Chapter 2 Short-term association between morbidity and daily concentrations of O_3 and PM_{10} in the Bajío region: A time series study

Capítulo 2 Asociación a corto plazo entre la morbilidad y las concentraciones diarias de O_3 y PM_{10} en la región del Bajío: Un estudio de series de tiempo

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Abstract

Short-term effects of air pollution on the health of residents in the region of Bajío in Guanajuato, Mexico were assessed from 2012-2015 using a time-series approach. Irapuato showed the highest number of exceedances (884) to the maximum allowable limit established by NOM-020-SSA1-2021, followed by Silao (477) and Salamanca (53), respectively. With respect to PM_{10}, all municipalities showed significant exceedances to the maximum allowable limit established by NOM-025-SSA1-2021; Celaya with 518, León with 281 and Salamanca with 210 exceedances, respectively. Comparing both pollutants, we concluded that the pollution due to PM_{10} is a hotspot in the Bajío region in comparison with pollution due to O_3. The association between PM_{10} and morbidity was positive and significant, since when PM_{10} concentrations increased, the risk values also increased: Irapuato with 0.32%, Silao with 0.24%, Celaya with 0.20% and León with 0.02%. In the case of ozone, correlations found were positive but not significant; therefore, we concluded that there was not a significant risk of morbidity by ozone exposure. Population between 0 and 59 years was identified as the most vulnerable age sub-group, suggesting that, activities of people played an important role in the exposure to these pollutants, since, people in this group comprises workers and students of all ages, who develop their activities outside home, just in the hours in which O_3 and PM_{10} reach their peak levels as a result of industrial activity and mobile sources.

Morbidity, association, exposure, contaminants, vulnerable

Resumen

Los efectos a corto plazo de la contaminación del aire en la salud de los residentes de la región del Bajío en Guanajuato, México, se evaluaron entre 2012 y 2015 mediante un enfoque de series de tiempo. Irapuato presentó el mayor número de excedencias (884) al límite máximo permisible establecido por la NOM-020-SSA1-2021, seguido de Silao (477) y Salamanca (53), respectivamente. Con respecto al PM_{10}, todos los municipios presentaron excedencias significativas al límite máximo permisible establecido por la NOM-025-SSA1-2021; Celaya con 518, León con 281 y Salamanca con 210 excedencias, respectivamente. Comparando ambos contaminantes, concluimos que la contaminación por PM_{10} es un punto caliente en la región del Bajío en comparación con la contaminación por O_3. La asociación entre PM_{10} y morbilidad fue positiva y significativa, ya que al aumentar las concentraciones de PM_{10} también aumentaron los valores de riesgo: Irapuato con 0.32%, Silao con 0.24%, Celaya con 0.20% y León con 0.02%. En el caso del ozono, las correlaciones encontradas fueron positivas, pero no significativas; por lo tanto, concluimos que no hubo un riesgo significativo de morbilidad por exposición al ozono. Se identificó a la población de 0 a 59 años como el subgrupo etario más vulnerable, sugiriendo que las actividades de las personas juegan un papel importante en la exposición a estos contaminantes, ya que en este grupo se encuentran trabajadores y estudiantes de todas las edades, quienes desarrollan sus actividades fuera de casa, justo en las horas en que el O_3 y el PM_{10} alcanzan sus niveles máximos como consecuencia de la actividad industrial y fuentes móviles.

Morbilidad, asociación, exposición, contaminantes, vulnerable

2.1 Introduction

Air pollution is one of the main causes of death and disease worldwide. It is widely supported by scientific evidence that air pollution is the major global public health risk factor (Bodor et al. 2022). According to WHO statistics, more than 80% of urban residents in Metropolitan Areas are exposed to air quality levels which exceeds the established permissible maximum limits in the regulations. The increase of atmospheric pollution caused by the combustion of fossil fuels, transport and industry, is responsible for the increasing morbidity and mortality, especially by respiratory and circulatory diseases. Chen et al. (2022) reports that short-term exposure to air pollutants is associated with elevated risk for myocardial infarction, stroke, heart failure and arrhythmic. Bergmann et al. (2020) reported that the exposure to high concentrations of air pollutants such as PM_{10} and O_3 is associated with both, mortality and morbidity diseases.

Due to differences in size, chemical composition and concentration, some atmospheric particles are very dangerous to human body. Particulate matter penetrates deep in pulmonary system, causing adverse effects on human health, particularly on respiratory and circulatory systems (Bagherian et al. 2016). The increased PM_{10} and $PM_{2.5}$ concentrations are associated with an increased morbidity in the European Union, reducing the average life span by 8.6 months (Bodor et al. 2022).

In addition to effects of PM_{10}, there is an increasing evidence that ozone may play a significant role in generating adverse health effects. Atmospheric ozone levels have become a growing public health concern, since O_3 is a powerful oxidant. Epidemiological studies have reported a positive and significant correlation between ozone levels and cardiovascular mortality and morbidity in different regions of the world (Lim et al. 2019; Raza et al. 2019; Yang et al. 2018; Yin et al. 2017). Biological mechanisms involved in O_3-induced cardiovascular diseases have been studied. Besides the impact on systemic inflammation and oxidative stress, O_3 exposure also have effects on lipid metabolism (Li et al. 2019).

Consequently, air pollution constitutes a significant threat to the population, particularly to population sub-groups, which can be considered as vulnerable such as children, elderly, asthmatic people or people with pre-existing conditions. Children are susceptible to poor air quality since their lungs are still developing (Ibrahim et al. 2021). Studies about exposure to air pollutants and health effects on children are well documented (Ab Manan et al. 2018; Cheng et al. 2021; Horne et al. 2018; Mazenq et al. 2017). On the other hand, older adults have increased their vulnerability to cardiovascular diseases. Therefore, it is important to get supporting evidence to develop pollution control policies in order to protect elderly.

In spite of, there is enough evidence supporting relationship between air pollution and morbidity (Carugno et al. 2021); studies about sex differences are scarce. Khan et al. (2019) found a higher risk of circulatory effects for women, approximately twice that for men, in response to short-term exposure to O_3 and PM_{10}.

Regarding to climate and seasonal patterns, some authors report that the synergy of heat or cold and air pollution may affect health diseases more severely than the single factor of heat or cold, or air pollution itself, suggesting that the effects on health associated to some pollutants could show a seasonal behavior (Wang et al. 2023). Mannucci et al. (2015) concluded that the combined exposure to heat and air pollution affect both, physical and mental health and recent studies suggest that short- and long-term exposure to PM_{10} and $PM_{2.5}$ may be responsible for onset or worsening of depressive symptoms (Buoli et al. 2018).

Evidence of the effects of the short-term exposure to air pollutants are conclusive for respiratory and circulatory mortality, and for hospital admissions (morbidity). Because air pollution imposes a significant number of mortalities and morbidities on society, it is very important to assess the extent of its effects on health (Calle-Martínez et al. 2023; Leili et al. 2023; Li et al. 2023; Pu et al. 2023; Wagner et al. 2023; Naghan et al. 2022). In the last years, many studies have applied time-series methods to evaluate these associations. In this way, Time-series studies are useful to provide valuable information that can be used by decision makers and health professionals to establish new air quality standards or regulations, or to change the current permissible maximum limits.

In this regard, some epidemiological studies have been carried out in Mexico to assess the association between atmospheric pollutants and morbidity; however, excepting Mexico City, the available data and information are not enough to get a diagnosis about the prevailing situation in the remaining metropolitan areas of the country. Therefore, the aim of this study was to assess the association between short-term exposure to PM_{10} and O_3 and morbidity during 2012-2015 in 5 Metropolitan Areas of the Bajío region in Guanajuato, Mexico, considering age sub-groups (0-59 years and >60 years), gender, all causes and specific cause (respiratory and circulatory diseases), seasonal trends in air quality data and meteorological variables. In addition, in this study, we assessed the effects derived from a hypothetical scenario in which daily mean concentration of atmospheric pollutants increases in 10%, in order to estimate the resulting association in a future scenario. Results obtained here, allowed us to quantify the number of exceedances to regulation for each pollutant, to identify in which region of the Bajío these exceedances are higher, and to identify in which areas of this region, relative risk indexes were higher, as well as the age sub –group more vulnerable.

2.2 Methodology

2.2.1 Study Area

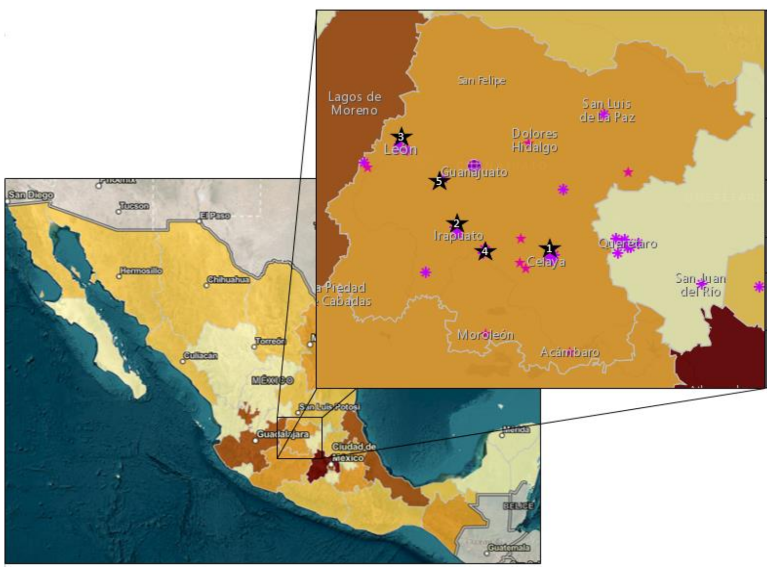
For this study, the municipalities of León, Silao, Irapuato, Celaya and Salamanca in the state of Guanajuato, Mexico were considered. These five municipalities constitute the Bajío corridor, which comprise a total of 2, 652, 893 habitants.

León is the most populated city in the state of Guanajuato, and the fourth-most populated city in the country, with 1,578,626 habitants. León is part of the macro region known as Bajío, located in the Central Mexican Plateau. The main economic activity in León is shoe and leather industry, but in the last decade, automotive industry has been developed, with several industrial parks in this sector.

In the case of Silao, this municipality is part of the Metropolitan Area of León with a total of 83, 352 habitants, and their main productive activities are agriculture and automotive. Salamanca has a population of 160, 682 habitants, being a region very industrialized, the main industries are energy, petrochemical, automotive, food and electronic. The municipality of Celaya is an important crossroad of trade toward the Northern and Western side of the country. Celaya has a total of 378, 143 habitants, and the main productive activities are agriculture, livestock, energy, electric, pharmaceutic, paper, chemical, steel and processed food. Finally, Irapuato is the second biggest municipality in Guanajuato, with 452, 090 habitants, being their main economic activities textile industry, automotive industry, and agriculture for exportation.

Locations of these municipalities are shown in Figure 2.1.

Figure 2.1 Location of municipalities of the Bajío region considered in this study



Municipalities	Coordinates	
	Latitude	Longitude
1. Celaya	20.52	100.82
2. Irapuato	21.12	101.6
3. León	21.10	101.64
4.Salamanca	20.58	101.2
5. Silao	20.95	101.43

Source: Own elaboration

The Bajío region has a humid subtropical climate (C_{wa} in the Köppen classification) with rains occurring along the summer. However, its climate closely borders on a semi-arid climate, with an average annual temperature of 19.9 °C, where the warmest month is May (with a maximum average of 31.7°C) and the coolest month is January (with a minimum average temperature of 7.7 °C).

2.2.2 Air quality and meteorological data

Air quality (For O_3 and PM_{10}) and meteorological data (Temperature and Relative Humidity) measured by from automatic monitoring stations in Metropolitan Areas of León, Celaya, Salamanca, Silao and Irapuato were obtained from SINAICA (National System of Air Quality Information) during 2012-2015. Methods used to measure criteria air pollutants concentrations are standardized methods. In the case of O_3, the principle of operation of the analyzer Photometry UV; whereas in the case of PM_{10}, is Gravimetric.

2.2.3 Applicable regulations

Reference values to protect public health are established by Mexican Federal Government who is the responsible to monitor compliance, the reference values are published in the Mexican Official Regulations (NOM) being obligatory at a national scale. Applicable NOM´s for each criteria air pollutant are presented in Table 2.1.

Table 2.1 Applicable NOM´s for each criteria air pollutant

Criteria Air Pollutant	Exposure time used for the assessment	Kind of Exposure	Allowed frequency	Maximum permissible limit value	Reference (NOM)
Ozone (O_3)	Hourly data (1 h)	Acute	It is not allowed	0.090 ppm	NOM-020-SSA1-2021
	Mobil average of 8 h		It is not allowed	0.065 ppm	
	Annual		Once a year	0.021 ppm	
PM_{10}	24 h	Acute	It is not allowed	70 µg/m^3	NOM-025-SSA1-2021
	Annual	Chronic	--	36 µg/m^3	
	24 h			0.040 ppm	

Source: NOM-020-SSA1-2021 for Ozone (O_3) and NOM-025-SSA1-2021 for PM_{10}

From air quality data and meteorological data set, time series for each pollutant and meteorological variable were integrated considering both, daily mean and daily maximum concentrations. From the reference values established for each criteria air pollutant, air quality was assessed and the exceedances were estimated. Missing data and the continuity in the records were assessed, in some cases; it was required to complete the databases for a given station. Therefore, it was necessary to establish some criteria to include or not data in the databases: First, to decide which stations would be included (only values from monitoring stations showing a valid data percentage >75% were considered). Second, if one or more stations showed missing data, to define how missing data would be imputated (to complete the database in which, despite complying with valid data percentage, missing data were isolated or intermittent, they were completed by using NIPALS approach).

2.2.4 Epidemiological data

Although National System of Air Quality Information (SINAICA) integrates air quality information from several cities in Mexico; in the case of health data, there is no a system which integrates morbidity data. However, it was possible to obtain this information (hospital admissions for Bajío region) during the study period from SINAIS (National System of Health Information). Databases in a monthly and annual base was requested to the corresponding authorities in the health sector for purposes of this study. Morbidity database from SINAIS is based in the international classification of diseases established by World Health Organization (WHO) revision CIE-10/2 considering respiratory system diseases (J00-J99) and circulatory system diseases (I00-I99). Morbidity data were assessed by hospital admission cause (all causes, respiratory and circulatory), gender (male and female), and age group (<1 year, 1-4 years, 5-59 years, 60-74 years and >75 years).

2.2.5 Time series analysis design

Time series study developed in the present research work involved the following stages:

- Assessment of temporal variations in morbidity rate in a monthly basis for all population, by age, by gender and by specific cause and by municipality during the study period (from January 1, 2012 to December 31, 2015).

- Assessment of temporal variations of O_3 and PM_{10} in a monthly basis by municipality for the study period (from January 1, 2012 to December 31, 2015).

- Assessment of air quality: Analysis of exceedances to reference values established as maximum permissible limits in NOM-020-SSA1-2021 for O_3, and in NOM-025-SSA1-2021 for PM_{10}.

- Estimation of the magnitude of the association between morbidity by all causes and by specific cause, and atmospheric pollution concentrations by municipality for each population sub-group. In this stage, meteorological variables were included (temperature and relative humidity).

a) Study subject: Hospital admissions occurring in the residents of the Bajío region during the period from January 1, 2012 to December 31, 2015.

b) Variables:

    - Response variables: Number of monthly hospital admission during the study period by all, respiratory and circulatory causes.

    - Explanatory variables: Criteria air pollutants (quantitative explanatory variable), monthly average concentration for O_3 and PM_{10} during the study period.

    - Meteorological variables (quantitative explanatory variable), monthly average values for maximum temperature, minimum temperature and relative humidity during the study period.

    - Gender (qualitative explanatory variable), number of hospital admissions by gender.

    - Age (qualitative explanatory variable), number of hospital admissions by age group.

    - Control variables (seasonality): seasons were classified as cold months (from November to February) and warm months (from May to August).

    - Confusion variables: Temperature and Relative Humidity.

Since the hospital admission did not occur at the same time in which the study subject is exposed to a given air pollutant concentration, is necessary to consider a certain delay time. Time delay was estimated from cross correlations of the series (mortality vs temperature, and mortality vs relative humidity) by using Infostat software v. 2008 (Di Rienzo et al. 2008), and selecting time delays according to their significance level.

In addition, it was required to carry out a pre-treatment of the time series, in this case, epidemiological data series were smoothed, by applying a non-parametric method (LOWESS: LOcally WEighted regression Scatterplot Smoothing); whereas in the case of air quality data, series were smoothed by using ARIMA method (Autoregressive Integrate Moving Average). The smooth procedure of time series was carried out by using statistical software XLSTAT v. 2017 (https://www.xlstat.com/es/).

2.2.6 Estimation of the association between morbidity by all causes and by specific cause, and criteria air pollutants concentrations for each population sub-group

Once, both time series, epidemiological and air quality were treated and smoothed; a Poisson model was applied to reduce Pearson residuals. However, it was necessary to apply a multivariate analysis to decide which variables will be added to the base model.

A principal component analysis (ACP) and a linear regression analysis (RLM) by using XLSTAT v. 2017 were applied to data series for morbidity; criteria air pollutants and meteorological variables. From ACP, the principal components contributing to the major percentage of data variability were obtained, considering those showing the major load of factor and a major statistical significance. A first approach was carried out with the Poisson basal model including those variables which contributed with significant information to explain the variability of dependent variable (daily morbidity).

Relative Risk Index (RRI) of daily morbidity associated to atmospheric pollution

To apply the Poisson model, the methodology was the same than APHEA (Katsouyanni, 1996) and EMECAN (Ballester et al., 2002) projects. This methodology is described in detail by Cerón-Bretón et al. (2018) and Ídem et al. (2021). Once, basal model has been established, the model is extended for each pollutant and its time delays. The construction of the auto-regressive Poisson model let to determine if the response variable depends or not on other variables. This effect is assessed by beta coefficient of each independent variable in the Poisson regression model. The general model to relate the response variable with different independent variables is the following:

$$\ln(E_y) = \beta_0 + \sum_{i=1}^{n} \beta_i x_{t,i} \tag{1}$$

Where E_y is the expected number of cases, β_0, β_i are the model constants, and x_{ti} are the explanatory variables.

The next step is to obtain the relative risk index (RRI) from beta coefficients as follows:

$$RRI_i = e^{\beta_i} \tag{2}$$

Where, RRI is the relative risk index associated to the explanatory variable *i* by increment unit of this variable, and β_i is the regression coefficient associated to the explanatory variable i in the model. Poisson regression analysis was carried out by using the statistical software XLSTAT v. 2017 (https://www.xlstat.com/es/). In this study, besides the Poisson model corresponding to the current atmospheric pollution conditions, a hypothetical scenario in which the concentration of each pollutant was increased in 10% separately was considered. In this case, again the regression parameters were obtained, a Poisson distribution was applied considering this increase and keeping the rest of variables unchanged. From obtained β_i values again, relative risk index was estimated for morbidity considering an increase of 10% in the magnitude of each explanatory variable. It let us to determine the effect on risk derived from a future hypothetical scenario.

2.2.7 Mapping of relative risk index for each municipality of the Bajío region in Guanajuato

The relative risk indexes (RRI) of daily morbidity by all causes associated to O_3 and PM_{10} in the Bajío region were mapped by using a Geographic Information Systems QGIS v. 2.14.7 (QGIS, 2017).

2.3 Results

2.3.1 Air Quality

Descriptive statistical for O_3 and PM_{10} of data registered from automatic monitoring stations in León, Celaya, Silao, Irapuato, and Salamanca is shown in Tables 3.1 and 3.2. From Table 3.1 it can be observed that for all period 2012-2015, the mean concentration for O_3 was 26.6224 ppb, reaching a maximum concentration of 73.6725 ppb in Irapuato. León and Celaya showed the lowest mean concentrations for ozone; whereas Irapuato and Silao showed the maximum levels of O_3.

Table 2.2 Descriptive Statistical for O_3 during the study period in the Bajío region

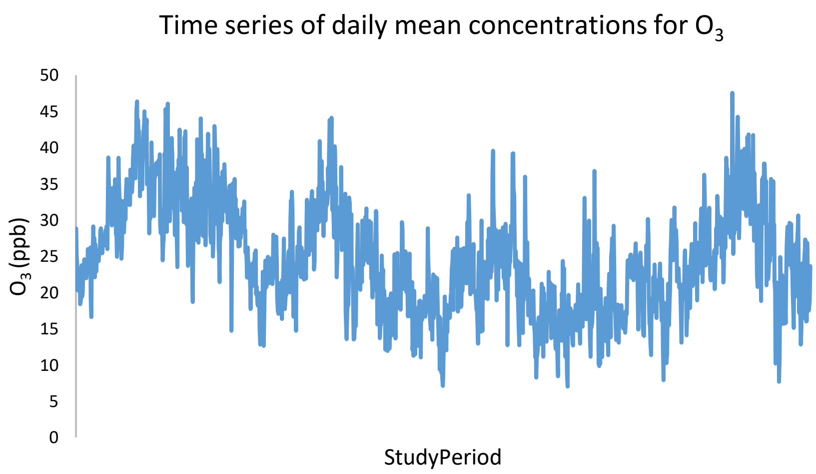
León				
Pollutant	**Mean Concentration**	**Standard deviation**	**Minimum**	**Maximum**
O_3 (ppb)	24.7017	7.5610	7.0235	47.5736
Celaya				
Pollutant	**Mean Concentration**	**Standard deviation**	**Minimum**	**Maximum**
O_3 (ppb)	25.2340	7.9457	6.5232	47.5068
Silao				
Pollutant	**Mean Concentration**	**Standard deviation**	**Minimum**	**Maximum**
O_3 (ppb)	28.8402	9.0672	7.5000	63.1788
Irapuato				
Pollutant	**Mean Concentration**	**Standard deviation**	**Minimum**	**Maximum**
O_3 (ppb)	29.0217	12.9467	5.7182	73.6725
Salamanca				
Pollutant	**Mean Concentration**	**Standard deviation**	**Minimum**	**Maximum**
O_3 (ppb)	25.3144	7.9857	8.7379	50.7264

Source: Own elaboration

The highest concentrations were observed during 2012 and 2015, whereas the lowest concentrations were registered during 2014. Ozone concentrations were in general higher during the warm months in comparison with the winter season, being 22% higher than those observed during cold months.

Time series for daily mean concentrations for O_3 during the period 2012-2015 in the Bajío region, are shown in graph 2.2. It can be observed a seasonal pattern, in which, the highest values of ozone concentration occurred during the summer months whereas, the lowest concentrations occurred during winter months.

Graph 2.1 Time-series for daily mean concentrations for Ozone during the study period in the Bajío region in Guanajuato



Source: Own elaboration

From Table 2.3 it can be observed that for all period 2012-2015, the mean concentration for PM_{10} was 54.1229 µg m^{-3}, reaching a maximum concentration of 160.9764 µg m^{-3} in the municipality of Celaya. The lowest mean concentrations were found for Silao and Irapuato; whereas the maximum values were registered in Celaya and Salamanca.

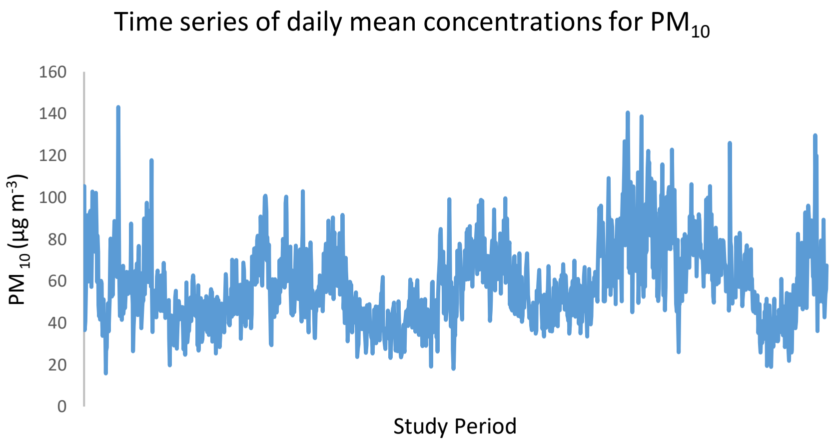
Table 2.3 Descriptive Statistical for PM_{10} during the study period in León, the Bajío region in Guanajuato

León				
Pollutant	**Mean Concentration**	**Standard deviation**	**Minimum**	**Maximum**
PM_{10} (µg m^{-3})	58.8244	19.3295	15.8481	143.1591
Celaya				
Pollutant	**Mean Concentration**	**Standard deviation**	**Minimum**	**Maximum**
PM_{10} (µg m^{-3})	69.1963	25.9990	18.9079	160.9764
Silao				
Pollutant	**Mean Concentration**	**Standard deviation**	**Minimum**	**Maximum**
PM_{10} (µg m^{-3})	41.9583	16.3670	8.7742	104.2083
Irapuato				
Pollutant	**Mean Concentration**	**Standard deviation**	**Minimum**	**Maximum**
PM_{10} (µg m^{-3})	45.5014	17.6875	8.8098	130.4270
Salamanca				
Pollutant	**Mean Concentration**	**Standard deviation**	**Minimum**	**Maximum**
PM_{10} (µg m^{-3})	55.1345	19.6767	14.9325	152.6935

Source: Own elaboration

The highest concentrations were observed during 2015, whereas the lowest concentrations were registered during 2013 and 2014. PM_{10} concentrations were in general higher during the cold months in comparison with the summer season, being 1.29 times higher than those observed during warm months. Time series for daily mean concentrations for PM_{10} during the period 2012-2015 in the Bajío region are shown in graph 2.2. It can be observed a seasonal pattern, in which, the highest values of PM_{10} concentration occur during the winter months whereas, the lowest concentrations occur during the summer months.

Graphic 2.2 Time-series for daily mean concentrations for PM_{10} during the study period in the Bajío region in Guanajuato



Source: Own elaboration

2.3.2 Epidemiological data

Descriptive statistical for the 5 municipalities in the region of Bajío was estimated, it was found that León (5.73) and Irapuato (2.94) showed the highest number of hospital admissions by all causes during the study period. On the other hand, Salamanca (1.09) and Silao (1.40) showed the lowest.

Morbidity rate is an epidemiological concept that refers to the number of persons which have a disease regarding to a given population and period. The total of population for each municipality was obtained from National Institute of Statistics, Geography and Informatics (INEGI). In the case of morbidity rate, the estimation considered groups of 1000 habitants.

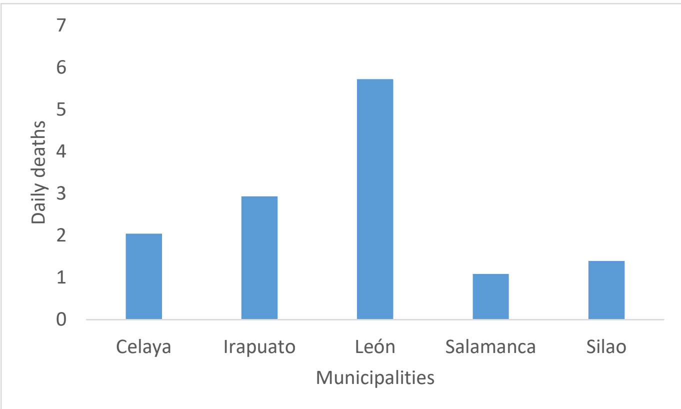
Silao (2.36-2.91) and Irapuato (1.51-2.25) showed the highest morbidity rate, whereas, Salamanca (1.22-1.71) showed the lowest. It is important to mention that in spite of León had the highest values of morbidity, its morbidity rate was low. It was found some uniformity in the results for all municipalities studied, for example, the highest values of the relative maximum for daily morbidity were found during November, December and January. In addition, it was observed a marked and evident seasonality, with the number of hospital admissions by all causes being higher during autumn and winter seasons. However, it was not observed any inter-annual trend.

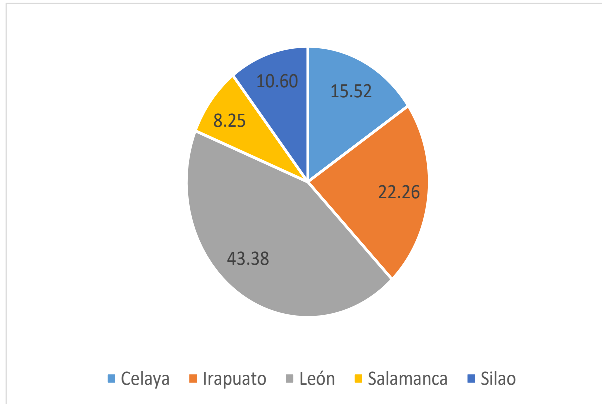
Regarding to age sub-group. It was possible to identify people between 5 and 59 years as the population group with the higher number and frequency of admissions; whereas the sub-group of 60-74 years and >75 years showed the lowest. In terms of gender, in León and Irapuato the number of admissions registered was similar in both, women and men. On the other hand, in Silao and Salamanca, women showed greater hospital admissions in comparison with men. Finally, in the municipality of Celaya, the number of admissions was higher in men.

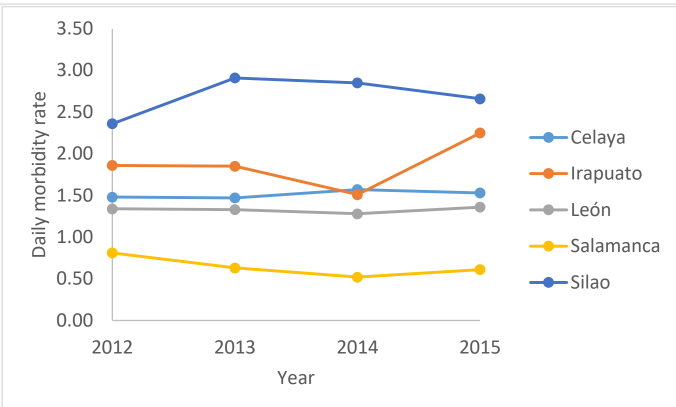
When respiratory cause was considered as the specific cause of hospital admission the highest number of admissions was found for people between 5 and 59 years, the same was observed when circulatory diseases were considered as specific cause. Regarding to the gender, in the sub-group of 5-59 years, 17.4 and 23.8% were men; whereas, between 21.8 and 24.2% were women.

From Graphic 2.3, it can be observed that León (43.38%) and Irapuato (22.26%) contribute in a great proportion of the total morbidity in the region of Bajío in Guanajuato; registering also the highest number of daily hospital admissions.

Graphic 2.3 Integrated information of daily morbidity during the study period in the Bajío region in Guanajuato







Seasonality:
+ autumn and winter
-Summer
men>women
All causes:
+ 5-59 years
- 0-4, 60-74 and >75 years

Respiratory causes:
+ 5-59 years
- 0-4, 60-74 and >75 years

Circulatory causes:
+ 5-59 years
- 0-4, 60-74 and >75 years

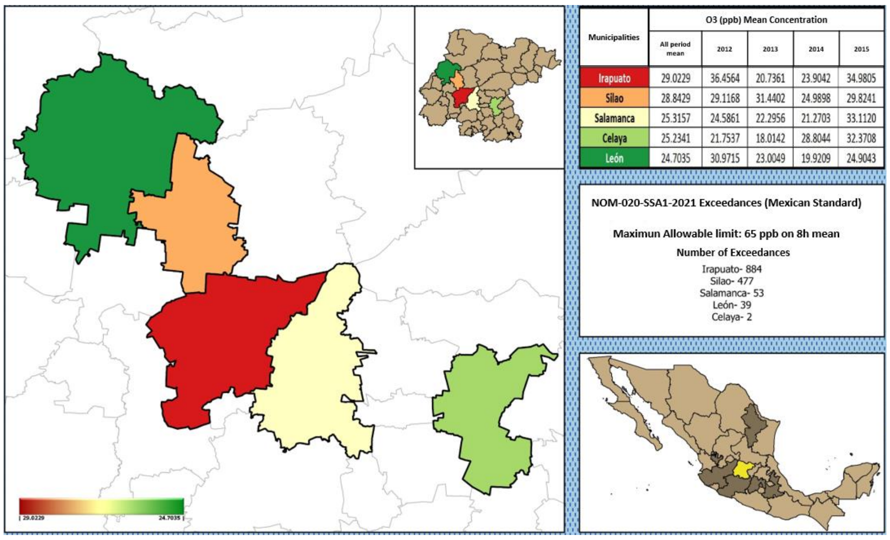
+higher morbidity values
-lower morbidity values

Source: Own elaboration

2.3.3 Exceedances to reference values established by NOM´s

In Graphcis 2.4 and 2.5, integrated information about the number of exceedances for O_3 and PM_{10} for the Bajío region in Guanajuato is shown. From Graph 3.4, it can be observed that, Irapuato, Silao and Salamanca presented the highest mean concentration values for O_3 during the all period. However, Irapuato showed the highest number of exceedances (884) to the maximum allowable limit established by NOM-020-SSA1-2021, followed by Silao (477) and Salamanca (53), respectively. It is to say, zones located in the middle part of the Bajío presented more photochemical pollution.

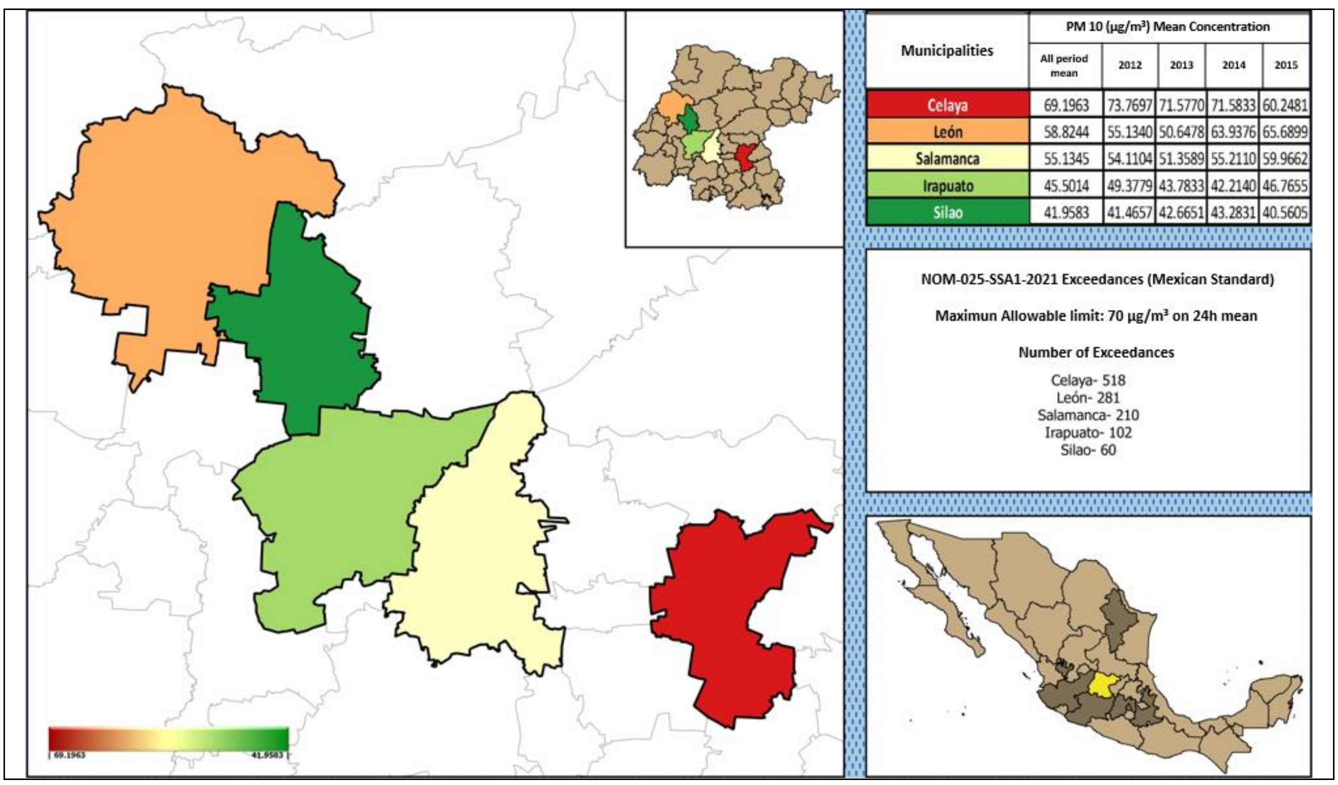
Graphic 2.4 Integrated information about the number of exceedances for O_3 in the Bajío region in Guanajuato



Source: Own elaboration

From Graph 3.5, it can be observed that, Celaya, León and Salamanca presented the highest mean concentration values for PM_{10} during the all period. All municipalities showed significant exceedances to the maximum allowable limit established by NOM-025-SSA1-2021; Celaya with 518, León with 281 and Salamanca with 210 exceedances, respectively.

Graphic 2.5 Integrated information about the number of exceedances for PM_{10} in the Bajío region in Guanajuato



Source: Own elaboration

2.3.4 Estimation and mapping of the relative risk index (RRI) for each pollutant by municipality

Bi-variate analysis, multivariate analysis and multiple regression of daily mortality data with explanatory variables.

- O_3-*All causes*

The association of this pollutant with daily morbidity considering bi-variate relations (Pearson coefficient) showed significant values only for Celaya and Salamanca. In the case of multiple regression analysis, the null hypothesis states that explanatory variable contributes significantly to the model, considering Fisher statistical test. If F<0.0001, it means that the risk of assuming the null hypothesis as incorrect is lower than 0.01%. From multiple regression analysis (RLM SC Type III), Irapuato, León and Salamanca were the municipalities which showed the lowest values of the statistical test (F<0.0001), therefore, we can conclude that ozone variable provided significant information to the prediction model for daily morbidity.

- *PM_{10}-All causes*

The association of this pollutant with daily morbidity considering bi-variate relations (Pearson coefficient) showed significant values only for León and Irapuato. In the case of multiple regression analysis, the null hypothesis states that explanatory variable contributes significantly to the model, considering Fisher statistical test. If F<0.0001, it means that the risk of assuming the null hypothesis as incorrect is lower than 0.01%. From multiple regression analysis (RLM SC Type III), Celaya, Irapuato and Silao, were the municipalities which showed the lowest values of the statistical test (F<0.0001), therefore, we can conclude that PM_{10} variable provided significant information to the prediction model for daily morbidity.

- *O_3-From 0 to 59 years*

The association of this pollutant with daily morbidity considering bi-variate relations (Pearson coefficient) showed significant values only for Celaya and Salamanca. In the case of multiple regression analysis, the null hypothesis states that explanatory variable contributes significantly to the model, considering Fisher statistical test. If F<0.0001, it means that the risk of assuming the null hypothesis as incorrect is lower than 0.01%. From multiple regression analysis (RLM SC Type III), León, Salamanca and Celaya, were the municipalities which showed the lowest values of the statistical test (F<0.0001), therefore, we can conclude that ozone variable provided significant information to the prediction model for daily morbidity.

- *PM_{10}-From 0 to 59 years*

The association of this pollutant with daily morbidity considering bi-variate relations (Pearson coefficient) showed significant values only for Irapuato, Celaya and Silao. In the case of multiple regression analysis, the null hypothesis states that explanatory variable contributes significantly to the model, considering Fisher statistical test. If F<0.0001, it means that the risk of assuming the null hypothesis as incorrect is lower than 0.01%. From multiple regression analysis (RLM SC Type III), Celaya, Irapuato and Silao, were the municipalities which showed the lowest values of the statistical test (F<0.0001), therefore, we can conclude that PM_{10} variable provided significant information to the prediction model for daily morbidity.

- *O_3->60 years*

The association of this pollutant with daily morbidity considering bi-variate relations (Pearson coefficient) showed significant values only for León and Silao. In the case of multiple regression analysis, the null hypothesis states that explanatory variable contributes significantly to the model, considering Fisher statistical test. If F<0.0001, it means that the risk of assuming the null hypothesis as incorrect is lower than 0.01%. From multiple regression analysis (RLM SC Type III), León, Salamanca and Silao, were the municipalities which showed the lowest values of the statistical test (F<0.0001), therefore, we can conclude that ozone variable provided significant information to the prediction model for daily morbidity.

- PM_{10}-*>60 years*

The association of this pollutant with daily morbidity considering bi-variate relations (Pearson coefficient) showed significant values only for León and Salamanca. In the case of multiple regression analysis, the null hypothesis states that explanatory variable contributes significantly to the model, considering Fisher statistical test. If F<0.0001, it means that the risk of assuming the null hypothesis as incorrect is lower than 0.01%. From multiple regression analysis (RLM SC Type III), León and Silao, were the municipalities which showed the lowest values of the statistical test (F<0.0001), therefore, we can conclude that PM_{10} variable provided significant information to the prediction model for daily morbidity.

- *O_3- Respiratory causes*

The association of this pollutant with daily morbidity considering bi-variate relations (Pearson coefficient) showed significant values only for Salamanca, Silao and León. In the case of multiple regression analysis, the null hypothesis states that explanatory variable contributes significantly to the model, considering Fisher statistical test. If F<0.0001, it means that the risk of assuming the null hypothesis as incorrect is lower than 0.01%. From multiple regression analysis (RLM SC Type III), Irapuato, León, Salamanca and Silao, were the municipalities which showed the lowest values of the statistical test (F<0.0001), therefore, we can conclude that ozone variable provided significant information to the prediction model for daily morbidity.

- *PM_{10}- Respiratory causes*

The association of this pollutant with daily morbidity considering bi-variate relations (Pearson coefficient) showed significant values only for Irapuato, León and Celaya. In the case of multiple regression analysis, the null hypothesis states that explanatory variable contributes significantly to the model, considering Fisher statistical test. If F<0.0001, it means that the risk of assuming the null hypothesis as incorrect is lower than 0.01%. From multiple regression analysis (RLM SC Type III), Celaya, Irapuato, León, Salamanca and Silao, were the municipalities which showed the lowest values of the statistical test (F<0.0001), therefore, we can conclude that PM_{10} variable provided significant information to the prediction model for daily morbidity.

- *O_3- Circulatory causes*

The association of this pollutant with daily morbidity considering bi-variate relations (Pearson coefficient) showed significant values only for León and Silao. In the case of multiple regression analysis, the null hypothesis states that explanatory variable contributes significantly to the model, considering Fisher statistical test. If F<0.0001, it means that the risk of assuming the null hypothesis as incorrect is lower than 0.01%. From multiple regression analysis (RLM SC Type III), León and Silao, were the municipalities which showed the lowest values of the statistical test (F<0.0001), therefore, we can conclude that ozone variable provided significant information to the prediction model for daily morbidity.

- *PM_{10}- Circulatory causes*

The association of this pollutant with daily morbidity considering bi-variate relations (Pearson coefficient) showed significant values only for León. In the case of multiple regression analysis, the null hypothesis states that explanatory variable contributes significantly to the model, considering Fisher statistical test. If F<0.0001, it means that the risk of assuming the null hypothesis as incorrect is lower than 0.01%. From multiple regression analysis (RLM SC Type III), Salamanca was the only municipality which showed the lowest values of the statistical test (F<0.0001), therefore, we can conclude that PM_{10} variable provided significant information to the prediction model for daily morbidity.

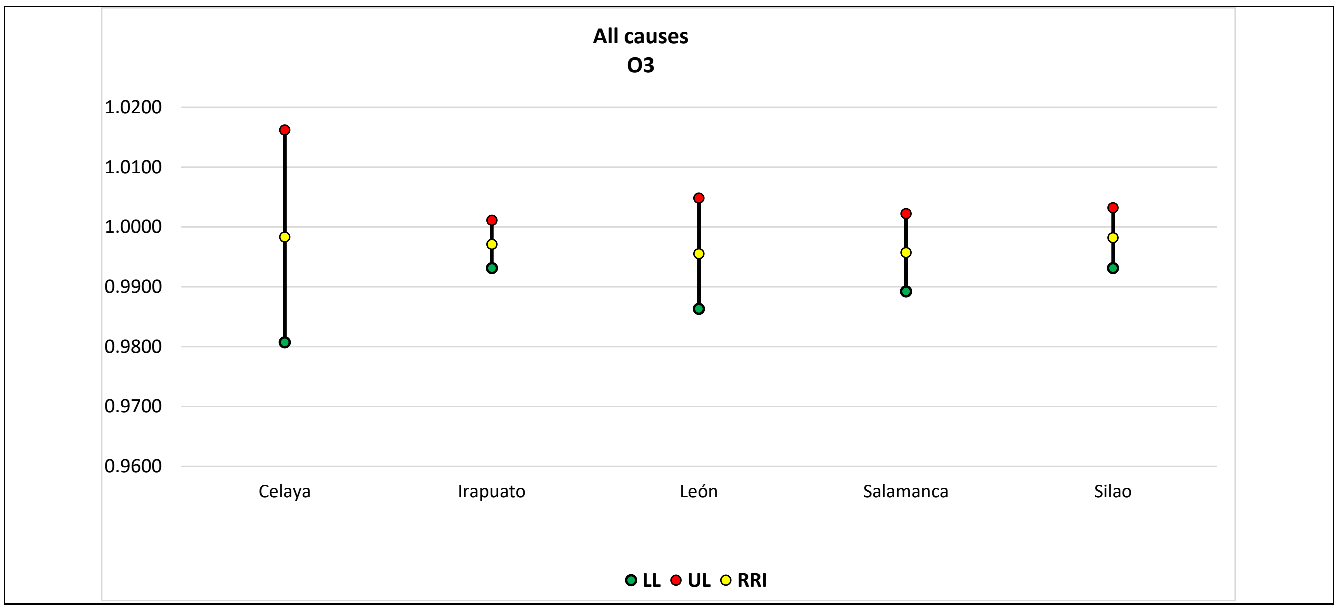
Estimation of Relative Risk Index (RRI)

Results for relative risk index (RRI) and the confidence interval (lower limit and upper limit) at 95% of confidence corresponding to an increase of 10% in the concentration of each pollutant are shown in Graphs 3.6-3.10 for O_3 and Graphs 3.11-3.15 for PM_{10} for morbidity by all causes, age groups (0-59 years and >60 years), respiratory and circulatory causes.

O_3

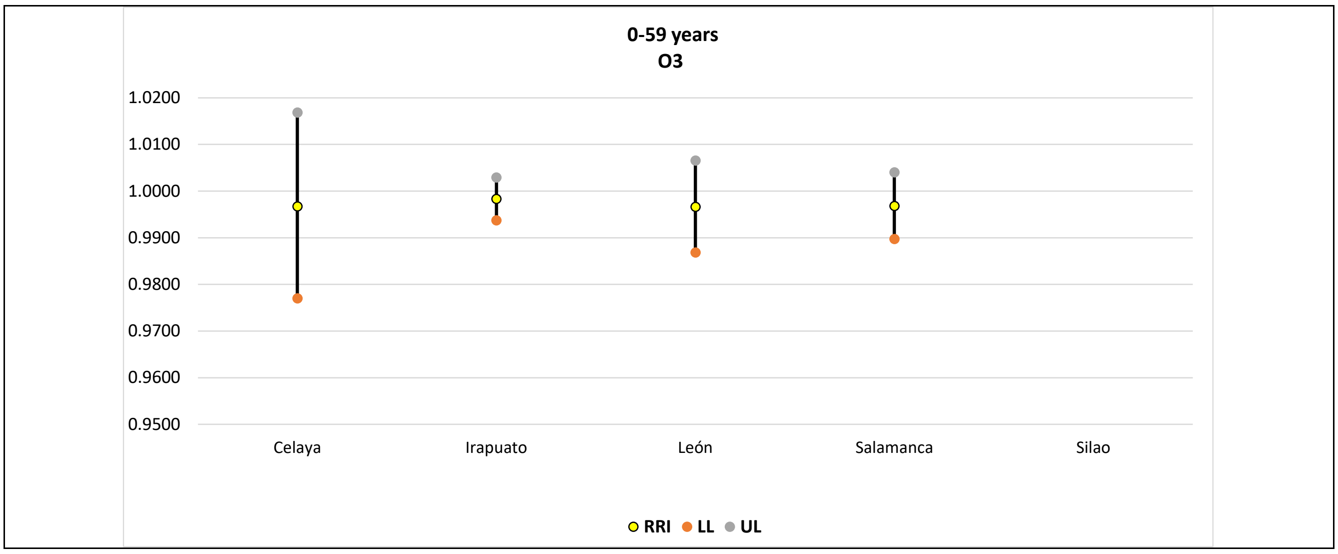
In Graphs 2.6-2.10, relative risk indexes (RRI) corresponding to an increase of 10% in daily mean ozone concentrations are shown. Celaya showed the highest significant correlations for morbidity by respiratory causes (IRR=1.0002) [IC95%: 0.9759-1.0250] during warm months. On the other hand, Silao showed the highest RRI values for morbidity by respiratory causes (IRR=1.0020) [IC95%: 0.9937-1.0104] and during the cold months [IC95%: 0.9726-1.0564] with an IRR=1.0136. The association between morbidity by all causes and ozone concentrations showed positive correlations in all municipalities, but this associations was not significant, being Celaya the highest with an IRR=0.9983 [IC95%: 0.9807-1.0162]. Regarding to the age-group, the age range between 0 and 59 years showed correlations not significant in all municipalities, excepting Silao which did not present any correlation. Finally, the association between morbidity and ozone concentrations in people major than 60 years, showed correlations not significant in León, Salamanca and Silao; whereas Celaya and Irapuato no did not present any correlation.

Graphic 2.6 Integrated information about relative risk index (RRI) and confidence interval (LL and UL) for O_3 considering morbidity by all causes in the Bajío region in Guanajuato



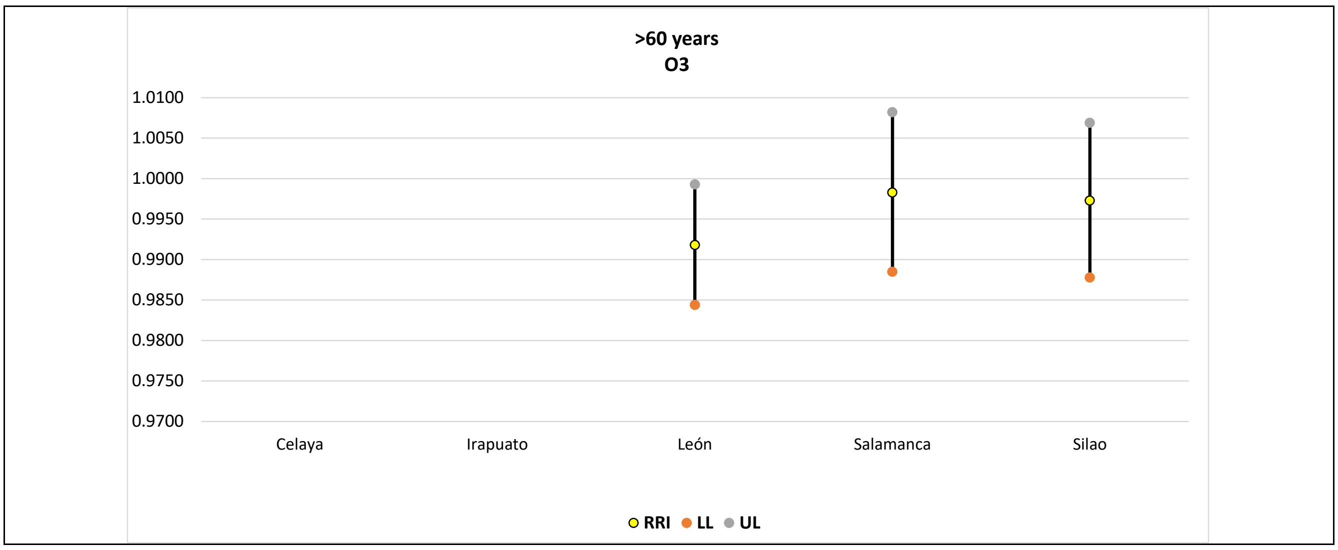
Source: Own elaboration

Graphic 2.7 Integrated information about relative risk index (RRI) and confidence interval (LL and UL) for O_3 considering the age group of 0-59 years in the Bajío region in Guanajuato



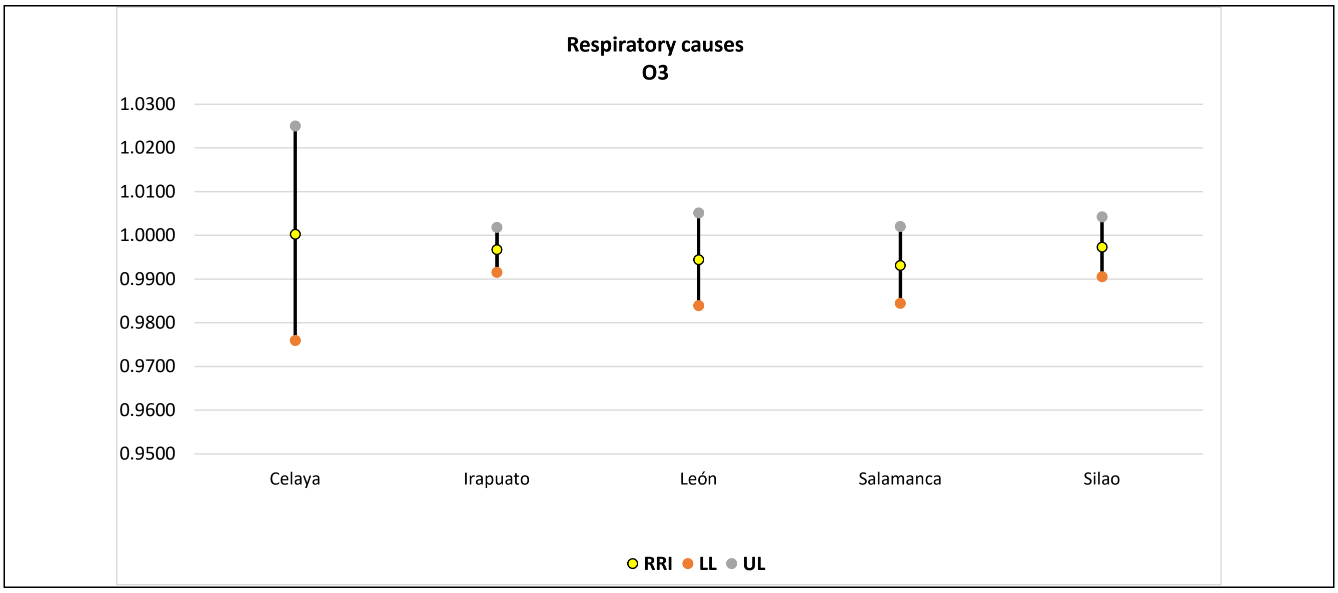
Source: Own elaboration

Graphic 2.8 Integrated information about relative risk index (RRI) and confidence interval (LL and UL) for O_3 considering the age group >60 years in the Bajío region in Guanajuato



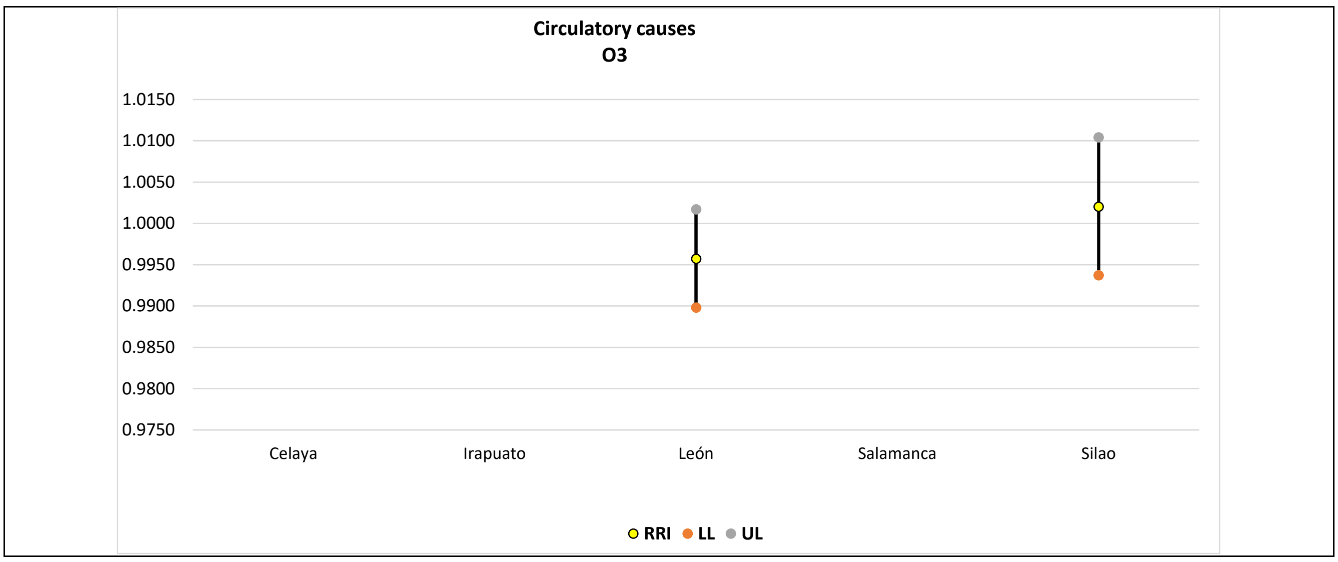
Source: Own elaboration

Graphic 2.9 Integrated information about relative risk index (RRI) and confidence interval (LL and UL) for O_3 considering morbidity by respiratory causes in the Bajío region in Guanajuato



Source: Own elaboration

Graphic 3.10 Integrated information about relative risk index (RRI) and confidence interval (LL and UL) for O_3 considering morbidity by circulatory causes in the Bajío region in Guanajuato

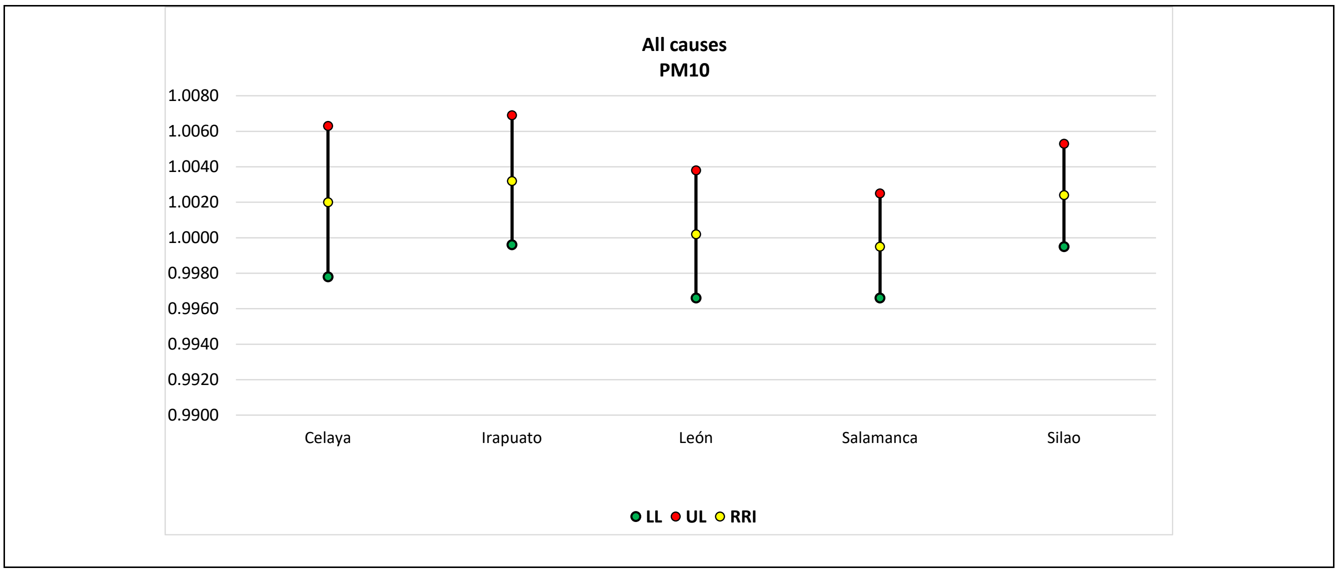


Source: Own elaboration

PM_{10}

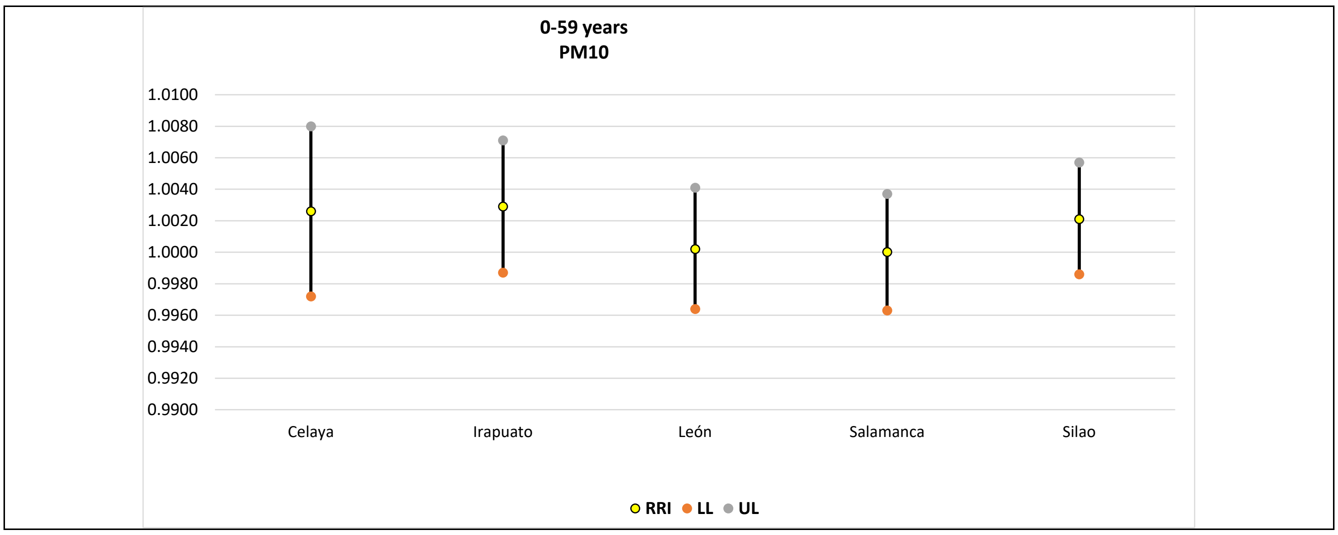
In Graphcis 3.11-3.15, relative risk indexes (RRI) corresponding to an increase of 10% in daily mean PM_{10} concentrations are shown. The highest RRI values were found for Irapuato for morbidity by all causes (IRR=1.0032) [IC95%: 0.9996-1.0069]; in the age range from 0 to 59 years (IRR=1.0029) [IC95%: 0.9987-1.0071] and for morbidity by respiratory causes (IRR=1.0034) [IC95%: 0.9988-1.0081] as can be observed in graphs 3.11, 3.12 and 3.14, respectively. In addition, this municipality also showed the highest risk during the cold months [IC95%: 0.9999-1.0094] with an IRR=1.0047. The association between morbidity and PM_{10} concentrations considering people major than 60 years [IC95%: 0.9985-1.0036], and morbidity by circulatory causes [IC95%: 0.9978-1.0023] were the highest for the municipality of León with IRR values of 1.0011 and 1.0001, respectively. Silao showed the highest risk during the warm months (IRR=1.0022) [IC95%: 0.9918-1.0128].

Graphic 2.11 Integrated information about relative risk index (RRI) and confidence interval (LL and UL) for PM_{10} considering morbidity by all causes in the Bajío region in Guanajuato



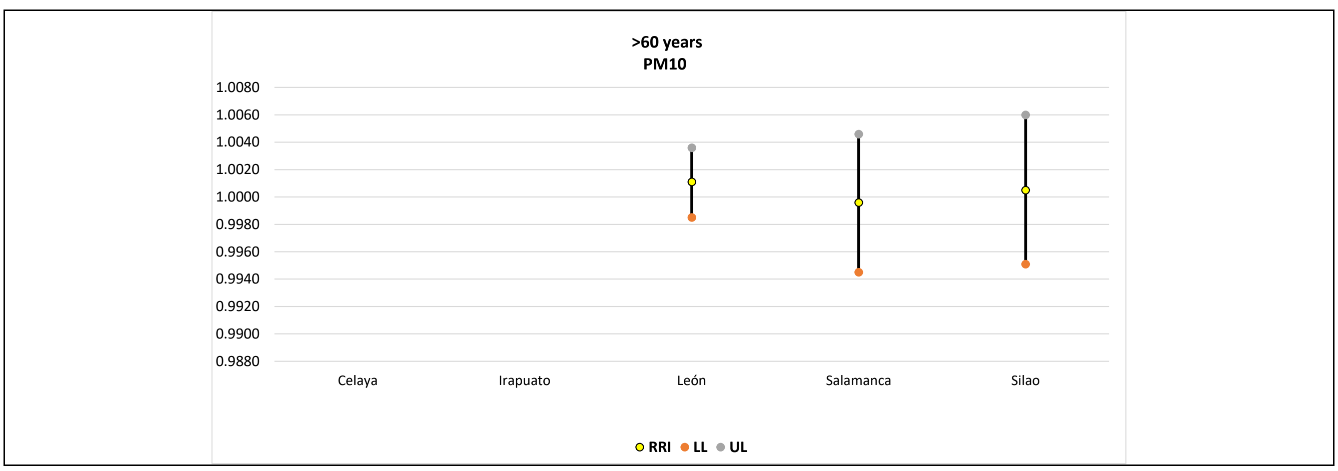
Source: Own elaboration

Graphic 2.12 Integrated information about relative risk index (RRI) and confidence interval (LL and UL) for PM_{10} considering the age group of 0-59 years in the Bajío region in Guanajuato



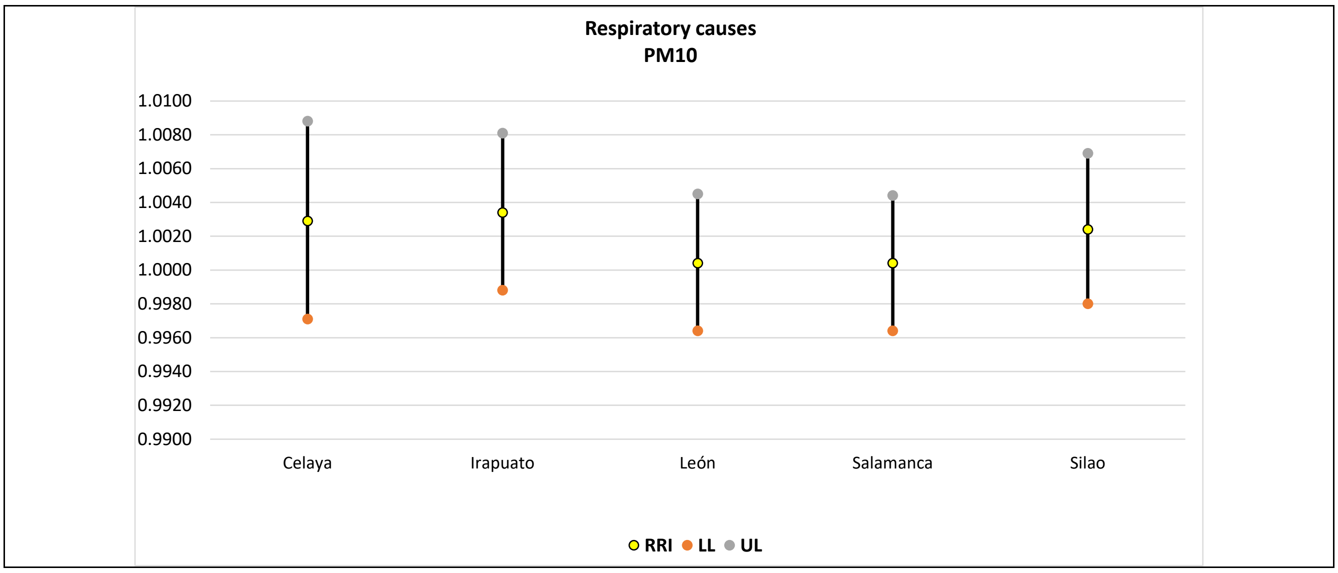
Source: Own elaboration

Graphic 2.13 Integrated information about relative risk index (RRI) and confidence interval (LL and UL) for PM_{10} considering the age group >60 years in the Bajío region in Guanajuato



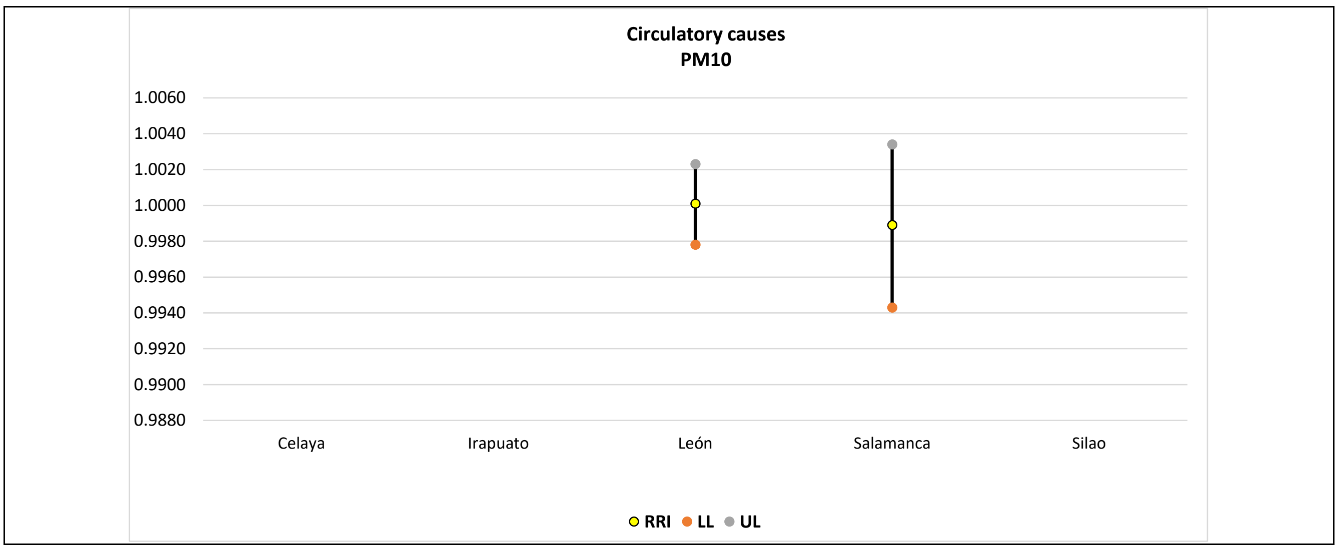
Source: Own elaboration

Graphic 2.14 Integrated information about relative risk index (RRI) and confidence interval (LL and UL) for PM_{10} considering morbidity by respiratory causes in the Bajío region in Guanajuato



Source: Own elaboration

Graphic 2.15 Integrated information about relative risk index (RRI) and confidence interval (LL and UL) for PM_{10} considering morbidity by circulatory causes in the Bajío region in Guanajuato

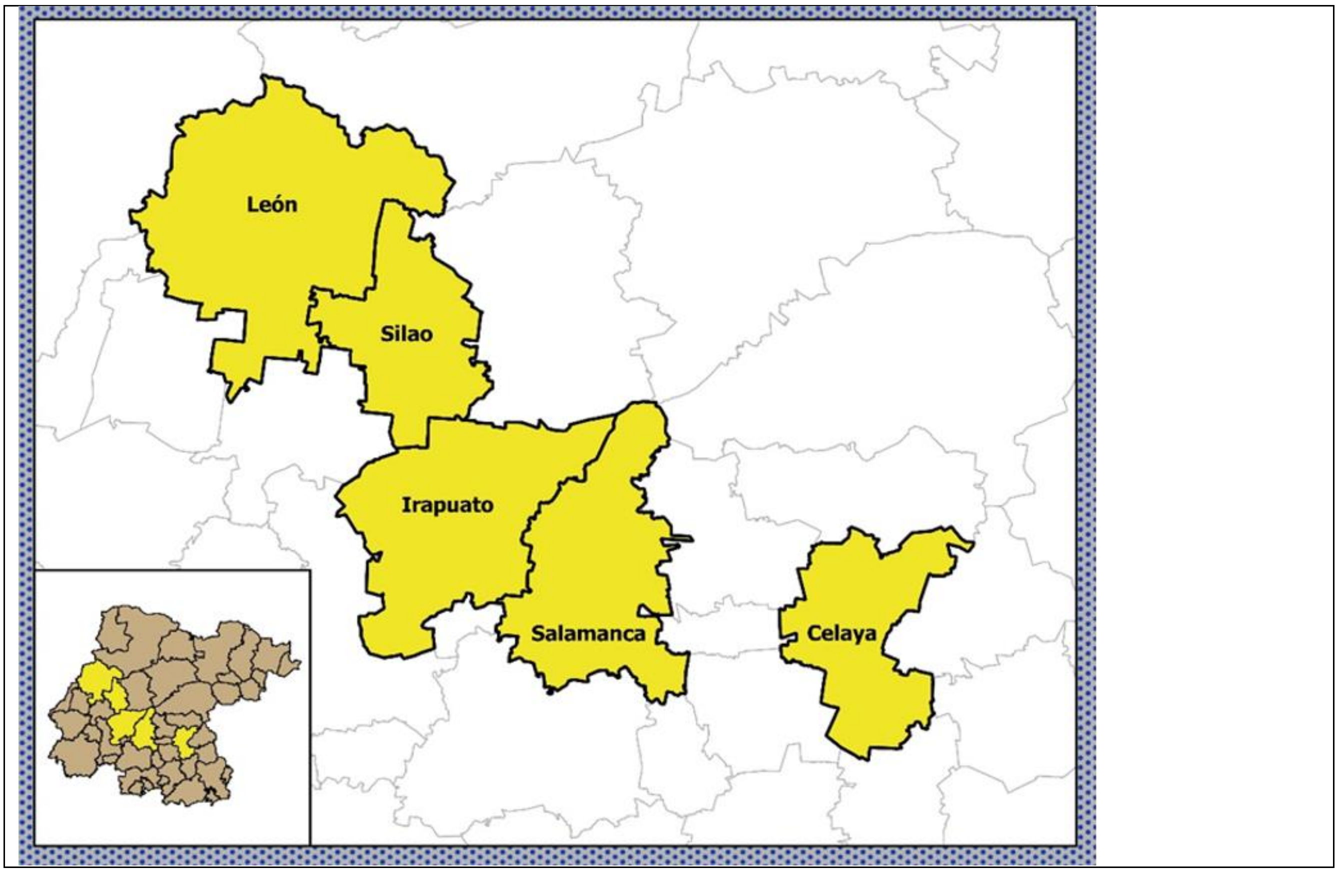


Source: Own elaboration

Integrated Mapping of Relative Risk Index for each pollutant.

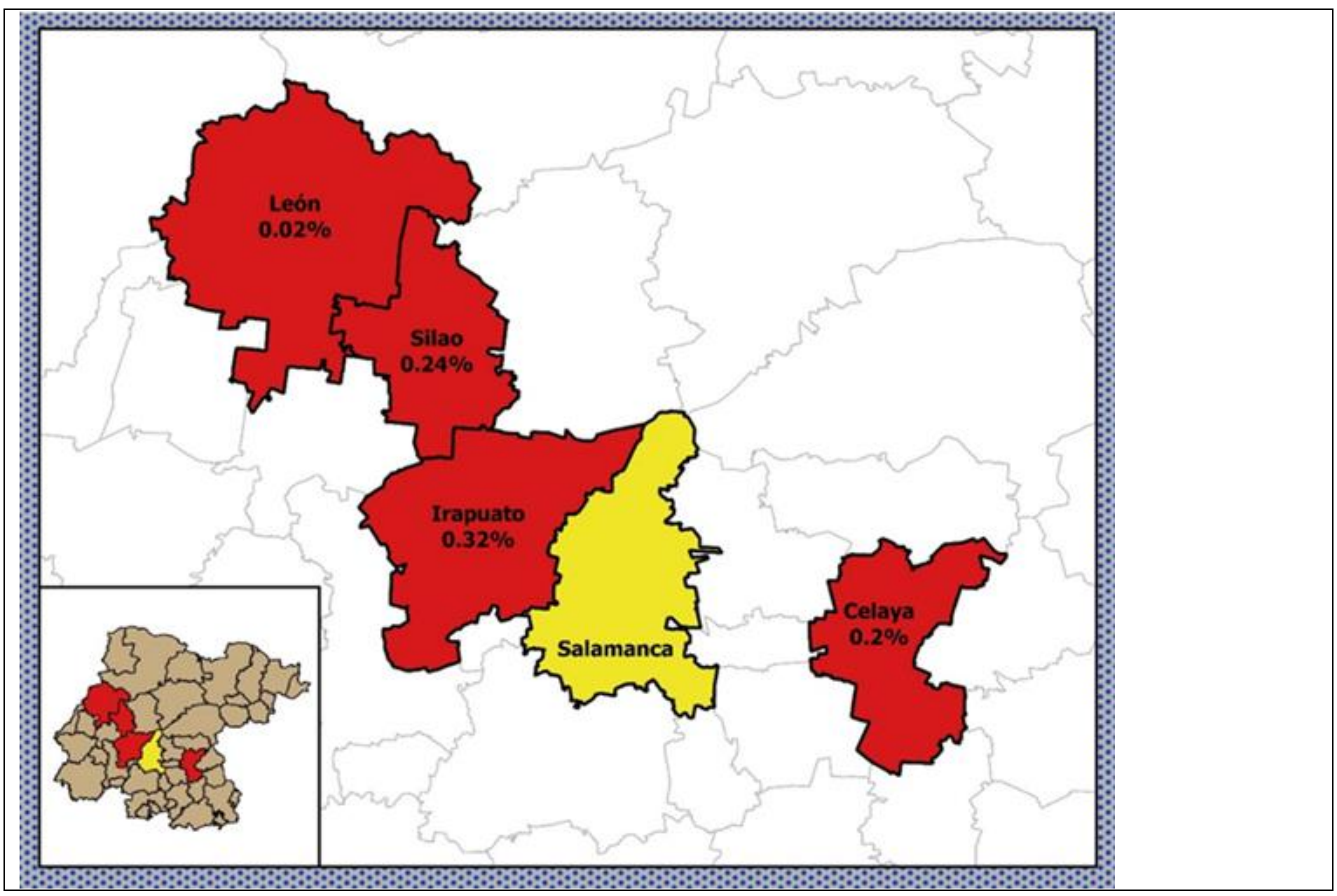
As can be observed in Graphic 2.16, an increase of 10% in the daily mean concentrations of ozone does not constitute a significant risk of morbidity in the municipalities studied, for this reason, all municipalities are in yellow, suggesting that there was a correlation, but this correlation was not significant. On the other hand, from Graphic 2.17, it can be observed that because of an increase of 10% in PM_{10} daily mean concentrations, morbidity showed an increase in Irapuato (0.32%), Silao (0.24%), Celaya (0.20%) and León (0.02%). These municipalities are in red, suggesting that there was a correlation, and this correlation was significant. In the case of Salamanca, which is presented in yellow, indicates that there was a not significant correlation.

Graphic 2.16 Integrated Mapping of Relative Risk Index (RRI) considering the hypothetic scenario in which O_3 concentrations increases in 10% in the Bajío region



Source: Own elaboration

Graphic 2.17 Integrated Mapping of Relative Risk Index (RRI) considering the hypothetic scenario in which PM_{10} concentrations increases in 10% in the Bajío region



Source: Own elaboration

2.4 Conclusions

Regarding to air quality, Irapuato, Silao and Salamanca presented the highest mean concentration values for O_3 during the all period. However, Irapuato showed the highest number of exceedances (884) to the maximum allowable limit established by NOM-020-SSA1-2021, followed by Silao (477) and Salamanca (53), respectively. It is to say, zones located in the middle part of the Bajío presented more photochemical pollution. With respect to PM_{10}, Celaya, León and Salamanca presented the highest mean concentration values for PM_{10} during the all period. All municipalities showed significant exceedances to the maximum allowable limit established by NOM-025-SSA1-2021; Celaya with 518, León with 281 and Salamanca with 210 exceedances, respectively. Comparing both pollutants, we can conclude that the pollution due to PM_{10} is a hotspot in the Bajío region in comparison with pollution due to ozone.

Silao (2.36-2.91) and Irapuato (1.51-2.25) showed the highest morbidity rate, whereas, Salamanca (1.22-1.71) showed the lowest. It is important to mention that in spite of León had the highest values of morbidity, its morbidity rate was low. It was found some uniformity in the results for all municipalities studied, for example, the highest values of the relative maximum for daily morbidity were found during November, December and January. In addition, it was observed a marked and evident seasonality, with the number of hospital admissions by all causes higher during autumn and winter seasons. However, it was not observed any inter-annual trend.

Regarding to age sub-group. It was possible to identify people between 5 and 59 years as the population group with the higher number and frequency of admissions; whereas the sub-group of 60-74 years and >75 years showed the lowest. In terms of gender, in León and Irapuato the number of admissions registered was similar in both, women and men. On the other hand, in Silao and Salamanca, women showed greater hospital admissions in comparison with men. Finally, in the municipality of Celaya, the number of admissions was higher in men.

From relative risk indexes found in this study; we can conclude that an increase of 10% in the daily mean concentrations of O_3 does not constitute a significant risk of morbidity in the municipalities studied; however, the scenario was very different with respect to PM_{10}, since when PM_{10} concentrations were increased, the risk values also increased: Irapuato with 0.32%, Silao with 0.24%, Celaya with 0.20% and León with 0.02%.

Population between 0 and 59 years was identified as the most vulnerable age sub-group, suggesting that, the habits and activities of people played an important role in the exposure to these pollutants, since, people in this group comprises economically active population and students of all ages, who develop their activities outside home just in the hours in which O_3 and PM_{10} reach their peak levels as a result of industrial activity and mobile sources. Therefore, decision makers can use reported data in this work to propose or improve regulations, programs or actions focused to protect population health between 0-59 years against atmospheric pollution effects in these municipalities.

2.5 Financing

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