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Environmental and Health Benefits Assessment of Reducing $PM_{2.5}$ Concentrations in Urban Areas in Developing Countries: Case Study Cartagena de Indias

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Abstract: High concentrations of particulate matter (PM) could significantly reduce the quality of useful life and human life expectancy. The origin, control, and management of the problem has made great steps in recent decades. However, the problem is still prominent in developing countries. In fact, often the number and spatial distribution of the air quality monitoring stations does not have an appropriate design, misleading decision makers. In the present research, an innovative assessment is proposed of the environmental, health and economic benefits corresponding to a 20% reduction in the $PM_{2.5}$ concentration in the urban area of Cartagena de Indias, Colombia. Cases of mortality and morbidity attributable to fine particles ($PM_{2.5}$) were estimated, with particular emphasis on mortality, emergency room visits and hospitalizations from respiratory diseases, in addition to their economic assessment using BenMAP-CE®. The novelty of using BenMAP-CE® in studying respiratory diseases and $PM_{2.5}$ exposure in developing countries lies in its ability to provide a comprehensive assessment of the health impacts of air pollution in these regions. This approach can aid in the development of evidence-based policy and intervention strategies to mitigate the impact of air pollution on respiratory health. Several concentration-response (C-R) functions were implemented to find $PM_{2.5}$ attributable mortality cases of ischemic heart and cardiopulmonary disease, lung cancer, respiratory and cardiovascular disease, as well as cases of morbidity episodes related to asthma exacerbation and emergency room/hospitalization care for respiratory disease. A 20% reduction would have avoided 104 cases of premature death among the population older than 30 in Cartagena, and around 65 cases of premature mortality without external causes.

Keywords: economic health benefits; urban area $PM_{2.5}$ concentrations; air pollution in developing cities; BenMAP-CE®

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1. Introduction

It is a proven fact that particulate matter with an aerodynamic diameter lower than 2.5 µm ($PM_{2.5}$) produces serious effects on human health [1,2], including the increase of mortality of cardiac and respiratory origin, and reduced lung capacity in asthmatic children and adults, among others [3–5]. Regarding morbidity, $PM_{2.5}$ is among the triggers for symptoms of different diseases that affect the respiratory tract, such as asthma [6,7]. Respiratory tract diseases have increased their occurrence in recent decades around the world and particularly among young people in developing countries [8]. Additionally, developing countries, for lack of experts and economic assets, often have problems managing air quality monitoring networks. This lead non-continuous data over time, with stations poorly representing the special distribution of the contaminants.

In Cartagena, one of the most polluted cities by fine particles in Colombia (Figure 1), respiratory diseases are one of the four main causes of mortality. Due to the warnings that $PM_{2.5}$ could be causing an important public health problem in terms of mortality and morbidity among the citizens [9], this study evaluates the health impact associated with $PM_{2.5}$ pollution in Cartagena. The effects of a 20% reduction in the $PM_{2.5}$ concentration in the urban area of Cartagena are estimated, considering health and economic benefits for the reduction of exacerbation episodes, hospital visits and hospitalizations due to childhood asthma, as well as mortality in adults mainly older than 30. Additionally, the present study clarifies the cause of deaths in Cartagena, estimating the degree of influence of $PM_{2.5}$ in the development of respiratory and cardiovascular diseases.

Figure 1. $PM_{2.5}$ annual mean (2014) in the main cities of Colombia.

2. Methodology

To estimate the cases of mortality and hospital care related to $PM_{2.5}$ concentrations in Cartagena, the concept of health impact function (HIF) was used, whose expression (1) is deduced from the log-linear model C-R functions, [10–12]:

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

where Δy is the variation in the number of cases of the endpoint under study, Δx is the variation of the concentration of the pollutant considered ($PM_{2.5}$ in this case, in $\mu g/m^3$), β is the epidemiological coefficient (dimensionless) that is deduced from the corresponding epidemiological study, y_0 corresponds to the base incidence of the disease considered, and *Pop* is the size of the population exposed to the pollutant.

In the case of the relationship of $PM_{2.5}$ with childhood asthma, which presents 'Cough' exacerbation as the main symptom, the logistic model adjusted for prevalence was applied (2):

$$\Delta y = \left(1 - \left(\frac{1}{((1-A)\cdot e^{\beta\cdot\Delta x} + A)}\right)\right)\cdot A\cdot Pop\cdot Prevalence \quad (2)$$

where Δy is the variation in the number of new episodes of "Cough" of asthmatic disease, or the probability of presenting Cough on a specific day, Δx is the variation of the concentration of the pollutant considered ($PM_{2.5}$ in this case), β is the epidemiological coefficient (dimensionless), *Prevalence* corresponds to the prevalence of asthma, *Pop* corresponds to the size of the population exposed to the pollutant, and A is a model correction constant considering the parameters evaluated in the study carried out in Los Angeles with asthmatic children who presented 'Cough, Wheeze, Shortness of Breath' as the main asthmatic symptoms [13]. The analysis flow used in the present study is shown in Figure 2.

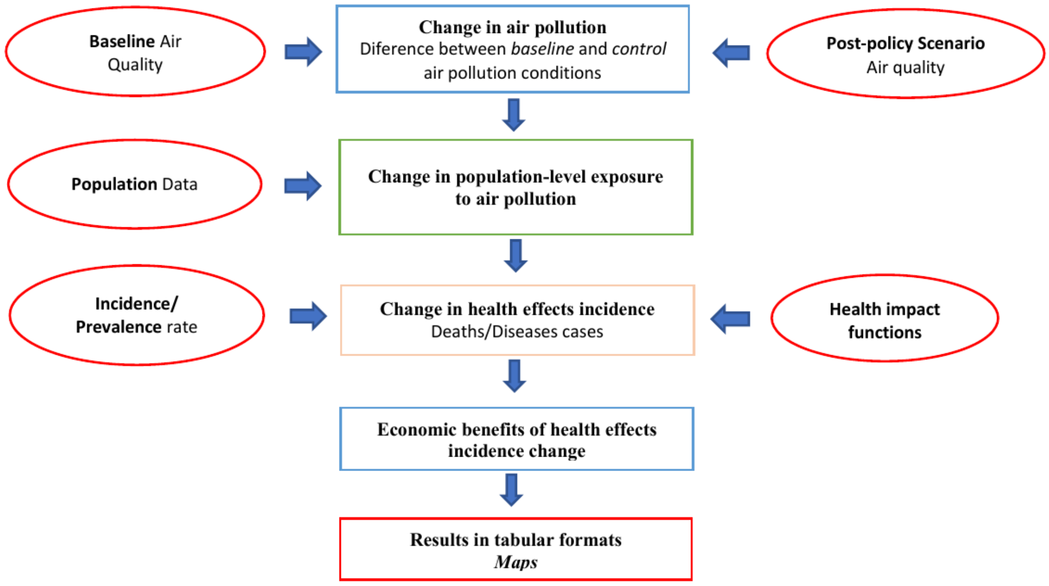

Figure 2. Workflow of the project (Source: [12]).

2.1. Software

The open-source software *Environmental Benefits Mapping and Analysis Programme—Community Edition v1.4* [12] was implemented (BenMAP-CE®) [14–17]. BenMAP-CE® is a tool that estimates the impact of criteria pollutants on human health. It was used to estimate the number of attributable cases of mortality, asthma exacerbation episodes, emergency room visits, and children's hospitalization services related to $PM_{2.5.}$ The city presents harmless concentration levels of other pollutants to human health [18]. The study was carried out with the data corresponding to the year 2014, since all the data on the mortality rate, prevalence of childhood asthma, and $PM_{2.5}$ concentrations in the city were available. The analysis has been limited to the consideration of different types of pathologies, taking into account the criteria established by the Institute of Immunological Research at the University of Cartagena [19]. The first criterion was to determine the influence of $PM_{2.5}$ in mortality cases, as well as in cases of emergency room visits for childhood asthma and hospitalizations that were sensitive to the presence of the air pollutant. The endpoint cases analyzed are the following: (1) Exposure to $PM_{2.5}$ and mortality from all causes (premature mortality). (2) Exposure to $PM_{2.5}$ and mortality from all causes "Non-Accidental". (3) Exposure to $PM_{2.5}$ and cases of ischemic mortality. (4) Exposure to $PM_{2.5}$ and cases of cardiovascular mortality. (5) Exposure to $PM_{2.5}$ and cases of cardiopulmonary mortality. (6) Exposure to $PM_{2.5}$ and cases of mortality from respiratory causes. (7) Exposure to $PM_{2.5}$

and cases of mortality from lung cancer. (8) Exposure to $PM_{2.5}$ and cases of emergency room visits for childhood asthma. (9) Exposure to $PM_{2.5}$ and hospitalization for respiratory causes and childhood asthma.

2.2. Exposure to $PM_{2.5}$

The city of Cartagena is geographically located in north of Colombia, with a population of 1,003,685 [20]. Cartagena sits on a flat topography with elevations lower than 250 m above sea level. The city's air quality surveillance system (SVCA, for its initials in Spanish) consists of six stations for the measurement and registration of criteria pollutants that are usually measured in cities. However, only three of them have $PM_{2.5}$ concentration measurement equipment installed, and one has PM_{10} equipment, all classified as "urban background" (Figure 3). The concentration of the pollutant may be affected by the contribution of sources subjected to the wind regime [21,22].

Name	Cardique station	Zona Franca La Candelaria station	Base Naval station
Class	Semi-automatic (Urban background)	Automatic (Urban background)	Automatic (Urban background)
Explanation	Cardique facilities Manzanillo island	FEPCO company facilities Industrial area "El Mamonal"	National Naval Base Tourist District

Figure 3. Characteristics of fixed fine particles measurement stations in Cartagena (Source: [18]).

$PM_{2.5}$ and PM_{10} concentrations were recorded daily from 2014 to 2016 and analyzed every 24 h (Figure 4). Incomplete series of concentrations were obtained due to the temporary contracts associated with technical staff and the lack of training among EPA employees, as well as the lack of proper maintenance of the station network. Therefore, the statistical analysis employing *R*-software for missing-data imputation was applied.

In the case of the station that records PM_{10}, the $PM_{2.5}/PM_{10}$ ratio was calculated. An average value of the $PM_{2.5}/PM_{10}$ ratio has been considered in the case of Cartagena of 0.5 units, as frequently reported in literature [23]. Population exposure was determined at the neighborhood level by interpolating the annual averages from the $PM_{2.5}$ annual and daily mean records using the Voronoi interpolation method (Voronoi neighborhood averaging, VNA) (n = 183 neighborhoods). The VNA is an algorithm used by BenMAP-CE® to interpolate air quality monitoring data to an unmonitored location. The software first identifies the set of monitors that best "surround" the population grid cell center, and then takes an inverse-distance weighted average of the monitoring values [12].

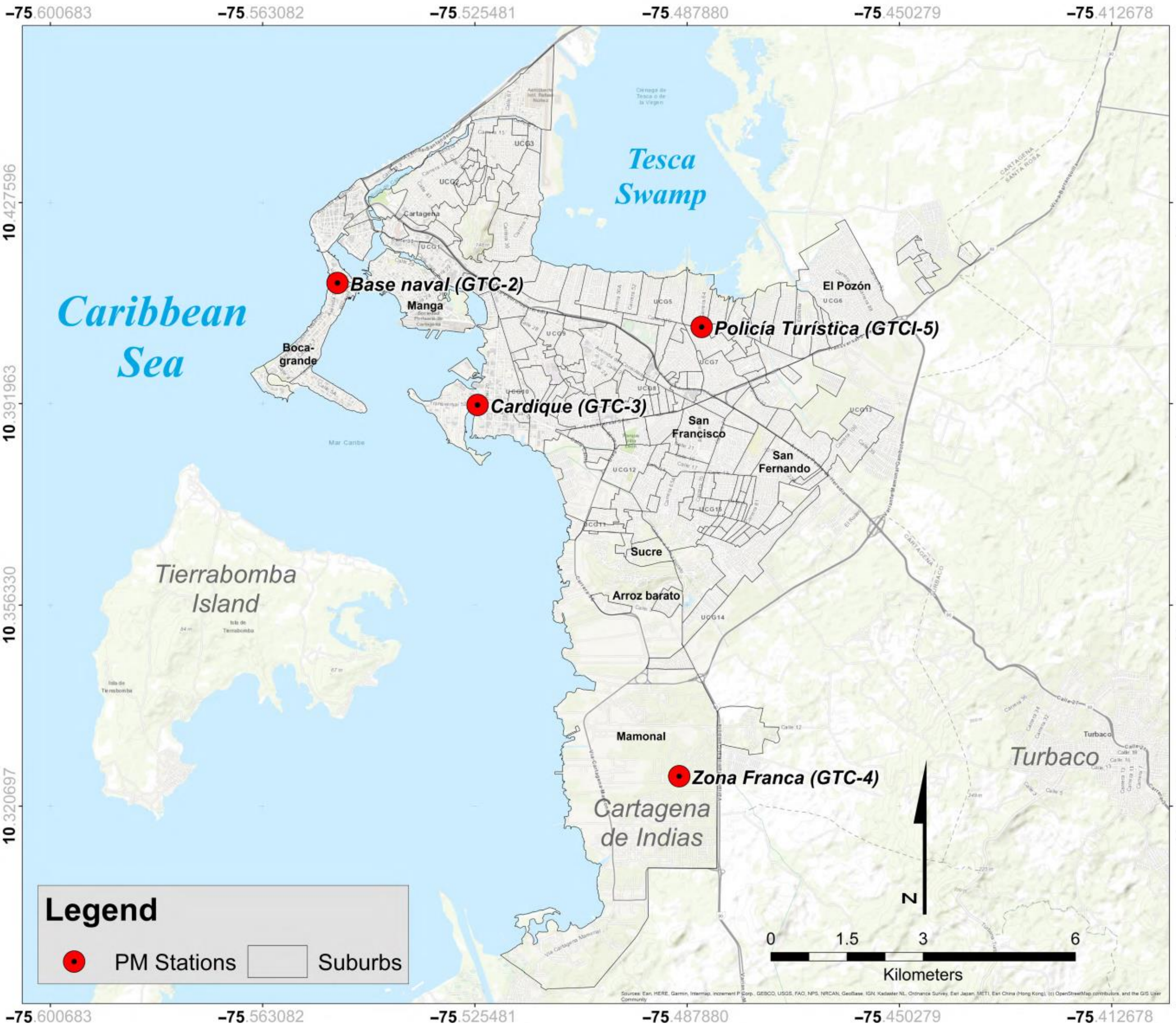

Figure 4. Geographical situation of fine particle measurement stations in Cartagena.

Baseline Incidence Rates and Population Size by Neighborhoods

Population data by age range from the records of the Census of the National Statistical Administrative Department of Colombia (DANE, for its initials in Spanish) [20,24], were used. Additionally, the prevalence records for childhood asthma were considered by socioeconomic stratum, specifically studying asthmatic exacerbation with the main symptom of "Cough", taking into account the criteria and data previously obtained [25]. The incidence of emergency room visits for asthma as well as for diseases related to the criteria of the Ministry of Health of Colombia was considered [26].

In Cartagena, the proportion of the youth population with asthma symptoms is particularly high, given that an average prevalence of the disease close to 20% is reached in the case of children under nine years. However, the ratios (prevalence rate) are in the age range between 10 and 18 years [27]. The disease manifests itself with recurrent asthmatic exacerbations, reaching prevalence values in "Cough" and "Wheeze" among the child population varying between 15% and 20%, depending on the socioeconomic stratum [28]. For emergency room visits in hospitals and clinics for childhood asthma, the incidence rate was 18 cases per 1000 inhabitants in children under 9 years of age, reducing values by close to half in the case of young people between 10 and 18 years. The incidence rate of hospitalizations for respiratory causes in children under 4 years was estimated at 17 cases per 1000 children, with asthma being the disease with the greatest impact. In the case of mortality, similar incidences were recorded for age groups in other regions of the world, considering the adult population (Table 1).

Table 1. Cartagena Mortality Rates (per 100 people per year) by Health Endpoint and Age Group, 2014.

Mortality Category	ICD-10 Codes	Age Ranges										
		30–34	35–39	40–44	45–49	50–54	55–59	60–64	65–69	70–74	75–79	80+
Mortality, All Causes	A00-Y98	0.1122	0.1562	0.2147	0.2332	0.3243	0.5351	0.8331	1.1561	2.0678	3.1045	9.2860
Mortality, Non Accidental	A00-R99	0.0459	0.1006	0.1572	0.1996	0.2816	0.4998	0.7978	1.1166	2.0266	2.9990	9.1429
Mortality, Ischaemic Heart Disease	I20-I25	0.0025	0.0060	0.0169	0.0167	0.0303	0.0660	0.1408	0.1578	0.3417	0.4521	1.1673
Mortality, Respiratory	J00-J98	0.0038	0.0045	0.0101	0.0201	0.0213	0.0550	0.0704	0.0986	0.2592	0.4671	1.8225
Mortality, Cardiopulmonary	I00-I78 J10-J18,	0.0038	0.0030	0.0033	0.0067	0.0142	0.0176	0.0117	0.0276	0.0589	0.0753	0.2108
Mortality, Cardiovascular	I20-I28 I30-I52 I60-I79	0.0114	0.0195	0.0422	0.0520	0.0784	0.1541	0.2786	0.4103	0.8012	1.2357	3.5773
Mortality, Lung Cancer	C34	0	0	0	0.0050	0.0089	0.0198	0.0322	0.0394	0.0471	0.1130	0.1656

2.3. Risk Coefficients

The different values of the epidemiological coefficients (β) were deduced from previously published epidemiological studies reported in Table 2.

Table 2. Effect coefficients applied in this research.

Health Endpoint	Epidemiologic Parameter (β) 95th Percentile	Pollutant	Author	Age
Mortality (All Cause)	0.0058268908 (σ = 0.00215707) *RR* = 1.06 (1.02–1.11) per 10 μg/m^3	$PM_{2.5}$ (annual avg)	[29]	30–99
	0.0029558802 (σ = 0.00099081) *RR* = 1.03 (1.01–1.05) per 10 μg/m^3		[30]	30–99
Mortality (Non-Accidental)	0.0039220713 (σ = 0.00049061) *RR* = 1.04 (1.03–1.05) per 10 μg/m^3		[31]	>30
	0.013976194 (σ = 0.000668443) *RR* = 1.15 (1.13–1.16) per 10 μg/m^3		[32]	>25
Ischemic Heart Disease	0.01655144 (σ = 0.0019384) *RR* = 1.18 (1.14–1.23) per 10 μg/m^3		[29]	30–99
	0.01397619 (σ = 0.00198877) *RR* = 1.15 (1.11–1.20) per 10 μg/m^3		[30]	30–99
Respiratory	0.00305292 (σ = 0.0039072) *RR* = 1.031 (0.955–1.113)~10 μg/m^3		[33]	30–99
Cardiopulmonary	0.00861776 (σ = 0.003032173) *RR* = 1.09 (1.03–1.16) per 10 μg/m^3		[29]	30–99
Cardiovascular	0.0058268908 (σ = 0.00096276) *RR* = 1.06 (1.04–1.08) per 10 μg/m^3		[31]	>30

Table 2. *Cont.*

Health Endpoint	Epidemiologic Parameter (β) 95th Percentile	Pollutant	Author	Age
Lung Cancer	0.01310282 (σ = 0.00428044) *RR* = 1.14 (1.04–1.23) per 10 μg/m^3	$PM_{2.5}$ (24 h-avg)	[29]	30–99
Asthma Exacerbation (Cough)	0.000985293 (σ = 0.00074712) *RR* = 1.03 (0.98–1.07) per 30 μg/m^3		[13]	5–18
Emergency Room Visits: Asthma	0.0147117 (σ = 0.0034923) *RR* = 1.15 (1.08–1.23) per 9.5 μg/m^3		[34]	<18
Hospitalization: Respiratory	0.00814968 (σ = 0.0024771) Increase = 15.8% (t statistic 3.29) per 18 μg/m^3		[35]	<4

RR = Relative Risk, σ = Standard Deviation, β = Epidemiologic Parameter.

2.4. Estimation of the Number of Disease Cases Attributable to Anthropogenic $PM_{2.5}$ Exposure

HIF procedure was used to calculate the number of premature deaths corresponding to mortality (1), due to the effect of anthropogenic $PM_{2.5}$, as well as cases of episodes from Cough, Wheeze, Shortness of Breath due to asthmatic causes (2), emergency room visits and hospitalization services for children with the same causes considering the population of each Cartagena neighbourhood.

2.5. Economic Assessment

An economic value is associated with sickness and deaths by $PM_{2.5}$ in Cartagena, applying the concept of "cost of illness" (COI) [36] and "value of statistical life" (VSL) [37] for mortality cases. Nevertheless, there are not uniform costs associated with asthma in Colombia; therefore, a unit price available in the Caldas District estimated in 2009 was considered, due to the similarity in the price of life and socioeconomic conditions. The price was updated in 2019 [38]. Three-unit costs were defined according to the endpoint studied:

1. Emergency Room Visits: COP 90,000 /visit · person (2009).
2. Children Hospitalizations (under 4 years) for respiratory causes: COP 1,500,000 /hospitalization (2009).
3. Cost of a person's life: A VSL of COP 1,008,000 (2009).

The economic evaluation of the attributable cases for the year 2019 was carried out considering Equation (3):

$$V = C \cdot U \cdot I_{2019} \quad (3)$$

where V corresponds to the assessment of benefits for attributable cases, C corresponds to cases attributable to $PM_{2.5}$, U is the unit cost, and I_{2019} is the consumer price index (CPI) to update the values to 2019 prices.

3. Results and Discussion

In Cartagena, road traffic represents the main source of $PM_{2.5}$ [39] due to the absence of other important combustion processes that can generate this pollutant. The average annual concentration of $PM_{2.5}$ registered exceeded the threshold established by Colombian and international air quality standards (5 μg/m^3). Due to the lack of qualified workers, there was a considerable loss of records from 2014 to 2016. For this reason, data completion algorithms were implemented, applying the statistical R-software to complete the PM records of the city. During this period, the highest concentrations of $PM_{2.5}$ were recorded at two specific stations in the city: one corresponding to the tourist area of Bocagrande (Naval Base Station) and another one located in the industrial area of El Mamonal (Zona Franca La Candelaria Station). In both stations, annual averages of around 27 μg/m^3 were recorded. Moreover, considering all stations, the registered $PM_{2.5}$ concentrations (and those estimated by interpolation) in the neighborhoods reveal values higher than 20 μg/m^3 mean value. The adverse effects of $PM_{2.5}$ on human health appear at concentrations greater than 5 μg/m^3 [31,40]. Therefore, $PM_{2.5}$ levels in Cartagena are extremely high and potentially harmful to human health (Figure 5).

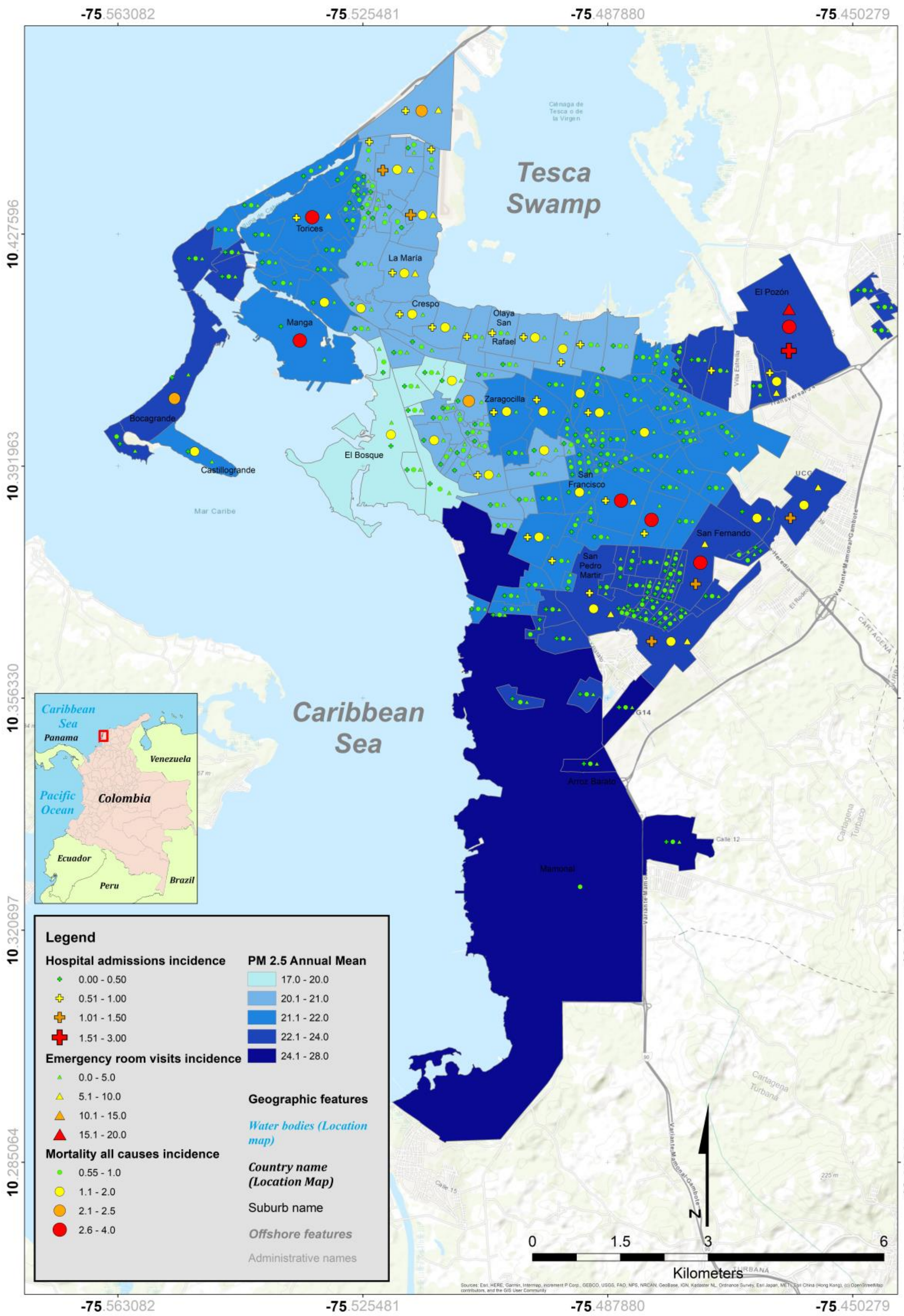

Figure 5. Impact of $PM_{2.5}$ on Cartagena population (2014).

Voronoi interpolation is a good estimate when spatially distributing the $PM_{2.5}$ concentrations recorded at the measurement stations. However, the concentration values of the pollutant may be susceptible to some uncertainty, especially in areas near the outer limits of the city [12].

3.1. Number Estimation of Deaths and Morbidity Cases Avoided Due to the $PM_{2.5}$ Reduction

Considering Cartagena's air quality management plan, 20% reductions in anthropogenic $PM_{2.5}$ would avoid approximately 104 (95% CI: 28–177) annual cases of death for all causes in Cartagena, which represents 0.021% of the total population 29 years and older.

Regarding the relation between $PM_{2.5}$ and mortality from non-accidental causes (epidemiological causes), the epidemiological parameters (β) were considered according to the literature (Table 2). The population characteristics of the studies found in the literature are in most cases similar to those of Cartagena.

In the mortality analysis in Cartagena, the population over 29 was considered. People over 99 are considered statistically negligible. The neighborhoods most affected by mortality in the city of Cartagena are El Pozón, San Fernando, Torices, Manga, and Bocagrande.

Five endpoints were considered to analyze mortality. In the case of ischemic heart disease mortality, 36 avoidable cases (95% confidence interval (CI): 28–44) were estimated after a 20% $PM_{2.5}$ reduction. Regarding cardiovascular mortality, considering a wide group including subclasses of the cardiac system, 35 avoidable cases (95% CI: 24-46) were estimated in the city.

Moreover, respiratory mortality occurs less frequently in the absence of O_3, with seven cases (55% CI: 1–14) occurring in Cartagena after a 20% $PM_{2.5}$ reduction. Considering lung cancer, a relatively low mortality rate is found in Cartagena with six cases (95% CI: 2–8) after a 20% $PM_{2.5}$ reduction. It should be noted that this rate is about three times lower compared to the mortality rate of developed countries such as the USA. Finally, four cases (95% CI: 1–6) of death due to cardiopulmonary mortality after $PM_{2.5}$ reduction in the city were revealed. Again, the El Pozón neighborhood is the most affected by these mortality classes.

According to the estimates of the epidemiological parameter (β) obtained in a study carried out in Rome, the number of annual preventable deaths (2014) from non-accidental causes after the corresponding reductions in $PM_{2.5}$ was 65 (95% CI: 49–81). In the case of the satellite adjusted estimates, the number of preventable deaths from non-accidental causes after $PM_{2.5}$ reductions was 227 cases (95% CI: 206–247) (0.046% of the population over 29), which means a significant increase in the number of avoidable cases compared to the application of the estimate deduced by [31].

A total of 48 cases (95% CI: 20–76) of hospitalization for respiratory causes was obtained in children younger than 4 after the reduction of $PM_{2.5}$, as well as 296 (95% CI: 160–427) visits from childhood asthma specialists. The number of emergency room visits for asthma in children under 17 has a very significant magnitude due to the high prevalence of the disease in the city, representing a serious health problem in the Colombian Caribbean coast among the young population. It is observed that neighbourhoods such as El Pozón and San Fernando would also benefit the most in the case of PM reduction.

In order to find a relationship between the variation of $PM_{2.5}$ concentrations and the prevalence of exacerbation due to asthma in the early stages of life, considering the population between 5 and 18 years, the logistics model concept was applied (2). The results of the logistic model in this case present two interpretations, probability of presenting a day with symptoms and number of new episodes with symptoms.

As a result, the probability of suffering a daily episode of Cough was obtained at 15% (75% CI: 2–27) after reducing the $PM_{2.5}$ concentration levels by 20%. The total analysed cases (Table 3) in the present study do not suppose even 50% of the endpoints that could be studied in relation to $PM_{2.5}$ due to the lack of resources to develop more extensive research. However, the study shows the magnitude of the problem to which the Cartagena population is exposed.

Table 3. Number of mortalities, hospital admissions (respiratory) and emergency room visit cases avoided in Cartagena if $PM_{2.5}$ levels had been 20% lower.

Endpoint Groups		* Number (% CI)	Age Range	Features
Mortality	All Cause	104 (29–177)	>29 (>25)	Annual Mean Metric
		53 (18–87)		
	* Non-Accidental	65 (49–81)		
		227 (206–247) *		
	Ischemic Heart Disease	36 (28–44)		
		31 (22–39)		
	Cardiovascular	35 (24–46)		
	Lung Cancer	6 (2–8)		
	Respiratory	7 (1–14)		
	Cardiopulmonary	4 (1–6)		
Hospital Admissions: Respiratory		48 (20–76)	<4	Daily Metric completed with Rsoftware
Emergency Room Visits: Asthma		296 (160–427)	<18	

* (95% CI) except Respiratory (55% CI).

3.2. *Economic Benefit Associated with Reducing Anthropogenic $PM_{2.5}$ Levels*

The present economic evaluation for $PM_{2.5}$ health and economic impact is a novel and useful technique. Important economic and social benefit will result from a 20% $PM_{2.5}$ reduction in the city. In a vulnerable population from an economic perspective, the monetization of environmental risks by neighborhood is essential to develop strategies whose purpose is the effective protection of the population health [41], (Figure 6) (Table 4).

Table 4. Economic benefits estimated in Cartagena.

Endpoint Groups		** Economic Valuation (% CI)
Mortality	All Cause	140.823 (39.766–247.589)
	* Non-Accidental	71.935 (25.292–122.335) [1]
		308.473 (274.429–368.103) [2]
	Ischemic Heart Disease	49.237 (38.745–63.621)
	Cardiovascular	47.735 (33.133–65.901)
	Lung Cancer	7.497 (3.371–11.947)
	Respiratory	9.900 (282–19.046)
	Cardiopulmonary	5.201 (1.669–8.930)
Hospital Admissions: Respiratory		97.8 (39.8–154.3)
Emergency Room Visits: Asthma		38.8 (19.7–59.6)

* Non-Accidental Mortality—[1] [31] [2] [32] ** (95% CI) except Respiratory (55% CI). Results in millions of Colombian Pesos.

Considering the number of preventable premature deaths from an overall perspective, the estimated economic benefit would be USD 46.9 million (all causes). On the other hand, the benefit associated with non-accidental deaths estimated with satellite measurements [32], would rise to USD 100 million (Figure 6).

As a general diagnosis of the air quality situation in Cartagena, it can be said that the city presents an "invasion of $PM_{2.5}$" that causes a high number of cases of mortality and especially emergency room visits due to asthmatic attacks (establishing an 'interim target' IT-2). Moreover, it can be inferred from the high average levels of concentration existing in the city (slightly higher than 25 μg/m^3 annual average) that $PM_{2.5}$ is linked to other clinical pathologies and critical events. It should be noted that the average annual concentration levels of $PM_{2.5}$ presented in Western Europe in recent years are between 5 μg/m^3 and 15 μg/m^3 [42,43], producing more than 200,000 premature deaths in the EU's top five economies, [44].

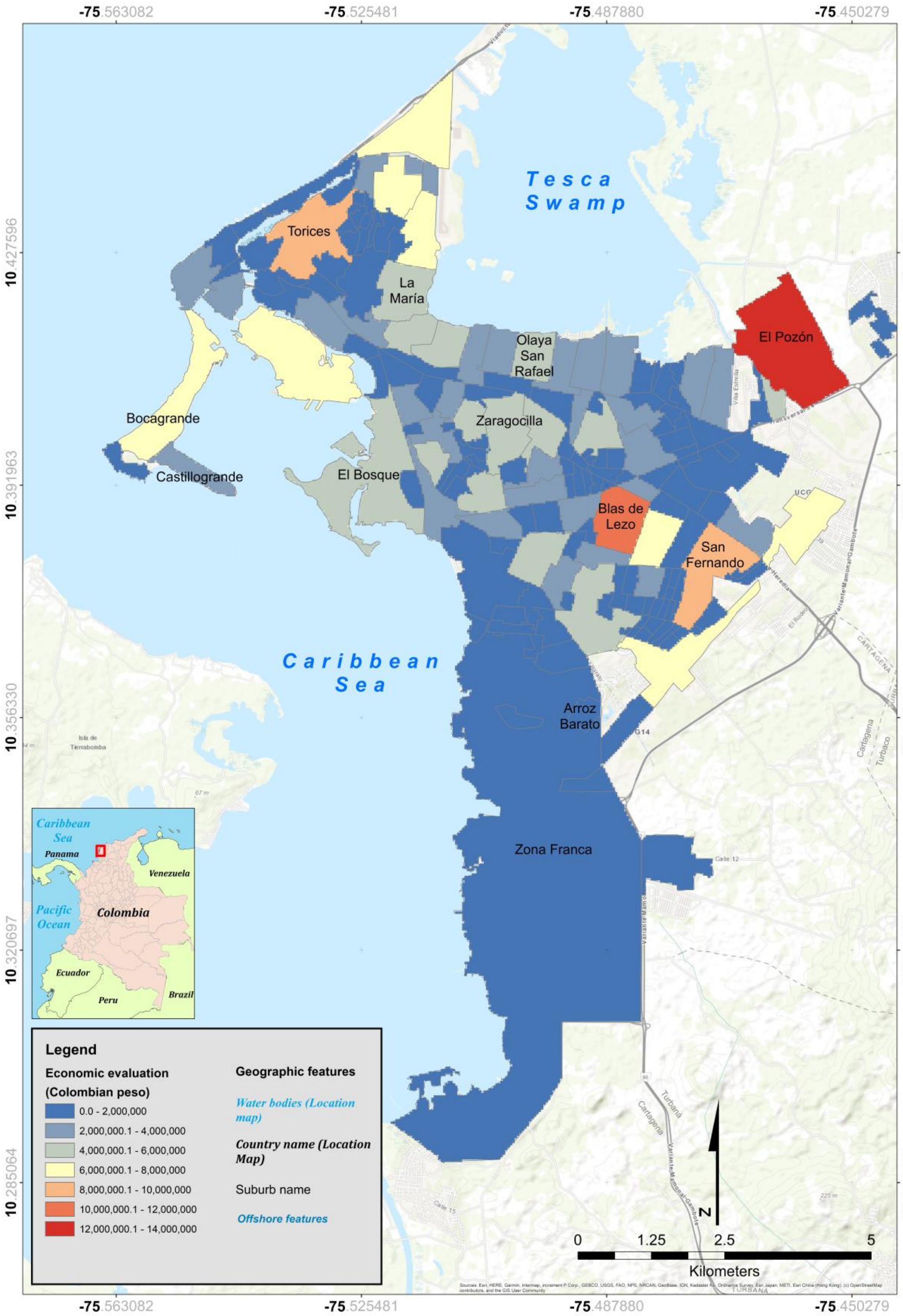

Figure 6. Economic assessment of reducing $PM_{2.5}$ in Cartagena (2014).

It is worth noting the low rate of hospitalization for respiratory causes in children that occurs in Cartagena compared to other Colombian cities such as Bogotá. In Bogotá the hospitalization rate exceeds 60 cases per 1000 [21], while in Cartagena it is around 20 cases per 1000. This suggests a health system deficit of available beds to adequately treat the disease. Furthermore, results obtained are proportional to other studies carried out at the international level [45,46].

The different values of the epidemiological parameter (β), and associated C-R functions applied in this study, were estimated in different epidemiological studies, mainly in the USA. Therefore, it follows that the health behavior of the population in Cartagena before the effect of $PM_{2.5}$ will be the same as in the case of epidemiological studies carried out in the USA, where this hypothesis would not be exact. Paying special attention to the C-R function associated with respiratory mortality, there is no clear association between $PM_{2.5}$ and this class of death in the absence of O_3, as a very small confidence interval was obtained in the results of the model (55% CI) by "single model". An extraordinarily high impact of childhood asthma was found in Cartagena, with a prevalence of the disease of about 20% among children.

This research has considered the urban scale study developed for the city of Sydney [46] as a reference, with a population approximately five times higher than that of Cartagena. In this case, 71 cases (95% CI: 52–91) of preventable premature deaths corresponding to a reduction of 0.8 $\mu g/m^3$ of concentration of $PM_{2.5}$ were estimated, assuming a 10% decrease in fine particles. The number of people by age range and the incidence of the endpoints analyzed are not equivalent between the two cities. Nevertheless, the results of avoided cases suggest that both investigations are comparable.

The current research constitutes a noteworthy addition to the domain of environmental and public health research, with particular relevance for developing nations. The study's key strength lies in the production of high-quality maps (Figures 5 and 6), achieved through ground-level measurements of $PM_{2.5}$ concentrations across the investigated urban area and the application of a loglinear model. These maps furnish an explicit depiction of the distribution of air pollution within the region under scrutiny, permitting a more precise and accurate appraisal of the potential environmental and health benefits associated with $PM_{2.5}$ reduction.

Recent studies in scientific journals in the last 5 years have shown the importance of high-resolution mapping for air pollution studies, with a focus on precision and detail. Such precise mapping provides valuable information for decision-making in public health and environmental policies [47,48].

In addition, the study's findings deliver insights into the potential advantages of reducing air pollution in other developing cities worldwide. The utilization of BenMAP-CE® and high-quality maps contributes to the study's rigor and validity, further supporting the results' crucial implications for public health and environmental policies in developing countries, considering budget limitations, the low number of pollutant monitoring stations, and the low skill levels of technical workers, among other penalizing factors.

4. Conclusions

Urban areas of developing countries have limited economic and human resources for managing problems related to air quality. The objective of the present study was to evaluate the environmental, health, and economic impact associated with a 20% $PM_{2.5}$ reduction in the city of Cartagena de Indias, Colombia. The calculation of the impact model in the city's neighborhoods was proposed, in a medium-sized city, which is considered a great level of detail the in analysis of the results. The methodology followed in this study allowed the finding of the economic benefits associated with a decrease in the concentration of $PM_{2.5}$ in the environment disaggregated in space. Likewise, the benefits and cases attributable to the variations in $PM_{2.5}$ concentration were estimated for different endpoints.

A significant economic benefit between USD 50 and 100 million could be saved annually in Cartagena, triggering a virtuous circle of benefits for the environment and for human health. Hundreds of lives every year could be saved by this reduction with incalculable positive effects from a social and economic point of view.

In Cartagena an average annual $PM_{2.5}$ concentration level of 25 $\mu g/m^3$ was found. This phenomenon frequently occurs in low- and middle-income cities in developing countries (thus establishing an interim target IT-2, according to WHO guidelines) [49,50].

In addition, a study carried out recently in the city indicates that one of the main generators of particles is road traffic, as high concentration levels of the pollutant are found in the areas with the highest number of vehicles [39].

Due to the high levels of $PM_{2.5}$ concentration in this Caribbean city, establishing a solid policy to face this serious public health problem is recommended. In order to do this, environmental education and social awareness campaigns must be carried out, promoting the use of public transport as well as the use of non-motorized vehicles among other mitigation measures.

Developing countries tend to experience higher levels of $PM_{2.5}$ pollution, which may contribute to the increased prevalence of these diseases in these regions. Employing the software tool BenMAP-CE® in these investigations allows for a more precise assessment of the health impacts of air pollution, by accounting for the spatial and temporal variability of $PM_{2.5}$ concentrations. Furthermore, the utilization of BenMAP-CE® permits the identification of the most susceptible populations, aiding in the development of effective interventions aimed at reducing exposure to air pollution.

Finally, the novelty of utilizing BenMAP-CE® in investigating the relationship between respiratory diseases and $PM_{2.5}$ exposure in developing countries is notable, as it provides a unique approach to understanding the health implications of air pollution in these regions. This approach can offer valuable insights into the development of evidence-based interventions to address the burden of respiratory diseases caused by air pollution.

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