 99%, while for annual average PM_{10} and $PM_{2.5}$ concentrations, the reduction varied between 42% and 72%, and 50% and 62%, respectively. The fact that this improvement is measured higher in terms of a number of exceedances rather than average PM concentrations confirms the conclusions of a previous study [6] about the different pollution sources that are responsible for background and for pick concentrations. In fact, many pollution episodes are related to seasonal agricultural activities (e.g., combustion of biomass residues after harvesting) as well as the phenomenon of dust transfer from the Sahara Desert when strong southerly winds blow, which usually outbreaks in winter. According to a study [22] conducted in five Greek territories, the latter phenomenon is responsible for 47% of the pollution episodes recorded from January 2009 to December 2011. No matter what happens with these pollution sources, the number of pollution episodes that occurred during the dry summer period, and are directly related to mining activities, was significantly decreased. These episodes are expected in an area that hosts large-scale surface mines, where extended areas are still active with excavation and dumping operations. The particles emitted into the air by these operations, in cases of long dry periods and winds of high speed, are dispersed in the greater mining area and are recorded as high PM concentrations in the monitoring stations. Therefore, to the extent that these operations have been decreased, the circumstances that favor the development of a pollution episode are less probable to occur.

In addition, the reduction in the production rate of the mines also resulted in significant improvement in the effectiveness of measures applied for dust depression. For instance, by reducing the traffic on unpaved roads, tanker trucks can keep the road surfaces wet, in some cases with reduced water consumption. In addition, by reducing the load of belt conveyors that transport lignite, wasted rocks, and ash, the efficiency of water sprinkling systems that have been installed along the conveyors and at the transfer points is improved.

Another conclusion of this study is that the particulates concentrations are inversely proportional to the distance of MS from the mining operations, sometimes regardless of their position concerning the prevailing wind direction. In addition, as was expected, the observed decrease in particulate concentrations is more significant at monitoring stations located closer to mines and/or thermal power plants. Focusing on the area of the Amynteon mine, Amynteon MS, which is the one located further from the pollution sources in a small town 5 km north of the mine, records the lowest PM concentrations. Anargiri MS, which was initially installed at a distance of 500 m from the mine crest, later it was moved to the square of the village, at a distance of 1.5 km from the mine borders. It is mainly affected by emissions of particulates coming from the Amynteon mine, which is located west of this station, and the external dumping area of Amynteon mine, which is located south, southwest. Agricultural activities there are to the north of the monitoring station, while to the east, there is Lake Chimaditis and agricultural activities. In the early years of the examined period, this MS exhibited severe pollution episodes no matter the direction of the wind that was blown. This situation was gradually changed, and in 2020 the few pollution episodes were related to wind coming from the external dumping area of the mine. Pentavrisos MS, although it is located 5 km southwest from the external dumping area of Amynteon mine, records low average PM concentrations but a relatively high number of pollution episodes. Previous studies [14] have shown that particulates collected in Pentavrisos MS originated from the mining complex of Ptolemais rather than that of Amynteon; although, Ptolemais mines are located further from this station and to the south, a direction that does not favor the transfer of particulates when the prevailing winds of the basin are blowing. This is proof of the existence of local wind currents that complicate further the air pollution pattern in the area under investigation.

Regarding the regression analysis results, the remarks can be divided into three categories:

Spatial differences. As expected, the air quality measurements at the monitoring stations located further from the mining activities exhibit the minimum correlation with the fluctuations in the rock excavations. The four monitoring stations under investigation demonstrate high *R*-squared values. However, Proastio MS, which is located at a distance of 750m from the crest of Mavropigi mine pit, exhibits the highest *R*-squared value for linear regression for all the three examined ambient air quality parameters: PM_{10} and $PM_{2.5}$ concentrations and the number of exceedances of daily average PM_{10} limit (i.e., pollution episodes). In particular, the correlation of both lignite production and total rock excavations with all ambient air quality parameters exhibits *R*-squared values ranging between 0.77 and 0.90. For comparison reasons, it must be mentioned that the distance of Pontokomi and Anargiri MSs from the neighboring mining activities is twice that of Proastio MS, while Kilada MS is located 7 km away from South Field mine and 3.5 km from Agios Dimitrios power plant.

Differences regarding the correlated parameters. In general, lignite production exhibits greater *R*-squared values when correlated with the number of pollution episodes, while when correlated with PM_{10} and $PM_{2.5}$ concentrations, the *R*-squared values are similar. In addition, total rock excavations exhibit similarly high *R*-squared values for PM_{10} concentrations and the number of pollution episodes. However, in three out of the four examined cases, *R*-squared values for $PM_{2.5}$ were significantly lower than those of the other air quality parameters.

Improvements were achieved by adding more independent variables. Annual precipitation seems to have some correlation with air pollution. On the contrary, this is not the case for annual average wind speed, which obviously is not representative of the number and the severity of extreme weather conditions (in terms of wind direction and speed) that are implicated in air pollution episodes.

The above remarks are supported not only by the *R*-squared values but also by *p*-value and t statistic tests, which were carried out using the same data series. Regarding the standard error of the regression analysis, its values in the case of the South Field mine are relatively low, taking into consideration how the values of the other statistical parameters vary. This can be probably explained by the fact that the standard error of the regression is independent of the dispersion of x values (lignite production or total excavations) within the examined time frame (years 2011–2020).

Finally, it is worth discussing the previous remarks, which were based on the correlation between the ambient air quality measurements in Anargiri MS and Amynteon MS. The latter station is located far from the mining activities in a direction that does not favor the transport of particulates from the winds prevailing in this part of the Ptolemaida basin. Therefore, it can be used as a reference station for a preliminary comparative analysis. According to this, the gradual reduction in rock excavations tends to minimize the differences between ambient air quality parameters measured in the monitoring station located nearby the mines and thermal power plants (Anargiri MS), with these measured in stations located relatively further away (Amynteon MS). Based on this fact, it can be safely predicted that the phase-out of lignite mining activities will result in air pollution close to the background level for rural areas of Southern Europe, which is determined mainly from seasonal agricultural activities and the operation of heating systems (burning diesel oil and biomass) during the winter. Although this development seems to happen regardless of the progress of the mine land rehabilitation and repurposing plan, which is described in the relevant environmental permit, it is worth mentioning that an ambitious land repurposing program is under development, taking advantage of financial tools available for the just energy transition of regions that host coal/lignite production activities. The implementation of this plan has already been started for the mine of Amynteon, which has entered the closure phase. The new land uses of this plan include forests, recreational areas around the lakes that will be formed in the final pits, agricultural land, industrial areas, and photovoltaic parks. Although earth moving works and other activities carried out to prepare the final mine surfaces temporarily add to the air pollution problem in the vicinity of the mines, it is sure that their contribution to the improvement in quality-of-life standards in the greater area will be remarkable.

5. Conclusions

The reduction in the rock volumes excavated and lignite quantities produced in the surface mines of Western Macedonia Lignite Centre during the 10-year period 2011–2020 resulted in a significant reduction in particulates concentrations in the entire lignite-bearing basin. This result is more so in the vicinity of mines that have already ceased operations, such as Amynteon and Kardia mines.

In general, the correlation of air quality parameters was better with total excavations and not with lignite production. From a different perspective, the correlation of mine production was better with the number of pollution episodes, quite good with PM_{10} concentrations, and less strong with $PM_{2.5}$ concentrations.

Based on the analysis presented in the previous paragraphs, it can be predicted that, after the phase-out of all electricity generation activities, the ambient air quality will reach the levels that are typical for rural areas of Southern Europe and Mediterranean countries. The contribution of diffuse sources, such as the thousands of hectares of excavation pits and, predominantly, waste heaps that have not yet been properly reclaimed and are covered by limited vegetation, seems to be insufficient to cause many pollution episodes. This is an important conclusion considering that the closure of lignite mines has recently been rescheduled from 2042 to 2028 (with the closure year likely to be revised from 2028 to another date, depending on the future electricity market). It essentially means that new economic activities that will be selected to compensate for the phase-out of the power generation industry, will be designed and implemented in parallel with a huge land rehabilitation program, without the well-known obstacles that existed until recently, which were, in general, related to air pollution and environmental degradation.

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