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Assessment of Respiratory Health Impacts of $PM_{2.5}$ by AirQ+ Software in a Sub-Saharan African Urban Setting

Mélanie Ngutuka Kinzunga [1,2,*], Daniel M. Westervelt [3,4], Daniel Matondo Masisa [5,6], Freddy Bangelesa [1,7], Paulson Kasereka Isevulambire [4], Thierry Tangou Tabou [8], Benoit Kabengele Obel [2], Guillaume Kiyombo Mbela [1] and Jean Marie Kayembe Ntumba [2]

1 Department of Environmental Health, School of Public Health, Faculty of Medicine, University of Kinshasa, Lemba, Kinshasa 01031, Democratic Republic of the Congo
2 Department of Internal Medicine, University Hospital of Kinshasa, Faculty of Medicine, University of Kinshasa, Lemba, Kinshasa 01031, Democratic Republic of the Congo
3 Lamont-Doherty Earth Observatory of Columbia University, New York, NY 10964, USA
4 Department of African Research Center on Air Quality and Climate, University Mohammed VI Polytechnic, Benguerir 43150, Morocco
5 Graduate Schools Public Health and Life Sciences and Health, University Paris Saclay, 94270 Kremlin-Bicêtre, France
6 Clinical & Biomedical Research Services Working Group, 92290 Châtenay-Malabry, France
7 Institute of Geography and Geology, University of Würzburg, Am Hubland, 97074 Würzburg, Germany
8 Department of Environmental Sciences, Faculty of Science, University of Kinshasa, Lemba, Kinshasa 01031, Democratic Republic of the Congo
* Correspondence: melanie.ngutuka@unikin.ac.cd; Tel.: +243-9-93-95-60-21

Abstract: Background: Ambient air pollution remains a major risk factor for population health worldwide. The impact of $PM_{2.5}$ air pollution is underestimated in sub-Saharan Africa due to a lack of epidemiological studies. AirQ+ is proposed to reduce these inequalities in research. The aim of this study is to assess, by AirQ+, the impact of prolonged exposure to $PM_{2.5}$ on respiratory health in Kinshasa in 2019, and to estimate the health benefits of reducing this air pollution. Methods: Population and mortality data were obtained from the Institut National de la Statistique and the Institut de Métrologie et d'Évaluation en santé, respectively. $PM_{2.5}$ concentrations were measured using PurpleAir PA-II-SD sensors, and average annual concentration was 43.5 $\mu g/m^3$ in 2019. AirQ+ was used to estimate the health effect attributable to $PM_{2.5}$ in adults aged over 25 in Kinshasa. Results: In 2019, the proportion of deaths attributable to $PM_{2.5}$ air pollution was 30.72% for ALRI, 26.55% for COPD and 24.32% for lung cancers. Each 10% reduction in current $PM_{2.5}$ levels would prevent 1093 deaths (from all causes) per year in Kinshasa. Life expectancy would increase by 4.7 years (CI 3.5–5.3) if the WHO threshold of 5 mg/m^3 were respected. Conclusions: The results of this study highlight the major respiratory public health problem associated with air pollution by fine particles in Kinshasa. AirQ+ was used to assess the impact of prolonged exposure to $PM_{2.5}$ and respiratory deaths among adults in Kinshasa and revealed that this number of deaths could be avoided by improving air quality.

Keywords: $PM_{2.5}$; long-term exposure; AirQ+, mortality; acute lower respiratory tract infections (ALRI); chronic obstructive pulmonary disease (COPD); lung cancer

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1. Introduction

Much recent data from international health and meteorological agencies reveal the correlation between exposure to air pollution and the high burden of morbidity and mortality on every continent [1,2].

Air pollution is responsible for 4.2 million premature deaths per year worldwide, 18% of which are attributed to chronic obstructive pulmonary disease (COPD) and 23% to acute lower respiratory tract infections (ALRI) [3]. $PM_{2.5}$ is widely considered to be the most

harmful air pollutant, due to its ubiquity in the environment and the wide range of adverse human health effects associated with its exposure [4].

In a recent study, Rodriguez-Urrego et al. showed a significant reduction in $PM_{2.5}$ concentrations in China, the United States and Europe [5].

Furthermore, Giani et al. estimated that reductive measures prevented thousands of premature deaths in the short and long term in China and Europe [6].

Finally, other studies in California [7] and Lombardy [8] have also shown significant reductions in $PM_{2.5}$ and NO_2 levels, contributing to a reduction in premature deaths and an improvement in quality of life.

In Africa, the burden of disease linked to air pollution is one of the highest in the world. Exposure to air pollution is the second highest risk factor for death in Africa [9]. Economic growth, population growth, uncontrolled urbanisation and a lack of environmental regulation could exacerbate effects on the environment and human health [10].

In sub-Saharan Africa, air pollution has increased in recent years [10]. In large sub-Saharan cities, air pollution is caused by vehicle exhaust, industry, open burning of waste and other materials, the use of biomass for cooking, and dust carried by unpaved roads and wind [11–13].

Efforts to reduce air pollution can have significant health benefits, including a reduction in premature deaths and a reduction in the exacerbation or development of a number of respiratory diseases [14–18]. In Africa in 2021, the increase in life expectancy would have been 2.9 years in the Democratic Republic of Congo (DRC), 2.7 years in Rwanda, 1.8 years in Lesotho, 1.8 years in Nigeria and 1.3 years in Egypt if the thresholds recommended by the WHO had been respected [19].

However, for the period 2010–2019, only 3% of African cities, towns and villages had sufficiently good air quality regarding particulate matter. Kinshasa had a high level of $PM_{2.5}$ ambient air pollution of around 43.5 $\mu g/m^3$ in 2019 [20] and 43 $\mu g/m^3$ in 2022 [21], far from the annual threshold of 5 $\mu g/m^3$ set by the WHO's air quality guidelines [22].

The impacts of air pollution are often exacerbated by environmental inequalities in terms of exposure to pollution, pollution monitoring and research [23]. However, few studies on the health impact of air pollution have been carried out in Africa, compared with other geographical areas [19].

This lack of research is thought to be due to the absence of a permanent air quality monitoring system in several countries, the weakness of the system for collecting routine health information, and the economic vulnerability of African countries, which makes it difficult to fund research in this field [23]. This hampers the development of control strategies that would enable public decision-makers to implement policies aimed at reducing air pollution. Hence the need to continue to encourage African researchers, particularly those in sub-Saharan Africa, to carry out less costly local studies using AirQ+ software. This tool has already been used in several epidemiological studies, notably in Asia and more particularly in Iran [24]. However, few African researchers have used this software.

The aim of this study is to assess the impact of prolonged exposure to $PM_{2.5}$ ambient air pollution on respiratory health in the city of Kinshasa using AirQ+ software and to evaluate the health benefits of different air pollution reduction scenarios in order to help decision-makers implement policies aimed at improving air quality.

2. Materials and Methods

2.1. Study Design

This research is an ecological study using AirQ+ software version 2.2 to evaluate the long-term respiratory mortality rate attributed to the concentration of $PM_{2.5}$ in Kinshasa from January to December 2019.

2.2. Study Population

The 2020 Statistical Yearbook of the Democratic Republic of Congo (DRC), published by the Institut National de Statistique (INS) [25], reports the population of the city of

Kinshasa in 2019 as 13,916,000 (4,542,000 aged 25 and over; 3,603,000 aged 30 and over). The target population for this study is adults aged 25 or 30 and over (depending on the health indicator studied).

2.3. Air Pollution Data and Death Data

2.3.1. Air Pollution Data

The data on air pollution in the city of Kinshasa for $PM_{2.5}$ were collected by a team from the Lamont-Doherty Earth Observatory at Columbia University, New York, in the United States of America. The team's conclusions were published in 2021 [20].

The data were collected in real time from hourly concentrations of air pollutants measured by a network of PurpleAir PA-II-SD sensors, which are considered to be low-cost sensors, between March 2018 and August 2020. Four air pollution measurement stations were deployed in Kinshasa for this study (Figure 1), precicely at the US Embassy in Kinshasa (Gombe), Cité de Bellevue (Kintambo), Université Pédagogique Nationale UPN (Ngaliema) and Ecole Régionale Post-Universitaire d'Aménagement et de Gestion Intégrée des Forêts et Territoirestropicaux (ERAIFT/Unikin) (Lemba).

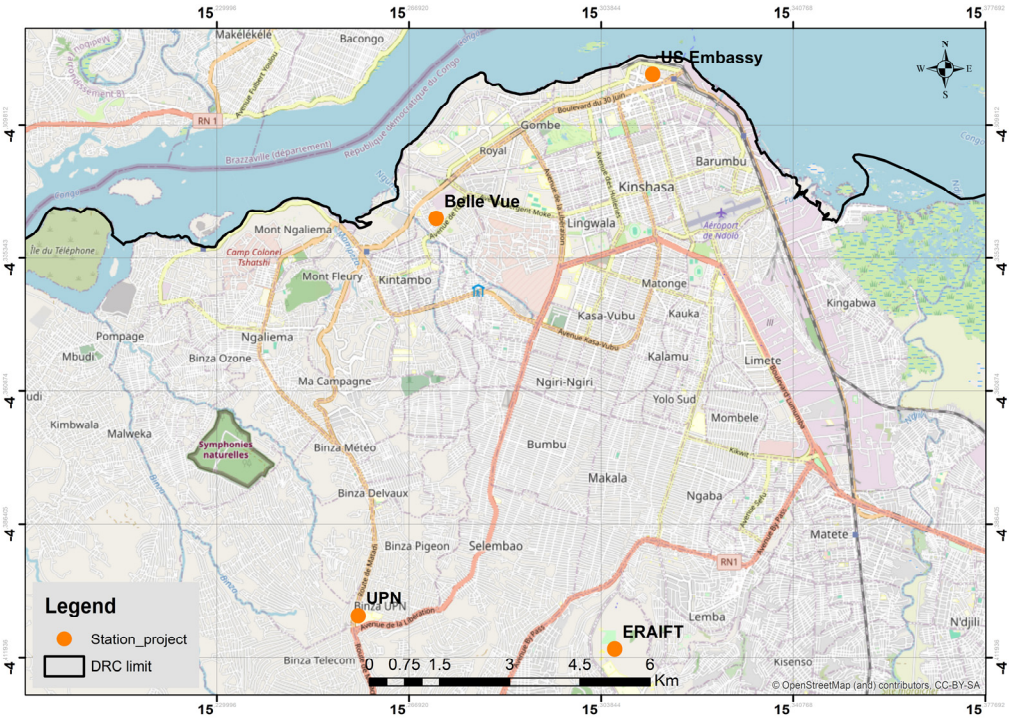


Figure 1. Map of the city of Kinshasa (DRC) showing the 4 measurement sites with Purple Air sensors.

Air pollution data were bias-corrected before being used in this study. A multiple linear regression (MLR) model and a random forest approach were used to bias-correct the PurpleAir data towards the reference monitor BAM-1020 in Kampala (Uganda). PurpleAir raw data from September 2019 to February 2020 were highly correlated with BAM-1020 measurements (r^2 = 0.88), but also had a mean absolute error (MAE) of around 14 µg/m^3. The use of two calibration models, multiple linear regression and random forests, reduced the MAE to 3.4 µg/m^3 and increased r^2 to 0.96. In this LMR model, daily averages of raw PurpleAir PM data, relative humidity and temperature were used as explanatory variables to predict the corrected PM concentration:

$$PM_{2.5} = \beta_0 + \beta_1 \times \text{PurpleAir } PM_{2.5} + \beta_2 \times T(^{\circ}C) + \beta_3 \times RH(\%) \quad (1)$$

$$MAE = \frac{\sum_{i=1}^{i=N} |PM_i^{ref} - PM_i^{LCS}|}{N} \quad (2)$$

where *PM* refers to PM (in μg m), *ref* is the BAM-1020 reference monitor, *LCS* refers to thelow-cost sensor data, *N* is total number of observations, and *i* is the time series variable

Kampala is the closest PM monitor to Kinshasa, and the climate of both cities is quite similar, as they are both located in the middle of the tropics. Both cities have two rainy seasons that peak in October–November and March–April. The annual mean temperature and relative humidity are 30.4 °C and 80% in Kinshasa and 27.8 °C and 75% in Kampala. Pollutant source profiles show many similarities in the two cities, particularly in household fuel use, which accounts for about 50–75% of total SO_2, BC (Black Carbon) and OC (Organic Carbon) emissions in each city. Although the total emissions are slightly higher in Kinshasa than in Kampala, the similarity of sources justified the applicability of sensor calibrations between the two cities. Additionally, qualitative information on particle size in the two cities obtained from satellite retrieval of the 2019 annual mean Angstrom exponent, retrieved by the MODIS Terra Deep Blue retrieval algorithm, gives a figure of approximately 1.5 in Kampala and 1.6 in Kinshasa, indicating a qualitative similarity in particle size distributions in each city.

Only the 2019 data were deemed suitable for analysis, as they represent the most comprehensive coverage of the entire calendar year, but $PM_{2.5}$ data in 2019 were collected largely at the US Embassy site only. The collection at three other sites only began in November 2019 (Figure 2). However, overall data analyses up to 2020 had shown that, despite some variation between the sites surveyed, average concentrations were within 10 μg/m^3 of each other, suggesting a good representation of these data at the city scale.

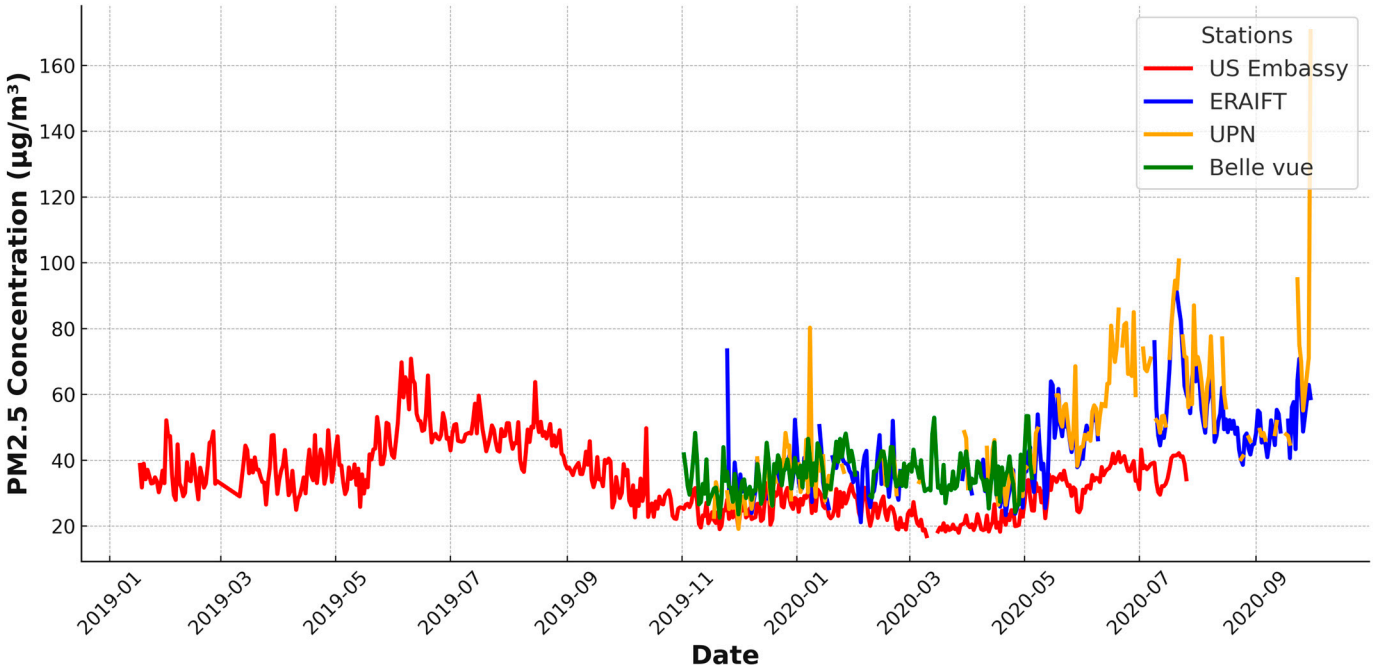


Figure 2. Daily profile of particulate matter (PM) at urban monitoring sites in Kinshasa, from January 2019 to September 2020.

The mean annual $PM_{2.5}$ concentration observed in Kinshasa in 2019 was 43.5 μg/m^3 [20]. The concentration of $PM_{2.5}$ at 43 μg/m^3 was confirmed in Kinshasa in 2021 with the QuantAQ-Modulair [21].

2.3.2. Death Data

The health event under examination is mortality. This encompasses mortality from specific respiratory causes, in addition to all-cause (non-accidental) mortality.

As mortality statistics are neither compiled nor published in the DRC, alternative sources were consulted in order to obtain information on mortality in the city of Kinshasa. These included the Institute for Health Metrics and Evaluation (IHME) [26].

In 2019, the crude death rate in the DRC, as reported by the IHME, was 9.4 deaths per 1000 population at mid-year. For the same period, the crude mortality rate for the city of Kinshasa was calculated to be 8.5 deaths per 1000 live births. The number of deaths observed in the city of Kinshasa was calculated by multiplying the national mortality rate provided by the IHME by the population of the city of Kinshasa, stratified by age (refer to Table 1).

2.4. Assessing the Impact of Air Pollution

In order to assess the mortality burden associated with prolonged exposure to $PM_{2.5}$ ambient air pollution in Kinshasa in 2019, the "AirQ+ version 2.2" software, developed by the WHO Regional Office for Europe [27], was employed. This entails calculating the proportion of deaths that can be attributed to air pollution, the number of deaths that can be attributed to air pollution (individually), and the number of deaths that can be attributed to air pollution per 100,000 population at risk. The methodology and concentration–response functions employed in AirQ+ are derived from epidemiological studies [28].

The quantification of the health effects of exposure to air pollutants is based on the concept of the attributable fraction and the calculation of years of life lost. In this instance, we employed the attributable proportion (*AP*).

The attributable proportion (*AP*), defined as the proportion of a health outcome that can be attributed to exposure in a given population over a given period, is calculated in this software using the following equation, as proposed by Bahrami [29]:

$$AP = \sum \{ [RR_{(c)} - 1] \times p_{(c)} \} / \sum \{ [RR_{(c)} \times p_{(c)}] \} \quad (3)$$

where, $RR_{(c)}$: relative risk for the health effect in exposure category c

$p_{(c)}$: proportion of the population in exposure category c.

In the absence of studies in the Democratic Republic of Congo (DRC), the relative risk values employed in this study are derived from the integrated exposure–response function (IER) obtained from epidemiological studies, for which the RR coefficients are predefined by the programme.

BE, the rate (or number of cases per unit of population) attributed to exposure *E* in the population can be calculated as:

$$BE = B \times AP \quad (4)$$

where *B* is the reference frequency (incidence) of the selected health parameter in the population.

In order to quantify the long-term effects of $PM_{2.5}$, the following data were provided: annual averages of $PM_{2.5}$ concentrations, population at risk, health data, such as reference rates for health effects, the cut-off value to be taken into account, and relative risk (RR) values [28].

2.5. Life Tables with AirQ+ and Loss of Years of Life

The formulas used by the AirQ+ module, along with the life tables, are mentioned in the document *Assessing the health impact of air pollution: life tables with AirQ+: Copenhagen: WHO Regional Office for Europe; 2021. License: CC BY-NC-SA 3.0 IGO* from the WHO.

In the above document, it is stated that the expected remaining lifetime (ELR) is ELR (at AGE) = Σ(from AGE to end) YL/number of people at AGE.

AirQ+ generates tables showing ELR values for threshold pollution levels, calculated using risk ratios adjusted by the relative risk associated with the observed pollution levels. Since the relative risk will be different for total mortality and cause-specific mortality, the delta ELR value displayed in the tables will vary accordingly.

$$\text{ELR lost} = \text{ELR (at threshold)} - \text{ELR (captured data)}.$$

As the AirQ+ software only calculates survival for overall respiratory mortality, to calculate survival for specific respiratory causes, we used the relative risks (RR) specific to each pathology entered in the software.

AirQ+ is capable of assessing the effects of both long-term and short-term exposure to air pollution. The software is capable of handling all pollutants regulated by the World Health Organization (WHO), including $PM_{2.5}$ [30].

This tool has been employed in a multitude of studies [19]. However, to date, to our knowledge, there are only seven African countries whose researchers have already used the AirQ+ software: Ghana [12], Ethiopia [31], Nigeria [32], Senegal [3], Morocco [33], Kenya [34] and Uganda [11].

In addition to the WHO AirQ+ software, some authors employed another software tool, primarily utilized by the United States Environmental Protection Agency (US EPA). This is the BenMAP software, which has been developed with the objective of estimating the potential public health impacts of reducing air pollution [35,36]. Nevertheless, researchers who have employed both software programs (AirQ+ and BenMAP) concurrently to evaluate the health consequences of air pollution and to quantify the health advantages of enhanced air quality have consistently yielded analogous outcomes. For instance, the study conducted by Sacks et al. in Budapest, Hungary, in 2020 serves as a case in point [37–39].

2.6. Statistical Analysis

The AirQ+ software facilitated the calculation of the impact of $PM_{2.5}$ in accordance with the World Health Organization (WHO) air quality guidelines [22], including interim targets, i.e., specific calculations based on different thresholds.

A log-linear model was employed to calculate the proportion attributable to relative risks (RR) for the impact assessments.

According to the AirQ+ glossary, August 2022 version [27], a log-linear function is given by

$$RR = \exp(\alpha + ß \log (X + 1))/\exp (\alpha + ß \log (Xo + 1)) [(X + 1)/(Xo + 1)] ß. \quad (5)$$

In the log-linear model, ß indicates the extent to which a one-unit increase in log (X) favours an expected increase in Y of ß units. The inserted ß was generated with fixed parameters: a threshold equal to 10 $\mu g/m^3$ for an average concentration of 20 $\mu g/m^3$.

AirQ+ enables users to calculate $PM_{2.5}$ impacts based on WHO air quality guidelines (2021), including intermediate target values. For specific calculations where impacts are quantified by selecting different cut-off points, it is more appropriate to use log-linear functions, particularly in the case of air pollution concentrations that are neither too low nor too high.

The RRs were derived from the integrated exposure–response function of the AirQ+ software. However, it should be noted that the exposure level considered in this study ($\geq$43.5 $\mu g/m^3$) is higher than those measured in the Western European and North American cohort studies ($\leq$30 $\mu g/m^3$), which provide the data for the meta-analysis used to generate these RRs [12].

3. Results

In 2019, McFarlane observed high levels of air pollution in Kinshasa, with an annual average $PM_{2.5}$ concentration of 43.5 $\mu g/m^3$ [20]. Considering the city's population and mortality data, we aimed to assess the potential impact of this pollution on excess mortality. We calculated mortality due to specific respiratory causes (acute lower respiratory infections, chronic obstructive pulmonary disease, and lung cancer) as well as all-cause (natural) excess mortality using the following parameters: the proportion of deaths attributable to air pollution, the number of premature deaths associated with air pollution individually, and the number of premature deaths per 100,000 people at risk. Additionally, we estimated the potential benefits of reducing $PM_{2.5}$ exposure. The results are presented in the tables and figures below:

3.1. Consideration of the Population and Mortality Data for Kinshasa

Table 1. Summary on mortality data in Kinshasa from the IHME and statistical yearbook of the DR Congo 2020 Ministry of Planning, baseline year 2019.

	Mortality Causes by Age Group (Year)	Deaths	Mid-Year Population	Mortality Rate (Per 100,000 Live Births)
1.	All causes (natural) (adults 30+)	33,191	3,603,000	921.2
2.	Chronic obstructive pulmonary disease COPD (adults 25+)	2544	4,542,000	56
3.	Acute lower respiratory infections ALRI (adults 30+)	2372	3,603,000	65.8
4.	Trachea, bronchus, Iung cancers (adults 25+)	426	4,542,000	9.4

3.2. Mortality Respiratory Specific Cause Among Adults Due to Ambient Air Pollution in Kinshasa

Table 2 indicates that air pollution was a significant contributor to adult respiratory causes of mortality, accounting for 30.72% of deaths from acute lower respiratory infections (Figure A1), 26.55% of deaths from chronic obstructive pulmonary disease (COPD) (Figure A2), and 35.6% of deaths from lung cancer (Figure A3).

Table 2. Kinshasa: Mortality respiratory causes among adults due to ambient air pollution, baseline year 2019, $PM_{2.5}$ = 43.5 μg/m^3.

Estimated Parameters	Acute Lower Respiratory Tract Disease (ALRI)	Chronic Obstructive Pulmonary Disease (COPD)	Trachea, Bronchus, Lung Cancers
Estimated Attributable proportion (%) (CI 95%)	30.72 (10.76–47.12)	26.55 (20.95–32.13)	35.6 (22.96–43.53)
Estimated number Attributable deaths (CI 95%)	729 (255–1118)	675 (533–817)	151 (98–186)
Estimated number of Attributable Deaths per 100,000 population at risk (CI 95%)	20.22 (7.08–31.02)	14.87 (2.74–17.99)	3.32 (2.15–4.09)

3.3. Mortality All-Cause (Natural) Among Adults Due to Ambient Air Pollution and Air Pollution Reduction Scenarios in Kinshasa

The overall estimated proportion of excess mortality attributable to air pollution in the city of Kinshasa in 2019 among adults aged 30 years and over (Table 3) was 25.64%, with an estimated number of attributable premature deaths of 8511 per year and a mortality rate of 236.03/100,000 for an annual $PM_{2.5}$ level of 43.5 μg/m^3 (Figure A4).

In reality, the 8511 "attributable deaths" (Table 3) can be interpreted as the annual impact of $PM_{2.5}$ levels measured in the city of Kinshasa (levels exceeding the WHO air quality objective for 2021 (5 μg/m^3)) on mortality in adults aged over 30 years.

Table 3. Kinshasa: Mortality all-cause (natural) among adults due to ambient air pollution and air pollution reduction scenarios, baseline year 2019, $PM_{2.5}$ = 43.5 μg/m^3.

	Scenario 1 (Figure A4)	Scenario 2 (Figure A5)	Scenario 3 (Figure A6)	Scenario 4 (Figure A7)	Scenario 5 (Figure A8)	Scenario 6 (Figure A9)
Estimated parameters	AQG ($PM_{2.5}$ = 5 μg/m^3)	IT-4 ($PM_{2.5}$ = 10 μg/m^3)	IT-3 ($PM_{2.5}$ = 15 μg/m^3)	IT-2 ($PM_{2.5}$ = 25 μg/m^3)	IT-1 ($PM_{2.5}$ = 35 μg/m^3)	Reduction by 10% of current $PM_{2.5}$ levels ($PM_{2.5}$ = 39.15 μg/m^3)
Estimated Attributable proportion (%) (CI 95%)	25.64 (20.1–28.24)	22.73 (17.73–25.08)	19.7 (15.3–21.78)	13.27 (10.22–14.74)	6.33 (4.83–7.06)	3.29 (2.5–3.68)
Estimated number Attributable deaths (CI 95%)	8511 (6670–9372)	7543 (5886–8323)	6537 (5079–7228)	4405 (3392–4891)	2102 (1604–2344)	1093 (831–1221)
Estimated number of Attributable Deaths per 100,000 population at risk (CI 95%)	236.23 (185.12–260.11)	209.36 (163.36–231.00)	181.43 (140.95–200.61)	122.25 (94.14–135.76)	58.33 (44.51–65.07)	30.33 (23.06–33.89)

Notes: AQG = Air quality guidelines; IT = interim target; Scenarios1–6 are long term, CI 95%–confidence interval.

3.4. Loss of Years of Life

If the level of exposure were reduced to average annual concentrations (threshold value) of 5 μg/m^3, a 30-year-old person would gain 4.71 years (Table 4) (Figure A10).

Table 4. Kinshasa: Estimated gain in life expectancy if the level of exposure were reduced to average annual concentrations (threshold value) of 5 μg/m^3.

	All-Cause Deaths	Respiratory-Related Deaths		
Estimated Parameters	**Non-Accidental Death**	**Acute Lower Respiratory Tract Disease (ALRI)**	**Chronic Obstructive Pulmonary Disease (COPD)**	**Trachea, Bronchus, Iung Cancers**
Life expectancy gain (Year) (CI 95%)	4.71 (3.51–5.32)	3.7 (1.24–5.86)	3.82 (1.28–6.06)	0.5 (0.18–0.77)

With regard to life expectancy in relation to mortality from specific respiratory causes, we found that, if the level of exposure were reduced to mean annual concentrations (threshold value) of 5 μg/m^3 for ALRI, a 30-year-old would have gained 3.78 years (Figure A11) and a 25-year-old would have gained 3.82 years for COPD (Figure A12) and 0.5 years for LC (Figure A13) respectively.

4. Discussion

AirQ+ is a software tool for quantifying the burden and impact of air pollution on health by estimating the attributable proportion, the number of individually attributable cases and the number of attributable cases per 100,000 people at risk.

To our knowledge, no study to date has assessed the impact of prolonged exposure to $PM_{2.5}$ on the respiratory health of the general population in the city of Kinshasa. The study by Mbelambela [38] assessed the relationship between short-term exposure to air pollutants, including $PM_{2.5}$, and respiratory health in the context of occupational exposure among public transport workers.

4.1. Mortality Respiratory Specific Cause Among Adults Due to Ambient Air Pollution

Exposure to air pollution can lead to an increased risk of death through two main mechanisms: pathologies of the respiratory system and pathologies of the cardiovascular system. Chronic exposure to air pollution can lead to mortality from various respiratory diseases such as asthma, COPD, LC and ALRI [39,40]. The pathophysiological mechanisms explaining the relationship between 'long-term' exposure to particles and respiratory mortality involve chronic inflammation of lung tissue and oxidative stress, onto which the acute exposure causing death is grafted [39].

The results of our study indicate that, in terms of mortality from specific respiratory causes attributable to ambient air pollution (Table 2), the following proportions can be attributed to these factors: 30.72% of deaths from ALRI, 26.55% of deaths from COPD and 35.36% of deaths from LC.

The 2022 State of Air Quality and Health Impact in Africa report estimated that 50% of deaths in Kinshasa were linked to $PM_{2.5}$ ambient air pollution for respiratory infections, 64% for COPD and 36% for LC (9). These results appear to be considerably higher than those observed in our study, although the pollution level used in the above-mentioned report (35.8 μg/m^3) is lower than that used in our study (43 μg/m^3).

With regard to the mortality rate (per 100,000 inhabitants) attributable to air pollution for specific respiratory causes (Table 2), the rates observed are as follows: the mortality rate for ALRI was 20.22 deaths per 100,000 population, while the rate for COPD was 14.87 deaths per 100,000 population. The LC mortality rate was 3.32 deaths per 100,000 population.

The results obtained in our study are lower than those reported by the WHO, which noted 74 deaths per 100,000 population for ALRI and 25 deaths per 100,000 population for COPD in DR Congo in 2019. However, our results are in line with those of the WHO for LC, for which the WHO reports 2.08 deaths per 100,000 population [41].

However, it is to be expected that our results will be significantly lower than the national average, given that our study focuses on the capital of the Democratic Republic of Congo, where health infrastructures are more concentrated than in the rest of the country. In addition, the region has a greater number of general practitioners and specialists than the rest of the country, and its population benefits from better access to healthcare [42].

4.2. Mortality All-Cause (Natrural) Among Adults Due to Ambient Air Pollution in Kinshasa and Scenarios for Reducing Air Pollution

Air pollution can also lead to cardiorespiratory diseases, which are often difficult to differentiate as purely respiratory or cardiovascular conditions. Cardiovascular disease, including cardio-ischaemic disease, heart failure and cerebrovascular disease, is also associated with increased mortality due to air pollution [39,40]. All-cause mortality, which includes all diseases excluding accidents and suicides, is considered to be a good indicator of the impact of air pollution on cardiorespiratory mortality. Studies have shown that the effect of air pollution on respiratory mortality lags behind its effect on all-cause or cardiovascular mortality [39,40].

The results of this study indicated that 8511 deaths were attributable to air pollution in 2019. However, the report *State of Air Quality and Health Impact in Africa 2022* indicates that, in 2019, 11,000 deaths were associated with $PM_{2.5}$, with an average annual $PM_{2.5}$ level of 35.8 $\mu g/m^3$ [9], whereas the average annual $PM_{2.5}$ level used in our study is 43.5 $\mu g/m^3$.

The difference between the two results can be attributed to the fact that our study focused on a specific age group (over 30), whereas the other study took into account the general population.

The estimated all-cause mortality rate attributable to $PM_{2.5}$ ambient air pollution was 236 per 100,000 people exposed (Table 3). In 2019, the WHO reported a lower rate for adults in the DRC, i.e., 209 deaths per 100,000 people at risk attributable to $PM_{2.5}$ ambient pollution [41]. It should be noted, however, that the WHO results are based on national mortality data, whereas the data presented here have been standardised by age and sex in order to highlight the Kinshasa data.

In addition, the mortality rate observed in our study is higher than the global average, where the mortality rate attributable to $PM_{2.5}$ ambient air pollution is estimated at 85 deaths per 100,000 exposed inhabitants, while the average for sub-Saharan Africa is 155 deaths per 100,000 exposed inhabitants [9].

For prolonged exposure to $PM_{2.5}$ concentrations above the WHO annual guideline of 5 $\mu g/m^3$, our study revealed a proportion attributable to $PM_{2.5}$ ambient air pollution of 25.64% for all-cause mortality. The results of our study attest to those found in other sub-Saharan studies conducted using AirQ+ software, which found an attributable proportion of 18% in 2019 for an annual mean concentration of $PM_{2.5}$ at 34.9 $\mu g/m^3$ in Kampala (Uganda) [11], and 17.7% (WHO interim target 3, i.e., 10 $\mu g/m^3$) for an annual $PM_{2.5}$ concentration at 42.4 $\mu g/m^3$ in Addis Ababa (Ethiopia) [31].

4.3. Scenarios for Reducing Air Pollution

Quantitative assessments of the health impact of air pollution can also be used to determine the health benefits of alternative scenarios for reducing pollution levels in a defined population.

The results of our study show that each 10% reduction in current $PM_{2.5}$ levels prevents 1093 deaths (from all causes) per year in Kinshasa.

Similar results have been reported in other studies conducted in the Northern Caribbean and in Accra, Ghana, indicating that reducing $PM_{2.5}$ concentrations has significant health benefits [12,43].

4.4. Loss of Years of Life

Our study, using AirQ+ software, also made it possible to express health impact assessments in terms of potential loss or potential gain in life expectancy: for example, with regard to the gain in all-cause mortality, if $PM_{2.5}$ concentration did not exceed 5 mg/m^3, a 30-year-old living in Kinshasa would see his life expectancy increase by 4.7 years (3.51 years–5.32 years).

In fact, the results of our study confirm those found by other researchers, who estimated a gain in average life expectancy of 2.9 years in DR Congo and 3.3 years for residents of Kinshasa if the country complied with WHO guidelines (i.e., lowered its average annual concentration from 34.6 $\mu g/m^3$ to 5 mg/m^3) [19]. According to this study, in the Democratic Republic of Congo (DRC), at a particulate pollution level of 34.6 $\mu g/m^3$, i.e., almost 7 times the WHO recommendation, average life expectancy is 2.9 years lower than it would be if the country complied with the WHO guideline. However, loss of life expectancy is 0.5 years for HIV and sexually transmitted infections, 1.2 years for water-borne diseases and 1.6 years for tropical diseases and malaria [19]. While health discourse in sub-Saharan Africa has focused on infectious diseases, such as HIV/AIDS and malaria, studies show that the health effects of exposure to particulate pollution are no less serious.

The air in several large African megacities contains high concentrations of $PM_{2.5}$ (Niger 80.1 $\mu g/m^3$; Nigeria 70.4 $\mu g/m^3$; Cameroon 64.5 $\mu g/m^3$; Mali 60.6 $\mu g/m^3$; Senegal 60.2 $\mu g/m^3$; Chad 59.3 $\mu g/m^3$; Gambia 58.1 $\mu g/m^3$ and Côte d'Ivoire 55.6 $\mu g/m^3$) [9]. Kinshasa, as a large rapidly growing megalopolis, is also affected by air pollution problems due to emerging anthropogenic sources. It has seen a rapid increase in the number of motorcycles, a fleet dominated by older vehicles, poorly managed, and largely unpaved roads, uncontrolled waste incineration and poor-quality fuel. It is also surrounded by the vast forested areas of the Congo Basin, and most of its population use charcoal for cooking [13].

While this study highlights the alarming situation in Kinshasa, other cities in the region face similar challenges. In 2019, air pollution contributed to 68,500 deaths in Nigeria, 16,600 in Sudan, 12,500 in Ghana, and 10,200 in Cameroon [9]. However, despite the reported increases in pollution in sub-Saharan cities, the lack of regular monitoring for most countries and, above all, the scarcity of studies assessing the effect of air pollution on the various health indicators is holding back the development of effective policies aimed at improving air quality in the region.

4.5. Strengths and Limits

This study has several strengths. This work is the first study to assess the impact of fine particle pollution on the respiratory health of adults living in Kinshasa using AirQ+ software. We used $PM_{2.5}$ data collected continuously in real time for a relatively long period and in residential areas, using low-cost sensors calibrated to a reference method "BAM 1020" with a correlation coefficient of 0.88. This correlation is also improved by the multiple linear regression model and the random forest approach (r = 0.96).

Unfortunately, the absence of local health data for our parameters of interest and the use of health data from international databases are the major limitations of our study.

Thus, our public health policy must devote resources to collecting vital statistics, particularly for mortality, and improve the collection of health data for emergency admissions and hospitalizations, especially for respiratory and cardiovascular diseases.

5. Conclusions

The results of this study highlight the major respiratory public health problem resulting from air pollution by fine particles ($PM_{2.5}$) in Kinshasa, contributing to a considerable number of deaths in this megalopolis. Among pollutants, $PM_{2.5}$ has significant adverse effects on the human respiratory system. In this study, the estimated relationship between prolonged exposure to $PM_{2.5}$ and adult respiratory deaths in Kinshasa was observed using AirQ+ software.

This AirQ+ tool has also made it possible to observe the negative effect of ambient $PM_{2.5}$ on total mortality (all-cause) of adults in Kinshasa. Finally, the AirQ+ data revealed the number of deaths that could be avoided if air quality were improved. However, further studies are urgently needed to understand the impact of ambient air pollution on population health in the sub-Saharan region, for example, conducting longitudinal epidemiological studies assessing the effects of ambient air pollution in the region through individual and demographic indicators, such as cause-specific mortality, hospitalizations and hospital visits. For decision-makers, this study provides factual evidence to support the

development of public policies aimed at improving air quality at local and regional levels, such as developing national standards, promoting the transition to cleaner cooking fuels, introducing more buses for public transport and banning all obsolete vehicles from the roads, investing in safe walking and cycling infrastructures, enacting laws and regulations against polluting industrial processes, setting up the best waste management systems, etc.

Author Contributions: Conceptualization, M.N.K., D.M.W., D.M.M., F.B., P.K.I., T.T.T., B.K.O., G.K.M. and J.M.K.N.; Methodology: M.N.K., D.M.W., D.M.M., F.B., P.K.I., T.T.T., B.K.O., G.K.M. and J.M.K.N.; Investigation: M.N.K., D.M.W. and P.K.I.; Software, M.N.K. and D.M.M.; Formal analysis: M.N.K., D.M.W., D.M.M., F.B., P.K.I., T.T.T., B.K.O., G.K.M. and J.M.K.N.; Data curation: M.N.K., D.M.W., P.K.I. and D.M.M.; Resources: M.N.K., D.M.W. and D.M.M.; Writing—Preparation of the original version, M.N.K. and J.M.K.N.; Writing—Revision and editing, M.N.K., J.M.K.N., G.K.M., D.M.W., T.T.T., F.B., D.M.M. and B.K.O.; Validation: M.N.K., J.M.K.N., G.K.M., D.M.W. and F.B.; Supervision, J.M.K.N., G.K.M., F.B. and T.T.T.; Project administration: G.K.M. and J.M.K.N. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data on $PM_{2.5}$ concentrations were collected in real time from hourly concentrations of the ambient air pollutant measured by a network of Purple Air PA-II-SD sensors, considered as low-cost sensors, between March 2018 and August 2020. These data are publicly available at: https://github.com/cmm2349/Kinshasa-AQ/tree/main/Corrected%20Data, (accessed on 12 April 2023). The number of deaths observed in the city of Kinshasa was obtained by multiplying the national mortality rate provided by IHME by the population of the city of Kinshasa, stratified by age. These data are publicly available from https://vizhub.healthdata.org/gbd-results/, (accessed on 12 April 2023).

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

Appendix A

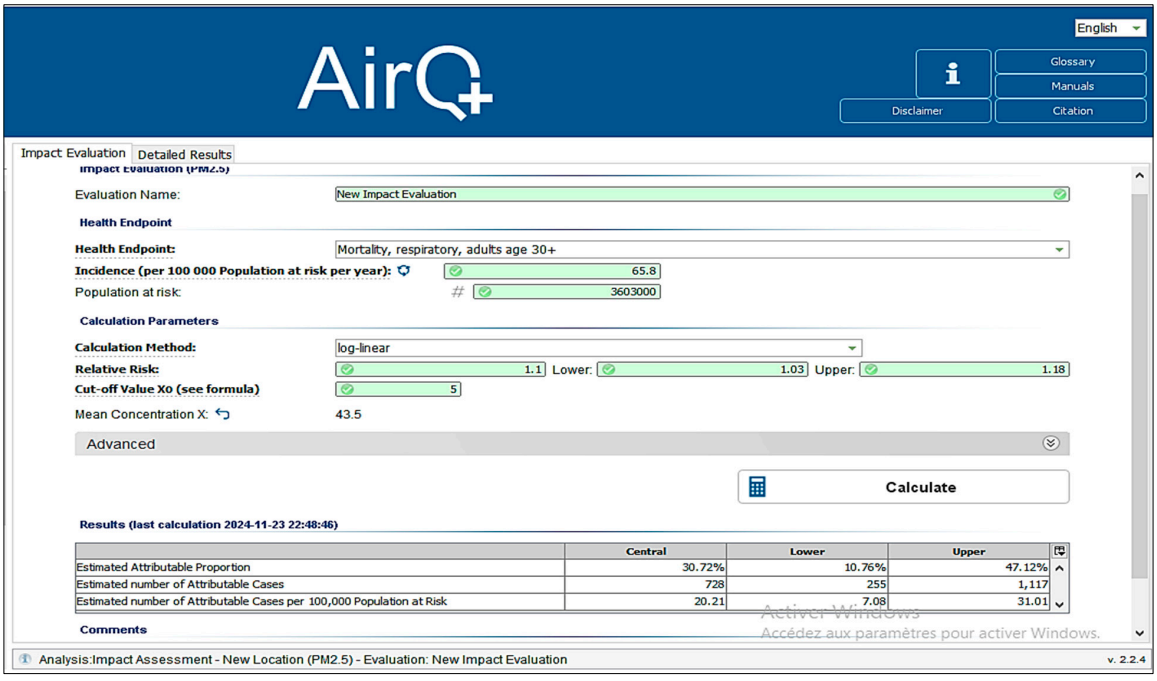


Figure A1. Analysis properties window in AirQ+: long-term $PM_{2.5}$ ambient air pollution and respiratory mortality due to acute lower respiratory infections (ALRI) in adults aged 30 and over.

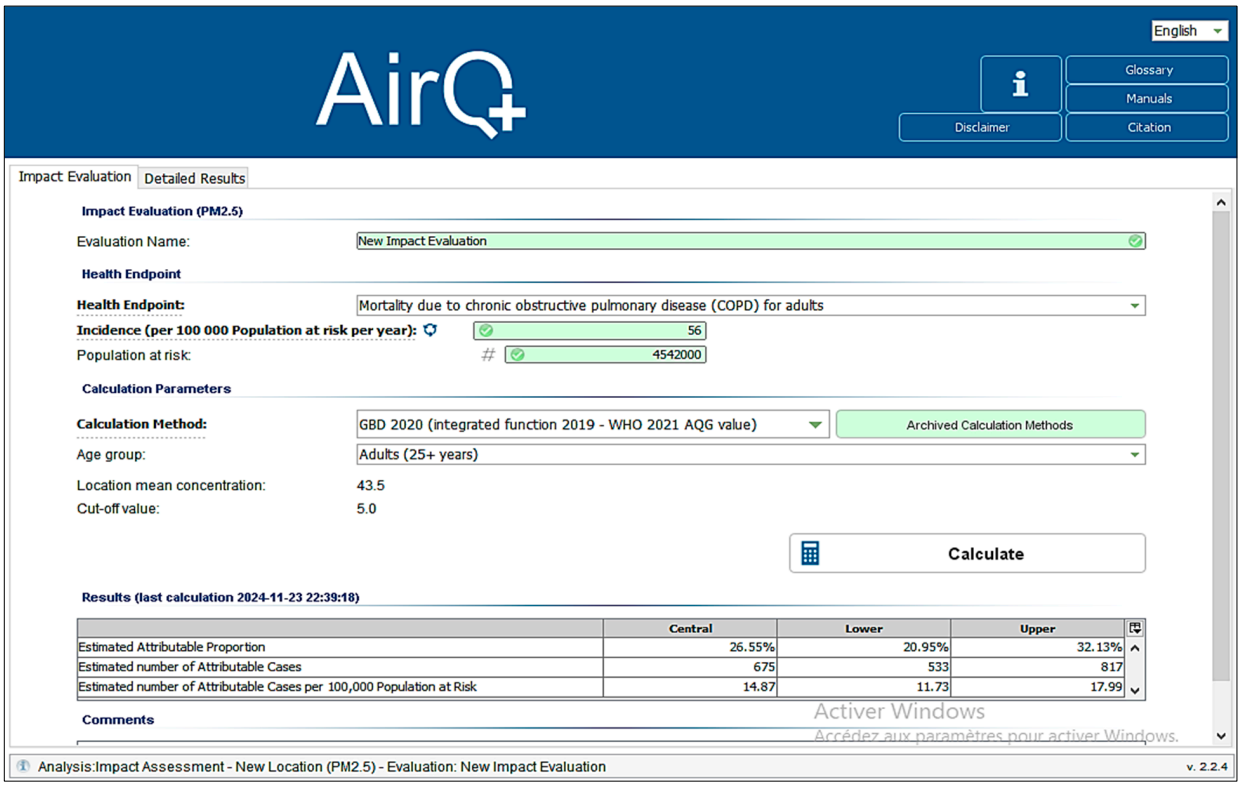


Figure A2. Analysis properties window in AirQ+: long-term $PM_{2.5}$ ambient air pollution and COPD mortality in adults aged 25 and over.

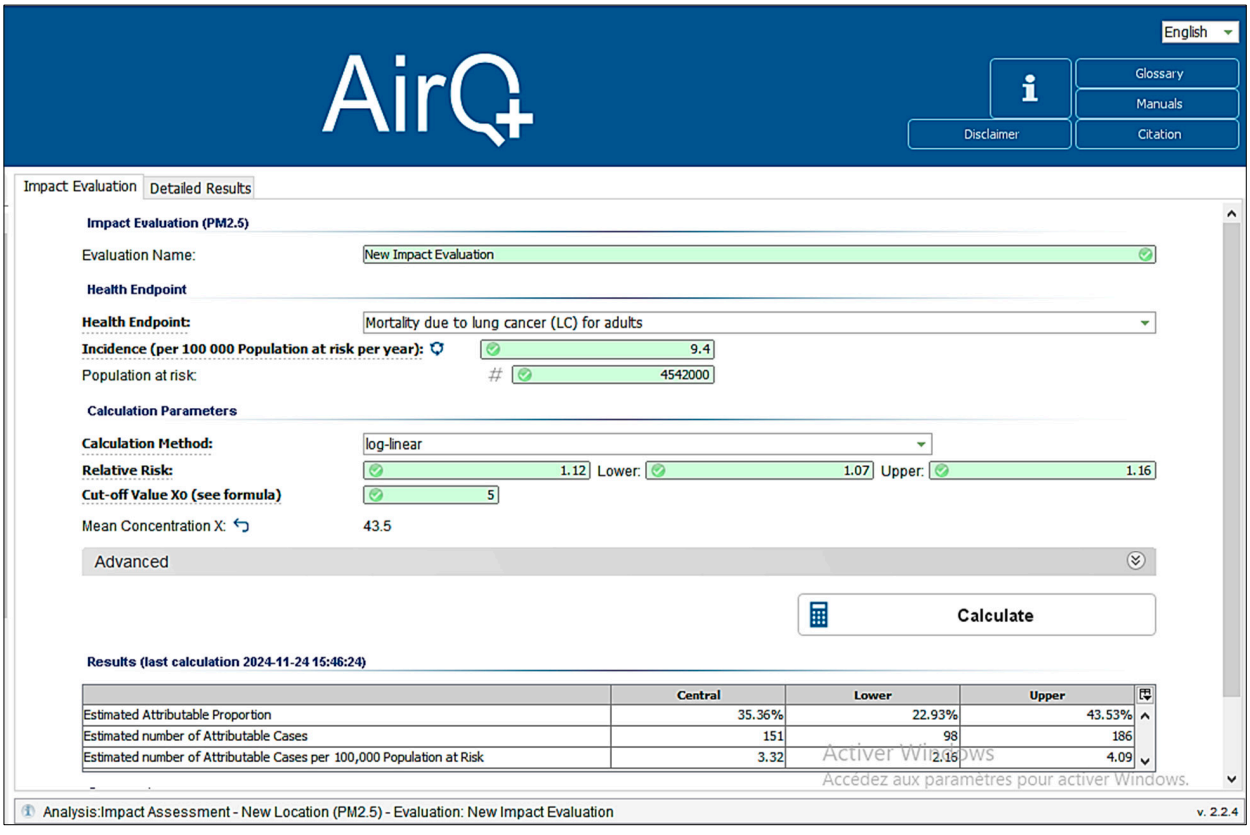


Figure A3. Analysis properties window in AirQ+: long-term $PM_{2.5}$ ambient air pollution and lung cancer mortality in adults aged 25 and over.

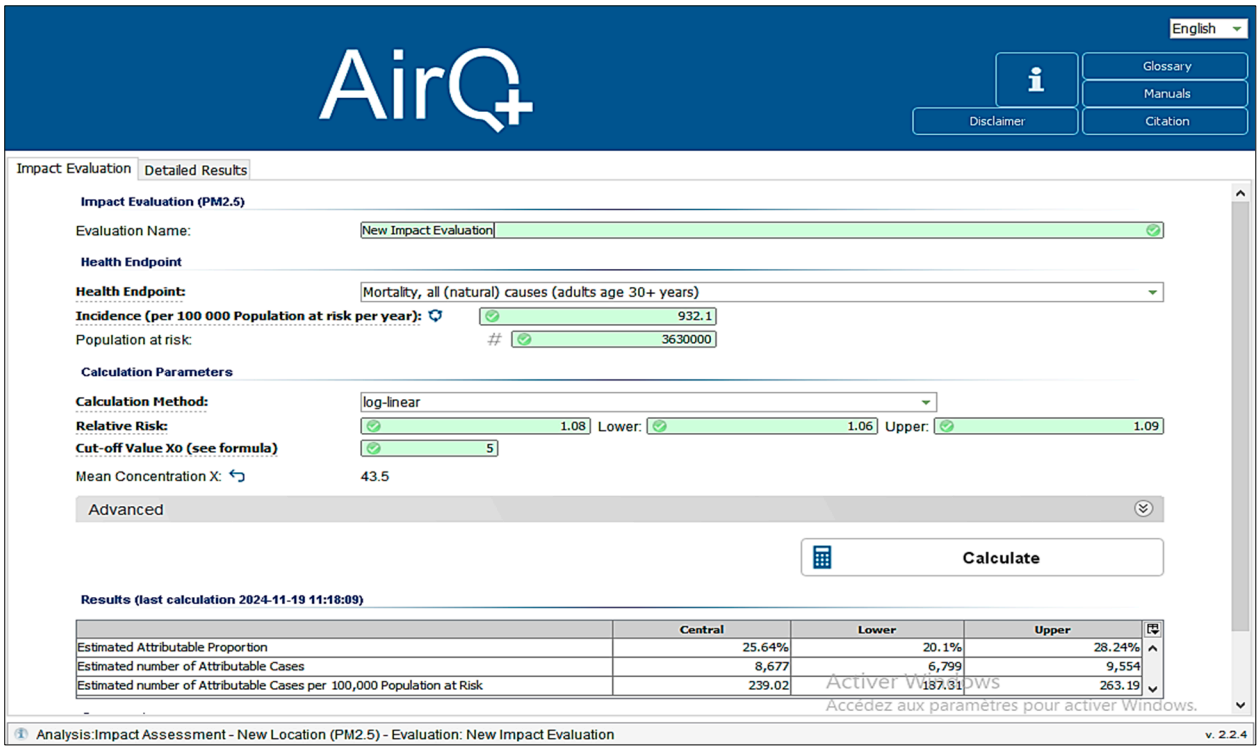


Figure A4. Analysis properties window in AirQ+: long-term $PM_{2.5}$ ambient air pollution and all-cause mortality in adults aged 30 and over at the 5 μg/m3 threshold (AQG: Air quality guidelines).

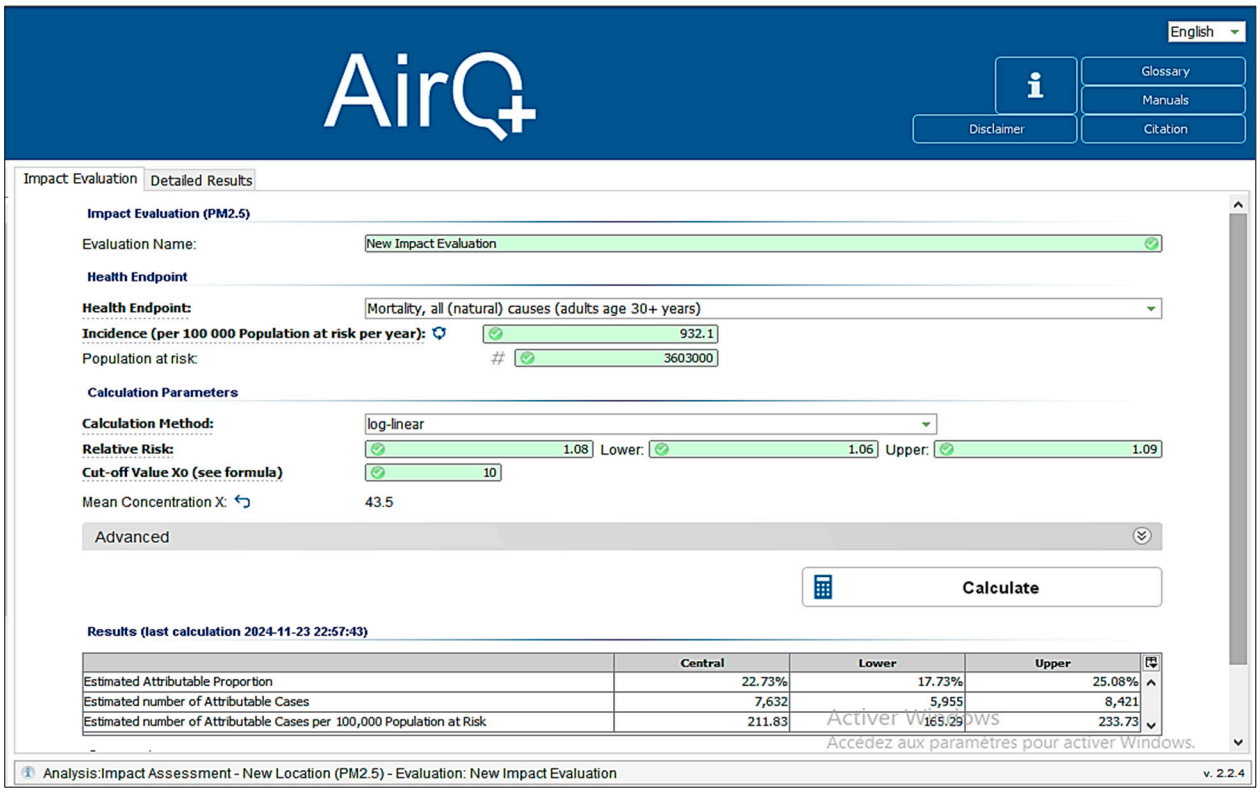


Figure A5. Analysis properties window in AirQ+: long-term ambient air pollution by $PM_{2.5}$ and all-cause mortality of adults aged 30 and over at the intermediate threshold of 10 $\mu g/m^3$ (IT-4: Interim target-4).

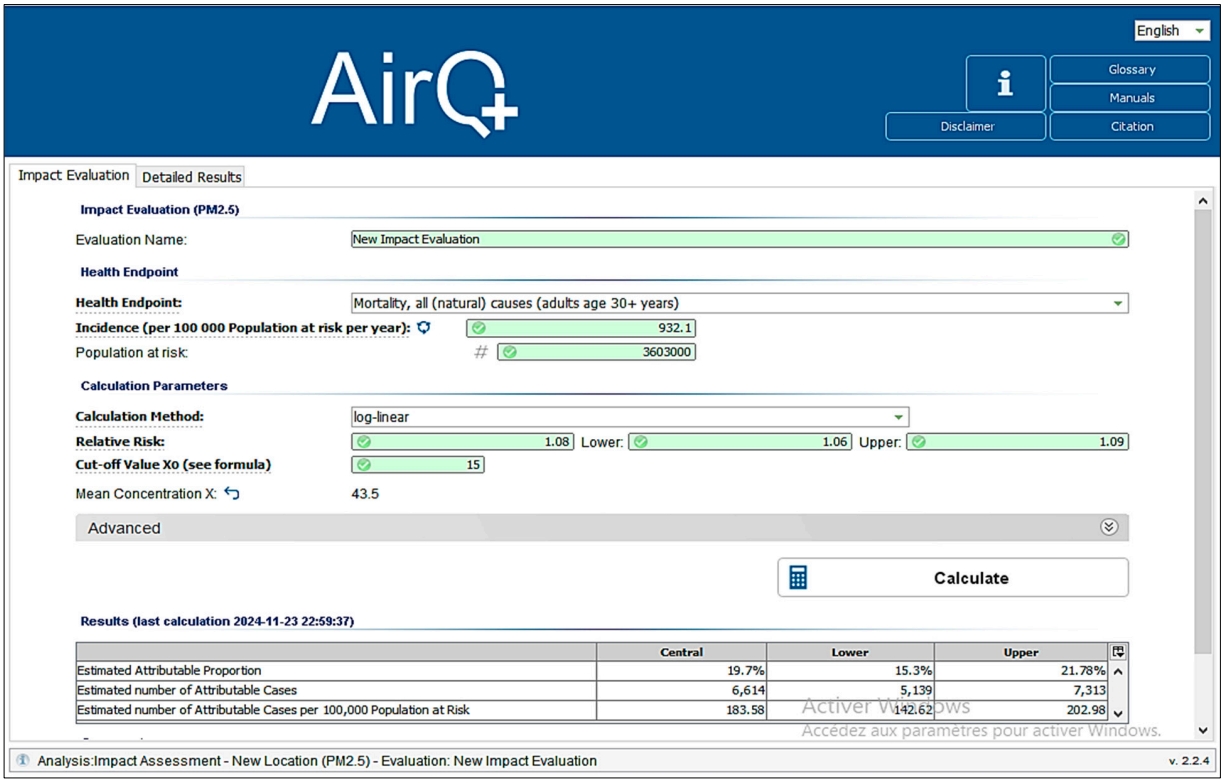


Figure A6. Analysis properties window in AirQ+: long-term $PM_{2.5}$ ambient air pollution and all-cause mortality in adults aged 30 and over at the intermediate threshold of 15 $\mu g/m^3$ (IT-3: Interim target-3).

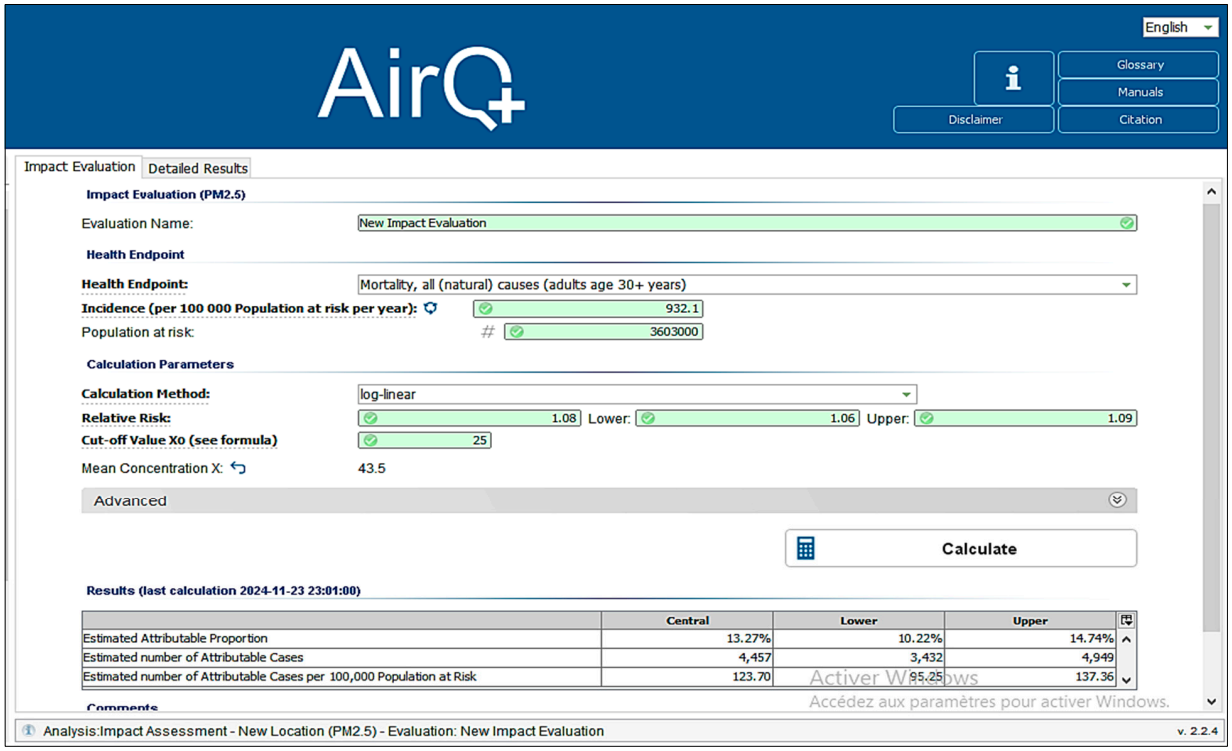


Figure A7. Analysis properties window in AirQ+: long-term $PM_{2.5}$ ambient air pollution and all-cause mortality in adults aged 30 and over at the intermediate threshold of 25 $\mu g/m^3$ (IT-2: Interim target-2).

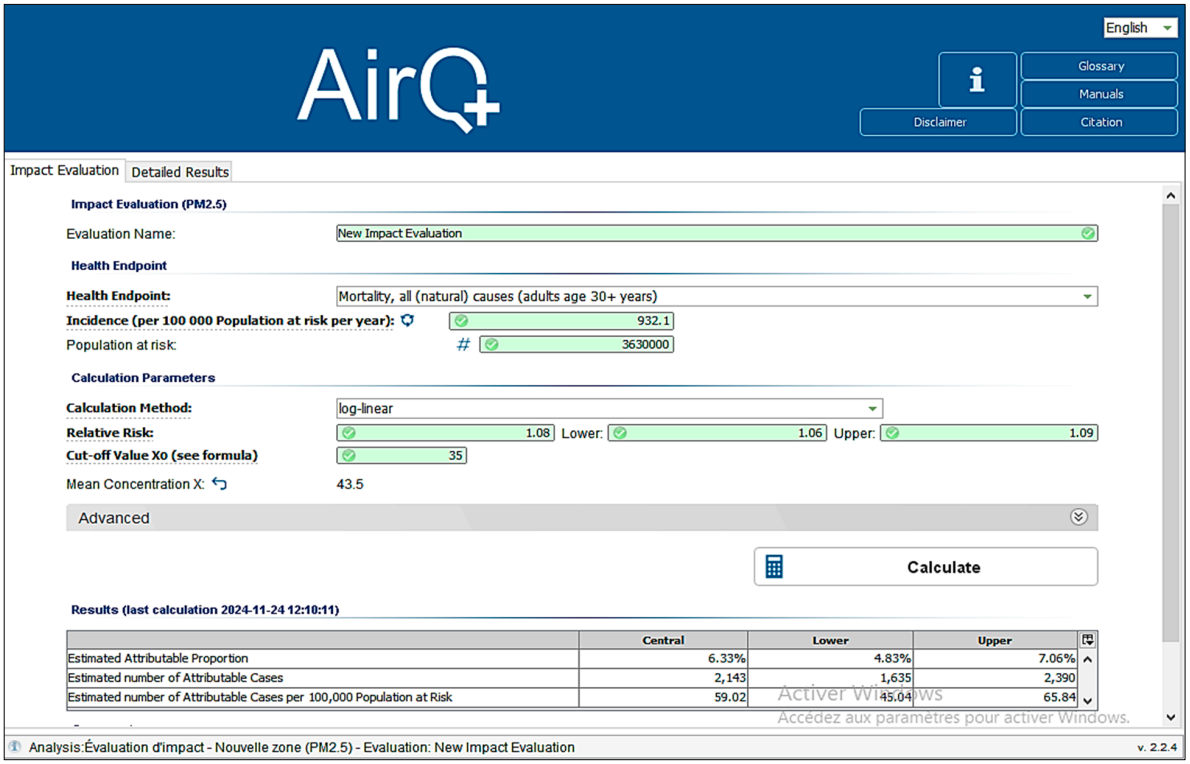


Figure A8. Analysis properties window in AirQ+: long-term $PM_{2.5}$ ambient air pollution and all-cause mortality in adults aged 30 and over at the intermediate threshold of 35 $\mu g/m^3$ (IT-1: Interim target-1).

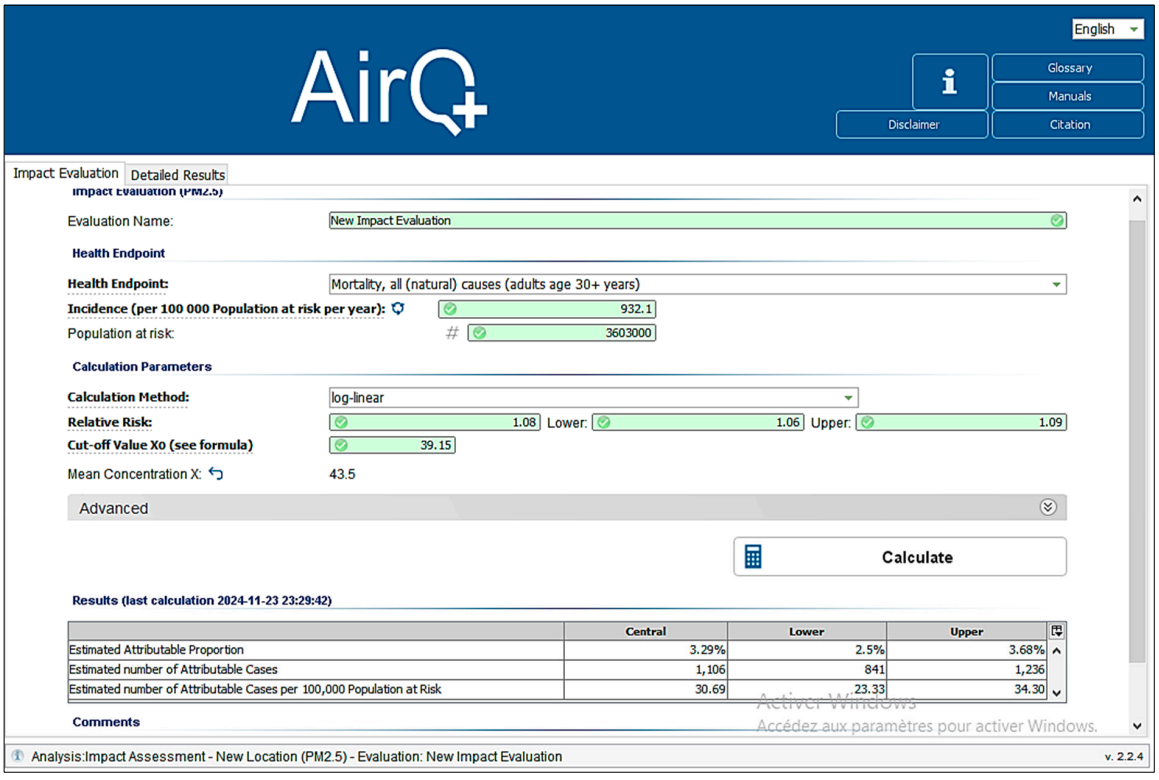


Figure A9. Analysis properties window in AirQ+: long-term $PM_{2.5}$ ambient air pollution and all-cause mortality in adults aged 30 and over for a 10% reduction in PM2.5 levels ($PM_{2.5.}$ = 39.15 $\mu g/m^3$).

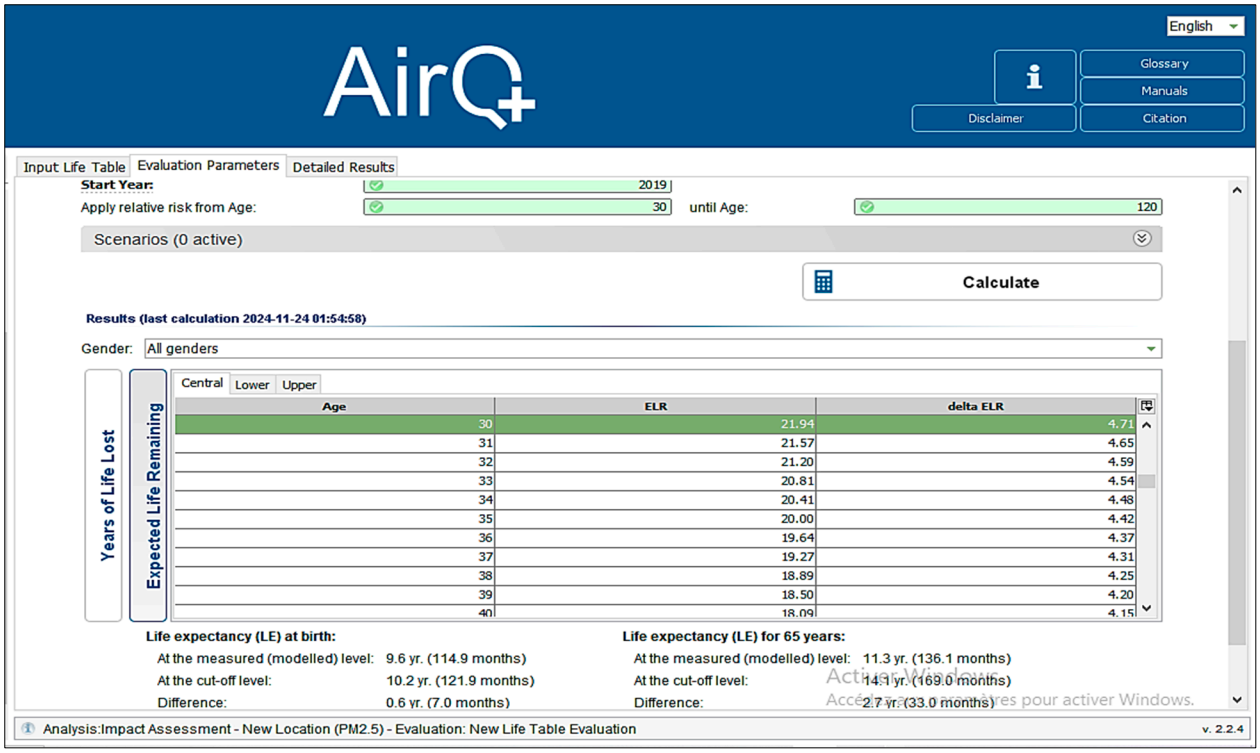


Figure A10. Life table results for expected remaining life due to all-cause mortality in the Assessment Parameters window.

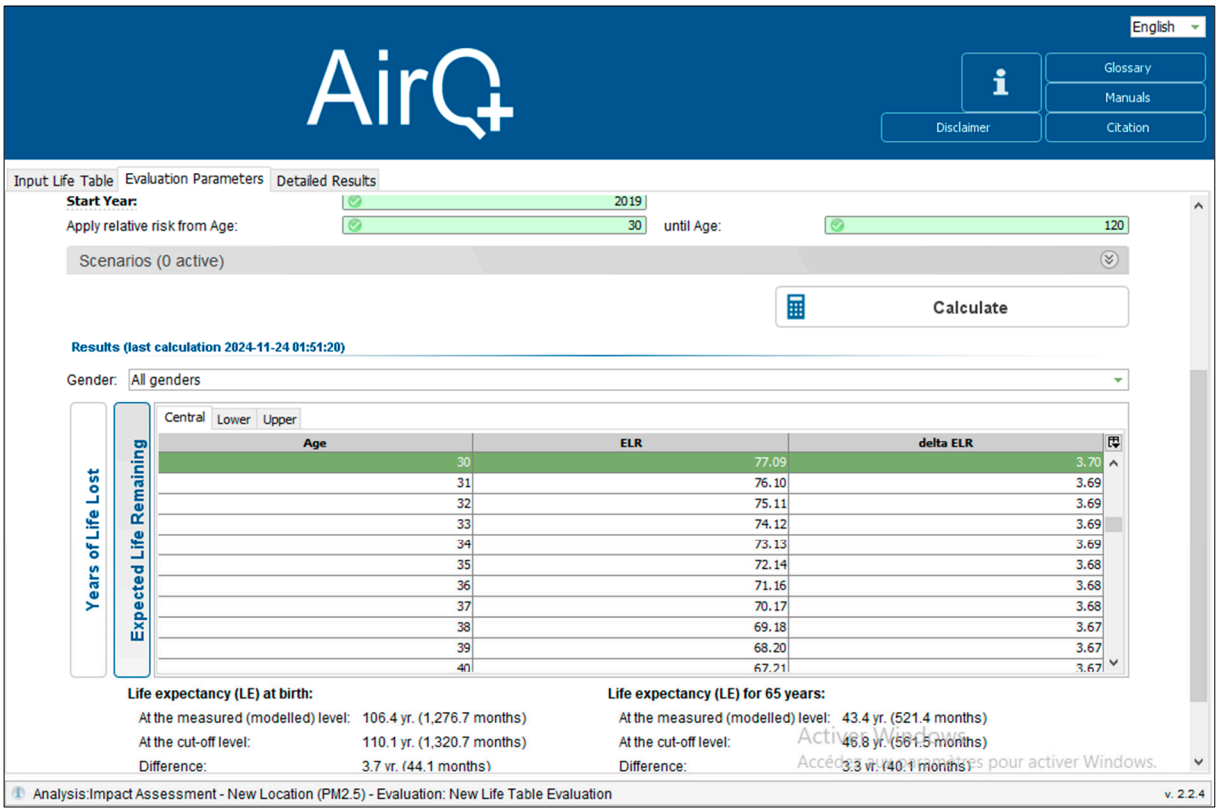


Figure A11. Life table results for expected remaining life due to acute lower respiratory tract infections (ALRI) in the Assessment Parameters window.

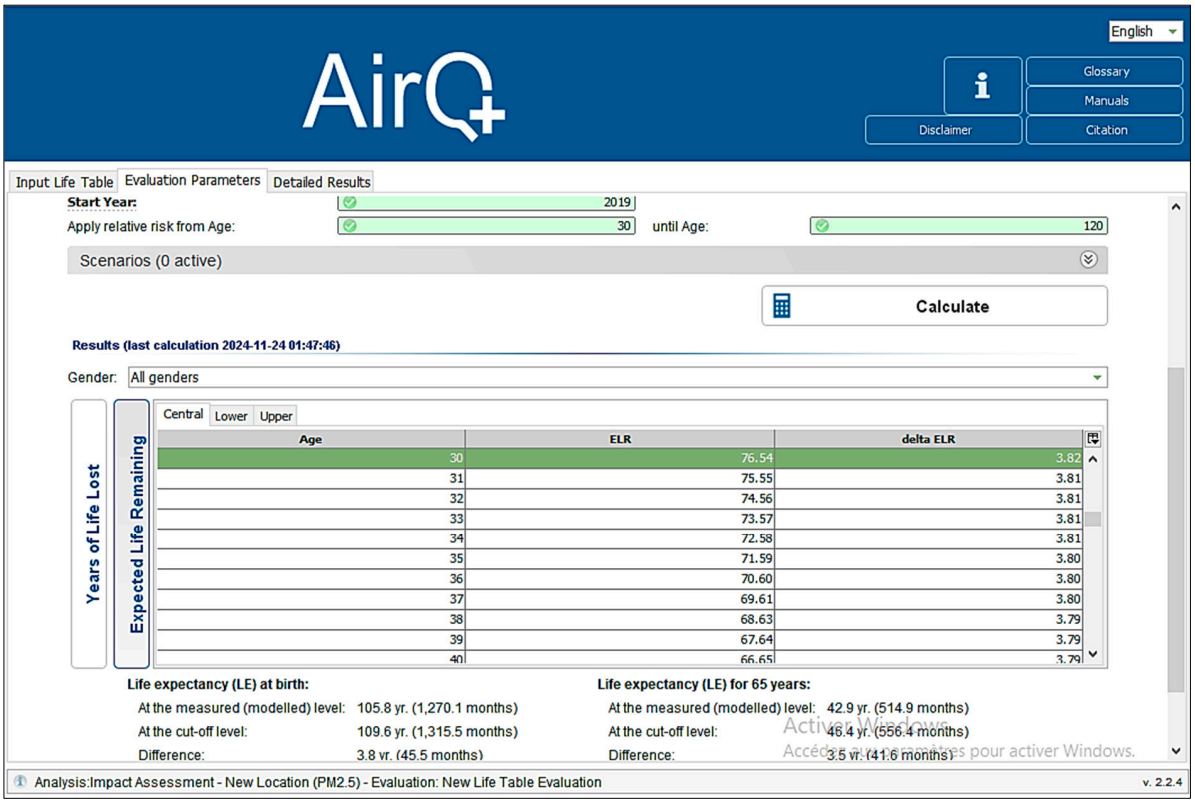


Figure A12. Life table results for expected remaining life due to Chronic Obstructive Pulmonary Disease (COPD) in the Assessment Parameters window.

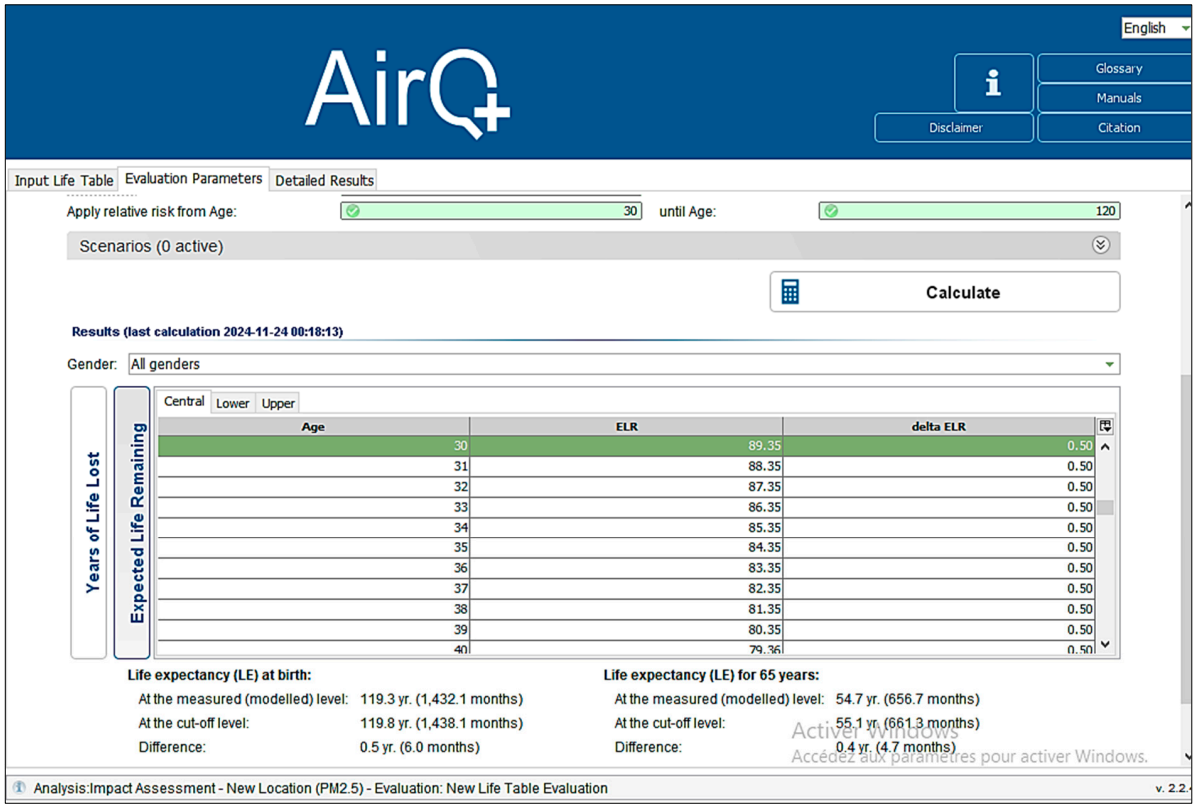


Figure A13. Life table results for expected remaining life due to lung cancer in the Assessment Parameters window.

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