

Article

Health-Based Approach to Determine Alert and Information Thresholds for Particulate Matter Air Pollution

Łukasz Adamkiewicz ^{1,*}, Katarzyna Maciejewska ², Krzysztof Skotak ³, Michał Krzyżanowski ⁴ ,
Artur Badyda ² , Katarzyna Juda-Rezler ²  and Piotr Dąbrowiecki ⁵

¹ European Clean Air Centre, 31-104 Krakow, Poland

² Faculty of Building Services, Hydro and Environmental Engineering, Warsaw University of Technology, 00-653 Warszawa, Poland; katarzyna.maciejewska@pw.edu.pl (K.M.); artur.badyda@pw.edu.pl (A.B.); katarzyna.juda-rezler@pw.edu.pl (K.J.-R.)

³ Department of Integrated Environment Monitoring, Institute of Environmental Protection—National Research Institute, 00-548 Warszawa, Poland; krzysztof.skotak@ios.edu.pl

⁴ School of Public Health, Imperial College London, London SW7 2BU, UK; m.krzyzanowski@imperial.ac.uk

⁵ Department of Infectious Diseases and Allergology, Military Institute of Medicine, 04-141 Warsaw, Poland; pdabrowiecki@wim.mil.pl

* Correspondence: lukasz.adamkiewicz@cleanaircentre.eu; Tel.: +48-792-468-018

Abstract: In this study Health Impact Assessment (HIA) methods were used to evaluate potential health benefits related to keeping air pollution levels in Poland under certain threshold concentrations. Impacts of daily mean particulate matter (PM)₁₀ levels on hospital admissions due to cardiovascular and respiratory diseases were considered. Relative risk coefficients were adopted from WHO HRAPIE project. The analyses covered period from 2015 to 2017, and were limited to the heating season (1st and 4th quarter of the year), when the highest PM₁₀ concentrations occur. The national total number of hospital admissions attributed to PM₁₀ concentration exceeding WHO daily Air Quality Guideline value of 50 µg/m³ was calculated for each of the 46 air quality zones established in Poland. We found that the reduction of the attributable hospital admissions by 75% or 50% of that expected for the “best case scenario”, with no days with PM₁₀ concentration exceeding 50 µg/m³ would require avoidance of exceedance by the daily mean PM₁₀ concentration of 64 µg/m³ and 83 µg/m³, respectively. These concentrations were proposed as the information and alert thresholds, respectively. The alert thresholds were exceeded on 2 and 38 days per year in the least and the most polluted zones, respectively. Exceedances of the information thresholds occurred on 6 and 66 days in these zones.

Keywords: health impact assessment; air pollution; PM₁₀; alert threshold; hospital admissions



Citation: Adamkiewicz, Ł.; Maciejewska, K.; Skotak, K.; Krzyżanowski, M.; Badyda, A.; Juda-Rezler, K.; Dąbrowiecki, P. Health-Based Approach to Determine Alert and Information Thresholds for Particulate Matter Air Pollution. *Sustainability* **2021**, *13*, 1345. <https://doi.org/10.3390/su13031345>

Academic Editors: Fabio Famoso and Jeffrey Wilson

Received: 21 December 2020

Accepted: 25 January 2021

Published: 28 January 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Mitigation of ambient air pollution is the biggest challenge related to limiting negative impacts of environmental pollution on health [1]. Globally, ca. 4.5 million deaths have been attributed to ambient air pollution in 2018 [2]. It was the sixth-most important risk factor, among the 87 factors considered in the Global Burden of Disease (GBD) analysis, and the most important among environmental factors [1]. Vast majority (92%) of the burden of disease globally is due to particulate matter (PM), with the remaining contribution due to ambient ozone. In Poland, the impacts of ambient PM exposure amount, according to the GBD project, to 27.8 thousand deaths per year [3]. Other analyses, conducted with different methods, input data, and assumptions, estimate ca. 46.3 and 58.0 thousand premature deaths annually related to this exposure [4,5]. All those results indicate that ambient air pollution, and especially particulate matter, is a significant environmental and public health problem globally and in Poland.

The burden of disease estimates are rooted in a well-established evidence demonstrating that long term exposure to PM_{2.5} (particles with aerodynamic diameter equal to or

smaller than $2.5\ \mu\text{m}$) has negative health consequences [6,7]. Long-term exposure to PM is associated with the increased risk of developing chronic diseases, as well as of premature death. Solid evidence also exists on effects of short term increases in exposure to PM_{2.5} and PM₁₀ (particles with aerodynamic diameter equal to or smaller than $10\ \mu\text{m}$), which may lead to a rapid deterioration of body functions resulting in emergency department visit or unplanned hospitalization, or in premature death.

European legislation enforces protection and improvement of air quality using a wide range of air quality management tools. Most of them aim at limiting emission of pollutants to atmosphere from various sources, such as road traffic; commercial, institutional and households sector; industrial processes and product use; energy production and distribution; and agriculture. An important class of these measures relates to short-term actions, particularly required during short time high concentration episodes when air pollution levels reach their peak concentrations, significantly threatening human health. According to Article 24 of the AAQ Directive (Directive 2008/50/EC on ambient air quality and cleaner air for Europe) [8], such measures, specified in short-term action plans (STAP), should be taken especially in the case of exceedance of one or more alert thresholds. An alert threshold is defined as “a level beyond which there is a risk to human health from brief exposure for the population as a whole and at which immediate steps are to be taken by the Member States”. The AAQ Directive itself enforces alert thresholds for only three substances: Sulfur dioxide, nitrogen dioxide, and ozone; however, many Member States have also introduced such thresholds for PM₁₀. Another type of threshold introduced by AAQ Directive is the information threshold, i.e., “a level beyond which there is a risk to human health from brief exposure for particularly sensitive sections of the population and for which immediate and appropriate information is necessary”. Such threshold is set by the AAQ Directive only for ozone, but some of the Member States have specified it for PM₁₀ as well.

Information and alert thresholds are linked to even less precise concept of air pollution/smog episodes. In a common sense, episode is an event when the concentrations of air pollutants reach particularly high values. In Poland, the term “episode” is almost exclusively related to PM pollution, being the most severe air quality problem in the country [9]. The definition of a PM₁₀ episode is even more unrestricted than of PM₁₀ information or alert thresholds, as various assessments can use their own criteria to define an episode. Since the first large study on PM episodes in Poland, conducted on behalf of the Chief Inspectorate of Environmental Protection [10], a commonly used “national” threshold for a PM₁₀ episode is $75\ \mu\text{g}/\text{m}^3$, but it has never been formally sanctioned.

The requirements for informing and alerting citizens about high concentrations of PM₁₀ are not unified between the EU Member States; in fact, they differ to a large extent—see Table 1. In the case of information thresholds, the largest daily mean value ($100\ \mu\text{g}/\text{m}^3$) is twice as high as the lowest one ($50\ \mu\text{g}/\text{m}^3$), while for alert threshold this difference is triple (150 vs. $50\ \mu\text{g}/\text{m}^3$). In both cases the highest thresholds are set in Czech Republic, Slovakia and Poland. It is worth noticing that in Poland until October 2019 these values have been even higher— $200\ \mu\text{g}/\text{m}^3$ and $300\ \mu\text{g}/\text{m}^3$ for daily information and alert thresholds, respectively. The discrepancy in the information and alert levels between countries leads to a situation when—given the same concentration of PM₁₀—citizens in different parts of Europe would or would not be warned about poor air quality. It is certainly a plight which preferably ought to be solved at a central EU level, but until this happens, Member States should introduce wisely chosen thresholds on national levels. These thresholds serve not only the protection of human health, but they play another—possibly even more important—role of involving the citizens in the process of monitoring the effectiveness of air quality management in their countries.

Table 1. Information and alert thresholds for daily mean particulate matter (PM)₁₀ concentration set by selected Member States. Source of data: [11].

	Luxembourg	Finland	Germany (Stuttgart)	Belgium	Austria (Graz)	Italy (Lombardy)	France	Spain	Norway	Hungary	Switzerland	Great Britain	Czech Republic	Slovakia	Poland
PM ₁₀ information threshold [$\mu\text{g}/\text{m}^3$]	50	50	-	50	50	50	50	50	50	75	75	76	100	100	100 ¹
PM ₁₀ alert threshold [$\mu\text{g}/\text{m}^3$]	-	50	50	70	75	75	80	80	150	100	100	101	150	150	150 ²

¹ 200 $\mu\text{g}/\text{m}^3$ before 2019; ² 300 $\mu\text{g}/\text{m}^3$ before 2019.

One of the possible reasons for the lack of consistency of the PM₁₀ alert threshold between countries is the fact that no guidance exists on how to determine such values, and therefore they are usually arbitrarily chosen by the authorities. Setting thresholds for the concentrations of air pollutants can be done for several reasons such as: Information on smog occurrences, air quality standards exceedances, health recommendations, or air quality index. The most extensive literature is available for air quality indices, since they can be introduced independently from existing legally binding rules, therefore research is done globally. There are two main types of methods for developing a threshold of air pollution, based on the number of exceedances and/or on health determinates. First approach focuses usually on the frequency of occurrence of a given concentration of air pollutants per selected time period and area. The second uses association between air pollution and adverse health effects [12].

The literature documents three general approaches to setting thresholds of PM₁₀ considering health effects of the pollution:

1. Using the World Health Organization Air Quality Guidelines (WHO AQG) as a base for threshold level;
2. setting threshold based on concentration–response functions (CRF) and recalculation to air pollution concentration;
3. assessing the number of health outcomes in a population and deriving an air pollution threshold based on it.

The first approach is relatively the simplest method for appointing PM₁₀ threshold level. The WHO AQG of PM₁₀ (which is equal to 50 $\mu\text{g}/\text{m}^3$ with 24 h averaging period [13]) is used as a reference and the threshold is set at, e.g., 100% or 200% of this value [14,15]. More complex methods from the second category use CRF parameters such as relative risk (RR) or excess risk (ER). The threshold is set with regard to the risk increase in relation to current air quality standard [16,17]. For example, a threshold of PM₁₀ can be calculated for a 50% increase of risk of hospital admission, as compared with the hospitalization risk assessed for the limit value of PM₁₀ (50 $\mu\text{g}/\text{m}^3$). The third method is the most complex, since it is based on calculations of the number of health outcomes (such as deaths, hospitalizations, or emergency department visits due to various diseases). This requires combining CRFs with baseline data on an incidence of selected health effects and PM₁₀ concentration [18–23]. CRF function can be based on local epidemiological studies or a metaanalysis of all regionally or globally available studies, such as used by WHO HRAPIE or other projects [24–26].

The aim of this study was to determine PM₁₀ daily mean concentrations for information and alert thresholds for Poland using human health perspective. Based on short-term health effects of air pollution, we have assessed the number of hospital admissions that could be avoided if a particular threshold concentration of PM₁₀ would not be exceeded, e.g., due to actions by proper authorities and the society following the forecast of reaching

an information or alert level of the pollution. The choice of the threshold concentrations is then based on expected health gains balanced by the frequency of the announcements in regions with various pollution levels.

2. Materials and Methods

The analysis was carried out using a 3-year dataset on air quality from 2015–2017, covering the whole Poland [27]. Air quality data included the measurements collected within the National Environmental Monitoring network, which is the official air quality measurement system of Poland, reporting its results to the European Commission. The analysis was aggregated to 46 air quality assessment zones [28], determined (as required by AAQ Directive) by the Regulation of the Minister of the Environment of 2 August 2012 on zones where air quality is assessed (AQ zones) (Journal of Laws of 2012, item 914)—see Figure 1.

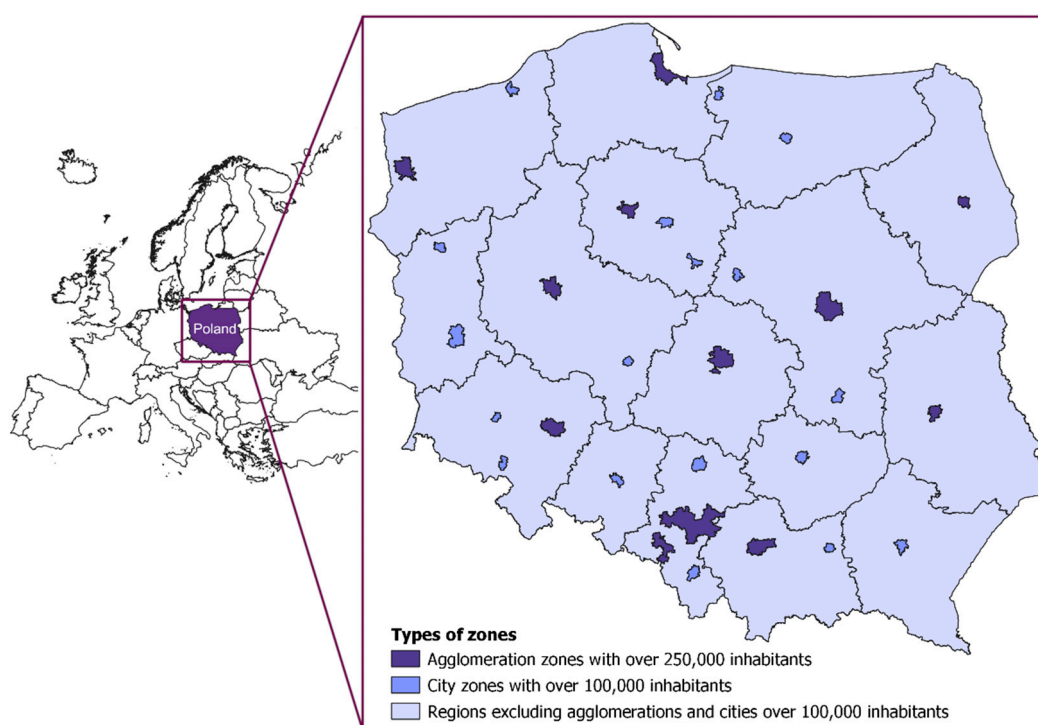


Figure 1. Air quality assessment zones in Poland.

Daily mean concentrations of PM₁₀ were collected from all manual stations (applying the reference gravimetric method [29]) in Poland, whose time coverage reached at least 75% of days in each year. To avoid additional uncertainty related to using PM data obtained via different measurement methods, automatic stations were excluded from the analysis. As PM₁₀ was monitored by over twice as many stations as PM_{2.5}, the analysis was carried out using the PM₁₀ fraction, even though the applied analysis of health effects is based on PM_{2.5}. To overcome this issue, a method of estimating PM_{2.5} levels from PM₁₀ measurements was developed for the purpose of this study. First, for each station where both PM₁₀ and PM_{2.5} were measured (marker stations), monthly average ratios of daily PM_{2.5}/PM₁₀ were determined in the whole analysed period. Afterwards, the stations where only PM₁₀ is observed were assigned to the corresponding marker stations, based on two criteria: (a) Geographic position belonging to the same air quality assessment zone and (b) similarity of localization characteristics. Finally, PM_{2.5} daily mean levels were calculated from PM₁₀ mean concentrations, using the monthly ratios determined for marker stations. Since the vast majority of PM₁₀ daily limit value exceedances occurs in

Poland during the so-called heating season, further calculations were limited to the 1st and 4th quarters of each year (January–March and October–December).

Data on population health was obtained from the National Health Fund, and included quarterly mean of daily counts of hospital admissions due to cardiovascular (ICD10 codes I00–I99) and respiratory (ICD10 codes J00–J99) disorders, separately for each of the 380 counties of Poland in the period 2015–2017.

The analyses were conducted taking into account short-term exposures to PM_{2.5} and its impact on daily number of cardiovascular (CV) and respiratory (RS) hospitalizations, with relative risk (RR) values per 10 µg/m³ of PM_{2.5} equal to 1.0091 and 1.0190, respectively [24].

In order to determine the recommended information and alert thresholds, a health-oriented approach was elaborated within this study. It was based on six scenarios, which assumed adoption of potential alert thresholds at the levels of 50, 75, 100, 150, 200, and 300 µg/m³ for daily mean concentration of PM₁₀, respectively. The thresholds were determined arbitrarily; however, they span from the WHO daily air quality guidelines value for PM₁₀ (50 µg/m³) up to the alert threshold which was in force in Poland until 2019 (300 µg/m³).

In each scenario, the original dataset on PM₁₀ concentrations was modified in a way that all records exceeding the respective threshold value in a given scenario (e.g., 50 µg/m³) were converted to this threshold value (50 µg/m³ in this case). Then, health impacts (number of hospitalizations) attributed to PM_{2.5} exposure were calculated for the modified (reduced) PM levels and compared with the base case, i.e., the impacts resulting from the PM_{2.5} levels estimated from the measured PM₁₀ concentration with the use of the month- and location-specific PM_{2.5}/PM₁₀ ratios. It was assumed that the alert system would be based on the mean daily PM₁₀ concentration averaged over all stations within a given zone. For example, in the 100 µg/m³ scenario alert would be issued for a certain zone if in this zone the mean concentration of PM₁₀ averaged over all its stations exceeded 100 µg/m³.

To calculate the potential reduction in hospital admissions due to reduction of PM concentrations, an approach recommended by the APHEKOM project [30] has been applied. For each of the analysed health outcomes, the change of the number of cases under particular scenarios has been calculated using the following health impact function:

$$\Delta y = y_0 \cdot (1 - e^{\beta \cdot \Delta x}) \quad (1)$$

where:

Δy —The decrease of the number of cases of a given outcome, associated with the decrease of PM concentrations;

y_0 —the baseline number of cases of a given outcome;

β —the coefficient of the concentration response function ($=\ln(\text{RR})$); and

Δx —the decrease of PM concentration in a given scenario (in 10 µg/m³).

Considering the continuity of the risk increase over all range of exposure levels observed in Poland, and the lack of a specific threshold below which no health effects can be expected, selection of the information and alarm thresholds is, to some extent, arbitrary. In the present approach, we propose that the selection of the information and alert threshold concentrations should assure substantial health gains (e.g., more than half of that in the “best case scenario”), and be relevant for most of the country. To fulfil this latter condition, and considering that air pollution is a problem in the whole Poland, the threshold exceedances should be observed at least a few times per year also in the zones with relatively good air quality to assure it remains “on the agenda” also there, and happen not too frequently in the most polluted zones to avoid the state of “continuous alarm”.

3. Results

The analysis was based on the PM₁₀ data from 151, 153 and 163 monitoring stations in 2015, 2016, and 2017, respectively. Three-years mean PM₁₀ ranged from 15.5 µg/m³ to

64.3 $\mu\text{g}/\text{m}^3$ in various zones (Table 2). The PM_{2.5}/PM₁₀ ratio varied markedly between the zones and months, justifying the use of local and month-specific conversion factors.

Table 2. Annual PM statistics for air quality (AQ) zones in the country in the period of 2015–2017.

	Mean	Min	Max
PM ₁₀ Mean [$\mu\text{g}/\text{m}^3$]	31.8	15.5	64.3
PM ₁₀ Median [$\mu\text{g}/\text{m}^3$]	24.5	11.6	42.0
No. of days >50 $\mu\text{g}/\text{m}^3$ per year	51	2	152
PM _{2.5} /PM ₁₀ October	0.74	0.57	0.99
PM _{2.5} /PM ₁₀ November	0.77	0.37	0.99
PM _{2.5} /PM ₁₀ December	0.80	0.41	1.00
PM _{2.5} /PM ₁₀ January	0.81	0.45	0.99
PM _{2.5} /PM ₁₀ February	0.81	0.48	0.97
PM _{2.5} /PM ₁₀ March	0.78	0.51	0.99

The frequency of PM₁₀ alerts that would be issued in all zones in Poland in the heating seasons of 2015–2017 decreases quickly with the increase of the threshold concentration and varies significantly between the zones (Table 3).

Table 3. Number of days with exceedances of PM₁₀ daily threshold value in the heating seasons of 2015–2017.

Daily Mean PM ₁₀ Concentration [$\mu\text{g}/\text{m}^3$ —Threshold Value	Number of Days per Heating Season with Exceedances of Threshold Value					
	Mean	Median	Lower Quartile (Percentile 25)	Upper Quartile (Percentile 75)	Min	Max
50	43.5	42.3	28.8	54.6	13.3	87.3
75	16.3	13.7	8.4	19.4	3.0	48.7
100	6.8	5.5	2.5	8.7	0.3	25.7
150	1.6	0.7	0.0	2.3	0.0	10.7
200	0.5	0.0	0.0	0.6	0.0	3.3
300	0.1	0.0	0.0	0.0	0.0	0.7

According to the performed analyses, for the most ambitious daily threshold value of 50 $\mu\text{g}/\text{m}^3$, PM alerts would be issued on average 43 times per year in all zones in Poland. In this scenario, the zone with the best air quality would face 13 alerts annually, while the most polluted zone—87 alerts. Conversely, the highest threshold amongst the analysed values—300 $\mu\text{g}/\text{m}^3$ —would result in no more than two alerts every three years (maximum frequency for all zones averaged over the three-year analysis period equals 0.67). It is worth emphasizing that such a high alert threshold (300 $\mu\text{g}/\text{m}^3$) has in fact been in force in Poland for 7 years (2012–2019) (Earlier, i.e., between 2008–2012, PM₁₀ daily alert threshold was set in Poland at 200 $\mu\text{g}/\text{m}^3$. Before 2008 no alert threshold for PM₁₀ was applied). All other scenarios, with simulated thresholds between 75 and 200 $\mu\text{g}/\text{m}^3$, would result in several alerts per year in most zones, while in the most polluted one there would be from 3 to 49 alerts annually for the 200 and 75 $\mu\text{g}/\text{m}^3$ scenarios, respectively.

The analyses revealed big differences between various regions of the country: In the most polluted zones PM alerts would be issued over ten times more often than in the cleanest areas. The zones with the worst air quality and thus most frequent alerts (at least 58 and 29 per year assuming the 50 $\mu\text{g}/\text{m}^3$ and 100 $\mu\text{g}/\text{m}^3$ daily threshold, respectively) are located in the southern and central parts of Poland and amongst them the Rybnik-Jastrzębie agglomeration faces the highest number of alerts (Figure 2). On the other hand, the cleanest regions are located in northern Poland, with the least number of alerts (less than 14 and 4 assuming the 50 $\mu\text{g}/\text{m}^3$ and 100 $\mu\text{g}/\text{m}^3$ daily threshold, respectively) issued in Podlaskie zone.

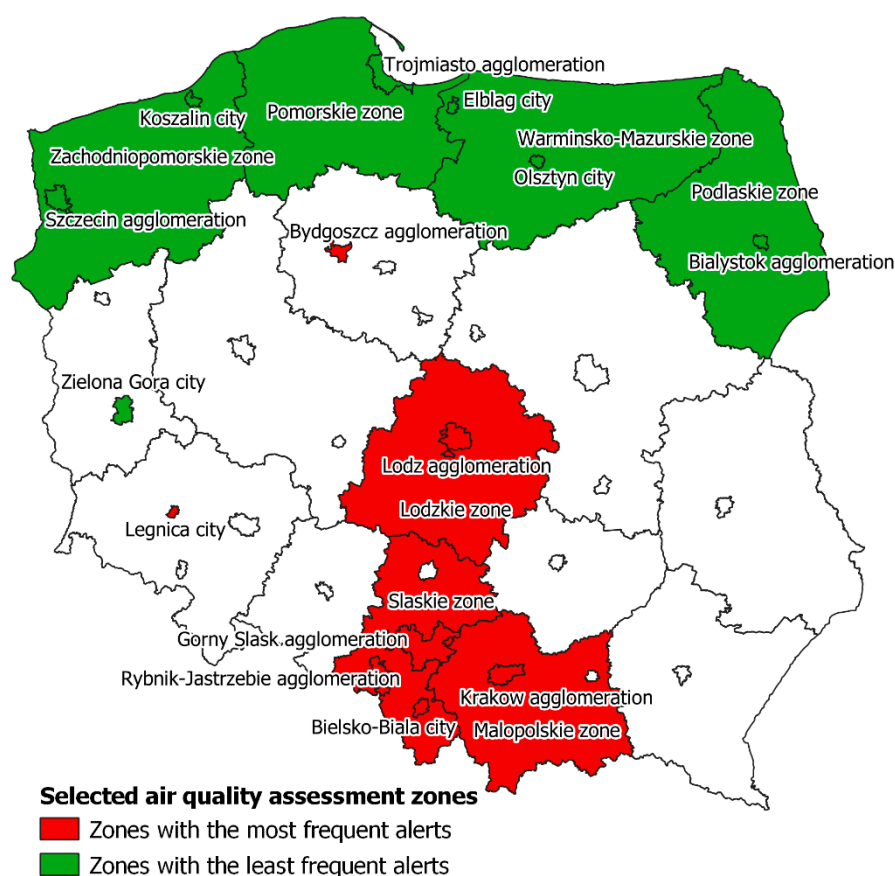


Figure 2. Location of zones with the most frequent (red) and the least frequent (green) potential PM alerts in Poland.

In the analysis considering health impacts of daily mean levels of PM, the scenario assuming $50 \mu\text{g}/\text{m}^3$ as an alert PM₁₀ threshold was selected as a reference, i.e., the “best case scenario” (BCS). No exceedance of daily mean of $50 \mu\text{g}/\text{m}^3$ is in agreement with WHO Air Quality Guidelines for PM₁₀ [13]. For all scenarios with higher threshold concentrations we calculated the number of CV and RS hospitalizations, which could potentially be avoided under each of the scenarios. The results are presented in Table 4.

Table 4. Calculated numbers of hospitalizations which could be avoided annually in Poland under six different scenarios of reduction of peak daily mean PM₁₀ concentrations.

Scenarios: Daily Mean PM ₁₀ Concentrations [$\mu\text{g}/\text{m}^3$] Not Exceeding	Analysis of Short-Term Impacts in the Heating Season	
	Number of Avoided CV Hospital Admissions per Year	Number of Avoided RS Hospital Admissions per Year
50	2896	4000
75	1341	1808
100	677	892
150	206	261
200	76	93
300	14	16

The potential positive effect of assumed scenarios decreases with increasing PM₁₀ daily threshold values. For both health endpoints, this decrease is very well described with exponential models—see Figure 3.

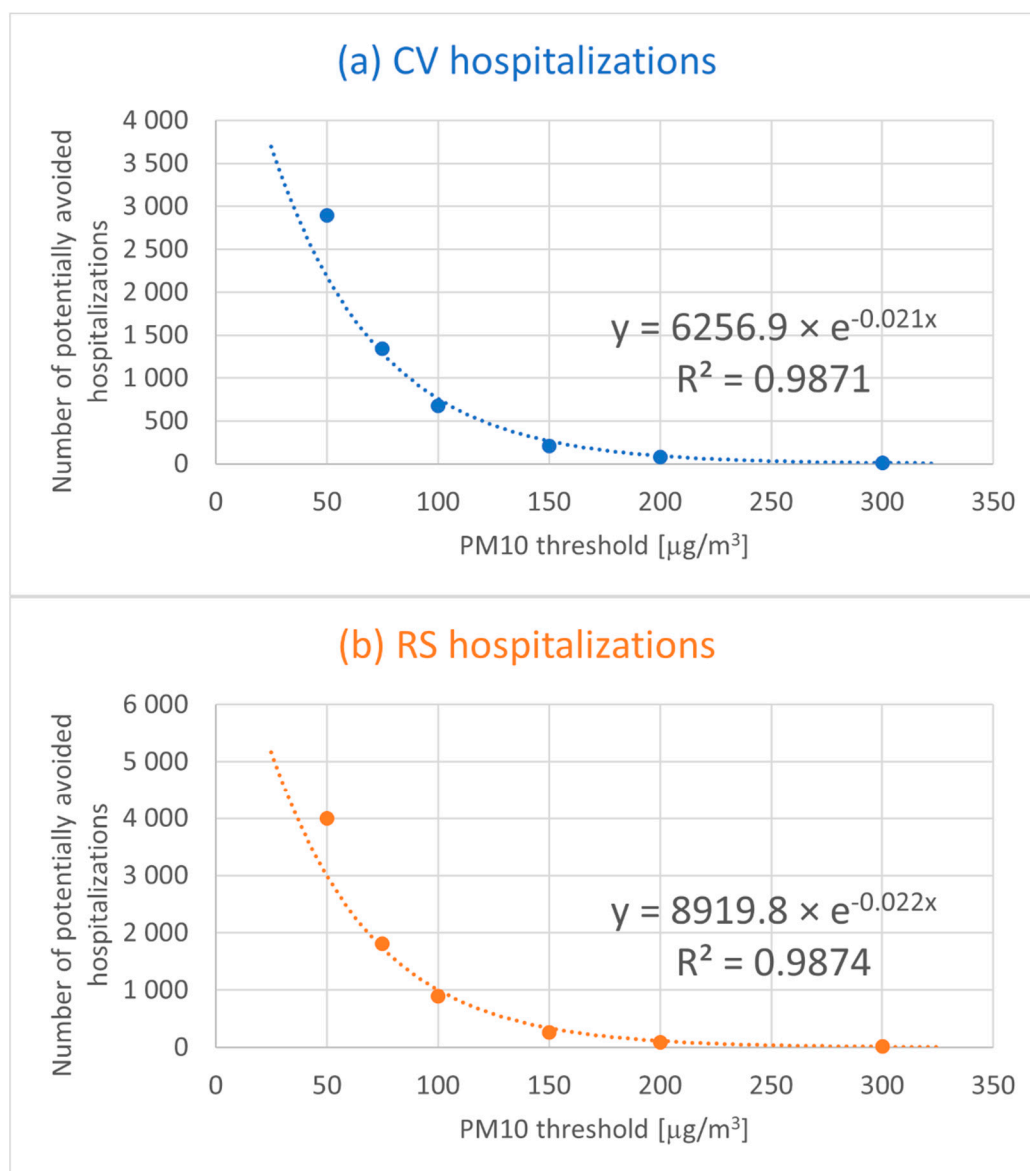


Figure 3. Dependence of the number of avoided cardiovascular (CV) hospitalizations (a), and respiratory (RS) hospitalizations (b) on the PM10 daily alert threshold in different scenarios.

The highest analysed daily threshold value, i.e., $300 \mu\text{g}/\text{m}^3$ is associated with very small potential for reduction of the number of hospitalizations within the country (annually 14 cases of CV and 16 cases of RS hospitalizations are potentially avoided). On the other hand, the BCS with $50 \mu\text{g}/\text{m}^3$ as a threshold value could lead to a reduction of around 3000 and 4000 CV and RS hospitalizations, respectively.

To recommend a new alert threshold based on population health perspective, inverted calculations were conducted in order to find out at which threshold PM10 daily mean concentrations certain impacts, e.g., 75% or 50% of the BCS, could be achieved. Selected results are presented in Table 5.

To achieve 75% of the health gain (reduced hospitalizations) expected for the BCS, the threshold equal to $64 \mu\text{g}/\text{m}^3$ would be required, and for 50% of BCS, the threshold for daily PM10 should be $83 \mu\text{g}/\text{m}^3$. As the results summarized in Table 2 indicate, such thresholds would be linked with limited frequency of alerts: On average 12 times per year in all zones in Poland (from less than 2 times in Białystok agglomeration located in the North-East part of Poland to 38 times in Rybnik-Jastrzębie agglomeration in the South—see Figure 4a). Suggested information threshold would be reached on average 25 times annually, ranging

from 6 times in Koszalin city and Podlaskie zone up to 66 times in the Rybnik-Jastrzębie agglomeration (Figure 4b).

Table 5. Threshold daily mean concentrations of PM₁₀, at which certain percent levels of the best-case scenario (BCS) of health impacts reduction would be achieved.

The % of BCS Achieved	Threshold Daily Mean PM ₁₀ Concentration [$\mu\text{g}/\text{m}^3$] for:	
	CV Hospitalizations	RS Hospitalizations
90%	55	55
80%	61	60
75%	64	63
70%	67	66
60%	74	73
50%	83	82
40%	94	92
30%	107	105
25%	116	113
20%	127	123
10%	159	154

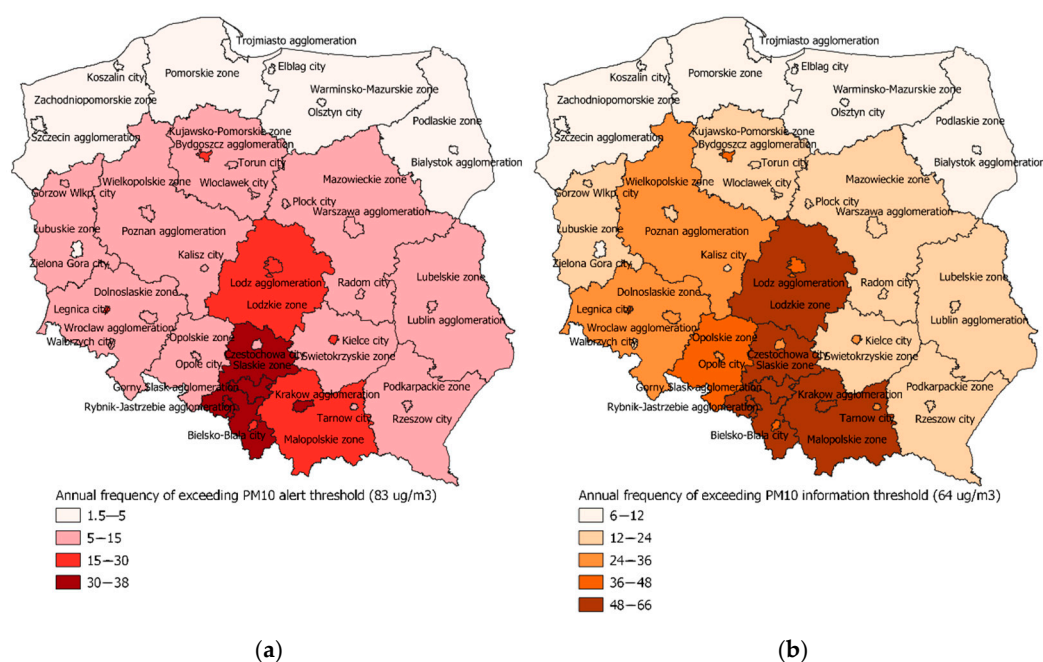


Figure 4. (a) Annual frequency of PM₁₀ alerts in all zones with suggested daily threshold set at $83 \mu\text{g}/\text{m}^3$; (b) annual frequency of exceeding the suggested PM₁₀ information daily threshold ($64 \mu\text{g}/\text{m}^3$) in all zones.

4. Discussion

The presented study aimed at optimizing the information and alert daily thresholds for PM with our own method based on population health impact perspective. It does include an arbitrary decision about the magnitude of the potential health gain associated with the prevention of peak concentrations but is transparent and based on the actual local data on air pollution and health.

Setting information and alert thresholds in the EU Member States is voluntary and there is no unified approach to this problem. Usually, such choice is based on statistical probability of frequency of exceeding certain concentrations. Our method is more complex and includes a health dimension introduced by quantifying potential health gains described

as potential reduction of hospital admissions which could be achieved if the smog alerts would be issued early enough to undertake efficient measures to improve air quality and prevent concentration peaks.

Calculations performed with the proposed method show that the relation between alert levels and health gains is exponential. The best-case scenario (BCS), i.e., alert threshold set at $50 \mu\text{g}/\text{m}^3$ (equal to daily WHO air quality guideline level, allowed in the EU to be exceeded 35 times per year), which would provide the largest reduction in health outcomes, was used as a reference. The proposed information threshold was set at 75% of the BCS and alert threshold at 50% of the BCS, which resulted in PM10 values of $64 \mu\text{g}/\text{m}^3$ and $83 \mu\text{g}/\text{m}^3$, respectively. If the air quality in Poland remained at a current level, these values would be, on average, exceeded in all zones 25 and 12 times per year, respectively. Lower thresholds would result in larger potential health gains, but would be announced more frequently, especially in highly polluted areas. On the other hand, higher thresholds would reduce the health gains and would be extremely rare in less polluted areas, even though also in these areas further improvement of air quality is necessary.

It is worth noticing that the approach used within this study has been based on the assumption that a certain PM10 daily alert threshold implies that this value is not exceeded in the zone, because proper short-term air quality improvement strategies are undertaken early enough to prevent the PM concentration increase above this threshold. Of course, such situation is an ideal one and most likely it would never be fully achieved in reality, however it is an assumption allowing determination of the recommended information and alert thresholds on the basis of potential measurable health benefits for the population, rather than setting these values arbitrarily.

Technically, the proposed scenarios consist of eliminating PM10 peak concentrations, exceeding a certain threshold values. Such type of a scenario was also applied in the APHEKOM recommendations; however, it was proposed to be used for calculating short-term impacts of ozone [30]. In present study it was used with the primary intention of determining reasonable values of information and alert thresholds for PM10, rather than estimating plausible health benefits due to decrease of population exposure to air pollutants.

The present approach has its limitations. The first group of limiting factors relates to input data uncertainty. The air quality monitoring in Poland is performed in more sites for PM10 than for PM2.5 concentrations, while the RR values for the short-term impact are set for PM2.5 levels. Therefore, it was necessary to recalculate PM10 to PM2.5, which results in an uncertainty. To reduce it, we have applied location- and month-specific PM2.5/PM10 conversion factors, which varied from 0.37 to 1.0. Such approach results in a smaller uncertainty than a commonly used fixed conversion factor of 0.7 while estimating PM2.5 levels based on PM10 measurements, as recommended in the guidelines of the APHEKOM project [30].

Hospital admission data was available for each commune, while data on PM exposure was an average for a whole zone, sometimes covering several dozen communes. Moreover, the existing differences in hospital availability in rural and urban areas were not accounted for, possibly affecting a reliability of the number of hospital admissions as an indicator of the incidence of considered health effects in various communes.

The concentration-response function used is based on studies conducted in various European countries (Czech Republic, France, Spain, UK) but not in Poland. While the association between short term changes in air pollution and mortality has been analysed for some cities in Poland [31,32], no such analysis was performed considering hospital admissions as the health outcome. It is possible that the health status of patients hospitalized due to cardiovascular and respiratory diseases, as well as its relation with daily air pollution levels, is different in Poland than in the other countries, with differently organized health system. This might introduce an error in estimation of the health gain due to the avoidance of the pollution peaks exceeding information and alert thresholds. This error could be

reduced if locally conducted epidemiological studies, linking hospital admissions with daily air pollution levels, would be available.

Smooth form of the relation between the health gain and exposure requires an arbitrary rule for setting of the threshold values, which remains the largest limitation of this study. We decided that the most justified approach would be to use some standard parameters of the health gain distribution, such as quartiles and therefore the proposed thresholds correspond with 75% and 50% of the BCS. However, any other percentile could have been chosen. In any case, this decision is informed by the ultimate gain of this action, which is population health protection.

Another limitation concerns differences in defining threshold exceedance. According to the national regulation, smog alerts are announced every time the alert threshold is exceeded even at a single monitoring station, although in an AQ zone there is usually more than one station. When health impact assessment is considered, population exposure to air pollutants is more accurately represented by an average concentration from all stations within a certain AQ zone. With such approach, alarms would certainly be announced with different frequency than if they were based on measurements from single stations. As proposed thresholds should primarily serve initiating short-term actions improving air quality, and such actions usually concern the area of the whole AQ zone, PM levels averaged over whole zones seem more adequate for our health-oriented method.

5. Conclusions

The proposed approach provides a transparent support to the decision makers for selection of the information and alert thresholds for air pollutants with health effects occurring at all observed concentrations, with no sharp changes in the slope of the concentration-response function. The information and alarm threshold was proposed to be set at PM₁₀ values of 64 $\mu\text{g}/\text{m}^3$ and 83 $\mu\text{g}/\text{m}^3$, respectively. They would provide 75% and 50% of the health gain expected to be achieved if PM₁₀ would not exceed the EU limit value of 50 $\mu\text{g}/\text{m}^3$. At the current air pollution levels in Poland, these values would be, on average, exceeded in all zones 25 and 12 times per year, respectively. Health gains expected to be due to the prevention of pollution levels exceeding the selected thresholds can be easily communicated to residents of affected regions, justifying and involving them in activities to improve air quality. With this approach, the information about excessive PM levels is communicated not only in areas with extremely poor air quality but also in regions with less frequent pollution peaks. This helps in perceiving air pollution as a national, and not only as a local health problem.

The advantage of the method presented in this study is that it provides the framework for science-based policies concerning atmospheric air quality. Thanks to the results of this analysis, in October 2019 Polish authorities issued an amendment to a national regulation, reducing the former PM₁₀ daily information and alert thresholds by half (from 200 to 100 $\mu\text{g}/\text{m}^3$ and from 300 to 150 $\mu\text{g}/\text{m}^3$, respectively). The presented method can also be used to determine thresholds for subsequent levels of air quality indices, providing more unified approach to informing the society about health risks of atmospheric air pollution.

Author Contributions: Conceptualization, M.K., K.M.; methodology, Ł.A., K.M., K.S., M.K., A.B., K.J.-R., and P.D.; software, Ł.A. and K.M.; validation, K.S., M.K., A.B., K.J.-R., and P.D.; formal analysis, K.M. and Ł.A.; investigation, K.M. and Ł.A.; resources, P.D. and Ł.A.; writing—original draft preparation, Ł.A. and K.M.; writing—review and editing, M.K., K.J.-R., K.S., A.B., and P.D.; visualization, K.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request due to restrictions eg privacy or ethical. The data presented in this study are available on request from the corresponding author. The data are not

publicly available due to the fact that it comes from various sources and has been processed for the purposes of this study.

Acknowledgments: We acknowledge National Health Fund for providing hospitalization data under the program “every breath counts”.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. GBD. Risk Factor Collaborators. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: A systematic analysis for the Global Burden of Disease Study 2017. *Lancet* **2018**, *392*, 1923–1994. [CrossRef]
2. HEI. *State of Global Air 2020*; Special Report; Health Effects Institute: Boston, MA, USA, 2020.
3. SOGA. Number of Deaths Attributable to PM_{2.5}. 2020. Available online: <https://www.stateofglobalair.org/data/#/health/plot> (accessed on 29 October 2020).
4. EEA. *Air Quality in Europe 2020 Report*; Report No. 09/2020; European Environment Agency: Copenhagen, Denmark, 2020.
5. Lelieveld, J.; Klingmüller, K.; Pozzer, A.; Pöschl, U.; Fnais, M.; Daiber, A.; Münzel, T. Cardiovascular disease burden from ambient air pollution in Europe reassessed using novel hazard ratio functions. *Eur. Heart J.* **2019**, *40*, 1590–1596. [CrossRef] [PubMed]
6. WHO. *Review of Evidence on Health Aspects of Air Pollution—REVIHAAP Project*; World Health Organization, Regional Office for Europe, European Centre for Environment and Health: Bonn, Germany, 2013.
7. USEPA. *Integrated Science Assessment for Particulate Matter*; EPA/600/R-19/188; United States Environmental Protection Agency: Washington, DC, USA, 2019.
8. EU. *Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on Ambient Air Quality and Cleaner Air for Europe*; European Union: Brussels, Belgium, 2008.
9. Reizer, M.; Juda-Rezler, K. Explaining the high PM₁₀ concentrations observed in Polish urban areas. *Air Qual. Atmos Health* **2016**, *9*, 517–531. [CrossRef]
10. CIEP. *Analysis of Selected Episodes of High Concentrations of PM₁₀ on the Basis of Measurement and Meteorological Data and Trajectory Analysis*; Chief Inspectorate of Environmental Protection: Warsaw, Poland, 2013.
11. Wiesen, M. *Air Pollution Emergency Schemes (Smog Alerts) in Europe*; Levegő Munkacsoport: Budapest, Hungary, 2017.
12. Gayer, A.; Adamkiewicz, Ł.; Mucha, D.; Badyda, A. Air quality health indices—Review. *Fire and Environmental Safety Engineering 2018 (FESE 2018)*. *MATEC Web Conf.* **2018**, *247*, 2018. [CrossRef]
13. WHO. *Air Quality Guidelines Global Update 2005: Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide*; World Health Organization Regional Office for Europe: Copenhagen, Denmark, 2006.
14. Thach, T.Q.; Tsang, H.; Cao, P.; Ho, L.M. A novel method to construct an air quality index based on air pollution profiles. *Int. J. Hyg. Environ. Health* **2018**, *221*, 17–26. [CrossRef] [PubMed]
15. Lokys, H.L.; Junk, J.; Krein, A. Making air quality indices comparable—Assessment of 10 years of air pollutant levels in western Europe. *Int. J. Environ. Health Res.* **2015**, *25*, 52–66. [CrossRef] [PubMed]
16. Sicard, P.; Lesne, O.; Alexandre, N.; Mangin, A.; Collomp, R. Air quality trends and potential health effects—Development of an aggregate risk index. *Atmos Environ.* **2011**, *45*, 1145–1153. [CrossRef]
17. Shen, F.; Ge, X.; Hu, J.; Nie, D.; Tian, L.; Chen, M. Air pollution characteristics and health risks in Henan Province, China. *Environ. Res.* **2017**, *156*, 625–634. [CrossRef] [PubMed]
18. Stieb, D.M.; Burnett, R.T.; Smith-Doiron, M.; Brion, O.; Shin, H.H.; Economou, V. A new multipollutant, no-threshold air quality health index based on short-term associations observed in daily time-series analyses. *J. Air Waste Manag. Assoc.* **2008**, *58*, 435–450. [CrossRef] [PubMed]
19. Hu, J.; Ying, Q.; Wang, Y.; Zhang, H. Characterizing multi-pollutant air pollution in China: Comparison of three air quality indices. *Environ. Int.* **2015**, *85*, 17–25. [CrossRef] [PubMed]
20. Wong, T.W.; Tam, W.W.S.; Yu, I.T.S.; Lau, A.K.H.; Wong, A.H.S. Developing a risk-based air quality health index. *Atmos. Environ.* **2013**, *76*, 52–58. [CrossRef]
21. Chen, R.; Wang, X.; Meng, X.; Hua, J.; Zhou, Z.; Chen, B.; Kan, H. Communicating air pollution-related health risks to the public: An application of the Air Quality Health Index in Shanghai, China. *Environ. Int.* **2013**, *51*, 168–173. [CrossRef] [PubMed]
22. Li, X.; Xiao, J.; Lin, H.; Liu, T.; Qian, Z.; Zeng, W.; Guo, L.; Ma, W. The construction and validity analysis of AQHI based on mortality risk: A case study in Guangzhou, China. *Environ. Pollut.* **2017**, *220A*, 487–494. [CrossRef] [PubMed]
23. Olstrup, H.; Johansson, C.; Forsberg, B.; Tornevi, A.; Ekeboom, A.; Meister, K. A Multi-Pollutant Air Quality Health Index (AQHI) Based on Short-Term Respiratory Effects in Stockholm, Sweden. *Int. J. Environ. Res. Public Health* **2019**, *16*, 105. [CrossRef]
24. WHO. *Health Risks of Air Pollution in Europe—HRAPIE Project. Recommendations for Concentration–Response Functions for Cost–Benefit Analysis of PARTICULATE Matter, Ozone and Nitrogen Dioxide*; World Health Organization, Regional Office for Europe, European Centre for Environment and Health: Bonn, Germany, 2013.
25. Chen, J.; Hoek, G. Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis. *Environ. Int.* **2020**, 105974. in press. [CrossRef]

26. Orleano, P.; Reynoso, J.; Quaranta, N.; Bardach, A.; Ciapponi, A. Short-term exposure to particulate matter (PM10 and PM2.5), nitrogen dioxide (NO₂), and ozone (O₃) and all-cause and cause-specific mortality: Systematic review and meta-analysis. *Environ. Int.* **2020**, *142*, 105876. [[CrossRef](#)] [[PubMed](#)]
27. GIOŚ. Główny Inspektorat Ochrony Środowiska. 2020. Available online: <http://powietrze.gios.gov.pl/pjp/archives> (accessed on 21 September 2020).
28. GIOŚ. Główny Inspektorat Ochrony Środowiska. 2020. Available online: http://powietrze.gios.gov.pl/pjp/content/measuring_air_assessment_zone_info (accessed on 21 September 2020).
29. Standard EN 12341: 2014. *Ambient Air—Standard Gravimetric Measurement Method for the Determination of the PM10 or PM2.5 Mass Concentration of Suspended Particulate Matter*; European Committee for Standardization: Brussels, Belgium, 2014.
30. Pascal, M.; Corso, M.; Ung, A.; Declercq, C.; Medina, S. *Guidelines for Assessing the Health Impacts of air Pollution in European Cities*; Aphekom Work Package 5, Deliverable D5; French Institute for Public Health Surveillance: Saint-Maurice, France, 2011.
31. Maciejewska, K. Short-term impact of PM2.5, PM10, and PMc on mortality and morbidity in the agglomeration of Warsaw, Poland. *Air Qual. Atmos. Health* **2020**, *13*, 659–672. [[CrossRef](#)]
32. Rabczenko, D.; Wojtyniak, B.; Wysocki, M.; Goryński, P. Short-term impact of air pollution by sulfur dioxide, particulate matter and nitrogen dioxide on mortality in Polish cities. *Przegl. Epidemiol.* **2005**, *59*, 969–979. (In Polish) [[PubMed](#)]