

# Masters Program in **Geospatial Technologies**



Spatiotemporal Analysis of PM10 and PM2.5 with EBK3D and  
Space-Time Cube in the City of Lisbon, Portugal

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Dissertation submitted in partial fulfilment of the requirements  
for the Degree of *Master of Science in Geospatial Technologies*

# Spatiotemporal Analysis of PM10 and PM2.5 with EBK3D and Space-Time Cube in the City of Lisbon. Portugal

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## DECLARATION OF ORIGINALITY

I declare that the work described in this document is my own and not from someone else. All the assistance I have received from other people is duly acknowledged and all the sources (published or not published) are referenced.

This work has not been previously evaluated or submitted to NOVA Information Management School or elsewhere.

Lisbon, February, 26th, 2024

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# Spatiotemporal Analysis of PM10 and PM2.5 with EBK3D and Space-Time Cube in the City of Lisbon. Portugal

## ABSTRACT

This thesis conducts a spatiotemporal analysis of particulate matter (PM10 and PM2.5) in Lisbon, Portugal, through 2022, utilizing Empirical Bayesian Kriging 3D (EBK3D) and Space-Time Cube analysis to explore pollution dynamics. Focused on how Particulate Matter (PM) levels vary across Lisbon and identifying distinct patterns during different traffic periods on weekdays and weekends. It employs geostatistical methods to analyze pollution levels, offering insights into the spatial and temporal distribution of PM concentrations. Key findings highlight areas with persistent high pollution and temporal fluctuations throughout the city. This research helps in the understanding of Lisbon's PM related air pollution.

### Sustainable Development Goals (SDG):



## KEYWORDS

Urban Air Quality

PM10

PM2.5

Empirical Bayesian Kriging 3D

Space-Time Cube

Emerging Hot Spot Analysis

Local Outlier Analysis

## ACRONYMS

**ARH** - Afternoon Rush Hour

**EBK3D** - Empirical Bayesian Kriging 3D

**EEA** - European Environment Agency

**ESDA** - Exploratory Spatial Data Analysis

**EU** - European Union

**GIS** - Geographical Information Systems

**IDW** - Inverse Distance Weighting

**MRH** - Morning Rush Hour

**ORH** - Off Rush Hour

**PM** – Particulate Matter

**PM10** - Particulate Matter up to 10 micrometers in size

**PM2.5** - Particulate Matter up to 2.5 micrometers in size

**WHO** - World Health Organization

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# 1 INTRODUCTION

Urban air pollution is a global threat that causes significant adverse health impacts on urban population. For this reason, air pollution is recognized as a great environmental concern. In order to address this issue, it is necessary to understand the processes that create this problem, its sources and how they behave in an urban environment. (EEA, 2018).

Air pollutants can be classified as primary (directly emitted to the air) or secondary (that are created in the atmosphere through chemical reactions). Depending on the emission sources, pollutants can be natural or anthropogenic. The health impacts that are caused by poor air pollution are associated with exposure time and can be considered as short- or long-term exposure. Depending on the type of pollutant, the EU and WHO define guidelines in order to protect public health. (WHO, 2018)

In Europe, particulate matter is considered as one of the most harmful pollutants to human health, due to its small size and its ability to penetrate huma's respiratory system, and in some cases reach the blood stream. The impact of this type of pollutant can vary depending on the duration of exposure and its composition, since particulate matter can be composed of multiple chemical components. (EEA, 2018).

This thesis aims to study the spatiotemporal behaviors of particulate matter (PM<sub>10</sub>, PM<sub>2.5</sub>) within the city of Lisbon, Portugal, throughout the year 2022, for different time periods, in order to answer the following research questions:

**RQ1:** How do PM<sub>10</sub> and PM<sub>2.5</sub> concentration levels vary spatially and temporally throughout different areas of Lisbon during 2022?

**RQ2:** Are there distinct patterns in the distribution of particulate matter during Morning Rush Hour, Off Rush Hour, and Afternoon Rush Hour on weekdays and weekends?

For this, data was divided into week days and weekends, as well as key daytime periods: Morning Rush Hour (MRH), Off Rush Hour (ORF), and Afternoon Rush Hour (ARH). Empirical Bayesian Kriging 3D (EBK3D) was used as a geostatistical three-dimensional interpolator with the Z being time. The output of the EBK3D was then used to create a Space Time-Cube of PM values over the year. Finally, Emerging Hot Spot Analysis and Local Outlier Analysis were used to identify spatiotemporal patterns.

## 2 LITERATURE REVIEW

### 2.1 Urban Air Quality

Air quality often serves as an indicator of the pollution levels in the air that we breathe. It can be defined as the introduction of substances in the environment by man, that can cause harm to human health, living resources, ecological systems, deteriorate material goods, or otherwise interfere with the legitimate use of the environment (Jonathan, 2005).

The globalization of the world economy and the evolution of the communication infrastructures has allowed the creation of a low cost, international mobility network that has never been seen before this era and, makes traveling greater distances more cost effective. While these developments have significantly bolstered the global economy, they have also created long term repercussions on air quality (Grossman,1994).

Air pollution is one of the main environmental problems in the world and, is caused mostly by the increase in the burning of fossil fuels which constitutes a serious threat to the environment and human health. According to estimates by the World Health Organization (WHO), around 4,2 million people die prematurely every year due to the harmful effects of air pollution. Multiple epidemiological studies have shown the a positive correlation between exposure to air pollution and an increase in multiple respiratory and cardiovascular diseases (WHO, 2018).

In the past, urban air pollution was considered to be mainly a local problem, mostly related to industrial emissions. Today industrial facilities have moved away from urban centers and the majority are located outside city limits. The increase in population in urban areas has led to an increase in movement, making road traffic the lead cause of poor air quality in urban areas (Bolund, 1999).

According to a 2018 report by the European Environment Agency (EAA, 2018), air quality in Europe in 2016 was significantly affected by vehicular emissions, with pollutants such as PM10, PM2.5, O3, and NO2 exceeding both European Union (EU) standards and World Health Organization (WHO) guidelines. The EAA report highlights that 15% of the urban population within the 28 EU member states resided in areas where PM10 levels surpassed EU limits, and 8% were in areas with PM2.5

concentrations above EU recommendations. Furthermore, NO<sub>2</sub> levels exceeded the acceptable limits for 7% of the urban population. The report also links almost 422,000 premature deaths in Europe to long-term exposure to suboptimal air quality. When evaluated against WHO guidelines, the data reveal that 42% of the EU population was exposed to PM<sub>10</sub> levels and 74% to PM<sub>2.5</sub> levels that exceeded WHO's recommended thresholds in 2016, with NO<sub>2</sub> exposure levels aligning with both EU and WHO standards. This highlights the discrepancy between EU and WHO air quality guidelines.

Air pollutants can be classified according to their source, chemical composition and, their physical state. Depending on the source, they can be anthropogenic or natural. The anthropogenic sources are the result of human activity, i.e. industrial or road traffic, while natural sources are the result of a natural phenomenon, i.e. volcanic eruptions or forest fires of natural origin. The origin of the pollutants can be divided into two types, primary and secondary pollutants. Primary pollutants are emitted directly from their sources to the atmosphere. Secondary pollutants are created in the atmosphere through chemical reactions. The chemical composition of pollutants can be classified as organic or inorganic depending on their chemical constituents. The final classification is related to their physical state, these can be particulate pollutants or gas pollutants. Particulate pollutants can be present in the atmosphere in solid and liquid state while gas pollutants are present in gas state.

The sources of pollutants can be divided into three categories: fixed sources, mobile sources, and area sources. The fixed sources are usually chimneys that tend to reach large spatial and temporal gradients of concentrations. Mobile sources are related with transportation and tend to have large spatial gradients close to roads, but become more homogenic as the distance from the road increases. Area sources are relatively constant in space but are relatively dispersed in larger areas (Winberry, 2008).

## 2.2 Particulate Matter

Particulate matter can be from both natural and anthropogenic sources. Natural sources can be marine salt, dust, volcanic ash, pollen, fungi spores, byproducts of forest fires, and many other natural sources that can produce small particles. Particles from anthropogenic sources can be byproducts of fossil fuel combustion (mainly from

vehicle exhaust and power plants), industrial processes, construction and many others. Particles with diameters less than 10  $\mu\text{m}$  can stay in the air for many days and be easily carried by wind, rain or be captured by vegetation or buildings (Roveli,2017 ).

Particulate matter formation can be primary or secondary, in which primary particles are realized directly to environment through a certain source (natural or anthropogenic) and secondary sources are formed in the atmosphere as the result of chemical reactions that lead to the creation of particulate matter. The main sources of primary PM in urban areas are: road traffic, fixed combustion (mainly domestic chimneys) and, industrial activities (Guevara,2016). Dust and sea are also important sources of primary PM, and are primarily influenced by wind. Black carbon has a similar chemical structure to graphite, and is mostly generated through improper combustion of fossil fuels (mainly diesel engines) (Zhu, 2002). Examples of secondary PM are sulfates and nitrates which are formed by the oxidation of  $\text{SO}_2$  and  $\text{NO}_2$  in the atmosphere into acids (Zheng, 2005). Compared to primary PM, the chemical processes involved in creating secondary PM are relatively slow, however they persist longer in the atmosphere.

Particle size is one of the most important characteristics of PM. The way of measuring their size is by defining their aerodynamic diameter, this is defined by the diameter of a spherical particle with a volumetric mass of  $1 \text{ g.cm}^{-3}$  (which is the same as water). This method is a simple way of categorize the different sizes of particles with different shapes (Brook, 2010).

There are several categories of PM depending on their aerodynamic diameter these are:

- Coarse Particles: Between 2.5 and 10  $\mu\text{m}$
- Fine Particles:  $\leq 2.5 \mu\text{m}$
- Ultrafine Particles:  $\leq 0.1 \mu\text{m}$
- Nano Particles:  $< 100 \text{ nm}$

The dimensions of particles not only determine their behavior in the atmosphere but also how they penetrate the human respiratory system. In general, fine particles tend

to have easier time penetrating the alveoli (tiny air sacs where the exchange of oxygen and carbon dioxide takes place) and bronchioles (small airways that lead to the alveoli) than coarse particles tend to not pass the nasopharynx (the upper part of the throat that lies behind the nose) (Brooke, 2010).

In terms of their composition, PM is made up by multiple components, including black carbon, organic carbon (CO), ion sulfate (SO<sub>4</sub>), ion nitrate (NO<sub>3</sub>), metallic composites, material originating from the earth crust, and sea salt. The properties of this complex group of particles can vary according to their composition and size, as well as their impact. For example, black carbon is related with a series of environmental impacts, such as rise in temperature, due to their ability to absorb light. The main components of the material originating from the earth crust include: aluminum (Al), silicon (Si), calcium (Ca), iron (Fe), these are mostly associated with coarse particles. In Europe, this type of particles represents almost 20% of the mass of coarse particles. This is more present in the Southwest and Southeast due to a drier and warmer climate, as well as the influence of dust particles from north Africa (Hajat, 2015).

In urban areas road traffic is one of the main sources of PM, followed by fossil fuels combustion in power plants, and industrial manufacturing (Lelieveld,2015). Besides engine combustion (which can vary depending on the age of the engine and the type of fuel used), there are other sources of PM related to road traffic, such as, brake pads wear, tire wear, and re-suspension of dust in the road surface (Bond, 2013).

### 2.3 Road Traffic related PM

Multiple studies have shown that the majority of emissions of PM in urban areas are related to road traffic. (Pant,2013; Ying,2015; Chih-I,2023) The PM emissions related to road traffic are classified according to their formation process. Internal combustion engines, both gasoline and diesel are pointed as the main mechanism to which PM is formed in urban areas. Additionally, road traffic related activities can also be the source of PM (Bond,2013).

Comparing exhaust emissions of motor vehicles running on gasoline and diesel shows that diesel engines release more PM into the atmosphere, compared to gasoline engines, studies also show that diesel heavy commercial vehicles are the ones that

produce more PM in the diesel category. Analyzing non exhaust related PM in cars can be difficult, as they can be influenced by many different factors, such as, the properties of the materials (type of tire, type of break, how rough the pavement is), and weather factors (temperature and humidity). Different countries or manufacturers can have multiple standards of construction, and for that reason analyzing non exhaust related PM emissions across Europe can show considerable variability (Thorpe,2008 ).

## 2.4 Impacts on health

Prolonged exposure to PM can have adverse health effects on human health and can be related to different health conditions, such as cardiovascular diseases, respiratory diseases, cancer, pregnancy complications and many others (Lee, 2021). Assessing the adverse effects of PM can be difficult because the air composition can vary from place to place and individuals can be exposed to a vast mixture of substances, that can have different effects depending on the person and the time of exposure (Bastos, 2019).

Operators of motor vehicles, passengers, pedestrians, or cyclists are often exposed to high concentrations of PM due to the proximity of roads in normal day to day activity. Operators and passengers of motorized vehicles have a higher probability of exposure to PM than does that travel by foot or cycle. However, considering that the latter is directly exposed to the air (not inside a motor vehicle) as well as longer commute times can lead to higher doses of PM inhaled and deposited in the respiratory system compared to those who travel in a motor vehicle (Bastos, 2019).

There are multiple scientific studies that demonstrate the relationship between exposure to PM and adverse health effects, independent of the level of development of the country. WHO establishes a clear relation between multiple diseases and even premature deaths related to PM, mainly PM10 and PM2.5 (WHO, 2018). PM2.5 in particular, due to its size, can easily penetrate the human respiratory system, and can even reach areas outside the pulmonary system, such as the nervous system. Evidence also suggests that PM can cause irritation in the pulmonary system and escalate existing chronic pulmonary diseases, such as asthma. PM is also composed of

different components which are harmful for the health, such as heavy metals, carbon composites, and even cancerogenic elements (WHO, 2018).

Studies also reported that short and long-term exposure to PM<sub>2.5</sub> can be associated with multiple health risks, such as cancer. In 2013 the IARC (International Agency for Research on Cancer) added PM<sub>2.5</sub> to its list of cancerogenic substances for human beings (IARC, 2013).

Coarse particles (PM<sub>10-2.5</sub>) ignore the natural defenses of the body like the nose and throat depositing themselves on the thorax. These can be expelled by the body through coughing or sneezing, however as PM<sub>2.5</sub> due to its size, are capable of penetrating deeper into the lungs, and can cause problems in the lungs and even hearth. Moreover, they can introduce harmful substances into the bloodstream and can stay in the body for longer periods of time (Chair, 2010).

## 2.5 Impacts on Environment

PM can have different impacts on the environment such as reduced visibility, mainly a problem in urban areas. The level of impact on the visibility depends based on multiple factors, such as density of the concentrated particles, the size of the particles, weather conditions, time of day, etc. Related to the lack o visibility is the reduction of solar radiation caused by the absorption of solar rays by the particles. This can lead to a decrease in temperature which can lead to serious environmental impacts (Dubey, 2018)

PM can also cause harm in vegetation and water bodies, if its concentrations are high and toxic or of big dimensions, they can reduce crop production blocking plants natural process. If they are alkaline or acid they can change the pH of water bodies, and if the particles are toxic they can get into contact with plants and animals and affect the food chain (Dubey,2018).

## 2.6 Guidelines

Despite efforts to improve air quality within the EU, many countries still registered exceed the quality standards established by the 2008 Air Quality Directive, an agreement among all member states setting pollutant threshold limits in the EU. These legally binding thresholds, transposed into national law for each member state, for Portugal thresholds are under the Directive 2008/50/CE of May 21. These values are notably less strident than those recommended by the World Health Organization (WHO). Table 1 delineates the standards defined by EU and WHO.

	Directive 2008/50/CE of May 21		WHO	
	Daily Limit Thresholds (24h) (average)	Annual Limit Thresholds (average)	Daily Limit Thresholds (24h) (average)	Annual Limit Thresholds (average)
<b>PM2.5</b>	-	25 $\mu\text{g}\cdot\mu\text{m}^3$	25 $\mu\text{g}\cdot\mu\text{m}^3$	10 $\mu\text{g}\cdot\mu\text{m}^3$
<b>PM10</b>	50 $\mu\text{g}\cdot\mu\text{m}^3$ , not exceed more than 35 days in one year	40 $\mu\text{g}\cdot\mu\text{m}^3$	50 $\mu\text{g}\cdot\mu\text{m}^3$	20 $\mu\text{g}\cdot\mu\text{m}^3$

**Table 1:** EU and WHO Thresholds

As reported by (Lopes, 2019), the European Environmental Agency's Air Quality Report (EEA,2018) reveals that 19% of air quality monitoring stations recorded exceedances of daily PM10 limit. Furthermore, annual PM10 concentrations breaches were detected at 6% of these stations. Regarding PM2.5 levels, annual limits were exceeded at 5% of stations throughout the EU. When assessed against WHO's stricter PM10 guidelines, 48% of stations from all reporting countries (with the exceptions of Estonia, Iceland, Ireland, and Switzerland) exceeded these thresholds. Similarly, for PM2.5, 68% of stations from the reporting countries (excluding Estonia, Finland, Hungary, Norway, and Switzerland) exceeded WHO' recommended limits. This report also highlights the stark contrast between EU and WHO standards, showing that in 2016, 13% of urban areas in the EU experienced levels surpassing EU limits for pollutants, a figure that escalates to 42% under WHO guidelines. For PM2.5 exposure, only 6% of the EU's urban population were subjected to concentrations above EU limits, a percentage that dramatically increases to 74% when evaluated against WHO standards.

The challenge of aligning with WHO's PM guidelines remains significant for Europe. Despite initiatives to reduce air pollution, numerous EU nations still report PM concentrations levels above the thresholds established by the 2008 directive. This gap between the EU and WHO standards highlights the urgent need for enhanced and more stringent measures to achieve the 2030 objective of meeting WHO guidelines.

## 2.7 PM dispersion

Weather conditions heavily affect PM dispersion being composed of two main components:

- **Vertical** component created by the turbulence generated by the thermic vertical gradient between the lower levels of the atmosphere.
- **Horizontal** component in which the wind is the main component in both transport and mixture.

Atmospheric processes and the circulation of high-pressure centers determine the weather above continents and oceans. High pressure centers also known as anticyclones are associated with great stability and low vertical mixture, for that reason, there is low dispersion of PM. Low pressure centers are associated with conditions of atmospheric instability with great turbulence which favors PM dispersion.

In winter colder days, the sun during the day heats the air next to the surface of earth. At the end of the day, after the sun sets there is a quick cooling of the air which is mostly felt closer to the ground. When lower layers of the atmosphere have lower temperatures than the ones at higher altitudes, it occurs a thermic inversion, which creates high atmospheric stability, and the dispersion conditions are lower. For this reason concentrations measured during this time period might be higher than the others (Zheng, 2005).

## 2.8 Mitigation Policies

Due to the increase in emissions produced by motorized vehicles, in particular urban areas, there was an increase concern by government bodies to control this type of

pollution. As mentioned above the EU directive of 2008 set goals and measures for member states to implement in order to improve Europe's air quality.

The concept of sustainable mobility is widely used in this document and is one of the main strategies to mitigate pollution levels. The goal is to increase the energy efficiency of movement in order to reduce its environmental impact. The main objectives of sustainable mobility are as follows:

- Minimize the use of personal transportation.
- Optimize the use of public transportation.
- Increase the use of soft modes of transportation (these are ways of transportation more friendly for the environment such as walking or cycling)

The implementation of these policies requires deep urban changes not only in a physical sense, with changes to urban infrastructure but also how the public sees these policies and the advantages of adopting to more environmentally friendly modes of transportation. There needs to be changes to the structure of territories, public transport infrastructure and public places better design to adopt these changes.

One of the first strategies implemented by member states to mitigate this type of pollution are the Low Emissions Zones (LEZ), these zones are designed to limit or restricted access to certain urban areas by certain types of vehicles.

In order to study the capability of LEZs a study was conducted in which analyzed changes in air quality of five EU member states that implemented LEZ (Denmark, Germany, Netherlands, Italy and UK). (Guevara, 2016) The study showed mixed results, although Germany showed a reduction in annual PM10 concentrations of up to 7% in those areas, the same results weren't shown in different urban areas. These results might be related to the type of vehicles that were restricted in German ZER (it restricts the entry to diesel vehicles and passenger vehicles while other countries only restricted diesel vehicles). The low percentage of the reduction of PM10 might also be due to the fact that the ZER limitations don't cause an impact in PM10 emissions of other sources (non-vehicular exhaust emissions), which represent a significant percentage of primary emissions of road traffic.

The Implementation of LEZs is not the only project used to better air quality, there are other measures of local, national and international planning and transport policies

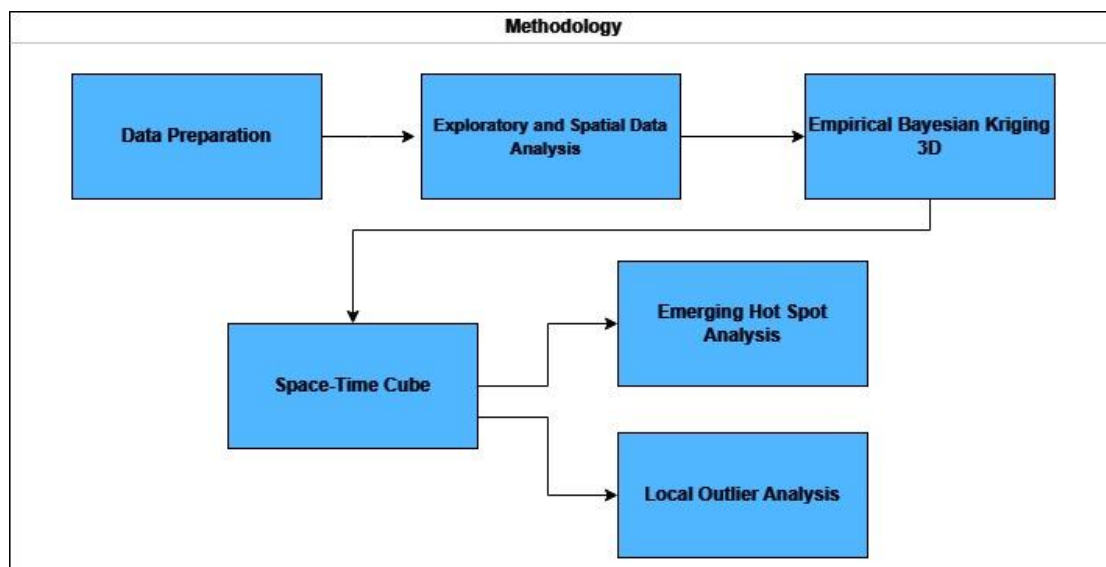
being implemented to help mitigate road traffic emission in urban areas. In New York City taxing fees were used in areas with high road traffic to increase the cost of circulation in certain areas during certain periods of the day. The goal was direct traffic flow to less congestion roads across the city. (Schaller, 2010)

In Beijing, China a temporary restriction of driving based on license plate numbers was used to control the number of cars allowed to drive every day. The system was based on the last digit of the license plate there was a day for odd and even numbers throughout the week. This system was used during the 2008 Olympic games and showed promising results in the reduction of road traffic emissions. After the games were held a less restrictive system was implemented and the restriction happen only once a week. However, it was slowly bypassed by the population as people bought both an even and odd license plate (Huijuan, Fujii & Managi, 2013).

### 3 METHODOLOGY

This chapter describes the methodology used in this thesis, which was divided into six stages, as seen on Figure 1.

The first stage of data preparation involved organizing the collected data, addressing any missing, incorrect, or inconsistent values to ensure data integrity. The next stage is the Exploratory Spatial Data Analysis (ESDA), where data was characterized using both spatial and descriptive statistics. The third stage involved doing a 3D interpolation of the data using the Empirical Bayesian Kriging 3D (EBK3D) method. The fourth stage involved taking the output of the EBK3D interpolation and integrating it in a Space-Time Cube using ArcGIS Pro software. The fifth and six stages an Emerging Hot Spot Analysis and Local Outlier Analysis was made using the Space-Time Cube created in the fourth stage.



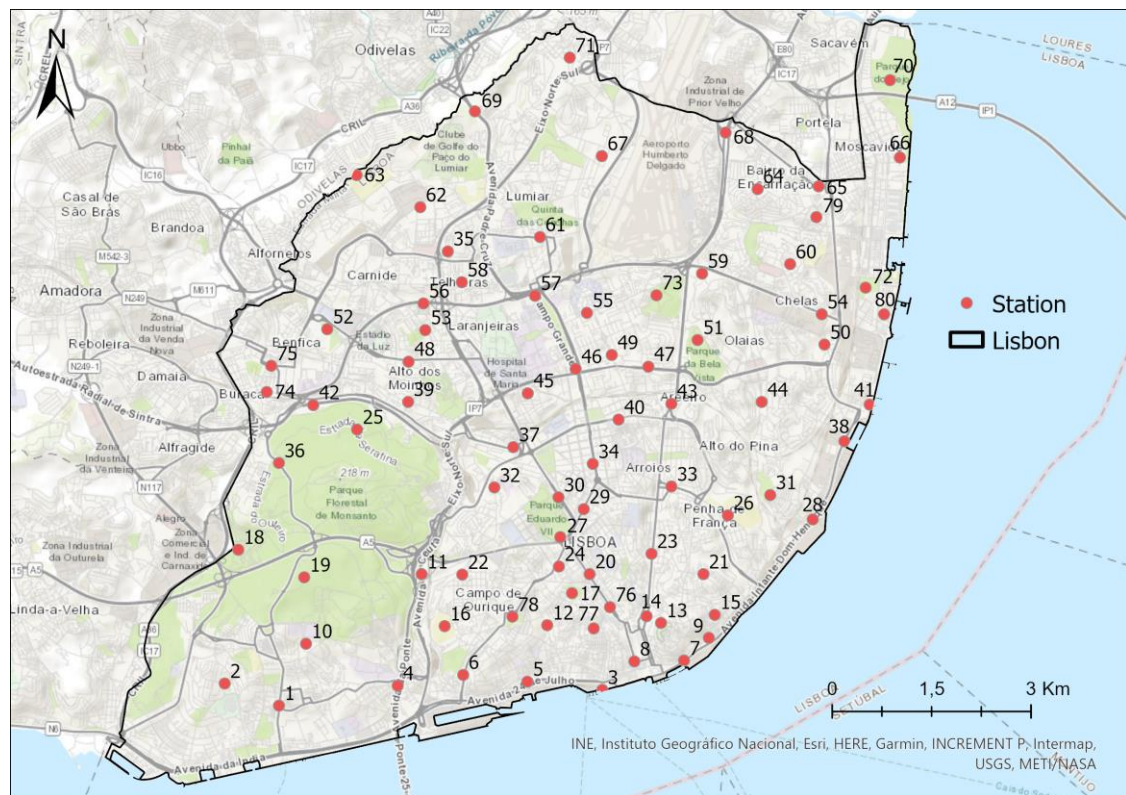
**Figure 1:** Methodology Flow Chart

#### 3.1 Data

The data used in this thesis is from an air quality monitoring network that is provided by the Lisbon municipality under the “Lisboa Aberta” program (Lisboa Aberta, 2024). The stations are managed by the consortium of MEO/Monitar/QART, and is also part of the European union program “Sharing Cities”. This network has been operational since august 2021, and is comprised of 80 monitoring stations that monitor different

environmental parameters, including PM10 and PM2.5 (Figure 2). These stations are equipped with sensors that measure the hourly average concentrations of these two types of PM. The location of each sensor may vary between light post or building. This monitoring network serves to reinforce the previous fixed monitoring network which at the time was only composed of 6 stations in the city of Lisbon. Due to these stations only been online since august 2021, for this study year 2022 was selected as it is at the time of writing this thesis the only year to which there is full data.

There is no metadata available related to the type of stations (if they are related to traffic or background), or the exact positioning of the stations (where they are mounted, at what height, etc.) which can influence the data as buildings play a crucial role in PM dispersion, so this needs to be taken into account when analyzing the results.



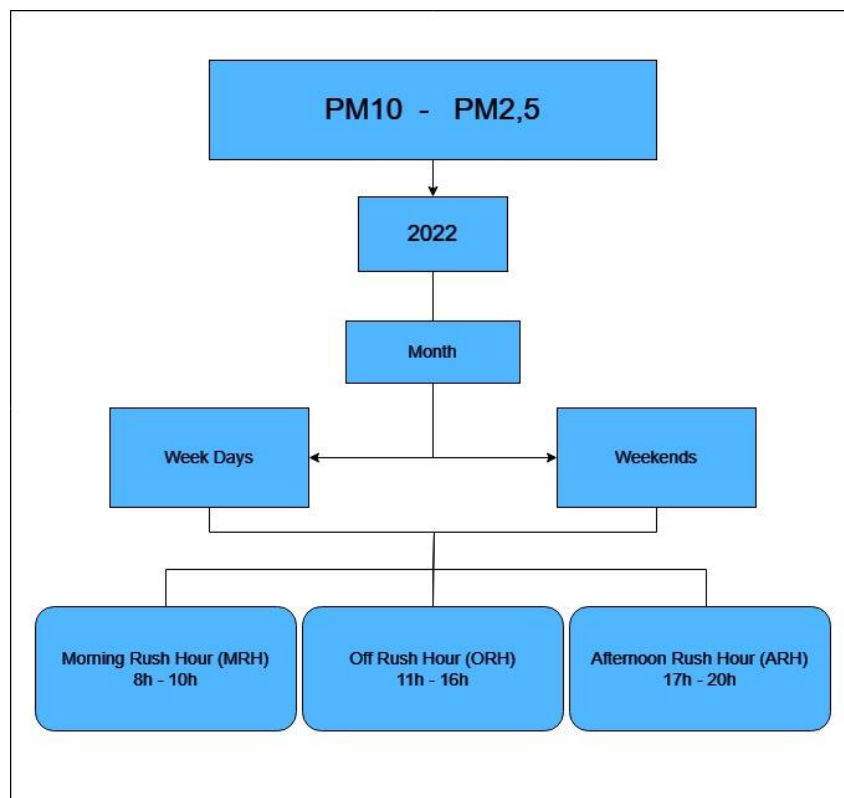
**Figure 2:** Monitoring Stations

### 3.2 Data Preparation

In this chapter the data preparation process will be explained. The initial step involved gathering PM10 and PM2.5 concentrations data for the year 2022 (as mentioned before it was the only available year) from all 80 monitoring stations. The collected

data underwent a thorough quality check, where error values marked as -99, as well as values exceeding 1500  $\mu\text{m}$  as they were also considered errors in the metadata, although this type of data error wasn't very common, and only appeared in less than 20 hours for the full year. Following this process, data was organized as seen in Figure 3. Data was organized by month and also divided into weekdays and weekends. Each of these subsets was then categorized into distinct time periods: Morning Rush Hour (MRH) from 8h to 10h, Off Rush Hour (ORH) from 11h to 16h, and Afternoon Rush Hour (ARH) from 17h to 20h, in order to analyze variations levels during different times of the day.

In instances where monitoring stations had missing data, a decision criterion was established to maintain the integrity of the dataset. Stations that reported less than 50% of data for any given month were excluded from the analysis for that specific month and time period. This was made to ensure the maximum number of stations was retained for each temporal segment without compromising data quality. Throughout this process, one station was removed from the data set (station 19), due to the high number of error and missing data. The preprocessing process was made using Microsoft Excel.



**Figure 3:** Data Preparation

### 3.3 Exploratory Spatial Data Analysis

In the Exploratory Spatial Data Analysis (ESDA) segment of the thesis, a comprehensive approach was adopted to understand patterns, anomalies, trends, and relationships. Summary statistics including minimum, maximum, and median allowed to get a better understanding of PM for each time interval. Skewness and kurtosis were calculated to quantify the asymmetry and peakedness of the data distribution, aiding in the identification of directional biases and the presence of outliers. Visualizations methods such as histograms and scatter plots were used to better understand the data. Finally, a preliminary Inverse Distance Weighting (IDW) interpolation was employed to estimate values and get an overall understanding of PM distribution. This process was conducted using ArcGIS Pro 3.0.

### 3.4 Empirical Bayesian Kriging 3D

Empirical Bayesian Kriging (EBK) is a geostatistical interpolation method that has evolved from the traditional kriging techniques, combining the strengths of Kriging with Bayesian statistical methods. The main difference between EBK and other Kriging methods is its empirical approach to model the underlying spatial autocorrelation in the data, which is essential for making accurate predictions. Traditional Kriging methods require a predefined semivariogram model to describe this spatial relationship, which can be challenging to determine accurately. EBK, however, automates this process by using the data itself for the generation of the semivariograms. This approach simplifies the modeling process and enhances the reliability of the interpolation by averaging over a range of possible semivariogram models. Additionally, it incorporates Bayesian statistics and automatically accounts for the uncertainty in the semivariogram model, providing a more robust and realistic estimation of spatial variability (Krivoruchko, 2019; Gribov, 2020).

Empirical Bayesian Kriging 3D (EBK3D) extends the capabilities of EBK into three-dimensional space. It uses the same empirical Bayesian framework to model spatial correlation in three dimensions. The major advantage of EBK3D is, as mentioned before the ability to handle 3D spatial relationships, as opposed to EBK which is limited to two-dimensional data. Both methods share the benefit of automating the semivariogram modeling process, which simplifies the user's task and reduces the level

of expertise that would otherwise be required in order to perform this type of spatial analysis. (Esri, 2024f)

The EBK3D was made using ArcGIS Pro 3.0 which provides a series of statistical metrics when building the semivariogram that were used to calculate a more accurate prediction. Each metric will be discussed below as outlined by Esri. (Esri, 2024a)

$$ME = \frac{1}{n} \sum_{i=1}^n (y_i - x_i)$$

**Mean Error (ME):** Calculated as the average of the differences between the predicted values ( $y_i$ ) and the observed values ( $x_i$ ).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - x_i)^2}$$

**Root Mean Square Error (RMSE):** It is the square root of the average of the squared differences between  $y_i$  and  $x_i$ .

$$SME = \frac{1}{n} \sum_{i=1}^n (y_i - x_i) / \sigma(y_i)$$

**Mean Standardized Error (SME):** It's the average of the standardized differences ( $y_i - x_i$ ) divided by the standard deviation  $\sigma(y_i)$ .

$$RMSSE = \sqrt{\frac{1}{n} \sum_{i=1}^n [(y_i - x_i) / \sigma(y_i)]^2}$$

**Root Mean Square Standardized Error (RMSSE):** Similar to RMSE but for the standardized differences, providing a normalized measure of error.

$$ASE = \sqrt{\frac{1}{n} \sum_{i=1}^n \sigma^2(y_i)}$$

**Average Standard Error:** This is the square root of the average of the squared errors  $\sigma^2(y_i)$ .

$$RVar = \frac{Var(y_i)}{Var(x_i)}$$

**Ratio of Variance (RVar):** A measure comparing the variance of predicted values ( $y_i$ ) with that of observed values ( $x_i$ ).

**Average Continuous Ranked Probability Score (CRPS):** A measure comparing the predictive cumulative distribution function with the empirical cumulative distribution function for each observation.

The goal being to have a ME and SME close to 0, RMSE and CRPS as low as possible, RMSSE close to 1, ASE approximate to RMSE, RVar near 1, and Percent in 95% interval close to 95%.

The analysis of these statistics helps in interpreting the variability of the predictions, such as, if ASE is approximately equal to RMSE and RMSSE is close to 1, the prediction variability is correctly assessed. If ASE is larger than RMSE and RMSSE is smaller than 1, it indicates an overestimation of variability. ASE is smaller than RMSE and RMSSE is greater than 1, there's an underestimation.

The process for the configuration of the EBK3D's advanced model parameters was done based on a combination of testing different modeling strategies, analysis of use case descriptions from Esri (Esri, 2024a), analysis of cross-validation outcomes, and the visual appearance of the interpolated surfaces. The parameters were changed based on a trial-and-error process using the criteria mentioned a before with the goal of achieving the ideal values. The parameters that were modified are the subset size, overlap factor, transformation type, semivariogram type, and order of trend removal, the remaining parameters were left as default. The parameters chosen will be explain further in the results as they are slightly different in PM10 and PM2.5 in order to fulfill the criteria mentioned above.

### 3.5 Space Time Cube

The ArcGIS Space Time Cube is a tool designed to analyze spatiotemporal data, in order to, effectively visualize and understand how a phenomenon (in this case PM values) change over both space and time. At its core, the Space Time Cube is a 3D data structure, where two axes represent spatial dimensions (X and Y coordinates) and the third axis represents time. This 3D representation allows for a comprehensive and dynamic analysis of data, providing insights that may not be easily comprehended through traditional 2D spatial analysis. (Esri, 2024b)

The cube is created using ArcGIS software and saved as NetCDF file. The key components of the cube are: the **Bins** which are a fundamental aspect of the cube, as it can be seen on the same figure, each individual smaller cubes are called a bin, each bin represents a specific spatial location at a specific time interval (in the case of this thesis each location has 12 bins, representing each a month of the year). The binning process turns continuous spatial and temporal data into a discrete set of spatial temporal units; Another key component is the **Data Aggregation** which means that within each bin, data can be aggregated in various ways depending on the analysis needs, ArcGIS provides a number ways in which data can be aggregated, but for this analysis no aggregation was used in order to have the values created during the interpolation; the final component is the **Temporal Dynamics** which is the ability to capture and represent temporal dynamics, data can be organized in different ways depending on the time period that is being studied, in this case is organized by month starting with January and ending with December (bottom to top).

ArcGIS provides three ways of creating a cube (Esri, 2024b) it can be created by aggregating points, from defined locations, and from a multidimensional raster. In this study the create space time cube from defined locations was used as it was the most suitable for the type of data. This method maintains the spatial integrity of the input features, ensuring the spatial component remains constant throughout the analysis. In order to create the cube using the values from the EBK3D analysis, a 500m fishnet grid was created and the time dimension was added (as the EBK3D doesn't create a time dimension), that grid was used to export the EBK3D prediction using the points created, a ID was also created for each of the points locations. Using this method, it satisfied all the necessary attributes required by the tool to create the space time cube.

### 3.6 Emerging Hot Spot Analysis

The Emerging Hot Spot Analysis is ArcGIS pro is a tool used for identifying trends and patterns in spatial-temporal data. It analyzes data within a Space Time Cube to categorize different areas as hot and cold spots based on their clustering over time. It calculates an hotspot analysis for each bin using the Gettis-Ord  $G_i^*$  statistic, a method that identifies Hot Spots and cold spots by comparing local statistics to the overall mean (Getis, 1992). A high positive  $G_i$  value indicates a hotspot, where values are

higher than the average, while a lower than average suggests a cold spot. Next the tool assesses these identified hot and cold spot trends utilizing the Mann-Kendall trend test (Mann, 1945; Kendall, 1975). It then classifies each location in the study area based on the trend z-score and p-value for each bin, which is then given one of seventeen categories (Esri, 2024d).

### 3.7 Local Outlier Analysis

The Local Outlier Analysis tool identifies spatial outliers within spatiotemporal datasets (Esri, 2024e). It categorizes each data point within the space time cube based on its spatial context, distinguishing between clusters and outliers. By analyzing spatial relationships, this tool highlights areas exhibiting significantly different behaviors compared to their surroundings. It uses the Anselin Local Moran's I statistic method to calculate the outliers (Anselin, 1995).

## **4 RESULTS**

### **4.1 Exploratory and Spatial Data Analysis**

#### **4.1.1 PM10**

#### **4.1.2 PM10 - MRH**

The results of the ESDA for PM10 MRH on week days and weekends, are described in Appendix A1.1 and A1.2 respectively. For week days the mean and standard deviation were greater on the months of January and February, and October through December with December having the highest values. The lowest values were registered in the months of April through June, overall, the mean values of every month stayed below the limit threshold, although in every month some stations had values over the limit threshold which is evident on the maximum values and the IDW, mainly on the months of October through December. Values were positively skewed, except for February, March, and October. Kurtosis values were for January and February, indicating that the distribution had heavier tails and more extreme values than the normal distribution. For the weekends mean and standard deviation values were lower than the week days but with a similar pattern. Only the months of May and August had negative skewness, with the rest being positive. Kurtosis was lower than 3 in January, February, August, and November, with the remaining months being higher. June and December had much more extreme value than the rest of the months. Overall values above the limit threshold were scientifically lower on the weekends than the week days for the same time period.

#### **4.1.3 PM10 - ORH**

ORH for week days and weekends is described in Appendix A1.3 and A1.4 respectively. For week days the mean values were higher on the months of January, February, and September through December. The lowest mean values were between April and June with a slight increase in July and August. Standard deviation was roughly the same, except for September which was much higher than the others. In terms of skewness all months had positive values. Kurtosis was lower than 3 in January, February, April, August, November, and December. September had the

highest value due to having very extreme value compared with the normal distribution. For the weekends, similar to the previous time period the mean and standard deviation values are lower on the weekends compared to week days, with similar trend regrading each month. All months showed positive skewness. Kurtosis was higher than 3, except for January and February, with the highest values in July and December. Overall ORH week days and weekends show similar patterns compared to the MRH, although ORH mean values are lower than MRH on both periods, ORH weekends showed a bigger number of exceeding levels of PM10 than MRH on the same days.

#### **4.1.4 PM10 - ARH**

ARH is described in Appendix A1.5 for weekdays and A1.6 for weekends. For week days mean and standard deviation values were higher in January, February, August, October, November and December, with December having much higher values than the rest of the months. The lowest values were in the months of April through June. For this time period August had bigger values compared to the trend of the other periods analyzed. All months were positively skewed. Kurtosis was higher than 3, except for the months of January, February, October, and November. August had much higher kurtosis value than the others, due to having higher and more extreme values compared with the normal distribution. For the weekends mean and standard deviation values were much lower than the weekdays, similar to the pattern observed before with the exception of September which had much lower values, and December with much greater values compared with the rest of the months. The skewness values were positive, except for August. Kurtosis was higher than 3, except for January, indicating that the distribution had more extreme values than the normal distribution. Overall, ARH on week days is slightly lower than the MRH on most months except for December, and slightly bigger than ORH. For weekends ARH is generally the lowest of the three except for the month of December.

#### **4.1.5 PM2.5**

#### **4.1.6 PM2.5 - MRH**

MRH is described in Appendix A2.1 and A2.2 for week days and weekends respectively. For weekdays the mean and standard deviation were greater in January, February, and September through December, with December having the highest value very close of passing the limit threshold, but overall, all months were below the limit. The skewness was positive across all months. Kurtosis was lower than 3, except for September, meaning that the distribution had lighter tails and less extreme values than the normal distribution. For the weekends standard deviation was stable across all months and the mean was also very similar, June had the lowest mean value and December the highest, however the difference is not that significant. All months had a positive skewness. Kurtosis was higher than 3, except for February, April, and September, which indicates the presence of more extreme values than the normal distribution. Overall MRH on week days is higher when compared with other time periods across almost every month. On weekends MRH is higher than other time periods in March, April, May, July, and August.

#### **4.1.7 PM2.5 – ORH**

ORH week days and weekends, is described in Appendix A2.3 and A2.4, respectively. On week days the standard deviation is stable across every month. Mean values are highest between January, February March, and October through December. All months are positively skewed. Kurtosis values are lower than 3, except for December, which means the distribution had lighter tails and fewer extreme values compared with the normal distribution. On weekends the standard deviation is stable across every month as well as the mean, with the highest value being December but overall the mean trend remains the same as other time periods with week days having higher mean values than weekends. Skewness values were all positive. Kurtosis values higher then 3, except for April and May, similar to MRH weekend values tend to have a higher kurtosis. Comparing ORH with other time periods, we can say that ORH is the lowest of the three on both week days and weekends.

#### **4.1.8 PM2.5 – ARH**

ARH on week days and weekends is described in Appendix A2.5 and A2.6. For the week days mean values are below the limit threshold with December coming very close to exceeding, values the lowest between April and July. Standard deviation values are stable and positively skewed across all months. Kurtosis is lower than 3, except for the month of May and September, similar to the other two time periods where on week days the kurtosis is lower than three with some exceptions. For weekends the mean and standard deviation are higher in January and December, with an overall trend of the mean similar to other time periods. Skewness is positive across all months. Kurtosis is higher than 3 in the months of February, March, May, August, September, and October, indicating higher or more extreme values in these months compared to the others. Overall comparing ARH is very similar with the MRH period slightly lower on average but shows very similar results on week days. During the weekends tends to be higher than MRH period during the months of January, October, November, and December.

## **4.2 Empirical Bayesian Kriging 3D**

EBK3D cross-validation statistics can be seen in Table 2. Overall, the method performed reliably with minor changes to the default advanced model parameters. There were some differences in the performance of the two different PM, but both achieved good results and had minor differences of results for each of the time periods. Different search neighborhoods were used for PM10 and PM2.5 mainly based on the visual aspect of the model and not based on the cross-validation results which showed insignificant changes. Using different sector types mainly impacted the visual aspect of the interpolated surface, and were selected based on these criteria alone. Looking at Table 2 the performance of each model was slightly different on each case, when setting the model parameters and analyzing the cross-validation results minor changes could be made to each, although they weren't significant and for that reason it was better to use a similar model for each case, changing the sector and neighborhood if significant changes were visualized. On most cases the ME and SME were both close to 0, showing a unbiased prediction. ASE was close to the RMSE and the RMSSE was close to 1 for PM10 weekends MRH, ORH, and ARH, week days didn't show as good results but it was still very close to that target, PM2.5

performed the best on both week days and weekends, with the exception of week days ARH. The percentage points inside the 95 percent interval were, with few exceptions, close to 95% suggesting that the model had and overall good performance. Average CRPS results showed slightly worse results for PM10 week days on the three periods and for PM2.5 weekends ORH. Analyzing the results, we can observe that generally the number of samples had a slight impact on the model performance, although the differences in the number of samples for each model is not significant.

			<b>MRH</b>	<b>ORH</b>	<b>ARH</b>
<b>PM10</b>	Week Days	Average CRPS	1,9253186	2,954744	0,001139868
		Inside 90 Percent Interval	93,628088	94,72991	92,53112033
		Inside 95 Percent Interval	95,968791	96,31094	95,02074689
		Mean	-0,345395	-0,56507	-0,193787353
		Root-Mean-Square	1,6717398	1,707321	2,730620898
		Mean Standardized	-0,034116	-0,06365	-0,014231785
		Root-Mean-Square Standardized	0,5605864	0,976796	1,10657277
	Average Standard Error	0,3723336	0,171405	0,121982943	
	Weekends	Average CRPS	0,377323	1,634583	0,678411438
		Inside 90 Percent Interval	91,961853	93,21383	91,25326371
		Inside 95 Percent Interval	95,776567	96,15877	96,08355091
		Mean	-0,064457	-0,10534	-0,182743435
		Root-Mean-Square	0,0265319	0,738225	0,674823928
		Mean Standardized	-0,003361	-0,01519	-0,016973458
Root-Mean-Square Standardized		0,6375992	0,774436	1,162878174	
Average Standard Error	0,0350026	0,116884	0,995211389		
<b>PM2.5</b>	Week Days	Average CRPS	0,6879175	2,066574	0,05082201
		Inside 90 Percent Interval	91,454082	91,21172	91,28686327
		Inside 95 Percent Interval	95,642857	94,94008	95,30831099
		Mean	-0,088983	-0,15541	-0,232171836
		Root-Mean-Square	0,7507313	0,218055	1,273589524
		Mean Standardized	-0,029168	-0,02872	-0,050844966
		Root-Mean-Square Standardized	0,2295961	1,059213	0,128480813
	Average Standard Error	0,3556574	1,262782	0,23568247	
	Weekends	Average CRPS	1,0612272	0,981601	0,234333473
		Inside 90 Percent Interval	90,087829	89,94845	90,33942559
		Inside 95 Percent Interval	95,483061	94,71649	95,03916449
		Mean	-0,147496	-0,1545	-0,081631622
		Root-Mean-Square	0,9669044	0,07903	0,506472409
		Mean Standardized	-0,039727	-0,03429	-0,018424825
Root-Mean-Square Standardized		0,0813832	0,015033	0,103117343	
Average Standard Error	0,970639	0,424993	0,493957064		

**Table 2:** EBK3D Model Parameters

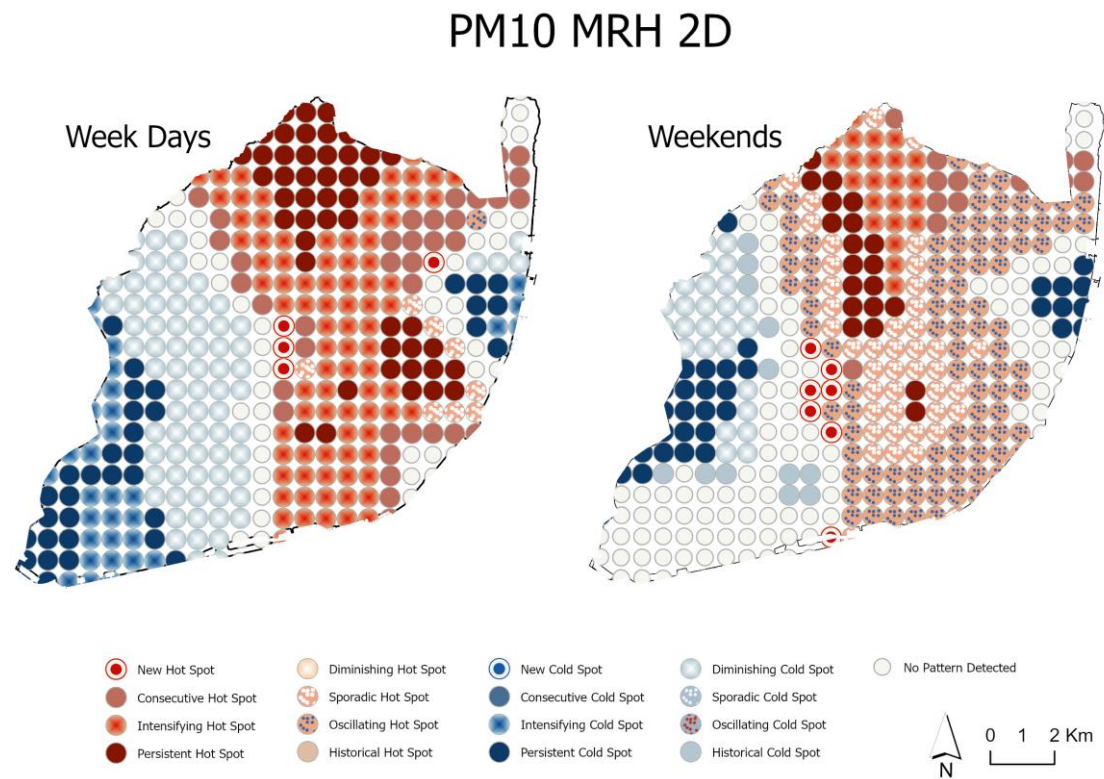
## 4.3 PM10 Emerging Hot Spot

### 4.3.1 PM10 - MRH

Based on the space-time cube of PM10 MRH (Figure 4), several hot and cold spots were identified (Table 3). For week days 10 types of spatial-temporal cold and Hot Spots were identified. Hot Spots were distributed mainly in the middle north and south of Lisbon creating a corridor of Hot Spots, while cold spots were identified in the east and west of the city. The categories Hot Spots include: consecutive, intensifying, new, oscillating, persistent, and sporadic. The number of Intensifying Hot Spots was the largest, meaning that these locations tend to increase over time and that its increase is statistically significant (Esri, 2022d). Persistent Hot Spots were the second highest, concentrated mainly in the north of Lisbon in the parishes of Santa Clara, Lumiar, part of Olivais (around the Lisbon Airport), and also near Penha de França, which indicates that these areas persistently a hot spot but statistically stable through time. Consecutive Hot Spots appear to border the Intensifying Hot Spots and represent a location generally aren't statistically significant Hot Spots until the last three time-step intervals (October, November and December). The areas that were identified as cold spots are mainly located in the western regions of Lisbon such as Belém, Ajuda, and Benfica, as well in the east around Marvila. The types of cold spots included: diminishing, Intensifying, persistent. Diminishing cold spots were the largest, meaning those areas are always statistically significant cold spots and keep decreasing through time. Persistent and Intensifying Cold Spots identify areas that are always statistically significant cold spots or were otherwise not significant until the last time-step interval.

Regarding the weekends during the MRH, the overall region of cold and Hot Spots remains the same, however the type of hotspot changes, with oscillating hot spot being the largest, meaning that has been a statistically significant hot spot in less than 90 percent of the time and oscillating between the two. Sporadic hot spot is the second largest which is similar to the oscillating in that is typically and on-again off-again hot spot.

Overall, the main differences between MRH week days and weekends, is that the hot and cold spots tend to vary in time more on the weekends than the weekdays, meaning that on the week days the pattern tends to be more consistent through time.



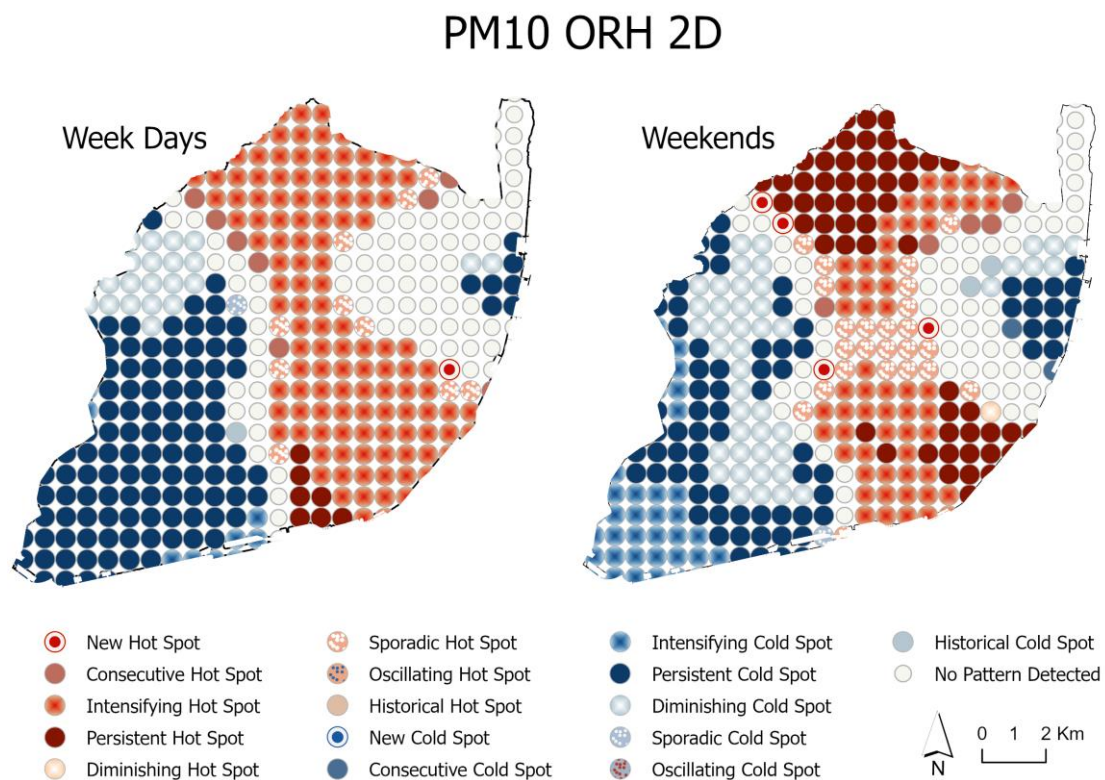
**Figure 4:** PM10 Morning Rush Hour, Emerging Hot Spot Analysis

WEEK DAYS	COUNT	%		WEEKENDS	COUNT	%
CONSECUTIVE HOT SPOT	42	7,29		Consecutive Hot Spot	26	4,52
DIMINISHING COLD SPOT	77	13,37		Diminishing Cold Spot	39	6,78
INTENSIFYING COLD SPOT	60	10,42		Historical Cold Spot	12	2,09
INTENSIFYING HOT SPOT	105	18,23		Intensifying Cold Spot	35	6,09
NEW HOT SPOT	12	2,08		New Hot Spot	18	3,13
NO PATTERN DETECTED	119	20,66		No Pattern Detected	160	27,83
OSCILLATING HOT SPOT	1	0,17		Oscillating Hot Spot	99	17,22
PERSISTENT COLD SPOT	59	10,24		Persistent Cold Spot	61	10,61
PERSISTENT HOT SPOT	81	14,06		Persistent Hot Spot	49	8,52
SPORADIC HOT SPOT	20	3,47		Sporadic Cold Spot	3	0,52
SUM	576	100%		Sporadic Hot Spot	73	12,70
				Sum	576	100%

**Table 3:** PM10 Morning Rush Hour, Emerging Hot Spot Analysis Classes

### 4.3.2 PM10 - ORH

The results of the emerging hot spot analysis for ORH can be found in Figure 5, as well as Table 4 with the counts of each class. During the weekdays, the results show different types of hot and cold spots. A significant number of Intensifying Hot Spots (26,7%) were observed, particularly in the south-central parishes of Santa Maria Maior, São Vicente, Penha de França, Arroios, as well as the center parts of Lisbon such as Avenidas Novas, parts of Alvalade, and at the north in Lumiar and Santa Clara, indicating a rise in PM10 levels over time. Persistent Hot Spots concentrated mainly in the parish of Misericórdia, reflect areas with stable but elevated PM10 values across time. Regarding the cold spots, persistent cold spots were predominantly found in the western regions of the city, in areas such as Belém, Ajuda, Alcântara, and Benfica, suggesting these areas have consistently lower PM10 values.



**Figure 5:** PM10 Off Rush Hour, Emerging Hot Spot Analysis

On the weekends, PM10 patterns shift slightly. The most prominent spots are Intensifying Cold Spots in the parishes of Belém and Ajuda, indicating a growing

trend towards lower values. Intensifying Hot Spots are observed in Misericórdia, Santa Maria Maior, and Santo António, suggesting these areas have an increase in PM10 during the weekends. Additionally, persistent Hot Spots in Lumiar and Santa Clara, and persistent cold spots on the western edge of Ajuda and parts of Benfica indicate areas where PM10 values remain consistently high or low through time, throughout the weekends. Sporadic Hot Spots in Avenidas Novas represent locations with fluctuating PM10 values, typically not consistent enough to form a pattern.

Overall, the specific types of hot and cold spots may vary between week days and weekends, the regions of Lisbon experiencing these phenomena remain consistent, with central areas more prone to Hot Spots and peripheral areas to cold spots.

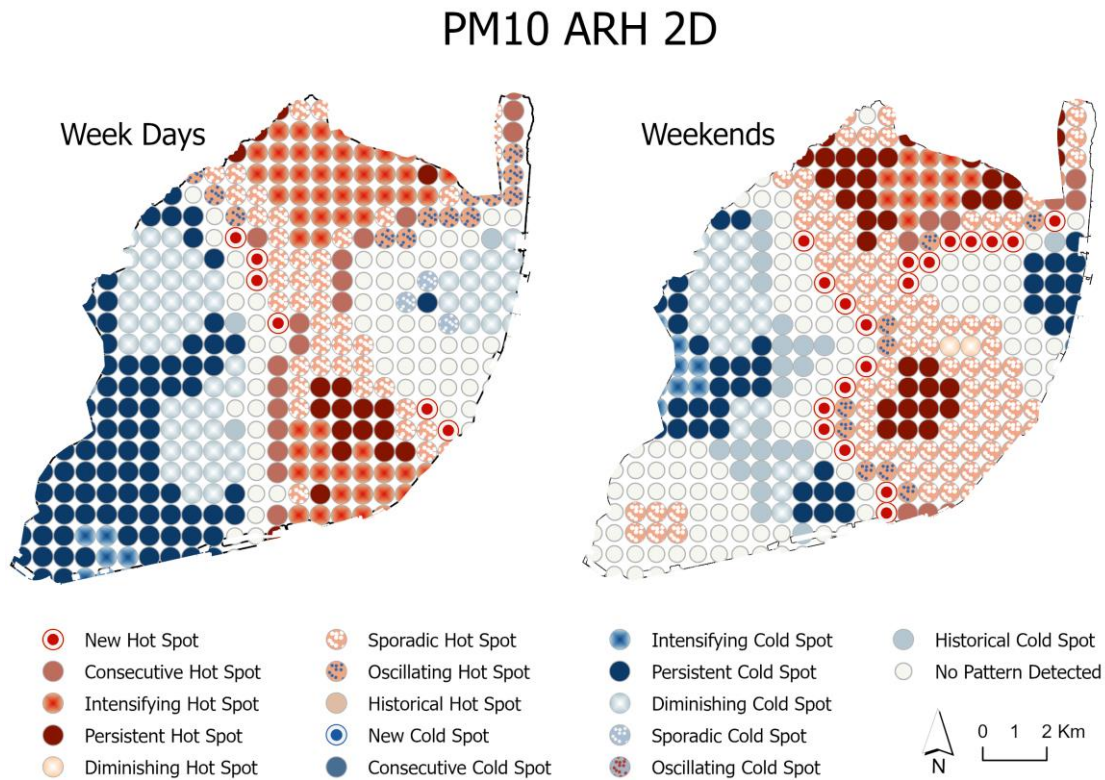
WEEK DAYS	COUNT	%	WEEKENDS	COUNT	%
CONSECUTIVE HOT SPOT	13	2,26	Consecutive Cold Spot	2	0,35
DIMINISHING COLD SPOT	34	5,90	Consecutive Hot Spot	5	0,87
HISTORICAL COLD SPOT	1	0,17	Diminishing Cold Spot	45	7,81
INTENSIFYING COLD SPOT	28	4,86	Diminishing Hot Spot	1	0,17
INTENSIFYING HOT SPOT	154	26,74	Historical Cold Spot	2	0,35
NEW HOT SPOT	5	0,87	Intensifying Cold Spot	47	8,16
NO PATTERN DETECTED	131	22,74	Intensifying Hot Spot	95	16,49
PERSISTENT COLD SPOT	140	24,31	New Hot Spot	9	1,56
PERSISTENT HOT SPOT	57	9,90	No Pattern Detected	112	19,44
SPORADIC COLD SPOT	2	0,35	Persistent Cold Spot	113	19,62
SPORADIC HOT SPOT	11	1,91	Persistent Hot Spot	111	19,27
SUM	576	100%	Sporadic Cold Spot	3	0,52
			Sporadic Hot Spot	31	5,38
			Sum	576	100%

**Table 4:** PM10 Off Rush Hour, Emerging Hot Spot Analysis Classes

#### 4.3.3 PM10 - ARH

Emerging hot spot analysis results for ARH on week days and weekends can be found in Figure 6 and Table 5. During the week days, Intensifying Hot Spots are prevalent, especially in the northern parishes of Lumiar, Olivais, Santa Clara, and southern areas such as Santa Maria Maior, São Vicente, and Santo António where PM10 levels tend to rise. The persistent Hot Spots, are located between Arroios, Santo António, and São

Vicente signifying locations that are always high compared to its neighbors. Sporadic Hot Spots are scattered across Avenidas Novas and areas bordering the Intensifying Hot Spots, indicating areas with variable but occasionally high PM10 values. Persistent cold spots make up a significant portion of the results, particularly in the western regions such as Belém, Ajuda, and south of Benfica, indicating consistently lower PM10 values. Diminishing cold spots located in the east in Marvila and the west in Alcântara, and Benfica show areas where PM10 values are decreasing in time.



**Figure 6:** PM10 Afternoon Rush Hour, Emerging Hot Spot Analysis

On the weekends, the pattern shifts slightly. The largest category of Hot Spots is the sporadic Hot Spots, indicating that central areas like Penha de França, São Vicente, Santa Maria Maior, Areeiro, Avenidas Novas, and Alvalade experience variable PM10 values through time, and are occasionally statistically significant Hot Spots. Persistent Hot Spots are more prominent in the areas of Arroios, Santo Antonio, Lumiar, and near the airport indicating that these are always significantly statistical hotspots. Historical cold spots in Campo de Ourique and near Campolide, as well as, persistent cold spots in Ajuda and Benfica indicate areas where lower PM10 values are a trend in time.

No pattern detected category is quite large on weekends, pointing towards areas where pm10 levels do not show a significant trend in time, which might be the result of a less structure of activity of weekends compared with weekdays.

Overall, ARH time period displays persistent patterns in certain areas, with intensifying values mainly in the central northern and southern parishes. Weekends tend to show more variability in terms of patterns due to the prominence of sporadic Hot Spots, but also areas of diminishing cold spots.

WEEK DAYS	COUNT	%		WEEKENDS	COUNT	%
CONSECUTIVE HOT SPOT	18	3,125		Consecutive Cold Spot	1	0,173611
DIMINISHING COLD SPOT	59	10,24306		Consecutive Hot Spot	14	2,430556
HISTORICAL COLD SPOT	3	0,520833		Diminishing Cold Spot	26	4,513889
INTENSIFYING COLD SPOT	11	1,909722		Diminishing Hot Spot	2	0,347222
INTENSIFYING HOT SPOT	89	15,45139		Historical Cold Spot	23	3,993056
NEW HOT SPOT	7	1,215278		Intensifying Cold Spot	21	3,645833
NO PATTERN DETECTED	107	18,57639		Intensifying Hot Spot	14	2,430556
OSCILLATING HOT SPOT	14	2,430556		New Cold Spot	1	0,173611
PERSISTENT COLD SPOT	140	24,30556		New Hot Spot	26	4,513889
PERSISTENT HOT SPOT	71	12,32639		No Pattern Detected	172	29,86111
SPORADIC COLD SPOT	3	0,520833		Oscillating Hot Spot	9	1,5625
SPORADIC HOT SPOT	54	9,375		Persistent Cold Spot	64	11,11111
SUM	576	100%		Persistent Hot Spot	85	14,75694
				Sporadic Cold Spot	6	1,041667
				Sporadic Hot Spot	112	19,44444
				Sum	576	100%

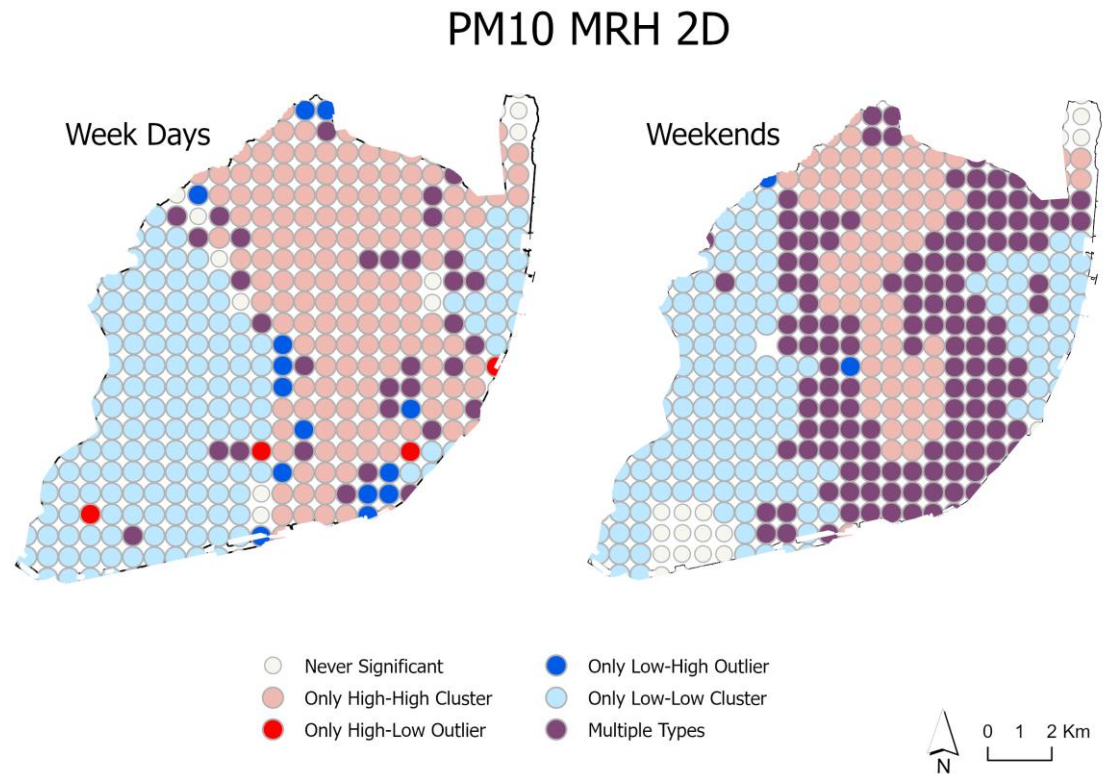
**Table 5:** PM10 Afternoon Rush Hour, Emerging Hot Spot Analysis Classes

## 4.4 PM10 Local Outlier

### 4.4.1 PM10 - MRH

The 2D presentation of the Local outlier analysis can be found in Figure 7 and Table 6. For week days the analysis identifies Only High-High Clusters as the most common type (38,02%), located in the parishes of Beato, São Vicente, Penha de França, Santo António, Avenidas Novas Alvalade, Lumiar, Santa Clara, and Olivais. These clusters identify areas where PM10 values are consistently higher than the average through time. Only Low-Low clusters are also significant (37,67%), occurring in the western part of Lisbon in the parishes of Alcântara, Ajuda, Belém, Benfica, and Carnide, and

in the east in part of Marvila, these indicate areas where PM10 levels are constantly lower than the surrounding areas through time. There is a small number of outliers mainly Low-High (2,78%) representing areas of low values surrounded by higher values, the same for High-Low but the opposite.



**Figure 7:** PM10 Morning Rush Hour, Local Outlier

Week Days	Count	%		Weekends	Count	%
Multiple Types	40	6,94		Multiple Types	147	25,52
Never Significant	79	13,72		Never Significant	59	10,24
Only High-High Cluster	219	38,02		Only High-High Cluster	163	28,30
Only High-Low Outlier	5	0,87		Only Low-High Outlier	2	0,35
Only Low-High Outlier	16	2,78		Only Low-Low Cluster	205	35,59
Only Low-Low Cluster	217	37,67		Sum	576	100%
Sum	576	100%				

**Table 6:** PM10 Morning Rush Hour, Local Outlier Classes

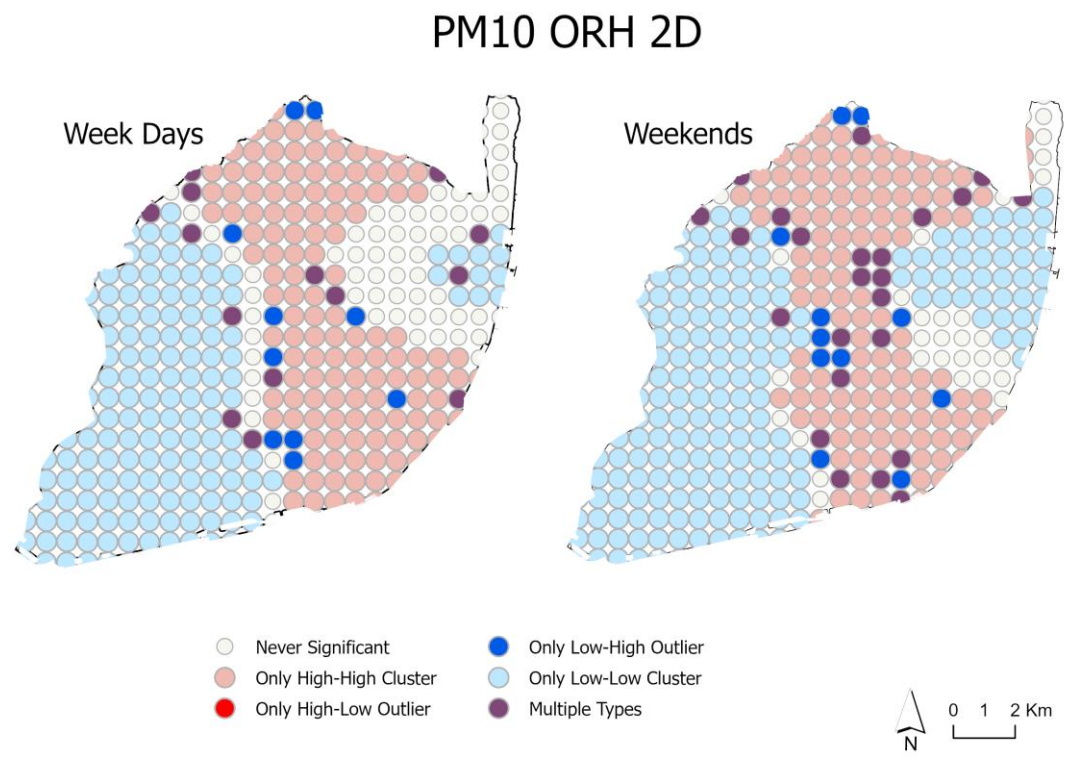
Weekends Multiple Types of clusters and outliers are more common (25,52%), and are located in the central area of Lisbon and create a border between only Low-Low cluster at the east and west, with only High-High clusters in the middle. Only High-

High cluster remain prevalent (28,30%) in central areas including the parishes of Avenidas Novas, Alvalade, Lumiar, and Santa Clara. Only Low-Low clusters are almost as common with 35,59% and are found in the western and eastern parishes of the city such as Alcântara, Ajuda, Belém, Benfica, Carnide, Marvila, Beato, mirroring the weekdays period in these areas.

In both week days and weekends the presence of never significant (13,72% on week days and 10,24% on weekends) indicates locations that don't statistically significant patterns.

#### 4.4.2 PM10 - ORH

ORH results are presented in 2D Figure 8 and Table 7. For ORH week days th largest class in Only High-High Clusters (39,24%) located in the central corridor of Lisbon including the parishes of Santa Maria Maior, São Vicente, Penha de França, Arroios, Santo Antonio, Avenidas Novas, Alvalade, Lumiar, Santa Clara, and Olivais. These are areas where PM10 levels are consistently higher than their surroundings in time. Only Low-Low Clusters are also prominent (38,54%), particularly in the western parishes such as Belém, Ajuda, Alcântara, and Benfica, as well as parts of Marvila and Parque das Nações in the east. Multiple Types (2,78%) and Only Low-High outliers (1,74%) are sporadic across the central corridor of the study area.



**Figure 8:** PM10 Off Rush Hour, Local Outlier

On weekends, the distribution shifts slightly but retains a similar pattern. Only High-High clusters (38,37%) remain very similar in distribution to weekdays. The only Low-Low clusters increase slightly to 41,84%, suggesting a bigger presence of areas with constantly low values compared with its spatiotemporal neighbors and are located in the parishes of Belém, Alcântara, Ajuda, Benfica in the west, and Marvila and Parque da Nações in the east. Multiple Types of clusters are more common (5,38%) on weekends which are scattered in the study area with small groups in Santa Maria Maior and Alvalade.

Week Days	Count	%		Weekends	Count	%
Multiple Types	16	2,78		Multiple Types	31	5,38
Never Significant	101	17,53		Never Significant	70	12,15
Only High-High Cluster	226	39,24		Only High-High Cluster	221	38,37
Only High-Low Outlier	1	0,17		Only Low-High Outlier	13	2,26
Only Low-High Outlier	10	1,74		Only Low-Low Cluster	241	41,84
Only Low-Low Cluster	222	38,54		Sum	576	100%
Sum	576	100%				

**Table 7:** PM10 Off Rush Hour, Local Outlier Classes

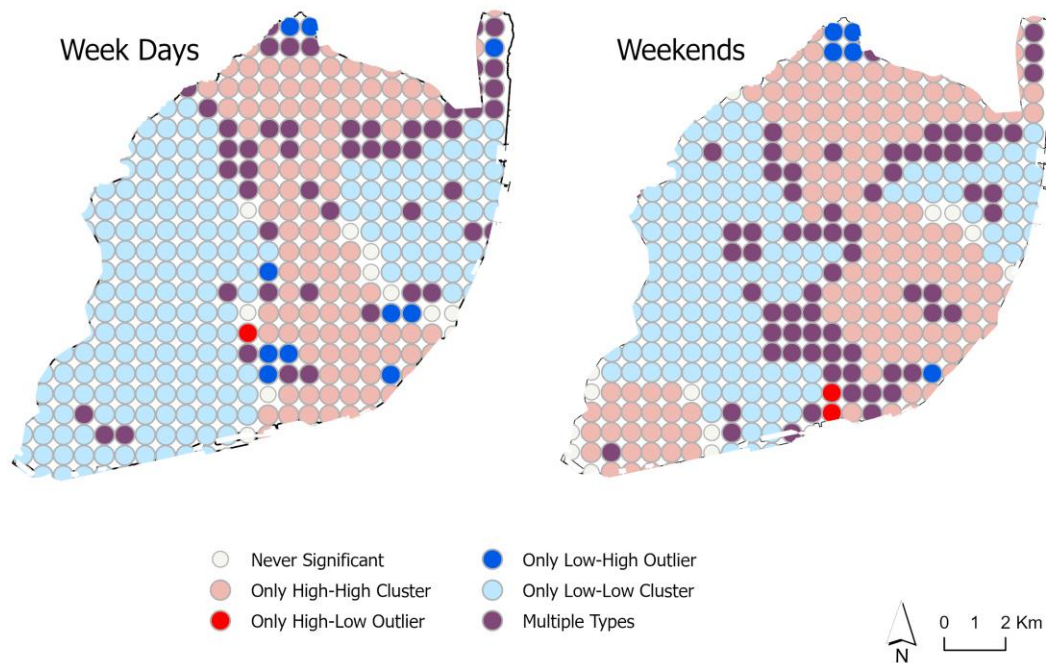
The never significant category, represents areas without statistically significant deviation from the average, accounts for 17,53% on weekdays and 12,15% on weekends, mainly in Beato and parts of Marvila, Alvalade, Olivais, and Parque das Nações.

Comparing week days and weekends, the presence of High-High and Low-Low clusters in the same areas suggests that the overall distribution remains relatively stable in the two time periods. The presence of Multiple Types and Low-High outliers on weekends compared to weekdays indicates a slight change in the distribution, however, not a significant one.

#### 4.4.3 PM10 - ARH

Figure 9 and Table 8 represent the results of the local outlier analysis. For the week days the only High-High clusters (34,90%), representing areas with significantly higher levels than their surroundings, are found in the parishes of Santa Maria Maior, São Vicente, Penha de França, Arroios, Santo António, Avenidas Novas, Alvalade, Lumiar, Santa Clara, and Olivais.

## PM10 ARH 2D



**Figure 9:** PM10 Afternoon Rush Hour, Local Outlier

Only Low-Low clusters make up a larger portion (46,18%), which indicates that the western areas of Belém, Ajuda, Alcântara, and Benfica, along with Marvila and Parque das Nações in the east, generally experience lower PM10 values than their surrounding areas through time. Multiple Types of clusters are noted in small numbers in the south of Olivais, Misericórdia, Campo de Ourique, Avenidas Nova, São Domingos de Benfica, and Parque das Nações (9,72%), indicating a mix of PM10 value distributions through time in these areas.

For the weekends, the pattern shifts slightly. The only High-High clusters remain predominant (41,67%) in similar areas as the week days, with the addition of Belém and Ajuda in the western part. The proportion of only Low-Low clusters decreases slightly to 33,51% but still represents a significant part of the locations of Alcântara, Benfica, São Domingos de Benfica, Olivais, and Parque das Nações, suggesting a more varied PM10 distribution.

Comparing the week days and weekends, both periods share similarities in their High-High and Low-Low clusters, indicating a consistent spatial distribution of higher and lower PM10 values in specific areas of Lisbon. The change in proportions, and in

particular the increase in Multiple Types and a slight decrease in Low-Low clusters in weekends shows slight changes in PM10 patterns on the weekends.

Week Days	Count	%		Weekends	Count	%
Multiple Types	56	9,72		Multiple Types	76	13,19
Never Significant	42	7,29		Never Significant	60	10,42
Only High-High Cluster	201	34,90		Only High-High Cluster	240	41,67
Only High-Low Outlier	1	0,17		Only High-Low Outlier	2	0,35
Only Low-High Outlier	10	1,74		Only Low-High Outlier	5	0,87
Only Low-Low Cluster	266	46,18		Only Low-Low Cluster	193	33,51
Sum	576	100%		Sum	576	100%

**Table 8:** PM10 Afternoon Rush Hour, Local Outlier Classes

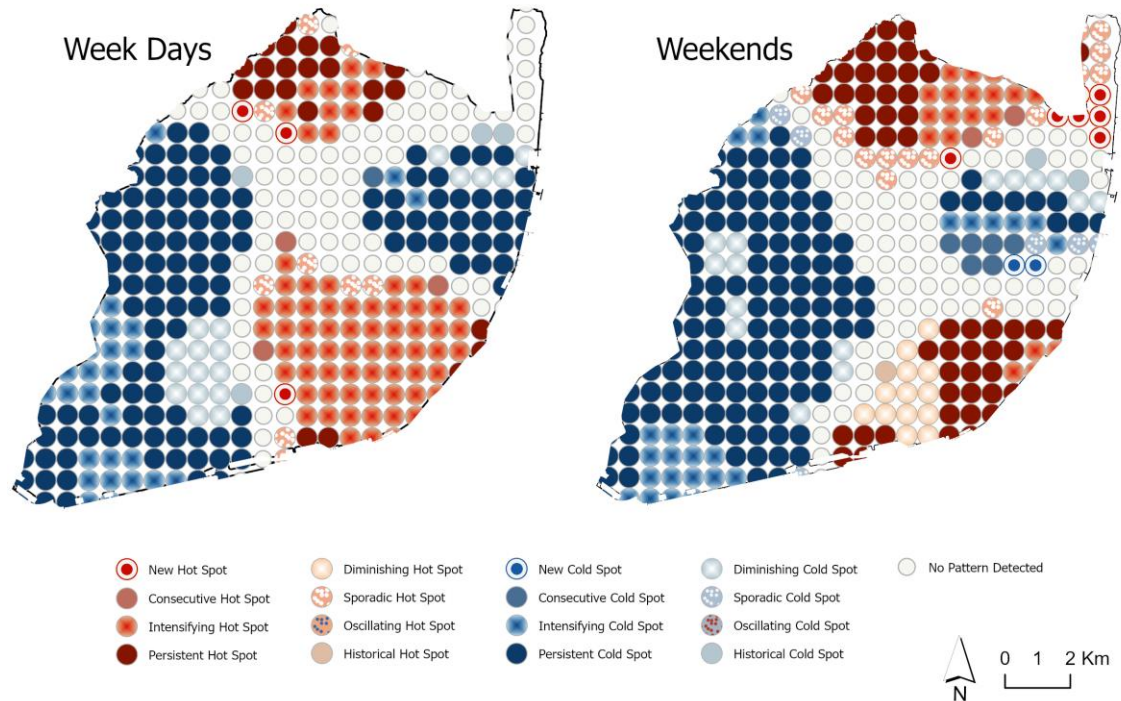
## 4.5 PM2.5 Emerging Hot Spot

### 4.5.1 PM2.5 – MRH

Results for the emerging hotspot analysis of PM2.5 done on the space-time cube, can be seen in Figure 10 and Table 9.

On week days persistent cold spots account for 28,65% of spots, particularly in the western areas like Belém, Ajuda, Benfica, and Carnide, along with a portion across Marvila in the east. These areas indicate a consistent trend over time without increasing intensity. The Intensifying Hot Spots (16,15%), are found in central and northern areas of the study area such as Beato, Penha de França, São Vicente, Santa Maria, Misericórdia, Santo Antonio, Arroios, Avenidas Novas, and the northern part of Olivais. These areas indicate an upward trend in PM2.5 values as time progresses. Diminishing cold spots in location like Alcântara, and Parque das Nações indicate the trend of reducing over time. No pattern detected category, appears in the central area of the city in X shape, these areas indicate a loss of statistically significant trends in PM2.5 levels in these areas.

## PM2,5 MRH 2D



**Figure 10:** PM2.5 Morning Rush Hour, Emerging Hot Spot Analysis

Weekends, persistent cold spots are very similar in terms of areas than the week days. Persistent Hot Spots emerge in the weekends in São Vicente, Penha de França, and Arroios, where high values have been consistently observed to tend to increase over time. Central and northern regions experience Intensifying Hot Spots but at a lower number than the week days, indicating a high but stable trend through time. No pattern detected remains similar to the week days.

Comparing MRH period across weekdays and weekends, it is clear that certain areas exhibit persistent trends, either hot or cold, indicating stable values throughout the year.

Week days	Count	%		Weekends	Count	%
Consecutive Cold Spot	3	0,520833		Consecutive Cold Spot	10	1,736111
Consecutive Hot Spot	3	0,520833		Consecutive Hot Spot	2	0,347222
Diminishing Cold Spot	18	3,125		Diminishing Cold Spot	15	2,604167
Diminishing Hot Spot	11	1,909722		Diminishing Hot Spot	12	3,819444
Historical Cold Spot	4	0,694444		Historical Cold Spot	2	0,347222
Intensifying Cold Spot	42	7,291667		Historical Hot Spot	1	0,173611
Intensifying Hot Spot	93	16,14583		Intensifying Cold Spot	31	5,381944

New Hot Spot	3	0,520833		Intensifying Hot Spot	27	4,6875
No Pattern Detected	159	27,60417		New Cold Spot	2	0,347222
Persistent Cold Spot	165	28,64583		New Hot Spot	7	1,215278
Persistent Hot Spot	62	10,76389		No Pattern Detected	110	19,09722
Sporadic Hot Spot	13	2,256944		Persistent Cold Spot	172	29,86111
Sum	576	100%		Persistent Hot Spot	145	25,17361
				Sporadic Cold Spot	9	1,5625
				Sporadic Hot Spot	21	3,645833
				Sum	576	100%

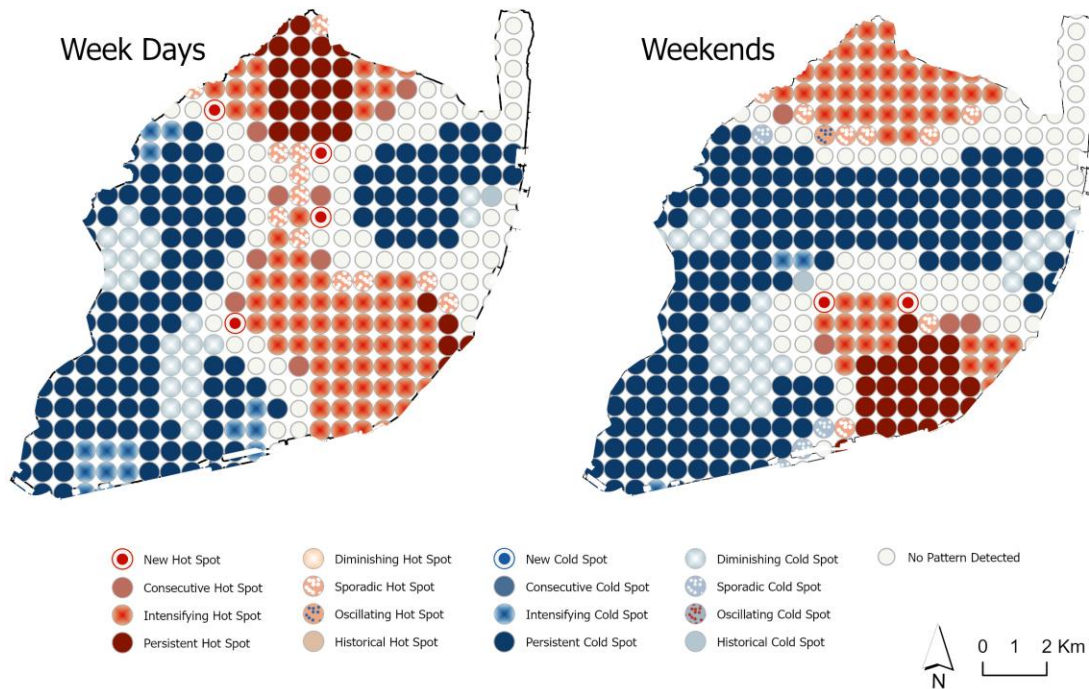
#### 4.5.2 PM2.5 - ORH

Emerging hot spot analysis of PM2.5 ORH are presented in Figure 11 and Table 10.

**Table 9:** PM2.5 Morning Rush Hour, Emerging Hot Spot Analysis Classes

During the week days the persistent cold spots are largely situated in Alcântara, Belém, Benfica, and Carnide. These locations consistently exhibit lower PM2.5 values compared with its spatiotemporal neighbors, Intensifying Hot Spots (18,06%), emerge strongly in the central and downtown parishes such as Beato, São Vicente, Penha de França, Santa Maria, Misericórdia, Arroios, Avenidas Novas, and extend to the north areas like Lumiar and Olivais north near the Lisbon Airport, indicating not only persistently high but also growing levels compared with its neighbors in time. Diminishing cold spots (3,82%) are present in locations such as Benfica and Alcântara, and show low values that are diminishing over time compared to its surroundings. No pattern detected (24,31%), split the study area in two between cold and Hot Spots, indicating region where no significant trend has been identified.

## PM2,5 ORH 2D



**Figure 11:** PM2.5 Off Rush Hour, Emerging Hot Spot Analysis

On the weekends the pattern adjusts slightly, with persistent cold spots now accounting for 37,50%, in the same areas as week days but with additional locations in the central areas. Intensifying Hot Spots (14,58%) are present in the north in the parishes of Lumiar, Santa Clara, and Olivais, as well as south areas, indicating a trend of increasing levels through time in relation to its spatiotemporal neighbors. No pattern detected (22,22%) is present in areas such as Parque das Nações and certain central regions that typically exhibit some pattern. Diminishing cold spots (4,69%) and sporadic Hot Spots (2,43%) are still present but in smaller percentages suggesting localized and less consistent patterns during the weekends.

Comparing the weekdays to weekdays the most noticeable difference between the two is that during the weekends cold spots tend to take over a larger area of the city while Hot Spots are denser with a trend of increasing through time.

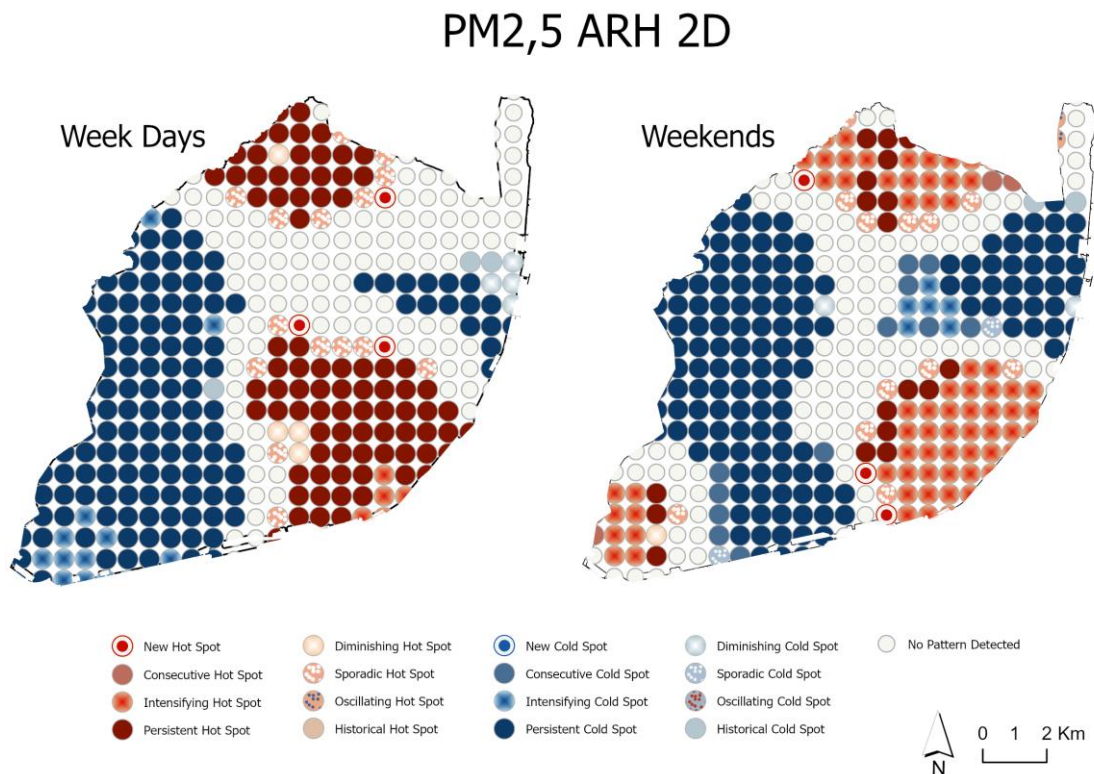
Week days	Count	%		Weekends	Count	%
Consecutive Cold Spot	3	0,52		Consecutive Cold Spot	8	1,39
Consecutive Hot Spot	10	1,74		Diminishing Cold Spot	27	4,69
Diminishing Cold Spot	22	3,82		Historical Cold Spot	1	0,17
Historical Cold Spot	1	0,17		Intensifying Cold Spot	3	0,52

Intensifying Cold Spot	19	3,30		Intensifying Hot Spot	84	14,58
Intensifying Hot Spot	104	18,06		New Cold Spot	1	0,17
New Hot Spot	4	0,69		New Hot Spot	2	0,35
No Pattern Detected	140	24,31		No Pattern Detected	128	22,22
Persistent Cold Spot	177	30,73		Oscillating Hot Spot	1	0,17
Persistent Hot Spot	78	13,54		Persistent Cold Spot	216	37,50
Sporadic Cold Spot	2	0,35		Persistent Hot Spot	78	13,54
Sporadic Hot Spot	16	2,78		Sporadic Cold Spot	13	2,26
Sum	576	100%		Sporadic Hot Spot	14	2,43
				Sum	576	100%

**Table 10:** PM2.5 Off Rush Hour, Emerging Hot Spot Analysis Classes

#### 4.5.3 PM2.5 ARH

During week days Figure 12 and Table 11 persistent cold spots (30,56%) are predominantly located in the western regions of Alcântara, Ajuda, belém, and Carnide.



**Figure 12:** PM2.5 Afternoon Rush Hour, Emerging Hot Spot Analysis

These areas consistently show lower PM2.5 levels, than its space time neighbors. Persistent Hot Spots (23,44%), are concentrated in the central areas such as Misericórdia, Santa Maria Maior, São Vicente, Penha de França, Arroios, Santo António, Avenidas Novas, Campolide, and in the north areas of Lumiar, Santa Clara, and Olivais, indicating areas where PM2.5 are high but stable over time. No Pattern Detected (32,64%), includes areas like Carnide, Alvalade, and Olivais, indicating areas where values don't exhibit any pattern through space and time.

On the weekends, the pattern of cold and hotspots shifts slightly. Persistent cold spots are substantial (32,81%), with a distribution similar to week days but extending to the western areas of Marvila, Parque da Nações, Olivais. Intensifying Hot Spots are in are larger the persistent Hot Spots and are located in the north, south areas as well as Belém, which during the week days shows intensifying or persistent cold spots. No pattern detected (28,99%) increases on the weekends with a bigger change being in the west parish of Belém and Ajuda.

Comparing the two, the main difference is the shift from persistent Hot Spots during week days to Intensifying Hot Spots on the weekends. This transition indicates that Hot Spots during the week tend to be more stable during time while on the weekends, they tend to increase through time.

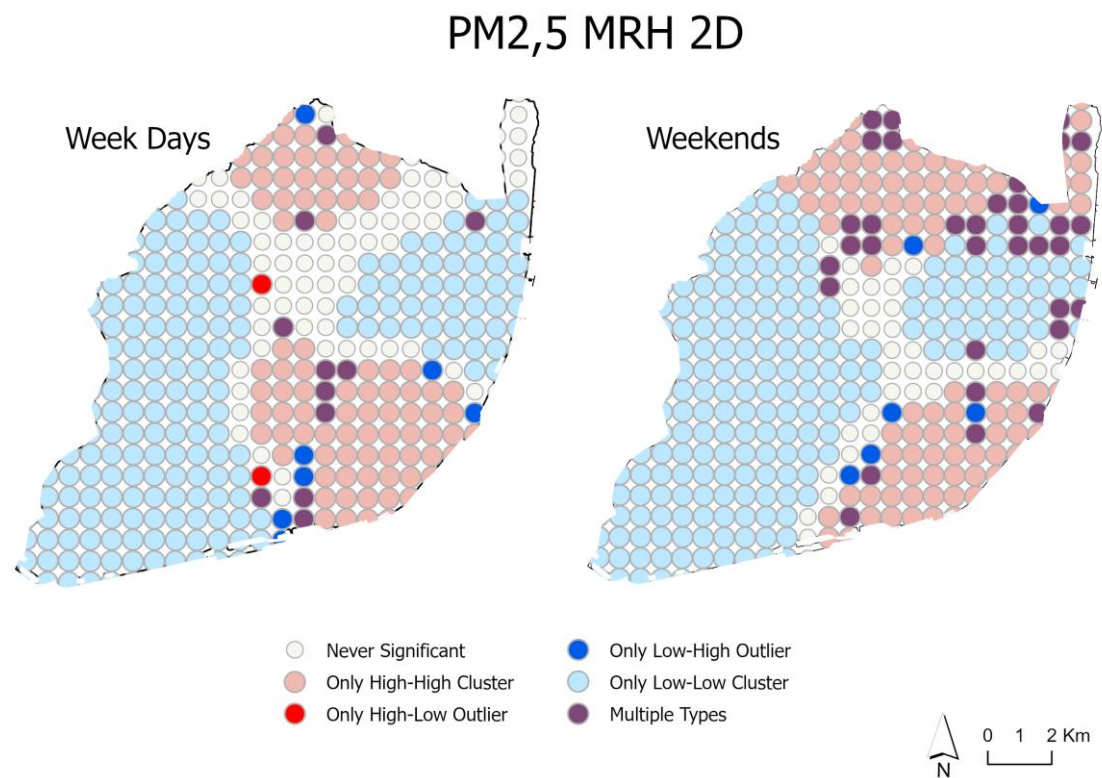
<i>Week days</i>	<i>Count</i>	<i>%</i>		<i>Weekends</i>	<i>Count</i>	<i>%</i>
<i>Consecutive Cold Spot</i>	1	0,17		<i>Consecutive Cold Spot</i>	15	2,60
<i>Diminishing Cold Spot</i>	7	1,22		<i>Consecutive Hot Spot</i>	8	1,16
<i>Diminishing Hot Spot</i>	11	1,91		<i>Diminishing Cold Spot</i>	2	0,35
<i>Historical Cold Spot</i>	3	0,52		<i>Diminishing Hot Spot</i>	1	0,17
<i>Intensifying Cold Spot</i>	15	2,60		<i>Historical Cold Spot</i>	2	0,35
<i>Intensifying Hot Spot</i>	17	3,65		<i>Intensifying Cold Spot</i>	6	1,04
<i>New Hot Spot</i>	3	0,52		<i>Intensifying Hot Spot</i>	101	17,53
<i>No Pattern Detected</i>	188	32,64		<i>New Hot Spot</i>	6	1,04
<i>Persistent Cold Spot</i>	176	30,56		<i>No Pattern Detected</i>	167	28,99
<i>Persistent Hot Spot</i>	135	23,44		<i>Oscillating Hot Spot</i>	7	1,22
<i>Sporadic Hot Spot</i>	16	2,78		<i>Persistent Cold Spot</i>	189	32,81
<i>Sum</i>	576	100%		<i>Persistent Hot Spot</i>	47	8,16
				<i>Sporadic Cold Spot</i>	2	0,35
				<i>Sporadic Hot Spot</i>	18	3,13
				<i>Sum</i>	576	100%

**Table 11:** PM2.5 Afternoon Rush Hour, Emerging Hot Spot Analysis Classes

## 4.6 PM2.5 - Local Outlier

### 4.6.1 PM2.5 – MRH

Analyzing the MRH (Figure 13, and Table 12) week days results of the local outlier analysis, we can observe that the largest category is the only Low-Low cluster (43,40%), in the western part of the study area in parishes such as Alcântara, Ajuda, Belém, Benfica, and Carnide, along with eastern regions of Parque das Nações, and Marvila. These clusters indicate areas where PM2.5 levels are low relative to their immediate temporal and spatial context. Only High-High clusters (28,65%) found in the southern parishes of the city like Beato, São Vicente, Santa Maria Maior, Penha de França, and Arroios, and in the north parishes of Lumiar, Santa Clara, and Olivais, represents areas where levels are high and similar to their surroundings.



**Figure 13:** PM2.5 Morning Rush Hour, Local Outlier

On weekends, the distribution pattern is somewhat similar. The only Low-Low cluster again forms the largest group (44,79%), suggesting that these areas maintain lower values relative to their neighbors through time. The only High-High cluster increases slightly on the weekends suggesting that certain areas continue to experience high values compared to their neighbors, consistent with the weekday pattern.

The Multiple Types for week days (2,08%) and weekends (6,08%) indicates areas that do not fit into a single category and have fluctuating and less predictable values.

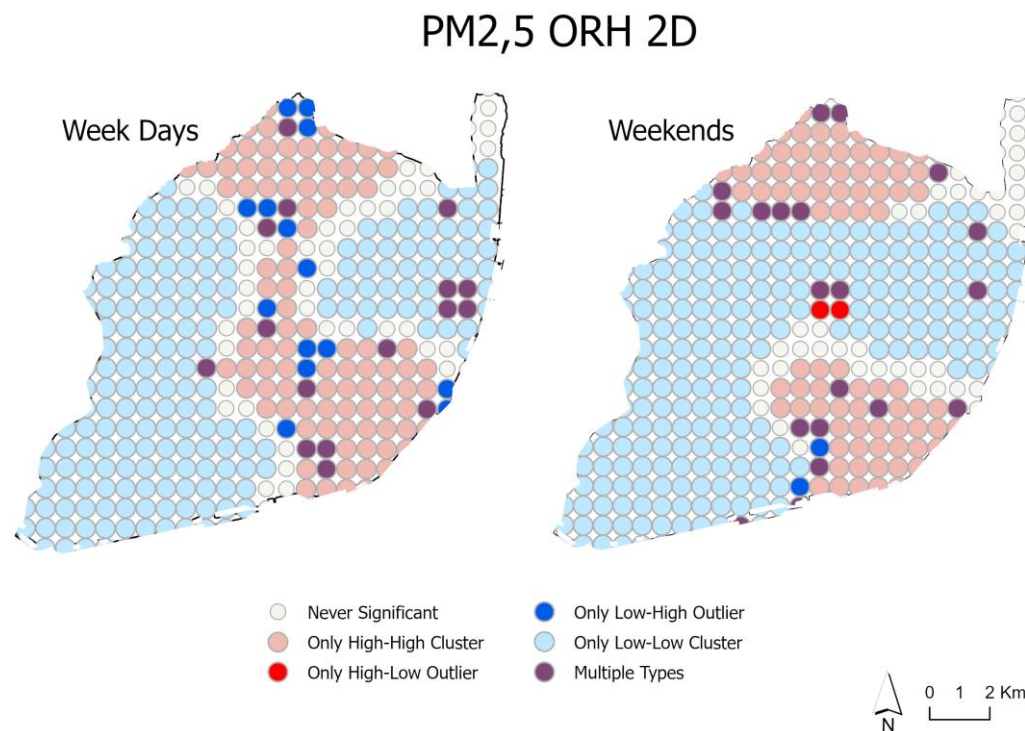
Overall, the persistence of the Low-Low and High-High clusters suggests that there are areas in Lisbon with consistently low or higher levels in their local contexts.

Week Days	Count	%		Weekends	Count	%
Multiple Types	12	2,08		Multiple Types	35	6,08
Never Significant	140	24,31		Never Significant	65	11,28
Only High-High Cluster	165	28,65		Only High-High Cluster	180	36,28
Only High-Low Outlier	2	0,35		Only Low-High Outlier	8	1,39
Only Low-High Outlier	7	1,22		Only Low-Low Cluster	258	44,79
Only Low-Low Cluster	250	43,40		Sum	576	100%
Sum	576	100%				

**Table 12:** PM2.5 Morning Rush Hour, Local Outlier Classes

#### 4.6.2 PM2.5 – ORH

ORH (Figure 14, and Table 13) week days only Low-Low clusters (43,58%) are the largest. They are present in the west part of Lisbon in the parishes of Alcântara, Ajuda, Belém, Benfica, and Carnide, and in the west in Marvila, Parque da Nações, and Olivais. These clusters indicate areas where PM2.5 levels are consistently lower than its space time neighbors.



**Figure 14:** PM2.5 Off Rush Hour, Local Outlier

Only High-High clusters (33,68%) are located in the parishes of Penha de França, São Vicente, Santa Maria, Arroios, and Santo António, as well in the north in Lumiar, Olivais, and Santa Clara. Indicating that PM2.5 values are significantly higher and similar to their surrounding areas.

On the weekends, the pattern shifts slightly. Only Low-Low cluster (50,17) is bigger in this period in similar areas as the weekends, with the addition of central parishes like Alvalade, Areeiro, and parts of Lumiar. Only High-High clusters (39,73%) decrease slightly, but remain significant, especially in the downtown areas and north of Lisbon.

Comparing the two periods, while Low-Low cluster remain the predominant category, there is a notable increase in these clusters during weekends. The slight decrease in High-High clusters in weekends could indicate that activities contributing to higher levels of PM2.5 are more prevalent during week days, however, the areas represented by these clusters remain largely consistent.

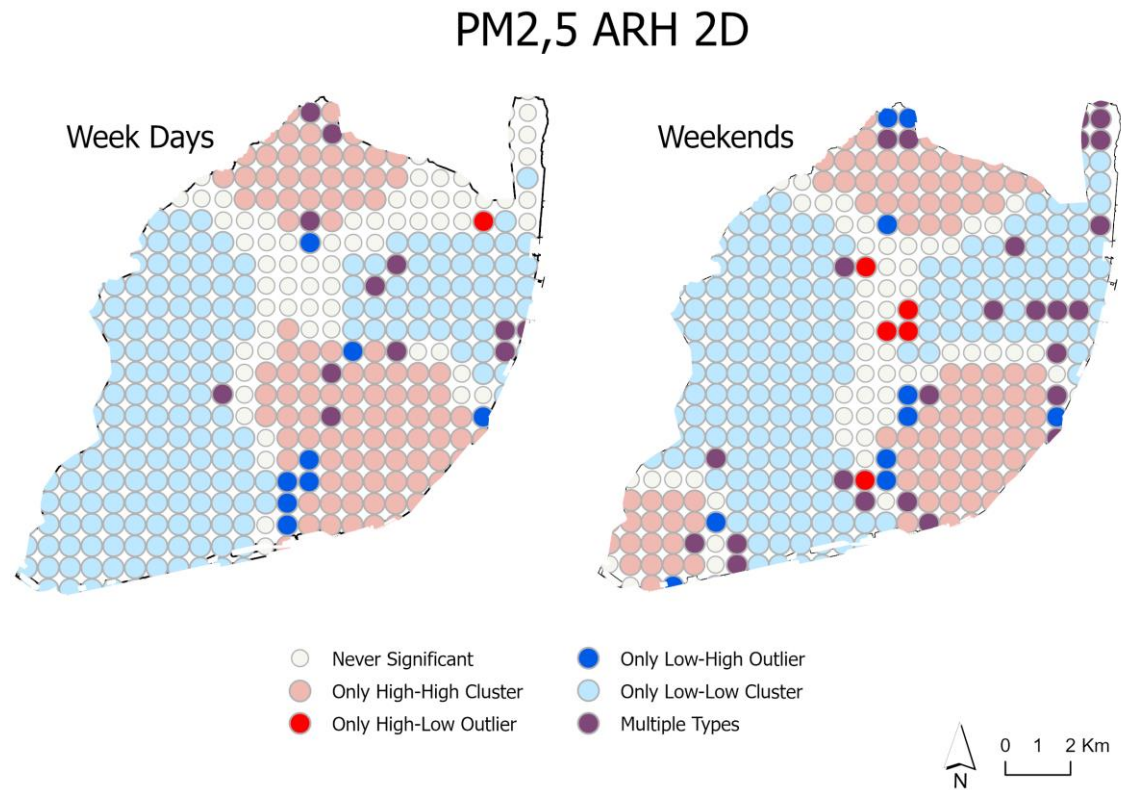
Week Days	Count	%		Weekends	Count	%
Multiple Types	16	2,78		Multiple Types	14	4,69
Never Significant	98	17,01		Never Significant	77	13,37
Only High-High Cluster	194	33,68		Only High-High Cluster	177	30,73
Only Low-High Outlier	17	2,95		Only High-Low Outlier	2	0,35
Only Low-Low Cluster	251	43,58		Only Low-High Outlier	4	0,69
Sum	576	100%		Only Low-Low Cluster	289	50,17
				Sum	576	100%

**Table 13:** PM2.5 Off Rush Hour, Local Outlier Classes

#### 4.6.3 PM2.5 – ARH

On week days, only Low-Low clusters (41,84%) remain the largest, in western areas such as Alcântara, Ajuda, Belém, Benfica, and Carnide, and east Alvalade, Marvila, Parque das Nações, and Olivais. These clusters identify areas where PM2.5 levels are consistently lower than their space time neighbors. Only High-High clusters (30,90%), located in downtown and central parishes. These areas are characterized by having PM2.5 levels that are significantly higher and similar to their space time surroundings.

During weekends, the only Low-Low cluster (41,49%) remains the largest, expanding slightly more from east to west in the central area of the city. The High-High clusters (30,03%) decreases slightly, however, northern areas remain consistent with the weekday pattern.



**Figure 15:** PM2.5 Afternoon Rush Hour, Local Outlier

Comparing the two, Low-Low clusters remain the most prominent category. The slight increase in Low-Low cluster during weekends suggests minor improvements in air quality in some central areas. High-High clusters remain consistent in the northern areas in both periods as well as downtown areas.

Week Days	Count	%		Weekends	Count	%
Multiple Types	13	2,26		Multiple Types	36	6,25
Never Significant	135	23,44		Never Significant	113	19,62
Only High-High Cluster	178	30,90		Only High-High Cluster	173	30,03
Only High-Low Outlier	1	0,17		Only High-Low Outlier	5	0,87
Only Low-High Outlier	8	1,39		Only Low-High Outlier	10	1,74
Only Low-Low Cluster	241	41,84		Only Low-Low Cluster	239	41,49
Sum	576	100%		Sum	576	100%

**Table 14:** PM2.5 Afternoon Rush Hour, Local Outlier Classes

## 5 DISCUSSION

Analyzing the concentrations of both pollutants in Lisbon during 2022, we observe that colder months, generally from October to February, tend to have higher concentration than during the hotter months. This pattern aligns with the effects of atmospheric stability, which is more present during colder months, where there are less optimal dispersion condition which can be a contributing factor for the higher concentrations measured (Zheng, 2005). Looking at the spatial distribution of PM concentrations in the city, we can see that more central and downtown areas tend to have higher concentrations than the surrounding areas, this could be the result of the effect that the urban infrastructure has on wind, which is the main component of horizontal dispersion, the presence of buildings, especially if they are denser as in these cases, it could impede the proper dispersion and result in higher concentration in those areas. Another area with constantly high values is in the northern region of the study area in the parishes of Lumiar, Olivais, and Santa Clara, which are located near the Lisbon Airport which can explain the high concentrations of PM measured in these areas.

Comparing week days and weekends results of the spatiotemporal analysis of PM10 highlights certain patterns in different time periods. Week days tend to show a more consistent spatiotemporal pattern, this is can be seen by the dominance of one or two types of hot and cold spots, as well as dominance of High-High or Low-Low clusters with few outliers. This can be explained by the more linear traffic behaviors during week days. In contrast, the weekend patterns show more diverse spatial patterns, the presence of a higher number of different hot and cold spots types, as a bigger number of outliers and Multiple Types, highlight a more diverse or less predictable pattern, which can be the result of the less structured nature of weekend activities.

Analyzing the spatiotemporal results for the different time periods, certain patterns can be identified. During week days MRH and ORH seem to be more consistent through time, dominated by Intensifying Hot Spots and persistent cold spots as well as fewer number of outliers compared with ARH period. ARH is represented with higher number of types of hot and cold spots, as well as, slightly more outliers. This shows

that MRH and ORH tends to show more homogenic patterns through the year, while ARH shows more diversity in the way it behaves through the year.

PM2.5 showed similar results to PM10 regarding the emerging hot spot analysis and local outlier analysis in terms of the overall behavior and relationships mentioned above, with distinctions mainly in the spatial extent and area density of the patterns identified. This type of PM shows a larger number of areas with no pattern detected, suggesting less statistically significant patterns when compared with PM10.

## 6 CONCLUSION

**RQ1:** How do PM10 and PM2.5 concentration levels vary spatially and temporally throughout different areas of Lisbon during 2022?

**RQ2:** Are there distinct patterns in the distribution of particulate matter during Morning Rush Hour, Off Rush Hour, and Afternoon Rush Hour on weekdays and weekends?

In conclusion, in this thesis PM10 and PM2.5 data across Lisbon in 2022 was collected preprocessed, interpolated using the EBK3D, which was then used to create a Space-Time Cube, Emerging Hot Spot Analysis and Local Outlier Analysis was made to better understand the spatiotemporal characteristics of these pollutants.

With regards to, RQ1: Both PM10 and PM2.5 concentrations exhibited spatial and temporal variability levels, PM values vary monthly, with colder months (October through February) having the highest concentrations. Central, downtown, and north eastern regions of the city had highest concentrations throughout the year.

Regarding RQ2: Distinct patterns were identified, week days showed higher but more consistent patterns than weekends. For the different time periods during week days as expected MRH and ARH had the highest concentration, however looking into its spatiotemporal patterns MRH and ORH showed more linear results throughout the year while ARH had more diverse trends over time. During weekends MRH and ARH showed different types of patterns while ORH was more consistent over time, highlighting the different types of activity in weekends.

The use of this methodology enabled to get a better understanding of PM10 and PM2.5 variations over time.

### **Limitations and Future Work**

The lack of detailed metadata about each station (type of station, high of the measuring device, etc.) may influence the results. Additionally, despite efforts in data preprocessing, issues related to data quality and missing values might still affect the findings. This study focusses on a monthly scale which limits the understanding of daily fluctuations Regarding future work, the EBK3D surface produced un this study

could be used as input for future studies, such as a more detailed analysis of Lisbon's low emission zones, more detailed studies on the relationship between PM patterns and hospital admissions due to respiratory diseases. These future directions can enhance our understanding of PM patterns and their broader implications.

## BIBLIOGRAPHIC REFERENCES

- Anselin, L. (1995). Local Indicators of Spatial Association—LISA. *Geographical Analysis*, 27(2), 93–115. <https://doi.org/10.1111/j.1538-4632.1995.tb00338.x>
- Bastos, J., Marques, P., Batterman, S. A., & Freire, F. (2019). Environmental impacts of commuting modes in Lisbon: A life-cycle assessment addressing particulate matter impacts on health. *International Journal of Sustainable Transportation*, 13(9), 652–663. <https://doi.org/10.1080/15568318.2018.1501519>
- Bolund, P., & Hunhammar, S. (1999). Ecosystem services in urban areas. *Ecological Economics*, 29(2), 293–301. [https://doi.org/10.1016/S0921-8009\(99\)00013-0](https://doi.org/10.1016/S0921-8009(99)00013-0)
- Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., ... Zender, C. S. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, 118(11), 5380–5552. <https://doi.org/10.1002/jgrd.50171>
- Brook, R. D., Rajagopalan, S., Pope, C. A., Brook, J. R., Bhatnagar, A., Diez-Roux, A. V., Holguin, F., Hong, Y., Luepker, R. V., Mittleman, M. A., Peters, A., Siscovick, D., Smith, S. C., Whitsel, L., & Kaufman, J. D. (2010). Particulate Matter Air Pollution and Cardiovascular Disease: An Update to the Scientific Statement From the American Heart Association. *Circulation*, 121(21), 2331–2378. <https://doi.org/10.1161/CIR.0b013e3181dbeece1>
- Cho, C.-I., Chen, J.-J., Chuang, K.-J., Chuang, H.-C., Wang, I.-J., & Chang, T.-Y. (2023). Associations of particulate matter, gaseous pollutants, and road traffic noise with the prevalence of asthma in children. *Chemosphere*, 338, 139523. <https://doi.org/10.1016/j.chemosphere.2023.139523>

EEA report. No12/2018: Air quality in Europe - 2018 report / European Environment Agency. (2018). Publ. Office of the Europ. Union. <https://doi.org/10.2800/92843>

Esri 2024a. *Cross Validation (Geostatistical Analyst)—ArcGIS Pro | Documentation.* (n.d.). Retrieved February 20, 2024, from <https://pro.arcgis.com/en/pro-app/3.0/tool-reference/geostatistical-analyst/cross-validation.htm>

Esri 2024b. *How Create Space Time Cube works—ArcGIS Pro | Documentation.* (n.d.). Retrieved February 20, 2024, from <https://pro.arcgis.com/en/pro-app/3.0/tool-reference/space-time-pattern-mining/learnmorecreatecube.htm>

Esri 2024c. *How Emerging Hot Spot Analysis works—ArcGIS Pro | Documentation.* (n.d.). Retrieved February 20, 2024, from <https://pro.arcgis.com/en/pro-app/3.1/tool-reference/space-time-pattern-mining/learnmoreemerging.htm>

Esri 2024d. *Emerging Hot Spot Analysis (Space Time Pattern Mining)—ArcGIS Pro | Documentation.* (n.d.). Retrieved February 20, 2024, from <https://pro.arcgis.com/en/pro-app/3.1/tool-reference/space-time-pattern-mining/emerginghotspots.htm>

Esri 2024e. *Local Outlier Analysis (Space Time Pattern Mining)—ArcGIS Pro | Documentation.* (n.d.). Retrieved February 20, 2024, from <https://pro.arcgis.com/en/pro-app/3.0/tool-reference/space-time-pattern-mining/localoutlieranalysis.htm>

Esri 2024f. *Empirical Bayesian Kriging 3D (Geostatistical Analyst)—ArcGIS Pro | Documentation.* (n.d.). Retrieved February 20, 2024, from <https://pro.arcgis.com/en/pro-app/3.0/tool-reference/geostatistical-analyst/empirical-bayesian-kriging-3d.htm>

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard,

- E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., & Snyder, P. K. (2005). Global Consequences of Land Use. *Science*, 309(5734), 570–574. <https://doi.org/10.1126/science.1111772>
- Getis, A., & Ord, J. K. (1992). The Analysis of Spatial Association by Use of Distance Statistics. *Geographical Analysis*, 24(3), 189–206. <https://doi.org/10.1111/j.1538-4632.1992.tb00261.x>
- Gribov, A., & Krivoruchko, K. (2020). Empirical Bayesian kriging implementation and usage. *Science of The Total Environment*, 722, 137290. <https://doi.org/10.1016/j.scitotenv.2020.137290>
- Guevara, M. (2016). Emissions of Primary Particulate Matter. In R. M. Harrison, R. E. Hester, & X. Querol (Eds.), *Airborne Particulate Matter: Sources, Atmospheric Processes and Health* (p. 0). The Royal Society of Chemistry. <https://doi.org/10.1039/9781782626589-00001>
- Hajat, A., Hsia, C., & O'Neill, M. S. (2015). Socioeconomic Disparities and Air Pollution Exposure: A Global Review. *Current Environmental Health Reports*, 2(4), 440–450. <https://doi.org/10.1007/s40572-015-0069-5>
- Kendall, M. G. (1975). *Rank Correlation Methods*.
- Krivoruchko, K., & Gribov, A. (2019). Evaluation of empirical Bayesian kriging. *Spatial Statistics*, 32, 100368. <https://doi.org/10.1016/j.spasta.2019.100368>
- Lee, J.-E., Lim, H. J., & Kim, Y.-Y. (2021). Publication trends in research on particulate matter and health impact over a 10-year period: 2009–2018. *Environmental Analysis Health and Toxicology*, 36(1), e2021005. <https://doi.org/10.5620/eaht.2021005>
- Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., & Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, 525(7569), 367–371. <https://doi.org/10.1038/nature15371>

- Lisboa Aberta, 2024. *Air Quality Data*. (n.d.). Retrieved February 20, 2024, from <https://lisboaaberta.cm-lisboa.pt/index.php/pt/dados/conjuntos-de-dados>
- Liu, Y., Gao, Y., Yu, N., Zhang, C., Wang, S., Ma, L., Zhao, J., & Lohmann, R. (2015). Particulate matter, gaseous and particulate polycyclic aromatic hydrocarbons (PAHs) in an urban traffic tunnel of China: Emission from on-road vehicles and gas-particle partitioning. *Chemosphere*, *134*, 52–59. <https://doi.org/10.1016/j.chemosphere.2015.03.065>
- Lopes, M., Russo, A., Monjardino, J., Gouveia, C., & Ferreira, F. (2019). Monitoring of ultrafine particles in the surrounding urban area of a civilian airport. *Atmospheric Pollution Research*, *10*(5), 1454–1463. <https://doi.org/10.1016/j.apr.2019.04.002>
- Management Association, I. R. (Ed.). (2018). *Climate Change and Environmental Concerns: Breakthroughs in Research and Practice*. IGI Global. <https://doi.org/10.4018/978-1-5225-5487-5>
- Mann, H. B. (1945). Nonparametric Tests Against Trend. *Econometrica*, *13*(3), 245. <https://doi.org/10.2307/1907187>
- Pant, P., & Harrison, R. M. (2013). Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review. *Atmospheric Environment*, *77*, 78–97. <https://doi.org/10.1016/j.atmosenv.2013.04.028>
- Rovelli, S., Cattaneo, A., Borghi, F., Spinazzè, A., Campagnolo, D., Limbeck, A., & Cavallo, D. M. (2017). Mass Concentration and Size-Distribution of Atmospheric Particulate Matter in an Urban Environment. *Aerosol and Air Quality Research*, *17*(5), 1142–1155. <https://doi.org/10.4209/aaqr.2016.08.0344>
- Schaller, B. (2010). New York City’s congestion pricing experience and implications for road pricing acceptance in the United States. *Transport Policy*, *17*(4), 266–273. <https://doi.org/10.1016/j.tranpol.2010.01.013>

- Thorpe, A., & Harrison, R. M. (2008). Sources and properties of non-exhaust particulate matter from road traffic: A review. *Science of The Total Environment*, 400(1–3), 270–282. <https://doi.org/10.1016/j.scitotenv.2008.06.007>
- WHO (2016). *Ambient (outdoor) Air Pollution Report*. (n.d.). Retrieved February 20, 2024, from [https://www.who.int/en/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health)
- WHO (2018). *Ambient (outdoor) Air Pollution Report*. (n.d.). Retrieved February 20, 2024, from [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health)
- Zheng, M., Salmon, L. G., Schauer, J. J., Zeng, L., Kiang, C. S., Zhang, Y., & Cass, G. R. (2005). Seasonal trends in PM<sub>2.5</sub> source contributions in Beijing, China. *Atmospheric Environment*, 39(22), 3967–3976. <https://doi.org/10.1016/j.atmosenv.2005.03.036>
- Zhu, Y., Hinds, W., Kim, S.-H., & Si, S. (2002). Study of ultrafine particles near a major highway with heavy-duty diesel traffic. *Atmospheric Environment*, 36, 4323–4335. [https://doi.org/10.1016/S1352-2310\(02\)00354-0](https://doi.org/10.1016/S1352-2310(02)00354-0)

## ANNEX

**Table 15A: Station ID and Location**

ID	Location	ID	Location
QAPM1000 01	Calçada da Ajuda	QAPM1000 41	Jardim do Braço de Prata
QAPM1000 02	Restelo - Rua Gonçalo Velho Cabral	QAPM1000 42	Travessa de Francisco Rezende
QAPM1000 03	Cais do Sodré	QAPM1000 43	Avenida Almirante Gago Coutinho
QAPM1000 04	Alcântara - Rua dos Lusíadas	QAPM1000 44	Avenida do Santo Condestável
QAPM1000 05	Avenida Vinte e Quatro de Julho	QAPM1000 45	Rua Frei Carlos
QAPM1000 06	Avenida Infante Santo	QAPM1000 46	Entrecampos
QAPM1000 07	Av Infante Dom Henrique (Chafariz Del Rei)	QAPM1000 47	Avenida dos Estados Unidos da América
QAPM1000 08	Baixa - Rua do Ouro	QAPM1000 48	Avenida Lusíada
QAPM1000 09	Praça do Comércio	QAPM1000 49	Avenida de Roma
QAPM1000 10	Alto da Ajuda - Rua Sá Nogueira	QAPM1000 50	Chelas - Rua Dr. José Espírito Santo
QAPM1000 11	Avenida de Ceuta	QAPM1000 51	Avenida José Régio
QAPM1000 12	Rua de São Bento	QAPM1000 52	Avenida Lusíada / Qta da Granja
QAPM1000 13	Rua Damasceno Monteiro	QAPM1000 53	Rua Lúcio de Azevedo
QAPM1000 14	Praça Martim Moniz	QAPM1000 54	Avenida Marechal Gomes da Costa
QAPM1000 15	Campo de Santa Clara	QAPM1000 55	Avenida do Brasil
QAPM1000 16	Cemitério dos Prazeres	QAPM1000 56	Avenida General Norton de Matos
QAPM1000 17	Jardim Botânico	QAPM1000 57	Campo Grande - Museu da Cidade
QAPM1000 18	Parque de Campismo de Lisboa	QAPM1000 58	Jardim Professor António Franco
QAPM1000 19	Monsanto - Alameda Keil do Amaral	QAPM1000 59	Parque da Vinha - Estação Meteorológica
QAPM1000 20	Avenida da Liberdade - Rua Manuel Jesus Coelho	QAPM1000 60	Olivais Sul - Quinta Pedagógica
QAPM1000 21	Rua dos Sapadores	QAPM1000 61	Quinta das Conchas - Avenida Maria Helena Vieira da Silva
QAPM1000 22	Campo de Ourique	QAPM1000 62	Estrada do Paço do Lumiar
QAPM1000 23	Avenida Almirante Reis	QAPM1000 63	Estrada Militar
QAPM1000 24	Rua Braamcamp	QAPM1000 64	Alameda da Encarnação
QAPM1000 25	Monsanto - Parque Ecológico	QAPM1000 65	Avenida Doutor Alfredo Bensaúde
QAPM1000 26	Parada Alto de São João	QAPM1000 66	Rua Ilha dos Amores
QAPM1000 27	Marquês de Pombal - Alameda Edgar Cardoso	QAPM1000 67	Rua Vasco da Gama Fernandes
QAPM1000 28	Beato - Avenida Infante Dom Henrique	QAPM1000 68	Laboratório de Bromatologia e Águas
QAPM1000 29	Avenida Fontes Pereira de Melo	QAPM1000 69	Calçada de Carriche
QAPM1000 30	Avenida António Augusto de Aguiar	QAPM1000 70	Rua Chen He
QAPM1000 31	Largo da Madre de Deus	QAPM1000 71	Estrada Militar às Galinheiras

QAPM1000 32	Rua de Campolide	QAPM1000 72	Rua Mário Botas
QAPM1000 33	Largo do Leão	QAPM1000 73	Rua Alferes Malheiro
QAPM1000 34	Avenida da República	QAPM1000 74	Rua da Venezuela
QAPM1000 35	Praça São Francisco de Assis	QAPM1000 75	Alm. P. Álvaro Proença EMQA
QAPM1000 36	Estrada de Monsanto	QAPM1000 76	Restauradores - Avenida da Liberdade
QAPM1000 37	Praça de Espanha	QAPM1000 77	Rua da Atalaia
QAPM1000 38	Marvila - Rua Pedro de Azevedo	QAPM1000 78	Jardim da Estrela
QAPM1000 39	Estrada de Benfica	QAPM1000 79	Avenida Doutor Francisco Luís Gomes / EMQA
QAPM1000 40	Avenida João XXI	QAPM1000 80	Rua Nau Catrineta cruz Rua Nova dos Mercadores

# APENDIX

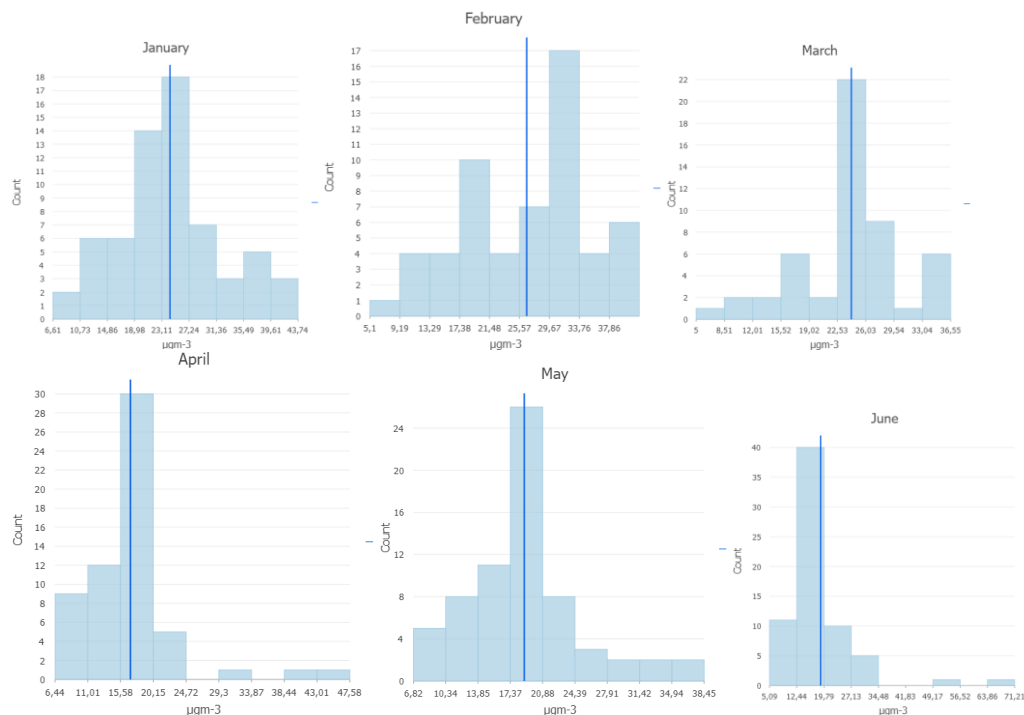
## A

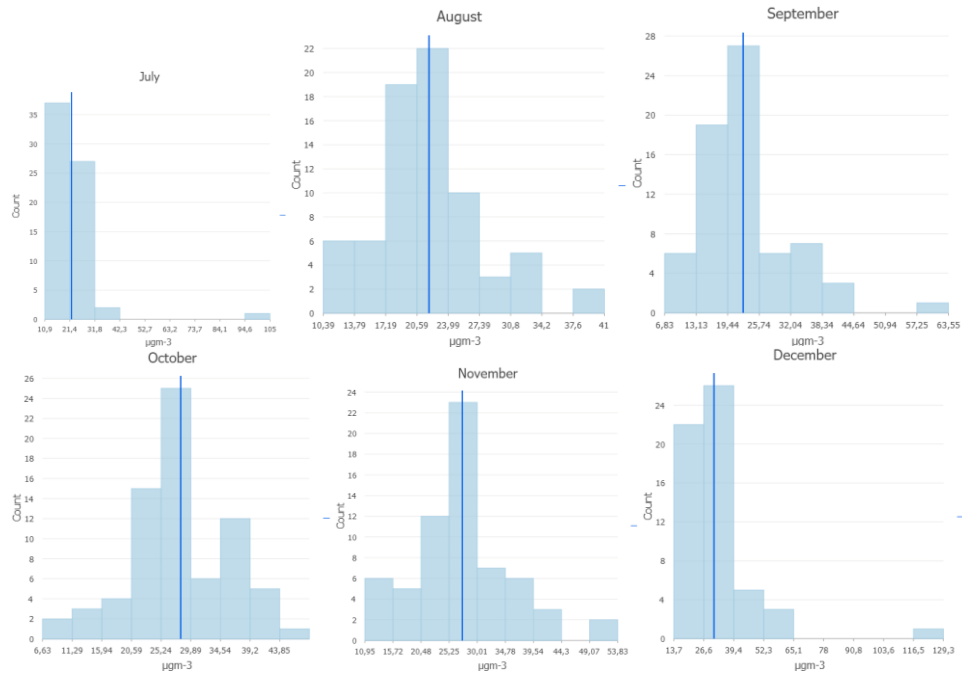
### A1 - PM10

#### A1.1 Morning Rush Hour Week Days

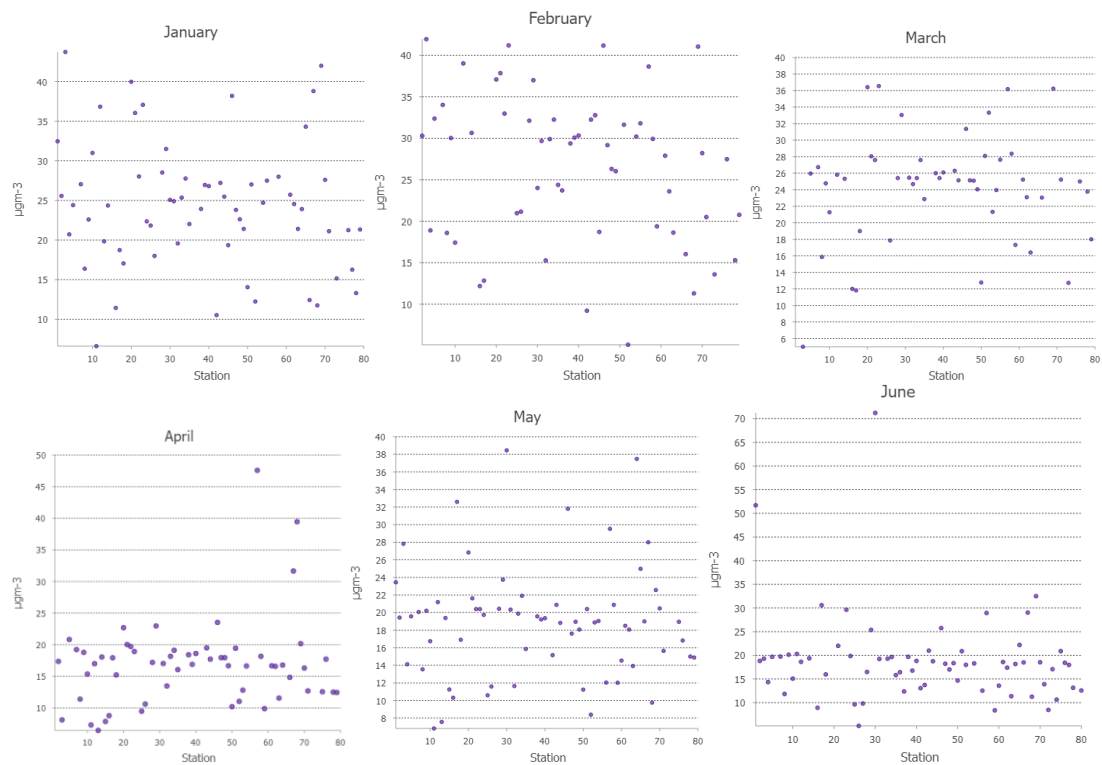
MRH WK	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	6,61	5,10	5,00	6,44	6,82	5,09	10,90	10,39	6,83	6,63	10,95	13,73
Maximum	43,74	41,95	36,55	47,58	38,45	71,21	105,05	41,00	63,55	48,50	53,83	129,34
Mean	24,34	26,56	24,25	16,95	18,88	18,87	22,07	21,90	22,52	28,31	27,48	30,96
StaDev	7,97	8,91	6,57	6,82	6,36	9,36	11,53	6,06	9,44	7,83	8,60	16,35
Median	24,40	29,18	25,23	17,00	19,05	18,34	20,81	21,41	20,33	27,82	27,17	27,52
Skewness	0,29	-0,30	-0,49	2,08	0,78	3,23	5,70	0,80	1,57	-0,15	0,70	3,97
Kurtosis	2,99	2,40	3,68	10,08	4,22	17,53	41,39	4,14	6,94	3,23	4,30	24,22

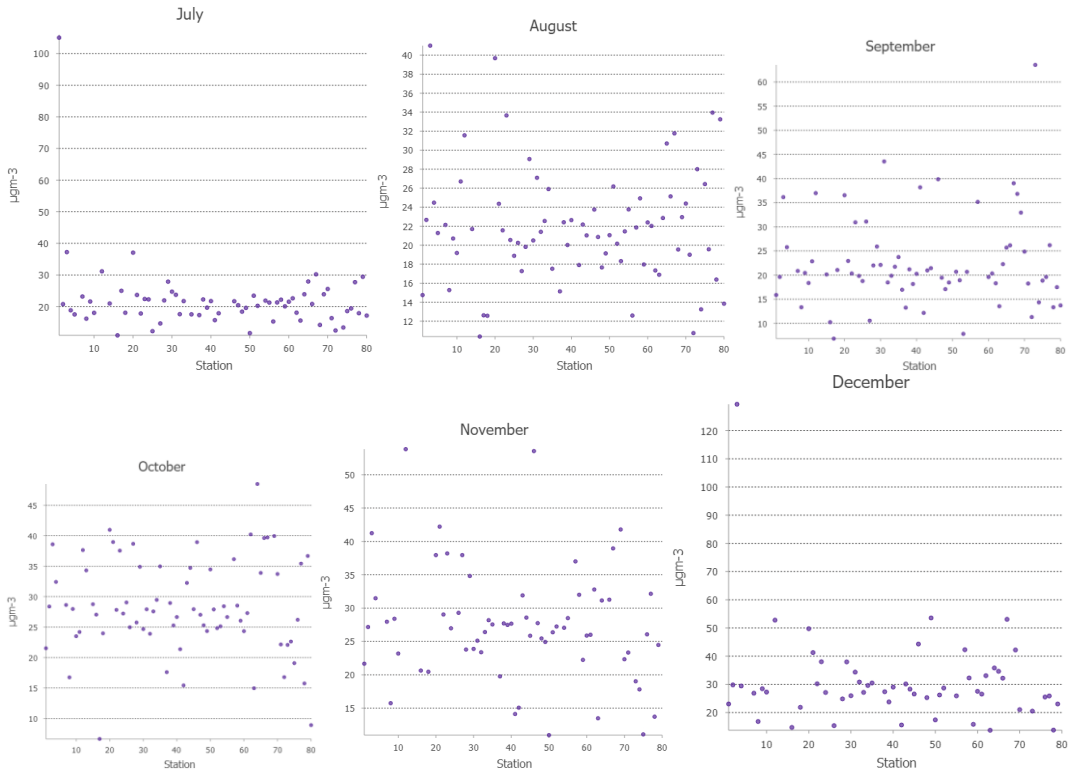
**Table 16A:** PM10 Morning Rush Hour Week Days Summary Statistics



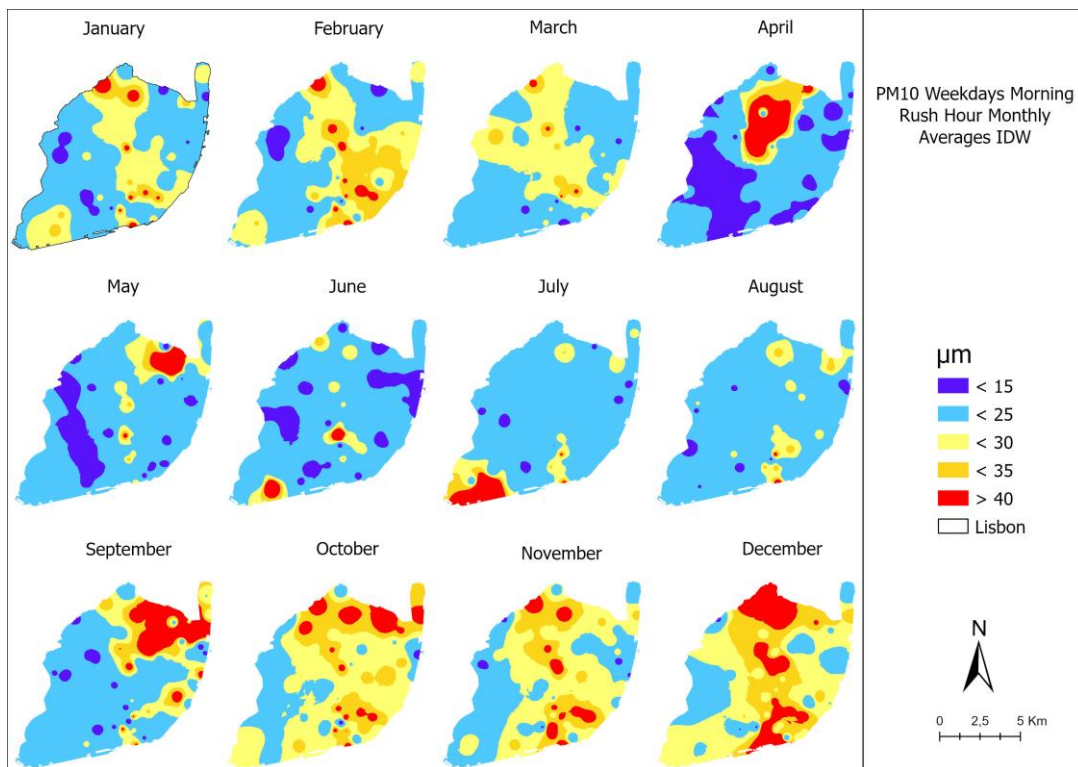


**Figure 16A: PM10 Morning Rush Hour Week Days Histogram**





**Figure 17A: PM10 Morning Rush Hour Week Days Scatter Plots**

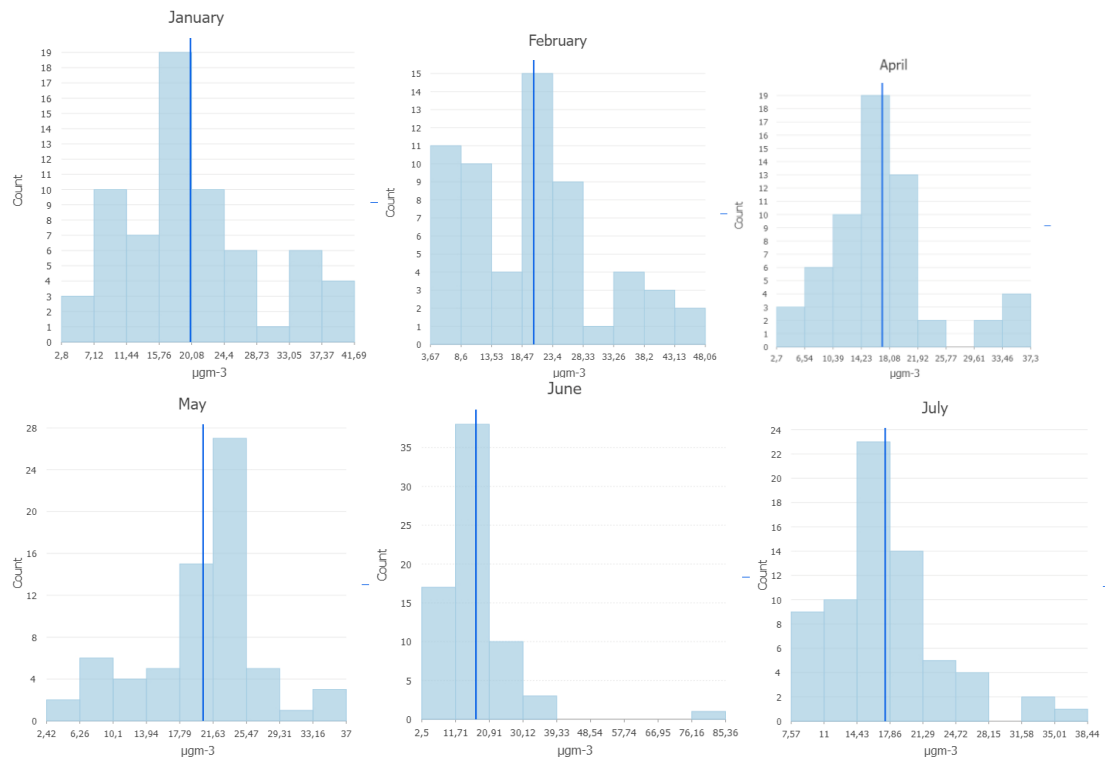


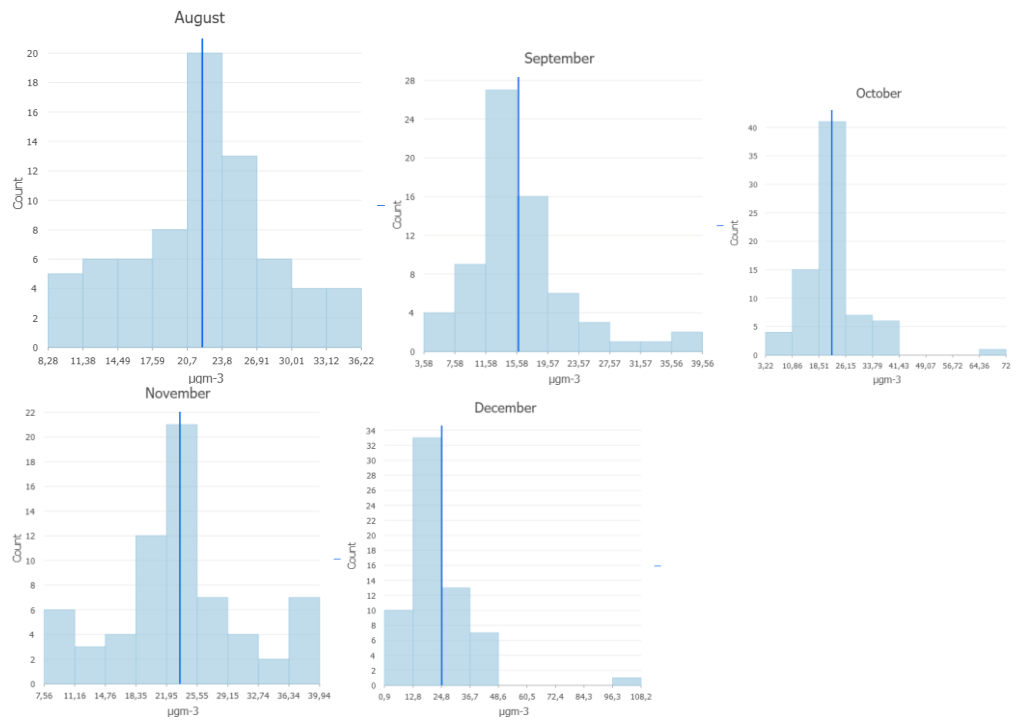
**Figure 18: PM10 Morning Rush Hour Week Days IDW**

## A1.2 – PM10 Morning Rush Hour Weekends

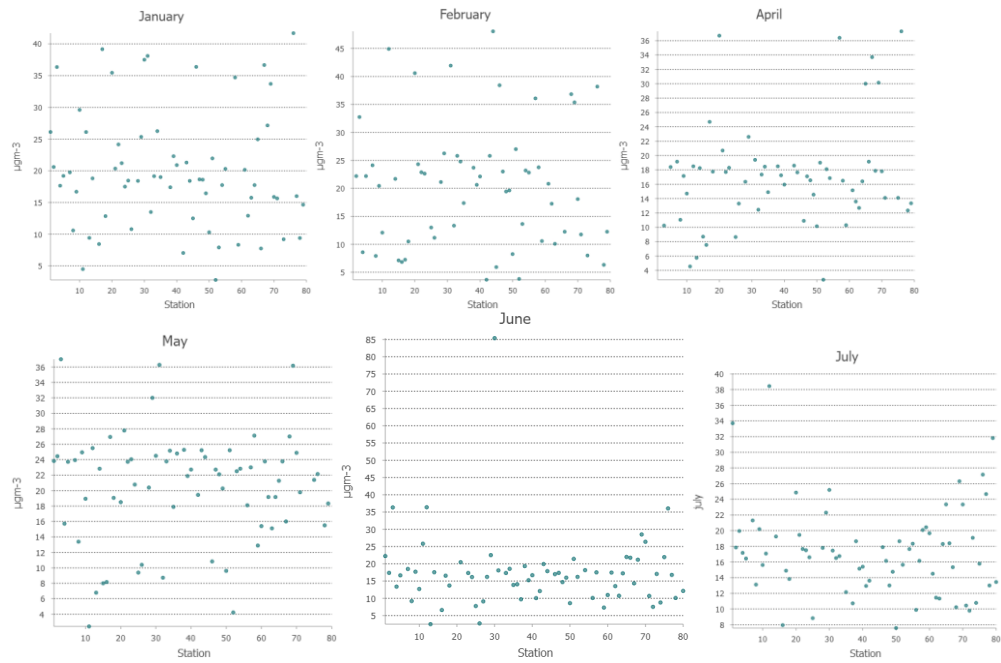
MRH WE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	2,80	3,67		2,70	2,42	2,50	7,57	8,28	3,58	3,22	7,56	3,92
Maximum	41,69	48,06		37,30	37,00	85,36	38,44	36,22	39,56	72,00	39,94	108,18
Mean	19,91	20,35		17,09	20,48	17,28	17,36	22,03	15,79	22,17	23,52	24,86
StandardDeviation	9,21	10,95		7,19	7,07	10,70	5,80	6,62	6,73	9,14	7,81	13,93
Median	18,65	20,81		17,10	22,14	16,68	17,07	22,72	14,44	21,23	23,83	22,90
Skewness	0,58	0,59		1,04	-0,33	3,92	1,14	-0,14	1,31	2,24	0,16	3,39
Kurtosis	2,77	2,74		4,62	3,41	25,13	5,15	2,74	5,67	13,54	2,73	21,21

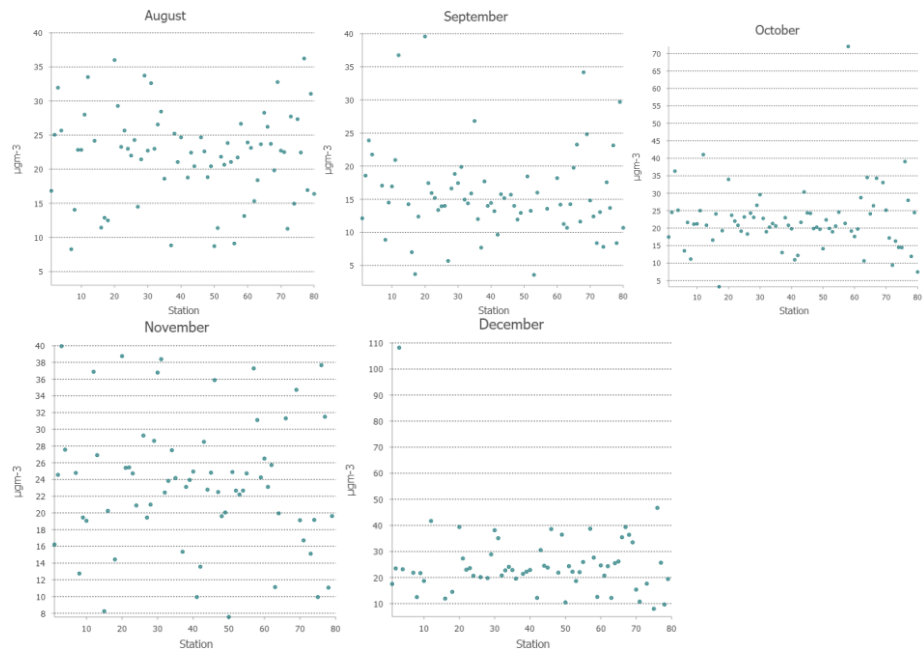
**Table 17: PM10 Morning Rush Hour Weekends Summary Statistics**



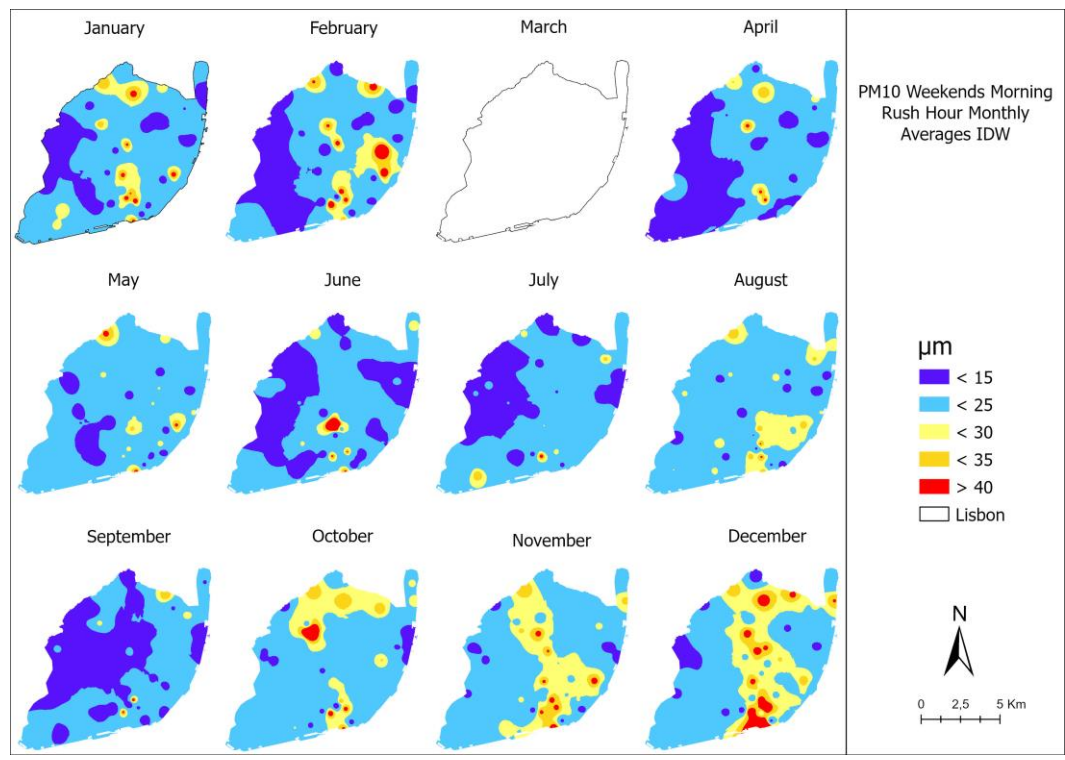


**Figure 19A: PM10 Morning Rush Hour Weekends Histograms**





**Figure 20A:** PM10 Morning Rush Hour Weekends Scatter Plots

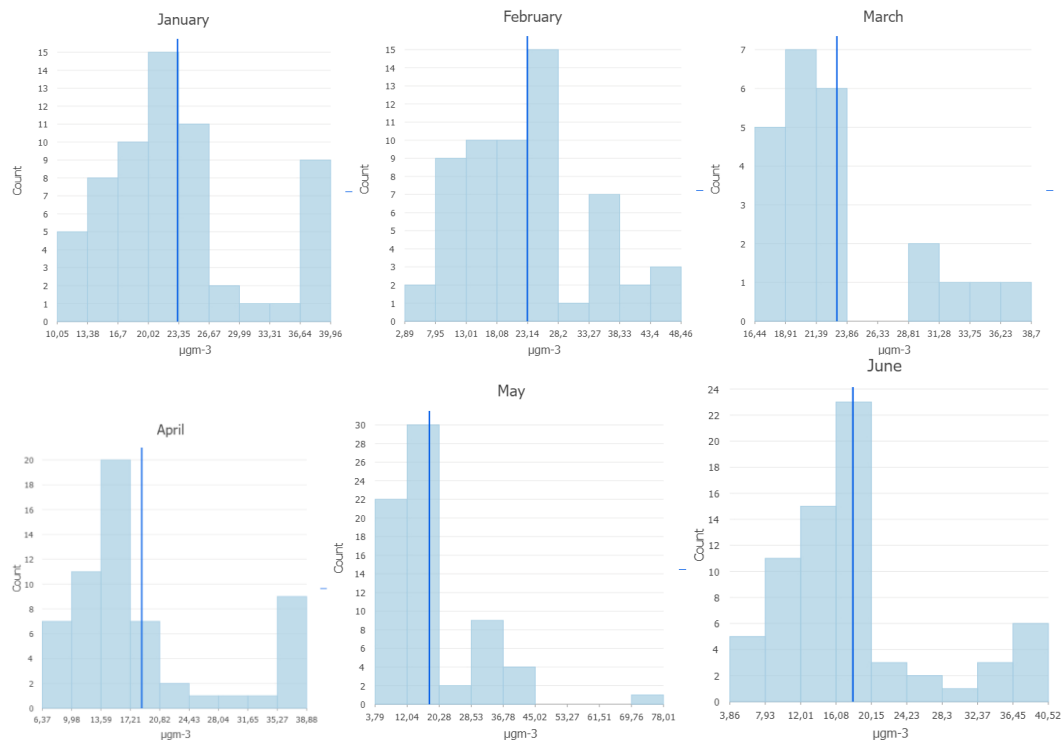


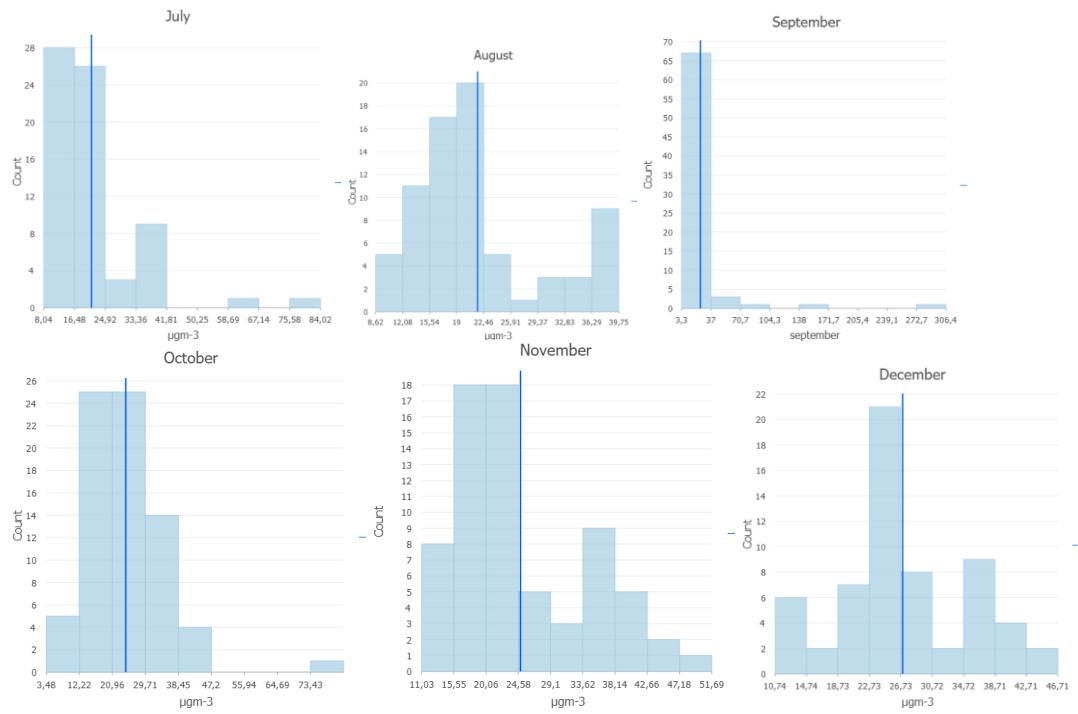
**Figure 21A:** PM10 Morning Rush Hour Weekends IDW

### A1.3 PM10 Off Rush Hour Week Days

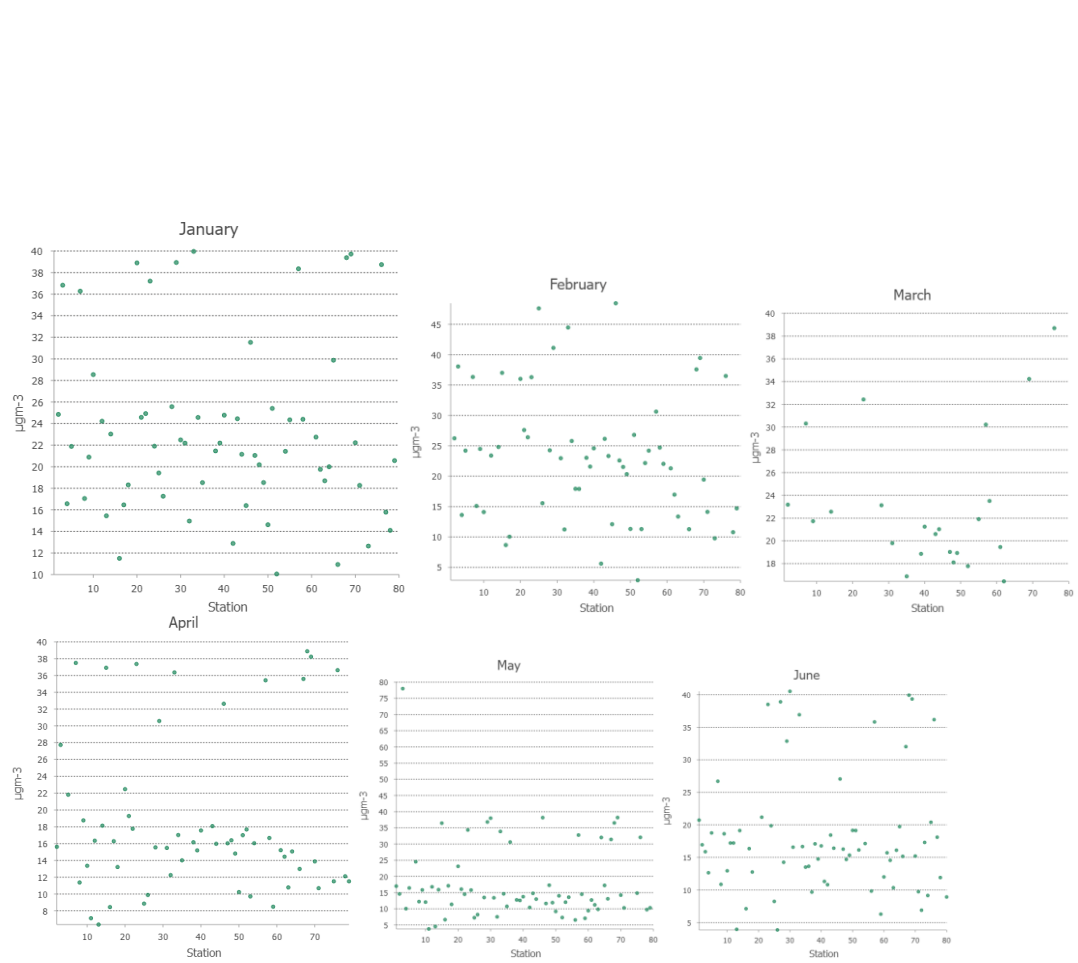
ORH WK	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	10,0 5	2,89	16,4 4	6,37	3,79	3,86	8,04	8,62	3,31	3,48	11,0 3	10,7 4
Maximum	39,9 6	48,4 6	38,7 0	38,8 8	78,0 1	40,5 2	84,0 2	39,7 5	306,4 2	82,1 8	51,6 9	46,7 1
Mean	23,2 2	23,0 8	23,0 5	18,6 0	17,7 7	18,0 3	21,1 3	21,6 7	24,82	24,5 3	24,8 8	26,9 7
StandardDeviation	8,02	10,6 0	5,98	9,24	12,0 8	9,12	12,3 9	8,23	39,52	10,7 5	9,59	8,60
Median	21,9 0	22,9 6	21,2 5	16,0 3	14,0 3	16,3 6	17,0 9	19,6 7	14,97	22,7 7	21,1 8	25,1 1
Skewness	0,76	0,50	1,24	1,10	2,28	1,13	2,74	0,86	5,70	2,06	0,80	0,28
Kurtosis	2,79	2,70	3,52	2,96	10,4 0	3,61	12,6 6	2,72	38,55	12,4 4	2,67	2,55

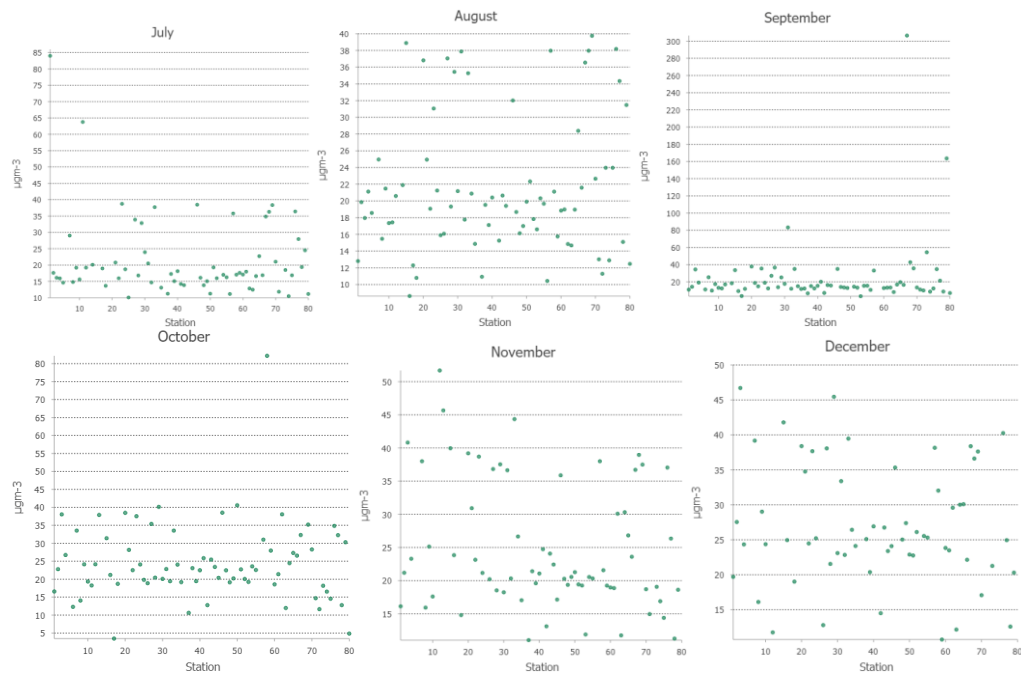
**Table 18A:** .PM10 Off Rush Hour Week Days Summary Statistics



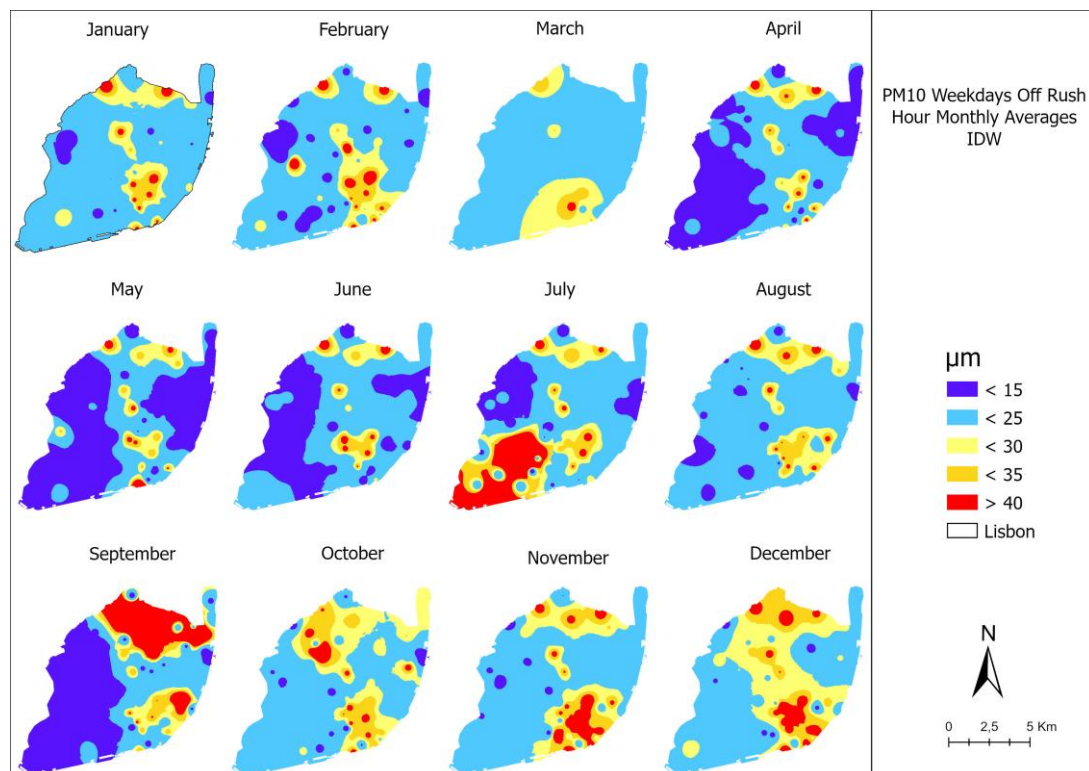


**Figure 22A: PM10 Off Rush Hour Week Days Histograms**





**Figure 23A:** PM10 Off Rush Hour Week Days Scatter Plots

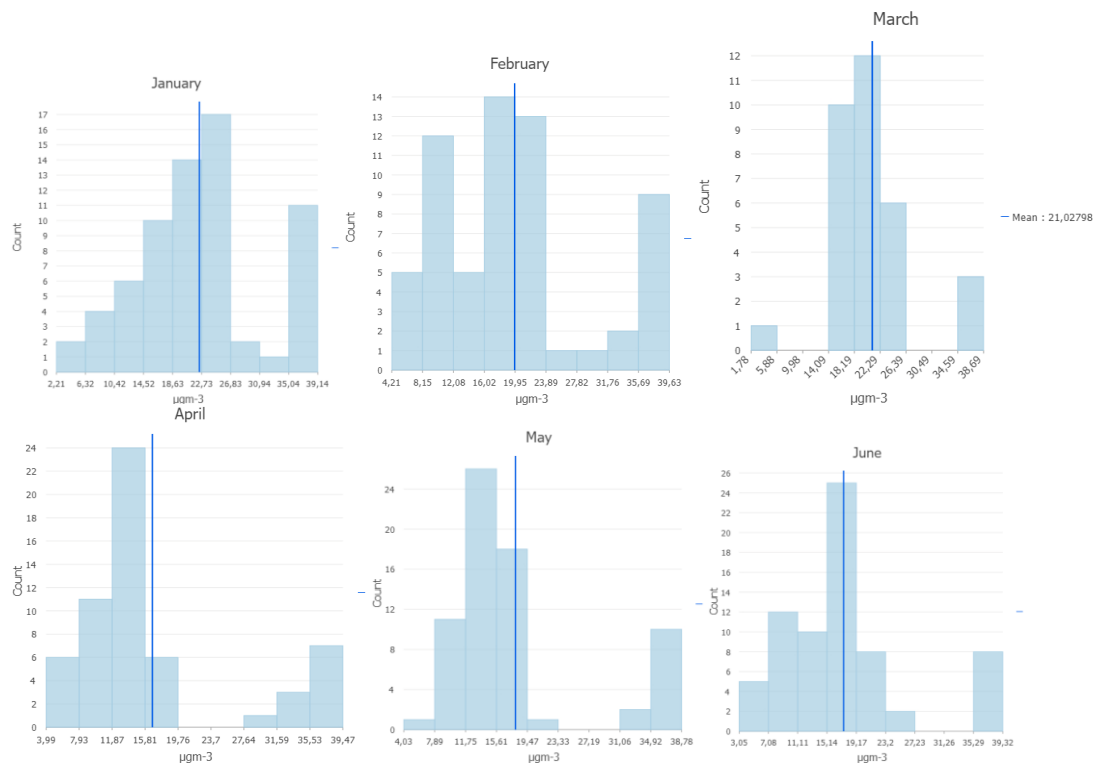


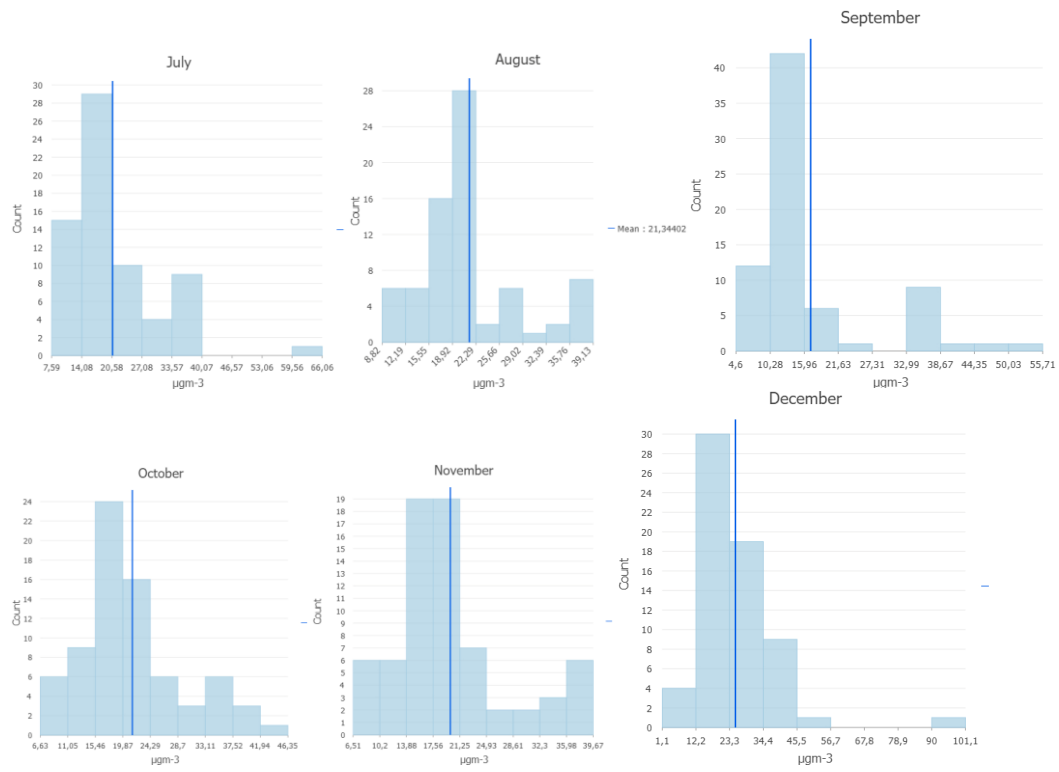
**Figure 24A:** PM10 Off Rush Hour Week Days IDW

## A1.4 PM10 Off Rush Hour Weekends

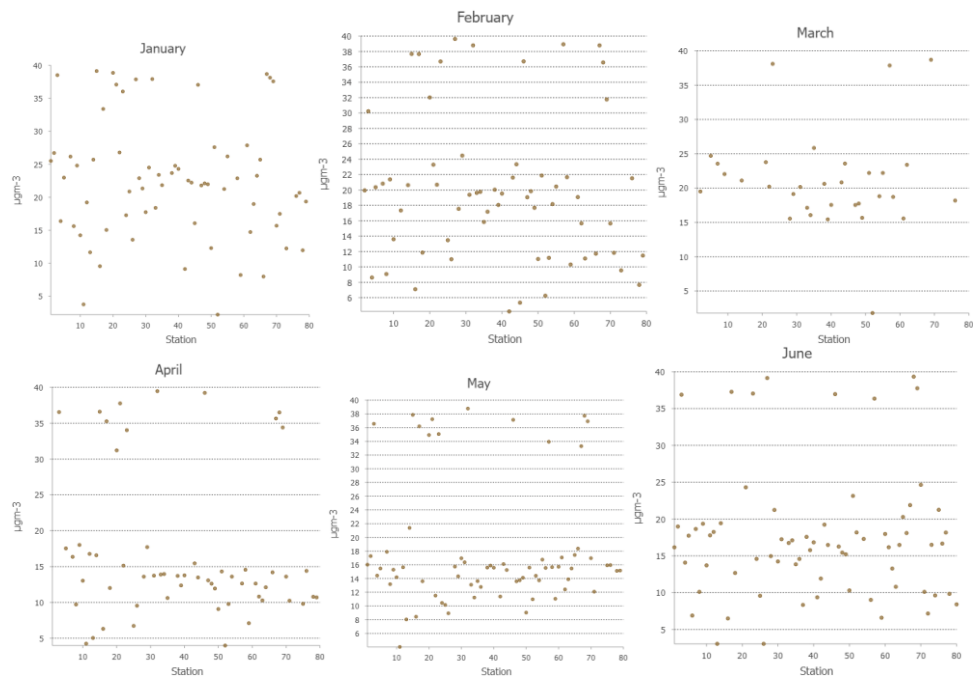
ORH WE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	2,21	4,21	1,78	3,99	4,03	3,05	7,59	8,82	4,60	6,63	6,51	1,10
Maximum	39,14	39,63	38,69	39,47	38,78	39,32	66,06	39,13	55,71	46,35	39,67	101,12
Mean	22,42	19,89	21,03	16,69	17,99	17,42	20,75	21,34	17,03	21,40	19,94	25,22
StandardDeviation	9,08	9,53	7,06	9,98	8,91	8,66	10,24	7,45	10,55	8,07	8,26	13,14
Median	22,11	19,54	20,19	13,60	15,54	16,49	17,25	20,26	13,14	19,47	18,41	23,08
Skewness	0,20	0,66	0,68	1,25	1,37	1,13	1,79	0,90	1,73	0,89	0,96	3,08
Kurtosis	2,64	2,65	5,44	3,22	3,56	4,01	7,20	3,48	5,27	3,45	3,37	18,65

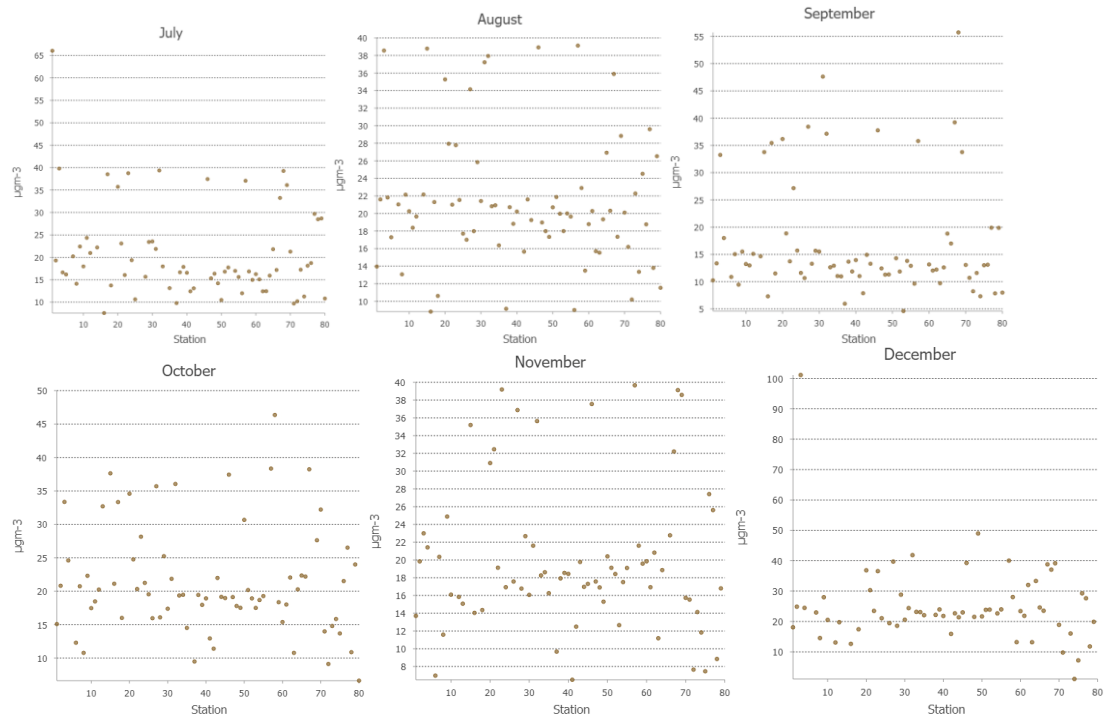
**Table 19A:** PM10 Off Rush Hour Weekends Summary Statistics



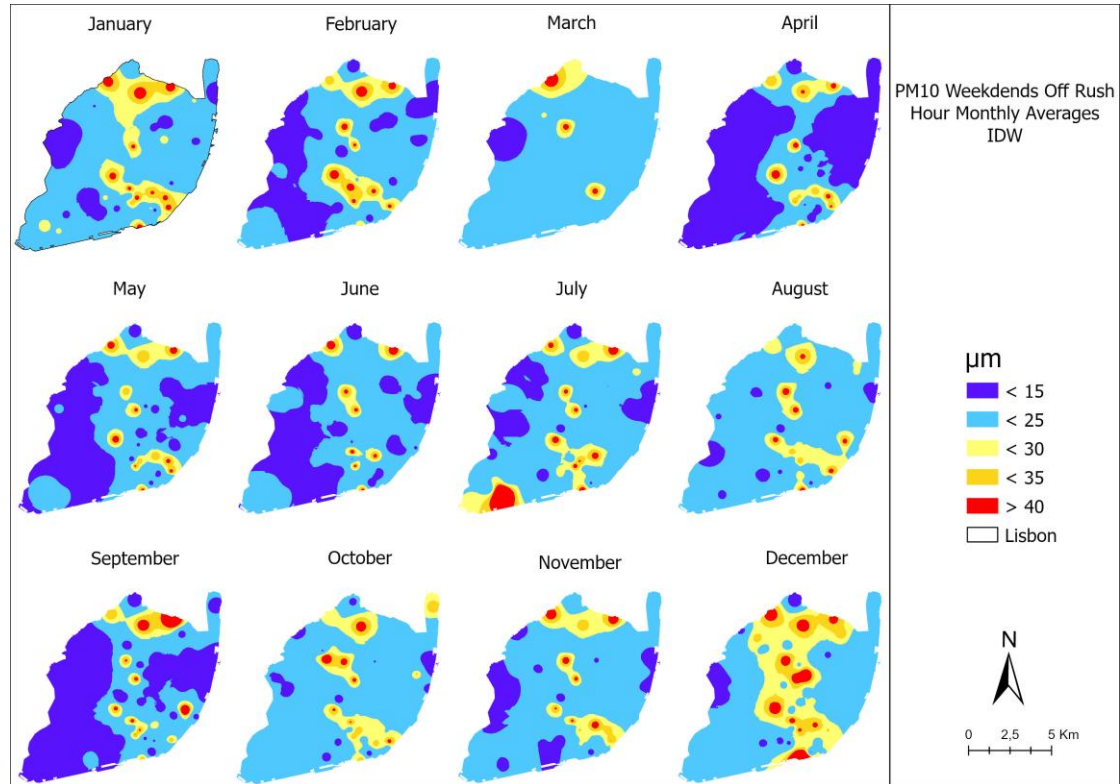


**Figure 25A: PM10 Off Rush Hour Weekends Histograms**





**Figure 26A: PM10 Off Rush Hour Weekends Scatter Plots**

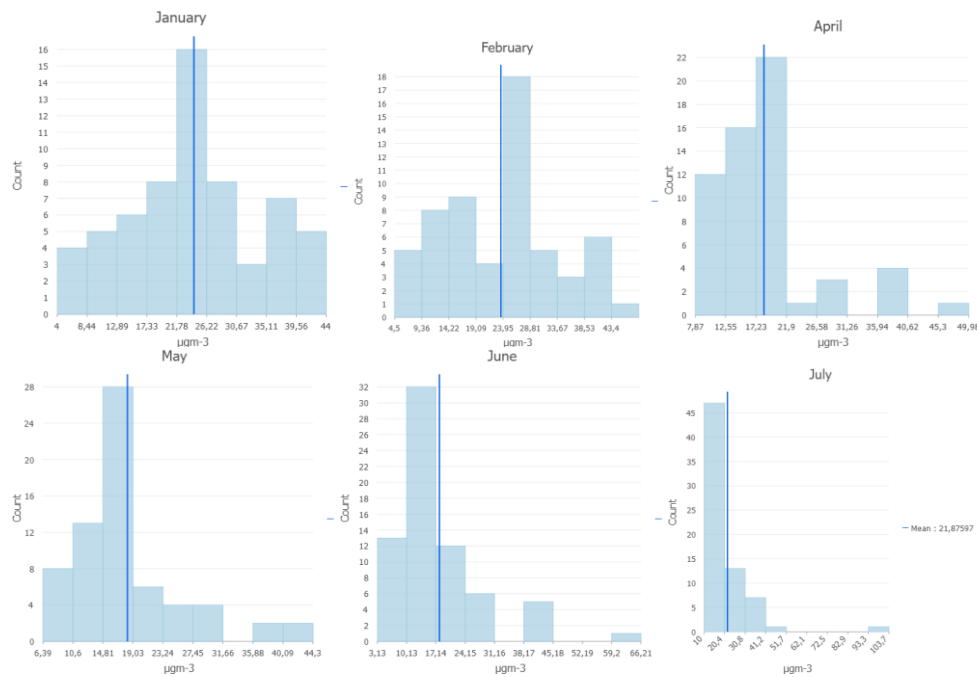


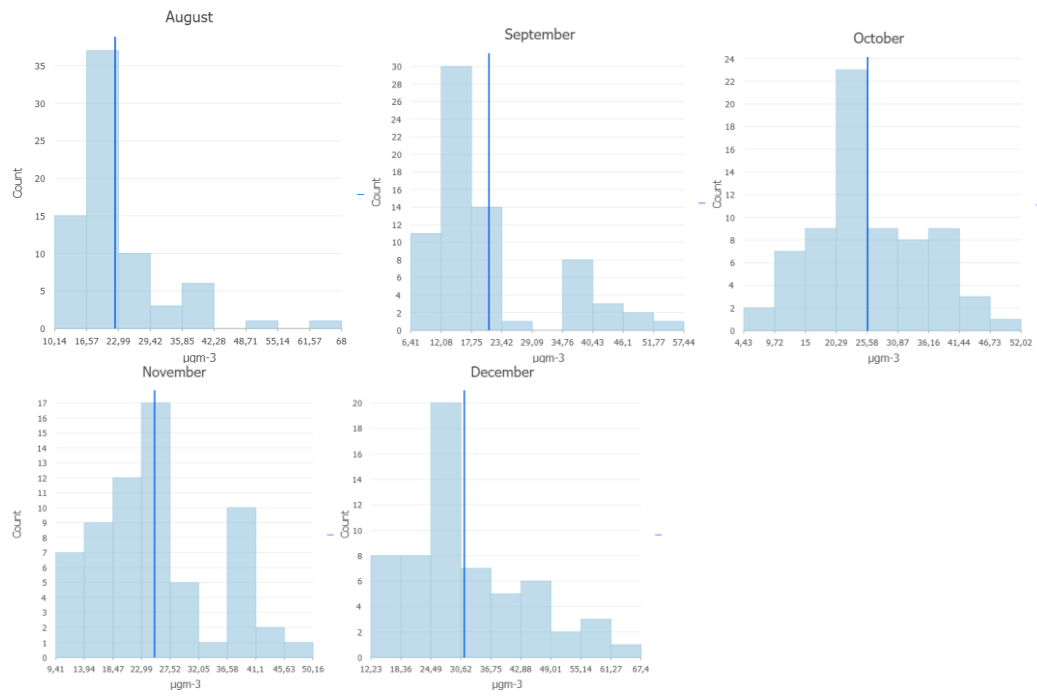
**Figure 27A: PM10 Off Rush Hour Weekends IDW**

## A1.5 PM10 Afternoon Rush Hour Week Days

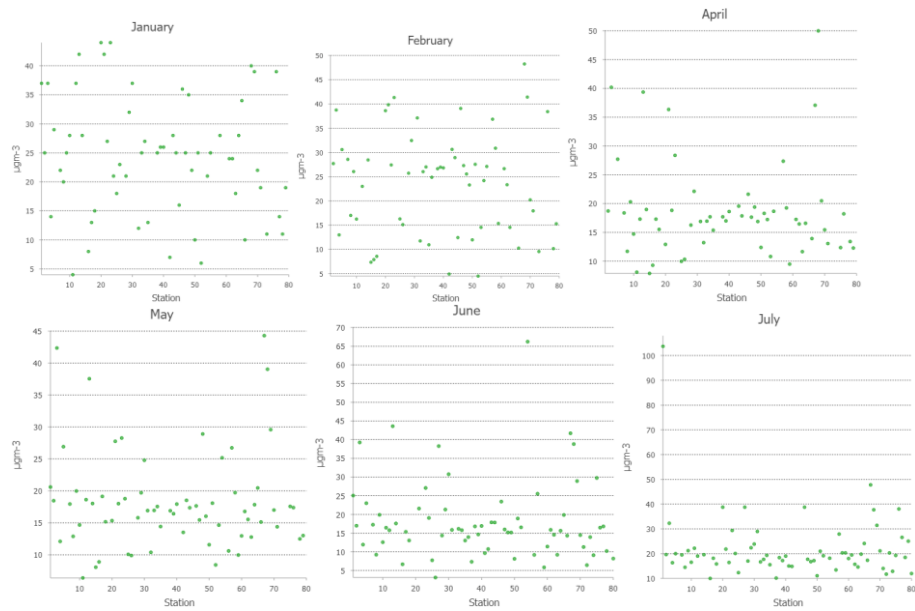
ARH WK	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	4,00	4,50		7,87	6,39	3,13	10,00	10,14	6,41	4,43	9,41	12,23
Maximum	44,00	48,26		49,98	44,30	66,21	103,73	68,00	57,44	52,02	50,16	67,40
Mean	24,32	23,55		18,45	18,25	17,98	21,88	22,31	21,01	25,68	25,07	31,31
StandardDeviation	10,16	10,56		8,15	7,67	10,46	12,58	9,33	11,47	9,55	9,28	12,53
Median	25,00	25,72		17,25	17,02	15,86	19,14	20,42	17,21	24,23	23,94	28,18
Skewness	0,08	0,11		1,86	1,53	2,05	4,31	2,29	1,35	0,31	0,49	0,75
Kurtosis	2,32	2,25		6,80	5,62	8,71	27,37	10,40	3,93	2,81	2,62	3,23

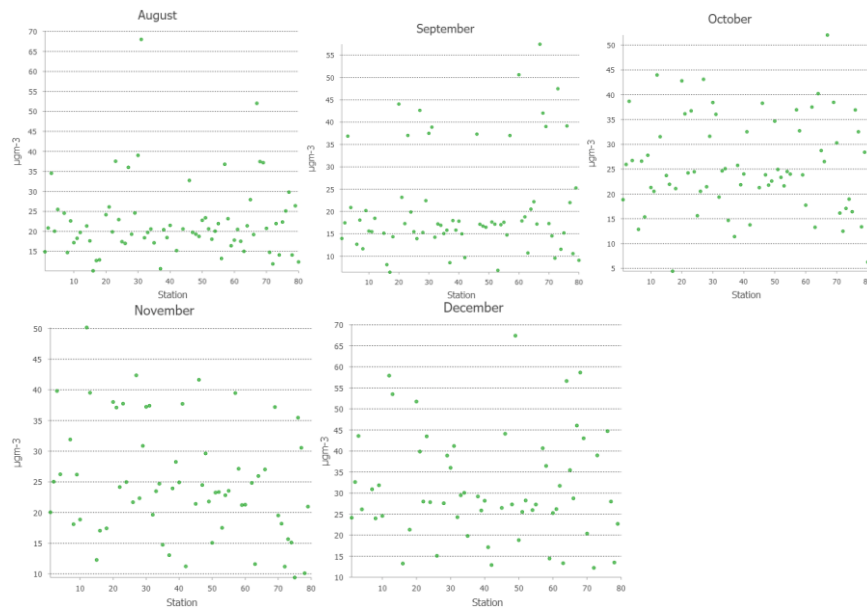
**Table 20A:** PM10 Afternoon Rush Hour Week Days Summary Statistics



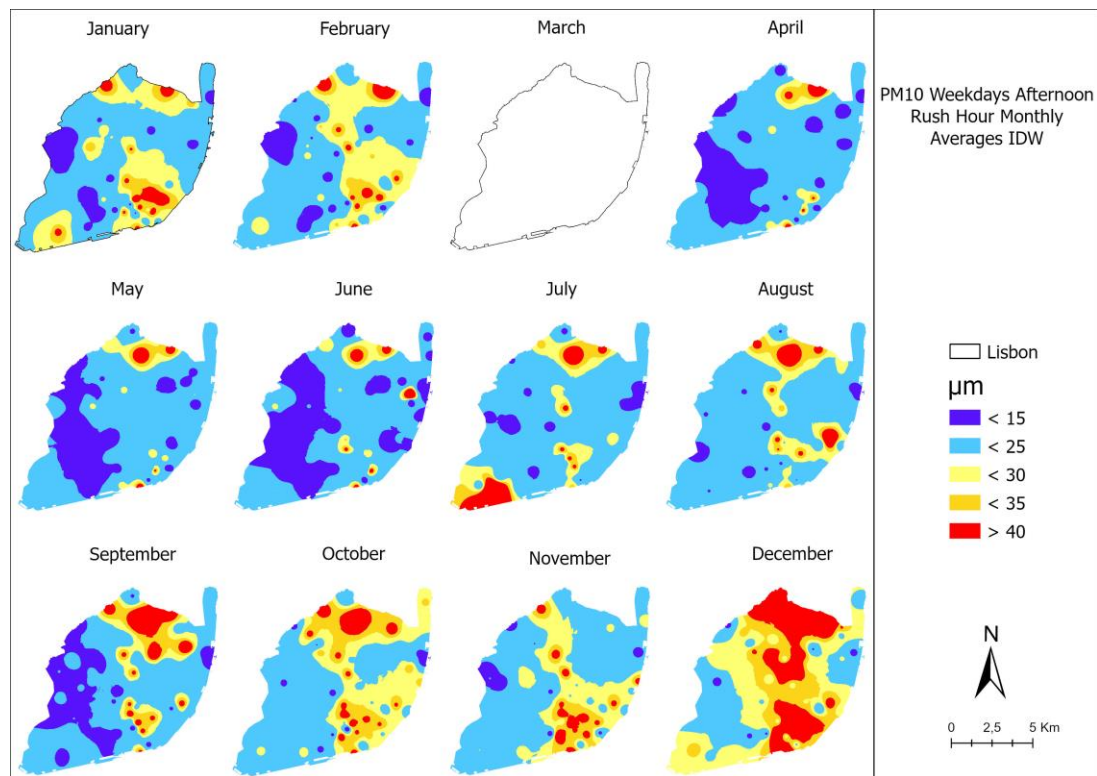


**Figure 28A: PM10 Afternoon Rush Hour Week Days Histograms**





**Figure 29A:** PM10 Afternoon Rush Hour Week Days Scatter Plots

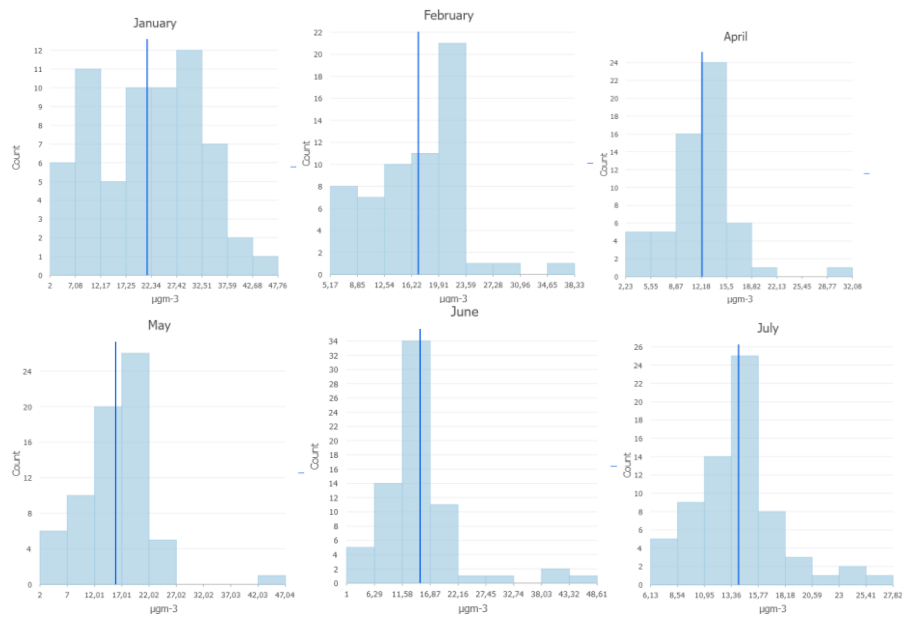


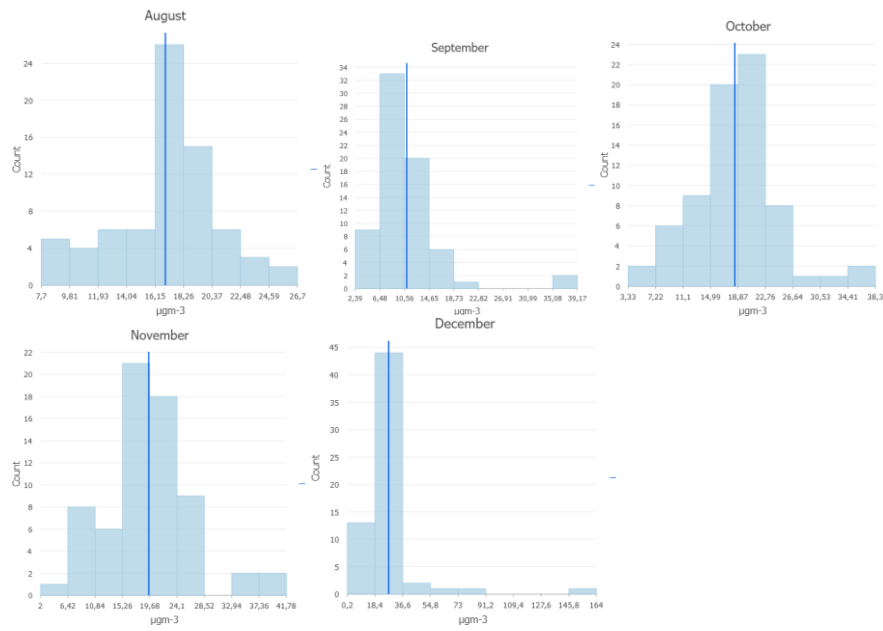
**Figure 30A:** PM10 Afternoon Rush Hour Week Days IDW

## A1.6. PM10 Afternoon Rush Hour Weekends

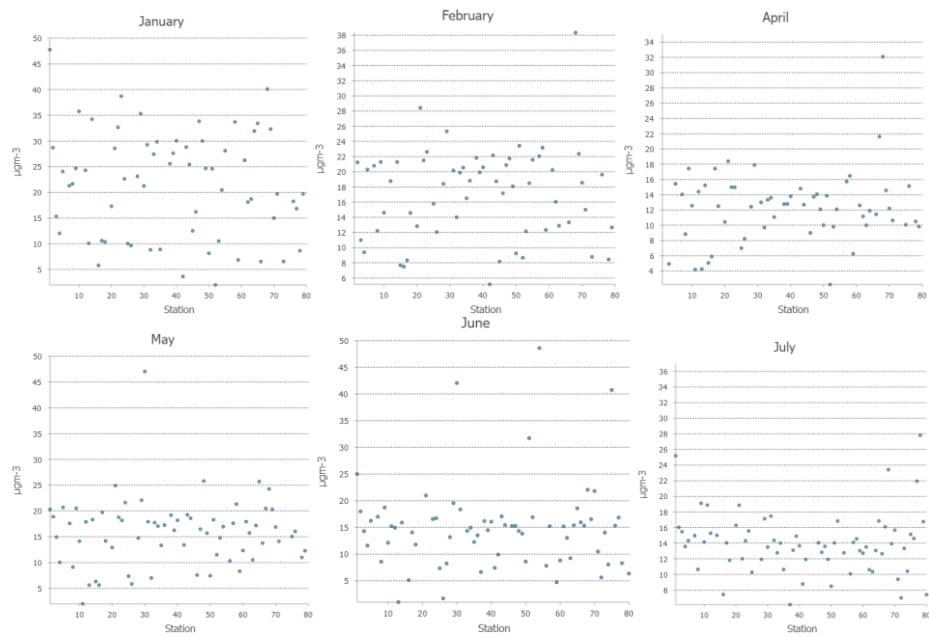
ARH WE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	2,00	5,17		2,23	2,00	1,00	6,13	7,70	2,39	3,33	2,00	3,17
Maximum	47,76	38,33		32,08	47,04	48,61	27,82	26,70	39,17	38,30	41,78	164,00
Mean	21,49	17,13		12,30	15,89	14,97	14,01	16,91	10,94	18,43	19,51	27,31
StandardDeviation	10,33	6,02		4,65	6,50	8,14	3,89	3,97	5,74	6,07	7,31	20,70
Median	22,63	18,56		12,57	16,89	14,94	14,00	17,30	10,25	18,45	19,15	25,04
Skewness	0,07	0,37		1,02	1,31	1,91	0,95	-0,25	3,08	0,57	0,45	4,98
Kurtosis	2,28	4,08		7,41	9,24	8,47	5,26	3,28	15,93	4,70	4,12	32,50

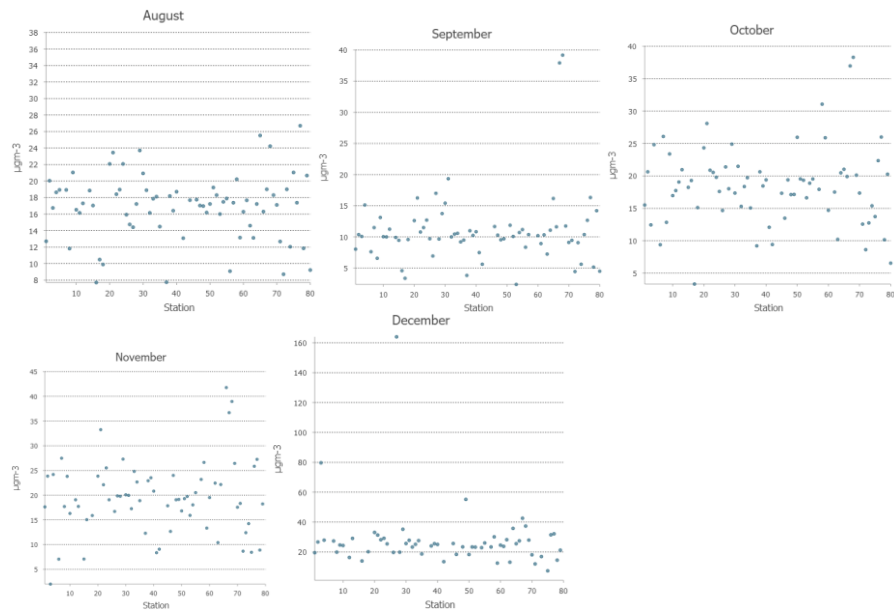
**Table 21A:** PM10 Afternoon Rush Hour Weekends Summary Statistics



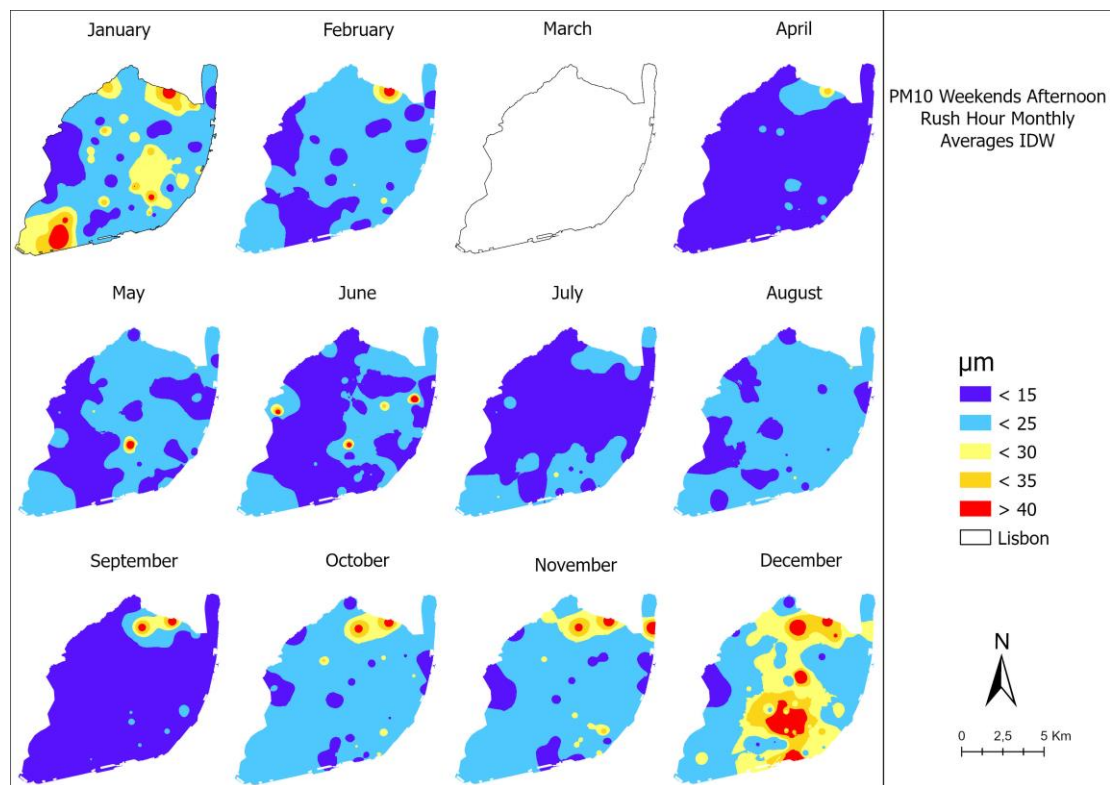


**Figure 31A: PM10 Afternoon Rush Hour Weekends Histograms**





**Figure 32A:** PM10 Afternoon Rush Hour Weekends Scatter Plots



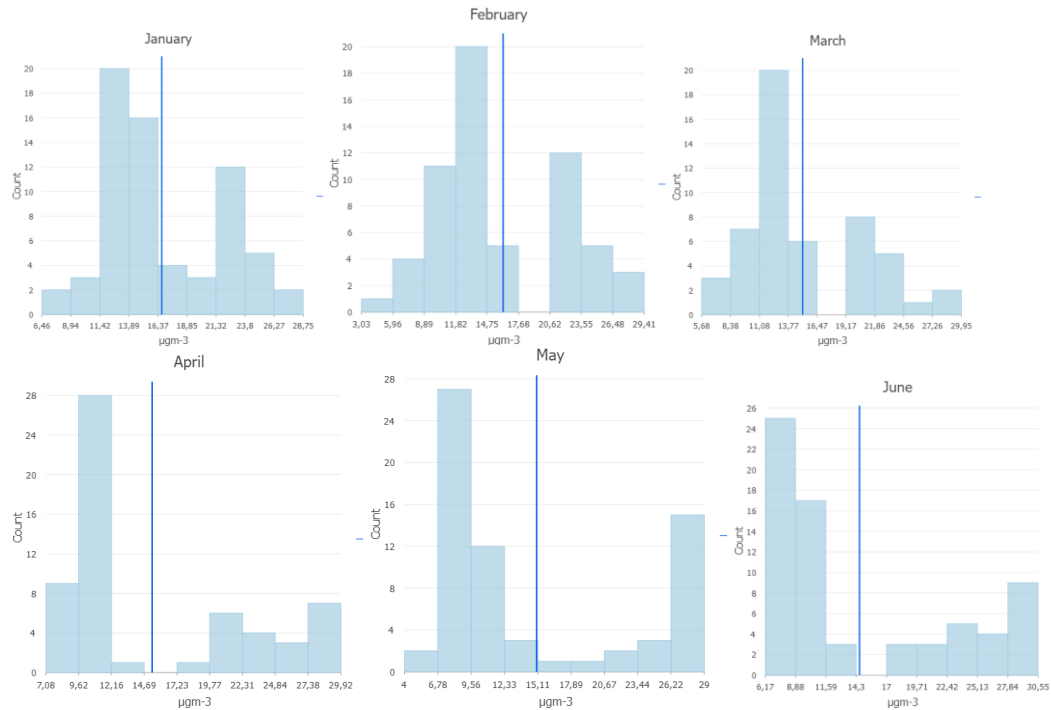
**Figure 33A:** PM10 Afternoon Rush Hour Weekends IDW

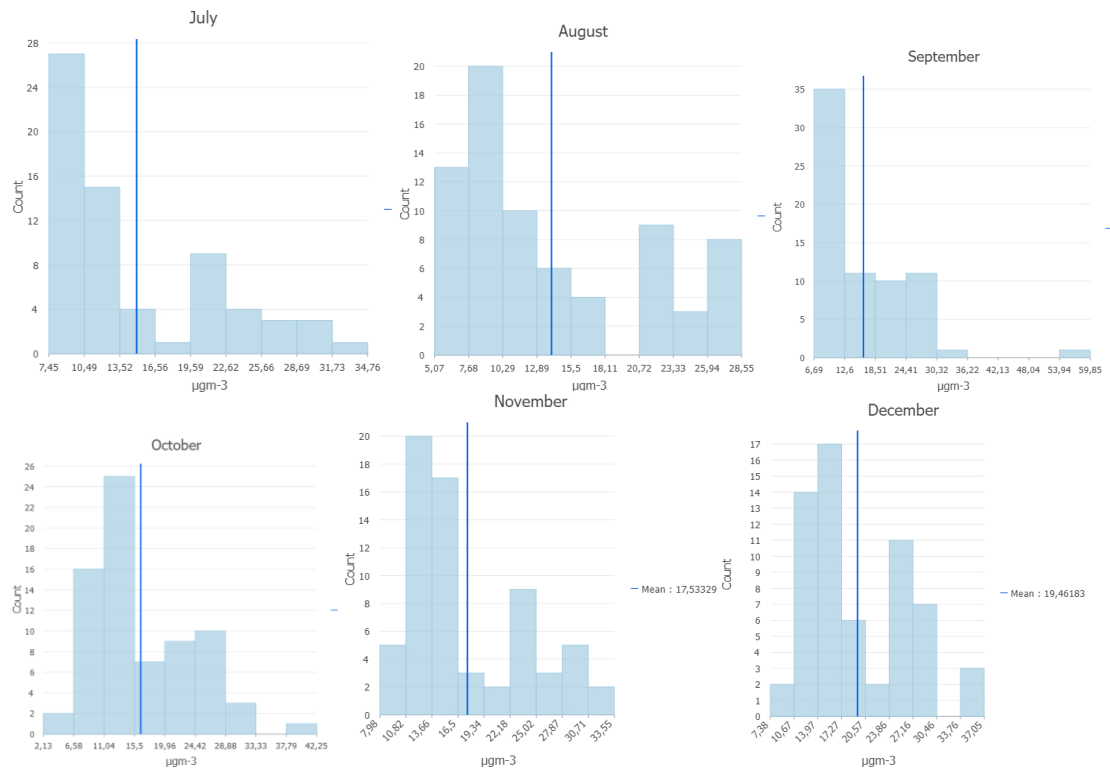
## A2. PM2.5

### A2.1. PM2.5 Morning Rush Hour Week Days

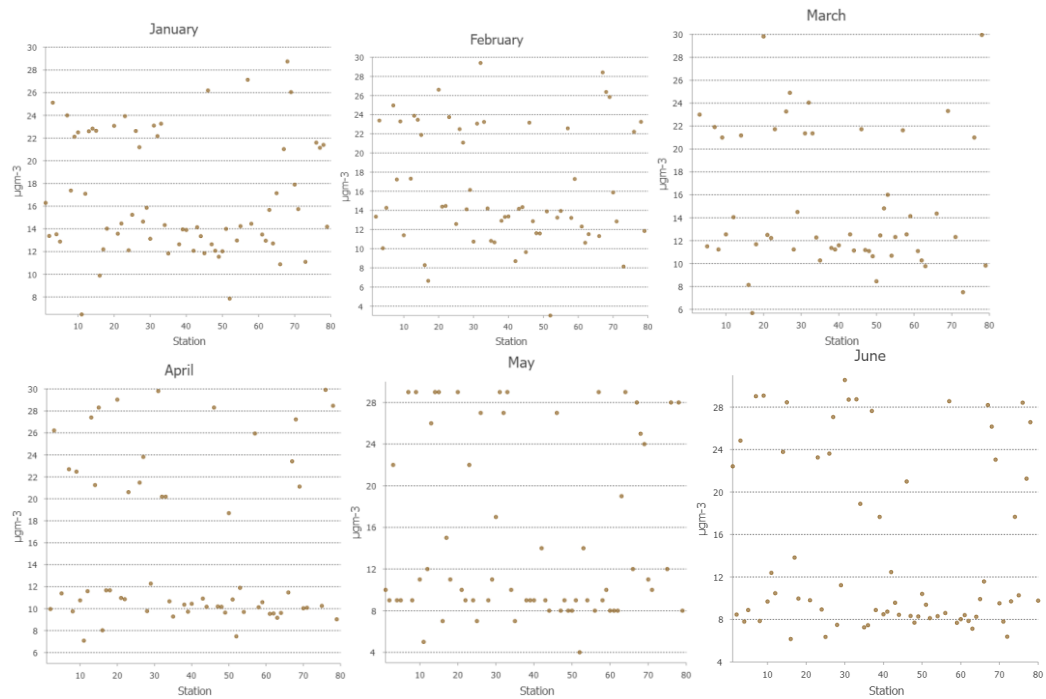
MRH WK	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	6,46	3,03	5,68	7,08	4,00	6,17	7,45	5,07	6,69	2,13	7,98	7,38
Maximum	28,75	29,41	29,95	29,92	29,00	30,55	34,76	28,55	59,85	42,25	33,55	37,05
Mean	16,69	16,25	15,12	15,31	15,02	14,60	14,97	14,01	16,21	16,42	17,53	19,46
StandardDeviation	5,19	6,15	5,91	7,35	8,53	8,22	7,12	7,32	8,72	7,36	6,41	6,88
Median	14,45	14,18	12,50	10,92	10,00	9,82	11,55	11,19	12,55	13,94	15,19	16,58
Skewness	0,50	0,38	0,82	0,81	0,72	0,77	0,97	0,75	2,13	0,90	0,89	0,63
Kurtosis	2,18	2,14	2,62	2,03	1,80	1,89	2,67	2,12	10,19	3,71	2,65	2,37

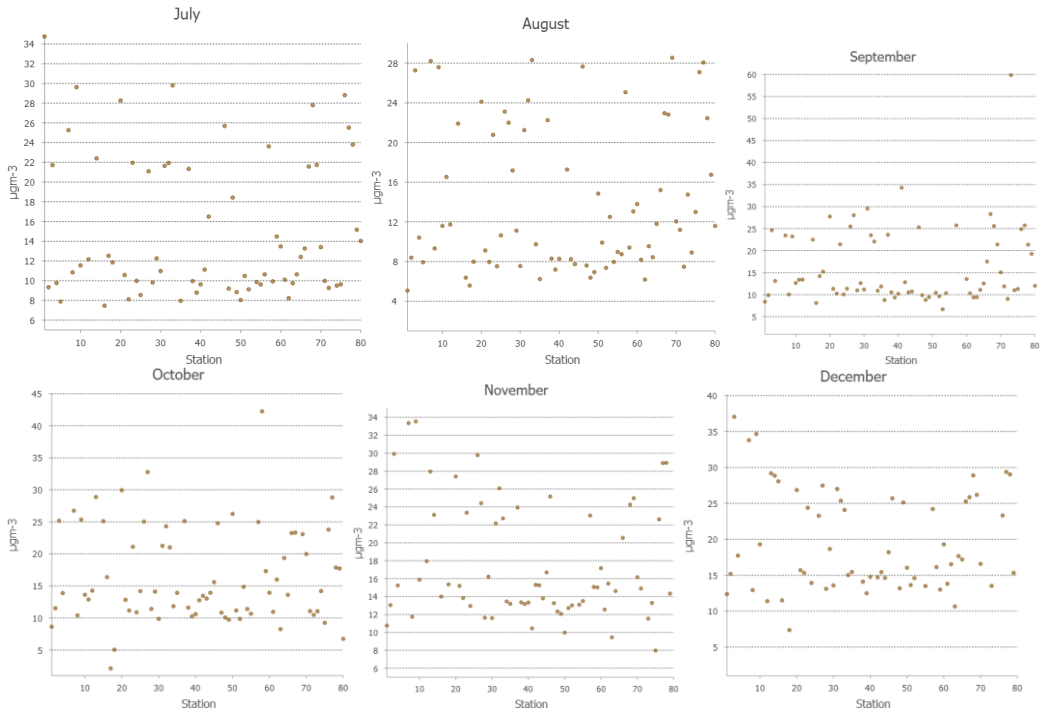
**Table 22A:** PM2.5 Morning Rush Hour Week Days Summary Statistics



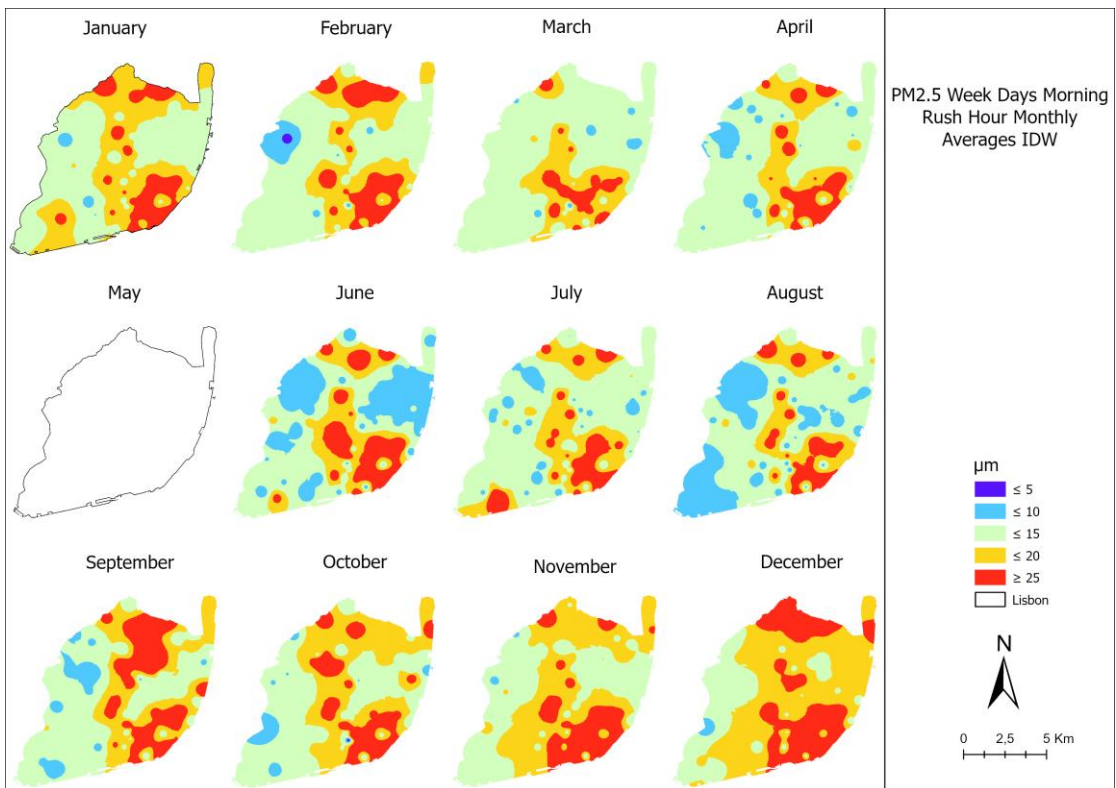


**Figure 34: PM2.5 Morning Rush Hour Week Days Histograms**





**Figure 35A:** PM2.5 Morning Rush Hour Week Days Scatter Plots

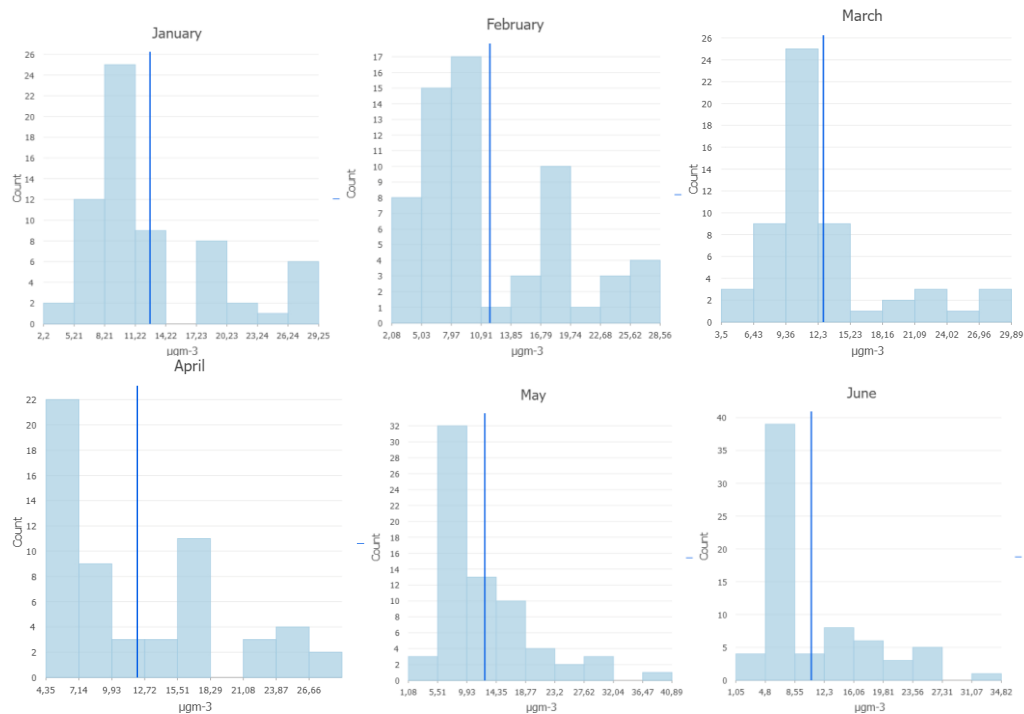


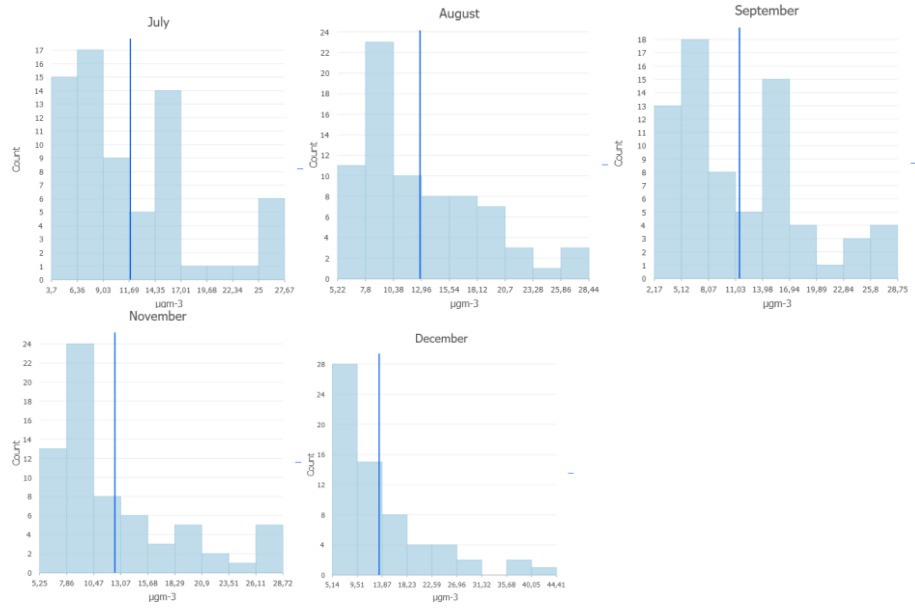
**Figure 36A:** PM2.5 Morning Rush Hour Week Days IDW

## A2.1.2 PM2.5 Morning Rush Hour Weekends

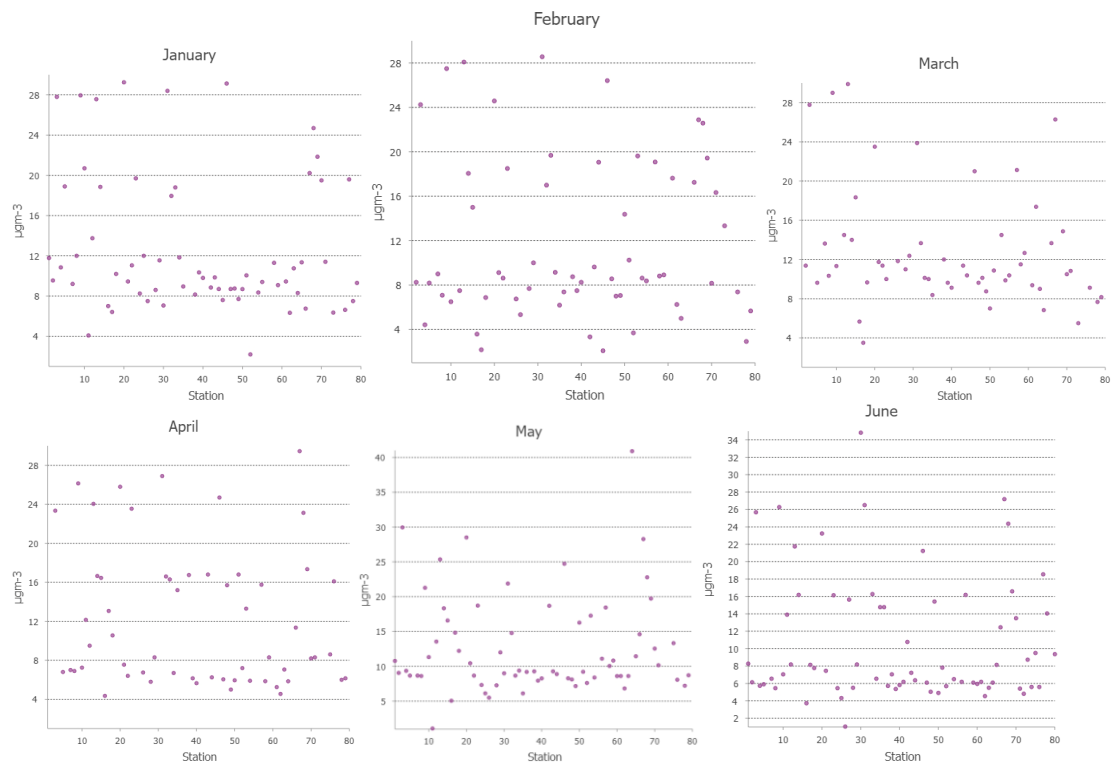
MRH WE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	2,20	2,08	3,50	4,35	1,08	1,05	3,70	5,22	2,17	2,22	5,25	5,14
Maximum	29,25	28,56	29,89	29,45	40,89	34,82	27,67	28,44	28,75	29,11	28,72	44,41
Mean	12,67	11,76	12,78	12,10	12,63	10,64	11,81	12,83	11,46	12,29	12,51	13,36
StandardDeviation	6,82	7,21	5,91	7,05	7,04	7,10	6,48	5,67	6,90	6,20	6,13	8,42
Median	9,85	8,75	11,00	8,30	9,39	7,45	9,61	10,89	9,25	10,71	10,00	9,91
Skewness	1,17	0,84	1,45	0,87	1,64	1,37	1,02	0,94	0,82	1,12	1,25	1,95
Kurtosis	3,29	2,57	4,50	2,55	5,97	4,17	3,21	3,15	2,79	3,63	3,61	6,60

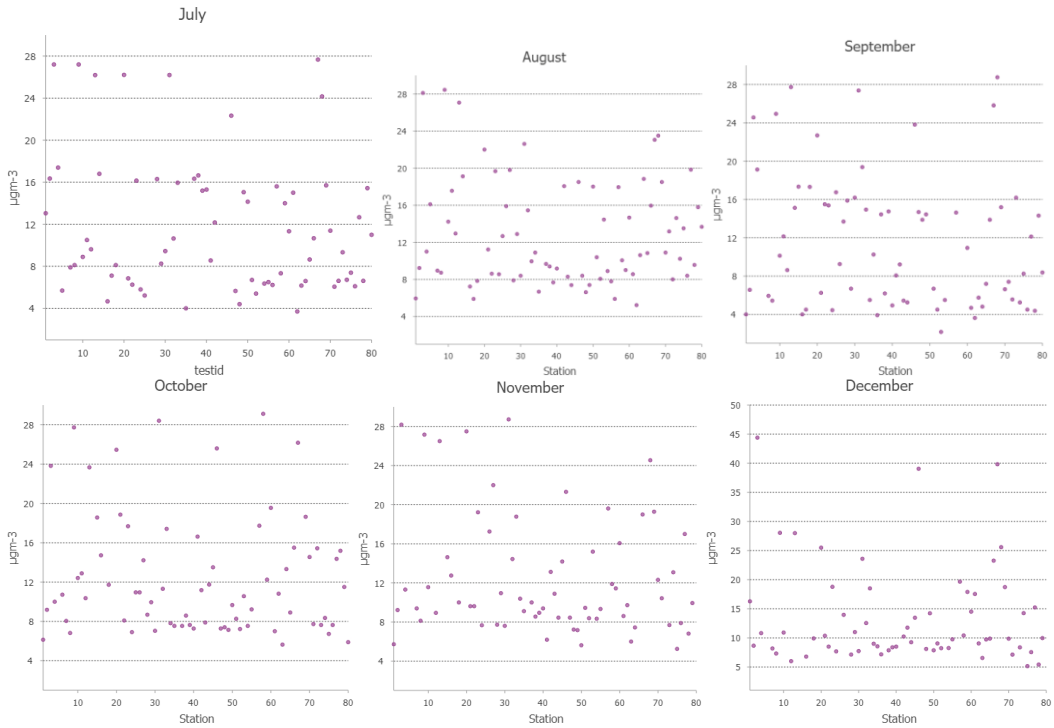
**Table 23:** PM2.5 Morning Rush Hour Weekends Summary Statistics



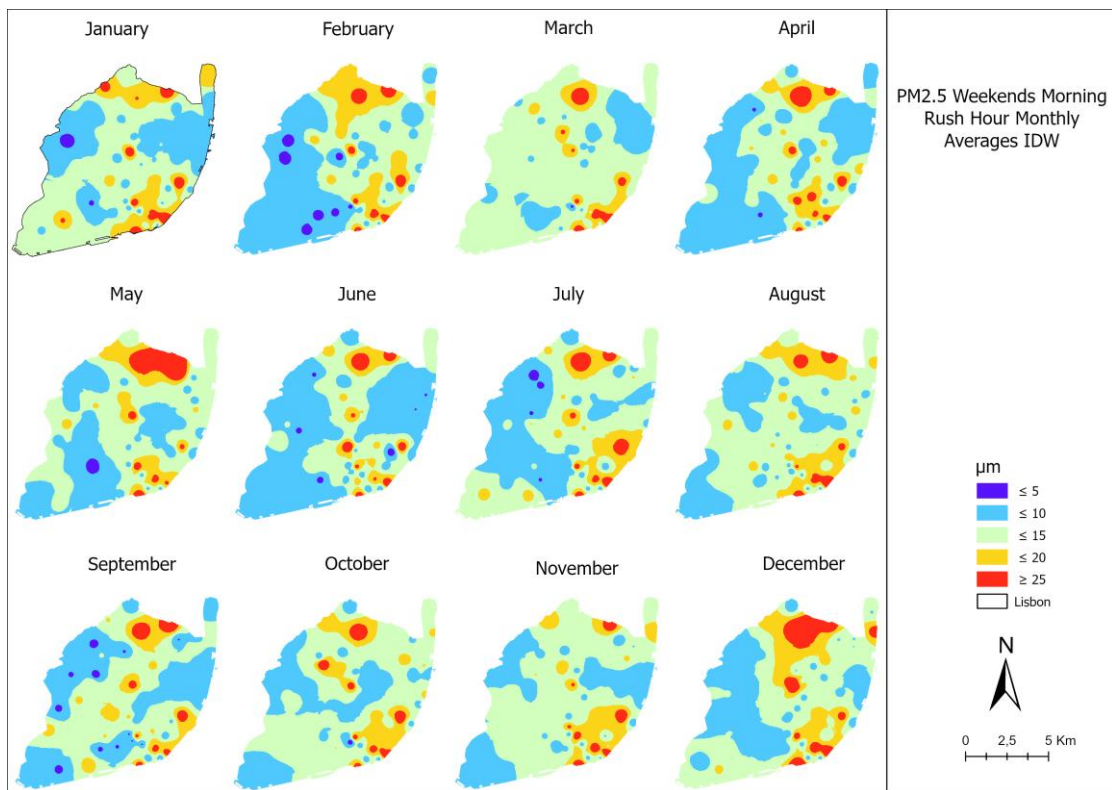


**Figure 37A: PM2.5 Morning Rush Hour Weekends Histograms**





**Figure 38A:** PM2.5 Morning Rush Hour Weekends Scatter Plots

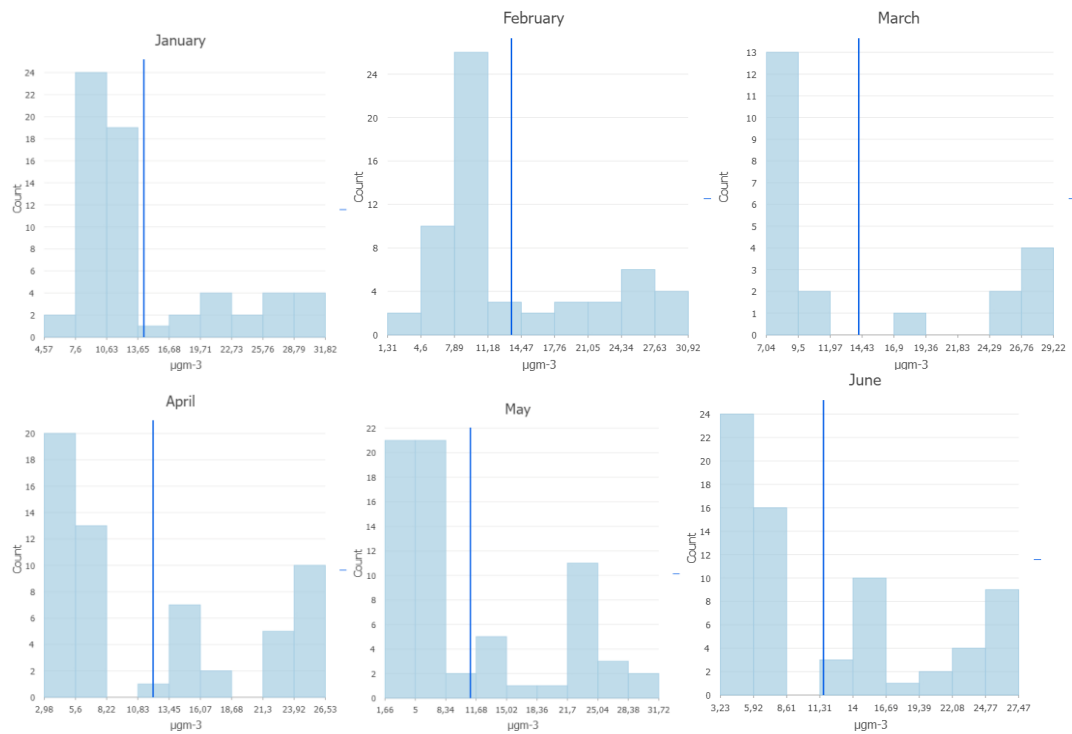


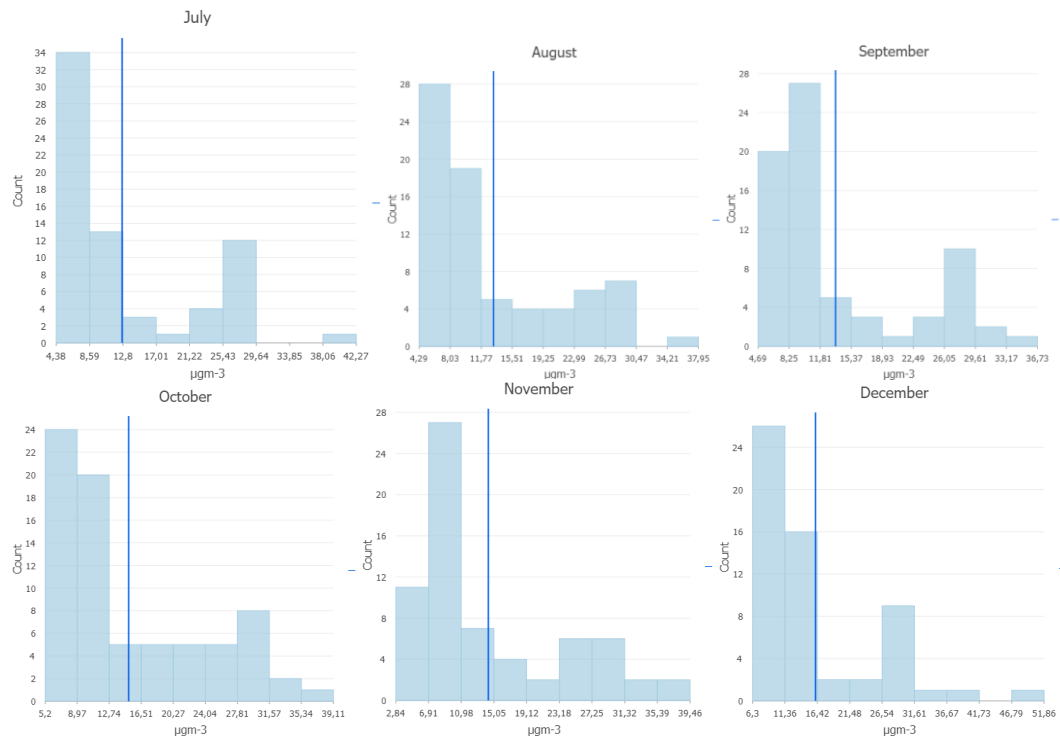
**Figure 39A:** PM2.5 Morning Rush Hour Weekends IDW

### A2.3. PM2.5 Off Rush Hour Week Days

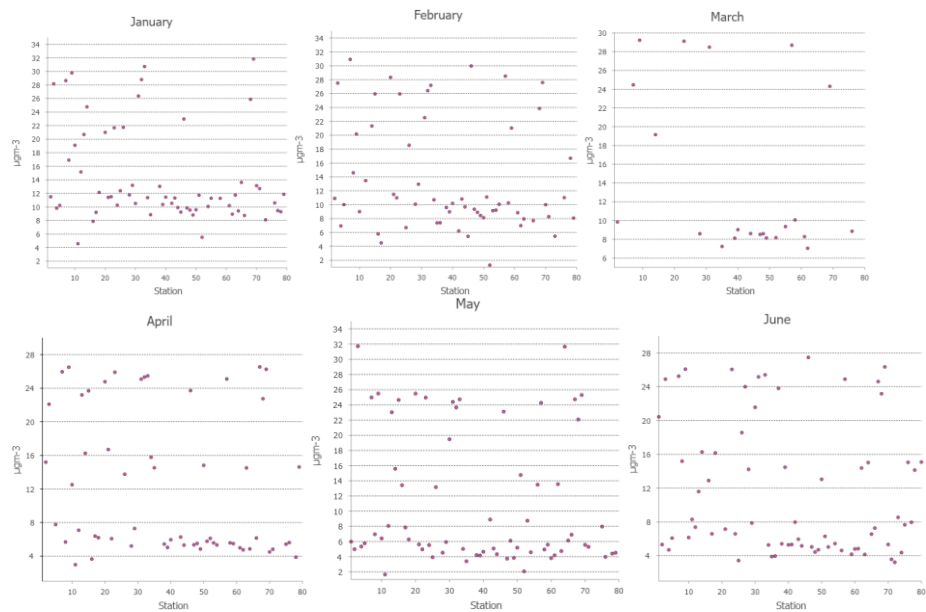
ORH WK	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	4,57	1,31	7,04	2,98	1,66	3,23	4,38	4,29	4,69	5,20	2,84	6,30
Maximum	31,82	30,92	29,22	26,53	31,72	27,47	42,27	37,95	36,73	39,11	39,46	51,86
Mean	14,22	13,50	14,18	12,10	11,04	11,61	12,69	13,27	13,58	15,04	14,35	16,14
StandardDeviation	6,95	7,88	8,67	8,40	8,74	7,91	8,93	8,19	8,27	8,66	9,37	9,82
Median	11,45	10,08	9,03	6,39	6,11	7,66	8,67	10,16	9,46	10,90	10,10	12,09
Skewness	1,22	0,92	0,91	0,66	0,96	0,77	1,18	1,03	1,17	0,93	0,99	1,49
Kurtosis	3,22	2,47	1,99	1,76	2,35	2,07	3,29	2,84	2,88	2,58	2,74	4,77

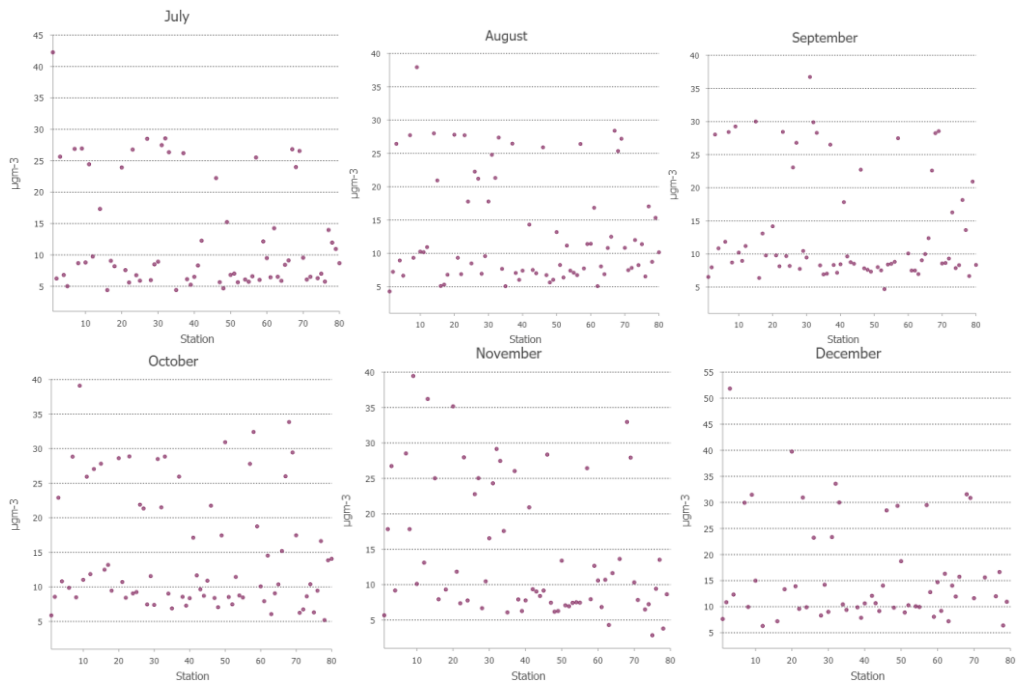
**Table 24A:** PM2.5 Off Rush Hour Week Days Summary Statistics





**Figure 40A: PM2.5 Off Rush Hour Week Days Histograms**





**Figure 41A:** PM2.5 Off Rush Hour Week Days Scatter Plots

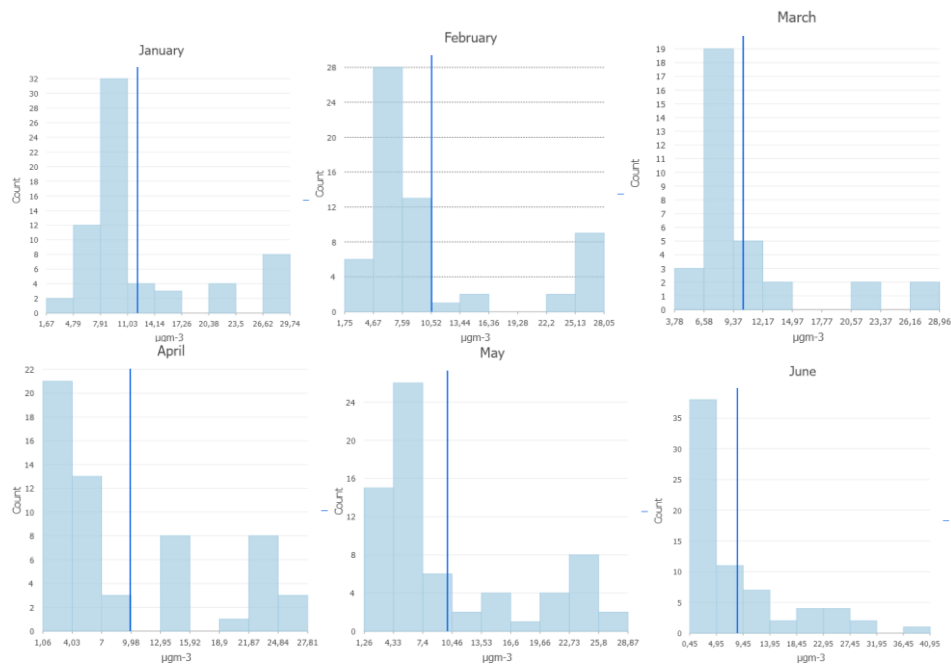


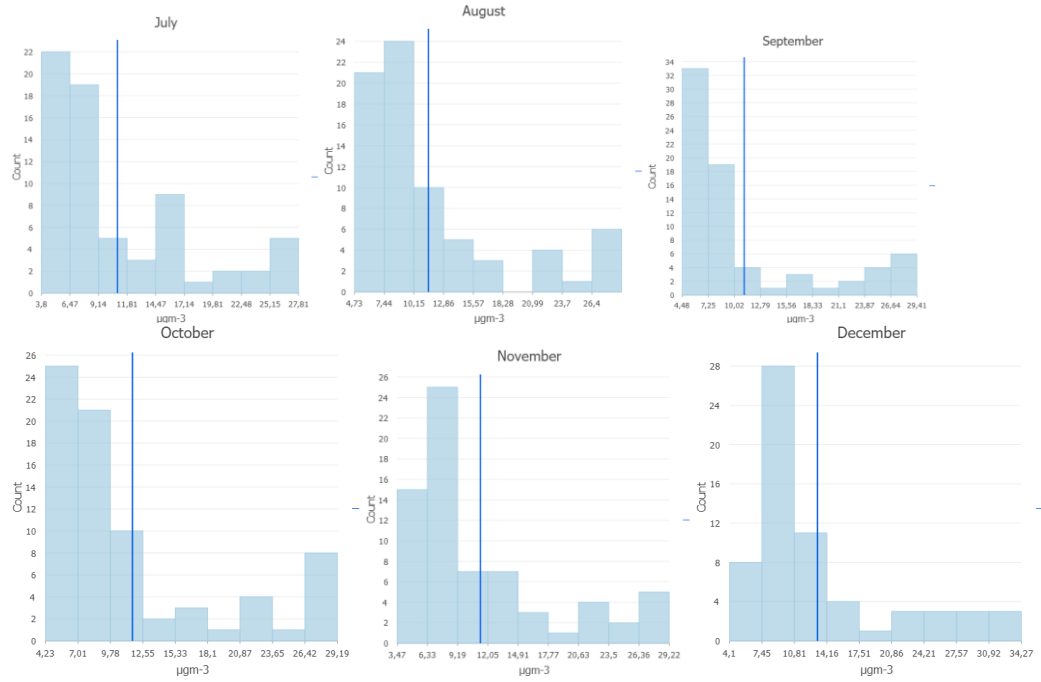
**Figure 42A:** PM2.5 Off Rush Hour Week Days IDW

## A2.4 PM2.5 Off Rush Hour Weekends

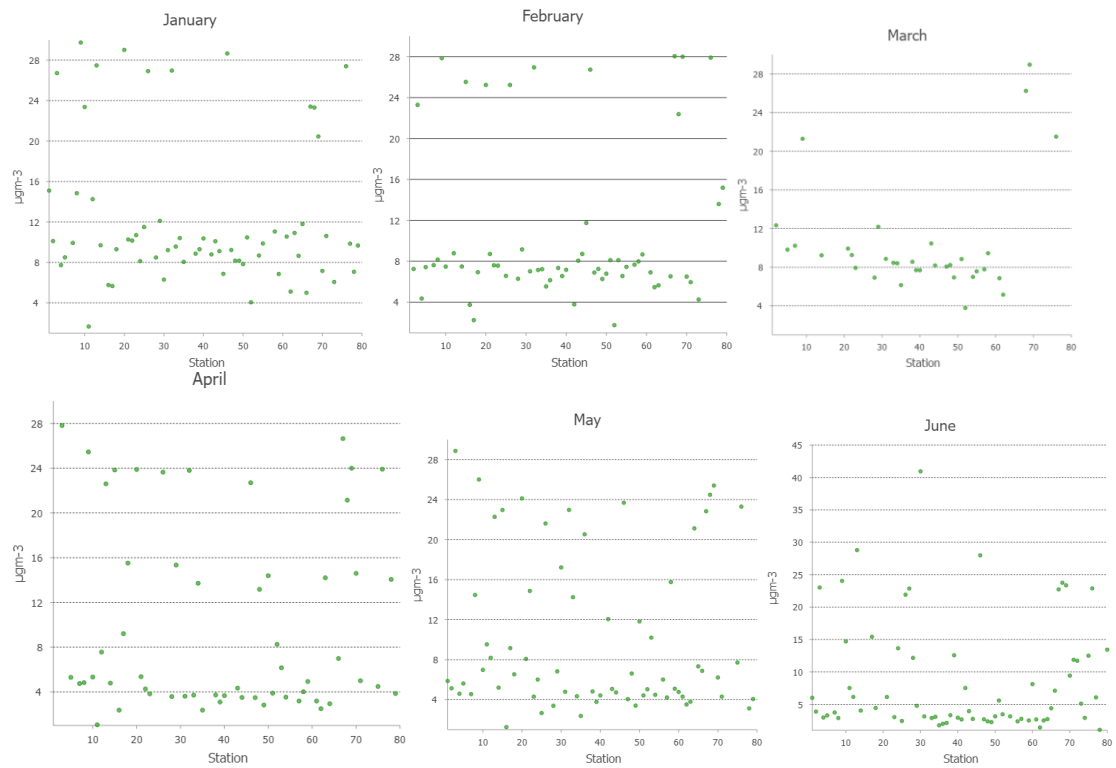
ORH WE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	1,67	1,75	3,78	1,06	1,26	2,45	3,80	4,73	4,48	4,23	3,47	4,10
Maximum	29,74	28,05	28,96	27,81	28,87	40,95	27,81	29,11	29,41	29,19	29,22	34,27
Mean	12,17	10,57	10,30	9,89	9,97	8,46	10,91	11,48	11,07	11,67	11,34	13,20
StandardDeviation	7,15	7,67	5,74	8,33	7,74	8,60	6,66	6,50	7,47	7,44	7,04	7,80
Median	9,86	7,45	8,45	5,00	6,21	4,04	8,10	8,73	7,39	8,30	7,98	9,21
Skewness	1,34	1,45	2,11	0,90	1,03	1,60	1,19	1,48	1,43	1,33	1,29	1,35
Kurtosis	3,54	3,52	6,55	2,24	2,55	5,03	3,26	4,07	3,46	3,37	3,41	3,51

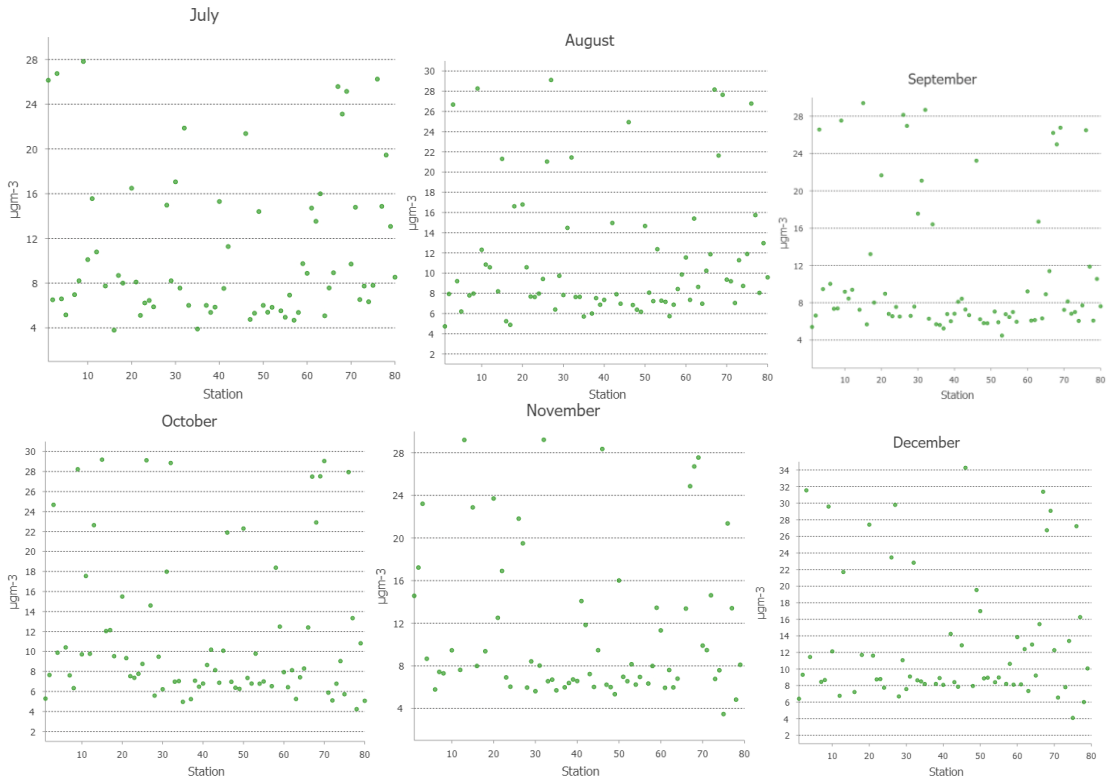
**Table 25A:** PM2.5 Off Rush Hour Weekends Summary Statistics





**Figure 43A: PM2.5 Off Rush Hour Weekends Histogram**





**Figure 44A:** PM2.5 Off Rush Hour Weekends Scatter Plots

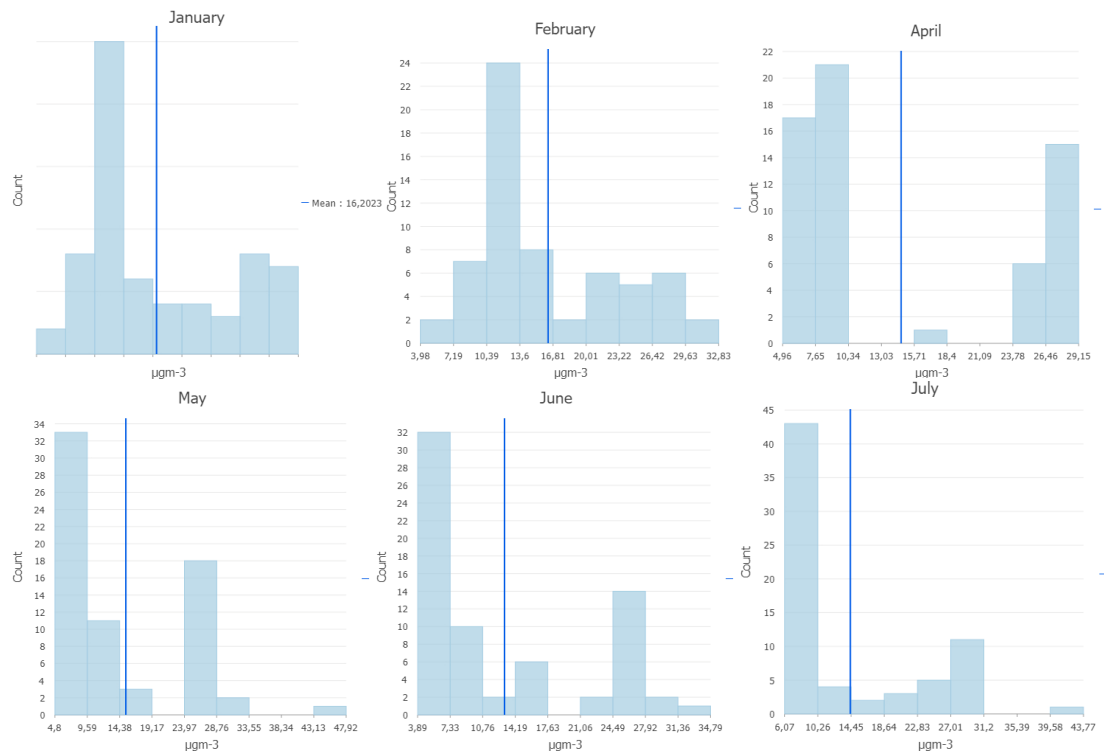


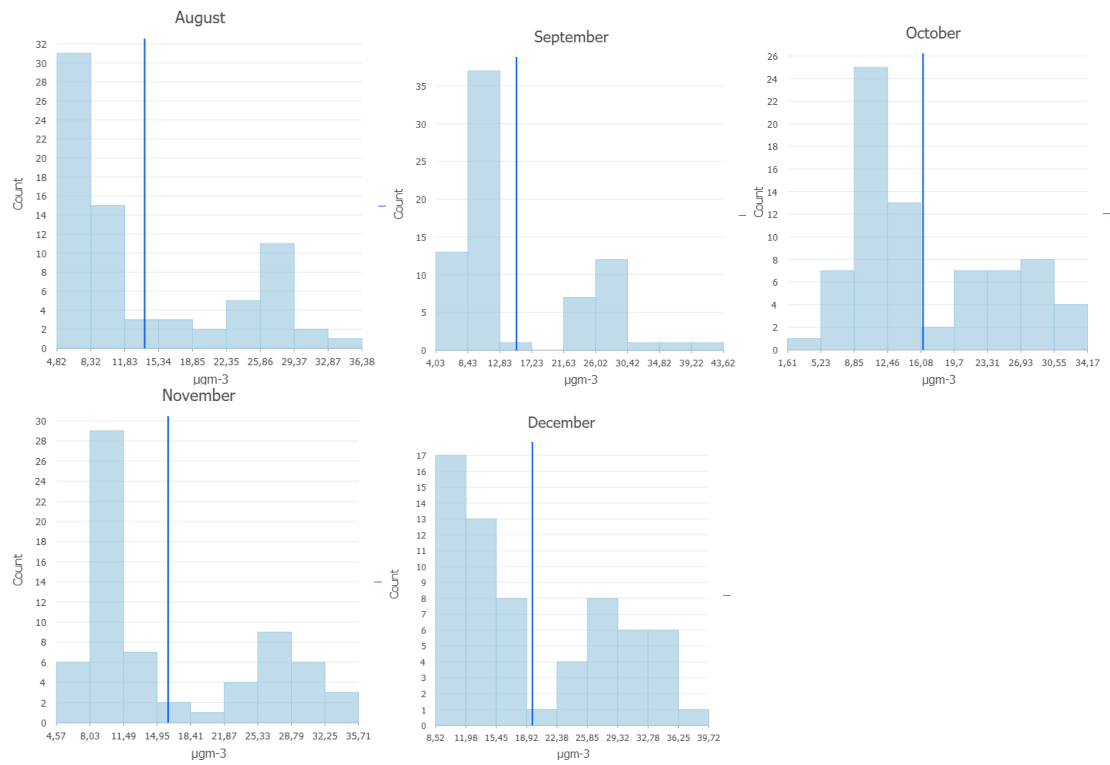
**Figure 45A:** PM2.5 Off Rush Hour Weekends IDW

## A2.5. PM2.5 Afternoon Rush Hour Week Days

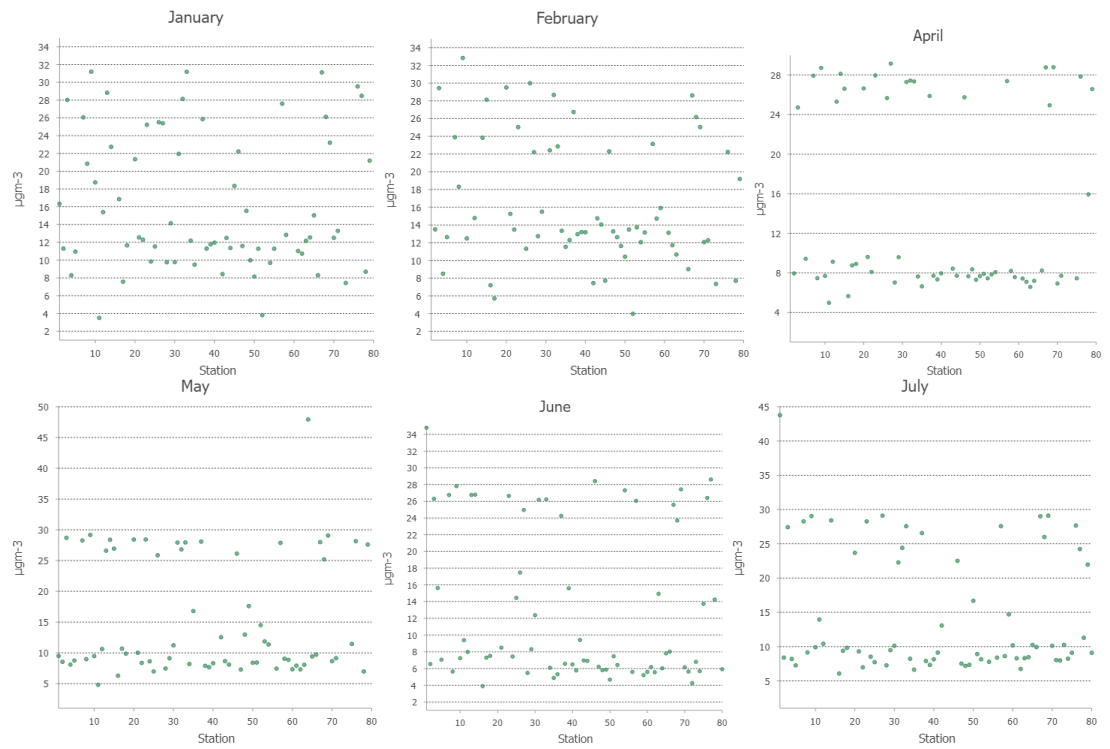
ARH WK	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	3,50	3,98		4,96	4,80	3,89	6,07	4,82	4,03	1,61	4,57	8,52
Maximum	31,19	32,83		29,15	47,92	34,79	43,77	36,38	43,62	34,17	35,71	39,72
Mean	16,20	16,34		14,65	15,31	13,06	14,36	13,90	15,13	16,31	16,09	19,58
StandardDeviation	7,60	7,16		9,33	9,54	9,12	8,87	8,75	9,54	8,01	9,04	8,91
Median	12,56	13,48		8,35	9,88	7,51	9,47	9,09	10,13	13,10	11,13	15,82
Skewness	0,57	0,61		0,60	1,03	0,81	1,13	0,89	1,08	0,57	0,70	0,54
Kurtosis	2,04	2,29		1,44	3,16	2,00	3,17	2,23	2,86	2,04	1,90	1,84

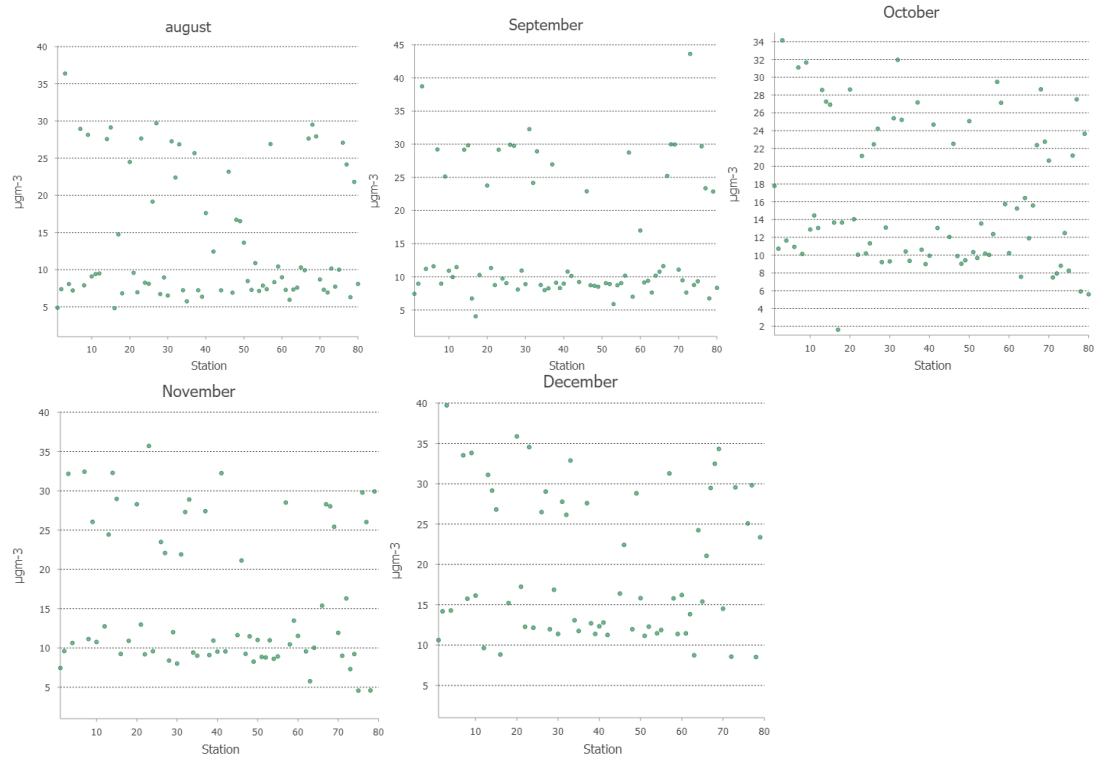
**Table 26A:** PM2.5 Afternoon Rush Hour Week Days Summary Statistics





**Figure 46A: PM<sub>2.5</sub> Afternoon Rush Hour Week Days Histograms**



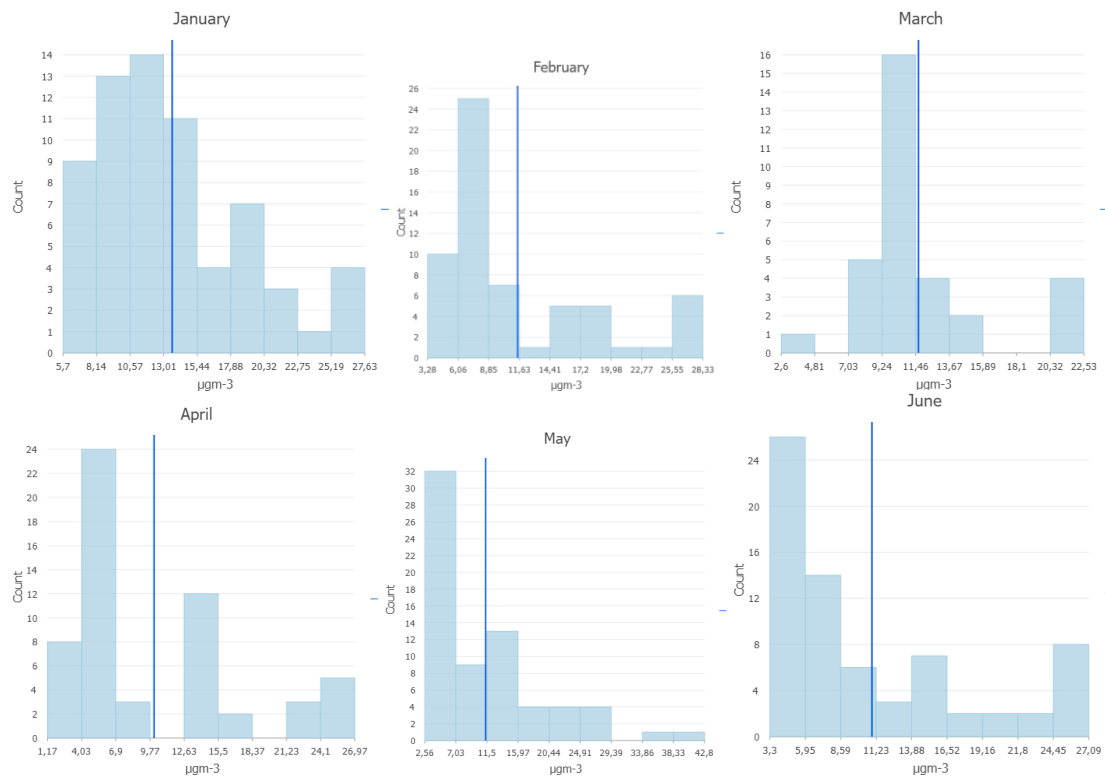


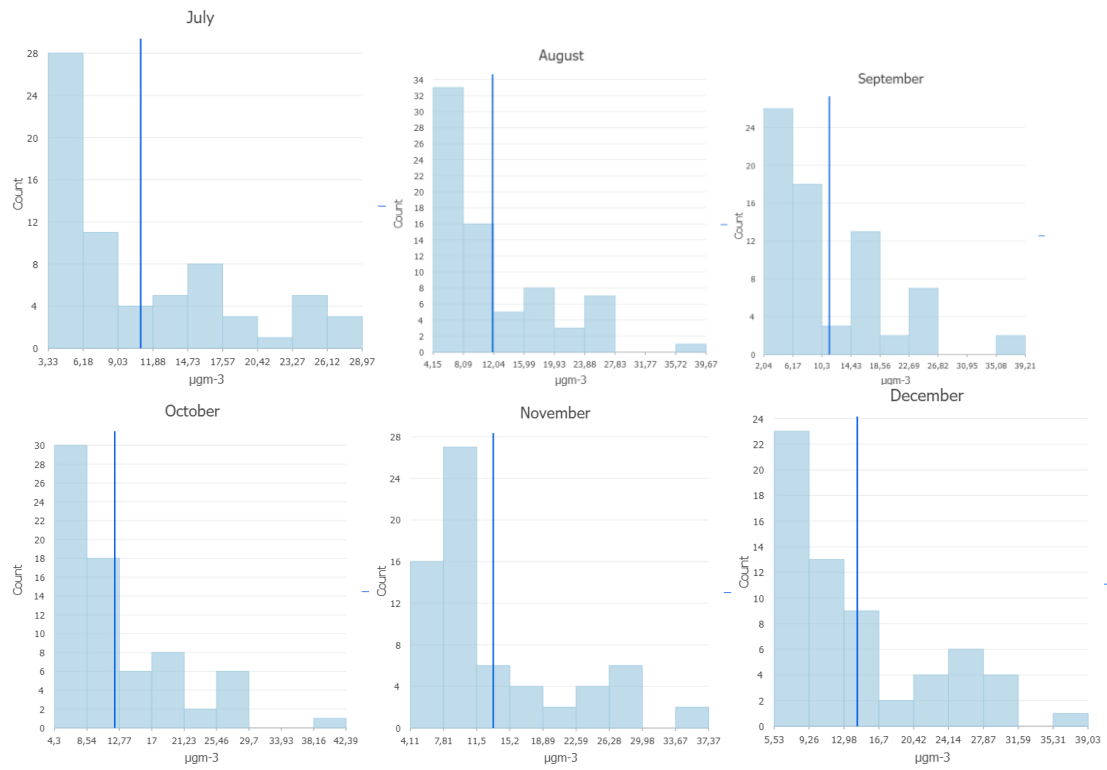
**Figure 47A:** PM2.5 Afternoon Rush Hour Week Days Scatter Plots

## A2.6. PM2.5 Afternoon Rush Hour Weekends

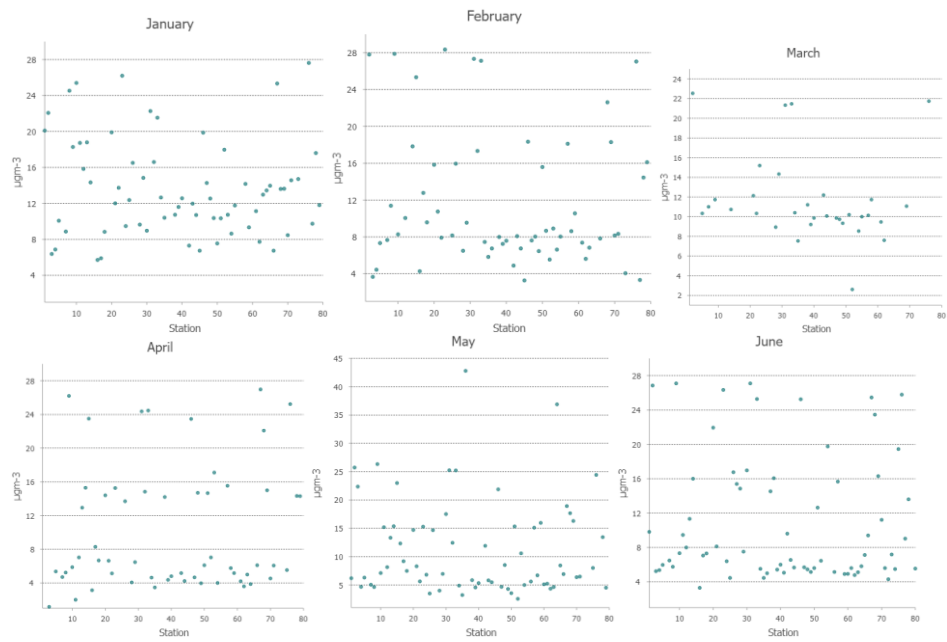
ARH WE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	5,70	3,28	2,60	1,17	2,56	3,30	3,33	4,15	2,04	4,30	4,11	5,53
Maximum	27,63	28,33	22,53	26,97	42,80	27,09	28,97	39,67	39,21	42,39	37,37	39,03
Mean	13,63	11,48	11,64	10,12	11,32	10,92	10,89	11,89	11,36	12,17	13,35	14,40
StandardDeviation	5,44	7,15	4,42	7,30	8,32	7,25	7,47	7,57	8,21	7,73	8,16	7,99
Median	12,57	8,17	10,33	6,10	8,00	7,30	6,80	8,93	7,42	9,15	10,11	12,17
Skewness	0,79	1,18	1,23	0,94	1,54	1,08	1,02	1,40	1,42	1,60	1,31	1,07
Kurtosis	2,91	3,24	4,39	2,64	5,42	2,81	2,82	4,41	4,63	5,37	3,61	3,20

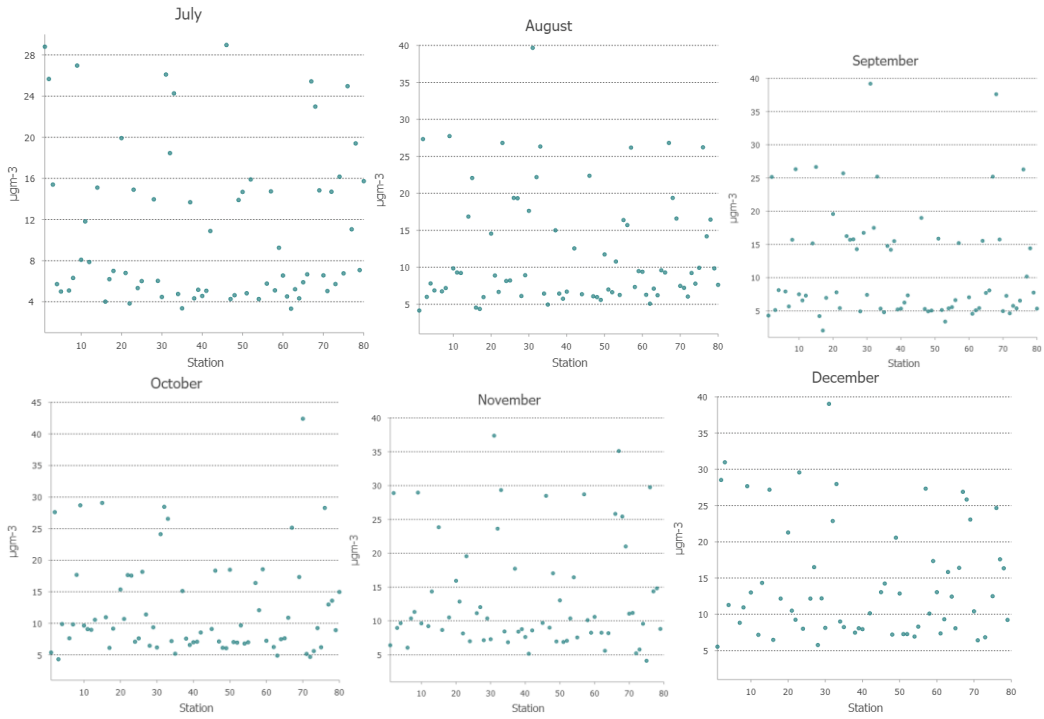
**Table 27A:** PM2.5 Afternoon Rush Hour Weekends Summary Statistics





**Figure 48A: PM2.5 Afternoon Rush Hour Weekends Histograms**

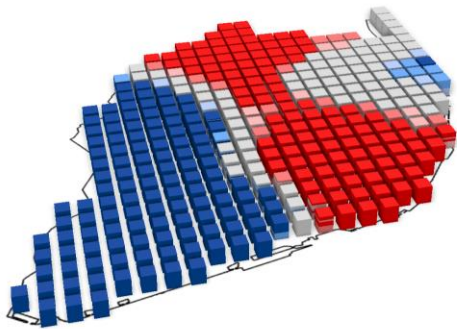




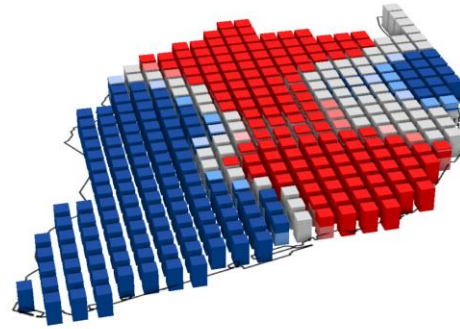
**Figure 49A:** PM2.5 Afternoon Rush Hour Weekends Scatter Plots

## APPENDIX – B

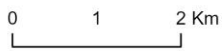
### PM10 ORH










Week Days

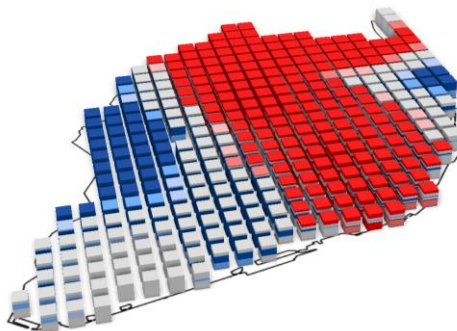


Weekends

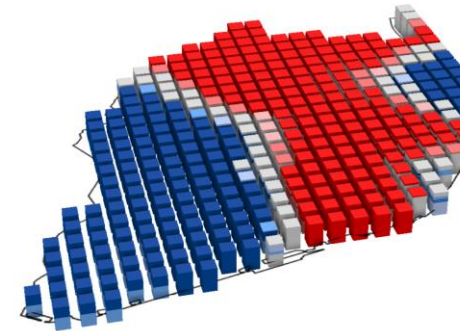


- |   |                           |  |                            |
|---|---------------------------|--|----------------------------|
|    | Hot Spot - 99% Confidence |   | Cold Spot - 90% Confidence |
|    | Hot Spot - 95% Confidence |   | Cold Spot - 95% Confidence |
|   | Hot Spot - 90% Confidence |  | Cold Spot - 99% Confidence |
|  | Not Significant           |  |                            |

### PM10 MRH




Week Days

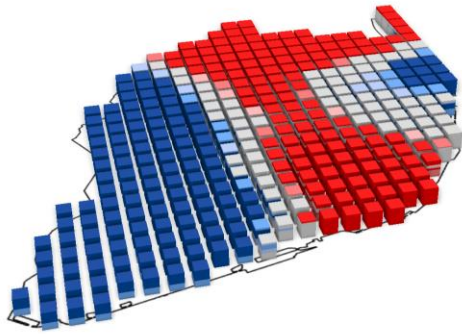


Weekends

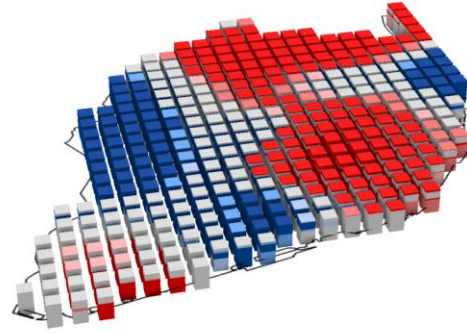


- |   |                           |   |                            |
|---|---------------------------|---|----------------------------|
|  | Hot Spot - 99% Confidence |  | Cold Spot - 90% Confidence |
|  | Hot Spot - 95% Confidence |  | Cold Spot - 95% Confidence |
|  | Hot Spot - 90% Confidence |  | Cold Spot - 99% Confidence |
|  | Not Significant           |   |                            |

## PM10 ARH



Week Days



Weekends

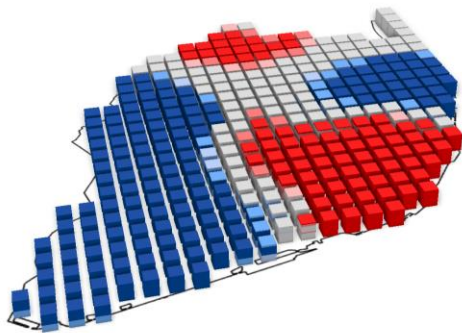
0 1 2 Km

- Hot Spot - 99% Confidence
- Hot Spot - 95% Confidence
- Hot Spot - 90% Confidence
- Not Significant

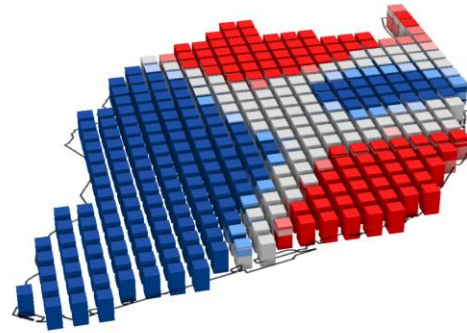
- Cold Spot - 90% Confidence
- Cold Spot - 95% Confidence
- Cold Spot - 99% Confidence

**Figure 50B:** 3D Visualization for PM10 Emerging Hot Spot Analysis

## PM2.5 MRH



Week Days



Weekends

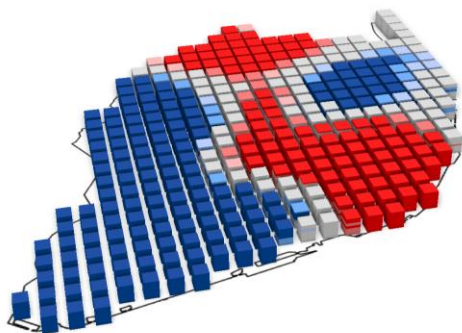
0 1 2 Km

- Hot Spot - 99% Confidence
- Hot Spot - 95% Confidence

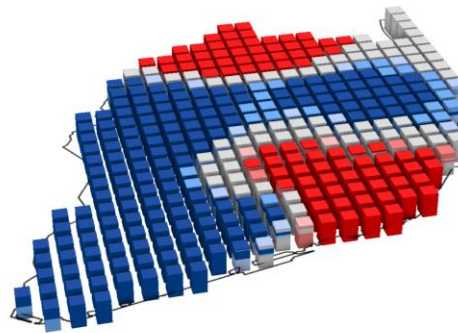
- Hot Spot - 90% Confidence
- Not Significant
- Cold Spot - 90% Confidence

- Cold Spot - 95% Confidence
- Cold Spot - 99% Confidence

## PM2.5 ORH



Week Days

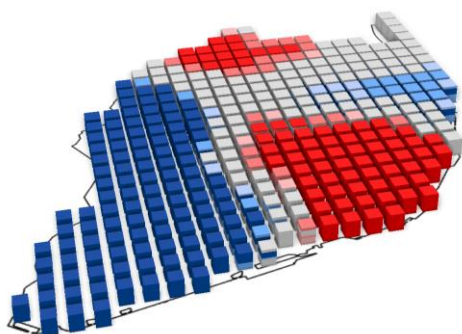


Weekends

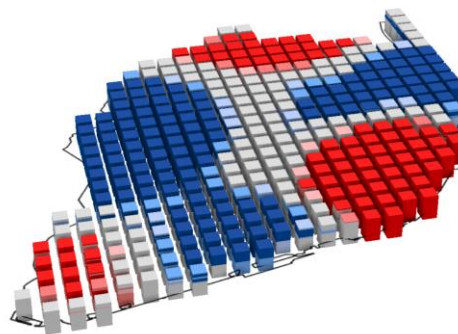


- |                           |                            |                            |
|---------------------------|----------------------------|----------------------------|
| Hot Spot - 99% Confidence | Hot Spot - 90% Confidence  | Cold Spot - 95% Confidence |
| Hot Spot - 95% Confidence | Not Significant            | Cold Spot - 99% Confidence |
|                           | Cold Spot - 90% Confidence |                            |

## PM2.5 ARH



Week Days



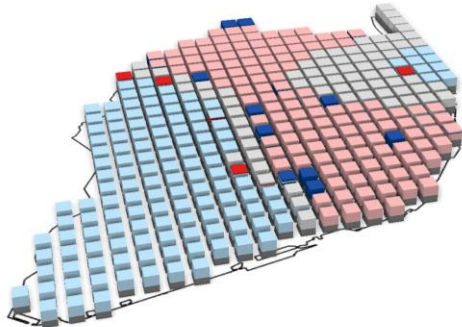
Weekends



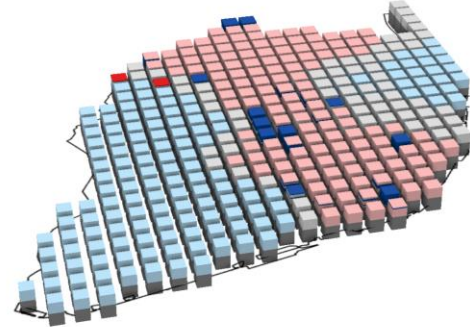
- |                           |                            |                            |
|---------------------------|----------------------------|----------------------------|
| Hot Spot - 99% Confidence | Hot Spot - 90% Confidence  | Cold Spot - 95% Confidence |
| Hot Spot - 95% Confidence | Not Significant            | Cold Spot - 99% Confidence |
|                           | Cold Spot - 90% Confidence |                            |

**Figure 51B:** 3D Visualization for PM2.5 Emerging Hot Spot Analysis

## PM10 ORH

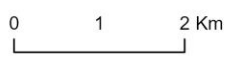


Week Days

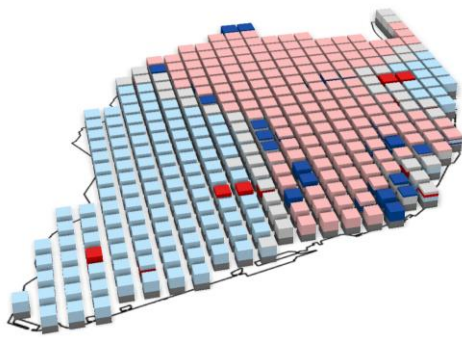


Weekends

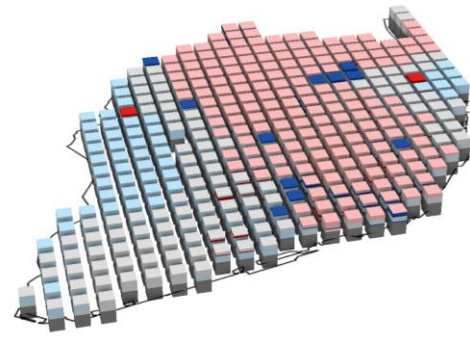
- Initial Time Step
- Not significant
- High-High Cluster
- High-Low Outlier
- Low-High Outlier
- Low-Low Cluster



## PM10 MRH

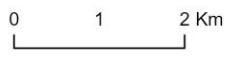


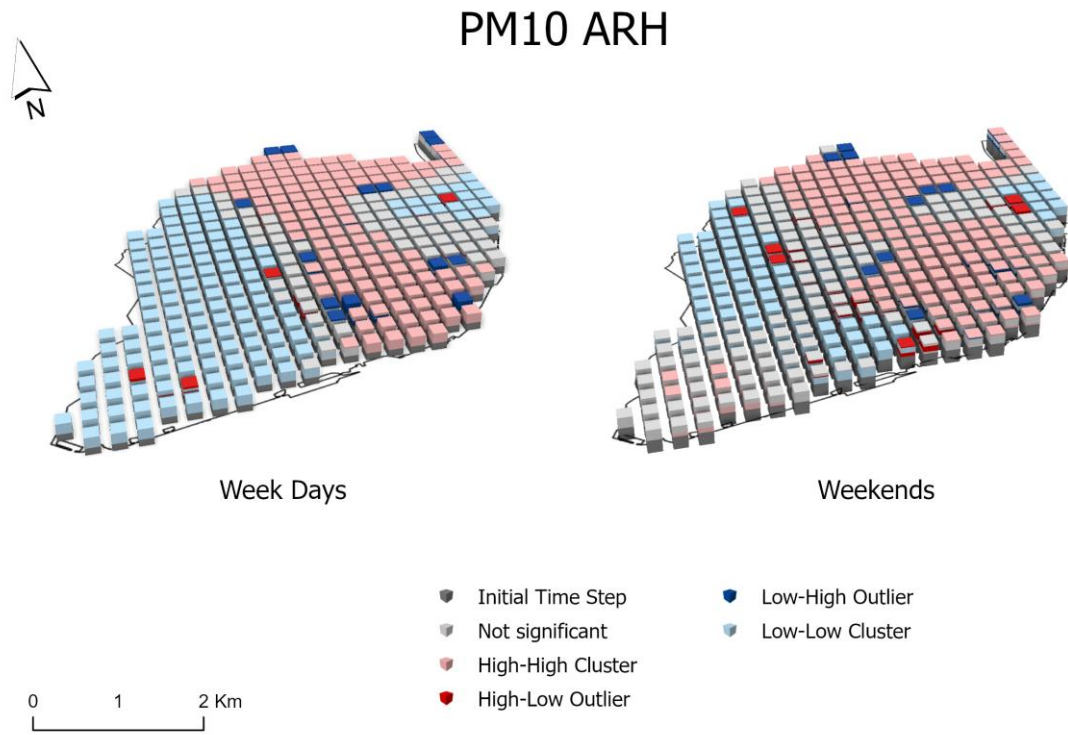
Week Days



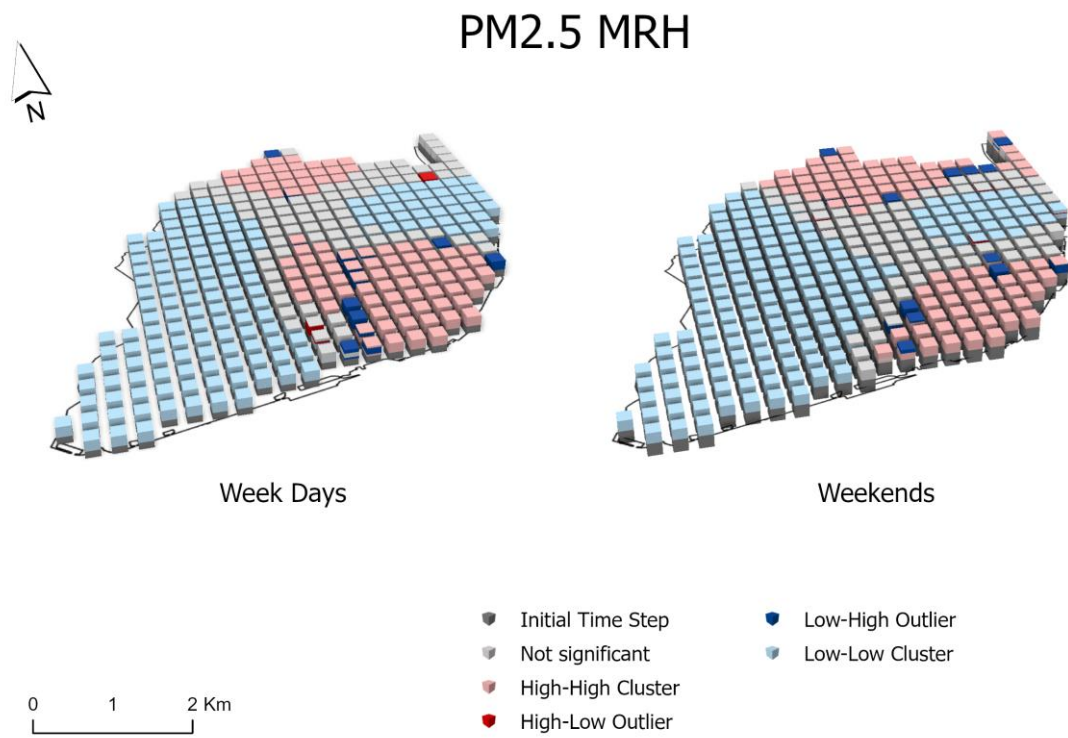
Weekends

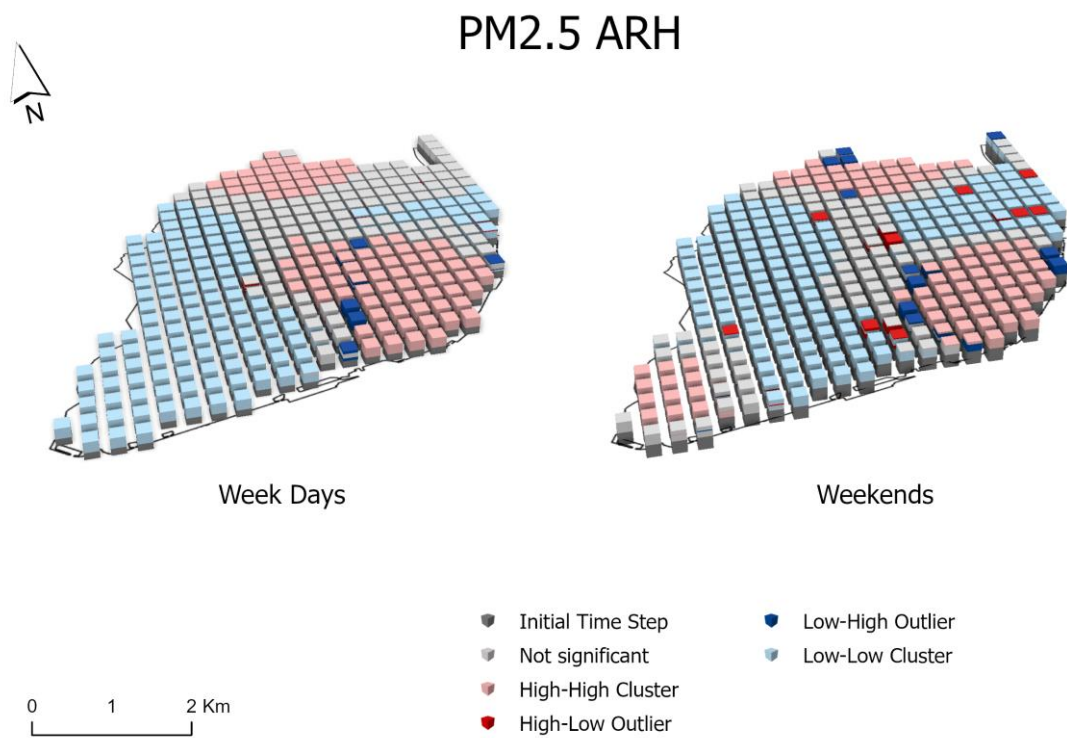
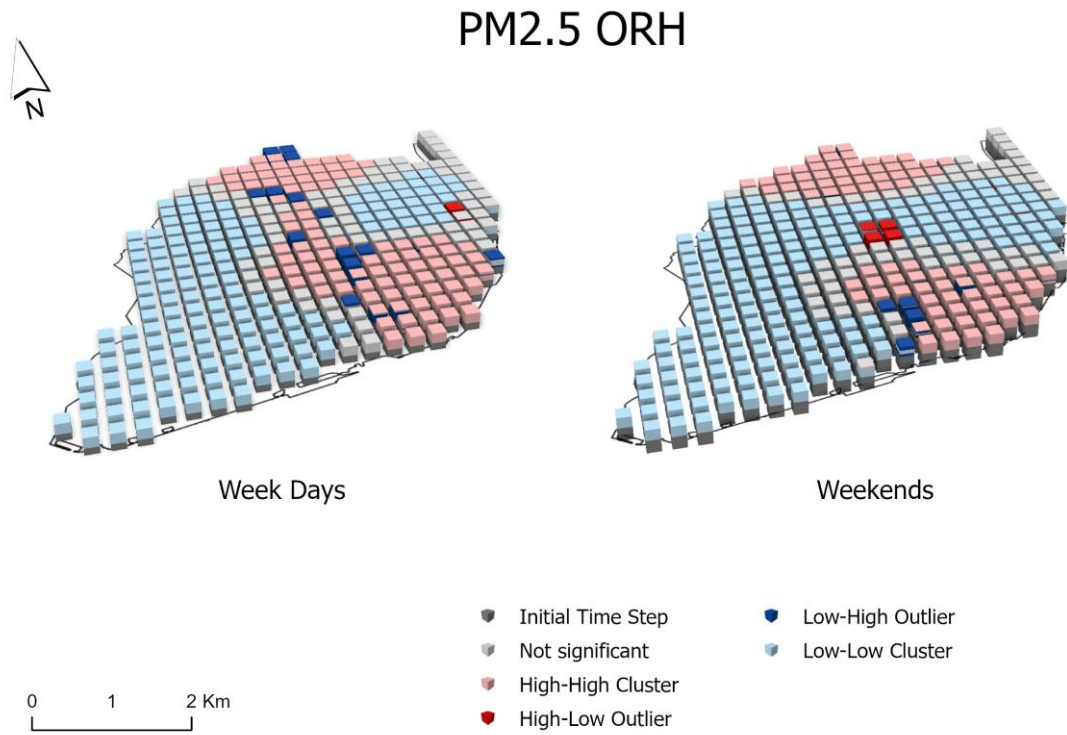
- Initial Time Step
- Not significant
- High-High Cluster
- High-Low Outlier
- Low-High Outlier
- Low-Low Cluster





**Figure 52B:** 3D Visualization for PM10 Local Outlier Analysis





**Figure 53B:** 3D Visualization for PM2.5 Local Outlier Analysis

2024

Spatiotemporal Analysis of PM10 and PM2.5 with EBK3D and Space-Time  
Cube in the City of Lisbon, Portugal

João Maria Telo Abreu Jardine Neto



Masters  
Program  
in **Geospatial  
Technologies**

