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The Cost of Air Pollution
A Case Study for the city of Cuenca, Ecuador

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The Cost of air pollution

A case study for the city of Cuenca, Ecuador

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Contents

1. Executive Summary 2
2. Introduction 4
3. Why air pollution? Why particulate matter? 6
4. Sources and impacts of PM pollution 11
   4.1. Sources of PM 11
   4.2. Health impacts caused by particulate matter 12
   4.3. Non-health related impacts of PM 13
5. Modeling the Economic Impacts of Air Pollution 15
   5.1. Background 15
   5.2. Modeling of PM2.5 pollution levels for each city district (parroquia) 17
   5.3. Mobility-adjusted population density by age-group for each city district 19
   5.4. Estimation of relative risk (RR) and population attributable fractions (PAF) 20
   5.5. Economic valuation of the burden of disease 23
6. The Costs of Air Pollution in Cuenca 26
7. Discussion and Conclusions 30
Annex 1. Literature review 32
Annex 2: PM concentration per city district (parroquia) 40
Annex 3. Distribution of population and net change after adjustment 41
Annex 4. Diseases associated with PM pollution and their differentiated impacts 43
References 44

1. Executive Summary

The Municipality of Cuenca ("Gobierno Autónomo Descentralizado Municipal del Cantón Cuenca") through its Environmental Management Commission (EMC), is taking important steps towards the strengthening of local capacities to manage Cuenca's environmental assets, and to promote initiatives to improve the quality of life of its population. Under a resources-constraint reality, EMC needs hard evidence and data to characterize the different environmental stressors they face and analyze their consequences. This information becomes a building block to establish priorities and support the decision-making process on public policy formulation.

In an attempt to answer those needs, the World Bank, in collaboration with EMC, has applied the Cost of Environmental Degradation (CoED) methodology to Cuenca. CoED is a fully-developed discipline, with internationally-agreed methodologies and equations. When applied to a specific environmental impact, it provides cost estimates associated to those impacts. These can be used as benchmarks to compare performance between locations, and are useful to prioritize the menu of intervention options. This report captures the main CoED results obtained for Cuenca.

Air pollution, and more specifically outdoor particulate matter (PM), was chosen as the priority source of environmental degradation to be studied. The Municipality is very advanced in its knowledge about PM pollution, and has plenty of studies and information about sources, urban quality levels and pollutant dispersion estimates. There was an interest to deepen the understanding around PM impacts, and estimate its specific effects on population. The topic was also especially relevant given its direct linkages to other emblematic sectors in Cuenca, such as tourism, and economic productivity broadly speaking. Reduce PM emissions becomes therefore an important challenge in order to promote regional green and inclusive development. The information obtained from this exercise is useful to inform policy and investment options. The analysis of these options is not, however, the subject of this report, which focuses on describing the methodology and discussing the results.

The study calculate costs based on human mortality estimates caused by outdoor PM pollution, which is the main, most significant impact. The results do not include costs of other PM impacts on humans, such as morbidity and cognitive alterations. These, however, are a small percentage of the envelope when compared to mortality costs. Other PM pollution impacts, such as indoor PM effects, or non-health-related impacts (such as impacts on infrastructure, crop productivity), are not accounted for in the final results. Therefore, the monetary values calculated for Cuenca are only a sub-set of the whole range of impacts caused by PM.

Cuenca is experiencing a significant population increase (from 110,000 in 1975 to over 350,000 in 2013), associated with an expansion of the urban sprawl, which has been proportionally larger than the population growth itself. Vehicular fleet has also exhibited rapid growth, with a yearly 12% increase for non-commercial vehicles since 1975. In addition, a change in behavior that gives preference to private or individual car transport over public transport has been observed (between 1992 and 2012 the amount of people using private cars or taxis as the main mode of transport increased from 20% to 43%). Air quality in Cuenca reflects somehow these trends, and

compares poorly to other Ecuadorian cities in relation to PM concentration, and is in the middle of the spectrum when compared to other international centers.

Multiple studies worldwide have demonstrated a consistent relation between the concentrations of fine particulate matter in the air and adverse impacts (respiratory symptoms, morbidity and mortality). Particulate matter is especially harmful to people with lung disease, and can trigger asthma attacks and cause wheezing, coughing, and respiratory irritation in individuals with sensitive airways, as well as other, more severe diseases. Epidemiological studies show that an increase in PM10 mass concentration of 10 μg m^{-3} results in an increase of 0.5 -1.5% in premature total mortality in case of short term/episodic exposure, and in an increase of up to 5% in premature total mortality in case of long-term/lifelong exposure.

Instead of calculating one single economic cost figure related to the mortality caused by outdoor PM pollution in Cuenca, different valuation methodologies have been applied in this study, and a range of cost estimates have been determined. Three approaches were used, the human capital approach (HCA), the value of a statistical life (VSL) approach, and the value of a statistical life year (VOLY) approach. Depending on the valuation approach, the cost of PM2.5 air pollution equals to a range of between 1.08% and 0.07% of regional GDP.

In terms of total costs, estimates range between a minimum of US$1.7 million (HCA) and a maximum of US$ 25.8 million (VSL approach) per year caused by PM pollution in Cuenca. Both HCA and VSL are often claimed as failing to adequately reflect the total economic value of human life when applied to air pollution, discussed in the report. Therefore, for applied analysis from which policy recommendations are to be derived, the use of VOLY is most recommended. Its cost estimates range between lower and upper bounds of US$6.5 and US$10.9 million, with an average of US$ 8.4 million per year in costs to Cuenca caused by PM mortality. In relation to regional GDP, this corresponds to an average of 0.35% of regional GDP, or a range of 0.27% – 0.45% of regional GDP. In terms of deceases, and according to the methodology applied, a total of 24 deaths should be attributed yearly to PM2.5 air pollution.

2. Introduction

In 2010, the Municipality of Cuenca, through its Environmental Management Commission (EMC), and the World Bank, through the Environment and Natural Resources Department, started a collaboration targeted towards strengthening EMC's capacity to better manage Cuenca's environmental assets, and to provide EMC with hard evidence and data that would serve as departing point for decision-makers towards the formulation of public policy. Two main areas of focus were chosen: (i) costs of environmental degradation for Cuenca; and (ii) climate change impacts and resilience measures for Cuenca.

The information obtained through the work carried out along the two main areas of focus aforementioned will support the EMC's efforts to internalize the socioeconomic impact of environmental degradation and improve natural resource management, address climate change challenges, and promote investment in sustainable infrastructure. This report describes the findings of the first area of focus.

The estimation of environmental degradation costs is a fully-developed discipline, with internationally-agreed methodologies and approaches. The estimates obtained through these studies provide decision makers with easy-to-interpret information about the implications of environmental impacts, and are often used as benchmark to compare performance on any single location. Assessments of the cost of environmental degradation are used with the specific purpose of estimating the socio-economic costs of the degradation, notably in terms of the health damage associated with environmental degradation. There was, thus, a double stimulus to perform a cost of environmental degradation study in Cuenca. On the one hand, EMC would be able to assign a monetary value to the health damage associated with environmental degradation (the degradation associated with air pollution was the chosen one) that could otherwise be overlooked; and on the other hand, it would gain familiarity and exposure into the field, and be equipped with the basic equations and approaches of the discipline (therefore enabling EMC to repeat similar calculations for other compartments of environmental degradation, such as water quality, soil degradation, noise and others). This report tries to capture the main results and to describe the assumptions and input data utilized, through a detailed step-by-step description of an internationally-accepted and validated methodology, an explanation of input data needs, equations used, assumptions made, and alternative calculation streams; and through the demonstration of this methodology as it is applied to the real case of air pollution in Cuenca. Future areas of work and expansion of the present study would be the identification and analysis of a set of measures targeted towards the reduction of those costs, together with an estimate of their cost-effectiveness, in order to systematically compare their benefits if pursued. Analyses about the cost of environmental degradation are often used as an environmental priority-setting tool, because it gives the estimated socio-economic costs of environmental degradation (air pollution, inadequate water supply, sanitation, hygiene and others). In this report, the methodology was used only for air pollution; similar studies could be replicated for other areas in order to have a full description of the different sources of pollution and the subsequent costs that Cuenca is subject to.

Air pollution, and more specifically outdoor particulate matter (PM), was chosen as the priority concern to be studied. The Municipality has plenty of studies and information about sources, quality levels, pollutant dispersion estimates, and had an interest to deepen the understanding around impact estimation. The topic was also especially relevant given its direct damage to human health, tourism sector, and economic productivity, turning therefore into an important aspect to manage in order to promote green and inclusive development. The information obtained from this exercise is useful in order to prioritize policy and investment interventions, and guide the development of key sectors such as transport or industrial production. These policies and investments are however not the subject of this report, which focuses on describing the methodology and discussing the results. Since the focus of the study is health impacts caused by outdoor particulate matter pollution, these results will not include other costs related to PM pollution impacts, such as indoor particulate matter effects (although indoor air pollution might influence outdoor concentrations), nor will it provide an insight on the non-health-related impacts of PM (such as impacts on infrastructure, crop productivity or others), and therefore the monetary values here calculated will be only a sub-set of the whole range of impacts caused by PM specifically and other atmospheric pollutants more broadly.

3. Why air pollution? Why particulate matter?

Ecuador's population is estimated at over 14 million inhabitants, most of whom are concentrated in cities. The country's rate of urbanization, as in many other major Latin American cities, is high. Cuenca is no exception to this, and the city has seen a population increase from 110,000 in 1975 to over 350,000 in 2013 (figure 1). The increase of the population in Cuenca has come associated with an expansion of the urban sprawl, which has been proportionally larger than the population growth itself (figure 2). It is well-known that declining ambient air quality is characteristic of urban areas, with industry and transport as major contributors to the pollution loading.

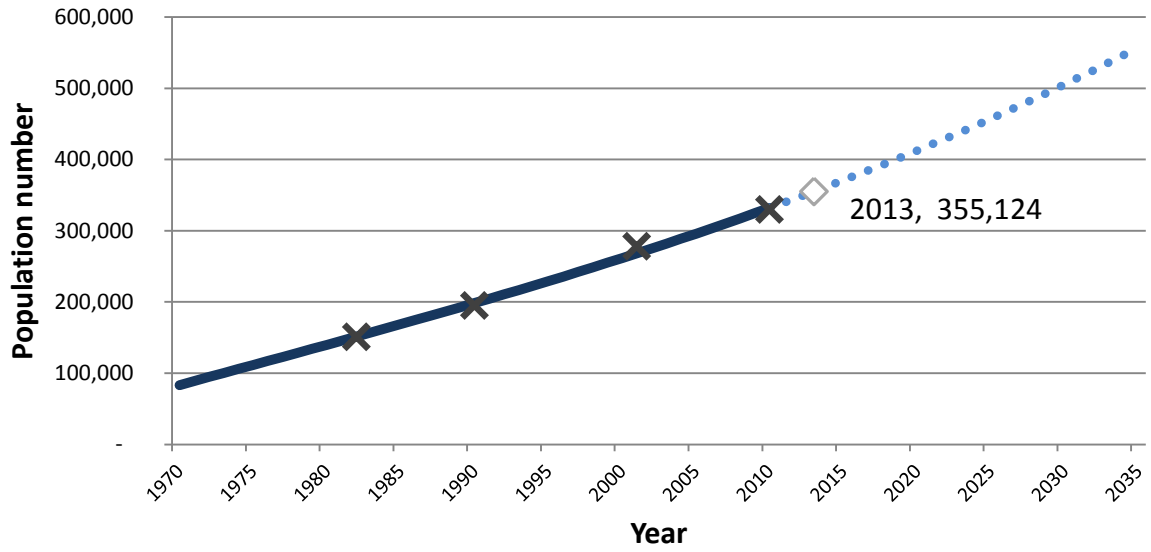


Figure 1. Population evolution in Cuenca and extrapolation.
Source: Own elaboration based on data from INEC (2014); Urban Plan (2014); and DMT (2014)

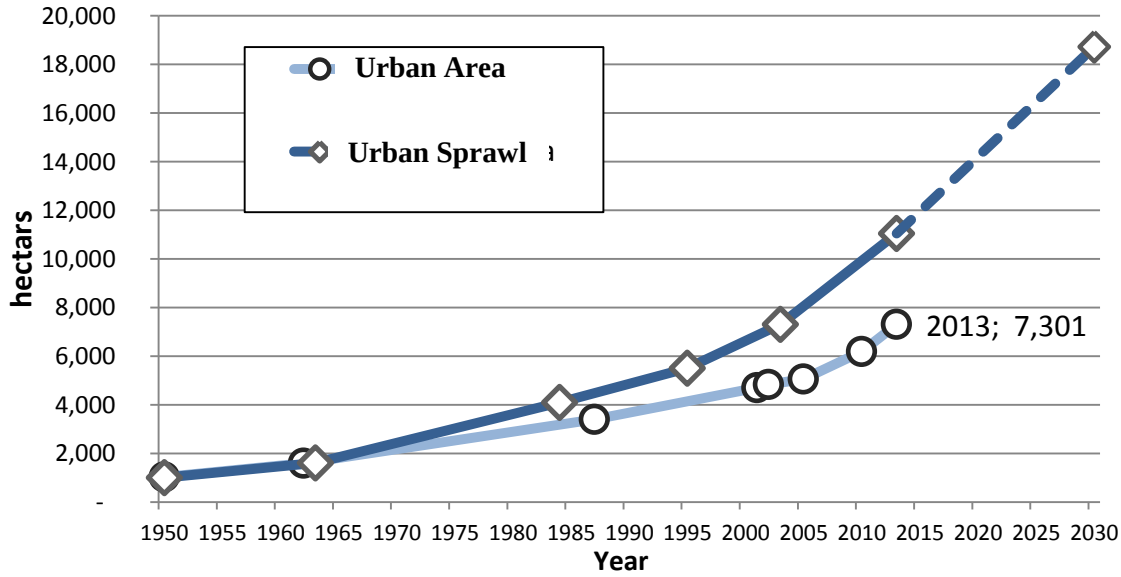


Figure 2. Urban area vs urban sprawl, both measured and extrapolated.

Source: Cuenca Urban Plan (2014).

One of the most studied atmospheric pollutants with regards to its human health effects is particulate matter, with well-known direct morbidity and mortality effects on population (other traditional air pollutants are CO, NOx, SOx, Tropospheric Ozone, and Volatile Organic Compounds). Particulate matter, or PM, is an important cause of adverse health impacts, notably respiratory illnesses, in adults and children, especially in large urban centers. Particulate matter is the outdoor air pollutant that globally is associated with the largest health effects. PM is also a major household air pollutant from the burning of solid fuels for cooking and, in cold climates, heating. Health effects of PM exposure include both premature mortality and morbidity. The methodologies to estimate these health effects have evolved as the body of research has increased.

Cuenca is an active municipality with regards to PM monitoring and modelling, and has fully implemented an air quality monitoring system. These are significant and very relevant efforts, because, as can be seen in figure 3, Cuenca compares poorly to other Ecuadorian centers in relation to PM concentration, and is in the middle of the spectrum when compared to other international centers (figure 4). Studies conducted by Cuenca's EMOV (Municipal Enterprise for Mobility, Transit and Transport) indicate that the main source of primary PM in Cuenca is vehicular transit, which contributes up to 85% of registered emissions in the Municipality. The remaining 15% comes from thermoelectric stations, activities that use solvents, industries, gas stations, liquefied gas for domestic use, open pits, wind erosion, air traffic, landfills and brick fabrics.

Representing the largest share of total emissions in Cuenca, taking a further look into the structure and most recent developments within the vehicular transit sector will establish a comprehensive framework in which air pollution impacts and the costs of air pollution have to be placed. It will allow developing hypotheses on how air pollution is likely to evolve in Cuenca based on recent experiences and it will inform the policy dialogue about priority intervention areas in order to address air pollution.

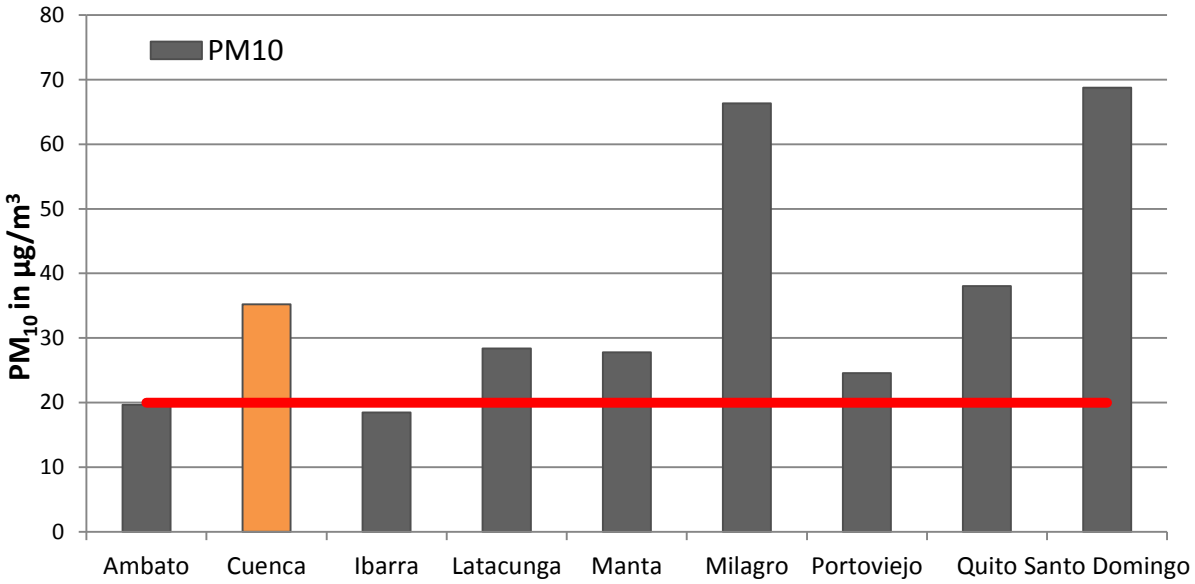


Figure 3. PM10 concentrations in several Ecuadorian cities, averaged for 2012.
Source: Ambient Air Pollution Database, WHO, May 2014

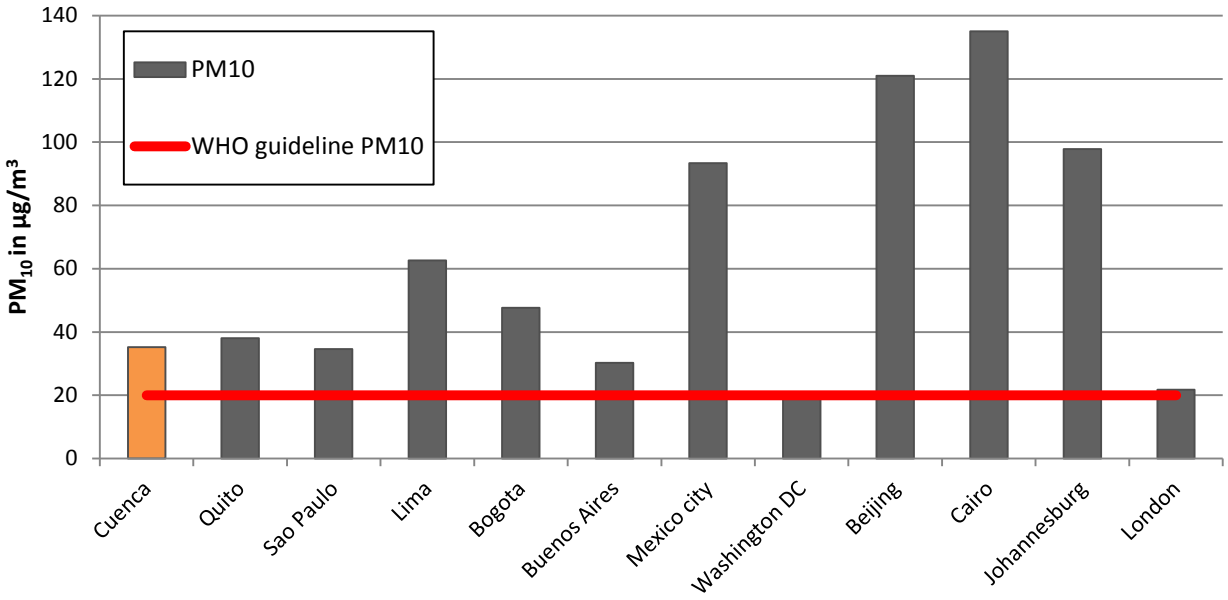


Figure 4. PM10 concentrations in some urban centers worldwide, averaged for 2012.
Source: Ambient Air Pollution Database, WHO, May 2014

Since 1975, the estimated annual growth rate for the non-commercial vehicle fleet is almost 12% (figure 5). This has led to significant traffic congestion, especially in and around the city center (figure 6). Population increase is not the only determinant in increased vehicle use. In addition, a change in behavior that gives preference to private or individual car transport over public transport (bus) has been observed. For example, between 1992 and 2012, the amount of people using private cars or taxis as the main mode of transport has increased from 20% to 43%. At the same time, the share of public bus transport has decreased from 58% to 40%, while foot passengers have remained about the same (table 1). PM10 emission loads in Cuenca, and other factors such as its topography, meteorology and others, explain why PM10 concentration levels in Cuenca are high and similar, for example, to those in Quito (figure 3).

Table 1. Transport Choices in Cuenca (1992 and 2012)

Means of Transport	1992	2012
Public Transport (Bus)	58%	40%
Private Cars and Taxis	20%	43%
By Foot	15%	14%
Others	7%	3%

Source: Municipality of Cuenca 2014

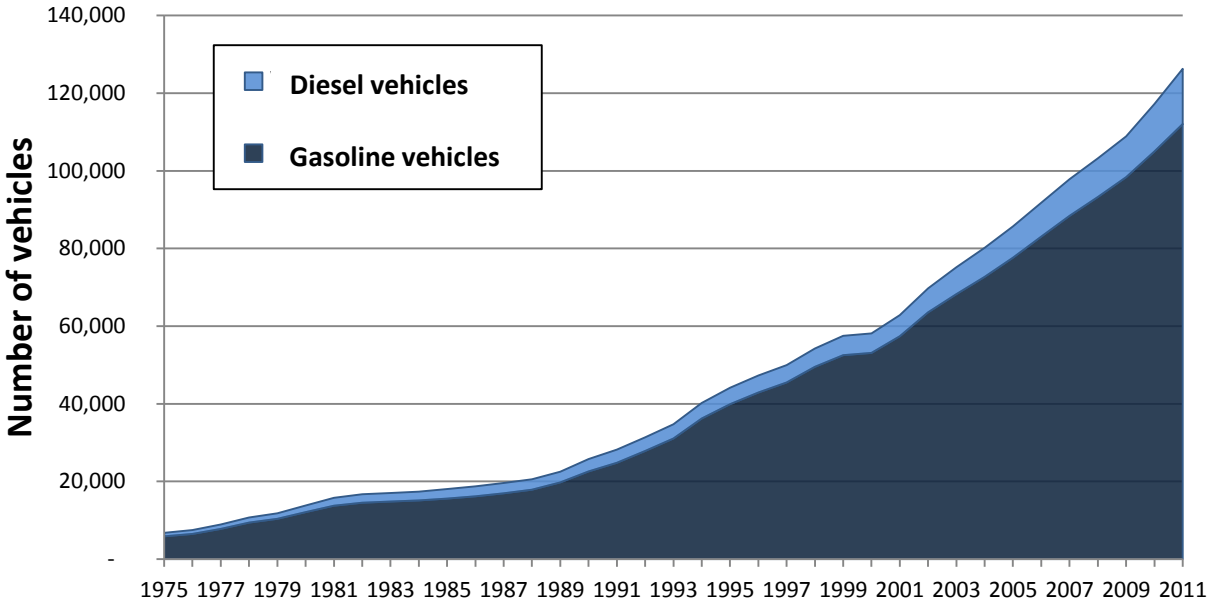


Figure 5. Registered vehicle numbers in Cuenca.
Source: DMT (2014) and EMOV (2011).

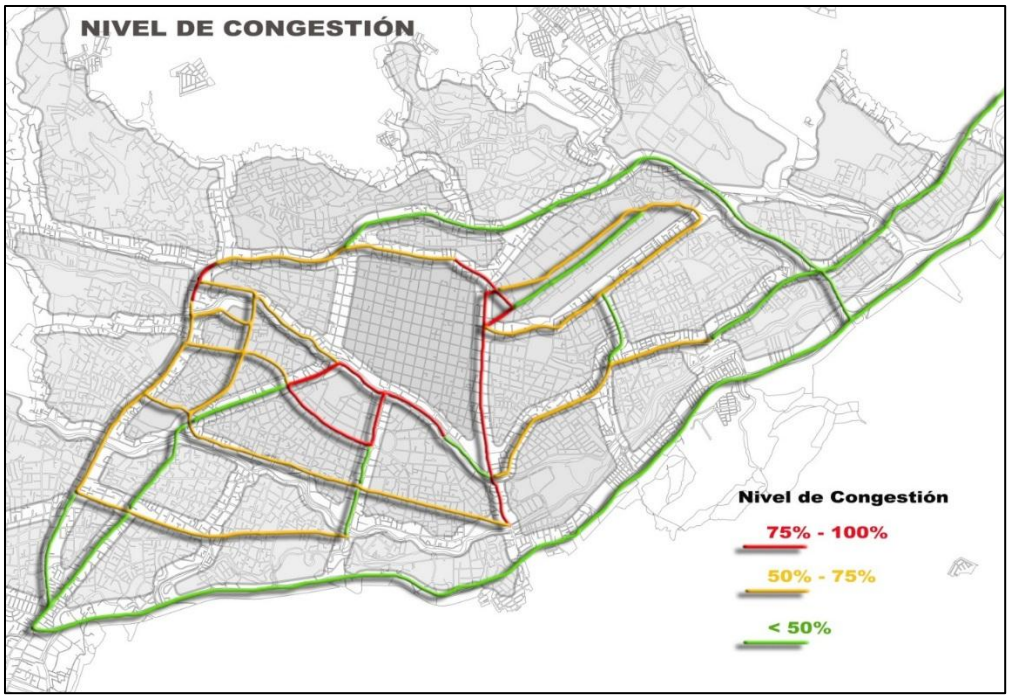


Figure 6. Level of traffic congestion in Cuenca
Source: Municipality of Cuenca, 2014

The average occupancy rate of vehicles in Cuenca has been calculated at about 1.9 passengers per vehicle. About three-quarter of vehicles have either a single occupancy (43%) or double occupancy (33%). Only 2.8% of vehicles have occupancy rates of 4 and more passengers. In terms of car ownership, the relative prosperity of the Municipality of Cuenca has also led to higher ownership rates compared to other cities such as Quito and Guayaquil, with ownership rates of 1 vehicle per 4 inhabitants for Cuenca and 1 per 5 and 1 per 10 for Quito and Guayaquil, respectively.

Given these developments and the air pollution that is associated with it, there is a need for the Municipality of Cuenca to better understand the extent of the impacts caused by PM pollution, and the economic costs associated with these levels of particle concentration in and around the city.

4. Sources and impacts of PM pollution

4.1. Sources of PM

Quantities of airborne particles (particulate matter, sometimes called as aerosols) in industrialized regions have increased markedly since the Industrial Revolution. Atmospheric particles range in size from a few nanometers to tens of micrometers. The sources of aerosols can be classified in either primary or secondary in nature. Primary particles can be furthermore divided as anthropogenic or natural depending on their origin. Examples of natural primary particles are wind-borne dust, sea spray and emissions from volcanoes and biomass burning. Among anthropogenic emissions, the particles generated in the combustion of fossil fuels are amongst the most prominent in an urban environment. Any combustion process caused by humans leads to the formation of particles. Main sources of anthropogenic particles thus include vehicle combustion of fuel, tire wear, dust re-suspension, industrial combustion – such as in thermoelectric stations-, agriculture biomass burning, indoor use of fuels for cooking and heating, mining and construction.

Secondary formed particles in the atmosphere derive from processes of gas-to-particle conversions, and can also have natural or anthropogenic origins. They come from chemical transformations of gaseous precursors such as sulfur dioxide, NOx and volatile organic compounds. HN3 (mostly generated from agricultural activities like fertilizer use and animal manure, as well as open sewage systems) is critical in the formation of secondary PM, through reactions with SO2 (mostly from energy combustion like power plants and industry) and NO2 (generated mostly through transport).

The lifetime of particles in the atmosphere ranges from a few days to few weeks, and this is why they are traditionally considered a local pollutant. Particulate matter causes urban air pollution, has adverse effects on human health, and also influence the earth's climate in a number of ways. Therefore, particulate matter, mainly the fine fraction, has impacts on both local and global scales.

The most recent PM source-apportionment study found for the city of Cuenca dates from 2007, and places diesel exhaust as the main contributor to both PM10 and PM2.5 (figure 7). As it can be seen from the figure, emissions from traffic (vehicles) are responsible for about a third of PM emissions. Moreover, if non-anthropogenic sources are excluded, traffic accounts for more than 50% of both PM10 and PM2.5 emissions (PM10 refers to particles less than or equal to 10 micrometers in diameter; this fraction is chosen as it is believed that is the main fraction that can be breathed into the lungs; the finer fraction of 2.5 micrometers (PM2.5), has even more potential to penetrate deep into the respiratory track causing further damage to the lungs).

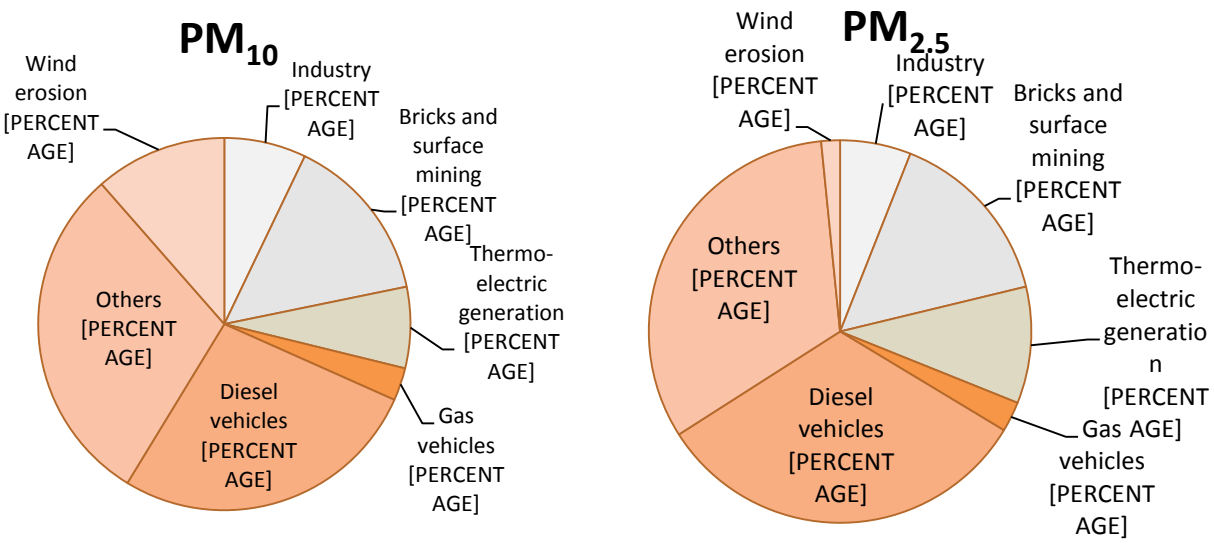


Figure 7. PM source apportionment for Cuenca.
Source: Adapted from Jerves, 2007.

4.2. Health impacts caused by particulate matter

One of the main, most evident and worrying effects of unusually high concentrations of particulate matter in the atmosphere is its influence on human health. Particulate matter is among the most harmful of all air pollutants, and there is growing concern related to the variety of health effects of particles, especially its fine fraction. Recent studies have demonstrated a consistent relation between the concentrations of fine particulate matter in the air and adverse effects on human health (respiratory symptoms, morbidity and mortality) for concentrations commonly encountered in many large and medium-sized cities worldwide.

When inhaled, sub micrometre particles evade the respiratory system's natural defences and lodge deep in the lungs. Particulate matter is especially harmful to people with lung disease. Exposure to particulate air pollution can trigger asthma attacks and cause wheezing, coughing, and respiratory irritation in individuals with sensitive airways.

Particles of special concern to the protection of lung health are PM2.5 (the term PMx means the total mass of aerosol particles with an aerodynamic diameter lower than x µm). These are known as fine particles and mainly come from motor vehicle exhaust and other sources such as power plants, stoves, coal-fired boilers, and gas-to-particle conversion. Fine particles are easily inhaled deeply into the lungs where they can be absorbed into the bloodstream or remain embedded for long periods of time. As an illustration, epidemiological studies show that an increase in PM10 mass concentration of 10 µg m^{-3} results in an increase of 0.5 -1.5% in premature total mortality in case of short term/episodic exposure, and in an increase of up to 5% in premature total mortality in case of long-term/lifelong exposure. Thanks to enhanced measurement of PM air pollution (PM2.5 and finer), scientific research is establishing similar relationships for such

pollutants. Annex 1 provides an extensive review of studies which are related to PM pollution, health impacts and their costs.

In addition to the increased morbidity and mortality described above, particulate matter, as well as other gasses and noise pollution can cause cognitive and neurological deficits, such as impaired perception and thinking process, fluid cognition, memory and executive functions during childhood, and potentially pose a risk factor for the development of Alzheimer's disease and the early onset of neurodegenerative processes (additional information and sources can be found in Annex 1).

4.3. Non-health related impacts of PM

Although the following sections will focus exclusively on the health impacts and economic loss caused by outdoor particulate matter, a brief summary of other additional PM-related impacts is provided here. These impacts provide an even stronger justification for action to reduce urban PM loads. In doing so, additional PM impacts on local and global climate, infrastructure and agriculture would also be avoided.

Climate
Besides health effects, the other major area where aerosols influence and affect nature is climate. Relation of particulate matter (also called "aerosols" within the climate change community) and climate change is still not fully comprehended, and has become a key issue in research studies. Increases in particulate matter concentration and changes in its composition, driven by industrialization and an expanding population, have adverse effects on the earth's climate and water supply, and particles in the air interact chemically in as yet unrecognized ways with atmospheric gases, altering the naturally occurring processes.
PM interacts with light, either reflecting or absorbing solar radiation (the so-called direct effect). Most naturally-occurring PM is highly reflective, and is able to reflect incoming solar radiation, thereby cooling the earth's surface and effectively offsetting greenhouse gas warming. However, aerosols containing black graphitic and tarry carbon particles (present in smoke and urban haze) are dark and therefore strongly absorb incoming sunlight, therefore warming the atmosphere. Particulate matter also exert an indirect effect by modifying cloud properties and altering water cycles.

Environment, agriculture and others
Fine particles impact visibility, creating haze and other conditions that interact with light and reduce visibility, altering the atmosphere and the perceived colors of objects viewed through the atmosphere. Particles are transported away from their sources, and they can settle on the ground or in water bodies, making them more acidic, affecting nutrient balances, disturbing ecosystems and others. Particulate matter has also been proven to have negative impacts on crop yields. Issues vary, and can include damages to the foliage, reduced growth and/or yield, to plant death. Carbon soot deposited on vegetation can inhibit the normal respiration and photosynthesis mechanisms within the leaf. The dust coating may affect the normal action of pesticides and other agricultural chemicals applied as sprays to foliage. In addition, accumulation of alkaline

dusts in the soil can increase soil pH to levels adverse to crop growth (extracted from Griffiths, 2003).

Infrastructure and cultural heritage
Particulate matter, especially black particles, create further impacts related to the deterioration of buildings and cultural heritage damage, through their capacity to dirty light-colored building surfaces (soiling). Urban-exposed building materials have been found to act as a surface in which particulate matter is deposited, and in addition to soiling, PM has the potential to modify the composition of the materials present in the stone surface. For example, black crusts have been extracted from monuments, and the origin of these crusts directly related to PM pollution (Saiz-Jimenez, 2004).

Given the multiple impacts described above, of which health impacts are of particularly serious concern for urban environments, particulate matter is a priority within the atmospheric pollution mix, and justifies the objectives of this report. In the following sections, the detailed methodology to estimate the costs to Cuenca of particulate matter, in terms of outdoor health impacts, and the calculations performed in order to arrive to an interval of values, will be illustrated.

5. Modeling the Economic Impacts of Air Pollution

5.1. Background

The study about the costs of environmental degradation in Cuenca, Ecuador is centered on the health impacts of particulate matter pollution. The majority of literature assessing the health impacts of air pollution impacts has selected particulate matter (PM) as the only or major pollutant to be considered (Brook et al., 2004; Lim et al., 2014). PM is the air pollutant most associated with adverse health impacts, and restricting the scope to one pollutant also mitigates the risk of overestimation of impacts, which could occur considering multiple pollutants (Bell et al. 2006). The general tendency has been to measure increasingly smaller levels of particulate matter. Currently, studies mostly consider impacts of PM2.5 pollution. This has evolved from formerly measuring only particulate matter with less than 100 µm diameter to particulates with diameters of 10 µm or less (PM10).

The present study solely focuses on the cost of mortality, i.e. estimation of the costs arising from deaths that are attributed to PM air pollution which would have not occurred in a counter-factual, clean ambient air environment. Hence, the cost of morbidity, i.e. the cost of temporary sickness caused by air pollution, neither the cost of treatment nor the opportunity cost of being sick measured by foregone productivity or leisure days, are considered. Additional analytical work and input data would be required to assess these costs, which, typically, are however just a small percentage compared to the costs of mortality (Ostro 1994; Abbey et al. 1995; Cogen et al. 2004). To assess the share of deaths caused by ambient air pollution in Cuenca we use integrated risk functions that were recently estimated by Burnett et al. (2014). These functions rely on a review of cohort studies that assessed the relationships between air pollution and long-term health impacts and also have been used as estimation methodology for the Global Burden of Disease (GBD) report 2014. Burnett et al. (2014) have established integrated risk functions for lung cancer (LC), acute lower respiratory infections (ALRI), chronic obstructive pulmonary diseases (COPD), ischemic heart diseases (IHD) and cerebrovascular disease (Stroke). Given the availability of these risk functions and the fact that these five disease categories are most commonly associated with air pollution, they also provide the analytical scope of the study. Table 2 presents respective codes established by the International Classification of Diseases (ICD)[1] codes as well as the affected population groups for each disease category.

[1] The International Classification of Diseases (ICD) is the standard diagnostic tool for epidemiology, health management and clinical purposes. This includes the analysis of the general health situation of population groups. It is used to monitor the incidence and prevalence of diseases and other health problems, proving a picture of the general health situation of countries and populations; http://www.who.int/classifications/icd/en/

Table 2. Disease categories

Disease categories	ICD Codes	Affected population
Lung Cancer (LC)	C33-34	Adults >25
Acute Lower Respiratory Infections (ALRI)	J10-J22	Children <5
Chronic Obstructive Pulmonary Diseases (COPD)	J40-J44; J47	Adults >25
Ischemic heart diseases (IHD)	I20-I25	Adults >25
Cerebrovascular disease (Stroke)	I60-I69	Adults >25

Having defined the scope of impacts and diseases as well as the methodology to link air pollution levels to health impacts (Burnett's integrated risk functions previously mentioned, which is a peer-reviewed, internationally accepted methodology) we can now follow a straightforward process for the valuation of air pollution in Cuenca. This step-by-step methodology, used for the cost estimates in this report, is outlined in figure 8. First, the distribution of PM_{10} pollution levels is modeled for each of Cuenca's 15 city districts (*parroquias*). As a second step, we estimate the mobility-adjusted population density by age-group (in five year intervals) within each city district. Having estimated the average pollution level and population density, we can use the integrated risk functions to estimate the population attributable fractions (PAFs) for each city district. Using epidemiological data and the estimated PAFs, we can compute the burden of disease (in terms of deaths) caused by ambient air pollution in step four. The fifth and final step is the economic valuation of air pollution based on years of life lost (YLL). Each of the subsequent sections will describe the data sources, data operations and methodologies used with each of the five steps in more detail.

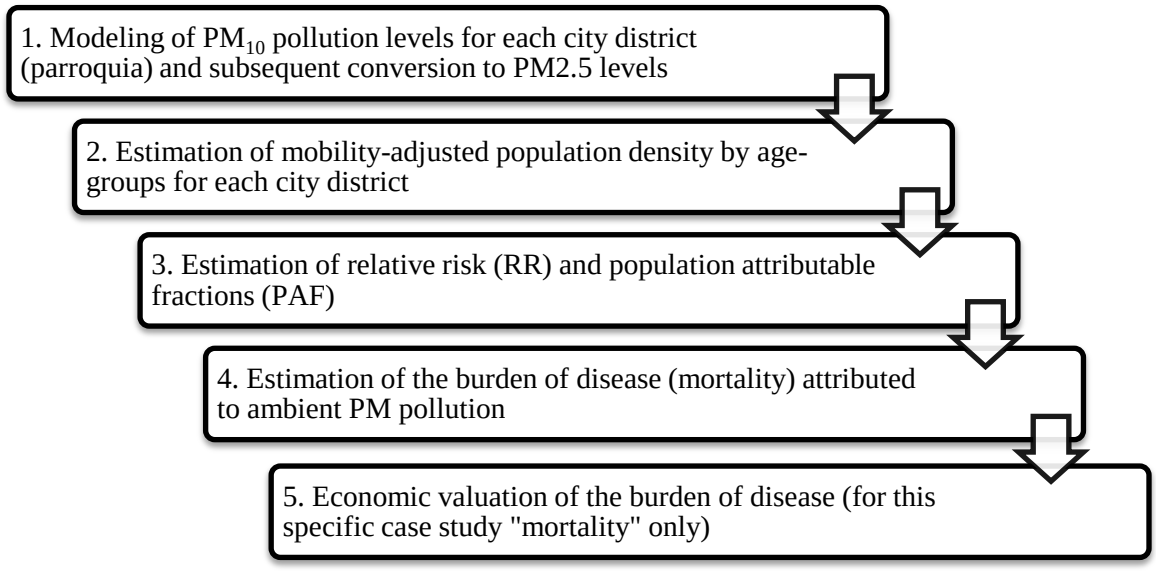


Figure 8. Step-by-step applied methodology

5.2. Modeling of PM2.5 pollution levels for each city district (parroquia)

As Burnett's integrated risk functions are based on PM2.5 pollution levels, PM2.5 pollution levels have to be modeled for the Cuenca. This is achieved by using the pollution-distribution model and PM_{10} pollution measurements to model the average $PM_{2.5}$ pollution level within each of Cuenca's 15 city districts (parroquias). In total, the municipality of Cuenca operates three air-quality monitoring stations that are outfitted with PM_{10} measurement equipment. The location of the measurement stations is depicted in figure 9. All three stations apply gravimetric measurement methods using high volume samples. The measurement stations located in the North (CCA; Colegio Carlos Arizaga) and South (EIE; Escuela Igancio Escandon) are both installed on the rooftop of schools at an altitude of almost 10m above the surrounding street level. The central station, located on the rooftop of the municipality building, is installed at an even higher altitude of more than 30 meters above the surrounding street level. The altitude of measurement for these stations is appropriate to measure the background, well-mixed concentration of pollutants within the urban context. It might however be problematic to reflect specific point emissions that affect population, as it potentially underestimates factual emission level in the streets of Cuenca. Streets in Cuenca, particularly in the historic center, are often very narrow and might prevent proper ventilation of the ambient air (the so-called street canyon effect), resulting in accumulation of particles emitted from traffic. Both factors might imply that PM emission levels measured in Cuenca, especially by the center station, are reflecting urban background PM levels and therefore underestimating actual emission levels on the ground (i.e. 2m above the surrounding street level). In fact, as the US-EPA measurement standards recommend, the measurement altitude for direct emission measurement should range between an altitude of 2 – 15m (Jerves, 2007), whereas the altitude of existing stations range between 9.5 and 30.5m.

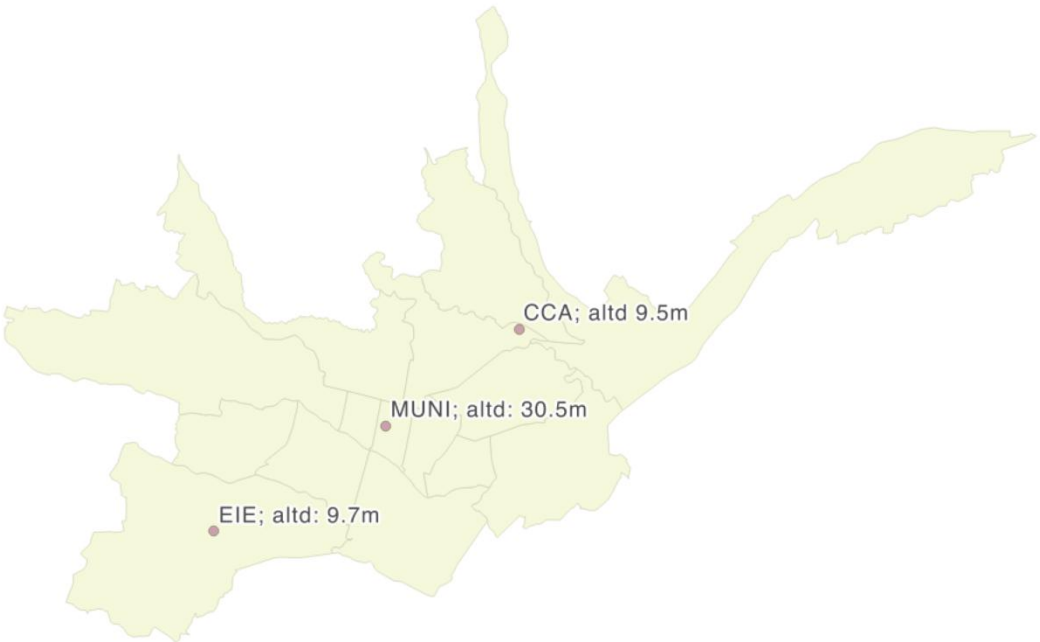


Figure 9. Location and altitude of PM10 measurement stations in Cuenca

PM2.5 measurements for Cuenca have just recently started, and the PM2.5 data measured so far was found to be inadequate for this study.[2] Therefore, PM10 data measured during 2012 was used as a basis for the study. The PM10 data (measured by Cuenca stations as a 24h average) was later converted to PM2.5 equivalent levels using the PM2.5 / PM10 conversion factor of Quito of 0.48 (WHO, 2014a).[3] The map in figure 10 shows the distribution of PM10 pollution levels ranging from high pollution levels (depicted by dark orange-brown shaded colors) in the Northeastern city districts to lower levels particularly in the center and Western city districts. Using a PM2.5 / PM10 conversion factor is not ideal, and using the one of Quito and applying it to Cuenca is likely to bring some level of error to the final result, given differences in emission sources in both cities. Once consistent PM2.5 measurements become available in Cuenca, these could be used to refine the results.

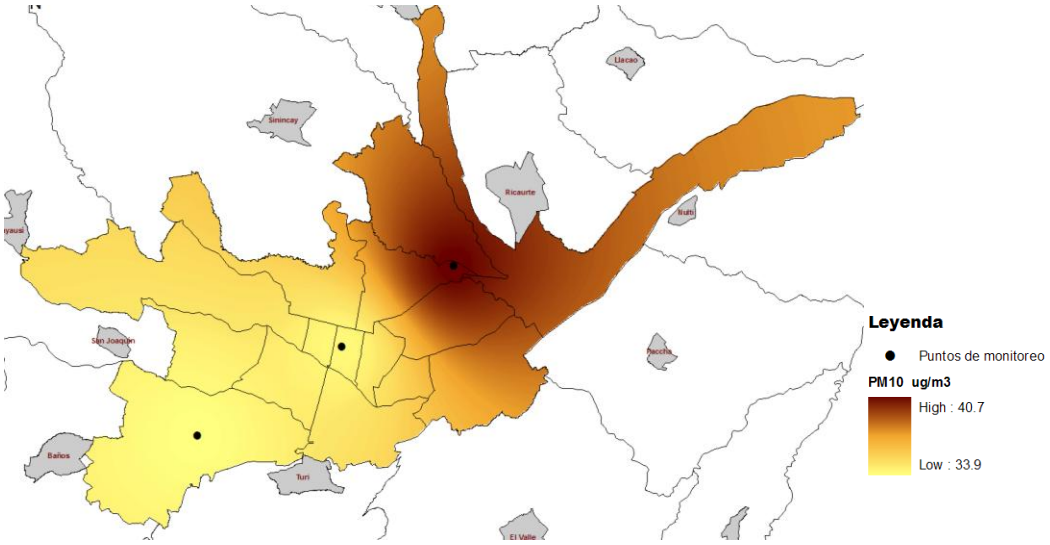


Figure 10: Spatial distribution of air pollution in Cuenca

The results of this PM_{10} modelling in the 15 *parroquias*, as provided by EMOV, were used in this study as the baseline to further estimate mortality and costs. A table presenting the modeled minimum, maximum and average PM_{10} pollution levels as well as the converted $PM_{2.5}$ levels for each city district is provided in annex 2. Once this average $PM_{2.5}$ pollution level per city district

[2] Besides the short time series of PM2.5 data, the existing PM2.5 measurement data still seemed to require further calibration and cross-validation

[3] The Quito PM2.5/PM10 conversion factor of 0.48 is rather low compared to national conversion factors of other Latin American countries published in the WHO-AAP database (WHO, 2014a).

has been estimated, it is then used in step three to estimate the relative risk and population attributable fraction (PAF).

5.3. Mobility-adjusted population density by age-group for each city district

Based on the 2010 population census (INEC, 2010), the population size and age-group structure for each of Cuenca's city districts is known. However, the actual ambient air quality prevalent at one's place of residence is not necessarily representative of the air quality one is predominantly exposed to. A significant share of people spend the majority of daytime outside their place of residence, for instance at their workplace or in case of students at schools and universities. In the case of Cuenca, PM emission levels are higher in the city districts close to the industrial park (NE Cuenca) and the city center. Both areas are likely to have a higher population during daytime due to the inflow of office workers and students (city center) or blue-collar workers (industrial park). Therefore, we adjust the population size for commuting patterns within each city district. Each district's population size, as will be shown later on, serves as weighting factor of the varying population attributable fractions across the 15 city districts. The adjustment is based on a mobility survey conducted by the municipality's transit department (DMT). The survey covered 5034 respondents between the age of 16 and 55 asking them about their daily commutation patterns and length of stay at each destination / place (Municipality of Cuenca, undated). The population density of each city district is adjusted for the mobility of its population using the following criteria: Each respondent that spends more than six hours outside his home city district (in which his place of residence is located) is relocated to the district within which he has spent the majority of the time outside his home. For example, person "A" living in district one spends four hours in district eight and two hours in district nine. Consequently, person "A" is relocated to district eight and thereby increasing the population density of the same district while decreasing the density of district one. The adjustment is done for five year interval age groups ranging between the age of five and 64. Younger or older persons are assumed to stay within their home district. As the survey does not cover respondents between the age five to 15 and 56 to 64, the next closest age group (e.g. 15-19 years for the age groups five to nine and ten to 14) is assumed to show a representative mobility behavior.[4]

The result of this adjustment procedure is that 100,094 persons are relocated to other districts, representing 35.9% of the population aged between 5 and 64 years in Cuenca or 30.3% of total population. Using the adjusted population data per city district, the share of each city district's age-group within the overall population of Cuenca is calculated in table 3. This table is obtained using as input the original distribution of population per age group among city districts based on the 2010 census (INEC, 2010). Both the original distribution of population based on the census, and the net change in population for each city district as a result of applying the corrections based on the mobility survey results are provided in annex 3).

[4] The survey under-sampled the population living in district 2 and 10. As a remedy the mobility behavior observed in district 7 is assumed to be representative for all age groups in district 2 and 10.

Table 3. Share of adjusted age-group population per city district

Share of adjusted age-group population per city district (parroquia)															
Age Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0-4	8%	3%	8%	2%	10%	2%	4%	7%	7%	3%	12%	4%	8%	17%	6%
5-9	15%	2%	6%	1%	13%	2%	2%	6%	7%	1%	20%	3%	5%	10%	7%
10-14	16%	2%	6%	1%	13%	2%	2%	6%	7%	1%	19%	3%	5%	10%	7%
15-19	15%	2%	6%	1%	13%	2%	2%	7%	6%	1%	19%	4%	5%	10%	6%
20-24	13%	4%	8%	2%	10%	2%	5%	6%	5%	2%	17%	4%	6%	14%	5%
25-29	12%	2%	7%	2%	11%	2%	4%	7%	7%	2%	20%	3%	5%	11%	5%
30-34	7%	4%	8%	1%	11%	2%	5%	5%	5%	2%	21%	4%	5%	16%	4%
35-39	9%	4%	7%	1%	9%	1%	4%	8%	5%	2%	18%	4%	8%	13%	6%
40-44	8%	4%	7%	2%	8%	1%	5%	7%	5%	3%	17%	4%	7%	17%	4%
45-49	8%	2%	8%	3%	10%	2%	4%	7%	5%	2%	20%	5%	10%	10%	5%
50-54	9%	4%	7%	2%	9%	2%	7%	6%	6%	3%	14%	5%	8%	13%	5%
55-59	8%	6%	7%	2%	9%	2%	8%	7%	7%	3%	12%	6%	5%	13%	4%
60-64	8%	7%	7%	2%	9%	2%	8%	6%	7%	4%	12%	6%	5%	12%	3%
65-69	9%	5%	6%	3%	8%	3%	7%	5%	6%	5%	12%	7%	8%	12%	4%
70-74	9%	5%	6%	3%	9%	3%	6%	5%	5%	5%	12%	7%	8%	11%	4%
75-79	10%	5%	5%	4%	10%	4%	7%	5%	5%	6%	11%	7%	8%	10%	4%
>80	9%	4%	5%	5%	8%	6%	7%	5%	6%	5%	11%	7%	8%	11%	3%
All	11%	3%	7%	2%	11%	2%	4%	6%	6%	2%	17%	4%	6%	13%	5%

5.4. Estimation of relative risk (RR) and population attributable fractions (PAF)

Every person bears a certain risk level to suffer from or even die due to one of the above-mentioned diseases (as listed in Table 2). Ambient air pollution is known to increase the relative risk (RR) of these diseases, i.e. relative to the already existing risk caused by other risk factors such as smoking, unhealthy diets, etc. The relative risk may thus not be interpreted as the risk of contracting disease "A" versus not contracting disease "A".

Burnett et al. (2014) estimated integrated exposure functions that explain the change in relative risk (RR) to contract disease *"k"* experienced by a person of age *"l"* exposed to an emission dose "z" ($PM_{2.5}$ measured in µg/m^3) vis-à-vis a counterfactual emission level "z_{cf}". The functions are further governed by three parameters (α, γ, δ) estimated by the authors and made available in their supplemental material. Equation (1) shows the function and definition of its components.

Equation (1)

$$RR(z)_{kl} = 1 + \alpha \ (1 - e^{(-\gamma(z - z_{cf})^{\delta}})$$

where

$RR(z)_{kl}$ *is the relative risk of disease k, and of age group l depending on z*

z is the factural $PM_{2.5}$ *emission level*

z_{cf} *is the contrafactual* $PM_{2.5}$ *emission level*

α, γ, δ *are parameters*

The relative risk of Lung Cancer (LC) and Chronic Obstructive Pulmonary Diseases (COPD) is estimated for all ages equally, but only for persons aged 25 or older. The relative risk for Acute Lower Respiratory Infections (ALRI) is estimated for all ages equally, but only for children aged 5 or younger. For Cerebrovascular disease (Stroke) and Ischemic heart diseases (IHD) the relative risk is calculated for age groups with five-year intervals, yet only for persons aged 25 or older. The counterfactual emission level is equal to 7.3 µg/m3, which is the mean of the lower and upper bounds of 5.8 to 8.8 µg/m3 applied and proposed by Lim et al. (2013).

After estimating the relative risk, we can compute the population attributable fraction (PAF)[5], using equation (2). PAF is computed for diseases *k* and age groups *l* for which we have previously estimated the relative risk. P_i is equal to the share of each district's population of Cuenca's total population adjusted for commuting patterns as explained in the previous section. The PAF is then used to determine the burden of disease attributable to the relative risk caused by ambient air pollution (Lim et al., 2013).

[5] The contribution of a risk factor to a disease or a death is quantified using the population attributable fraction (PAF). PAF is the proportional reduction in population disease or mortality that would occur if exposure to a risk factor were reduced to an alternative ideal exposure scenario (eg. no tobacco use). Many diseases are caused by multiple risk factors, and individual risk factors may interact in their impact on overall risk of disease. As a result, PAFs for individual risk factors often overlap and add up to more than 100 percent (http://www.who.int/healthinfo/global_burden_disease/metrics_paf/en/).

Equation (2)

$$PAF_{kl} = \frac{\sum_{i=1}^{n} P_i(RR_{kl} - 1)}{\sum_{i=1}^{n} P_i(RR_{kl} - 1) + 1}$$

where

RR_{kl} *is the relative risk of disease k and age group l*

P_i *is the share of population affected*

Equation 3 is finally used to calculate the burden of disease (in terms of mortality for this specific case study) caused by ambient air pollution. B is the annual burden of diseases. D_{kl} is the number of deaths caused by disease k within age group l. PAF_{kl} is equal to the previously computed population attributable fraction of disease k and age group l.

Equation (3)

$$B = \sum_{k=1}^{t} \sum_{l=1}^{s} D_{kl} PAF_{kl}$$

where

B is the annual burden of disease

D_{kl} *is the number of deaths caused by disease k within age group l*

PAF_{kl} *is the population attributable fraction of disease k and age group l*

The underlying data used to define D_{kl} are death statistics for the year 2012 provided by the national statistics bureau of Ecuador (INEC, 2012). The death statistics are reported up to the level of the urban parish (parroquia) of Cuenca (not to be confused with the city districts also referred to as parroquias[6]). For each case the dataset provides information on sex, date of birth and death, place of residence and cause of death (identified by ICD-code). As the data cannot be further disaggregated on city district level, we are limited to calculate the burden of disease on the aggregated level identified by the urban parroquia of Cuenca. Still we account for spatial differences in pollution levels by computing the RR for each city district and thus weighing the aggregated PAF accordingly.

[6] Ecuador has 24 provinces that are first-level administration units. These are again divided into second-level units (cantons) and further into third-level units, which are rural and urban parishes (parroquias).

5.5. Economic valuation of the burden of disease

Estimating the economic cost of the burden of disease can be done using the value of a statistical life (VSL) or the human capital approach (HCA). The VSL is estimated by studies using either stated or revealed preference methods (such as contingent valuation methods or hedonic pricing, respectively). Most VSL studies use contingent valuation methods (i.e. stated preference methods) (OECD, 2012). These, however, do not estimate the value of human life, but instead estimate the value of a prevented death. This is done by asking respondents for their willingness to pay (WTP) if the risk of dying from e.g. cancer is reduced by 1 case for every 100,000 persons. If the WTP is equal to US$30, then for every 100,000 paying individuals one case of death would be prevented. Consequently, the value of statistical life (VSL) would be equal to US$3 million.

Most known VSL studies have been conducted in high-income countries, and to the author's knowledge, there are no known VSL studies for Ecuador or any immediate neighboring country. In 2012 the OECD prepared an extensive meta-study covering 856 VSL studies. A common approach is the benefit transfer of a high-income country VSL estimate to a low-income country adjusting for differences in income level (adjusted for power purchasing power parity) as shown in equation (4).

Equation (4)

$$VSL_{Ecuador} = VSL_{OECD}\left(\frac{Y_{Ecuador}}{Y_{OECD}}\right)^{e}$$

where

Y_i *is the national income per capita* $(GDP\ adjusted\ for\ PPP)$

e *is the income elasticity to transfer VSL*

As one conclusion of OECD's meta-study, it is proposed to transfer the mean VSL estimate of OECD countries (US$3 million) considering 50% error bounds and using an income elasticity of 0.8, with 0.4 and 1.2 as lower and upper boundaries, respectively.

According to Cropper (2014), in most cases a unitary income elasticity (e=1) is applied. Transferring the VSL is very sensitive to the applied income elasticity. Hammitt and Robinson (2011) propose to use an income elasticity of e> 1 for benefit transfers of VSL estimates from high to low income countries. We will compute the VSL for Ecuador using income elasticities in intervals of 0.2 between the lower and upper bounds of 0.4 and 1.2 as suggested by the OECD (2012). The final elasticity can then be selected considering the VSL/Y ratio. According to Miller (2000, cited in Cropper and Sahin, 2009), the ratio for high-income countries is about 140. For lower-middle to upper-middle income countries, such as Ecuador, the ratio is believed to be significantly lower at about VSL/Y ≈ 80 (Robinson and Hammitt, 2009). Consequently, we will

choose the income elasticity most closely corresponding to a VSL/Y of 80. The next lower and upper interval will be used as lower and upper bounds, respectively.

The HCA, in contrast to the VSL approach, only considers the lost productivity measured by the present value of a person's future earnings, which are approximated by the average gross domestic product (GDP) per capita. In general, the HCA is a lower bound to value the cost of air pollution induced mortality. As Connelly and Supangang (2006) point out by citing Sen (2004), the HCA is restricted to measuring losses of income only and does not capture the losses in utility caused by disability or even death (for the person affected and its environment, e.g. family members). In contrast, the VSL approach allows capturing the entire utility loss of death. The VSL approach can be considered more realistic, as life is also more than generating income (Hammitt and Robinson, 2011).

There is another critical difference between the HCA and VSL approach. In contrast to the VSL approach, the HCA differentiates at which age death occurs, since the present value of future earnings is calculated considering the remaining life expectancy. Taking into account the remaining life expectancy can make a large difference in valuing the cost of air pollution. Within the global burden of disease study 2010, for instance, more than 50% of lives lost are persons of age 70 years or older (Lim, 2013). Accounting for differences in remaining life expectancy, in addition to the difference in capturing losses of utility, is a further crucial factor leading to diverging estimates. As a remedy, the VSL approach can be modified to also consider the remaining statistical life expectancy at the age of death. This is referred to as the value of a statistical life year (VOLY) approach (OECD mortality risk valuation). Analogously to the calculation of an annuity's regular payment, the VOLY is computed based on the VSL as shown in equation (5).

Equation (5)

$$VOLY = \frac{\delta(VSL)}{1 - (1+\delta)^{-T}}$$

where

δ_i *is the discount rate*

T *is the remaining life expectancy*

$$for \lim_{\delta \to 0} \; VOLY = \frac{VSL}{T}$$

As we will use age-independent VSL estimates, we need to compute the VOLY for a reference case, i.e. just like the VSL the VOLY is thus assumed to be constant.[7] VOLYs have been

[7] As the VOLY is inversely related to the age-specific variable T, computing the VOLY specifically for each age (or age-group) using an age-independent estimate of VSL would lead to higher VOLYs at decreasing remaining life expectancy (T). This is of course would discriminate younger generations and further would lead to similar results compared to just using the VSL approach with the only deviation being determined by the discount rate.

calculated using male reference cases aged between 35 and 45 (EC, 1998). For our analysis we use a discount factor of 3% and a male reference case within the age bracket of 40-44 years. The applied remaining life expectancy of 21.7 years was calculated using the WHO standard life table, applying a discount factor of 3% and standard age weights (K=1) as well as interpolating between the age bracket's lower and upper bounds (WHO, 2014).

It is an ethical debate to decide whether the value of life is dependent on age, for instance valuing the life of an 11 year old child differently compared to the life of an 80 year old person. Further, there are different perceptions inasmuch the loss of utility, captured by both VSL and VOLY approaches, should be considered. As this study does not want to present one point-estimate of the economic cost, but rather a range, we will consider all three approaches.

For the HCA and VOLY approach we need to determine the years of life lost (YLL) for the numbers of deaths per sex and age group. YLL is computed using the following equation (6).

Equation (6)

$$YLL = \sum_{i=1}^{I} \sum_{j=1}^{S} N_{ij} L_{ij}$$

where

N_{ij} *is the quantity of annual deaths of sex j and age group i*

L_{ij} *is the remaining life expactancy of sex j and age group i*

The remaining life expectancy, $L_{ij,}$ for each sex and age group is calculated using standard WHO life tables (WHO, 2014b). $L_{ij,}$ is sensitive to the applied discount factor and age weights. A discount factor of 3% and standard age weights (K=1) are applied.

6. The Costs of Air Pollution in Cuenca

In the following, the results of applying the methodologies and assumptions illustrated before are presented. Table 4 shows the number of deaths caused by the previously identified disease categories. The majority of deaths are related to cerebrovascular diseases (Stroke), causing in total 60 deaths (or 35% of all deaths) in Cuenca for the year 2012.

Table 4. Deaths caused by diseases associated with PM air pollution in Cuenca, 2012

Disease category	**ICD codes**	**Affected population**	**Deaths**	
			Female	Male
Lung Cancer (LC)	C33-34	Adults >25	12	10
Acute Lower Respiratory Infections (ALRI)	J10-J22	Children <5	3	5
Chronic Obstructive Pulmonary Diseases (COPD)	J40-J44; J47	Adults >25	28	14
Ischemic heart diseases (IHD)	I20-I25	Adults >25	22	17
Cerebrovascular disease (Stroke)	I60-I69	Adults >25	24	36
Total			**89**	**82**

The majority of deaths, more than 66%, occur among the elderly, aged 70 years or older. Annex 4 shows a table with the distribution of deaths among age groups and sex. Deaths for ages 5 – 24 are not included, as the integrated risk functions do not specify a risk for these age groups. Using the average $PM_{2.5}$ pollution level (annex 2) per *parroquia* and the relative risk functions as specified in equation (1), we can estimate the relative risk per age group and city district. Subsequently, considering the adjusted share of age-group population (table 2) the overall population attributable fraction (PAF) based on equation (2) is computed per disease category.

The computation of the PAF allows estimating the number of deaths or the burden of disease (in terms of mortality) that is caused by ambient air pollution following equation (3). Multiplying the disease (and age-group) specific PAF times the number of deaths as reported in annex 4 yields a burden of disease as reported in table 5. According to our estimation methodology, in 2012 a total of 24.26 deaths can be attributed to $PM_{2.5}$ air pollution. This is equivalent to 14.2% of all deaths caused by the identified disease category within the age of 0 to 4 and 25 and older.

Table 5. Burden of disease attributable to PM2.5 air pollution

	Female					Male				
Age group	**LC**	**IHD**	**Stroke**	**ALRI**	**COPD**	**LC**	**IHD**	**Stroke**	**ALRI**	**COPD**
0-4	-	-	-	0.26	-	-	-	-	0.43	-
25-29	-	-	-	-	-	-	-	0.36	-	-
30-34	-	-	0.34	-	0.08	0.09	-	-	-	-
35-39	-	0.80	-	-	-	-	0.40	0.33	-	-
40-44	-	-	-	-	-	-	-	0.30	-	-
45-49	-	0.34	0.28	-	-	0.09	-	0.57	-	-
50-54	0.09	0.62	0.26	-	-	0.09	0.31	0.53	-	-
55-59	-	0.29	-	-	-	-	0.29	0.24	-	-
60-64	-	0.26	0.43	-	0.08	0.09	-	0.43	-	-
65-69	0.28	0.93	0.38	-	0.23	0.19	-	0.75	-	-
70-74	0.19	0.20	0.82	-	0.08	-	0.20	0.49	-	-
75-80	0.28	0.17	0.14	-	0.15	-	0.69	0.42	-	0.15
>80	0.28	1.26	1.28	-	1.55	0.37	1.26	1.86	-	0.93
SUM	*1.12*	*4.87*	*3.95*	*0.26*	*2.17*	*0.94*	*3.15*	*6.29*	*0.43*	*1.08*
Subtotal					**12.36**					**11.89**
Total										**24.26**

There is no significant difference in the total number of deaths between females and males. Yet, as females have higher life expectancy, we also compute years of life lost (YLL) differentiated by sex. YLL is computed applying equation (6), in which the remaining life expectancy is calculated based on standard life tables (WHO, 2014). Table 6 shows the computation of YLL for both sexes applying a discount factor of 3% and standard weights (K=1).

The economic cost of the burden of diseases is estimated using the HCA, VSL and VOLY approaches. Regarding the HCA, we use the 2012 regional and real GDP per capita for the canton of Cuenca of 2009 of US $7,243.[8] As discussed in the methodology, there is no VSL estimate available for Ecuador and a benefit transfer of the recommended VSL for OECD countries is sensitive to the applied income elasticity as shown by equation (4). Based on PPP adjusted GDP per capita for OECD countries and Ecuador in 2012 (World Bank, 2014) the VSL estimate for Ecuador is computed for income elasticities ranging between 0.4 and 1.2 (table 7). We choose an income elasticity of 1, at which level the ratio of the VSL/GDP per capita (adjusted for PPP) is closest to 80 - the recommended ratio for low-middle to high-middle income countries (Cropper, 2014). Consequently, the VSL for Ecuador is equal to US$ 821,079. The VSL estimates with income elasticity 0.8 and 1.2 are used as lower and upper bounds, respectively.

[8] The Central Bank of Ecuador has only made available regional GDP estimates up to 2009. Using the real growth in national GDP (World Bank, 2014), the regional GDP for Cuenca is approximated applying linear extrapolation.

Table 6. Years of Life Lost (YLL) due to PM2.5 ambient air pollution

Age group	Remaining life expectancy		Deaths		Years of Life Lost (YLL)		
	Female	Male	Female	Male	Female	Male	Total
0	34.87	34.75	0.26	0.43	9.03	14.99	24.02
5	37.35	37.21	-	-	-	-	-
10	37.47	37.30	-	-	-	-	-
15	36.22	36.02	-	-	-	-	-
20	34.08	33.84	-	-	-	-	-
25	31.39	31.11	-	0.36	-	11.35	11.35
30	28.40	28.08	0.42	0.09	11.99	2.63	14.62
35	25.30	24.91	0.80	0.72	20.18	18.05	38.24
40	22.19	21.74	-	0.30	-	6.61	6.61
45	19.16	18.63	0.62	0.66	11.86	12.32	24.18
50	16.26	15.65	0.98	0.93	15.92	14.55	30.48
55	13.52	12.83	0.29	0.53	3.87	6.74	10.61
60	10.97	10.19	0.77	0.53	8.46	5.38	13.84
65	8.60	7.80	1.82	0.94	15.62	7.33	22.96
70	6.45	5.71	1.29	0.70	8.32	3.98	12.30
75	4.59	4.00	0.75	1.27	3.44	5.07	8.51
80	1.53	1.30	4.37	4.43	6.70	5.77	12.47
		Sum	**12.36**	**11.89**	**115.40**	**114.77**	**230.17**

Table 7. Estimates of VSL for Ecuador using different income elasticities

Income elasticity e	**0.4**	**0.6**	**0.8**	**1**	**1.2**
VSL Ecuador (in USD)	1,786,598	1,378,731	1,063,977	821,079	633,633
Ratio VSL Ecuador / GDP per capita (PPP)	177.4	136.9	105.6	81.5	62.9

According to equation (5), using a remaining life expectancy of 21.7 years and the VSL estimate of US$ 821,079, a VOLY is equal to US$ 36,399. VOLY estimates for VSL estimates with lower and upper bounds of income elasticities are also calculated to indicate the range of estimate.

Table 8 presents the estimated economic cost of PM2.5 ambient air pollution in the city of Cuenca by valuation approach. The cost of the burden of disease ranges between a minimum of US$1.7 million (HCA) and a maximum of US$ 25.8 million (VSL approach). The estimated cost according to the VSL and VOLY approach vary significantly due to applied income elasticities. One should primarily consider the VSL- and VOLY-based estimations with a unitary income

elasticity when comparing it to the HCA approach, as the others shall only indicate a range. Still the difference in valuation outcome between all three methods is remarkable.

Table 8. Economic cost of PM2.5 ambient air pollution in Cuenca

Valuation approach	Income elasticity	$ of VLS/VOLY	Valuation of lives lost	Valuation of life of years lost
VSL	0.8	$1,063,977	$25,808,224	
	1	**$821,079**	**$19,916,399**	
	1.2	$633,633	$15,369,639	
VOLY	0.8	$47,167		$10,856,486
	1	**$36,399**		**$8,378,031**
	1.2	$28,090		$6,465,391
HCA	-	**$7,243**		**$1,667,018**

7. Discussion and Conclusions

An analysis was conducted to estimate the Cost of Environmental Degradation caused by outdoor ambient PM pollution in Cuenca, Ecuador. Instead of determining one single economic cost value, the study applied different valuation methodologies and determined a range of cost estimates to account for the variation between different techniques. Depending on the valuation approach, the cost of PM2.5 air pollution equals to a range of between 1.08% and 0.07% of regional GDP.

Resulting in lower-bound values of air pollution damages, the HCA approach is often claimed as failing to adequately reflect the total economic value of human life by only considering average human productivity, and that there are of course many more dimensions that need to be considered. In comparison, and as described in detail in the analysis, both the VSL and VOLY approach also account for the loss in utility entailed in human life. However, the VSL approach may be particularly vulnerable when applied for valuing the costs of air pollution, as a clear majority of deaths occur among the elderly and there is empirical evidence that the VSL decreases with age (Aldy and Viscusi, 2007; Alberini, 2004). Consequently, the VSL estimate might substantially overestimate the cost of air pollution. Applying a constant VOLY instead of a constant VSL, at least accounts for remaining life expectancy, which is arguably one of the main determinants of age-dependent VSL. Therefore, for applied analysis from which policy recommendations are to be derived, the use of VOLY is most recommended. Its cost estimate ranges between lower and upper bounds of US$6.5 and US$10.9 million, with an average of US$ 8.4 million. In relation to regional GDP, this corresponds to an average of 0.35% of regional GDP, or a range of 0.27% – 0.45% of regional GDP.

While this study focused only on mortality associated with air pollution, as it represents the largest share of the Cost of Environmental Degradation, other aspects and economic impacts, which have not been integrated in the current quantitative analysis, should also be considered. These include, for example, costs associated with morbidity and illness, cognitive and learning effects with associated short, medium, and long-term economic implications, reduced amenity values or impact of air pollution on cultural heritage, especially buildings, and others.

One key source of uncertainty of this analysis remains that, at the time the calculations were performed, the technical approach for measuring air pollution in Cuenca was still being improved, and available data suffered from several shortcomings. For example, some measurement stations were too far off the ground, and data for PM2.5 was not yet available at the scale needed, so that PM2.5 data had to be modeled based on PM10 pollution data and using a known PM10/PM2.5 ratio for Quito. The uncertainty in the results is likely underestimating the real values, because actual PM10 measurements in Cuenca are likely to underestimate actual emission levels at the street level. Lastly, the effects of indoor air pollution have not been considered in this study. All these considerations, and the limited scope of impacts analyzed, underlines that the average cost estimates of this study are to be understood as conservative estimates. However, as mortality impacts are believed to be greater than 80% of total economic cost (Hammitt and Robinson, 2011), the attained estimates represent nonetheless the bulk share.

From an environmental management viewpoint, a variety of options exist for addressing air pollution in Cuenca. These options can be broadly categorized into either policy or investment measures, or a combination thereof. Policies and regulatory interventions could, for example, address the quality of fuels used in Cuenca by setting minimum fuel quality standards, mandatory technical check-ups of engines and emission testing requirements with the objective to enhancing the quality of engines, the introduction of a traffic zoning systems in the city of Cuenca contingent on the emission category of cars, and many more. In many cases, such policy reforms would have to be complemented by public sector investments. Investments could be concentrated on public campaigns to, for example, change engine technology for buses used in Cuenca (e.g. switching from diesel to natural gas or electricity driven public transport), or set up an incentives program for taxis to switch to natural gas or hybrid powered vehicles. These investment programs would, in turn, be enhanced by the adequate set of policies, for example zoning systems that would provide preferred access to vehicles with lower emissions.

Economic analysis (Cost-Benefit Analysis) can be applied as a useful tool to prioritize among these interventions options with respect to their efficiency and cost effectiveness. Some policy reforms may also require to understand the political economy of reforms, for example, when taxi technology or bus technology of private firms is to be changed. A political validation process, e.g. stakeholder consultations, is commonly an essential ingredient for successful policy reform.

Annex 1. Literature review

Ambient air pollution is a complex mixture of different types of pollutants, i.e. gases and particulate matter (PM), originating from various sources. In Latin America and the Caribbean (LAC), the priority pollutants associated with health and other impacts are PM_{10}[9], $PM_{2.5}$, nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), ozone and lead, as well as carbon dioxide (CO_2). Noise pollution is a further type of air pollution that has recently been classified as a particular type of air pollution, and relevant literature is also included in this literature review.

The complex mixture of air pollutants equally results in a complex impact scenario in which a varying combination of different pollutants lead to different impacts at different levels. These scenarios can be differentiated into four main categories of impacts: 1 – health; 2 - cognitive and neurological deficits; 3 - cultural heritage; and 4 - ecosystems. Furthermore, economic values can be assigned to these impacts; this is done at the end of this review.

Table A1. Selection of literature on impacts associated with air pollution

Impacts	LAC	Global	East Asia	USA	EU
1. Health					
Cardiovascular (adults)	a, c	a, b	i		
Respiratory (adults/ children)	a, c, d, e				
Pulmonary (adults/ children)	a, c, g		j	k	
Pre/Postnatal (children)	h	A		l	
2. Cognitive	m, n, o, p, q	A		r	s
3. Cultural Heritage		T			u
4. Ecosystems		v, w			

a. Onursal, Gautam 1997
b. Larsen, Hutton, Kkanna 2008
c. Romieu, Gouveia, Cifuentes 2012
d. Estrella et al. 2005
e. Mallol et al. 2010
f. Bell et al. 2006
g. Harris et al. 2011
h. Gouveia, Bremner, Novaes 2004
i. HEI 2010
j. HEI 2012
k. Valavanidis, Fiotakis, Vlachogianni 2008
l. Currie, Neidell, Schmieder 2009
m. Calderón-Garcidueñas et al. 2011
n. Calderón-Garcidueñas et al. 2008
o. Calderón-Garcidueñas et al. 2007
p. Trombetta Zannin et al. 2003
q. Trombetta Zannin et al. 2013
r. Mohai, Kweon, Lee, Ard 2011
s. Clark et al. 2012
t. Watt et al. 2009
u. Watkiss et al. 2006
v. Slabbekoorn, Halfwerk 2009
w. Barber, Crooks, Fristrup 2009

[9] PMx refers to the fraction of airborne particles with a diameter equal or below X micrometers. PM10 and PM2.5 are frequent cuts used in literature, since PM10 is the "breathable" fraction of particles in the air, and PM2.5 are particles small enough in diameter to penetrate deep into the lung's alveoli.

1.1. Adults

For adults, the main health impacts addressed in the reviewed literature are cardiovascular, respiratory and pulmonary diseases.

1.1.1. Cardiovascular

Cardiovascular diseases comprise the rise in blood pressure/hypertension, ischemic heart disease, which are mainly caused by the exposure to PM, lead and CO.

Case studies carried out as part of a study by the Health Effects Institute (HEI) in selected LAC cities demonstrated that in seven out of nine cities (Sao Paolo/ Rio de Janeiro/ Porte Alegre, Brazil; Santiago, Chile; Monterrey/ Toluca/ Mexico City, Mexico) PM_{10} was positively and significantly associated with an increased risk of mortality from cardiovascular diseases for both all-age group and elderly (≥65). Also, a correlation between PM_{10} exposure and cerebrovascular-stroke mortality was observed in five LAC cities in the same study (Romieu, Gouveia and Cifuentes, 2012). For lead exposure, case studies in Mexico City showed a relationship to lead levels in the human body. Another study estimates for the LAC region that a 1 $\mu g/m^3$ increase in ambient lead level would cause 20 – 65 premature deaths, 18 – 50 nonfatal heart attacks among 100,000 40 to 59 year old males, and 45 – 89 hypertension cases among 1,000 20 to 70 year old males (Onursal, Gautam 1997). Human exposure to CO reduces the blood's capability to transport oxygen causing the heart to work harder and, thereby, increasing the pulse rate, e.g. (Onursal, Gautam 1997).

Literature on other regions includes another HEI study carried out in four selected cities in East Asia (Shanghai, Wunan, Bangkock and Hong Kong), showing findings similar to the LAC region: A 10-$\mu g/m^3$ increase in PM_{10} concentration resulted in a 0.6% increase in mortality rate including both all natural and cause-specific (i.e. cardiovascular and respiratory) daily mortality. However, the dominant pollutants varied across the cities with PM_{10} and O_3 having a higher impact in Bangkok than in the Chinese cities. When conducting multi-pollutant scenarios, NO_2 gained importance and resulted to be least sensitive to the inclusion of other pollutants in the Chinese cities, while for Bangkok PM_{10} remained crucial (HEI 2010).

Larsen, Hutton and Kkanna (2008) argue that due to increasing urbanization and ageing population, and taking into account the high vulnerability of elderly to heart-related illnesses, the health impacts of outdoor PM pollution may increase. Even if there was no change in age and cause of death distribution, mortality from PM pollution might potentially increase by the same rate as the annual population growth in large cities (Larsen, Hutton and Kkanna, 2008).

1.1.2. Respiratory

The most common respiratory diseases resulting from air pollution are asthma, acute respiratory illnesses (ARI), and bronchitis. Exposure to PM including mainly PM_{10}, $PM_{2.5}$ and black smoke is the main cause for these diseases, but also SO_2 as well as NO_x have significant impact. CO can trigger adverse health impacts when synergizing with other pollutants (Onursal, Gautam 1997).

Several case studies in LAC urban areas showed an increase in respiratory illnesses with higher PM concentrations (Mexico City, Mexico; Los Andes, Chile), as well as a decrease in respiratory and bronchitis/asthma-related visits to the Emergency Room with a reduction of PM exposure (Vila Parisi, Brazil). Respiratory mortality among elderly and men is more responsive to PM_{10} exposure changes than total mortality. The HEI's study from 2012 concluded that in eight of nine investigated LAC cities, PM_{10} exposure has led to an increase in mortality from respiratory causes (Romieu, Gouveia and Cifuentes, 2012). Effects from PM exposure are typically exacerbated by SO_2, and vice versa, as SO_2 is absorbed by the upper respiratory tract leading to bronchitis and similar symptoms (Onursal, Gautam 1997).

For nitrogen oxides, studies have so far only shown evidence of a relationship of indoor NO_2 exposure to health as the susceptibility to respiratory infection and airway resistance in asthmatics are increased. Also, occupational exposure causes inflammation to bronchitis and broncho-pneumonia, a.o. Adverse health effects from ozone can already be observed in a five minute period with short-term (coughing e.g.) and long-term (asthma e.g.) effects (Onursal, Gautam 1997).

Bell et al. (2006) assessed the impact of air pollution control policies – 10% reduction of PM_{10} and ozone between 2000 and 2020 – on three Latin American cities (Santiago, Sao Paulo, and Mexico City): Compared to the business-as-usual scenario, over 3,300 deaths in Mexico City, over 500 respiratory hospital admissions in Santiago, and almost 80,000 asthma attacks in Sao Paulo could be averted by 2020 through such measures.

Literature on the East Asia region includes a series of case studies by the HEI in Ho Chi Minh City, Vietnam, which concluded that a 10 $\mu g/m^3$ increase in levels of mainly NO_2 but also of PM_{10} can lead to a significant excess risk of ALRI hospitalizations of children. However, this observation was only valid for the dry season (HEI 2012).

1.1.3. Pulmonary

Typical pulmonary diseases caused by air pollution include lung cancer, pneumonia and Chronic Obstructive Pulmonary Disease (COPD). Alongside respiratory symptoms, several air pollutants – in particular PM, NO_x and ozone – have shown long-term effects of reducing lung functions.
The HEI study from 2012 showed an increase in mortality from cardiopulmonary disease and COPD due to PM_{10} exposure for all ages in eight out of nine analyzed cities (Romieu, Gouveia and Cifuentes, 2012). A cohort analysis in Quito, Ecuador, provided evidence on the relation of air pollution, indicated through $PM_{2.5}$ and NO_2, and rates of hospitalization for pneumonia. Anemia was found as a facilitator for the occurrence of pneumonia (Harris et al. 2011).

The relationship between increased lung cancer risk and air pollution has been addressed in studies (e.g. ecologic, cohort, case-control), but often the potential influence of the study subjects' smoking behavior was not considered in the same study resulting in inconsistent findings. Still, the largest series of case studies in the US have shown a correlation: Mortality from lung cancer after adjusting for other factors like smoking habits increased significantly to 14% for a difference of 10 $\mu g/m^3$ of $PM_{2.5}$ (Valavanidis, Fiotakis and Vlachogianni, 2008).

1.2. Children

For children, the main health impacts addressed in the reviewed literature are respiratory and pulmonary diseases as well as effects resulting from pre- and postnatal exposure.

1.2.1. Respiratory

The 2012 HEI study could identify significant correlation of PM_{10} exposure and mortality from lower respiratory infections for children of 1-14 years in Sao Paolo, Santiago de Chile, and Mexico City (Romieu, Gouveia and Cifuentes, 2012). Also, short-term exposure to indoor NO_2 leads to lower respiratory illnesses (cough, runny nose, sore throat) and increased sensitivity to urban dust and pollen (Onursal, Gautam 1997).

An example from school children in Quito, Ecuador, showed that outdoor CO (mainly from vehicular emissions), which binds hemoglobin reducing oxygen delivery, is associated significantly with an increase in ARI cases among those children attending schools in high-traffic areas (Estrella et al. 2005).

Generally, asthma prevalence in children varies widely among Latin American cities, with the majority of the cities showing a prevalence of current symptoms (mainly wheezing) and lifetime asthma of 15% or more (Mallol et al. 2010). Local ecological factors typical of each locality have usually been identified as the main determinants, but Mallol et al. (2010) further challenge the general perception that socioeconomic factors (poverty, hygiene) do not represent risk factors.

1.2.2. Pulmonary

Case studies in Brazil on health effects from PM exposure show that infant mortality from pneumonia increases (Rio de Janeiro), and that a reduction in PM concentration leads to the improvement of pulmonary functions among six year olds. For ozone, on the contrary, study evidence in Mexico City could also lead to the conclusion that chronic exposure could result in the development of tolerance to it among children and young adults (Onursal, Gautam 1997).

1.2.3. Pre- and postnatal exposure

Prenatal exposure to CO can lead to reduced birth weight and retarded postnatal development (Onursal, Gautam 1997). For a 1 ppm increase in mean exposure to CO during the first trimester, a reduction of 23 g in birth weight was estimated in a study carried out in Sao Paulo, Brazil (Gouveia, Bremner and Novaes, 2004).

In New Jersey, USA, a study generated robust results concluding that CO has negative effects on infant health both before and after birth, even at the low levels of ambient CO observed in the year of the study (2009). They further found that a one unit decrease in mean CO levels in the first two weeks of life saves roughly 18 lives per 100,000 births, which represents a reduction in the probability of infant death of about 2.5% (Currie, Neidell and Schmieder 2009).

1.3. Cognitive and neurological deficits

Deficits related to cognitive and neurological functions are found to be caused by 1) gases and PM as well as by 2) noise pollution, and are mainly observed among children.

1) For the former, the exposure to CO can impair perception and thinking (Onursal, Gautam 1997). Exposure of children to severe urban air pollution (PM_{10}, $PM_{2.5}$, ozone) in Mexico City was found to potentially impact the trajectory of cerebral development and cause cognitive deficits in areas of fluid cognition, memory and executive functions during childhood when compared to children in low pollution environments of similar socio-economic status (Calderón-Garcidueñas et al. 2011, Calderón-Garcidueñas et al. 2008). Based on their findings in another study on Mexico City, Calderón-Garcidueñas et al. (2007) suggest that chronic exposure to urban air pollutants – PM and ozone mainly – can potentially pose a risk factor for the development of Alzheimer's disease and that neurodegenerative processes may start at a young age when exposed to air pollution.

2) In terms of noise pollution, a case study carried out based on surveys in Curitiba, Brazil, showed a relation of noise disturbance through traffic (73%) and neighbors (38%) to cognitive impacts, such as irritability (58%), concentration difficulties (42%), or sleeping disorders (20%). The same study, however, showed the significance of the objectiveness of the noise emission analysis (Trombetta Zannin et al. 2003). A survey study on a university campus in Parana, Brazil, resulted similarly in concentration difficulties and irritation as well as annoyance (Trombetta Zannin et al. 2013).

Studies on other regions provide further evidence of the link of air pollution to poorer student academic performance: In Michigan, USA, schools in areas with the highest air pollution levels, which are identified as mainly chemicals including lead, demonstrated the lowest attendance rate (as a potential indicator of poor health) and the highest rate for failed state educational tests (Mohai, Kweon, Lee, Ard 2011). In a secondary analysis of the 2001-2003 Road Traffic and Aircraft Noise Exposure and Children's Cognition and Health (RANCH) project in the UK, the authors argue that there is no significant effect of air pollution on children's health and cognition, such as poorer recognition memory and conceptual recall memory, when particularly aircraft noise is given (Clark et al. 2012).

1.4. Cultural Heritage

Besides their impacts on human health and cognitive functions, gases and black particles have further impact on the deterioration of buildings, thus damaging infrastructure as emblematic buildings and deteriorating the cultural heritage, by increasing the corrosivity of the atmosphere and dirtying light-colored building surfaces, respectively. The soiling is caused by acid chemicals resulting from sulphur and nitrogen oxides – products of domestic and industrial fuel burning – that are incorporated into rain, snow, fog or mist. Also gases like ozone or CO_2 have been shown to react with some materials potentially causing their degradation. Generally, the damages can be of physical (resulting in mechanical breakdown), chemical and biological, as well as of soiling nature and occur at even lower levels of pollution than those that create damage to biological systems (Watt et al. 2009).

Their effects are evaluated by developing dose-response functions similar to as it is done for health impacts. As heritage buildings are typically more diverse than modern buildings, the concrete effects cannot be as easily identified (Watt et al. 2009). Studies have so far largely focused on the European region and rather on materials than the monument itself showing that the pollutants most implicated in acid damages are SO_2 and NO_2 mainly and the most significant impacts being on natural stone and zinc coated materials. The degree of soiling of buildings depends on the type of particulate emission: E.g. diesel emissions have a stronger effect than petrol or domestic coal emissions due to their particulate elemental carbon content. Factors for the soiling degree include the blackness per unit mass of smoke, particle size distribution, chemical nature, as well as surface orientation and micro-meteorological conditions (Watkiss et al. 2006).

1.5. Economic valuation of air pollution

Table A2. Selection of literature for the economic valuation of air pollution

	Morbidity	Mortality	Morb. & Mort./ DALY	Cultural Heritage
LAC	a	c	c, d, e	
Global				h
East Asia			f	
USA	b			
EU			g	i

a. Cifuentes et al. 2005
b. Shah, Nagpal, Brandon 1997
c. Sanchez-Triana, Johnson 2013
d. Bell et al. 2006
e. The World Bank 2007
f. Faiz, Gautam, Burki 1995
g. Pascal et al. 2013
h. Watkiss et al. 2006
i. Watt et al. 2009

The economic valuation of health impacts due to air pollution can be divided into morbidity (sickness), which is often associated with hospitalization, and mortality (premature deaths). To enable and facilitate magnitude comparisons with other risk factors, the Disability-Adjusted Life Years (DALY) approach is frequently used combining both morbidity and mortality through the sum of Years Lost due to Disability (YLD) and Years of Life Lost (YLL).

Based on these identified impacts, monetary values are attempted to be assigned to them to estimate the economic benefits of reducing air pollution. This is typically given by the individual's willingness to play (WTP) to avoid the illness, which is often estimated based on individual survey questionnaires as part of the Contingent Valuation Method (CVM). CVM ask individuals in various forms about their WTP for mortality risk reduction (Sanchez-Triana, Johnson 2013) and has been used in the United States to value respiratory diseases like bronchitis or COPD (Shah, Nagpal, Brandon 1997). Otherwise, for morbidity further measures include the cost of illness (COI) approach (comprising the cost of treatment and the opportunity cost of time lost to illness) as well as restricted activity days (RAD) or estimated work loss days (WLD) (Shah, Nagpal, Brandon 1997). For mortality, the Value of a Statistical Life (VOSL or

VSL), Value of a Life Year (VOLY), or the human capital approach are used to estimate the individual's WTP. The VSL calculates as: VSL = WTP_{Ave} * 1/ R where WTP_{Ave} is the average willingness-to-pay (US$ per year) per individual for a mortality risk reduction of magnitude R (Sanchez-Triana, Johnson 2013). The main approaches to estimate VSL are by determining revealed preferences – mainly through hedonic wage estimating labour market wage differentials associated with differences in occupational mortality risk – and stated preferences, which is mostly relying on CVM (Sanchez-Triana, Johnson 2013). The resulting VSL depends on the characteristics of the risk of death: age at death, time between exposure and death (i.e. latency), and nature of the underlying risk (Pascal et al. 2013).

Table A3. Low and high estimates for VSL in selected LAC countries (Sanchez-Triana, Johnson 2013)

	VSL low, mn US$	VSL high, mn US$
Argentina	0.69	1.77
Chile	0.67	1.72
Mexico	0.65	1.67
Panama	0.62	1.59
Costa Rica	0.51	1.30
Peru	0.44	1.13
Colombia	0.44	1.12
Ecuador	0.39	0.99
El Salvador	0.32	0.82
Bolivia	0.25	0.65
Guatemala	0.25	0.63
Honduras	0.21	0.54
Nicaragua	0.20	0.51

For the LAC region, however, the economic analysis still proves to face constraints which becomes evident when applying different health impacts models (US based vs. LAC based) and obtaining different results in the valuation of health impacts. This highlights the need for better estimates of LAC valuations that are comparable to the more comprehensive US based ones (Cifuentes et al. 2005). Hence, using the more inclusive US COI figures in order to estimate health costs due to morbidity for LAC, an IADB report concludes that about US$2.2 billion (bn) to US$6.2 bn per annum in COI benefits might be realized, depending on the pollution control scenario (Cifuentes et al. 2005). According to studies in the US – assuming that this is equally the case for developing countries – COI figures typically represent the lower bound of morbidity costs when compared to WTP studies; Cifuentes et al. (2005) measured a WTP of 0.4-1.4% of income over all LAC cities investigated. Bell et al. (2006) calculated in their study that by avoiding over 156,000 deaths, 4 million asthma attacks, 300,000 children's medical visits and nearly 48,000 cases of chronic bronchitis in three Latin American cities due to policies, monetary savings result to be between US$21 to US$165 bn. Both health and economic benefits turned out to remain significant during a sensitivity analysis.

On country-level, Sanchez-Triana and Johnson (2013) calculated lower and upper bounds for the VSL related to air pollution for various LAC countries (table A3), which range between US$0.2 mn (Nicaragua) and US$0.69 mn (Argentina) for the lower bound and between US$0.51 mn and US$1.77 mn for the upper bound.

For Costa Rica, the health costs of urban air pollution due to morbidity and mainly mortality were calculated in a World Bank report to amount to around 1.1% of the national GDP in 2011 with an estimated 350 premature deaths and nearly 4,700 lost DALY associated with PM exposure (Sanchez-Triana, Johnson 2013). For Peru, annual costs from increased morbidity and mortality due to outdoor air pollution were estimated to be close to 3 % of GDP in 2003, which is higher than other comparator countries such as Colombia and several North African countries (The World Bank 2007). By the means of the human capital approach, air pollution related health costs in Mexico City were estimated (The World Bank 2007, taken from Faiz, Gautam, Burki 1995) and exceeded US$ 1.10 bn/year: US$840 mn from particulate pollution (mortality and morbidity); US$ 100 mn from ozone (morbidity); and US$ 130 mn from airborne lead (compensatory education due to loss of IQ points in children, treatment of children with excess lead in the blood, hypertension in adults and myocardial infarctions).

When considering literature on other regions, long-term impacts of chronic exposure to $PM_{2.5}$ was investigated for 25 European cities resulting in an increase in life expectancy at the age of 30 ranging from 0 (Stockholm) to 22 months (Bucharest) when complying with the WHO air quality threshold of 10 $\mu g/m^3$. The corresponding significant monetary gains would amount to €31 bn (around US$35.5 bn) per year for all 25 cities. Reducing PM_{10} to the WHO limit would result in annual economic benefits of €19 bn (around US$22 bn) associated with the avoided hospitalization (Pascal et al. 2013).

The economic costs of air pollution impacts on cultural heritage has so far only been calculated based on the real costs of maintenance and repair as the most straightforward approach, although the big challenge remains to estimate the fraction of air pollution contribution. Indirect costs can, e.g., be approximated by the means of valuing welfare loss of damages to cultural heritage, e.g. through CVM (Watt et al. 2009). A case study on The Clean Air for Europe (CAFE) Programme, as described by Watt et al. (2009), estimates the cost of material damage in Europe as a cause of air pollution to amount to €1.13 bn (around US$1.3 bn) in 2000 and decreasing to €0.74 bn (around US$ 0.85 bn) by 2020 due to new EU legislation on emission regulation. Generally, due to lack of data it has so far been proven to be difficult to quantify the effects in simple damage cost values, but valuation studies have shown that people place a significant value on cultural heritage (Watkiss et al. 2006).

Annex 2: PM concentration per city district (parroquia)

City District (Paroquia)		Concentration of PM_{10}			Concentration of $PM_{2.5}$		
		Min	**Max**	**Mean**	**Min**	**Max**	**Mean**
1	Bellavista	34.27	37.73	35.58	16.45	18.11	17.08
2	Caaribamba	34.77	36.99	35.68	16.69	17.76	17.13
3	El Batan	34.06	34.83	34.47	16.35	16.72	16.55
4	El Sagrario	34.1	34.51	34.21	16.37	16.56	16.42
5	El Vecino	34.33	40.7	38.14	16.48	19.54	18.31
6	Gil Ramirez Davalos	34.12	34.54	34.27	16.38	16.58	16.45
7	Huayna Capac	34.24	36.17	34.99	16.44	17.36	16.80
8	Machangara	37.48	40.63	38.56	17.99	19.50	18.51
9	Monay	35.76	39.37	37.67	17.16	18.90	18.08
10	San Blas	34.26	36.25	34.85	16.44	17.40	16.73
11	San Sebastian	34.38	35.51	35.01	16.50	17.04	16.80
12	Sucre	34.22	34.74	34.48	16.43	16.68	16.55
13	Totoracocha	35.33	40.61	38.79	16.96	19.49	18.62
14	Yanuncay	33.9	34.69	34.15	16.27	16.65	16.39
15	Hermano Miguel	37.37	40.69	39.17	17.94	19.53	18.80

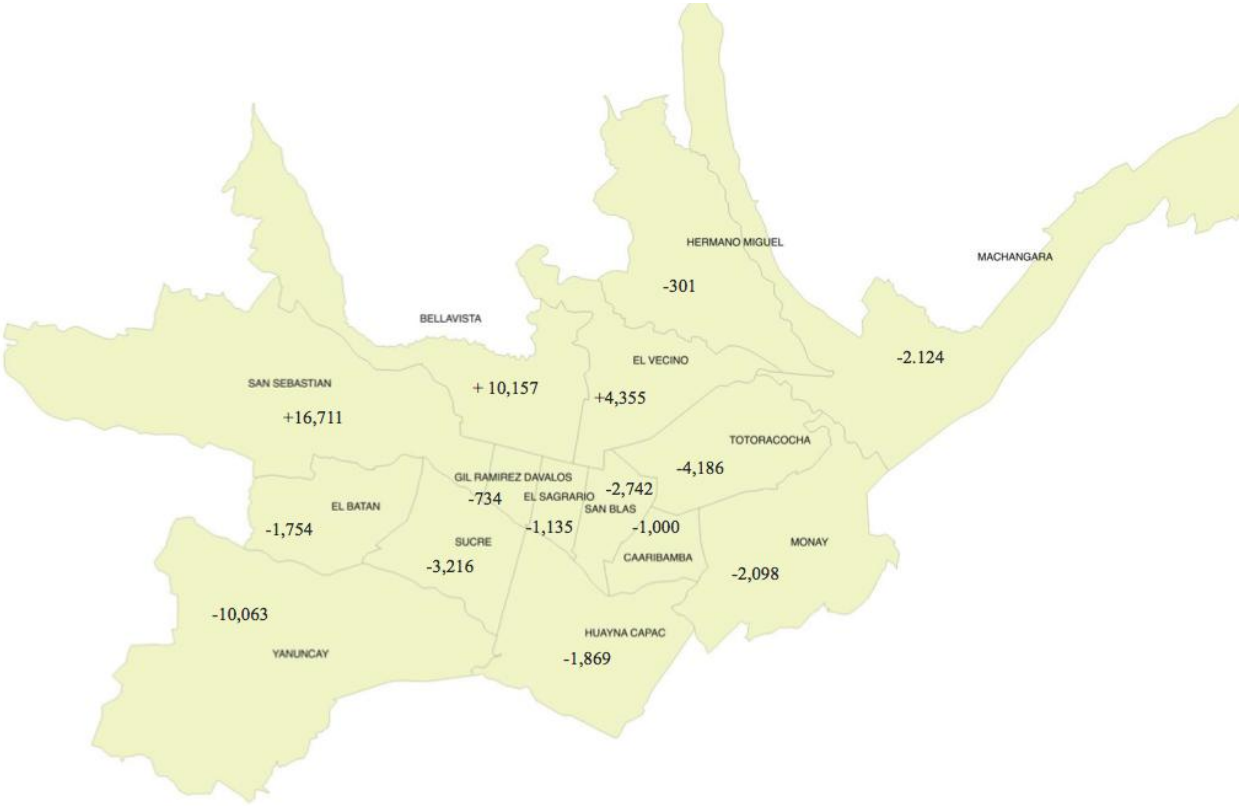
PM10 measurements in Cuenca are obtained as a 24h average, and then converted into year averages.

Annex 3. Distribution of population and net change after adjustment

Share of age-group population per city district (based on INEC census 2010).

Age Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0-4	8%	3%	8%	2%	10%	2%	4%	7%	7%	3%	12%	4%	8%	17%	6%
5-9	8%	3%	8%	2%	10%	2%	4%	7%	7%	3%	13%	4%	8%	16%	6%
10-14	8%	3%	8%	2%	10%	2%	4%	8%	7%	2%	13%	4%	8%	16%	6%
15-19	8%	3%	8%	2%	9%	2%	4%	8%	6%	3%	12%	4%	8%	16%	5%
20-24	8%	4%	8%	2%	10%	2%	4%	7%	7%	3%	11%	5%	7%	16%	6%
25-29	8%	3%	8%	2%	11%	2%	5%	7%	7%	3%	11%	5%	8%	16%	5%
30-34	8%	3%	7%	2%	9%	2%	5%	7%	7%	3%	12%	5%	8%	16%	5%
35-39	8%	4%	7%	2%	9%	2%	5%	7%	7%	3%	12%	5%	8%	16%	5%
40-44	8%	4%	7%	2%	9%	2%	5%	8%	7%	3%	12%	5%	8%	16%	5%
45-49	8%	4%	7%	2%	8%	2%	5%	7%	7%	3%	12%	6%	8%	16%	5%
50-54	8%	4%	8%	2%	8%	2%	6%	6%	8%	3%	11%	6%	7%	15%	4%
55-59	8%	5%	7%	2%	7%	2%	7%	5%	7%	3%	11%	7%	8%	15%	4%
60-64	9%	6%	7%	2%	8%	2%	6%	5%	6%	4%	12%	7%	9%	13%	4%
65-69	9%	5%	6%	3%	8%	3%	7%	5%	6%	5%	12%	7%	8%	12%	4%
70-74	9%	5%	6%	3%	9%	3%	6%	5%	5%	5%	12%	7%	8%	11%	4%
75-79	10%	5%	5%	4%	10%	4%	7%	5%	5%	6%	11%	7%	8%	10%	4%
>80	9%	4%	5%	5%	8%	6%	7%	5%	6%	5%	11%	7%	8%	11%	3%
All	8%	4%	7%	2%	9%	2%	5%	7%	7%	3%	12%	5%	8%	16%	5%

Net change in city district population after adjustment



Annex 4. Diseases associated with PM pollution and their differentiated impacts

Age group	Female	Male	Total	in % of total deaths
0-4	3	5	8	4.7%
5-9	0	0	0	0.0%
10-14	0	0	0	0.0%
15-19	0	0	0	0.0%
20-24	0	0	0	0.0%
25-29	0	1	1	0.6%
30-34	2	1	3	1.8%
35-39	2	2	4	2.3%
40-44	0	1	1	0.6%
45-59	2	3	5	2.9%
50-54	4	4	8	4.7%
55-59	1	2	3	1.8%
60-64	4	3	7	4.1%
65-69	12	6	18	10.5%
70-74	9	4	13	7.6%
75-79	7	9	16	9.4%
80+	43	41	84	49.1%
Total	89	82	171	100%

This table complements Table 2 and Table 4 presented in the main text. The table presents the frequency of deaths that are *inter alia* associated with air pollution. For the case of Cuenca, it confirms the conventional categorization that most diseases that are also associated with air pollution affect adults above age 25, and only ALRI affects also children with respect to mortality. Other known impacts, especially those related to morbidity, but also cognitive impacts, are not part of the data presented here. As presented in Table 5, deaths directly caused by air pollution were calculated at a statistical rate of 24.26 per year.

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