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Adverse Health Effects (Bronchitis Cases) Due to Particulate Matter Exposure: A Twenty-Year Scenario Analysis for the Greater Athens Area (Greece) Using the AirQ+ Model

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Abstract: It is well known that air pollution has a negative impact on human health. Research has shown an increasing trend in hospital admissions due to respiratory and heart diseases during and after consecutive days of high or even medium air pollution levels. The objective of this paper is to provide quantitative and qualitative data concerning the impact of long-term air pollution on the health of residents living in the Greater Athens Area (GAA). More accurately, the prevalence of bronchitis in children and the incidence of chronic bronchitis cases in adults due to particulate matter exposure are estimated utilizing the AirQ+ model. For this purpose, daily average concentrations of particulate matter with an aerodynamic diameter less than or equal to 10 μm (PM_{10}) from five different locations within the GAA, covering the period 2001–2020, are used. The results show a significant correlation between PM_{10} concentrations and adverse health effects (R^2 = 0.9). Interestingly, there were more cases of children suffering from bronchitis disease than cases of adults. In addition, it was observed that the unhealthiest areas in the GAA are the center of Athens city (mean annual PM_{10} concentration in 2019: 36 $\mu gr/m^3$), as well as suburban areas (Lykovrissi and Marousi: mean annual PM_{10} concentrations in 2019 were 27 $\mu gr/m^3$ and 28 $\mu gr/m^3$, respectively). Finally, a decreasing trend for both PM_{10} concentrations and the prevalence of chronic bronchitis across the GAA was observed through the examined 20 years, which was significantly higher over the period 2010–2020.

Keywords: PM_{10} exposure; bronchitis; AirQ+ model; Athens; Greece

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1. Introduction

Since breathing is essential for life, clean air is vital not only for humans but for all creatures on earth. However, in large urban centers the degradation of air quality is high, and the inhalation of pollutants in concentrations above the limits proposed by the WHO causes serious damage to human health.

High concentrations of particulate matter in the atmosphere are associated with an increase in the number of hospital admissions due to respiratory infections, bronchitis, asthma, and pneumonia. The size of suspended particles, their chemical composition and their coexistence with other pollutants are determining factors for environmental pollution. According to the European Environmental Agency [1], the burdening of human health is affected by the residence area, the population density, and the existing ventilation, as well as the duration of exposure to harmful particles. Gibson et al. [2] stated that respiratory diseases cause one sixth of all deaths worldwide. In the European Union (EU), one eighth of deaths every year are due to diseases of the respiratory system. Lung diseases in particular are responsible for six million hospital admissions and air pollution is recognized as the main aggravating component affecting the human respiratory system [3].

It should be mentioned that the airways (bronchi) of people with asthma are more sensitive to various stimuli and react more strongly than people without asthma [4]. It is a problem that concerns both adults and children. Ferrante et al. [5] found that asthma has become the most frequent chronic disease among children and is one of the major causes of hospitalization among those younger than 15 years of age. There is a significant correlation between the hospital admissions as well as outpatient visits due to episodes of bronchial asthma and the concentration of SO_2, O_3, and PM_{10} in the atmosphere, in particular during days with high temperature and humidity [6,7].

In recent years, there has been an increase in asthma cases. In Greece, asthma is a chronic respiratory disease that affects approximately 5% of children and 2.5% of adults. The frequency of asthma incidences is increased in Attica, the Peloponnese, and Crete, while lower rates are found in Northern Greece and the island regions [8]. This is because of differences in the prevailing climatic conditions in each region, as well as the different exposure to irritants and allergens in the environment. The air quality in each region is another important parameter. Nastos et al. [9] showed that the increase in child hospitalization in Athens is associated with a rise of PM_{10} concentrations. These results are in line with similar studies worldwide [10–12]. In addition, it was found that the more days of exposure to air pollutants, the more asthma hospitalizations were recorded. Regarding adults, many researchers have highlighted an increase in doctor visits and hospital admissions for respiratory and heart diseases during days of continuous exceedances of PM concentrations [13,14]. A recent epidemiological study has demonstrated a synergistic effect of PM_{10} concentration and ambient temperature on elderly mortality [15], while Canova et al. [16] indicated that an increase in asthma and chronic pulmonary disease rate was related to a 10 $\mu gr/m^3$ increase in PM_{10} concentrations.

The improvement in air quality could bring significant health benefits, such as reduced premature deaths and cardiovascular and respiratory diseases. It is not only important to consider the negative effects of air pollution on public health, but also the assessments of the potential positive health effects that will be achieved through the reduction in air pollutants and particle concentrations [17]. For this reason, many tools have been developed worldwide. The software AirQ+ version 1.3, which is provided by the WHO, performs calculations that render the environmentalist able to recognize the magnitude of the health effects due to exposure to air pollution [18]. Applications of the AirQ+ software worldwide have indicated that increased hospitalizations due to cardiovascular and respiratory diseases occur when the mean annual PM_{10} concentration is higher than the standard level [19]. It was also estimated that a reduction on the annual mean $PM_{2.5}$ concentrations would drive a consequent reduction in the incidence of ischemic heart diseases (IHD), chronic obstructive pulmonary diseases (COPD), lung cancer (LC), stroke, and the number of working days lost (WDL) [20]. The impact of air pollutants on human health can also be assessed through the integration of different technics: data statistics (spatial and temporal trends), population attributable fraction using the AIRQ+ model, and burden of disease using Disability-Adjusted Life Years (DALYs) [21]. Usually PM_{10}, $PM_{2.5}$, and $PM_{10}/PM_{2.5}$ are calculated with the AirQ+ software in order to examine the effects on total mortality, respiratory and cardiovascular mortality [22,23], as well as hospital admissions [24–26]. Another useful tool is the Global Burden of Disease (GBD), which is led by the Institute for Health Metrics and Evaluation (IHME) at the University of Washington. By applying GBD to the characteristics of childhood asthma (DALYs, mortality) by age group [27], trends in chronic respiratory disease-related mortality [28,29] as well as the effect of $PM_{2.5}$ concentrations on asthmatic children were quantified [30]. The global burden of disease from the major air pollution sources and through the personal exposure to $PM_{2.5}$ was estimated by McDuffie et al. [31]. The Environmental Benefits Mapping and

Analysis Program—Community Edition (BenMAP—CE) is another tool, released by the U.S. Environmental Protection Agency (U.S. EPA), which is used for the estimation of the health and economic benefits of attaining Ambient Air Quality Standards mainly in the U.S. [17]. Among the main differences between the above tools are the estimation method of nonlinear effects with AirQ and GBD, and the calculation of potential economic benefits with the BenMAP—CE. As can be understood from the literature, the majority of studies have investigated the effect of particulate matter on human health with the use of statistical approaches and/or software. However, for the Greater Athens Area, which is the most populated area in Greece (approx. 4.5 million inhabitants), the qualitative and quantitative effect of long-term exposure to PM_{10} particulate pollution on public health remains unclear. In Greece, national data on asthma have been collected and reported by HAS since 2009 and are updated every five years. Specifically, in 2014, HSA reported that 3.1% of the population aged 15–24 years, 6.3% of the population aged 65–74 years, and 9.1% of the population aged 75+ years were affected by asthma. Furthermore, according to a 2019 HSA publication, it is reported that asthma is the first disease which children aged 2–14 years develop [32]. The main problem for Greece is that data are collected annually separately by each hospital and are publicly available under request, but the national registration is carried out every five years.

The aim of the present study is the quantification of the spatiotemporal variation in suspended particles (PM_{10}) in the Greater Athens Area over a twenty-year period (2001–2020 period), and the investigation of the adverse health effects due to long-term exposure to PM_{10}, especially chronic adult bronchitis cases (CBI) and prevalence of bronchitis in children (BC) in Athens, Greece via the application of the AirQ+ model. This software was selected among others because a long timeseries of PM_{10} concentrations was available and a relevant module for the impact of PM_{10} exposure on health exists in AirQ+. A state-of-the-art analysis of the temporal variation in public health due to particulate matter is also presented. The characteristics, as well as the parameters that lead to high pollutant concentrations in the Greater Athens Area, are presented in Section 2. The PM_{10} measurements and the AirQ+ software that were used for the estimation of the impact of particulate pollution on public health are also presented in Section 2. The results and discussion on the findings of the present study are explained in Section 3. Finally, the main conclusions are summarized in Section 4.

2. Materials and Methods

2.1. Study Area Description

The Greater Athens Area (GAA) is located within the Attica basin and it is the most populated area in Greece. It belongs to the Attica Region (Figure 1) and it is the most densely populated region of Greece, accounting for 1/3 of the country's population (3.09 million) [33]. The region of Attica is in the southeastern part of Central Greece. It is a triangular peninsula that is bathed by the Aegean Sea and is defined by five mountains that surround the Attica basin (Egaleo, Poikilo, Parnitha, Penteli, and Ymittos). It has a typical Mediterranean climate with mild rainy winters and hot dry summers. The temperature remains high during the winter, with the average value in January being around 9.2 °C. During the summer temperature reaches very high levels, while a heat wave and temperatures above 40 °C are recorded two to three times every year [34].

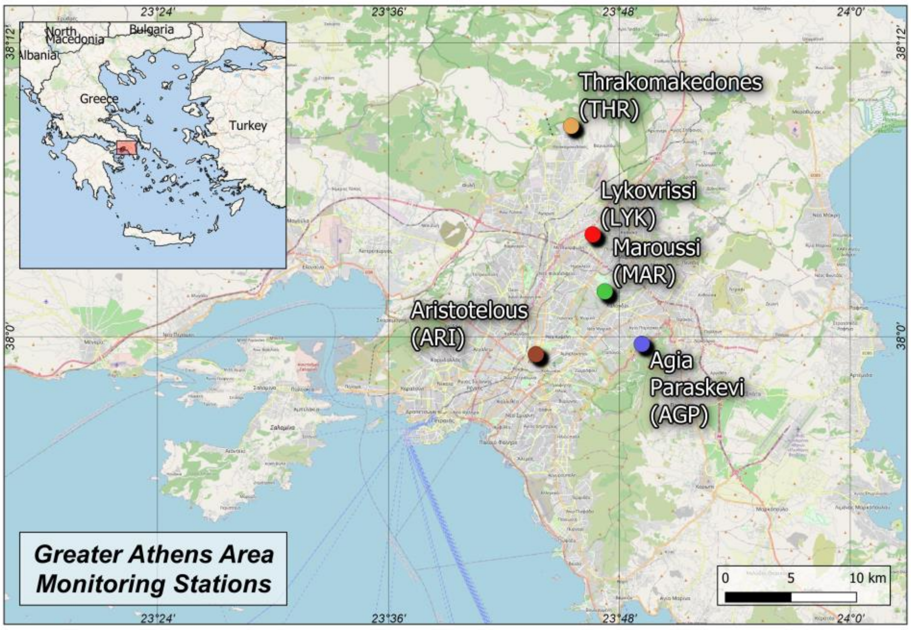


Figure 1. Map with the location of PM_{10} monitoring stations within the GAA (Satellite image by ESRI).

Air pollution in the GAA is mainly due to anthropogenic activities, such as road transport, industry, emissions due to building heating consumption, and vehicle emissions [35]. It is assumed that at least 2 million vehicles circulate every day within the GAA [36]. Moreover, there are many natural reasons that exacerbate the GAA's air pollution problem, such as Mediterranean sunshine, which is the key factor in enhancing levels of photochemical pollution and transboundary air pollution, mostly for PM_{10}, which is the transportation of dust particles from neighboring North African countries [37]. This phenomenon is also known as a Sahara dust event [20,38]. During spring and autumn, desert dust phenomena come about in Athens with an occurrence of approximate 30 days per year [39]. Although most such dust events arise from the Sahara Desert, some of them arise from the Arabian Peninsula. Previous studies, on assessing the health effects from desert dust events in the city of Athens, showed that they were associated with an increase in childhood asthma admissions [40], while the consequences on mortality could not be adequately associated with PM_{10} levels [41]. Moreover, Trianti et al. [42] confirm that desert dust episode days are associated with higher respiratory emergency room visits and hospital admissions. This effect is not sufficiently explained by increased PM_{10} levels. According to recent research on chemical composition, the desert dust was found to contain nine metals, such as lead, arsenic, iron, and nickel. This fact suggests that the wind-borne sand contains chemical elements derived from anthropogenic sources such as industry and automobile traffic. It has been confirmed that the desert dust particles pass over urban centers, or even mega-cities such as Cairo, that have a polluted atmosphere [40,43].

It should be also emphasized that the air pollution problem is aggravated further by topographical factors such as the surrounding/encircling mountains, the narrow street canyons, temperature inversion effects, the low wind speed, and the high air temperature [42,44]. Moreover, when sea breezes enter from the Saronic Gulf in the southwest, affecting the Athens basin, then the conditions of dispersion of air pollutants in the Greater Athens Area deteriorate greatly [45].

2.2. Air Pollution Data and Population

In the present study, two scenarios concerning the health effects of the residents of the Greater Athens Area due to long-term exposure to air pollution were considered. The first scenario concerned cases of bronchitis in children, and the second concerned cases in adults.

For this purpose, PM_{10} mean daily concentrations covering the period 2001–2020 were obtained from five different air pollution monitoring stations (Figure 1) located in the GAA. These stations belong to the air pollution monitoring network of the Attica region, which belongs to the Directorate of Climate Change and Air Quality (KAPA) and is operated under the supervision of the Hellenic Ministry of Environment and Energy (MEE) [46].

The locations of the air pollution monitoring stations examined in this paper are shown in Figure 1. The specific map was produced with the use of Quantum GIS by means of ESRI images.

Table 1 presents detailed data concerning the five monitoring stations. The examined monitoring stations are classified as urban traffic (UT), urban background (UB), and suburban background (SB) based on their location and their categorization due to air pollution sources. Furthermore, the local district population data of each station, taken from the Hellenic Statistical Authority (HAS) according to the 2011 population census [32], are provided. Finally, Table 1 depicts the PM_{10} data completeness. The five examined locations were selected because their data completeness was at least 80.0%. The statistical analysis and the processing of PM_{10} concentrations were carried out in accordance with the directive 2008/50/EC of the European Parliament [47], which sets an annual threshold concentration value of 40 μgr/m^3 and a 24 h threshold value of 50 μgr/m^3 that should not to be exceeded more than 35 times per year.

Table 1. The characteristics of the examined air pollution monitoring stations within the GAA.

	Aristotelous	**Agia Paraskevi**	**Maroussi**	**Thrakomakedones**	**Lykovrissi**
Abbreviation	ARI	AGP	MAR	THR	LYK
Area Size km^2	39	8	13	4	4
Longitude	23.727617	23.819421	23.787372	23.758195	23.788986
Latitude	37.988066	37.995110	38.030837	38.143521	38.067793
Characterization	UT	SB	UB	SB	SB
Population	664,000	60,000	73,000	6200	10,000
Population (Kids)	65,670	5934	7220	613	1000
PM_{10} Data Completeness	87.10%	90.02%	81.20%	83.36%	90.21%

2.3. AirQ+ Model

Health effects due to long-term PM_{10} exposure were quantified using the AirQ+ model (version 1.3) developed by the World Health Organization (WHO) Regional Office for Europe [18]. The AirQ+ model requires the following data:

1. Details of the area: location and total population.

   Table 1 data was used.

2. Mean annual PM_{10} concentration (PM_{10}).

For each year of the period 2001–2020 and for each one of the five examined locations within the GAA, a dataset of PM_{10} mean daily concentrations was constructed (i.e., $20 \times 5 = 100$ datasets).

3. Type of the health impact:
   (a) Prevalence of bronchitis in children (BC), measured as BC cases per 100,000 inhabitants.
   (b) Adult chronic bronchitis long-term incidence in adults (CBI), measured as CBI cases per 100,000 inhabitants.
4. The Relative Risk (*RR*): A statistical parameter used in epidemiological studies, given by the exponential formula:

$$RR = exp^{[\beta(X - X_o)]} \quad (1)$$

where, (X) is the annual mean concentration and (X_o) is the cut-off, i.e., the lowest concentration of PM_{10} during the year, the concentration below which no quantification of the health impact is considered. The WHO Regional Office for Europe suggests X_o = 20 μgr/m^3. Additionally, β is an empirical variable used to estimate the change in *RR* for a different value of *X*, for which WHO, after epidemiological studies, suggests for Europe β = 0.0008 [36,44,48,49]. RR is an important function in determining the mortality or morbidity of health outcomes from an ambient air pollutant exposure within a given area. The RR is an indication of the degree of the probability of experiencing health effects when pollutant exposure concentration increases (per 10 μgr/m^3 increase). The AirQ+ software model is based on default RR datasets from cohort studies and city-specific baseline incidence rates (BI) (a total number of expected incidents per 100,000 inhabitants per year) for health risk estimation [18,50]. It should be noted that the AirQ+ (version 1.3) [50,51] requires, in advance, a user choice at the beginning of the data input between the prevalence of bronchitis in children and adult chronic bronchitis so it can utilize the suitable and corresponding RR; i.e., for children 1.08 (0.98–1.19) and for adult 1.008 (1.0048–1.0112). These values are proposed by the HRAPIE experts [51] as a result of attempting to provide the best evidence-based estimation concerning the relationship between pollutants and health outcomes. The value 1.08 of RR represents an 8% additional incidence of bronchitis in the child population for every 10 μg/m^3 increase in PM_{10}. Additionally, 0.98 and 1.19 are the lower and upper bounds of RR, respectively. Similarly, the 1.008 of RR represents an 0.8% additional incidence of bronchitis in the adult population for every 10 μg/m^3 increase in PM_{10}. Therefore, 1.0048 and 1.0112 are the lower and upper bounds of the RR. However, there are some limitations concerning the application of the AirQ+ software including: (a) the production of annual results (it is not possible to study the seasonal variability of the impact from particulate pollution on health), (b) the use of specific pollutants (only particles—PM_{10} and $PM_{2.5}$—can be selected at the AirQ+ application), and (c) the interaction between pollutants cannot be studied.

With the use of the AirQ+ software, two scenarios were investigated in order to estimate the health effects of PM_{10} for the whole examined period 2001–2020 on an annual basis [18,50]. In the first scenario, the long-term effects on children's health, as measured by the prevalence of bronchitis (BC) due to PM_{10} concentrations, was investigated using the default RR values: 1.08 (CI 1.00–1.19). In the second scenario, the incidences of chronic bronchitis in adults (CBI) were estimated, using the default RR values: 1.008 (CI 1.0048–1.0112). It should be noted that Greece, harmonized with the guidelines of the Europe Council, has set a cut-off concentration value of 20 μgr/m^3 as the lowest assessment threshold [51]. This default limit means that the AirQ+ software calculates the burden on human health when the pollution exceeds this concentration.

3. Results and Discussion

3.1. Statistical Analyses of the PM_{10} Concentrations Timeseries

Table 2 presents the results obtained from the statistical analysis of PM_{10} concentrations for the periods 2001–2010 and 2011–2020. Overall, a steady reduction in PM_{10} concentrations was identified across the region through the examined years, with a significantly higher decrease over the 2010–2020 period. More specifically, for the period 2011–2020 PM_{10} concentrations were reduced by about 20 μgr/m^3 in all parameters and in all regions except for the annual minimum. The annual maximum concentration of PM_{10} was not recorded at Aristotelous station (in the center of Athens) but at the stations of Lykovrisi, Agia Paraskevi, and Thracomakedones. This confirms that the closed topography of the Attica basin and the sea breeze coming in from the south from the Saronic Gulf exacerbate air pollution in the suburbs. Moreover, the difference between the two periods can be explained by the growing use of the underground/metro and Attiki Odos highway, which both discharge a lot of the center's traffic jams. Specifically, two new lines of the underground train started to operate in 2000 and thereafter have served daily about 1.0–1.5 million passengers [52,53]. Furthermore, in 2001, the new 70km Attiki Odos urban highway, the regional ring of the GAA and the backbone of the Attica basin road network, started to operate. This highway provides fewer traffic jams, higher speeds, and lower emissions [54]. Moreover, in 2002–2003, bus lanes were created on the right side of the roads for the exclusive use of public buses [55]. As a result of this measure, there has been an overall improvement in traffic mainly in the city center, resulting in a reduction in PM_{10} concentrations. In addition, in 2001, the new Eleftherios Venizelos international began to operate away from the urban fabric on the eastern side of the GAA, replacing the old international airport that was very close to the center of Athens, south of the GAA. The new airport is connected to the city center as well as to most suburban areas, with the new metro lines and the new urban highway "Attiki Odos" opposite to the old airport, which was accessible only by private car, taxi, or public bus, usually through the city center [56]. Furthermore, the Greek economic crisis (2009 to date) has brought a significant reduction in construction and energy consumption, resulting in the diminution of excessive use or even the cessation of car and oil heating system use. Moreover, in 2020 and especially the period from mid-March to mid-May, the outbreak of COVID-19 resulted in major social distancing measures that contributed to the lowest traffic volume in recent years.

Table 2. Indicators for assessing the impact of PM_{10} and the annual mean concentration (μgr/m^3) at each station for two periods (2001–2010, 2011–2020).

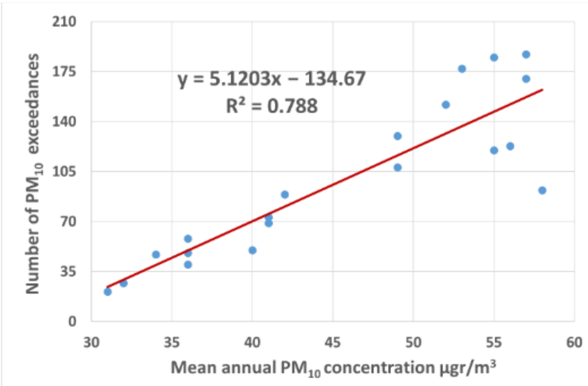
Parameter	ARI		AGP		MAR		THR		LYK	
	2001–2010	2011–2020	2001–2010	2011–2020	2001–2010	2011–2020	2001–2010	2011–2020	2001–2010	2011–2020
Annual Average	54	37	35	21	47	31	30	21	55	29
Cold Season Average	57	40	30	19	52	35	27	20	56	32
Warm Season Average	51	34	39	22	41	27	33	23	53	27
Annual 98th Percentile	115	95	98	52	114	92	82	58	122	89
Annual Minimum	8	6	17	11	12	7	5	4	10	7
Annual Maximum	191	164	226	193	207	193	211	180	247	188

Comparing mean seasonal concentrations, lower concentrations were recorded at traffic stations (ARI, MAR, LYK) during the warm periods, while at the suburban stations (AGP, THR), PM_{10} concentrations were much higher in the warm period (about 3 μgr/m^3 difference at THR and AGP stations for the period 2011–2020).

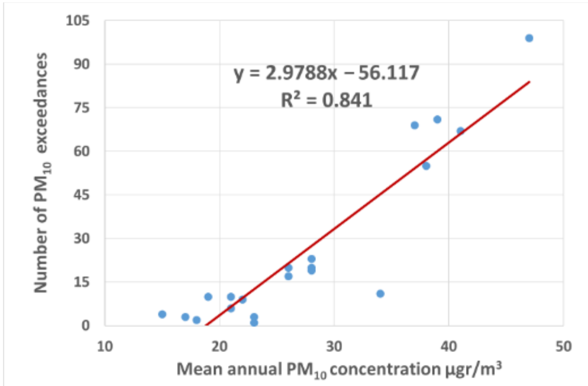
Figure 2 depicts the correlation between the annual number of PM_{10} daily exceedances and the mean annual value of PM_{10} for all the examined stations. These two parameters are strongly correlated since R^2 is significantly high and ranges from 67.7% up to 93.4% for all examined stations. It should be noted that the ARI station has the highest annual number of exceedances and at the same time the highest PM_{10} mean annual concentration. This verifies that the center of Athens is the most polluted area, and more measures need to be taken by the State in order to reduce PM_{10} air pollution.

3.2. Scenario Results (AirQ+ Application Results)

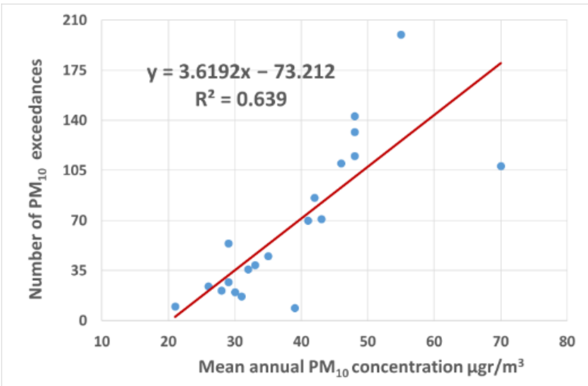
The following figures present the results of the estimates of respiratory causes using the AirQ+ software due to PM_{10} in the GAA. Figure 3 depicts the cumulative annual prevalence of bronchitis in children (BC) per 100,000 inhabitants during 2001–2020 attributable to PM_{10}, as summed over the five examined monitoring stations in the GAA. A significant decreasing annual trend of BC within the GAA was observed. By implementing the least squares method, a very strong linear correlation with a coefficient of determination R^2 = 0.934 is presented. It is also shown that the annual reduction in BC was about of 59.79 cases per year.



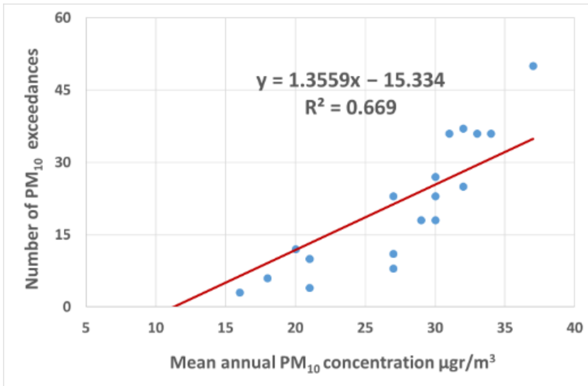
(a) ARI



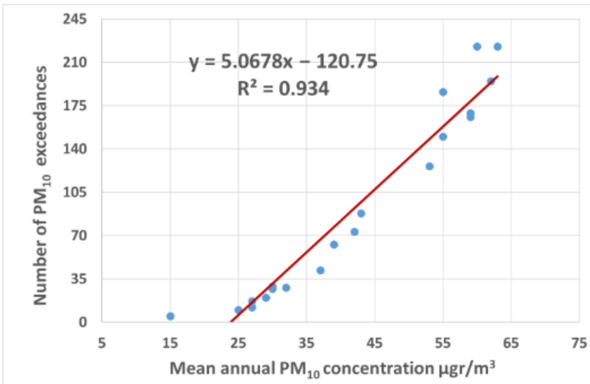
(b) AGP



(c) MAR



(d) THR



(e) LYK

Figure 2. Annual number of PM_{10} exceedances vs. the mean annual concentrations of all examined stations within the GAA.The red line refers to the central trendline. Period 2001–2020. ((**a**): ARI, (**b**): AGP, (**c**): MAR, (**d**): THR, (**e**): LYK).

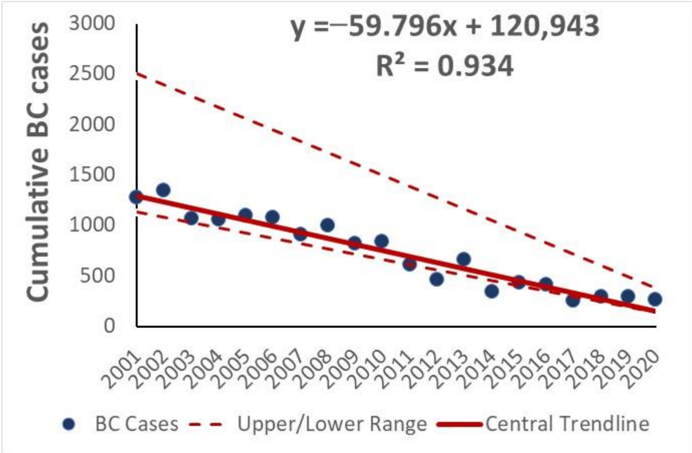


Figure 3. Annual variation in cumulative number of BC due to PM_{10} exposure. GAA. Period 2001–2020.

Figure 4 depicts the cumulative annual number of CBI in adults per 100,000 inhabitants during the examined period 2001–2020 attributable to PM_{10}, summed over the five examined monitoring stations. A significant decreasing trend of CBI within the GAA was also observed. By implementing the least squares method, a very strong linear correlation with a coefficient of determination $R^2 = 0.953$ is presented. Furthermore, an annual reduction in CBI of approximately 7.2 cases per year is also shown.

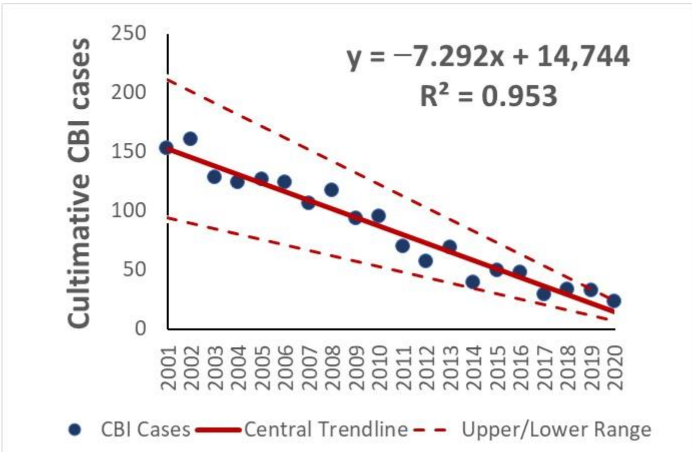


Figure 4. Annual variation in cumulative number of adults' chronic bronchitis incidents due to PM_{10} exposure. GAA. Period 2001–2020.

Comparing the two above figures revealed that children seem to be more sensitive to air pollution due to PM_{10} than adults. The worsening of the frequency and intensity of asthma attacks in children with the change in air pollution is pointed out, as other researchers have identified for the Great Athens Area [9,57].

In the following Figures 5 and 6, human harmful exposure to PM_{10} is further investigated utilizing the AirQ+ software. For this, the mean annual PM_{10} concentration was calculated for each one of the five examined monitoring stations within the GAA during the period 2001–2020.

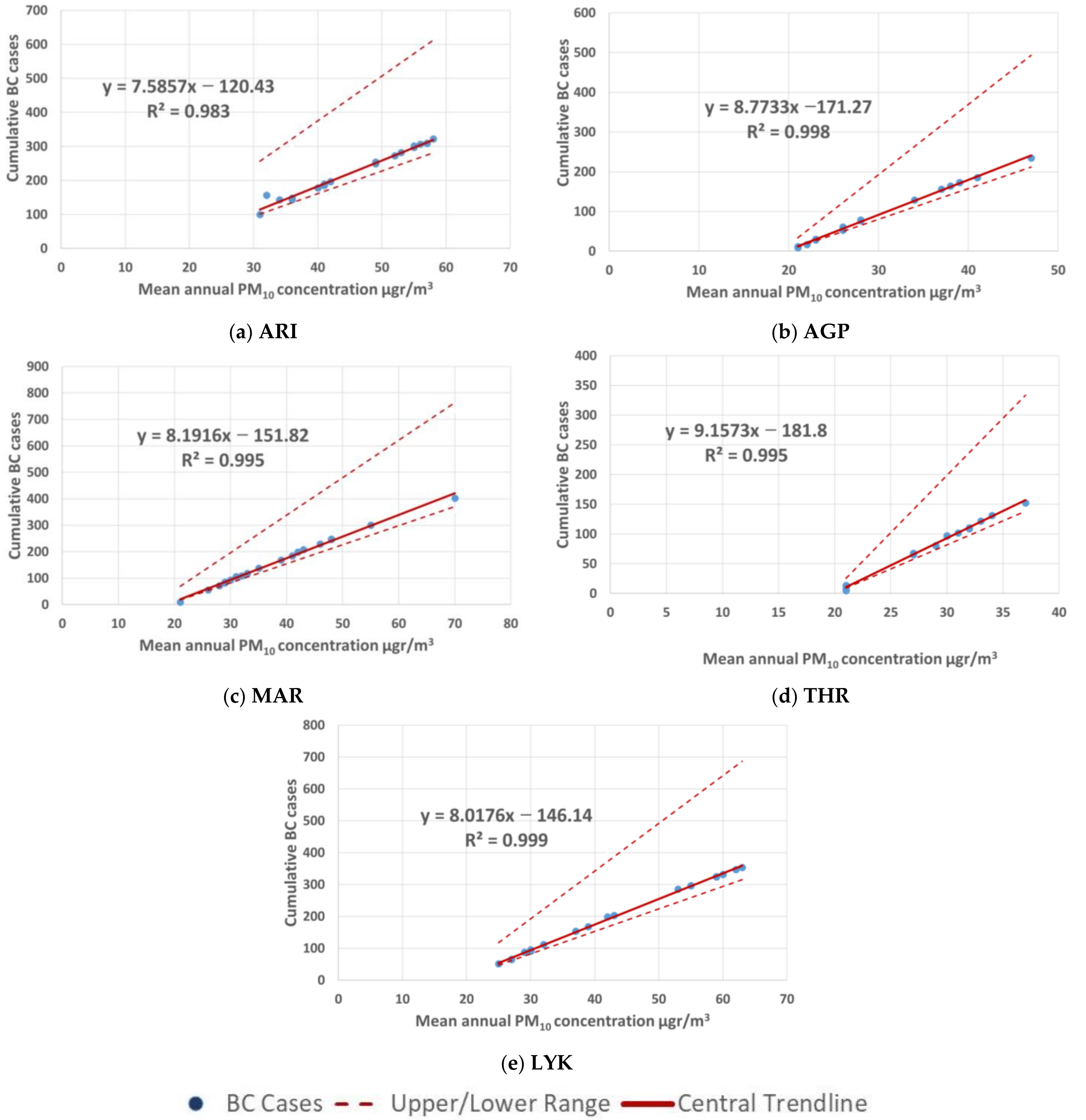


Figure 5. Annual variation in cumulative number of prevalence of bronchitis in children due to PM_{10} exposure vs. mean annual concentrations of all examined stations within the GAA. Period 2001–2020. ((**a**): ARI, (**b**): AGP, (**c**): MAR, (**d**): THR, (**e**): LYK).

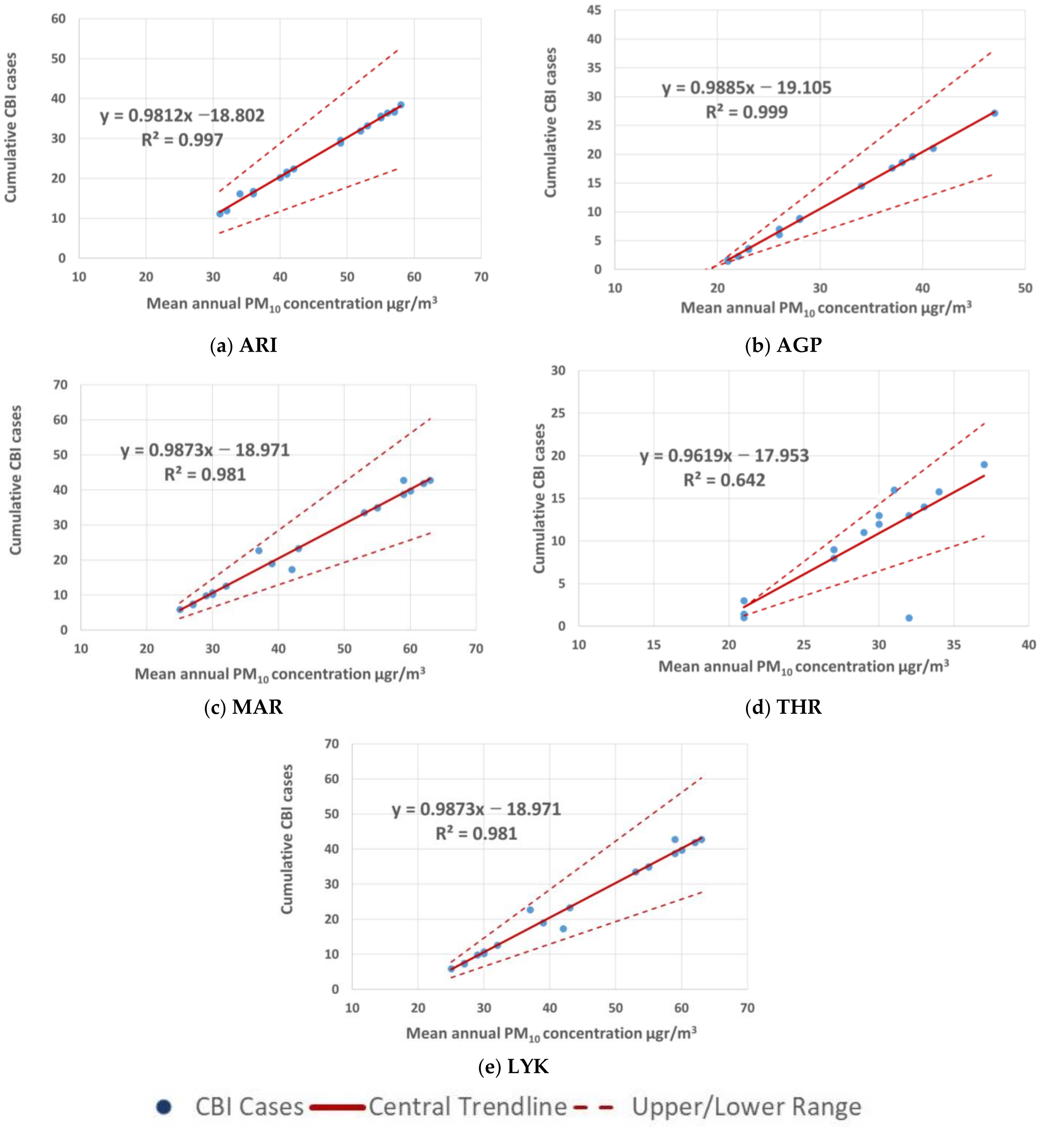


Figure 6. Annual variation in cumulative number of bronchitis incidents in adults due to PM_{10} exposure vs. mean annual concentrations of all examined stations within the GAA. Period 2001–2020. ((**a**): ARI, (**b**): AGP, (**c**): MAR, (**d**): THR, (**e**): LYK).

In Figure 5, the correlation between the annual variation in the cumulative number of bronchitis in children (BC) and the annual mean concentration PM_{10} for each monitoring station is indicated. The presented equations reveal a strong linear correlation between the BC and the increased PM_{10} concentrations. For instance, at Marousi station (MAR) the highest mean annual PM_{10} concentration was found in 2002 (70 μgr/m^3), and 402 cases of BC were calculated with the AirQ+ for the same year. However, the lowest mean annual

PM_{10} concentration at the same station was recorded in 2020 (21 μgr/m^3) and only 10 cases of BC were calculated with the AirQ+. All examined air pollution monitoring sites (i.e., ARI, AGP, MAR, LYK, and THR) showed a high value of R^2, approximately 0.99. This fact implies the danger when high mean annual PM_{10} concentration level occurs thus resulting in increased BC episodes.

Furthermore, from the linear regression equations, it appears that the lowest level of mean annual PM_{10} concentration concerning bronchitis in children (BC) was 15.8 μgr/m^3 for ARI, while AGP presented 19.5 μgr/m^3, MAR 18.5 μgr/m^3, THR 19.8 μgr/m^3 and LYK 18.2 μgr/m^3. These values lead to a mean annual PM concentration threshold value for the GAA equal to 18.4 $\pm$ 1.6 μgr/m^3. Above this value it seems that there is an impact on human health, especially on BC cases. It should be noted that these projections are based on a concentration value of 20 μgr/m^3 as the lowest assessment threshold, according the guidelines of the European Council [47].

According to an investigation by the multicenter European Study of Cohorts for Air Pollution Effects (ESCAPE), Beelen et al. [58] noted that long-term exposure to particulate matter air pollution was associated with natural-cause mortality, even within concentration ranges well below the present European annual mean limit value such as PM_{10} = 13.7 μgr/m^3. Moreover, in a similar study in England, Carey et al. [59] associated particle matter concentrations of 15.9 μgr/m^3 with increased all-cause mortality. Puett et al. [60] observed analogous effects among women living in the northeastern US areas. The risk in all-cause and of CVD increased when PM_{10} reached 15.1 μgr/m^3.

The following graphs (Figure 6) show the same results. The mean values of PM_{10} were utilized as input in AirQ+ to calculate the number of bronchitis incidents in adults, for all examined stations in the observation period (2001–2020). Therefore, according to the equations, PM_{10} values have a strong correlation with the cumulative number of adult bronchitis incidents. Most of the stations (i.e., ARI, AGP, MAR and LYK) presented a high value of R^2, approximately 0.99. The THR station showed a different R^2 = 0.64 because for some periods of time it was out of operation. These results identify again the high PM_{10}-related health effects in areas with high levels of pollution (e.g., at LYK station in 2004 the PM_{10} mean annual concentration was 63 μgr/m^3 and 43 cases of chronic bronchitis in adults were calculated, while the corresponding values for the year 2019 are 27 μgr/m^3 and only 7 cases). Moreover, from the below linear regression equations, it can be seen that the lowest level of mean annual PM_{10} concentration concerning bronchitis in adults (CBI) was 19.1 μgr/m^3 for ARI, while AGP presented 19.4 μgr/m^3, MAR 19.5 μgr/m^3, THR 19.4 μgr/m^3, and LYK 19.2 μgr/m^3. These values lead to a mean annual PM_{10} concentration threshold value for the GAA equal to 19.3 $\pm$ 0.2 μgr/m^3. Above this value it seems that there is an impact on human health, especially for CBI cases in adults.

Hart et al. [61] observed similar results among men living in the northeastern and midwestern United States. The risk of CVD increased when PM_{10} reached 16.0 μgr/m^3. Hansell et al. [62], in their study investigating modeled concentrations of air pollution in residents of England and Wales, associated 16.5 μgr/m^3 PM_{10} with respiratory diseases. Additionally, in a similar study in California, Lipsette et al. [63] related the long-term exposure to $PM_{10} \geq 18.2$ μgr/m^3 to increased human health risks.

Furthermore, the annual number of bronchitis cases for both children and adults was investigated in relation to the annual number of exceedances, i.e., days where PM_{10} concentrations exceed the European Council (EC) [47] daily threshold of 50 μgr/m^3. In Figure 7, the cumulative number of bronchitis cases in children versus the annual number of PM_{10} exceedances is observed for all of the investigated areas. A choice between a linear or exponential model was made in order to achieve a higher coefficient of determination (R^2) in the charts. As shown in Figure 7, the linear adjustment model for AGP, THR, and LYK stations explains about 90% ($R^2 \approx 0.90$) of the variation in the annual cases of pediatric bronchitis, and the exponential adjustment model for ARI and MAR stations explains about 75% ($R^2 \approx 0.75$). Additionally, when the number of exceedances is greater than or equal to 35, the number of bronchitis cases in children due to PM_{10} exposure increases. This seems to be in full agreement with the limit number of 35 exceedances per year, which was established by the EU [47] for the protection of public health.

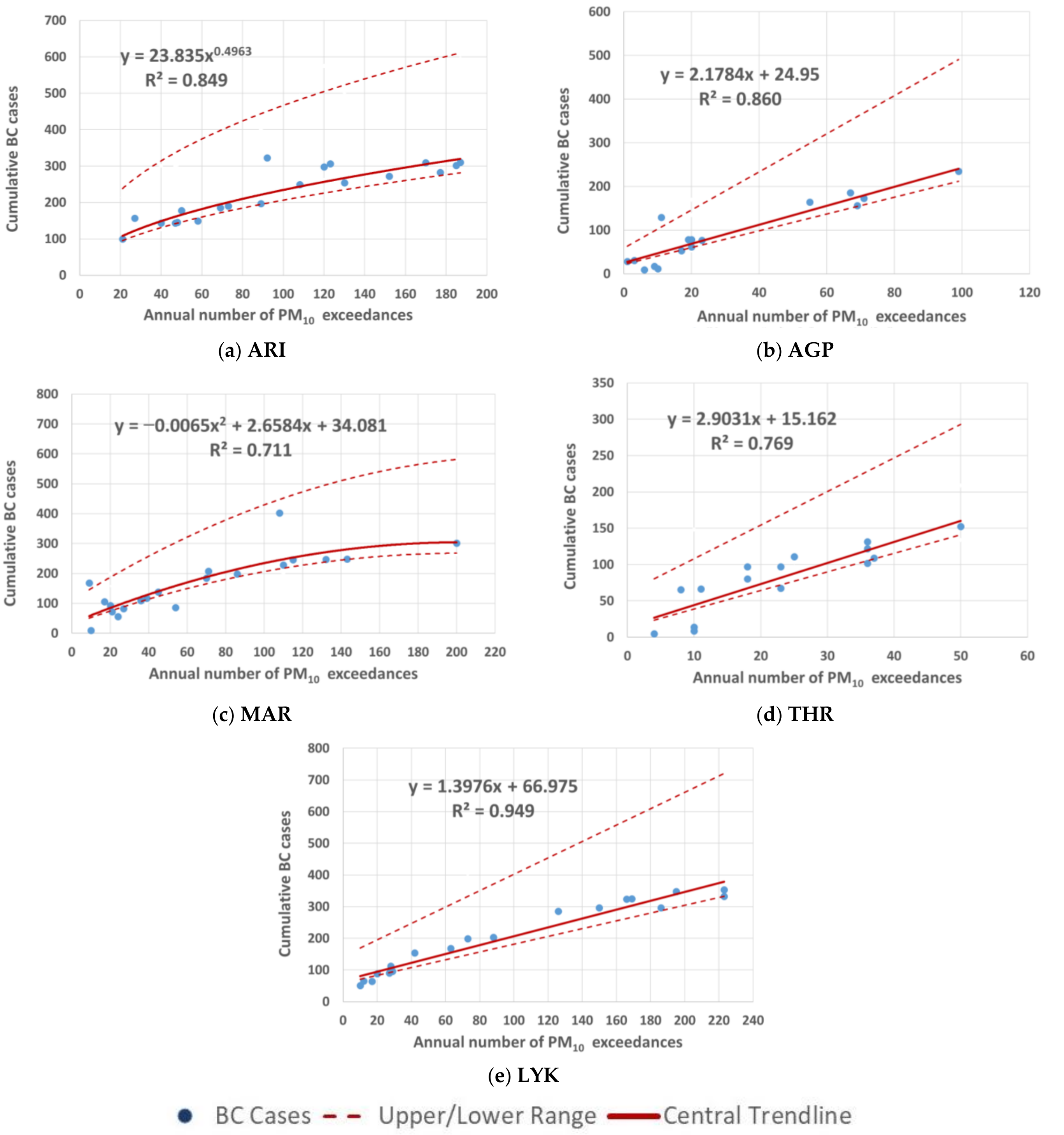


Figure 7. Annual variation in cumulative number of prevalence of bronchitis in children due to PM_{10} exposure vs. annual number of PM_{10} exceedances of all examined stations within the GAA. Period 2001–2020. ((**a**): ARI, (**b**): AGP, (**c**): MAR, (**d**): THR, (**e**): LYK).

Moreover, in Figure 8, the cumulative number of bronchitis incidents in adults versus the annual number of PM_{10} exceedances is presented. The findings of the following graphs are in line with the previous results. The linear adjustment model for AGP, THR, LYK, and MAR stations explains about 62–93% ($R^2 \approx 0.62$–0.93) of the variation in the annual cases of bronchitis incidents, and the exponential adjustment model for ARI explains approximately 90% ($R^2 \approx 0.89$).

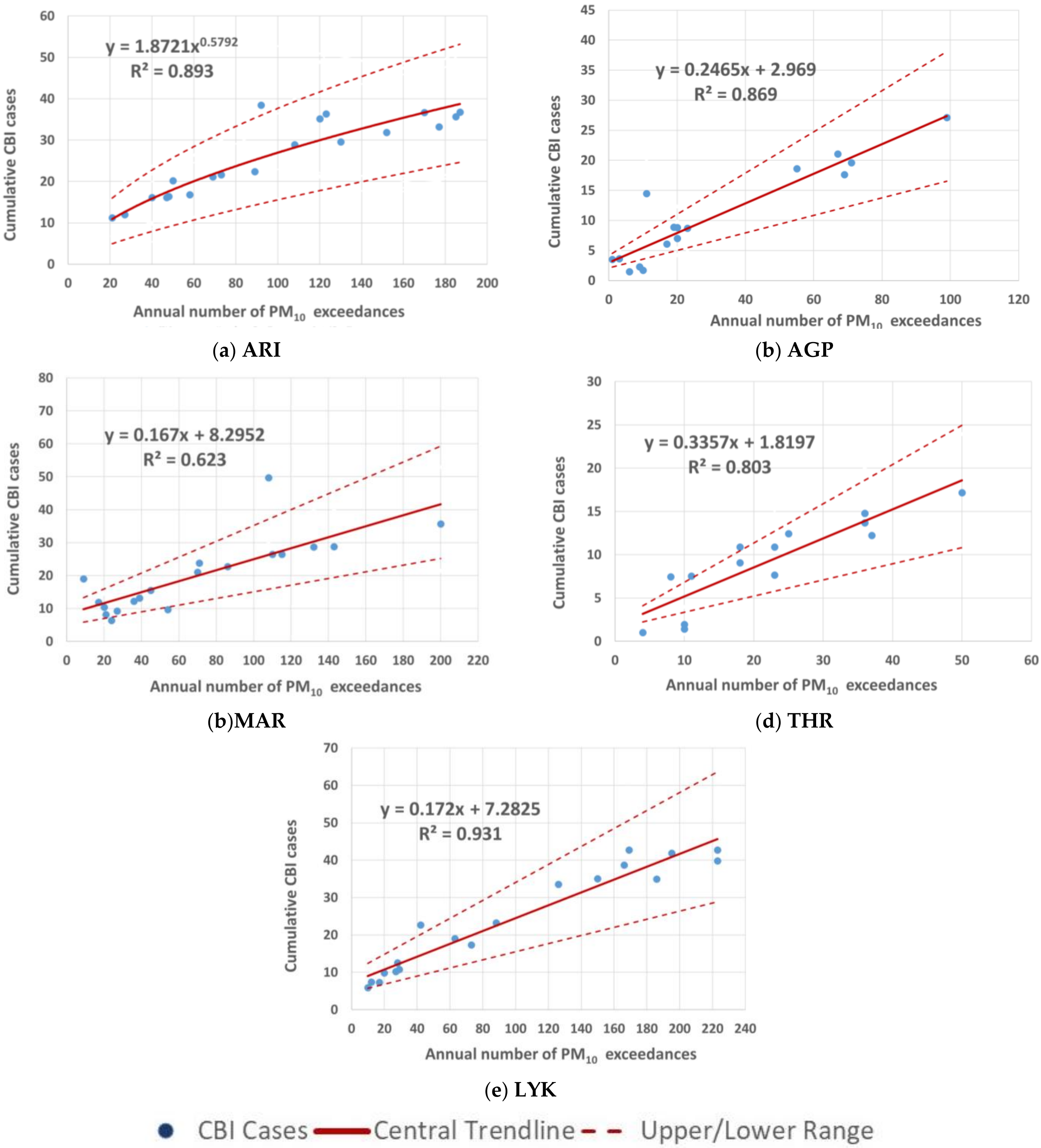


Figure 8. Annual variation in cumulative number of bronchitis incidents due to PM_{10} exposure vs. annual number of PM_{10} exceedances of all examined stations within the GAA. Period 2001–2020. ((**a**): ARI, (**b**): AGP, (**c**): MAR, (**d**): THR, (**e**): LYK).

These results are very encouraging because they prove that the AirQ+ software has the required sensitivity to detect time variations in the health impact incidents resulting from PM_{10} exposure. This points out once again how dangerous it is for human health to live in an area where the PM_{10} limits set by the EU have been exceeded.

According to AirQ+, the number of children suffering from childhood asthma due to PM_{10} is higher compared to the corresponding adult cases. For this reason, Figure 9 shows the estimated distribution of child asthma attacks within the GAA in relation to the total population and activities in each study area. More specifically, Figure 9 presents the spatial distribution of the mean annual child bronchitis prevalence during the last twenty years (2001–2020), based on the population of each location. The data was processed and visualized in QGIS (Quantum Geographic Information System) [64] environment which is an open-source software that can perform data analysis on spatial distributed databases, as well as to compose and export graphical maps of various data-types.

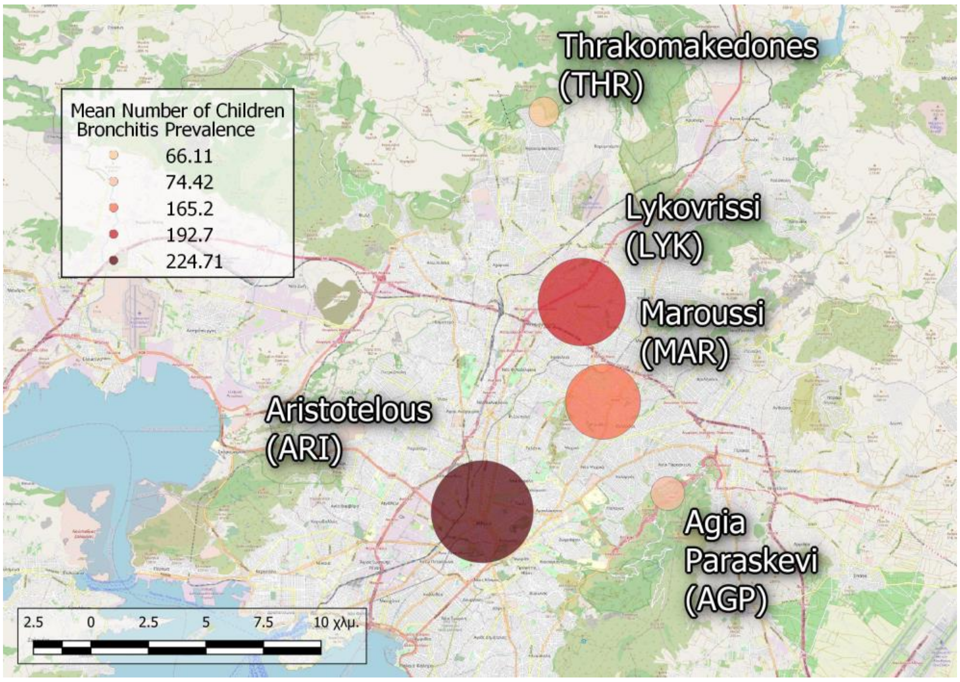


Figure 9. Spatial distribution of childhood bronchitis prevalence during the period 2001–2020, based on the population of each location. (Satellite image by ESRI).

The center of Athens (ARI) is the most densely populated area and at the same time the most air polluted area. This is why, according to estimates, there is a mean annual number of 224.71 childhood bronchitis cases, followed by Lykovrisi with 192.7 cases, and Maroussi with 165.2 cases. The other areas present lower diseases incidences based on their population (see Figure 1).

By applying the same process, Figure 10 shows the estimated distribution of adult chronic bronchitis incidence within the GAA in relation to the total population and activities in each study area. The image depicts the same area, where the center of Athens (ARI) is the most densely populated, and at the same time, the most affected area with 25.84 cases, followed by Lykovrisi with 22.80 cases and Maroussi with 19.01 cases.

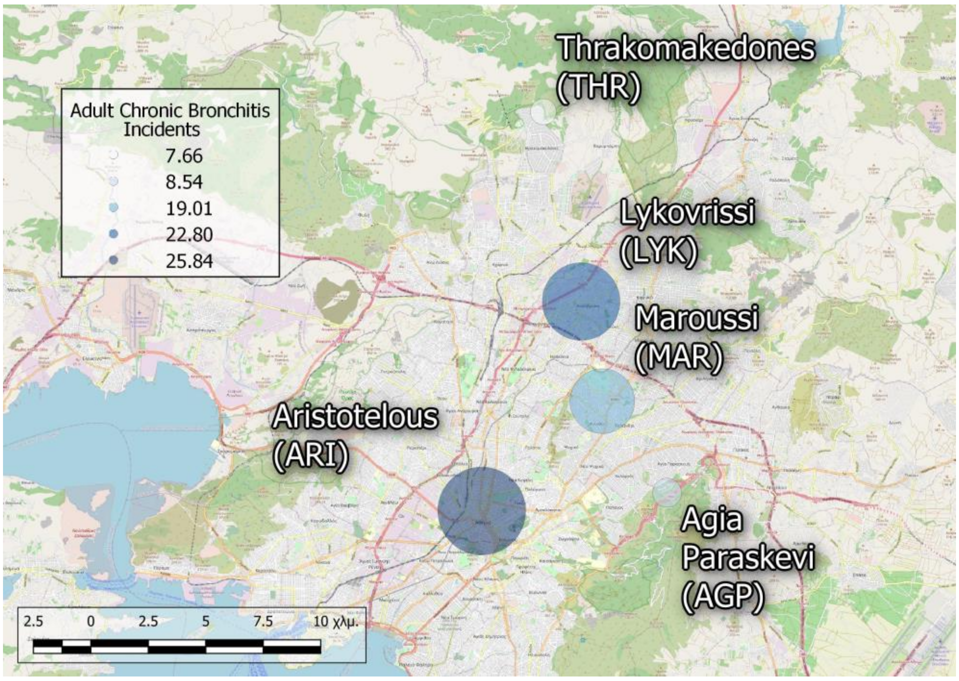


Figure 10. Spatial distribution of adult chronic bronchitis prevalence during the period 2001–2020, based on the population of each location. (Satellite image by ESRI).

Table 3 presents a comparative analysis of respiratory disease incidence per 100,000 inhabitants due to PM_{10} for different locations worldwide, calculated by using the former software version AirQ2.2.3 (2004) and the version AirQ+ v1.3 (2016). The version AirQ2.2.3 (2004) processes cases related to respiratory diseases presented in more detail as Hospital Admissions Respiratory Disease (HARD). As expected, most studies have used this older AirQ version.

The version AirQ+ v1.3 (2016) is a more detailed tool which abandons the Hospital Admissions Respiratory Disease (HARD) model of respiratory disease cases for measures of Prevalence of Bronchitis in Children (BC) and Chronic Bronchitis Incidence (CBI).

The effects of long-term exposure to high PM_{10} concentrations can damage human health. It seems that the city of Volos, Greece, and the city of Suwon, Seoul, Republic of Korea, can be compared with locations within the GAA and generally within Athens. In these cities, the average annual PM_{10} concentrations range from 30 μgr/m^3 to 50 μgr/m^3 and the annual number of HARD cases per 100,000 inhabitants ranges between 20 and 40.

The third following city is Tehran, the capital of Iran, with an average annual average PM_{10} concentration of 90.6 μgr/m^3 and an average annual number of HARD cases of 77. It is worth mentioning that the holy city of Mecca in Saudi Arabia and Cairo, the capital of Egypt, show significant exceedances of PM_{10}, with a large effect on the case of HARD per year. Moreover, the city of Yasuj, Iran, with an average annual average of PM_{10} concentration of 92.4 μgr/m^3, has the maximum number of both CBI (215) cases and the BC (7959) cases.

Table 3. Comparative analysis of health endpoint cases per 100,000 inhabitants due to PM_{10} exposure for different sites worldwide.

Location	Period	Mean Annual PM_{10} ($\mu gr/m^3$)	Health Impact (Cases per 100,000 Inhabitants)	RR	Reference
Volos, Greece	2007–2011	41.2	HARD 32	1.008	[49]
Suwon City, Seoul, South Korea	2011	52.0	HARD 39	1.008	[65]
Tehran, Iran	2010	90.6	HARD 77	1.008	[66]
Holy City of Makkah, Saudi Arabia	2012–2013	195.5	HARD 2504	1.096	[67]
South Shoubra El-Kheima, Cairo, Egypt	2008–2009	267.0	HARD 4919	1.274	[68]
North Shoubra El-Kheima, Cairo, Egypt	2008–2009	306.0	HARD 10,941	1.138	[68]
North Helwan, Cairo, Egypt	2008–2009	382.0	HARD 5002	1.290	[68]
South Helwan, Cairo, Egypt	2008–2009	441.0	HARD 4053	1.377	[68]
Aristotelous (Athens city center), Greece	2001–2013	50.1	HARD 40	1.008	[24]
Lykovrissi, Greece	2001–2013	50.3	HARD 40	1.008	[24]
Maroussi, Greece	2001–2013	44.5	HARD 35	1.008	[24]
Piraeus (port), Greece	2001–2013	44.2	HARD 36	1.008	[24]
Agia Paraskevi, Greece	2001–2013	32.1	HARD 21	1.008	[24]
Thrakomakedones, Greece	2001–2013	30.0	HARD 20	1.008	[24]
Mashhad, Iran	2014–2015	82.9	HARD 805	1.008	[69]
Hamada, Iran	2014–2015	69.9	HARD 104	1.013	[70]
Yasuj, Iran	2013–2018	92.4	CBI 215 BC 7959	1.008 1.017	[71]
Aristotelous (Athens city center), Greece	2001–2020	45.5	CBI 26 BC 225	1.008 1.08	Present research
Agia Paraskevi, Greece	2001–2020	27.5	CBI 9 BC 74	1.008 1.08	Present research
Maroussi, Greece	2001–2020	38.7	CBI 19 BC 165	1.008 1.08	Present research
Thrakomakedones, Greece	2001–2020	25.8	CBI 8 BC 66	1.008 1.08	Present research
Lykovrissi, Greece	2001–2020	42.1	CBI 23 BC 193	1.008 1.08	Present research

HARD: Hospital Admissions Respiratory Disease, AirQ2.2.3. BC: Prevalence Bronchitis in Children, AirQ+ v1.3. CBI: Chronic Bronchitis Incidents, AirQ+ v1.3.

For validation of the AirQ+ software results, official patient admission data from Attikon University General Hospital for the years 2010 and 2019 were collected. The admissions of patients with pulmonary symptoms were counted and compared with the mean annual variation in PM_{10} concentrations. The temporal variation in PM_{10} and the admissions due to respiratory diseases at Attikon hospital is presented at Figure 11. In 2010 we observe that when there is an increased concentration of the pollutant there is an increase in hospital admissions. We also find that during the periods of the seasonal phenomenon of the Sahara Desert dust event, there is an increase in the number of bronchitis episodes (28 March 2010–10 April 2010 and 22 October 2010–10 November 2010). A similar increase occurs during the winter months, when the atmosphere is polluted by particulate matter emitted by appliances that cover the heating needs for the periods of 12 February 2010–26 February 2010 and 17 December 2010–31 December 2010. Similar results were found for the year 2019. Increased concentration of PM_{10} pollutant increases hospital admissions with pulmonary symptoms. Climatic conditions such as the Sahara Desert effect enhance the increase in bronchitis episodes (22 April 2019–20 May 2019 and 19 October 2019–23 November 2019). Similarly, during the cold season, when the need for heating is high, PM_{10} concentrations increase and there is an increase in the number of patients in the hospital (14 February 2019–24 February 2019 and 11 December 219–23 December 2019). It is obvious that the increase in PM_{10} is followed by an increase in hospital admissions, which is in line with the findings from the AirQ+ application.

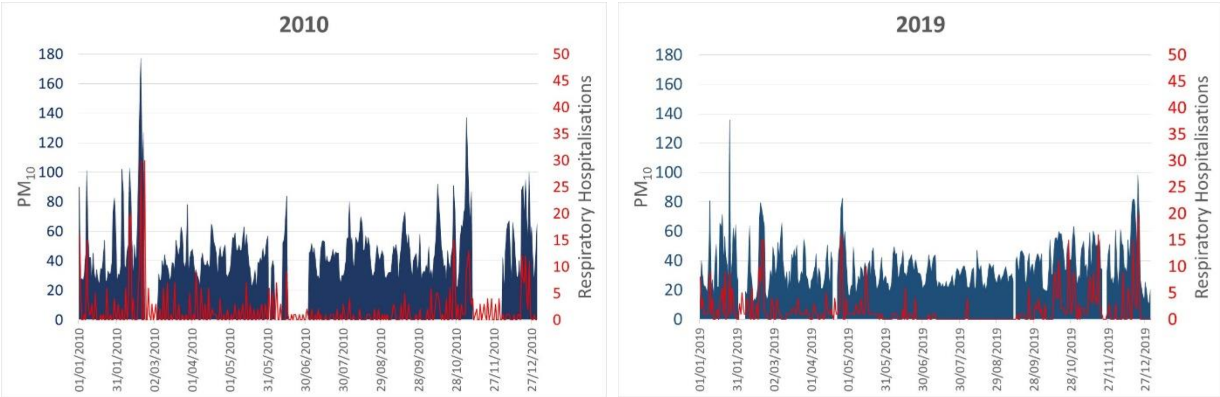


Figure 11. Timeseries of PM_{10} (μgr/m^3) concentrations and hospital admissions at the University General Hospital "ATTIKON".

4. Conclusions

The aim of the present research was to assess and evaluate the long-term adverse health effects due to exposure to particulate matter, according to WHO guidelines. An effort was made to fill the gap of real epidemiological data for Greece and especially for the wider area of Athens for a long time period with the application of the AirQ+ software. The estimation of bronchitis cases in children and adults, attributed to exposure to PM_{10}, in the Greater Athens Area during the period 2001–2020, was carried out. Additionally, range estimates of bronchitis prevalence in both children and adults was analyzed per 100,000 people, as a result of annual average PM_{10} exposure.

The main conclusions of the present study can be summarized as:

- For the GAA, the average annual PM_{10} concentrations range from 21 μgr/m^3 to 57 μgr/m^3, the annual number of CBI cases per 100,000 inhabitants ranges between 8 and 26 cases and the annual number of BC cases ranges between 74 and 225 cases.
- The most polluted areas are the center of Athens (ARI), Lykovrisi (LYK), and Maroussi (MAR), where people suffer from chronic bronchitis disproportionately compared to the rest areas.
- There is a strong correlation between bronchitis cases in children and adults and PM_{10} threshold concentration exceedances. It is remarkable that there are more cases of children suffering from lung disease than adults.
- A steady reduction in both PM_{10} concentrations and chronic bronchitis effects was identified across the region through the examined years, with a significantly higher decrease over the 2010–2020 period. This is due to the construction activities that took place (the new Attiki Odos urban highway, the metro, the new Eleftherios Venizelos international airport) which led to an overall improvement in traffic, mainly in the city center, as wells as the economic crisis and the subsequent reduction in energy consumption for heating and transportation, and the withdrawal of old vehicles.
- The PM_{10} concentration starting point for valid outcomes (meaning no hospital admissions) ranges between 15.8 μg/m^3 and 19 μg/m^3. Several studies worldwide present similar results. More specifically, the five lowest levels reported or estimated were 13.7 μg/m^3 [58], 15.0 μg/m^3 [72], 15.1 μg/m^3 [60], 15.9 μg/m^3 [59], and 16.0 μg/m^3 [61]. Based on the evaluation of these studies, WHO [73] recommends 15 μg/m^3 as the lowest concentration level for Air Quality Guidelines (AQG). However, the above studies, as well as the present one, suggest that health effects may occur at low levels of pollution.
- Measures need to be taken to reduce both children and adult's exposure to high concentrations of PM_{10} pollutants which consequently will lessen the incidence of respiratory symptoms, asthma, and hospital admissions due to poor air quality.

Overall, assessing a direct relationship between different PM_{10} concentrations and their effects on human health is quite difficult due to the interaction with other air pollutants. However, with the use of the AirQ+ model, which is proposed by the WHO, the effects of air pollutants on human health can be estimated satisfactorily. Further research should consider the study of the direct impact of childhood asthma and adult chronic bronchitis cases due to PM_{10} exceedances on the National Health System, society, and economy (healthcare cost, school absences, life expectancy of patients).

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